

PAPER • OPEN ACCESS

Performance of Unglazed Photovoltaic-Thermal Collectors for Cooling Purpose

To cite this article: T Matuška *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **290** 012081

View the [article online](#) for updates and enhancements.

You may also like

- [Output power behavior of passivated emitter and rear cell photovoltaic modules during early installation stage: influence of light-induced degradation](#)

Ritsuko Sato, Tetsuyuki Ishii, Sungwoo Choi et al.

- [Parametric Study for the Treatment of Simulated Cetirizine Wastewater Using Electrochemical Methods: Optimization and Cost Analysis](#)

Shivani Agnihotri, Parminder Kaur, Vikas Kumar Sangal et al.

- [Thermodynamic Energy Efficiency of Electrochemical Systems Performing Simultaneous Water Desalination and Electricity Generation](#)

I. Atlas, S. Abu Khalla and M. E. Suss

The advertisement features a green background on the left with the ECS logo and text. The right side has a dark teal background with white text and an image of a scientist.

ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

A robotic arm is shown assembling components in a factory setting, and a female scientist is shown in profile, looking at a colorful chart or graph.

Performance of Unglazed Photovoltaic-Thermal Collectors for Cooling Purpose

T Matuška, N Pokorný and V Shemelin

Czech Technical University in Prague, UCEEB, Czech Republic

tomas.matuska@fs.cvut.cz

Abstract. Unglazed photovoltaic-thermal (PVT) collectors for combined usable heat and electricity production are still expanding on the market. Besides the summer heat production and whole year electricity production the unglazed PVT collectors can be used also for night cooling (sky radiation and wind convection heat exchange). Different unglazed PVT collectors have been experimentally tested for verification of reliable model for night cooling operation. Based on the results, the model has been implemented into simulation software TRNSYS. Simulation analyses of the cooling performance for different climate and operation conditions have been performed. While best of tested unglazed PVT collectors can achieve average specific cooling power around 110 W/m^2 ($80 \text{ kWh/m}^2\text{.season}$) at chilled water temperature 20°C in the climate conditions of central and northern Europe, in the climate conditions of south Europe these unglazed PVT collectors achieve not more than 38 W/m^2 ($27 \text{ kWh/m}^2\text{.season}$) during summer season (June–August).

1. Introduction

Night radiative cooling has been subjected to the deep research over the last 20 years [1–4]. However, night radiative cooling is still not used in today's buildings due to the lack of commercially available components and the low power density, which requires large roof surface areas. On the other hand, there are many buildings completely covered with PV panels for electricity production. Therefore, a combination of photothermal and photovoltaic technology in one facility (unglazed PVT collector) could provide an interesting solution as for night radiative cooling as for electricity production.

Unglazed PVT collectors were originally developed to increase the efficiency of photovoltaic cells by decreasing their operational temperature. It is achieved by using an absorber as a heat sink and heat transfer fluid at low temperature. As a result, annual electricity production could be increased. On the other hand, the application of unglazed PVT collectors for water heating purposes is limited to the applications with low operating temperature or to warm climatic areas. Thus, PVT collectors are perfectly suitable for applications where the electricity production is a priority and the use of low-potential heat is only added value. For instance, one of the most widely used application of unglazed PVT collectors is a combination with a heat pump, where PVT collectors preheat the heat transfer fluid in the evaporator circuit. Another possible application is a swimming pool water heating or cold water preheating.

At the same time, the high heat losses of unglazed PVT collectors could be used for the night cooling applications. The utilization of unglazed PVT collectors for the night cooling has already been investigated by the University of Stuttgart within Solar Decathlon competition [5]. There is, however, still a huge lack of knowledge about feasibility of unglazed PVT collectors for the cooling purposes.



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

The present work investigates a cooling potential of different unglazed PVT collectors which are currently on the market. The paper presents the experimentally validated mathematical model of unglazed PVT collector developed for night cooling purposes and the results of long-term simulations.

2. Model of unglazed PVT collector

Model of unglazed PVT collector which takes into account operational conditions during the night time is still not available in TRNSYS library [6]. At the same time there is Type 50b for PVT collector which is convenient only for day time simulations. Also well-known type 203 for unglazed PVT collector is not applicable for night time. Due to this fact a new type of unglazed PVT collector was developed and implemented into the TRNSYS (type 233). Model is based on the external and internal energy balance. Both balances proceed in the iteration loop. External energy balance calculates heat transfer between ambient and absorber. Internal energy balance calculates heat transfer between absorber and heat transfer fluid. The mathematical model considers different direction of radiative and convective heat flux. Model also takes into consideration situations when ambient air temperature is higher than collector fluid temperature and the heat is brought by convection from ambient and lost by radiation towards to sky. Moreover, the model takes into account geometrical and physical properties of the absorber by fin efficiency factor F' [-]. Using the heat removal factor F_R [-] it is possible to calculate collector cooling power from inlet temperature. Heat removal factor is given by

$$F_R = \frac{\dot{m} \cdot c}{A_G \cdot U} \left[1 - \exp \left(-\frac{A_G \cdot U \cdot F'}{\dot{m} \cdot c} \right) \right] \quad (1)$$

where \dot{m} [kg/s] is mass flow rate, A_G is gross area of the collector and U [W/m².K] is overall heat transfer coefficient.

Cooling power during the night time is determined from heat flux balance. To consider different absorber properties and geometry, the well-known Duffie and Beckman equation was modified [7]. To determine night cooling power the solar heat gain was replaced by radiative heat loss and as a result the cooling performance is given by

$$\dot{Q}_{ch} = F_R \cdot A_G \left[-\sigma \cdot \varepsilon_{abs} \cdot (T_{abs}^4 - T_{sky}^4) - U \cdot (T_{in} - T_a) \right] \quad (2)$$

where T_{in} [K] is fluid inlet temperature to the collector, T_a [K] is ambient temperature, σ [W/m².K⁴] is Stefan-Boltzmann constant, ε_{abs} [-] is emissivity of the PVT absorber surface, T_{abs} [K] is surface temperature of the absorber, and T_{sky} [K] is sky temperature.

3. Experimental validation of the model

Measured data for four tested variants of unglazed collectors were compared with simulated data using developed mathematical model. Reference unglazed thermal collector (REF) consists of two fully wetted absorbers connected in series (see in Figure 1).

Absorber of the reference collector has no PV cells and special paint has been applied with high IR emissivity value 0.925. Material of the collector absorber was steel with thermal conductivity around 100 W/m.K. Due to the reference collector design a very good heat transfer can be achieved. Total gross collector area is 1.44 m².

Two unglazed PVT collectors commercially available were tested as well. Variant VAR1 is PVT collector with sheet and tube absorber. Copper tube register is laser welded on the metal sheet. Tube register consist of 8 tubes with internal diameter 7 mm. Distance between tubes was 13 cm. Gross area of the PVT collector is 1.65 m². This variant was tested without insulation (VAR1) and with insulation on the back side (IVAR1) in order to evaluate the benefit of thermal insulation application for night cooling (see in Figure 2 and Figure 3).



Figure 1. Reference unglazed solar thermal collector



Figure 2. Unglazed PVT collector with sheet and tube absorber (VAR1)



Figure 3. Unglazed PVT collector with sheet and tube absorber – insulated on the back side (IVAR1)



Figure 4. Unglazed PVT collector with polymer absorber (VAR2)

Variant VAR2 of unglazed PVT collector is based on polymer absorber (see Figure 4). The absorber is fully wetted as well as for reference collector but thermal conductivity of the absorber material is low about 0.22 W/m.K. Absorber consists of 165 channels with internal diameter 3.5 mm. Moreover, between the channel structure with fluid and ambient there are layers of PV cells, encapsulation and final glass pane which all reduce the heat transfer from fluid to ambient. Gross area of this collector is 1.65 m².

Collectors were tested in Solar laboratory at Department of Environmental Engineering, Faculty of Mechanical Engineering (CTU in Prague). To evaluate the cooling power temperature sensors Pt100 and magnetic flow meter have been used in testing loop. Mass flow rate for every variant was set to 40 kg/h.m². For measurement of climate parameters a multisensor (ambient temperature, atmospheric pressure, relative humidity) has been used and radiative heat flux has been measured by pyrgeometer. Measured data were compared with simulated data by the model. Figure 5 and Figure 6 show a comparison of measured and simulated outlet temperature from the collector for all variants. The mathematical model is in a good agreement with the measured data. In several cases there are deviations between modelled and measured data due to fact that model does not consider thermal capacity of the collector, so it cannot reflect precisely dynamic changes of the fluid inlet temperature. Verified model was then used in TRNSYS simulation.

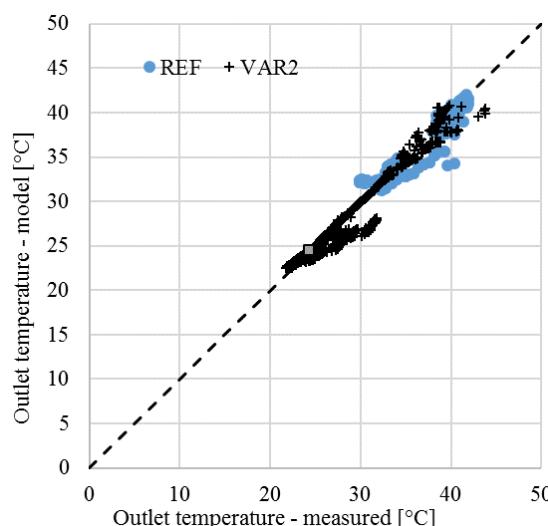


Figure 5. Comparison between measured and simulated outlet temperature from the collector for variant REF and VAR2

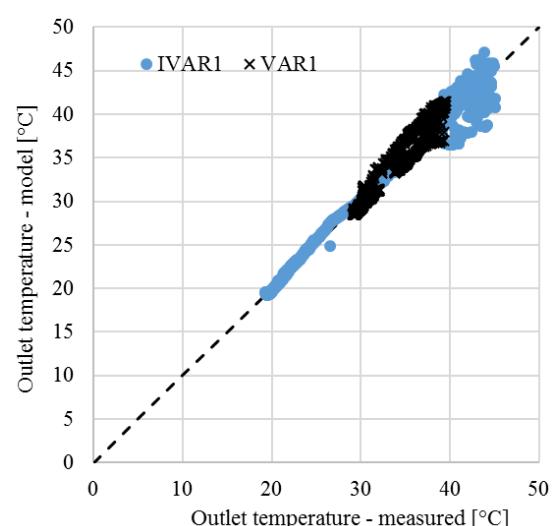


Figure 6. Unglazed PVT collector with sheet and tube absorber – additional insulation on the back side (variant IVAR1)

4. Sky temperature modelling

A key parameter in the evaluation of the radiative cooling performance is the sky temperature. So, to quantify the performance of night cooling system reliably, relevant sky effective temperature should be considered.

There is a number of models that have been proposed to estimate the effective sky temperature in literature. Generally, the models could be categorized into two groups: clear sky and cloudy sky models. Moreover, each group could also be divided into direct sky temperature models and atmospheric emissivity correlations.

4.1. Clear sky models

For clear sky models, Table 1 lists the selected correlations. The direct models for effective sky temperature estimation are based only on dry bulb temperature (Models 1–2). The emissivity models

take into account the humidity of ambient air by means of dew point temperature T_{dp} [°C] (Models 3–5) or water vapour pressure P_v [mbar] (Models 6-7). The effective sky temperature is determined by using the following equation [8].

$$T_{sky} = (\varepsilon_{sky})^{0.25} T_{amb} \quad (3)$$

Table 1. Clear sky temperature models [9].

	Model	Authors
1	$T_{sky} = T_{amb} - 20$	Garg
2	$T_{sky} = 0.0552 T_{amb}^{1.5}$	Swinbank
3	$\varepsilon_{sky} = 0.741 + 0.0062 T_{dp}$	Berdahl and Fromber
4	$\varepsilon_{sky} = 0.711 + 0.56 T_{dp}/100 + 0.73(T_{dp}/100)^2$	Berdahl and Martin
5	$\varepsilon_{sky} = 0.8004 + 0.00396 T_{dp}$	Bliss
6	$\varepsilon_{sky} = 0.34 + 0.11 P_v^{0.5}$	Robitzsch
7	$\varepsilon_{sky} = 0.56 + 0.08 P_v^{0.5}$	Centeno

4.2. Cloudy sky models

As for cloudy sky models, the impact of cloudiness on sky temperature is difficult to evaluate and only few researchers attempted to predict it. The overview of cloudy sky direct models (Models 8–10) suitable for night time is presented in Table 2. The main problem with existing cloudy sky atmospheric emissivity models is that they are based on daytime clearness indices and in the result, there is only one constant value of clearness index for the whole night. Thus, the time series of sky temperatures cannot be adequately represented, as moving clouds cannot be considered.

One of few atmospheric emissivity models which can be used for sky temperature estimation in the cloudy night is the Berdahl and Martin [10] corrected model for the cloudy sky. The key advantage of the model is an application of a cloudy sky fraction (f_{cloud}), which can be read from the weather file. Currently, the weather data includes values for hourly cloudy sky fraction, so the effective sky temperature could be estimated adequately even in the night.

Table 2. Cloudy sky temperature models [9].

	Model	Authors
8	$T_{sky} = T_{amb}$	Dreyfus
9	$T_{sky} = T_{amb} - 6$	Whillier
10	$T_{sky} = 0.037536 T_{amb}^{1.5} + 0.32 T_{amb}$	Fuentes
11	$\varepsilon_{sky} = \varepsilon_{sky-clear} + \varepsilon_{cloud} (1 - \varepsilon_{sky-clear}) f_{cloud}$	Berdahl and Martin

4.3. Sky temperature model selection

In order to provide long-term simulations of unglazed solar collectors for cooling purposes, both the direct sky temperature and atmospheric emissivity models were analysed and compared to the

experimentally determined effective sky temperature. The aim is to evaluate which correlation can be used for long-term simulations. The effective sky temperature was calculated based on the value of longwave radiation heat exchange between the sky and body of pyrgeometer sensor. The sky temperature is then calculated by the relationship:

$$T_{sky} = \left(\frac{Q_o}{\sigma} \right)^{0.25} \quad (4)$$

Figure 7 and Figure 8 illustrate a comparison between clear sky models and cloudy sky models, the ambient temperature and the measured sky temperature for a 24-hour period. In the case of the cloudy sky the atmospheric emissivity models are not presented in the comparison because they require additional inputs which were not measured.

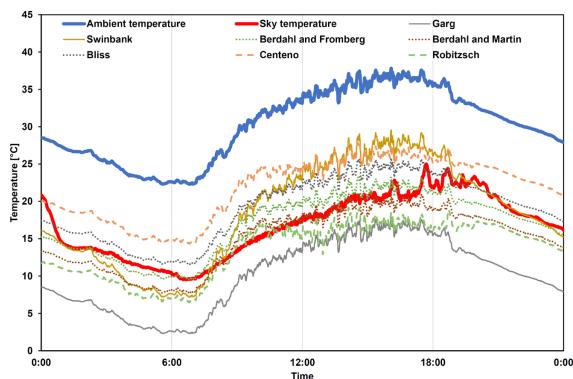


Figure 7. Computed sky temperatures based on clear sky models and measured value of sky temperature over a 24-hour period.

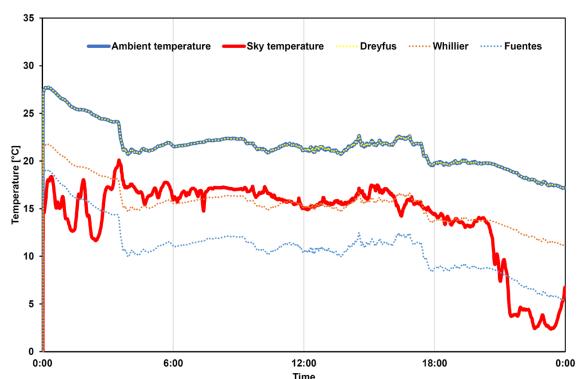


Figure 8. Computed sky temperatures based on cloudy sky models and measured value of sky temperature over a 24-hour period

As a result of analysis, the Berdahl and Martin correlation for clear sky and Whillier correlation for cloudy sky shows the lowest deviation from the measured value for clear and cloudy sky consequently. Nevertheless, the Berdahl and Martin corrected model (Model 11) for the cloudy sky was used for long-term performance simulations.

5. Simulation analysis

Mathematical model implemented into TRNSYS was used for several analyses. Firstly, simplified simulation analysis was provided for performance comparison of four different variants during one night. Simulation was done for Prague climatic conditions. Two different nights during summer were chosen (clear and cloudy). At the beginning of the night the storage was homogenously heated up to 40 °C. Then 2 m² of collector area was used to discharge 100 l storage by 40 kg/h.m² mass flow rate. The simulation results are presented in Figure 9 and Figure 10. In both cases the reference variant REF showed the best performance from the compared variants. Regarding the commercially available variants of PVT collectors, variant VAR1 has better cooling performance in both cases.

Another simulation analysis has been done for three different climatic conditions (Stockholm, Prague, and Madrid). Simulation time step was 10 minutes. Only summer season June-August were chosen for simulation because the cooling power over the whole year is not representative. Cooling gain during winter is very high due to low ambient temperature (mainly convection-based cooling) but not usable (low or zero cooling demand in buildings). Different system was chosen for the simulation with storage tank volume 2000 l discharged by PVT collector area 80 m². As in previous case, the storage tank is cooled down from initial 40 °C every night. Mass flow rate was set to 40 kg/h.m². Cooling gain

during summer season is presented in Table 3. Although reference collector has the highest cooling gain, the difference from other variants in cooling gain is only from 11 % to 25 %. Specific cooling gain for all variants is from 56 to 85 kWh/m².season.

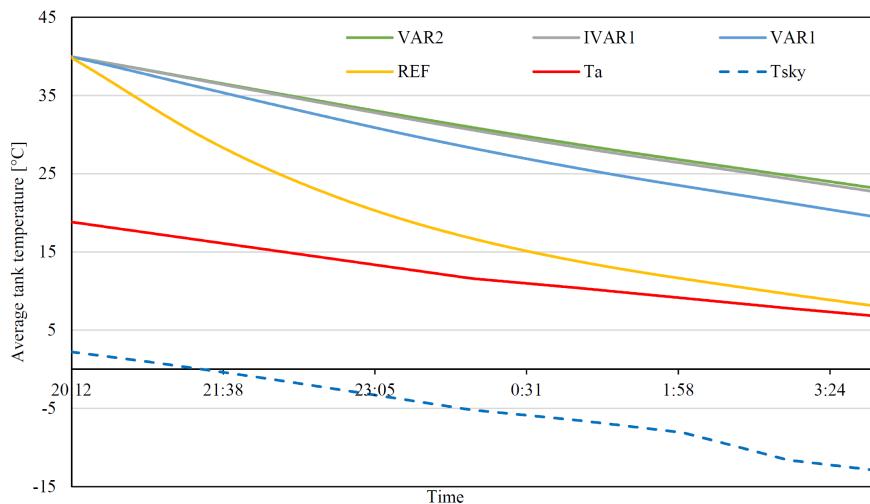


Figure 9. Night cooling of 100 l storage (Prague climatic conditions) – clear sky.

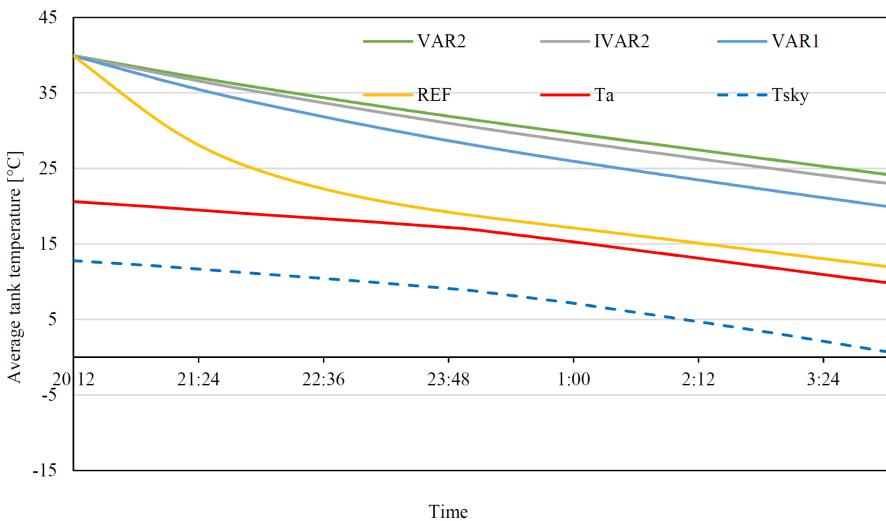


Figure 10. Night cooling of 100 l storage (Prague climatic conditions) – cloudy sky

Simulations were performed also for constant inlet temperature (without storage). Comparison of summer cooling gain for constant inlet temperature 20 °C is shown in Table 4. In this case reference collector has approximately three times higher specific cooling gain. Average specific cooling power of reference collector for central and northern Europe is about 325 W/m².season. For tested commercially available PVT collectors the highest specific cooling power achieved was 110 W/m² in summer season for central and northern Europe and 38 W/m² in summer season for south Europe. Therefore, there is a significant potential for innovation of PVT collector design according to night cooling purpose.

Table 3. Comparison of summer cooling gain (2000 l, 80 m²)

	REF [kWh/season]	VAR1 [kWh/season]	IVAR1 [kWh/season]	VAR2 [kWh/season]
Stockholm	6702	5966	5477	4979
Prague	6528	6026	5697	5223
Madrid	5791	5143	4942	4467

Table 4. Comparison of summer cooling gain for constant inlet temperature 20 °C

	REF [kWh/m ² .season]	VAR1 [kWh/m ² .season]	IVAR1 [kWh/m ² .season]	VAR2 [kWh/m ² .season]
Stockholm	232	79	56	55
Prague	226	77	55	52
Madrid	76	27	25	19

6. Conclusion

New mathematical model of unglazed PVT collector for night cooling purposes was developed and implemented into TRNSYS environment. The model has been experimentally verified for unglazed thermal collector and three different variants of unglazed PVT collector available on the market. While best unglazed PVT collectors can achieve average specific cooling power around 110 W/m² (79 kWh/m².season) at chilled water temperature 20 °C for climate conditions of central and northern Europe, these collectors could not achieve more than 38 W/m² (27 kWh/m².season) during summer season (June-August) in the climate condition of south Europe location due to higher ambient temperature in night time.

Acknowledgments

This work has been supported by the Ministry of Education, Youth and Sports within National Sustainability Programme I, project No. LO1605.

References

- [1] Erell E and Etzion Y 2000 Radiative cooling of buildings with flat-plate solar collectors *Build. Environ.* **35** 297–305
- [2] Dimoudi A and Androutsopoulos A 2006 The cooling performance of a radiator based roof component *Sol. energy* **80** 1039–47
- [3] Farahani M F, Heidarnejad G and Delfani S 2010 A two-stage system of nocturnal radiative and indirect evaporative cooling for conditions in Tehran *Energy Build.* **42** 2131–8
- [4] Argiriou A, Santamouris M and Assimakopoulos D N 1994 Assessment of the radiative cooling potential of a collector using hourly weather data *Energy* **19** 879–88
- [5] Eicker U and Dalibard A 2011 Photovoltaic–thermal collectors for night radiative cooling of buildings *Sol. Energy* **85** 1322–35
- [6] Solar Energy Laboratory 2009 *User Manual: TRNSYS 17 a TRAnsient SYstem Simulation program – Volume 4 – Mathematical Reference* vol 4
- [7] Duffie J A and Beckman W A 1991 *Solar Engineering of Thermal Processes* (Wiley)
- [8] Centeno M 1982 New formulae for the equivalent night sky emissivity *Sol. Energy* **28** 489–98
- [9] Algarni S and Darin Nutter PhD P E 2015 Survey of Sky Effective Temperature Models Applicable to Building Envelope Radiant Heat Transfer *ASHRAE Trans.* **121** 351
- [10] Martin M and Berdahl P 1984 Characteristics of infrared sky radiation in the United States *Sol. energy* **33** 321–36