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Performance Analyses of a Trigenerative Plant Configuration for a WISC PVT Systems

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ABSTRACT

Energy consumption for cooling of buildings is becoming increasingly important, with a great influence on the emission of polluting gases and the exploitation of energy resources. Air conditioning systems typically use compression cooling machines that consume a lot of energy. In virtuous buildings, the compression systems are powered by photovoltaic systems so as not to require additional energy from outside. Other technologies exploit solar thermal energy in absorption/adsorption machines to produce cooling energy. In both cases, "renewable energy" is obtained only during daytime hours, exploiting massive resources during the night hours. The photovoltaic/thermal panels allow the simultaneous production of thermal and electrical energy, still at the same time, if not glazed (WISC systems) they can produce cooling energy by exploiting radiative cooling during the night, thus allowing continuous production of cooling energy during the entire day. This study presents a patented highly efficient trigenerative photovoltaic thermal system (PVT), able to generate heating, cooling, and power. Using a mathematical model validated with experimental data obtained with a pilot plant, it is demonstrated that the extractable cooling power in each panel is about 50-60 W. The results show that this system allows for to production and storage of cooling energy more than 3°C less than the minimum air temperature that occurs during the night.

1. INTRODUCTION

By 2030, Italy must install 12 GWp of "rooftop" photovoltaic plants, which must be technically and economically efficient. The loss of power conversion efficiency because of raised PV cell temperature is one of the major worries for PV systems. For crystalline Si solar cells, an increase of 1°C in the working temperature gives rise to losses of power conversion efficiency of about 0.45% [1], while an increase of 10°C causes twice the degradation rate [2]. Thus, many different strategies have been studied to reduce the operating PV cell's temperature, like as the installation of PVT solar collectors in conventional configurations (power + heat) [3]; spraying flowing water on the photovoltaic modules [4]; increasing the heat exchange surfaces with the addition of cooling fins in the PV modules [5]; use of phase change materials (PCM) [6].

Photovoltaics, photovoltaic/thermal, and thermal collector systems usually operate during the daytime for solar energy harvesting, without taking advantage of the radiative cooling (RC), which is determined by the long-wave radiation (LWR) emitted to the sky vault, which can be exploited. Under a clear summer night, sky temperatures can be less than 0°C, even-10°C could happen. Radiative cooling of solar cells is receiving increased interest because of its lightweight, low cost, and passive exploit [7, 8]. RC can be easily harnessed during nighttime, while during the daytime, the high solar gain requires the RC materials to be selective, reflective in the wavelength band from 0.3 to 3 μm, and emissive in the Atmospheric Window. These selective features can be achieved using metamaterials [9], photonic structures [10], and nanoparticle-based [11]. The combination of Radiative Cooling & Solar Energy systems (RC&SEs) provides multifunctionality, increased operational time, and higher energy gains per unit area.

One of the first studies on nighttime radiative cooling was conducted by removing the glazing from a PVT module in the study [12], observing an RC power gain of 60-65 W/m^2. In such a study, the spectral optical properties of the RC system were not considered. The exploit of radiative cooling in a building-integrated PVT system was evaluated as significant in hot regions, and vice versa in colder regions [13].

Table 1. Categorization of RC&SEs based on the output achievement and operational time

Solar Energy System	Output Achievement	
	Daytime	Night-time
Photovoltaic (PV)	Power Cell's cooling	Radiative cooling
Photovoltaic Thermal (PVT)	Power Cell's cooling Solar Heating	Radiative cooling
Flat Plate Thermal Collector (ST)	Solar Heating Radiative cooling	Radiative cooling

A categorization of RC&SEs based on the output achievement and operational time (daytime and/or nighttime) is provided by Ahmed et al. [14]. Table 1 summarizes the above-mentioned classification.

The PV plants can exploit the RC during the daytime to reduce solar cell operating temperature and improve the system's electrical efficiency and the reliability of the photovoltaic modules. This option can be used as an alternative or in addition to the other techniques adopted for cooling the PV cells.

PV modules have solar cells that are usually encapsulated with glass (SiO_2), which has MIR emissivity from 0.8 to 0.9 [15] and therefore can provide radiative cooling without using any additional RC surfaces on top. PVT collectors can achieve daytime PV cooling and solar heating alongside the nighttime RC. Flat plate thermal collectors can produce daytime solar heating and nighttime RC, or can exploit simultaneously solar heating and RC during the daytime. In the study of Bilbao and Sproul [16], experimental data on a PVT-water system have determined circa 750 Wh/m^2/day of cooling for Sydney climate during summer months. The TRNSYS model developed to evaluate the heat losses shows that radiation and convective losses account on average for 57 and 40% of the total heat losses, whereas the back and heat edge losses account for just 3%. The cooling effect of photovoltaic panels using water spray with various types and diameters to reduce the temperature and performance of photovoltaic panels was presented by Wibowo et al. [17].

The techniques currently used to exploit nocturnal radiative cooling are usually not integrated with conventional solar systems, so they require additional equipment (e.g., heat exchange) and fitting that needs space for their installation, limiting the available space for conventional solar panels. Furthermore, these systems require the creation of additional hydronic circuits from scratch, increasing the costs and the global economic feasibility.

Other solutions integrate electric refrigerators with PVT panels, which are used as heat exchangers to dissipate heat and not directly produce cooling energy, therefore not exploiting radiative cooling in passive mode.

Nocturnal RC to chill the photovoltaic cells, although contemplated in some patents, does not allow the valorization of the thermal energy produced (environmental heating and DHW production).

The proposed PVT trigenerative system achieves the production of refrigeration energy both for cooling buildings at night, without the need to use electrically powered refrigeration machines, and to increase their efficiency and limit their decay through the cooling of photovoltaic cells in the event of reaching critical temperatures (e.g., heat waves). Compared to the standard configuration of PVT plants, consisting of solar panels and a hot storage tank connected via a hydraulic distribution network to the solar circuit and the user, the proposed system requires the installation of a second tank intended for the storage of cold fluid, as well as a management system for the hydraulic circuits.

In addition to the description of the trigeneration system, this paper shows the results obtainable for a full-scale plant, using a mathematical model validated with a pilot plant.

2. ENERGY BALANCE FOR A RADIATIVE COOLING SURFACE

Water vapor and atmospheric gases diminish the heat transfer from the earth, mostly emitted in the Mid-Infrared band (MIR), wavelength from 4 to 25 μm; while, in the Atmospheric Window (AW) band, wavelength from 8 to 13 μm, the atmosphere is impressively transparent, allowing thermal radiation to pass through.

The radiative cooler surface is commonly positioned on the top of the solar cells and designed to be highly transmissive in the solar band (0.3-4 μm) to optimize electricity production. And highly emissive in the MIR band (4-25 μm) to reduce the solar cell temperature.

The thermal fluxes from/to an RC surface can be used to evaluate the net radiated cooling power as shown in Figure 1 [18]:

$$Q_{net,rad} = Q_{em,s} - Q_{atm} - Q_{sun} - Q_{conv} \tag{1}$$

where,

$Q_{em,s}$ = thermal radiation emitted from the RC surface, function of the directional spectral emissivity of the surface ε_s (λ,θ) and the blackbody spectral radiation intensity at the temperature of the cooled surface T_s,

Q_{atm} = atmospheric radiation absorbed by the RC surface, function of the directional spectral absorptivity of the surface $\alpha_{s,LW}$ (λ,θ), which is usually posed equal to the directional emissivity spectral of the atmosphere $\varepsilon_{atm}(\lambda,\theta)$ in accordance with Kirchhoff's radiation law,

Q_{sun} = solar radiation power absorbed by the RC surface, function of the directional spectral absorptivity of the surface $\alpha_{s,SW}$ (λ,θ),

Q_{conv} = non-radiative heat transfer between the RC surface and the ambient.

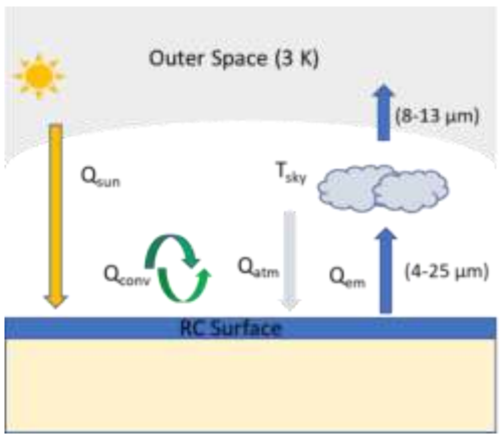

Figure 1. Heat fluxes from/to an RC system rearranged from [14]

It should be noted that only within the AW (8-13 μm) thermal radiation goes to outer space. The RC surface should be positioned as much as possible horizontally to maximize the outgoing infrared radiation. Otherwise, the increase of the tilt upsurges the incoming infrared radiation, mainly caused by the reduction of the sky view factor from the RC surface, less "visual thickness" of the atmosphere in the zenith direction [19].

Some authors provided correlations between effective outgoing long-wave radiation (L_{WR}) and the inclination angle or the zenith angle [20].

A worthy assessment of the sky temperature (T_{sky}) is essential when modelling the performance of radiative cooling systems. The concepts of effective T_{sky}, and effective sky emissivity (ε_{sky}) have been introduced to determine the infrared sky radiation.

Many models based on empirical or semi-empirical correlations are available in the literature to calculate the effective sky temperatures/emissivity. Most of them are valid only for clear sky conditions, while others apply some factors to take into account the cloudy conditions.

In the research of Eicker and Dalibard [12], and Vall and Castell [20], a list of models is provided to calculate effective sky emissivity or temperatures for clear and cloudy sky conditions.

The infrared sky radiation is mainly dependent on the water content of the atmosphere, with 90% of the sky radiation originating from the first kilometer above ground and 40% from only 10 m above ground.

Ideally, RC surfaces, which should be perfect emitters in the infrared AW (8–13 μm) and a perfect reflector elsewhere, could achieve a cooling power of 100 W/m^2 and temperatures 50°C lower than ambient temperature [21].

Figure 2 shows an example of a building-integrated PV which could take advantage of daytime cooling of the solar cells and nighttime radiative cooling for space chilling.

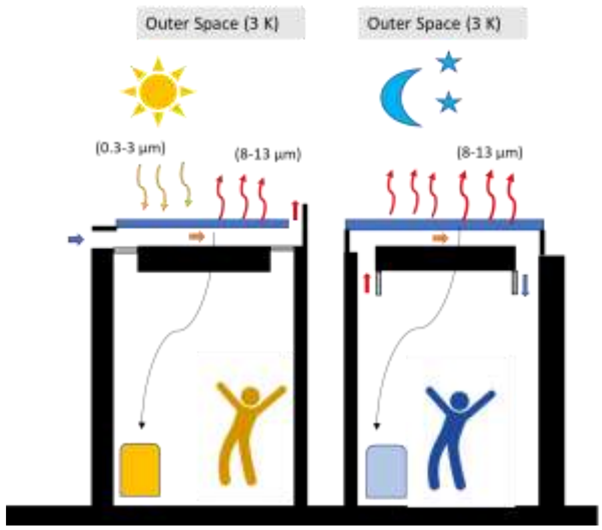

Figure 2. Building-integrated PV for daytime PV cell's cooling, nighttime space cooling [18]

It is worth noting that the building-integrated PV can also be installed vertically, so creating a building-ventilated PV façade [22], which in addition to PV cell's cooling and nighttime space cooling reduce also reduces the solar heat gain during the summer season.

3. DESCRIPTION OF THE TRIGENERATIVE PVT SYSTEM

PVT plants normally operate only during the daytime to provide power and heat generation. Depending on the application, these plants can operate either to optimize power production or the thermal output. Thereby, to optimize power production, the fluid has to cool the PV cells to increase their efficiency, whereas to privilege heat generation, a certain temperature of the fluid must be reached as a function of the request (e.g., space heating, domestic hot water, thermal cooling, etc.).

The presented trigenerative PVT system, which has received the patent EP4056922 (A1) - 2022-09-14, compared to the standard configuration of PVT plants, consisting of solar panels and a hot storage tank connected via a hydraulic distribution network to the solar circuit and the user, requires the installation of a second tank intended for the storage of cold fluid, as well as of a management system for the hydraulic circuits. The production of the refrigerated fluid is obtained both by exploiting night-time radiative cooling and the cooling potential of the flowing water used for the production of domestic hot water (DHW). In particular, the water is taken from the network, with temperatures of the order of 12-15°C, used for the production of DHW, before being heated in the hot storage, and is passed into the cold tank to lower the temperature of the fluid within it. Moreover, the heat exchange between the cold tank and the mains water causes its free pre-heating. Overall, a "dual source" cooling system is created, radiative cooling + valorization of mains water cooling potential, not contemplated in any of the current applications. Figure 3 shows the hydronic circuits from the PVT solar collectors alternatively to the hot or the cold thermal storage.

The main innovative features of the invention are related to:

-Simultaneous generation of the three energy carriers (trigeneration), electricity, heat, and cooling energy,

-Cooling of the cells, increase in electrical efficiency of the order of 5%, without water consumption,

-Increase in the thermal efficiency of the PVT system due to the pre-heating of the domestic water inside the cold tank,

-Chilled water can be used in radiant heat/cooling panels or mechanical ventilation systems,

-Simplicity of construction, all that is needed is the installation of a tank for storing the refrigerated fluid and adaptation of the system management/regulation system,

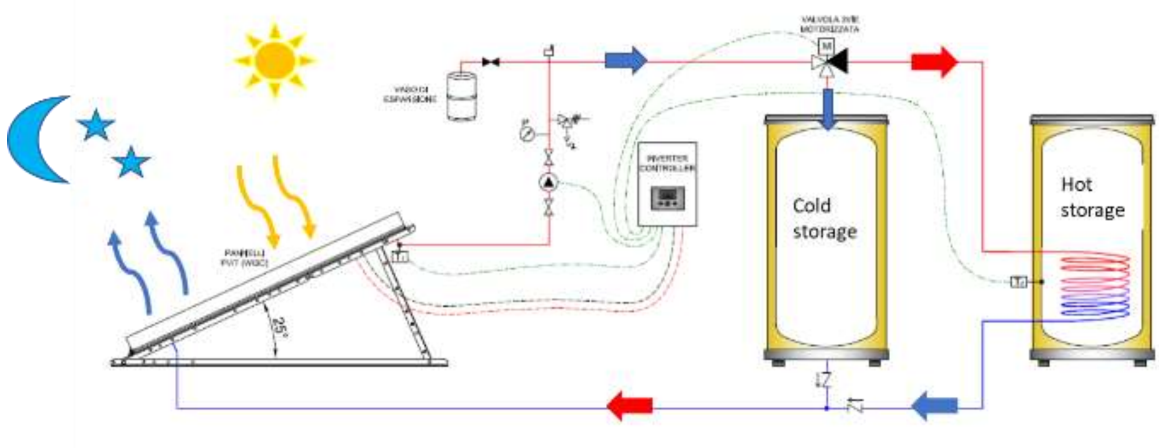

Figure 3. Hydronic circuits of the PVT trigenerative system

-Use of chilled water in periods different from when it is produced,

-Installation of additional radiative cooling equipment is not envisaged,

-No construction modifications to the current PVT manifolds are necessary, as the models already on the market can be used,

-The additional energy consumption is due to the operation of the circulation pump during the night period, equal to approximately 2-3 W, compared to the cooling energy produced of 50-60 W per PVT panel.

4. DEVELOPMENT STAGE AND CURRENT TRL

At present, preliminary experimental analyses have been carried out on a PVT system installed at the DIEEI of the University of Catania, which partially replicates the one proposed in the current invention, thus identifying a state of progress of the invention as TRL4. In fact, laboratory and outdoor tests are being carried out. Theoretical-experimental analyses of the system are envisaged to determine the optimal configurations and characteristics of the individual components through numerical simulations.

The subsequent development phases involve the creation of a prototype, complete with all the components on which to complete the tests in an outdoor environment to achieve a TRL 6/7. Figure 4 shows the PVT plant used as a case study.

Shortly, this roadmap involves progressing from the current TRL4, marked by initial experimental phases and a numerical model, towards a more advanced stage. The aim is to achieve a higher technology readiness level by implementing theoretical-experimental analyses and validating the system through prototype testing in an outdoor environment.

Figure 4. PVT plant at the University of Catania [23]

5. NUMERICAL ANALYSES

With the aim of predicting the radiative cooling capacity considering different configurations and installation positions, a numerical model has been developed in Matlab environment.

5.1 Numerical model

The model considers the thermal balance of each panel layer, as well as the incoming, outgoing, and stored energy flows.

Figure 5 shows the schematization of the system on which the numerical model is based, while in Figure 6, the energy balance equations of each layer are explained.

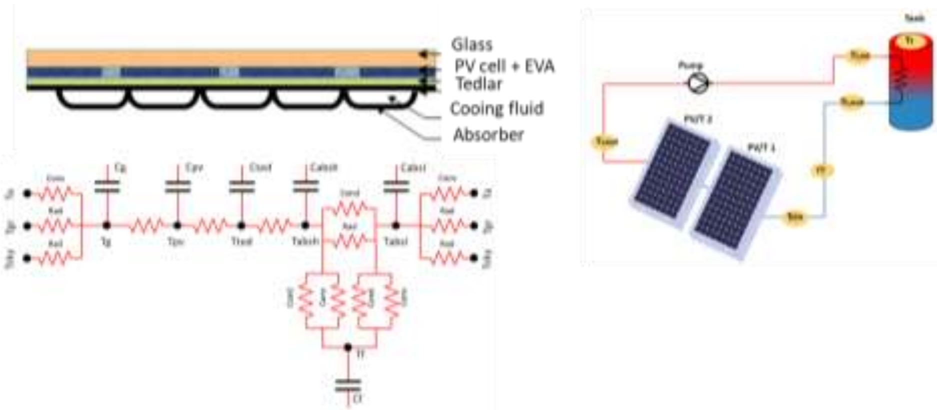

Figure 5. Schematization of the system

Layers	Equations	
Glass	$(\rho_g \delta_g C_g)\frac{dT_g}{dt} = \alpha_g G + hr_{g,sky}(T_{sky} - T_g) + hr_{g,gr}(T_{gr} - T_g) + hv_{g,a}(T_a - T_g) + hc_{PV,g} PF(T_{PV} - T_g) + + hc_{Ted,g}(1 - PF)(T_{Ted} - T_g)$	(2)
PV cells	$PF(\rho_{PV}\ \delta_{PV}\ C_{PV})\frac{dT_{PV}}{dt} = [(\tau_g \alpha_{PV} - \eta_e)\, G + hc_{PV,g}(T_g - T_{PV}) + hc_{Ted,PV}(T_{Ted} - T_{PV})]PF$	(3)
Tedlar	$(\rho_{Ted}\,\delta_{Ted}\,C_{Ted})\frac{dT_{Ted}}{dt} = (1 - PF)\tau_g \alpha_{Ted} G + (1 - PF)hc_{Ted,g}(T_g - T_{Ted}) + PF \cdot hc_{Ted,PV}(T_{PV} - T_{Ted}) + hc_{abs h,Ted}(T_{abs h} - T_{Ted})$	(4)
Absor-ber	$(\rho_{absh}\,\delta_{absh}\,C_{absh})\frac{dT_{abs h}}{dt} = hc_{abs h,Ted}(T_{Ted} - T_{abs h}) + (1 - PC)hc_{absl,abs h}(T_{absl} - T_{abs h}) + +PC \cdot hr_{absl,abs h}(T_{absl} - T_{abs h}) + hc_{f,abs h}(T_f - T_{abs h})$	(5)
	$(\rho_{absl}\,\delta_{absl}\,C_{absl})\frac{dT_{abs l}}{dt} = hc_{absl,f}(T_f - T_{absl}) + (1 - PC)hc_{absl,abs h}(T_{abs h} - T_{absl}) + PC \cdot hr_{absl,abs h} \cdot (T_{absl} - T_{abs h}) + hc_{f,abs h}(T_f - T_{abs h}) + hr_{sky,absl}(T_{sky} - T_{absl}) + hr_{gr,absl}(T_{gr} - T_{absl})$	(8)
Fluid	$(\rho_f\,\delta_f\,C_f)\frac{dT_f}{dt} = hc_{f,abs h}(T_{abs h} - T_f) + hc_{absl,f}(T_{absl} - T_f) + \dot{m}\, C_f\,(T_{out} - T_{in})$	(7)
Tank	$(M_t C_f)\frac{dT_t}{dt} = \varepsilon_H\, \dot{m}\, C_f\,(T_{t,out} - T_t) - \dot{m}_l C_w(T_t - T_{sup}) - U_t\, S_t\,(T_t - T_a)$	(8)

Figure 6. Overview of the balance equations for the PV/T layers and tank

One of the main parameters for the correct evaluation of the potential of these plants concerns the exchanges with the celestial vault. In this regard, the celestial vault has been considered as a black body, where the temperature of the sky is calculated using the Brunt formula:

$$T_{sky} = \left(0.55 + 0.0654\left(RH \cdot e^{\left(65.81-\frac{7066.2}{T_a}-5.976\cdot\ln(T_a)\right)}\right)^{1/2}\right)^{0.25} \cdot T_a \quad (2)$$

where, RH indicates relative humidity.

5.2 Validation

To verify the accuracy of the mathematical model, the numerical results were compared with the experimental data observed in the PVT pilot plant, installed at the university campus of Catania, relating to a summer period.

For validation, the simulations are conducted considering the real plant, which is composed of two panels, a radiative exchange surface equal to 3.32 m^2, a tilt angle equal to 10° and a fluid flow rate equal to 3 l/min.

Figure 7 shows the climate data of the days under examination.

Figure 8 shows the comparisons of the thermal power exchanged by the heat transfer fluid, calculated considering the temperature difference between the outlet and inlet of the fluid in the panel and the flow rate.

It is possible to note that the results drawn from the model are consistent with what was observed in situ. In detail, during the day, very variable powers occur with peaks that reach up to 1500 W. This is due to a non-continuous flow of the heat transfer fluid, because the circulation is dictated by the control of the temperature of the photovoltaic cells, which therefore activates the circulation when it exceeds the maximum level imposed. Differently, during the night period, the heat transfer fluid is circulated continuously to try to obtain a thermal level as low as possible, thus showing more constant profiles, which are approximately 50 W.

Figure 9 shows the comparison between the simulation results and the observed ones, relating to the temperature inside the tank.

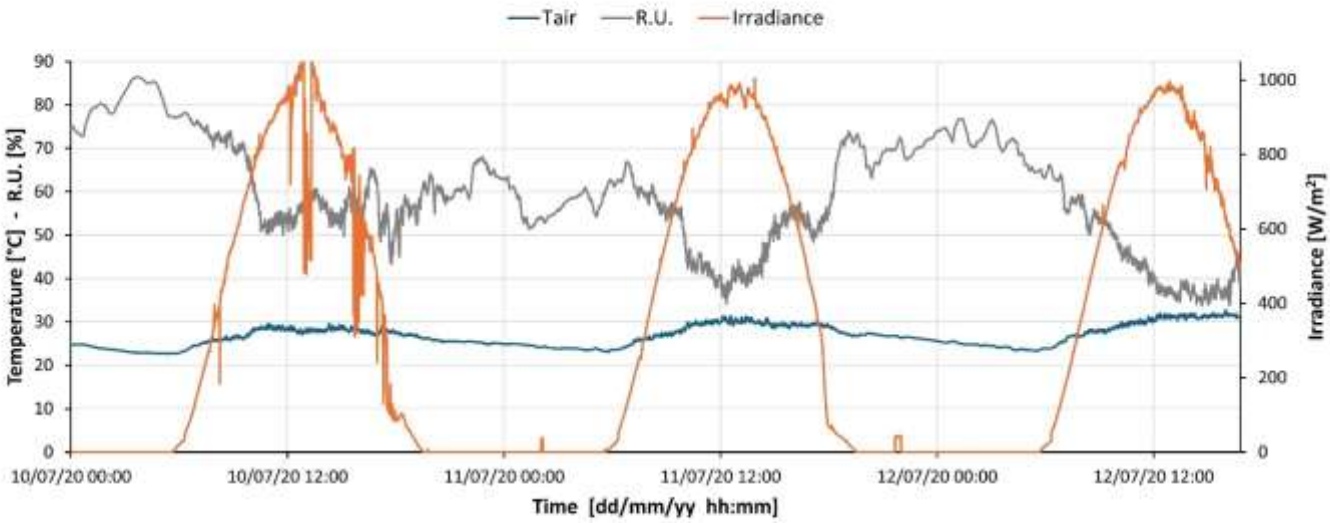

Figure 7. Meteorological data

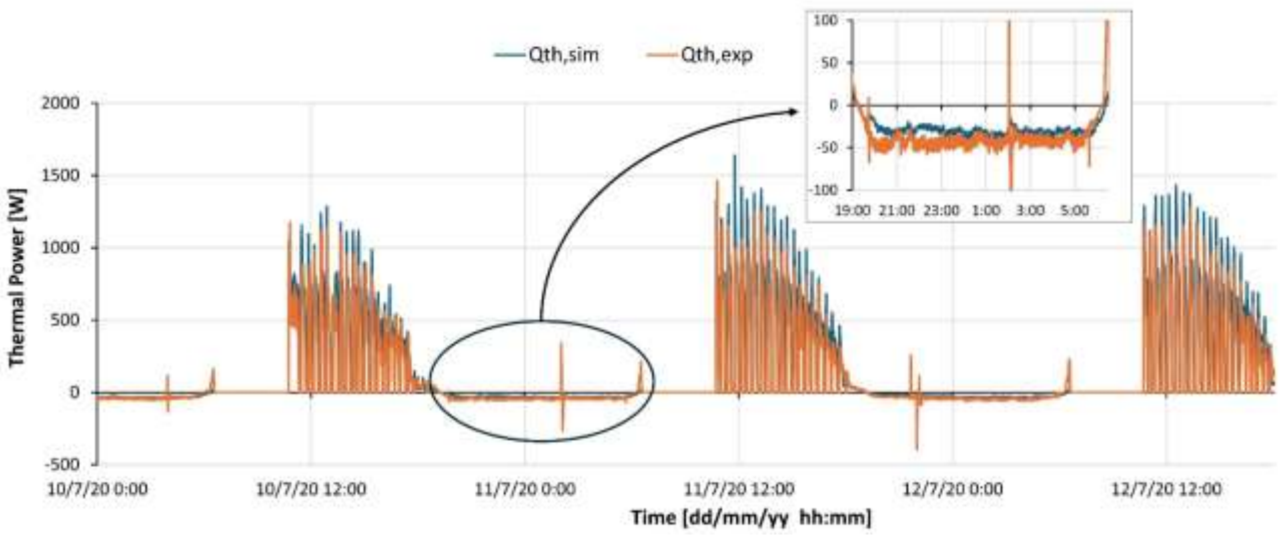

Figure 8. Comparison between simulated and observed exchanged thermal power

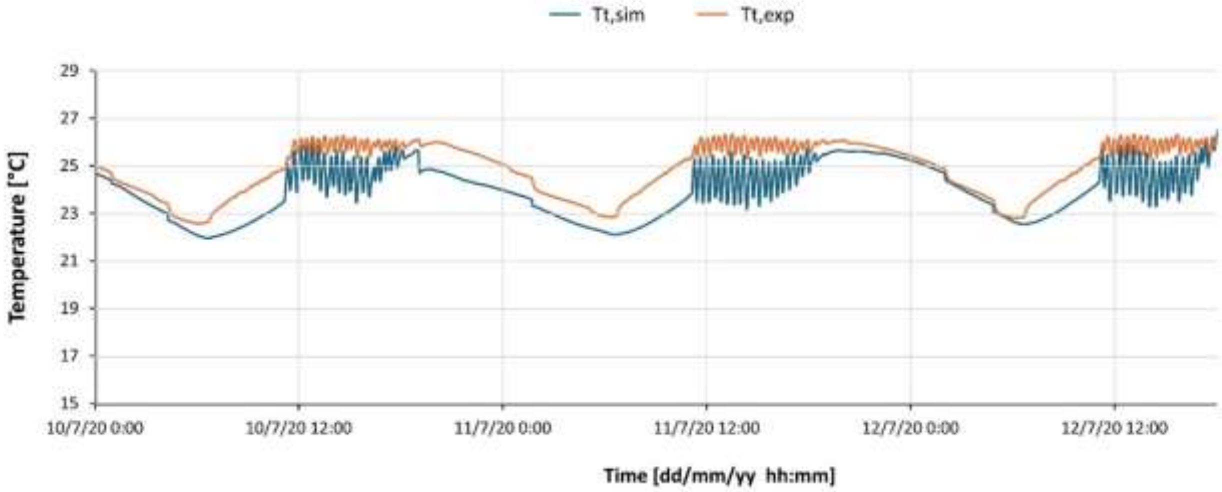

Figure 9. Comparison of simulated and observed storage tank temperatures

Figure 10. Outdoor temperature (T_{air}), outlet temperature of working fluid ($T_{panel,out}$), and tank temperature (T_t) for a full scale system

It is possible to highlight that the simulated tank temperatures are always very similar to the measured ones, with differences of less than one degree Celsius. The only moments where there is a greater difference are in the early morning, when solar radiation hits the outside of the tank and influences the reading of the real temperature sensor.

5.3 Radiative cooling in domestic systems

The expected performances with the proposed system are illustrated below, considering the system in domestic sizes, i.e., a PVT system with a peak electrical power of 3 kW, therefore composed of 12 panels.

Figure 10 shows the achievable performances of the proposed system configuration, sized on a domestic scale, calculated considering the climate data shown in Figure 7. In detail, the data for the night between July 10th and 11th are shown (similar results are obtained for all the other nights).

The simulation results show a good potential for radiative cooling. In fact, the temperatures of the fluid exiting the panels, as well as those of the storage tank, are about 3-3.5°C lower than the air temperature, with a minimum temperature reached in the tank of about 20.3°C. This guarantees greater cooling compared to night ventilation.

Furthermore, the first preliminary analyses indicate a potential of about 50-60 W per panel in line with the analyses developed by Zhao et al. [18].

6. APPLICATIONS AND TECHNOLOGICAL POTENTIAL

The invention finds application in all users who require the installation of systems that use PVT collectors, both newly built and in the retrofitting of existing solar thermal or photovoltaic systems. The privileged users are single or small multi-floor residential buildings, which need to generate renewable power, heating, and cooling energy.

In fact, the continuous increase in temperatures and the increasingly frequent occurrence of tropical nights, a direct consequence of ongoing climate changes, have led to an exponential increase in the installation of air conditioning systems during the summer season, which emit thermal waste into the external environment, exacerbating the formation of urban heat islands.

The use of electric cooling systems has, as a further counterpart, the release of thermal waste into the external environment, exacerbating the formation of urban heat islands.

Embracing affordable, environmentally friendly technologies is pivotal in our quest to minimize energy usage and combat urban heat, effectively addressing both sustainability and cost-efficiency challenges in our cities.

The cooling energy produced with the proposed system allows the external air temperature to be reduced during the night, using night ventilation or radiant systems, avoiding heat and noise emissions.

Figure 11 shows the great feasibility of the proposed system, which can be used for space heating and cooling, DHW production, as well as power generation.

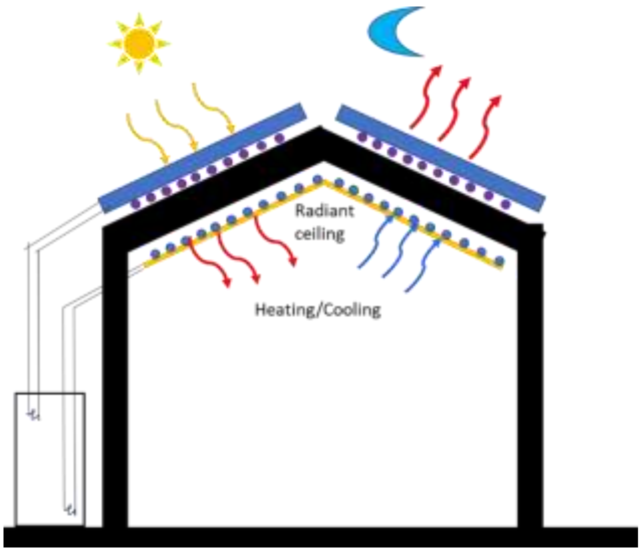

Figure 11. Employment of the trigeneration PVT system for space heating and cooling

It is possible to assert that the potential market of the system is very broad; it is sufficient to note that the European road map envisages achieving the objective of having zero-energy buildings in the immediate future. The main reference market could be the sector of zero energy balance buildings (NZEB or ZEB), both in the case of new constructions and renovations, in which the production of electricity, heat, and energy from renewable sources is required. refrigerator.

The invention increases the flexibility of active users, therefore lending itself well to participation in the emerging markets of flexibility services.

7. CONCLUSIONS

The main innovative features of the patented PVT trigenerative system are:

-Simultaneous generation of the three energy carriers (trigeneration), electricity, heat and cooling energy,

-Cooling of the cells, increase in electrical efficiency of the order of 5%, without water consumption, and in the event of reaching critical temperatures (e.g., heat waves), reducing their degradation

-Increase in the thermal efficiency of the PVT system due to the pre-heating of the domestic water inside the cold tank,

-Chilled water can be used in radiant heat/cooling panels or mechanical ventilation systems,

-Simplicity of construction, all that is needed is the installation of a tank for storing the refrigerated fluid and adaptation of the system management/regulation system,

-Installation of additional radiative cooling equipment is not envisaged,

-No construction modifications to the current PVT manifolds are necessary, as the models already on the market can be used,

-The additional energy consumption is due to the operation of the circulation pump during the night period, equal to approximately 2-3 W, compared to the cooling energy produced of 50-60 W per PVT panel,

-Also feasible in traditional solar thermal systems,

-Almost zero environmental impacts as there is no consumption of resources in the operation phase or release of thermal waste, which leads to a worsening of the microclimate in urban areas.

Moreover, the invention's applicability extends to burgeoning markets, particularly in developing countries, where the demand for environmentally friendly air conditioning solutions is anticipated to surge. Theoretical-experimental analyses of the system are envisaged to determine the optimal configurations and characteristics of the individual components through numerical simulations. Future developments foresee collaborations, some already underway, with organizations and companies operating in the field of solar cooling to integrate the proposed system with other technologies, in particular with DEC systems, to further expand its application areas. Among the possible applications, the one that is believed to be feasible for the creation of a business case is the installation of demonstrators for residential users would allow the performance of the proposed solution to be tested in terms of energy efficiency, installation and management costs.

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NOMENCLATURE

C	specific heat, J. $kg^{-1}.K^{-1}$
G	solar irradiation, $W.m^{-2}$
hc	cond. heat transfer coef., $W.m^{-2}.K^{-1}$
hr	rad. heat transfer coef., $W.m^{-2}.K^{-1}$
hv	conv. heat transfer coef., $W.m^{-2}.K^{-1}$
PF	packing factor, dimensionless
R.H.	Relative humidity, dimensionless
T	Temperature, K
t	Time, s
U	thermal transmittance of tank, $W\text{-}K^{-1}$

Greek symbols

α	absorptivity, dimensionless
δ	thickness, m
ε	emissivity, dimensionless
η	electrical efficiency, dimensionless
ρ	density, $kg.m^{-3}$
τ	transmission coef., dimensionless

Subscripts

a	air
abs	absorber
f	fluid
g	glass
gr	ground
in	inlet
out	outlet
PV	photovoltaic
PVT	Photovoltaic/thermal
sky	sky
sup	supply water
t	tank
Ted	tedlar
w	water