# Is enhanced radiative cooling of solar cell modules worth pursuing?

A.R. Gentle and G.B. Smith
School of Mathematical and Physical Sciences
University of Technology Sydney
PO Box 123, Broadway NSW 2007 Australia

**Abstract**
Recent suggestions that worthwhile additional cooling of 1.0°C to 1.5°C below what glass covers in solar cell modules already achieve, hence raised power output, will occur via enhanced thermal radiation to the sky with special nanostructures, is examined. Rigorous thermal models indicate these observations require a much lower hemispherical emittance ($E_H$) for the benchmarks of silica and glass covers near 0.75. If the currently accepted value for $E_H$ of glass of 0.84 applied even $E_H = 1.0$ would provide inadequate extra cooling. An accurate angular emittance profile for glass does predict this lower $E_H$. Complete models include solar heating, heating by atmospheric radiation, cooling by convection and side/base losses. Unfortunately any large lift in radiative output from raised $E_H$ at normal cell temperatures is mostly annulled by the accompanying fall in convective cooling. The link of $E_H$ to angular IR response points the way to novel coating approaches which may achieve the desired cooling gains. This has wider implications for buildings and other solar technologies. Direct power gains from accompanying anti-reflectance add value.

Keywords : Si solar cells, radiative cooling, hemispherical emittance, glass

## 1. Introduction
It is well known that each degree of cooling of a silicon solar cell can add 0.4% to 0.5% to its power output. Thus extra average cooling of a cell by more than 1.5°C above what current good module practice achieves in any location might be worthwhile. Recent reports using modified radiative cooling [1-3] aroused much interest. The impression arises that worthwhile power gains by enhancing output of thermal radiation relative to that from current modules are achievable. While aspects of these studies contain intrinsically interesting science detailed quantitative analysis of each of the contributions to heat gains and cooling rates in standard Si PV cell module designs indicates that an emphasis on extra radiative cooling alone will have little benefit. We show that the weak gains in heat radiated out from raised emittance relative to glass are largely annulled at the relevant temperatures by an associated drop in convective loss. Specific examples follow for a relevant range of hemispherical emittance values. It is very important that any new approach accurately references a correct benchmark for cells in current modules. The starting point for extra cooling is not a bare doped Si wafer or bare PV cell but these under glass. Glass emits more radiant heat than a silica cover as glass has a slightly higher emittance. Since silica was the reference module cover used in [2] the cooling observed will have been larger than if glass was used. Cells in glass covered modules are already cooler by around 5°C compared to the bare wafer system from a combination of

(i) net radiative cooling off the glass (ii) convective cooling of the glass cover at average local wind speeds (iii) those thermal losses which arise at other module surfaces due mainly to conduction and convection. (iv) the net generation of heat by the silicon cell. Each of these four aspects of PV module cooling and heating, from a detailed modeling perspective are addressed in section 2. The dependence of glass and silica spectral response at all angles of incidence (from normal to 90°) across the Planck (black body) radiation range from 2.5 μm to 35 μm plays a central role in assessing what material modifications might best achieve extra module cooling. These optical properties are also essential for an accurate estimate of heat gained from absorption of incoming atmospheric radiation.

Raising hemispherical emittance ($E_H$) of solar transmitting module covers to close to that of a black body, was a core purpose of the nanostructured solar transmitting surface reported in reference [2]. Achieving this will enhance net radiation output. However the detailed thermal analysis in sections 2 and 3 following shows that impact on average daytime module operating temperature of an $E_H$ value approaching 1.0 remains small when a complete thermal analysis is carried out. Raising the $E_H$ value close to that of a true black body was also not well demonstrated. This is a common issue because accurate estimates of $E_H$ values of materials which emit well is not straightforward. We will show that it is very important to accurately include contributions to emission which emerge at very oblique angles to the surface, that is in the zone 75° to 90° to the normal. However absorption or emission data in this zone is difficult and sometimes impossible to acquire experimentally. Thus it is often implied or estimated by extrapolation. For example it is hard to measure reflectance accurately at angles of incidence above 70° to 80°.

More specifically we will demonstrate for glass, for silica, and in general, that even if IR reflectance is very low out to angles of incidence up to around 65°, this condition is not sufficient to ensure a very high $E_H$. Reflectance must also not fall away significantly at angles of incidence from 70° to 90°. Such a fall off is however highly likely if the surface is effectively seen to be smooth and hence specular by incoming IR radiation. For common smooth surfaces IR reflectance increases as incidence angle rises. This detracts from the goal of a very high emittance since *a radiative cooling rate close to that of a black body requires that emittance in all exit directions remains very high.* Both float glass and smooth silica are specular for IR radiation. In sections 3 and 4 we model the evolution of $E_H$ as the angular aperture about the normal opens wider. This shows for smooth glass and silica, that emission in very oblique directions has a major impact on cooling rates, making them lower than often expected. This analysis also provides a better understanding of the PV cooling observations reported in reference [2].

Improved accuracy in defining hemispherical emittance ($E_H$) and the flow on from that to better discrimination between different materials and surface structures according to their ability to radiate, is important elsewhere in the energy and environmental sector. For example the influence of angular dependence of IR response on hemispherical emittance will impact on heat flow from roofing, walls and windows into buildings. Cool roofs generally require a very high hemispherical emittance. However some special exceptions are worth noting. A very special recent category of cool roofs with solar absorptance below ~4% [4,5], along with surfaces developed specifically for use in some night sky cooling systems can ultilize mid-range $E_H$ values, of order 0.6 to 0.3. These emit strongly only at wavelengths where the atmosphere is transparent, while reflecting most incoming atmospheric IR radiation. Their ideal performance limit is thermal equilibrium with space. In these even more atmospheric radiation is reflected if surface reflectance rises with angle of incidence because the atmosphere radiates more strongly in directions closer to the horizontal. This is the exact opposite angular behaviour of what we will show is required of the best solar module covers which need $E_H$ close to 1.0. Such mid-$E_H$, IR spectrally selective surfaces should only be contemplated if their systems spend most of their operating time below or just above ambient [10], and thus they should not be considered for PV module covers, or the majority of cool roofing.

## 2. Heat flow analysis

The four components of heat gain or loss that must be included in any comprehensive analysis of PV cell cooling were listed in the introduction. Net radiative cooling [item (i)] is the difference between emitted and absorbed infra-red radiation. The emitted radiation is determined by the hemispherical emittance of the cover's outer surface ($E_H$) and its temperature ($T_{cover}$). The amount of absorbed thermal radiation varies with the surface material, and the intensity of incoming IR radiation from the sky. The emittance properties of the atmosphere, and ambient temperature ($T_a$) determine this incoming irradiance. In summer incoming IR from the sky can reach around 350 to 400 $Wm^{-2}$ so cannot be ignored, though solar heating still dominates overall heat gain. A common approximation is to treat the clear sky as a black body emitting at a temperature $T_{sky}$ which is lower than ambient. More accurate treatments, as used in our modeling here and in reference [2], utilize the full IR spectral absorptance of the cover and the incoming IR spectral density of atmospheric radiation. Both vary with incidence angle. Humidity also impacts strongly on the angular profile of the incoming IR radiation, and this variation is included explicitly and accurately in our models.

The main heat input, item (iv), is absorbed solar energy less electric power delivered to an external load. Convective cooling, item (ii), depends on local wind speed, and for operating modules it dominates total cooling rate. Any test system which suppresses convective loss and raises temperatures above normal operating temperatures is a not an ideal guide in this work as a rise in steady state temperature will enhance cooling by radiation. Item (iii), side and base losses, are the minor components of cooling but must be included in a full analysis. Their magnitude is estimated using an effective U value for the module.

The decrease in radiative cooling off smooth glass due to an increase in IR reflectance at exit angles above 50° is further compounded by the extra geometric weighting at oblique incidence angles from the larger solid angles in this zone. This high angle impact is quantified in a novel way in this study. We will also show that even a black body solar transmitter at all exit angles has only moderate output gain to offer a PV module. A high IR absorptance in this high angle of incidence zone is hard to achieve in smooth or nanostructured covers with high solar transmittance. As reported in the 1980's by Rubin's group at LBNL [4, 5] there was a wide spread in the various experimental $E_H$ values reported for glass. IR data to the highest exit angles is rarely available while good calorimetric data is limited. The rigorous calorimetric study by Schleiger [6] found that for silica $E_H$=0.73 ± 0.3. Our thorough analysis following predicts the glass $E_H$ value to be 0.75, not 0.84 as commonly accepted, and for silica it predicts $E_H$ = 0.73 in agreement with [6].

As a result of the uncertainties in data a modeling approach to IR absorptance from 75° to 90° was needed for this range [4, 5]. We outline below how that approximate analysis led to higher than actual values of $E_H$. Accurate modeling at high angles is possible when the complex indices n(λ), k(λ) are well specified. The old approach led to the widely used $E_H$ value for glass of 0.84 and a standard ratio of $E_H/E_0 \sim 0.93$ for high emittance specular materials. $E_0$ is normal incidence emittance as found usually by IR spectrophotometers and for glass is ~0.89 at room temperature. This $E_H/E_0$ ratio is useful as many laboratories can measure $E_0$ but not $E_H$. Unfortunately the approximate algorithms used in the early work appear to have under-estimated IR reflectance of glass at very high incidence angles. Our analysis is based on accurate n, k values for glass which are close to those used in the early study [4, 7]. The important differences we now uncover are thus traceable to divergences in the model accuracies at high angles of incidence. Agreement is close at angles of incidence up to around 75° but despite this we will show that the $E_H/E_0$ ratio for glass is close to 0.8 with $E_H$ = 0.75.

We add support to this finding by showing that the recently observed extra PV cooling achieved with a special nano-cover relative to that found with a silica cover [1] can only have arisen because the silica had $E_H$ value near 0.73. We also show that if the $E_H$ value of current PV module covers was the commonly accepted glass value 0.84 this would almost eliminate extra cooling as a viable possibility. However our accurate value of around 0.75 may still make it just viable.

This issue of underestimating the hemispherical emittance integral goes well beyond solar cell cooling to other solar technologies, and to defining building surfaces thermally in energy simulation models. It also points to a need to re-examine related standards for determining hemispherical emittance of dielectrics. We foreshadow this in a detailed more general upcoming study of hemispherical emittance and IR angular properties. Hemispherical emittance accuracy becomes more important the hotter a radiating surface gets relative to ambient. The range 40°C to 50°C common in solar cells with no concentration is only 15°C to 25°C above ambient temperature. Such conditions still require a good estimate of the hemispherical emittance ($E_H$) for exploring whether worthwhile cooling gains are feasible. However the following complete analysis for glass over solar cells shows that convective cooling dominates radiative heat losses, with the inter-play between convective and radiative loss diminishing the impact of raising $E_H$. At hotter surface temperatures than those in PV modules cooling rates will become more sensitive to raising $E_H$.

3. **Emission angular profile and hemispherical emittance**

Before some complete cooling results we present aspects of the angular dependent cooling problem highly relevant to solar cells. The same models we used recently to accurately describe the observed temperatures of new cool roof materials when exposed outdoors [8, 9] apply. The angle of incidence dependence of IR spectral absorptance of the cover $A_{cov}(\lambda,\theta)$ was modelled and used to study how emittance evolves as the axially symmetric solid angle defined by $\theta$ increases.

The radiative output above a flat surface into a solid angle which does not extend to the full hemisphere or $\theta = 90°$ is modelled as a function of the extent of the solid angle cone from the normal. This demonstrates the importance of the relative contribution of very oblique incidence angles. We label this limited solid angle emission relative to the emission of a black body over the same limited solid angle as $\Delta E_H(\Delta\theta,T_{cov})$ and it is calculated in equation (1). $\Delta E_H(\Delta\theta,T_{cov})$ is in effect a partial hemispherical emittance. $P(\lambda,T_{cov})$ is the Planck emission spectrum at $T_{cov}$. The evolution of the integrals in equation (1) combines the effect of the increase in solid angle and the decrease in directional emittance, as the angle of incidence increases. If we set $\theta_1 = 0°$ in equation (1) and $\theta_2$ increases in steps, we can observe the evolution of $\Delta E_H$ towards $E_H$ as the upper angle $\theta_2$ increases to 90°. The result at $\theta_2 = 90°$ is the true hemispherical emittance ($E_H$) since $\Delta E_H(90°,T_{cov}) = E_H$. This evolution is seen in figure 1 for silica and glass. $\sigma$ is the Stefan-Boltzmann constant.

$$\Delta E_H(\Delta\theta, T_{cov}) = \frac{\int_{\theta_1}^{\theta_2} d\theta\,(2\pi\sin\theta)\int_0^{\infty} d\lambda A_{cov}(\lambda,\theta)P(\lambda,T_{cov})}{\left[\int_{\theta_1}^{\theta_2} d\theta\,(2\pi\sin\theta)\right]\sigma T_{cov}^4} \qquad (1)$$

The directional emittance profile for both materials is also given in fig. 1. This is not dependent on solid angle and follows from integration over wavelength of $A_{cov}(\lambda,\theta)P(\lambda,T_{cov})$ at each $\theta$ value. Terminating the partial hemispherical emittance evolution plot at around 70° or 75° leaves a value of glass hemispherical emittance close to what has been commonly accepted up until now, but extending to the full hemisphere causes a large additional drop.

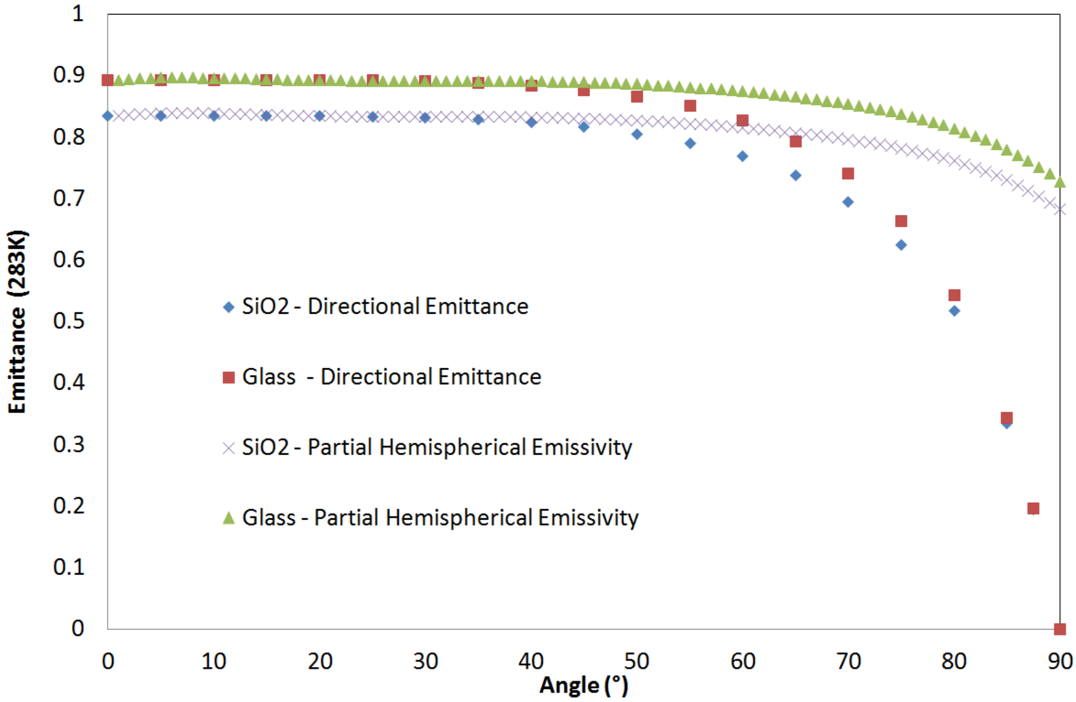


Figure 1. For silica and glass; emittance E(θ) as a function of exit angle θ to the normal, and partial hemispherical emittance ΔEH(θ) as a function of cone angle range from the zenith over which emission occurs.

## 4. Results and discussion

Clear sky atmospheric radiation does add heat input [2] and is thus included in our models, but PV cell solar absorptance dominates heat gain. For any surface sitting at more than a few degrees above ambient [8] a very high hemispherical emittance does help to maximise cooling and minimize steady state cell temperatures. However convective cooling and any other cooling that does not occur via the cover must be accurately included to assess the relative importance of radiative loss. The final cell and cover temperature under any set of conditions depends on the admix of radiative, convective and other heat output results. These are not independent. For example if thermal emission increases as a result of a large increase in $E_H$, convective cooling then drops significantly to limit the overall rate of heat loss and the fall in cell temperature. Table 1 at the representative environmental conditions in the caption, gives some comparisons as module cover surface $E_H$ values vary from glass and silica values to $E_H$ =1.0 (black body). In this table the glass and silica $E_H$ data is based on accurate angular results we have modeled based on IR refractive indices out to 90° angles of incidence for silica and glass. They match known data to its cut-out about 70°. $E_H$ of glass was found to be near 0.75, so is well under the usual value of 0.84 when high angles are included. A range of $E_H$ from 0.73 to 1.0 is in the table, to explore whether it is worthwhile to have a higher $E_H$ relative to glass and silica, and to see its influence on the other cooling components.

TABLE 1. Steady state cover temperature $T_C$ and cooling admix for surfaces with varying hemispherical emittance. Set conditions: absorbed solar energy of cell module fixed at 800 $Wm^{-2}$, ambient 17°C, wind speed 1.05 $ms^{-1}$, U (side/base) 2 $Wm^{-2}°K^{-1}$, dew point 4.2° (so humidity as PWV = 6.06 mm or as RH= 0.426).

| Surface | $E_H$ | $T_C$ °K | Convective loss cover $Wm^{-2}$ | Radiative loss cover $Wm^{-2}$ | Side/base loss $Wm^{-2}$ | Sum cover losses $Wm^{-2}$ |
|---|---|---|---|---|---|---|
| silica | 0.73 | 43.9 | 564 | 182 | 54 | 746 |
| glass | 0.75 | 43.6 | 558 | 189 | 53 | 747 |
| | 0.85 | 42.6 | 535 | 211 | 50 | 746 |
| | 0.90 | 42.2 | 526 | 221 | 51 | 748 |
| | 0.95 | 41.9 | 519 | 231 | 50 | 750 |
| Black body | 1.0 | 41.5 | 511 | 241 | 49 | 752 |

Extra cooling to more than 1.5°C below the cooling glass achieves already requires the $E_H$ value to be over 0.90. Note if the long accepted glass $E_H$ ~0.84 applied instead of our proposed value of 0.75 even a solar transmitting near black body cover would not be worth pursuing, unless very cost-effective to apply. What is interesting at the $T_{cover}$ values of interest for solar cells is that the large rise in radiative output with rise in $E_H$ is largely cancelled by the drop in convective loss at the very small wind speed used in table 1 data of 1.05 $ms^{-1}$. As a result total cover losses vary by less than 5 $Wm^{-2}$ from warmest to coolest cells in table 1 despite the variation of $E_H$ from 0.73 to 0.95. Had wind speed been higher, as it often is, cells would be cooler and the value of any higher $E_H$ than glass almost negligible. Likewise a lower average fraction than 0.8 of solar insolation ending up as heat within the cell would reduce advantages of high $E_H$ over that of glass. Some angular IR data to around 60° was provided for the nano-photonic high emittance surface proposed in reference [2] for better cell cooling. It was falling at higher angles as expected so like glass will likely have an $E_H$ value well below that indicated out to the data cut-off angles. From the trend in their angular emittance data as the angle increases, and from table 1 we expect their hemispherical emittance ($E_H$) to lie between 0.87 and 0.90. This would explain the observed cooler temperature observed relative to silica of 1.5°C. The same $E_H$ value for the cover would reduce cell temperature by at most 1°C below that when it is covered by glass.

Contributions to cell cooling by convection are more than double those by radiation. Any set-up then that diminishes convective cooling should be avoided. while PV modules operating in locations which feature extended periods with cool sea breezes may further lower the relative contribution of radiative loss. The dynamic variability of cooling rates even for a fixed insolation also means the gains in total energy output not peak watts should be used as basis for evaluation. Changes to roof design on which the modules are mounted can add extra convective cooling from the module base [10, 11] but add cost. Deliberate extraction of module heat as a source of useful heat or pre-heat, so called PV/T technology, also adds cooling [12] as do phase change materials (PCMs) which can be recharged at night [13].

As noted above sky window selective emitters do not have a role in cooling solar cells. They aim to reflect much of the down-welling atmospheric IR [8, 14] and have been proposed for cooling PV cells [3]. Their hemispherical emittance ($E_H$) is far too low, so their use would actually increase operating temperature relative to glass. Only if a surface can be cooled to ambient or below are these of interest for sky cooling [8] but conventional Si PV cells subject to the Shockley–Quiesser limit [15] cannot achieve this temperature regime.

## 4. How can surfaces be modified to cool enough?

If we rule out adding extra infra-structure such as that used in references [11-14], can re-engineering a module cover's spectral and angular properties provide worthwhile extra cooling and power output? Specifically can one or more special thin film or coating layers, produce an extra 1.5°C or more of cooling above what glass over Si now achieves? From the above analysis we are left with two main possibilities (i) optical designs that reduce solar heat gain (from those photons not available for efficient carrier generation) (ii) an angular profile in IR spectral absorptance $A_{cov}(\lambda,\theta)$ which at very high angles to the normal does not drop to any significant degree. That is in contrast to glass and most smooth inorganic dielectrics the high values of emittance at near normal incidence must be retained or only fall slightly out to 90° incidence. It would be interesting if the additional layer on the glass to raise emittance could anti-reflect the glass at solar wavelengths while also enhancing high angle IR absorption. This may be feasible. Reflecting back through the cover more of the solar radiation that now passes into the module and through the cell but is not converted to charge carriers may also help. Reflective layers at the rear of the cells are in use already for extra power gain and if well chosen may add cooling as well. A higher cover emittance at all exit angles if combined with an anti-reflectance impact at solar wavelengths, and reflectors behind the cell, may together improve I-V characteristics, both directly and via better cooling. However to be of value for raising cell output power, hemispherical emittance must exceed 0.90. This is a challenging goal for a surface with high solar transmittance.

## 5. Conclusion

Enhanced radiative cooling of solar cells to more than 1.5° below what is already being achieved with a module glass cover in a normal set–up without added infrastructure is challenging, but just possible. It requires attention to the angular properties of emittance and a proven "full hemisphere" $E_H$ value over 0.90 to be convincing. Any power gains achieved are likely to be small and absent at moderate wind speeds with cell cooling by convection dominant even at near still conditions. If $E_H$ in glass were 0.84 and silica just below this, even an IR black body solar transmitter could not add the extra 1.5°C of cooling required, nor the 1.3°C achieved recently relative to silica.

The clear evidence from this recent Si cell cooling data, and our models based on complex indices, is that the commonly used value of hemispherical emittance of glass of around 0.84 is too high. Emittance values in the high angle range have a major impact by lowering the hemispherical emittance. This is a central issue in much solar technology not just photovoltaics and involves existing emittance standards for many dielectrics. Where surface temperatures on any system are above those considered in this letter accuracy in hemispherical emittance becomes progressively more important. Then, as opposed to the PV cell case, radiative cooling does eventually dominate.

Acknowledgment
This work was supported by a current Australian Research Council Discovery Project grant DP140102003.

References

[1] L. Zhu, A. Raman, K.X. Wang, M.A. Anoma, S. Fan, Radiative cooling of solar cells, Optica, 1 (2014) 32-38.
[2] L. Zhu, A.P. Raman, S. Fan, Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody, Proceedings of the National Academy of Sciences, 112 (2015) 12282-12287.
[3] T.S. Safi, J.N. Munday, Improving photovoltaic performance through radiative cooling in both terrestrial and extraterrestrial environments, Opt. Express, 23 (2015) A1120-A1128.
[4] M. Rubin, Optical properties of soda lime silica glasses, Solar energy materials, 12 (1985) 275-288.
[5] M. Rubin, D. Arasteh, J. Hartmann, A correlation between normal and hemispherical emissivity of low-emissivity coatings on glass, International communications in heat and mass transfer, 14 (1987) 561-565.
[6] E.R. Schleiger, Measurement of Total Hemispherical Emittance of Transparent Materials at Low Temperature, Appl. Opt., 6 (1967) 919-923.
[7] C.K. Hsieh, K. Su, Thermal radiative properties of glass from 0.32 to 206 µm, Solar Energy, 22 (1979) 37-43.
[8] A. Gentle, G. Smith, Performance comparisons of sky window spectral selective and high emittance radiant cooling systems under varying atmospheric conditions, in: Proceedings Solar2010, The 48th AuSES Annual Conference, 2010.
[9] A.R. Gentle, G.B. Smith, A Subambient Open Roof Surface under the Mid-Summer Sun, Advanced Science, 2 (2015).
[10] P. Biwole, M. Woloszyn, C. Pompeo, Heat transfers in a double-skin roof ventilated by natural convection in summer time, Energy and Buildings, 40 (2008) 1487-1497.
[11] L. Gaillard, C. Ménézo, S. Giroux, H. Pabiou, R. Le-Berre, Experimental Study of Thermal Response of PV Modules Integrated into Naturally-ventilated Double Skin Facades, Energy Procedia, 48 (2014) 1254-1261.
[12] H. Jouhara, J. Milko, J. Danielewicz, M. Sayegh, M. Szulgowska-Zgrzywa, J. Ramos, S. Lester, The performance of a novel flat heat pipe based thermal and

PV/T (photovoltaic and thermal systems) solar collector that can be used as an energy-active building envelope material, Energy, (2015).
[13] M.I. Sohel, Z. Ma, P. Cooper, J. Adams, R. Scott, A Theoretical Investigation of a Solar Photovoltaic Thermal System Integrated with Phase Change Materials, in: 12th International Conference on Sustainable Energy technologies (SET-2013), Hong Kong, China, 2013, pp. pp. 1265-1272.
[14] A.R. Gentle, G.B. Smith, Radiative heat pumping from the earth using surface phonon resonant nanoparticles, Nano letters, 10 (2010) 373-379.
[15] W. Shockley, H.J. Queisser, Detailed balance limit of efficiency of p‐n junction solar cells, Journal of applied physics, 32 (1961) 510-519.