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Night Radiative Cooling With Unglazed PVT-Water Collectors: Experimental Results and Estimation of Cooling Potential

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Abstract

A PVT-Water collector was built and tested 24 hours per day during a period of six months in Sydney, Australia. The results provided enough experimental data to accurately build and tune a PVT model of the system in TRNSYS. The experimental setup included a pyrgeometer used for the calculation of the radiation losses to the sky. This article presents the experimental results obtained during the night radiative cooling periods and results from simulations carried out with the tuned TRNSYS model for the estimation of the sky cooling potential for this application. The results show that the unglazed PVT water system can achieve good levels of night cooling (around 750 Wh/m^2 of cooling per night during summer months) with radiation losses accounting for circa of 60% of the total cooling achieved and convection losses for 40%. Simulations show that similar night radiative cooling levels are obtained for other climates with minimum of 400 Wh/m^2 per night in Singapore to around 900 Wh/m^2 in Tucson, Arizona.

Keywords: *Sky Cooling, Night Radiative Cooling, PVT-Water*

1. Introduction

The use of night radiative cooling has been explored (Robinson and Sharp, 2012) and tested (Hamza et al., 1995) in several systems and applications, particularly in the cooling of buildings using PVT systems (Fiorentini et al., 2015; Yong et al., 2015). However, most of the examples found in the literature are carried out without accurate measurements of the sky temperature (except for Eicker and Dalibard, 2011), so estimations of the effective sky temperature are used instead. Unglazed PVT systems, either using air or water as the working fluid, are particularly well suited to provide radiative cooling due to the non-selective nature of the absorber (solar cells). However, limited information can be found in the literature regarding the portion of cooling provided by convection losses and by radiation losses. In the case of PVT air systems, the total cooling obtained can sometimes be mixed with the effects of ventilating a building using cooler ambient air, also known as night purging. On the other hand, in PVT water systems the portion of cooling done by convection and radiation losses of the absorber can be calculated directly.

This study uses high resolution experimental data (one minute) to tune and validate a TRNSYS model that has shown to produce very good levels of accuracy (Bilbao and Sproul, 2012), which in turn is used to simulate the potential of radiative cooling in different climates. The aim of the study is to provide a first comparison between experimental and simulation results and a detailed analysis of the night radiative cooling potential of unglazed PVT-water modules using a validated model. The measured data and simulations show promising results for night radiative cooling. However, further work is required and more and better sky temperature measurements are required across the world to properly assess radiative cooling.

2. Method

An experimental setup was built at the University of New South Wales (UNSW), Sydney, Australia. The setup involved a PVT water system, a weather station and a 24/7 data logging system. The weather station included a pyranometer for measuring solar irradiance and a pyrgeometer for the calculation of the sky

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temperature, both installed on the plane of the PVT system (34° tilt and 7° azimuth). The experimental data was used to tune and validate a steady state PVT model developed in TRNSYS by the authors (Bilbao and Sproul, 2012), called Type850. The model is capable of taking into account the sky temperature for the accurate calculation of radiative thermal losses to the sky.

The validated model was then used to estimate the night radiative cooling potential on different climates for rooftop PVT installations in TRNSYS. A detailed description of the experimental setup and the validation process is presented below.

2.1 Experimental Setup and Data Quality

The experimental setup uses a closed circuit water system connecting the PVT water module with a 100 liters storage tank. A frameless Siemens PV module (SM110) was used to build the PVT-water module using a fully wetted collector. The system is completed by a pump which maintains the water circulating between the PVT module and the tank 24 hours a day, unless a stagnation experiments is being carried out. This setup provides a natural way of 'resetting' the system each day, by releasing to the environment the thermal energy stored in the tank during the day, via night radiative cooling using the PVT module.

Table 1 shows all the sensor and logging equipment used for the experiment. Uncertainty calculations for the measurements and a more detailed description of the experimental setup can be found in Bilbao and Sproul (2015).

Table 1 – Measurement Equipment used in the Testing Rig

Type and Model	Measurement
Thermocouple 1	Inlet temperature (°C)
Thermocouple 2	Outlet temperature (°C)
Thermocouple 3	Lower end of PVT module, between PV module and collector (°C)
Thermocouple 4	Top end of PVT module, between PV module and collector (°C)
UCC Flow Meter DFC9000	Flow rate (pulses)
Hukseflux Pyranometer SR12	Global irradiance at module plane (W/m^2)
Hukseflux Pyrgeometer IR02	Far infrared radiation at module plane (W/m^2)
Vaisala Weather Transmitter WXT520	Ambient Temp (°C), Wind Speed (m/s), Relative Humidity (%), measured two meters above PVT module
dataTaker DT505	Log PVT data (currents, voltages, temperatures, and flow rate)
dataTaker DT80	Log weather data

Much care was taken in designing and building the experimental setup in order to collect as much data as possible. However, there were small problems during the six months the system was collecting data, from sensors, to the PVT module, to the pump, that impeded the logging of good quality data during the whole period. Thus, only days with a full data set were used for this publication, as shown in Table 2, which are equivalent to four months of full data.

Table 2 - Number of days with good quality experimental data

Data	Jan 12	Feb 12	Mar 12	Apr 12	May 12	Jun 12	Total days
PVT – PV	30	29	23	3	22	30	137
Irradiance	31	29	31	22	26	30	169
Sky Temp	13	29	31	19	24	30	146
Total days	**13**	**29**	**23**	**3**	**22**	**30**	**120**

A summary of the weather data (POA solar irradiance, daily average dry bulb temperature, and daily average sky temperature) obtained during the months of the experiment is shown in Fig. .

Fig. 1: Summary of Weather Data

2.2 Tuning of the model and experimental validation

The tuning and validation method consisted in an iterative process using theoretical values as a starting point for each parameter in the model. Selected parameters of the model were varied on each iteration and the residuals against the experimental results calculated. The electric parameters were fitted first (efficiency and temperature coefficient of the PV cell) followed by thermal parameters (heat loss coefficients and total heat transfer coefficient between the absorber and the fluid, U_{pv-f}).

The theoretical values used for the parameters provided acceptable results in thermal and electrical outputs with mean bias errors (MBE) below 2%. Hence, only few parameters were fine-tuned resulting in a MBE of -0.4% and a coefficient of variation for the root mean square error (CVRMSE) of 9.8% for the electrical output, while for the thermal output the best result obtained was an MBE of 0.1% and a CVRMSE of 16.3%. However, for this study the thermal output and thermal losses of the PVT system are most relevant for evaluating the night radiative potential. A linear regression (see Figure 1) for the thermal losses shows good agreement between the experimental data and the model with an R^2 of 0.96 for hourly data, which confirms the good performance of the model.

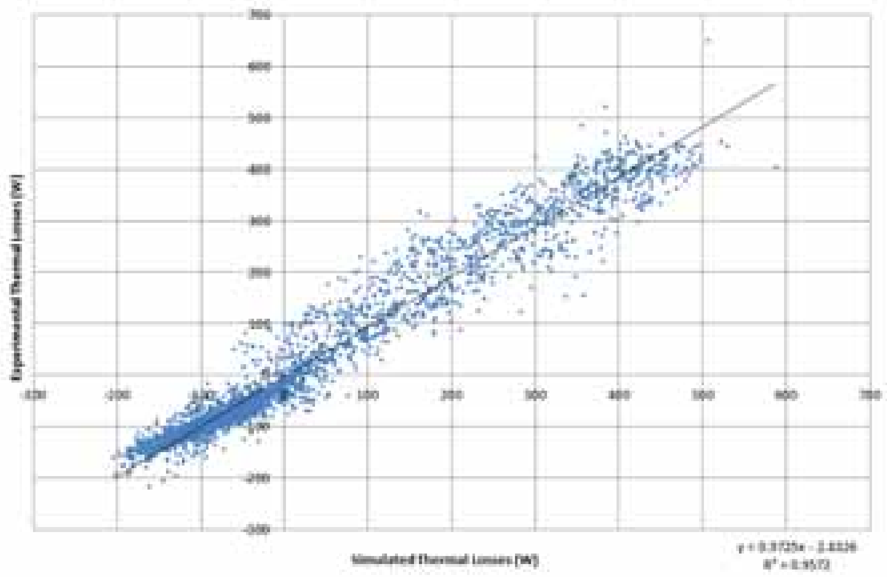

Fig. 2: Comparison of Simulated Thermal Losses (TRNSYS Model) and Experimental Thermal Losses

2.3 Annual Simulations for Different Climates

Simulations were carried out using TRNSYS 16. The tuned model Type 850 was selected for the PVT-water module (of 1 m^2) in conjunction with standard TRNSYS types for pump (Type3b), pipes (Type709), weather engine (Type15), and water tank (Type4c). The water tank was used as a thermal mass reservoir in order to imitate the scenario of providing night radiative cooling to a building. The tank starts ends the day warm and then is progressively cooled during the night by the PVT system. This resembles the experimental setup described above and provides a more realistic simulation than assuming a constant inlet temperature for the PVT system.

Other important assumptions are described below:

- Meteonorm TMY2 weather files were used for all locations.

- PVT modules on all locations were assumed to be installed flat on a 10 degrees tilt roof facing south or north, depending on the hemisphere. Given the high levels of insulation at the back of the PVT modules this could be considered equivalent to a BIPVT roof installation.

- Potential effects of the surroundings were not taken into account. However, the effects of potential heat islands (within the urban landscape) are minimized by choosing a rooftop installation with 10 degrees tilt which ensures a good sky view factor.

- A constant flow rate of 0.02 kg/s.m^2 was used.

- The cities of Singapore, Tucson (Arizona), Sydney (Australia), and Hamburg (Germany) were selected for this study given their diverse climate classifications (Af, BSh, Cfa, and Dfb respectively).

3. Results and Discussion

The analysis of the experimental data showed that, on average, the PVT-water system can provide, on average, circa of 750 Wh/m^2 of cooling per day on Sydney climate during summer months (Jan-Mar). The cooling potential increases, as expected, during autumn and winter months to 1,000 Wh/m^2, as shown in Figure 3. However, building cooling is usually not required during these months, at least on the Sydney climate, except for very specific building loads like data centers.

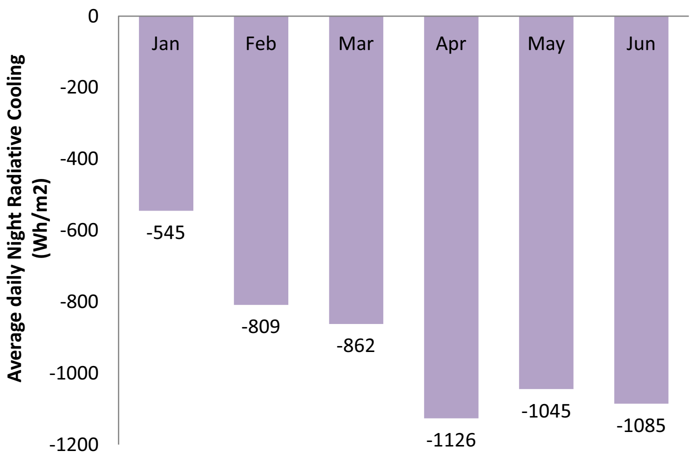

Fig. 3: Average Daily Night Radiative Cooling by a PVT-water module in Sydney from measured data

The results on show good potential for using PVT water systems for night cooling in Sydney climate. However, in order to design systems and really assess the cooling potential it is important to understand how this cooling is achieved, i.e., the portion of radiative and convective heat losses at night as part of the total cooling. The model developed in TRNSYS (Type850) was hence used to calculate the heat losses of the PVT-water module (top radiation, top convection, and back and edges) during night time using the same weather data obtained from the experiment. The results (Figure 4) show that radiation losses (Q_{rad}) account on average for 57% of the total heat losses, while convective losses (Q_{conv}) from the top surface of the module are responsible for the 40% of the heat loss and the back and edge losses (Q_{be}) for only the 3%. Figure 4b also shows that the radiative cooling portion is slightly larger during winter months (mostly due to the increase of clear nights in Sydney when compared to summer) but is still relevant during summer. This ratio however is not fixed and depends greatly on the inlet water temperature and wind speed. For example, the closer the inlet water temperature is to ambient, the less important will be the convective heat loss to ambient and the more relevant will be the portion of radiative heat losses. This effect can be clearly observed in the simulation results for a clear summer night shown in Figure 5. In the simulation (from 8pm to 5am) the sky radiative cooling increases during the night as the sky temperature drops (effectively increasing the gap with the ambient temperature) while the convective losses drop as the temperature of the inlet water becomes closer to ambient temperatures.

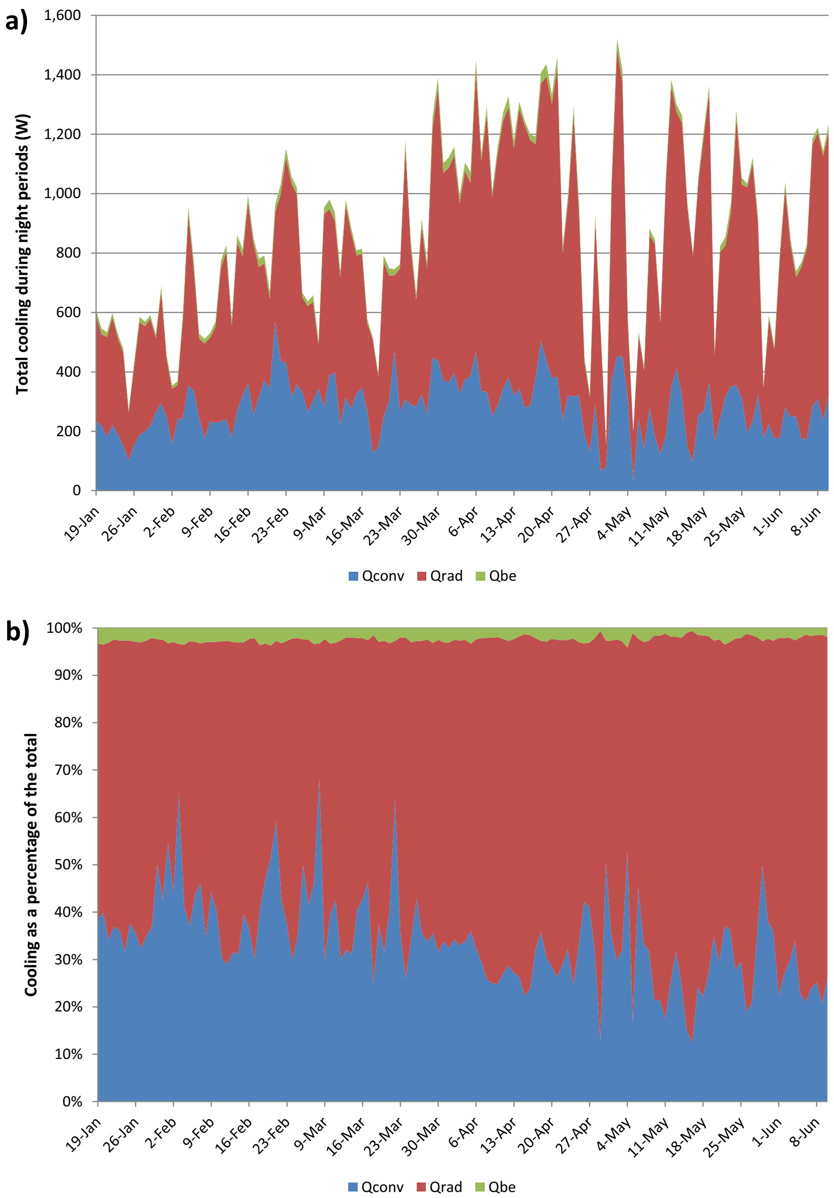

Fig. 4: Estimated daily heat losses or 'cooling' (top convection, top radiation, and back and edge) for the experimental PVT water system during night periods, in a) Wh and b) as a percentage of the total

These results have important ramifications and present interesting options for unglazed PVT modules, as they could be used for combined cooling/heating cycles, providing electricity, space heating during day winter months and cooling during clear summer nights, effectively a trigeneration system. An efficient hydraulic design for the PVT system is of paramount importance, as the benefits of providing space cooling/heating and the potential efficiency gains by cooling the PV cells can be outweighed by an inefficient water and air moving system (Farshchimonfared et al., 2015).

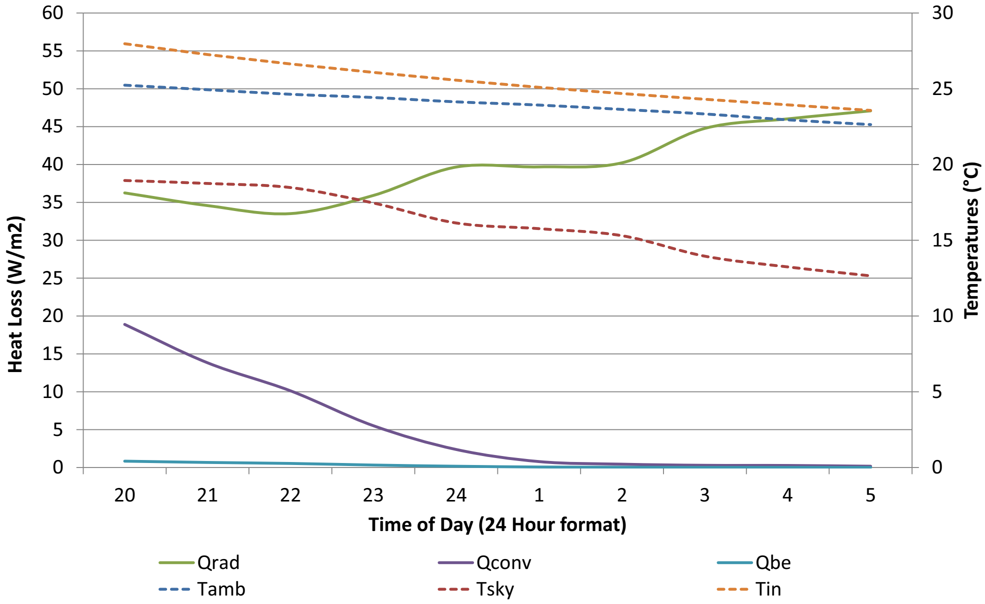

Fig. 5: Convective and radiative losses during a night

Of course, the cooling (and heating) capacity will depend on the weather conditions of the specific site and the type of installation along with tilt, orientation, and surroundings. This type of night radiative cooling might not be suitable for tropical zones, with high humidity and overcast days, but it might prove successful for temperate climates. Therefore, a set of simulations were carried out for four different climates (cities of Singapore, Tucson, Sydney, and Hamburg) in order to assess the potential of night radiative cooling under different conditions. A summary of the results for the year-long simulations are presented in Figure 6.

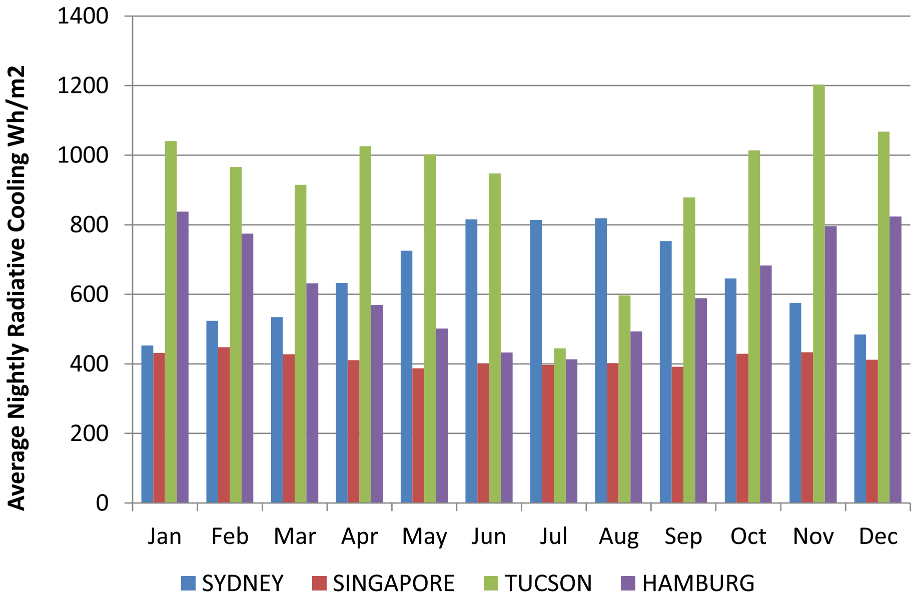

Fig. 6: Average PVT nightly radiative cooling during the year for different locations

As expected, the climate of Singapore produced limited night cooling potential around the year, with the average hovering around 400 Wh/m^2 per night. The drier climate of Tucson provided more than double of the cooling capacity with an average of 925 Wh/m^2 per night during the year. The night radiative cooling potential in Tucson is relatively constant during the year except for the months of July and August corresponding to the monsoon season in Arizona. On the other hand, Sydney offers similar night radiative cooling as Singapore during the (Sydney) summer months, with an increase cooling potential in winter (notice that Figure 3 shows measured data for Sydney and Figure 6 shows simulated data for Sydney with TMY2 data files, hence the discrepancy in values). A similar result is obtained for Hamburg, but with the corresponding seasons for the north hemisphere, with around 450 Wh/m^2 of cooling per night during summer and more cooling potential during winter (when the additional cooling potential is probably not needed). However, autumn and spring seasons (when present) seem to offer the best balance between night radiative cooling potential and cooling need.

Despite the difference in climates the model showed that on average it is always possible to obtain some level of night radiative cooling (see Figure 7). When compared to the output of convective cooling during night time, the results from the model and TMY2 weather files show a predominance of the radiative heat loss portion of at least 80% of the total. This differs from the measured results from the test rig built at UNSW in Sydney where the convective portion was closer to 40%. Given the fact that Type850 model shown good agreement to the measured data when using the logged weather data for the site, the difference can only be attributed to the weather file and difference in location. Furthermore, when running a simulation for Sydney with TMY2 data and the PVT module tilted at 30 degrees instead of 10 degrees, the model does show an increase in convective cooling and reduction in radiative cooling (Figure 7).

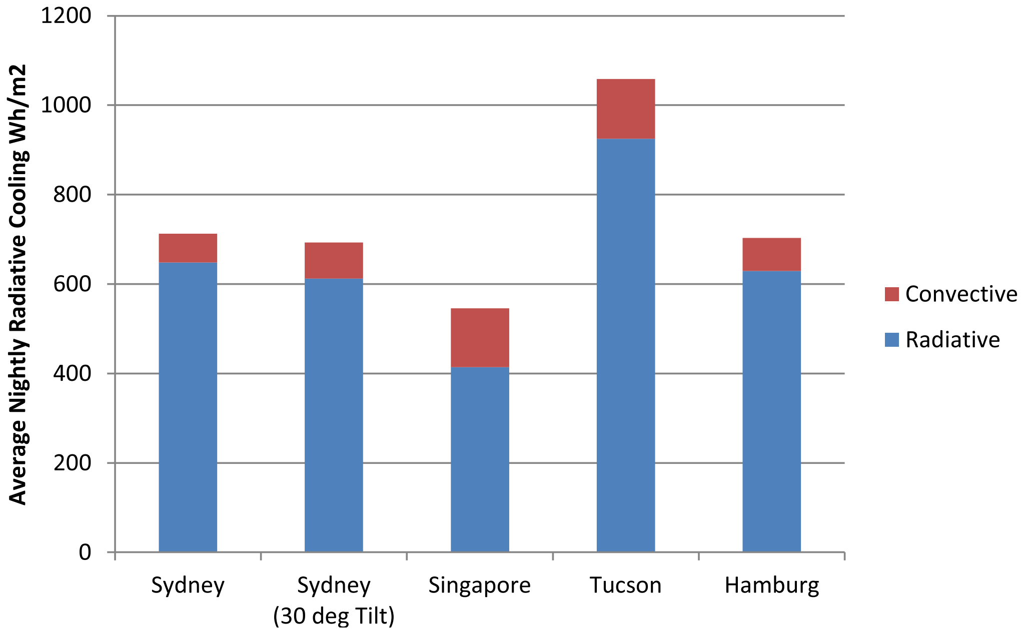

Fig. 7: Average PVT nightly radiative and convective cooling for different locations

If night radiative cooling is a better option than night purge or normal air conditioning for providing space cooling to buildings will depend on many factors including HVAC design and climate, as mentioned above. However, night radiative cooling using PVT water systems (using unglazed PVT modules) could be used as a complement for those technologies.

Further work and a more extensive analysis are required in order to explore and optimize the use of PVT water systems as a real trigeneration option. Moreover, with research already underway to assess the solar potential of all surfaces in the built environment (Redweik et al., 2013) it could be possible to use a similar approach to assess the night radiative cooling potential by including a sky view factor analysis.

4. Conclusions

PVT systems can offer important levels of night radiative cooling, which depends on the climate. From Singapore to Tucson (Arizona), the results of the simulations showed radiative cooling potential of the unglazed PVT system from 400 Wh/m^2 to 900 Wh/m^2 per night and that it is possible to provide cooling through the whole year, which might be beneficial for some applications like data centers. An additional 10% to 20% cooling can be obtained from convective cooling, although the portion of radiative and convective cooling depends on many variables including weather and system design and operation. More importantly, results seem to indicate that night radiative cooling is a real possibility for complementing night purge and other low energy cooling options. Consequently, it makes sense to use unglazed PVT systems already integrated into buildings as tri-generation systems, in order to use the full potential of the technology.

5. References

Bilbao, J. I., Sproul, A. B., 2012. Analysis of Flat Plate Photovoltaic-Thermal (PVT) Models. World Renewable Energy Forum (WREF 2012), Denver.

Bilbao, J. I., Sproul, A. B., 2015. Detailed PVT-water model for transient analysis using RC networks. Solar Energy, 115, 680–693.

Eicker, U., Dalibard, A. 2011. Photovoltaic–thermal collectors for night radiative cooling of buildings. Solar Energy, 85, 1322–1335.

Fiorentini, M., Cooper, P., Ma, Z., 2015. Development and optimization of an innovative HVAC system with integrated PVT and PCM thermal storage for a net-zero energy retrofitted house. Energy and Buildings, 94, 21–32.

Hamza, A., Ali, H., Taha, I.M.S., Ismail, I.M. , 1995. Cooling of water flowing through a night sky radiator. Solar Energy, 55, Pages 235–253.

Farshchimonfared, M., Bilbao, J. I., Sproul, A. B., 2015. Channel depth, air mass flow rate and air distribution duct diameter optimization of photovoltaic thermal (PV/T) air collectors linked to residential buildings. Renewable Energy, 76, 27–35.

Robinson, B.S., Sharp, M.K., 2012. Space Cooling Potentials for Ambient Sources with Thermal Energy Storage. World Renewable Energy Forum (WREF 2012), Denver.

Redweik, P., Catita, C., Brito, M., 2013. Solar energy potential on roofs and facades in an urban landscape. Solar Energy, 97, 332–341.

Svensson, M. K., 2004. Sky view factor analysis – implications for urban air temperature differences. Meteorological Applications, 11, 201–211.

Yong, C., Yiping, W., Li, A., 2015. Performance analysis on a building-integrated solar heating and cooling panel. Renewable Energy, 74, 627–632