Potential of Façade-Integrated PVT With Radiant Heating and Cooling Panel Supported by a Thermal Storage for Temperature Stability and Energy Efficiency

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Abstract

Hybrid photovoltaic/thermal (PVT) systems combine electric and thermal energy generation and provide noiseless operation and space-saving features. As the efficiency of photovoltaic (PV) panels increases at low surface temperatures, this paper suggests combining the PVT panel with a radiant cooling and heating panel in one system. A thermal storage tank fluidly connects the heat-exchanging pipes at the back of the PVT system and radiant panel. The upper portion of the tank feeds the radiant panel and the lower portion of the tank is connected to the PVT system. The proposed device is expected to function in connection with a heat pump that feeds the thermal storage. Using the dynamic thermal simulation software Polysun, the performance of the proposed façade-integrated device was investigated while considering the surface temperatures and energy production in the moderate climatic condition of the city of Munich. The results indicate a substantial impact on the efficiency of the PV module with an increase of up to 35% in the electricity production of the PV due to the lowered surface temperature. The obtained results contribute to façade-supported cooling/heating and electricity generation through the novel coupling and integration of PV, PVT, and radiant cooling elements.

Keywords

Photovoltaic/thermal systems, radiant cooling, building-integrated photovoltaic, façade, solar cooling

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1 INTRODUCTION

Façade-integrated energy generation essentially contributes to the increase in the energy efficiency of buildings. In such an unconventional local energy generation approach, remarkable savings are achieved through the reduced efforts and losses in the transportation and conversion processes. In building-integrated photovoltaics, photovoltaic (PV) cells absorb a significant portion of the irradiated energy. This results in a significant increase in the surface temperature of the PV panel. The increased cell temperature substantially reduces the overall module efficiency. The output performance of the PV decreases by 0.4-0.5% for each degree increase in the cell temperature (Natarajan, Mallick, Katz, & Weingaertner, 2011). This is calculated in comparison with the standard test conditions (STC), where 25°C and 1000 W/m^2 are set as the standard values of ambient temperature and solar irradiance (G), respectively. Furthermore, according to experiments, the STC parameters do not represent the real operating conditions of PV panels (Razak et al., 2016). In an investigation by Radziemska (2003), the increase in surface temperature led to a power deterioration of 0.65% per kelvin. Obviously, in hot climates, this effect is more severe owing to the relatively higher ambient temperatures.

Despite low ambient temperatures in moderate climates, the absorbed solar irradiance leads to remarkable losses as it also increases the cell temperature (Huld & Gracia Amillo, 2015). This effect is particularly noticeable in façade-integrated PV module, for example, a south-oriented vertical PV module in Europe. Another important factor that affects the module efficiency is wind velocity, which is associated with convective heat transport. Huld and Gracia Amillo (2015) claimed that despite the clear impact of this factor, ambient temperature and solar irradiance are still the two primary parameters that affect the efficiency. This is particularly true in the case of crystalline silicon-based cells. Obviously, the geographical location performs a role in the intensity of either factor and results in a fluctuation in module efficiency ranging from -15% to +5% (Huld & Gracia Amillo, 2015). Moreover, the surface cooling of the PV has an inverse effect and increases the electricity production efficacy (Pathak, Pearce, & Harrison, 2012). Therefore, associating cooling with façade-integrated energy provides the potential for a further increase in efficiency. This indicates a deviation from the fact that high cooling loads often occur during times of high solar irradiation.

PV cells can be cooled by attaching pipes that circulate a fluid at the back of the PV absorber. This combination of two systems is called hybrid PV/thermal (PVT) technology (Zhang, Zhao, Smith, Xu, & Yu, 2012). The fluid in the pipes absorbs the thermal energy from the heated surface and delivers it to another point for uses such as potable water heating. Depending on the design of the system, water is usually used as a refrigerant owing to its higher thermal capacity. Moreover, the generated thermal energy can also be used for other applications such as potable water, air, and room heating. Kern and Russell (1978) were the first to present this technology in 1978.

Basically, a PVT system includes the functions of both a PV panel and a solar collector. Besides the increased space efficiency, it offers lesser installations and more cost reductions. According to a study by Charalambous, Maidment, Kalogirou, and Yiakoumetti (2007), a PVT system can produce more energy per unit area than a pair of PV panels and a solar collector located next to each other. Generally, the generated heat in the PV surface that is absorbed by the fluid is of low quality for domestic hot water uses or room heating. Therefore, several PVT domestic hot water generation systems are equipped with auxiliary heaters connected to the heat exchanger at the top of the hot water storage tank to compensate for the thermal energy deficit (Aste, Del Pero, & Leonforte, 2012). Furthermore, heat can be used for cooling energy generation. Prieto, Knaack, Auer, and Klein (2017) discussed the potential of façade-integrated PVT systems for solar-assisted cooling based on the principles of solar cooling addressed by Henning (Henning and International Energy Agency, 2004). However, these approaches are limited by the outlet temperature of the fluid that comes out of the PVT system, as significantly high temperatures in the range of 90-110 °C are often required for the operation of the absorption or adsorption chiller. This issue is beyond the scope of this paper.

Radiant cooling and heating systems have garnered significant interest owing to their potential to achieve high thermal comfort, low energy demand, noiseless operation, and space-saving features. In these systems, water pipes are attached to the back of a radiating panel. The circulating chilled water is delivered through the pipe and it cools down or heats up the panel, which eventually exchanges heat with other surfaces primarily through radiation or convection (Rhee & Kim, 2015; Stetiu, 1999). The radiating panels can be integrated into floors, ceilings, walls, or any room surface. However, the surface temperature of the panel must remain above the dewpoint temperature of the air in the room to avoid condensation on the surface. Several studies explored different methods to eliminate the risk of condensation, which often occurs in the cooling scenario (Bayoumi, 2018b; Hindrichs & Daniels, 2007; Hong, Yan, D'Oca, & Chen, 2017; Seo, Song, & Lee, 2014; Song & Kato, 2004; Vangtook & Chirarattananon, 2007; Zhang & Niu, 2003).

The potential of combining façade-integrated radiant cooling and the PVT system in one device was investigated (Bayoumi, 2018a). The cooling water is supplied by a chiller to the radiant panel; the return water is supplied to the PVT system and the return water of the PVT is supplied back to the chiller. The simulation results of this investigation concluded that in the selected warm climate, an increase of 35% in power conversion efficiency was achieved when compared to a conventional PV system. In another study, a detailed calculation of the heat transfer process was presented in association with thermal comfort simulations in several locations (Bayoumi, 2020). The results indicated a substantial impact of thermal comfort as well as energy generation efficiency. In both studies, the simulated façade device is attached to a heat pump or chiller that supplies the radiant cooling panel surface with cold water. Further, a pipe links the return of the radiant cooling surface with the supply of the PVT element. This helps to cool down the surface of the PVT element using relatively cool water that has already cooled the radiant cooling surface. Both studies were limited to the room cooling process, which recommends further exploration of the potential for developing such devices for both purposes, i.e., room cooling and heating.

The potential of a façade-integrated solar heater with thermal storage was discussed by Pugsley, Zacharopoulos, Mondol, & Smyth (2020). It primarily focused on the domestic use of warm water. The results indicate significant potential for increasing the efficiency of the heat generation process as well as the utilisation factor. This is primarily owing to the potential for overnight water storage. However, the potential for radiant heating for room climatisation was not considered in the proposed solution.

The present research suggests a combination of a façade-integrated PVT panel with a radiant cooling/heating panel and thermal storage located between both panels. The thermal storage is connected to a heat pump and supplies both panels with water. The analysis includes the impact of thermal storage on increasing the efficiency of the system through the reduced energy demand of the heat pump.

2 METHODS

The basic components of the proposed façade-integrated system are a PVT panel, 150 l thermal storage, radiant heating and cooling panel, and heat pump that can be attached to the system. The characteristics of the heat pump are outside the scope of this proposal. As illustrated in Fig. 1, while the PVT is located on the external side, the radiating surface faces the interior space and the thermal storage is located between both panels. The inlet and outlet points that connect the system with the heat pump are located on the side of the thermal storage. This implies that thermal storage is the distributor of the hot and cold water to the panels. The system was modelled using Polysun to assess the performance and functionality of the proposed system.

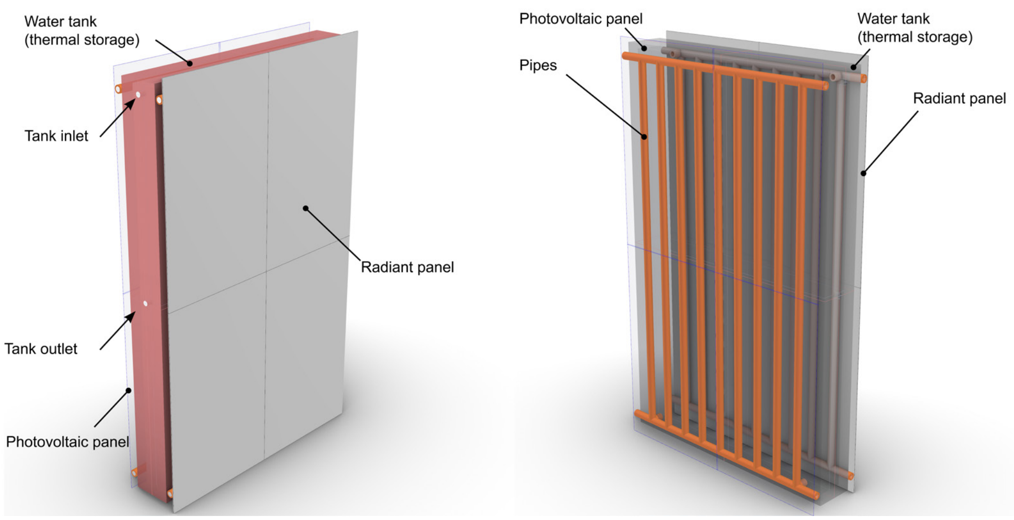


FIG. 1 Left: Axonometric drawing showing the radiant heating/cooling panel from inside; Right: External view showing the pipes attached to the back of the photovoltaic/thermal (PVT) panel. A high level of transparency has been set to the PVT panel for illustrative purpose

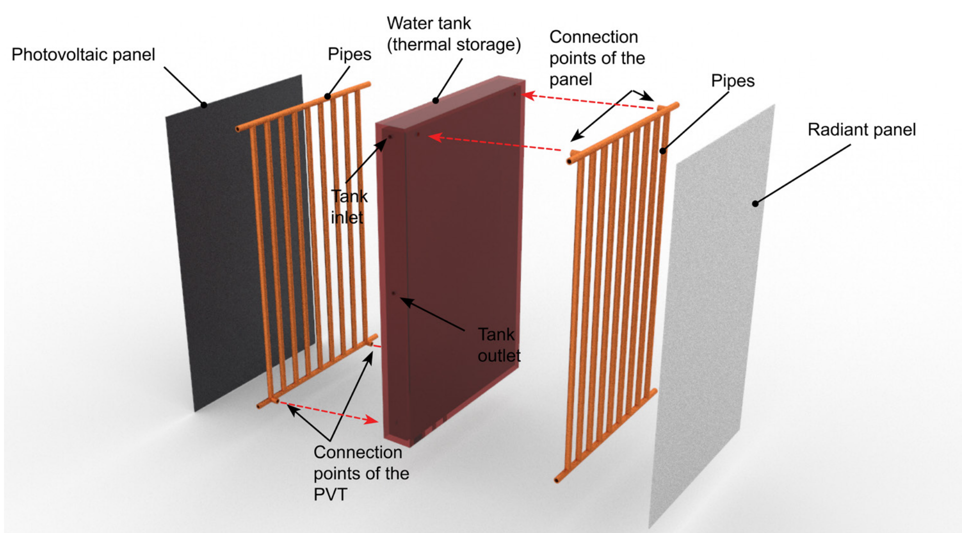
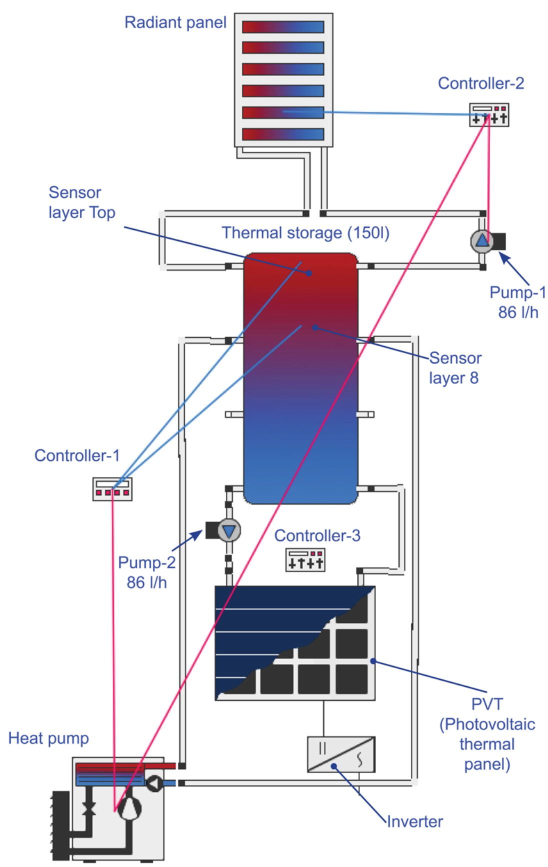


FIG. 2 Exploded axonometric drawing of the system

The exploded axonometric drawing in Fig. 2 illustrates the basic relationships between the components. It can be observed that the radiant panel is connected to the thermal storage through supply and return connections located in the upper part. In the lower part, the supply and return connections transfer relatively cold water to the PVT system. In this approach, the thermal storage works as a water exchange medium between the three elements: PVT, radiant panel, and heat exchanger. Further, this concept benefits from the temperature stratification that occurs during thermal storage. Thus, cold water always goes to the PVT element and the output warm water goes to the radiant panel in winter. In summer, the cooling is not significantly affected because the radiant cooling panel operates at temperatures in the range of 18-24 °C, which is one of the advantages of a so-called high-temperature cooler.



Controller-1		
Cut-in tank temperature	[°C]	20
Cut-off tank temperature	[°C]	20
Maximum tank temperature	[°C]	22
Control inputs		
Layer temperature sensor on	[-]	Storage tank: Layer 8
Layer temperature sensor off	[-]	Storage tank: Top Layer
Control outputs		
On/Off heating device	[%]	Heat pump: On/Off
Controller-2		
Control inputs		
Sensor input-1	[°C]	Radiant cooling temperature
Sensor input-2	[°C]	Average outdoor temperature
Control outputs		
Pump-1	[%]	On/Off
Heat pump	[W]	Conrolled power heat generator
Operating status		
If Sensor input-1 (i1>23)	then	Pump-1 -> off
If Sensor input-1 (i1>23)	then	Heat pump -> off
If Sensor input-2 (i2>20)	then	Pump-1 -> on
If Sensor input-2 (i2>20)	then	Heat pump-> 100 W
If Sensor input-1 (i1<20)	then	Pump-1 -> on
If Sensor input-1 (i1<20)	then	Heat pump -> 100 W
Controller-3		
Control inputs		
Sensor input-1	[°C]	PVT panel temperature
Control outputs		
Pump-2	[%]	On/Off
Operating status		
If Sensor input-1 (i1>22)	then	Pump-1 -> on
If Sensor input-2 (i2<20)	then	Pump-1 -> off

FIG. 3 Left: Layout of the simulated system; Right: Parameters of the controllers

The image on the left in Fig. 3 illustrates an overview of the simulated model using Polysun. It can be observed that the system includes two main pumps attached to each panel in addition to the primary heat pump. The pumps are operated by output signals from a set of controllers that read input signals from the surface temperatures of the radiant and PVT panels. In addition, the water temperature on different layers of the tank sends input signals to Controller-1. The table on the right of the figure lists the protocols and operation statuses of the three controllers. The simulation was performed for 8760 h and covers the four seasons of the year. According to the schematic diagram, the height of the water supply and return in each component, including the thermal storage, is crucial as it affects the thermal quality of the water. The listed configuration is the result of different arrangements and indicates the optimum outcome. The system includes a DC/AC inverter attached to the PVT system. However, the efficiency of the inverter is not considered in the context of this study, and the analyses were primarily limited to the DC output. The proposed system has been filed for patenting (US patent application number: 16999129).

TABLE 1 Specifications of the photovoltaic/thermal module

ELECTRICAL DATA [1]			
Typical power	(Pn)	[Wp]	245
Open circuit voltage	(VOC)	[V]	
Maximum power voltage	(Vpm)	[V]	
Short circuit current	(Isc)	[A]	8.74
Maximum power current	(Ipm)	[A]	8.17
Module efficiency	(η)	[%]	15.5
Maximum system voltage		[V DC]	1000
Reverse current load	(lr)	[A]	15
Temperature coefficient - Pn	(Υ)	[%/°C]	-0.43
Temperature coefficient - VPm	(β)	[%/°C]	-0.34
Temperature coefficient - Ipm	(α)	[%/°C]	0.065
[1] STC condition: irradiance = 1000 W/m^2, cell temperature = 25 °C			
THERMAL DATA - IN THE CASE OF PVT			
Aperture area		[m^2]	1.59
Thermal efficiency [2]	(η_0)	[%]	56
Nominal thermal power [3]		[W]	888
Volume flow rate		[l/m]	1.5-2.5
Flow losses		[mmH_2O]	400-900
Fluid volume		[l]	0.9
Coefficient α1 [2]		[-]	9.12
Coefficient α2 [2]		[-]	0
Effective thermal capacity		[kJ Kg^{-1} K^{-1}]	20
IAM K0 at 50 °C			
[2] Based on aperture area			
[3] PV OFF conditions referred to (Tm-Ta) = 0			
SPECIFICATION			
Cells		[-]	60 poly-Si
Thickness		[mm]	156
Electrical connectors		[-]	MC4
Hydraulic connector		["]	1/2 female
Dimensions		[mm]	1638 x 982 x 41
Weight		[kg]	27

For the purpose of testing the practicality of the presented invention, a location that requires heating and cooling was selected. Consequently, Munich, Germany, was selected as the standpoint for the simulations. An orientation to the south with an inclination of 90° was selected. The assessment focused on the surface temperatures of both the PVT system and radiating panel corresponding to external factors such as outdoor temperature and irradiance into the PVT module. One of the advantages of radiant heating systems is to provide heating with a relatively low surface temperature and thus less heating power. For this to work effectively, the temperature of the room surfaces should be homogeneous and within the human comfort zone. Besides air tightness, this requires well insulated walls, floors, and ceilings, as well as effective radiant heating elements. In this study, the surface temperature was set to around 21°C. The quality of the room surfaces and their insulation properties, which obviously affect the room temperature, were out of the scope of this paper. More focus was given to the surface temperature of a single radiant heating/cooling element. Obviously, more elements may be needed in a room depending on its heating load.

The radiating panel comprises an aluminium sheet with a thermal conductivity of approximately 202 W/m.K and specific heat capacity (Cp) of 871 J/kg.K. Further, the selected size of the radiating panel is similar to the PVT module, which is 1 m × 1.65 m. The pipes of both panels are of the same size, and the water mass flowrate is also identical across the components of the system. However, the water mass flowrate to/from the heat pump and the storage tank can be varied according to the heating or cooling demand of the system. Table 1 lists the specifications of the PVT module.

3 RESULTS AND DISCUSSION

An overview of the simulation results is shown in Fig. 4. The average data over the course of one year are presented. The preliminary axis depicts the temperatures in degrees Celsius and the secondary axis depicts the energy in watts. The light grey curve indicates the PVT DC electric energy production in watts and the black curve indicates the thermal energy exchange between the heat pump and the thermal storage in watts. The outdoor temperature is indicated by the yellow curve. The light blue curve depicts the surface temperature of the radiating panel that achieves the cooling and heating functions of the room. While the PVT panel temperature is indicated by the dark blue curve, the pink curve indicates the surface temperature of a typical PV panel under the same conditions. From the first glimpse, it can be noted that in summer, a difference of approximately 12 K is achievable between the surface temperature of the PV and the PVT panels. This suggests that the proposed system has succeeded in significantly cooling down the surface temperature.

From the figure, it can be observed that the temperature of the radiating element is stable at approximately 21 °C and varies within a small range of 1-1.5 K. This reflects the impact of thermal storage on stabilising the temperature of the radiating panel. Another advantage of the relatively cool water at the bottom of the tank is that the surface temperature of the PVT panel in summer is significantly lower than the outdoor temperature. In winter, the panel temperature is maintained above 0 °C when the outside temperature is below 0 °C to avoid the requirement for antifreeze solutions. However, this aspect can be further optimised using controlling schemes.

From the results of other simulations, it can be noted that the surface temperature of a conventional PV panel reaches 52.8 °C in the selected location. In the proposed system, the maximum surface temperature reached 37 °C. This difference has significant advantages for energy production and performance enhancement. As described earlier, for every 1 K increase in the surface temperature of the PV panel above 25 °C, a reduction of 0.5% in the performance is expected. From the diagram, it is also clear that the PVT DC electric energy production increases in winter, spring, and autumn, when the altitude of the sun is relatively low. During these seasons, the radiating panel presents a surface temperature that is reliable for maintaining the mean radiant temperature of the room within the comfort range. The generated electric energy can be used to operate the electric-driven heat pump.

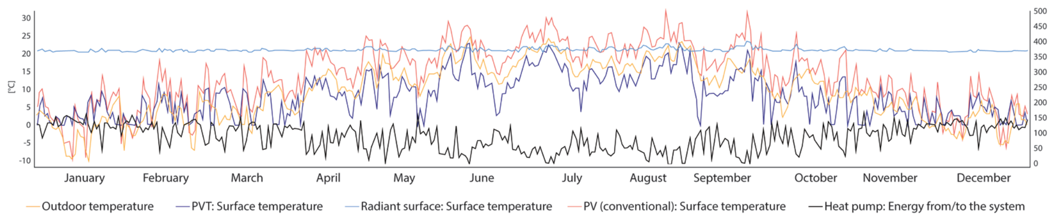


FIG. 4 General overview on the system performance over the course of one year

Fig. 5 illustrates a comparison of the simulation results for the energy production in DC between a conventional PV system and the proposed PVT system. The brown and orange curves represent the energy production using the PV and PVT systems, respectively. Generally, higher electricity production is expected in autumn, winter, and spring owing to the low altitude of the sun on the south façade. It is notable that a substantial increase in production efficiency can be achieved using the PVT system. This is primarily owing to the cooling effect and the reduction in surface temperature caused by the integrated thermal storage tank. Further, the difference in electricity production reaches to more than 35%.

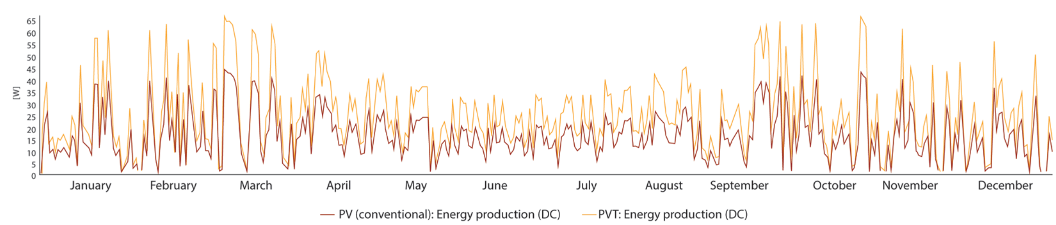


FIG. 5 Comparison in energy production in DC

A detailed observation during a high-temperature summer period in the first two weeks of July is shown in Fig. 6. It is important to notice the effect of ambient temperature on the surface temperature of the conventional PV and proposed PVT systems. The right axis presents the solar irradiance into the module area. A remarkable temperature increase was observed in the first case that exceeds the outdoor temperature by approximately 40%. Conversely, the PVT system presents a reduced module surface temperature in most of the cases, which reaches up to 10% of the outdoor temperature. The surface temperature of the radiant cooling/heating panel is stable and marginally affected by the outdoor temperature. It moderately varies between 20 and 24 °C. However, there is a clear indication that the surface temperature of the PV module is significantly affected by the solar irradiance into the module area. It is notable that both curves are in correlation.

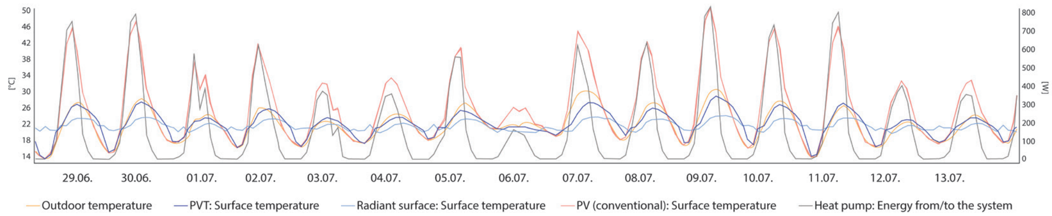


FIG. 6 Detailed observation during a high-temperature summer period

In winter, another detailed observation was performed around the beginning of February and the results are shown in Fig. 7. A significant increase in the surface temperature of the conventional PV system is evident from the figure. As noted in the previous figure, unlike the conventional PV module, the surface temperature of the PVT system is less likely to be affected by solar irradiance. The surface temperature of the radiant cooling/heating panel is nearly stable at 20 °C despite the extreme drop in temperature that reaches up to -12 °C.

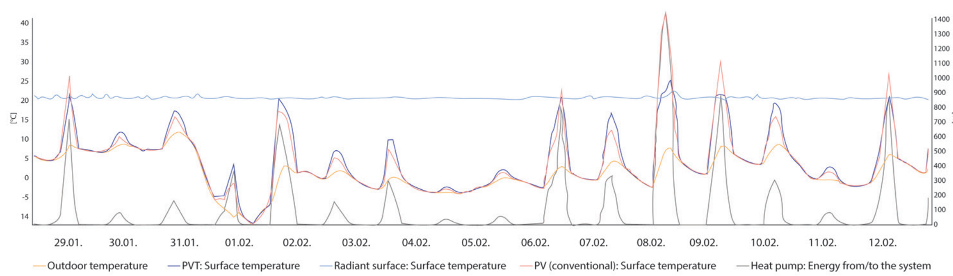


FIG. 7 Detailed observation during a low-temperature winter period

To provide a validation for the increased efficiency of the proposed and simulated system over conventional ones, two comparisons have been made against existing systems whose live statistical data are available online. Both PV systems are located in Munich. The characteristics of each system are outlined in Table 2.

TABLE 2 Table 2 Framework of the reference systems

SYSTEM NUMBER	[-]	1	2
System name	[-]	dahoam (pvoutput.org, 2020a)	GB53 (pvoutput.org, 2020b)
System size	[kW]	4.176	4.5
Number of panels	[-]	16	20
Panel capacity	[Wp]	260	225
Inverter	[-]	Samil SolarLake 4500 TL-D	SMA Sunnyboy 3600 TL
Maximum efficiency (inverter)	[%]	97.6	97
Orientation	[-]	South	South West
Tilt	[°]	37	42

Using the simulation software PolySun, comparisons have been made between the proposed system and each of the reference systems. Therefore, in each simulation the framework of the proposed system has been modified to match the reference case. These modifications were essentially applied to the panel capacity, inverter efficiency, orientation, and tilt angle. The comparisons shown in Fig. 8 and Fig. 9 depict the difference in the accumulated monthly AC output of the PV panels (primary axis) and the associated increase/decrease in module efficiency (secondary axis).

The diagram in Fig. 8 presents an overall increase in the PV output of the proposed system over the reference system-1. It is clear that in the cold months remarkable increases in efficiency can be noticed. This is basically attributed to the decreased surface temperature of the panels. This is notable as the radiant panels are used for heating and the upper part of the thermal storage supplies it with relatively warm water. Therefore, the water coming out of the thermal storage and moving at the back of the panel doesn't seem to negatively affect the efficiency of the module. Further, a slight decrease in the output in February can be seen. This exception maybe attributed to the statistically collected climate data that are embedded in the simulation software and may have different data regarding the irradiance and cloudiness of the site in comparison to the real readings from the system. This obviously affects the simulated output. Moreover, thanks to the proposed an increase in efficiency of up to 31% can be noted.

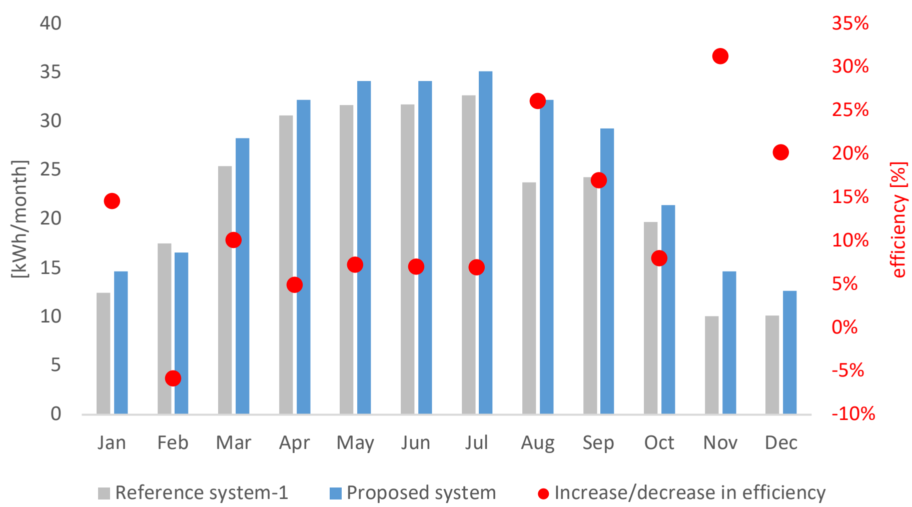


FIG. 8 Comparison between the proposed system and the reference system-1

A more remarkable increase in efficiency is noted in Fig. 9, where the efficiency of the proposed system has improved by 47% over the reference case. Generally, the electrical output of the PV panel has substantially increased over the course of the 12 months. This is of particular interest in summer as, despite the increased ambient temperature, the cooled water from the thermal storage helped reduce the surface temperature and thus increase the module efficiency. However, the increased module efficiency and thus PV output are amongst the advantages of the proposed system that combines radiant cooling, radiant eating, thermal storage, and energy generation with an increased efficiency in one façade-integrated device.

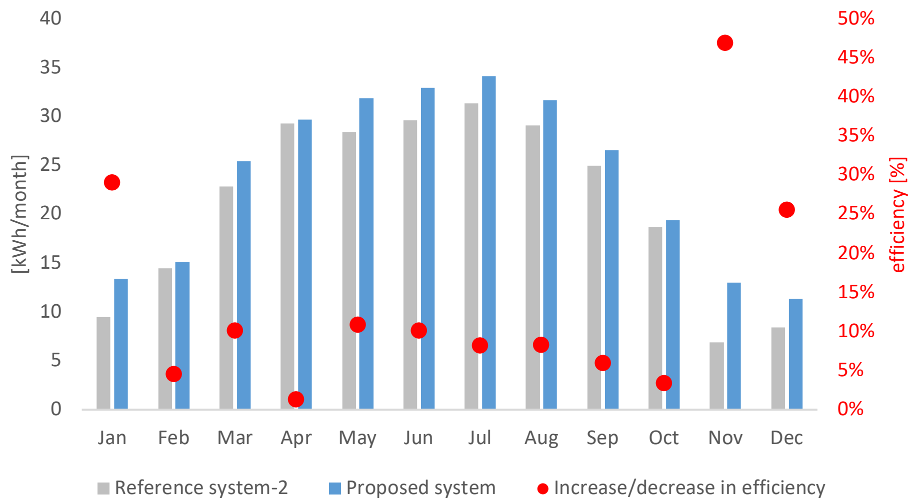


FIG. 9 Comparison between the proposed system and the reference system-2

4 CONCLUSION

This paper has presented the potential of a façade-integrated device where the PVT panel is located on the external side and the radiant cooling/heating surface faces an interior space; moreover, a thermal storage tank is located between the panels. Both elements are connected through thermal storage. A comparison with conventionally free integrated PVs was included. The results indicate the high potential of the proposed system over the conventional PV system in terms of reduction in surface temperature and increase in electricity production efficiency. As high cooling loads coincide with high façade irradiance, the proposed solution has practical applications for an integrated building envelope system. The system also helps save space as it combines energy generation with radiant cooling/heating and integrates this into the building envelope. The impact of the thermal storage was clear in stabilising the surface temperatures and eliminating the correlation between the solar irradiance and the surface temperature. Furthermore, the cooling or heating energy can be directly generated using a heat pump that is connected to the thermal storage. The proposed system can be developed in different sizes and depths and can be incorporated into walls, roofs, or inclined surfaces at any angle. Multiple elements can be connected in series to achieve higher cooling and heating loads.

Key advantages:

- A year-long solution in locations where heating and cooling are required.
- The integration of thermal storage reduces overheating.
- Increased efficiency for electricity, cooling, and heating.
- A shorter reaction time owing to thermal storage.
- Supply of heating energy during both the day and night.
- Good façade insulation owing to the various layers of materials, including the thermally insulated storage tank.
- No requirement for antifreeze as the thermal storage can supply warm water to the PVT element when required.

- The entire system is a wall element that can be sized flexibly. The thickness of the system can vary, and the water tank can also have variable thicknesses.
- A larger system can also include potable water production.

Further research and development can be conducted to convert the panel to a window element that is operable to allow fresh air intake during periods of pleasant temperature. Instead of cooling pipes, capillary tubes can be attached to the surfaces to achieve higher performance and a slimmer design.

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