Optimization of deterministic controls for a cooling radiant wall coupled to a PV array

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Abstract

Thermally activated building systems (TABS) can work as thermal energy storage (TES) systems, which are useful in shifting the energy use of space cooling and heating in buildings. The present study analyses and optimizes simple deterministic control concepts for radiant wall supplied by a heat pump for cooling purposes. First, the "solar" concept was studied, which was focused on exploiting the output of a photovoltaic (PV) array. Secondly, a "peak load shifting" concept exploiting the low electricity cost and high heat pump energy efficiency during night periods was evaluated. The results showed that the "solar" concept saved between 57% and 95% in comparison to a conventional control in different PV installed capacities. Moreover, the optimized "peak load shifting" concept had lower operation cost than the conventional control with most of the PV configurations proposed. Therefore, the study showed that the investment in the PV array was fully harnessed only with specific controls. Furthermore, the "solar" control concepts were found to help achieving the goals of net-zero energy buildings by maximising self-consumption of renewable energies in the building, as well as reducing the total imported/exported energy.

Keywords: radiant wall; cooling; energy savings; optimization; control

1 Introduction

The agreement issued by the United Nations convention on climate change held in Paris [1] recognized the challenge that climate change represents to human societies. Moreover, it specifically identified the reduction of greenhouse gases emissions as a priority objective.

Renewable energies are essential to decarbonize the energy sector. Statistical ~~A~~analysis of historical data on energy production and CO_2 emissions showed renewable energies direct causality effect in the reduction of greenhouse gases emissions. For example in Pakistan, a 1% increase in the renewables share implied a 1.086% decrease of the national CO_2 emission [2]. A similar study on Brazil, Russia, India, China, and South Africa (BRICS countries) showed that the trend will be to increase the renewables share, which could represent decreasing 0.2601% the CO_2 emissions per 1% increase of renewables [3]. On the other hand, simulations of energy models in Europe showed reductions of 95% CO_2 emissions in a scenario with a strong cooperation between countries through interconnection and high renewable electricity system, with shares of generation of 65 % for wind-power, 15 % for hydro power, and still considering solar energy and energy storage [4].

The stochastic nature of renewable energy sources usually causes a mismatch between energy availability and energy demand. Therefore, energy storage is essential into achieving a highly renewable energy system. The feasibility of integrating renewable energy sources into the energy sector depends on the generation cost and the backup energy requirements. These parameters are improved by efficient transmission between countries and by energy storage [5]. Simulation of a scenario with 80% of renewables share in Europe showed the necessity of energy storage, independently of the interconnection capacity between countries [6]. Similarly, a scenario with 100% renewable system showed that location, type, and sizing of electric energy storages (EES) depended on the economic and transmission factors between countries [7]. These studies showed the importance of energy storage, however, they only considered EES, mainly taking into account pumped hydro power, hydrogen batteries, adiabatic compressed air, stationary lithium-ion batteries, and redox-flow batteries.

Within this context, thermal energy storage (TES) is a technology useful for the integration of renewable energies in different sectors, either in the supply side of the power grid or as an improvement for demand side management, where special interest arise for buildings flexible management [8]. Moreover, TES can have similar application to EES, as found for cooling in building, in which the most suitable technology depended on the specific boundary conditions of each case [9], such as magnitude of the load, tariff scenario, and space availability. Also in buildings, just the integration of phase change materials (PCM) as TES could reduce 3% of the CO_2 emissions related to fuel use for heating and cooling [10]. Better results were found using a TES with phase change material for integrating free-cooling, which lead to energy savings above 50%, especially in locations with outdoor temperature swing between 12 and 15 K [11]. TES showed good potential for energy savings and improvement of demand side management in buildings, but these technologies can also cover a wider range of applications, with short and long term storages, different temperature ranges, and different sectors [12].

Yet, the good performance of TES is dependent on adequate control strategies. As shown for TES in buildings, the demand flexibility and reduction of cost was achieved only under optimal control [13]. One example is found in district heating systems, which is a heating concept complex to manage due to the interaction of multiple consumers with stochastic demand profiles with different generators. Moreover, the integration of TES to the district heating grid further increases the complexity of its control, as the variables to consider for cost optimization increase. Therefore, some research showed that reduction of the system cost was only achieved under advanced controls, such as model predictive control (MPC) [14]. Another approach showed that TES allowed for optimal control of a gas-fired combined heat and power (CHP), allowing the power plant to produce electricity in high price hours while storing heat in order to match the heating and domestic hot water demand of a set of buildings connected through district heating ~~[15]~~. Among the TES systems considered in that study, activation of building thermal mass showed promising results [15].

Thermally activated building systems (TABS) are forms of TES integrated into the building structures for heating and cooling purposes [16]. These consist of pipes or ducts embedded into the building structure, which actively use the thermal mass as heat storage. Then the heat is transferred to indoor spaces through the building surfaces (walls [17], floors [18], and/or ceilings [19]). Hence, TABS can be considered as short term and low temperature TES, with the special characteristic of being actively charged but passively discharged. Moreover, the characteristic of TABS make them suitable for the integration of renewable energy sources into buildings heating and cooling. Common set-ups are TABS with ground-source heat exchangers (GSHE) [17], geothermal heat pumps (GHP) [18], and cooling towers [19]. Moreover, TABS can increase the heating and cooling efficiency of building, which synergise with their good integration of renewables. Such advantages TABS a technology suitable for achieving net-zero energy buildings [20].

One interesting set-up for reducing the cost and CO_2 emissions of space heating and cooling in buildings consists of a photovoltaic (PV) array supplying electricity to a heat pump that uses TES to offset the mismatch between the energy supply, which depends on the sun, and the demand. This configuration was implemented with photovoltaic-thermal panels (PVT), in which the heat was stored in a water tank that improved the temperature of the evaporator of the heat pump [21]. Another set-up with photovoltaic-thermal panels using a water tank as TES was capable of providing 96% of the electricity demand and all the heat demand of a house in Netherlands [22]. Similarly, a case in which the system was coupled to a radiant floor had its performance improved by complementary usage predictive model control [23]. Another study used the same control strategy, but changing the set-up so that the heat pump coupled to the PV array used both a water tank and a radiant floor as TES [24].

Previous research related to the present article showed the peak load shifting capability of radiant walls [25], even under internal loads [26]. Moreover, the experimental research was used to validate a numerical model of the radiant wall [27]. This was later implemented in a control study that showed that the potential of the PV array was only exploited if the heat pump was operated under a specific solar control [28]. Otherwise, simpler peak load shifting strategies led to similar operation cost, but without requiring the PV array. However, the results showed that the control parameters of the deterministic strategies could be optimized.

The present article optimises these control strategies on a configuration consisting of a PV array coupled to a heat pump that supplies a radiant wall. Specifically the two main control strategies studied were a solar concept that aimed to maximise the use of PV production, and a simple peak load shifting strategy exploiting the lower cost of off-peak periods. This research provides new knowledge in the integration of distributed renewable energy through the use of thermal storage.

2 Methodology

The study was based on the simulation of a room cooled with radiant walls, hence the first section of the methodology summarizes the model, which was validated and used in previous research. After that, the main parameters taken into account in the simulation are presented, with a description of the calculation of the operation cost, the control concepts, and the data used in the simulation. Finally, the experiments carried out are described, which consist first in a sensitivity analysis of the control parameters followed by its optimization in different cases.

2.1 Simulation model

In order to follow the research from previous experimental campaigns [23,24], the simulation model was developed to describe the performance of the experimental set-up. This consisted of a simplified room exposed to outdoor conditions, as shown in Figure 1. The room had an internal size of 5.25 x 2.7 x 2.7 m and radiant walls on each of its surfaces, as shown in Figure 2 and further explained in previous articles [23,24]. The radiant wall model itself was modelled with finite volume method (FVM), using a 2D mesh that provided detailed information of the heat transfer. This numerical model was validated with experimental data of the experimental room, achieving good prediction of the indoor and outdoor surface temperatures as well as heat flux into the pipes for different orientations of the wall (East, South, and West). Additionally, the model was used to evaluate the most important design parameters of the radiant wall, more details on the validation and the parametric studies were presented in Romani et al. [25]. Afterwards, the radiant wall model was integrated to the whole room model, which was developed according to the Seem methodology [27] considering six surfaces. Four walls (East, South, West, and North), ceiling slab, and floor slab are modelled. Moreover, the model considered constant infiltrations and heat transfer with the ground, more details of this model were presented in Romani et al. [26].

Figure 1. Cubicle used for experimentation of a radiant wall performance. Experimental test-site belonging to University of Lleida and placed in Puigverd de Lleida (Spain)

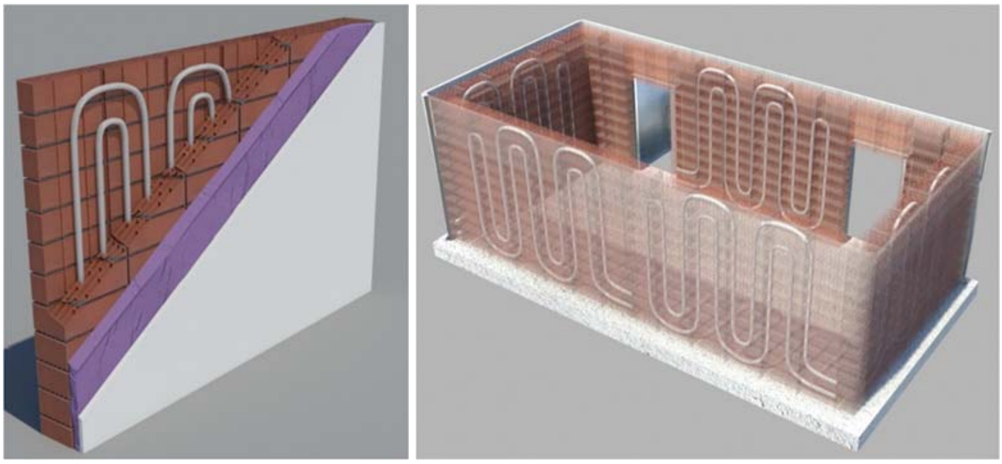

Figure 2. Structure of the radiant wall (left) and distribution of the radiant loops in the experimental room

The room was cooled with an air-to-water heat pump directly connected to the radiant walls. The performance of the heat pump was modelled through the data provided by a manufacturer for a LH33E/2GES-2Y-40S compressor. The simulation assumed a constant supply temperature of 15 ºC to the radiant walls but variable temperature at the condenser side. The COP curve of the heat pump is shown in Figure 3, it includes the compressor efficiency and the fan energy use. The PV array was modelled with horizontal panels of 1.68 m^2 each. The efficiency of the panels was considered constant with a value of 15%.

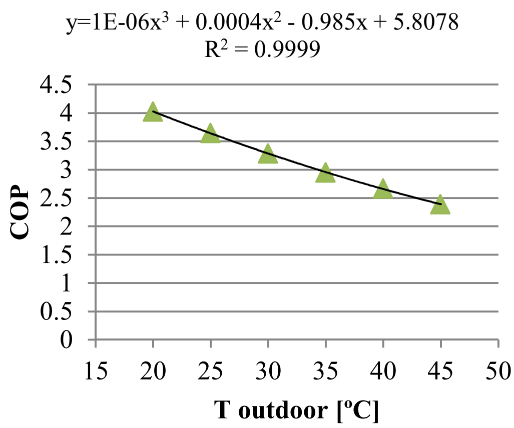

Figure 3. Heat pump performance

The cooling load of the room was caused by the outdoor conditions and internal heat gains. The latter load represented a domestic occupancy of the room, with higher internal loads during early morning and afternoon, average internal loads during the night, and very low for the working hours. For simplification, the internal loads were applied to all days of the week. The profile of the internal loads is presented in Figure 4.

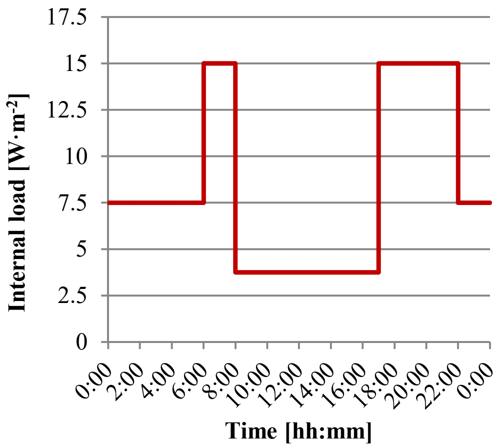

Figure 4. Internal loads profile

The full description of the room model and the modification of the FVM, a well as the details of the heat pump and PV panels were presented in Romani et al. [28].

2.2 Operational cost

The operational cost was calculated with the imported energy from the grid required for operating the heat pump. The PV panels output power was subtracted from the simultaneous power from the heat pump in order to obtain the imported energy. Moreover, the excess production of the PV panels was not taken into account, so that the cost was calculated with the absolute imported energy from the grid.

The energy cost prices used to calculate the cost were taken from reference domestic tariffs in Spain. The cost of the maximum peak power energy use for domestic tariffs in Spain is constant, as the research of this paper did not influence the installed power of the system the cost of the power term was not taken into account. Then, the operational cost was calculated with equation 1.

$$C_{op}[€] = E_{peak} \cdot C_{peak} + E_{off} \cdot C_{off} \qquad \text{Eq. 1}$$

Where C_{op} is the total operational cost of the heat pump. E_{peak} was the energy consumed and C_{peak} was the cost of electricity during peak periods, which happened from 1 pm to 11 pm and had a value of 0.147675 €·kWh^{-1}. On the other hand, E_{off} was the energy consumed during the off-peak periods, that was from 11 pm to 1 pm and had an electricity cost (C_{off}) of 0.067255 €·kWh^{-1}.

2.3 Control concepts

Previous research [28] showed that the potential of a PV array was only exploited if specific "solar" control concepts were used. In the opposite case, simple "peak load shifting" control concepts without PV could achieve similar cost savings than conventional control with PV. Moreover, the results pointed that the control parameters of each concept could be optimized.

Hence, in this research two control concepts were studied in depth, both based on lowering the thermal level (decreasing the temperature) of the wall by removing heat in favourable periods, which is referred to as pre-cooling. On one side there was the "solar following" concept, in which the system pre-cooled if sufficient PV output was available. On the other hand, the "peak load shifting" concept pre-cooled during the off-peak periods. Both control concepts had two operation modes: the "comfort" mode, and the "charge" mode.

The "comfort" mode ensured that the room temperature did not exceed the comfort range. It activated the heat pump if the indoor temperature exceeded 26 ºC and stopped it when the temperature decreased below 24 ºC. This activation was independent of the output of the PV panels or the cost of electricity.

In contrast, the objective of the "charge" mode was to pre-cool in the cubicle by decreasing the set-point. Once charging was engaged, the heat pump was activated if the indoor temperature was above 22 ºC and turned off if below 21 ºC. However, the conditions for engaging the "charge" mode depended on the control concept. In the "solar following" concept, charging was allowed if the power output of the PV array exceeded a certain threshold, a parameter defined as minimum PV power output (P_{min}). In the "peak load shifting" concept, the charging was scheduled, engaging the "charge" mode during certain hours in the off-peak period, which was constrained by precooling the start hour (h_{start}) and end hour (h_{end}). The scheme of the control concepts is shown in Figure 5 for "solar following" and Figure 6 for "peak load shifting".

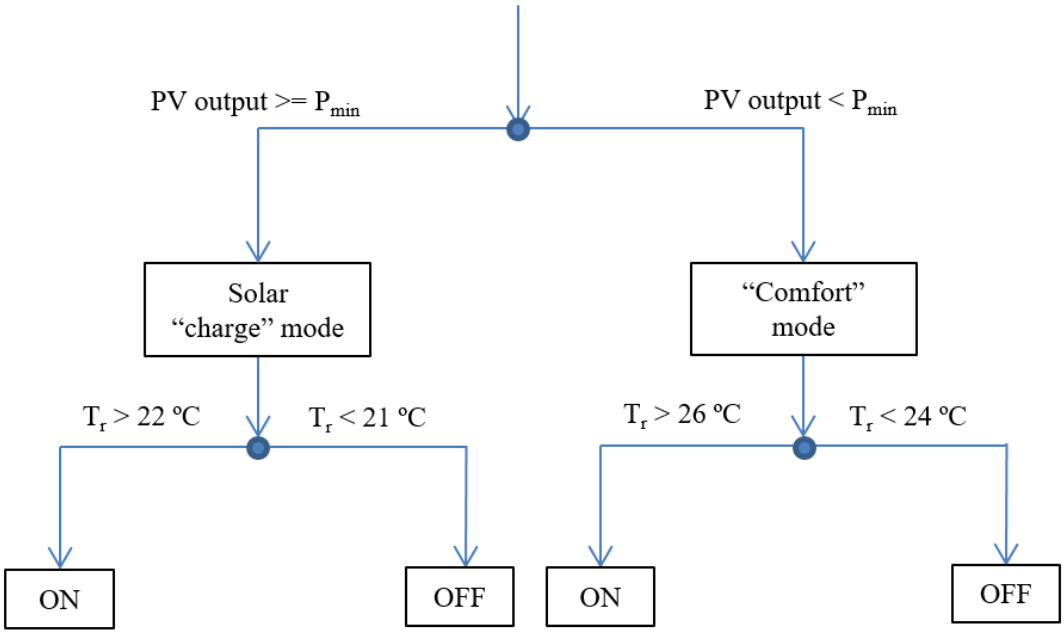

Figure 5. "Solar following" control concept

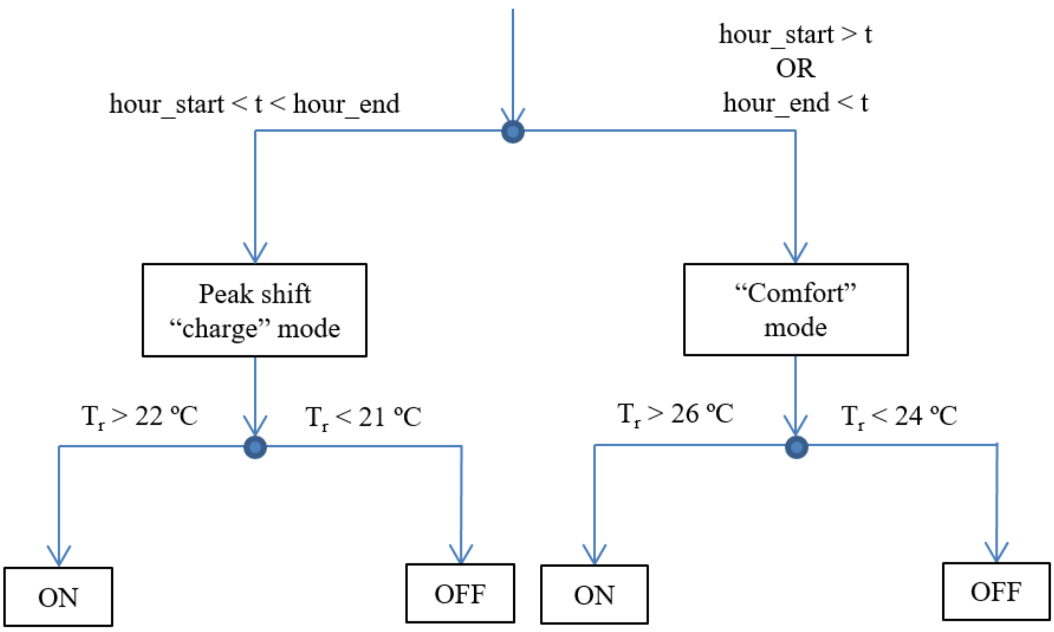

Figure 6. "Peak shift" control concept

2.4 Evaluation parameters

The performance of the control concepts was evaluated mainly with three parameters, the "HP energy use", the "solar fraction", and the "charge mode fraction". HP energy use refers to the overall energy use of the heat pump in the simulation process, expressed in kWh, without considering the origin of the energy or the operation mode. On the other hand, the solar fraction represents the percentage of the “HP energy use” that was directly supplied by the PV panels. This parameter was calculated considering only the simultaneous production of PV and consumption by the heat pump, without considering any storage of the produced energy. Finally, “charge mode fraction” implies all the energy used by the heat pump while engaging the “charge” modes explained in section 2.3.

2.5 Simulation data

The experimental data used as case study was measured in a test-site in Puigverd de Lleida (Spain) [32] during May to September 2016 (both included). The climate of the site is classified as Csa (hot summer and mild cold winter) according to Köppen-Geiger climate classification [33]. The measurements include outdoor temperature and global solar radiation, on top of the data from the cubicles themselves, which registered indoor ambient temperature and humidity as well as temperatures at different positions and surfaces of the wall. The vertical radiation on each wall was estimated from the measured horizontal radiation by using solar radiation models.

2.6 Sensitivity analysis

The influence of the control parameters was analysed in a parametric study. Several cases of each control concepts were run, varying the “minimum PV power output” and the PV nominal power (P_{PV}) in the “solar following” concept. For the “peak-load shifting” concept the schedule of the pre-cooling was applied at midnight, sunrise, and noon periods, with length of two or four hours. The summary of the performed tests is presented in Table 1.

Table 1. Summary of sensitivity analysis cases

	Solar following		Peak load shifting
Variable	P_{min} (W)	P_{PV} (W)	$h_{start} – h_{end}$
Possible values	125 ; 250 ; 375 ; 500 ; 625 ; 750	252 ; 504	Midnight 0:00 – 2:00 ; 0:00 – 4:00 ; Sunrise 5:30 – 7:30 ; 4:30 – 8:30 Noon 9:00 – 13:00 ; 11:00 – 13:00

2.7 Optimization of control parameters

The optimization of the control concepts was carried out with GenOpt v3.1.1 optimization software [34]. The optimization algorithm used was generalized pattern search (GPS) Hooke-Jeeves with single seed in which the cost function to be minimized was the operation cost of the heat pump for the cooling season. Two sets of optimization were carried out, first optimizing the “minimum PV power output” (P_{min}) of the solar following concept to start charge process, with different amount of PV installed capacity. The second optimization regarded to the start and end time of the “peak load shifting” concept without panels. All optimizations were based on perfect knowledge of the weather and solar conditions. Therefore, the objective was to find the best control parameters for the studied set of data. Moreover, the control parameters were forced to be constant for the whole season, hence a single value was obtained.

Moreover, the results of both optimizations were compared to the performance of the set-up with different PV surface, but with the heat pump operating only under “comfort” mode. Table 2 presents the summary of the optimisation cases.

Table 2. Summary of optimization cases and reference simulations

Control concepts	Optimized parameters	Cases (P_{PV})
No control (“comfort” mode”)	-	0 W 252 W 504 W 756 W 1008 W 1260 W
Solar following	P_{min}	0 W 252 W 504 W 756 W 1008 W 1260 W
Peak load shifting	h_{start} ; h_{end}	0 W

3 Results

3.1 Sensitivity analysis of “solar following” concept

The results of the sensitivity study of the “solar following” concept are presented in Figure 7 and Table 3. As expected, the ~~highest~~ higher the PV installed capacity had the ~~lowest~~ lower the operational cost, as seen in all the cases with equal P_{min} but different nominal power. As reference, the comparison of the cases with lower operation cost in each PV set-up showed a difference of 64 %.

The analysis of this best cases showed that the minimization of the operational cost was closely related to the maximization of the "solar fraction", which was a logical conclusion, as the energy provided by the PV does not report any operational cost. However, the maximisation of the "solar fraction" was balanced by the increase of energy use of the heat pump during "charge" mode.

With low values of P_{min} the energy used in the "charge" (charge mode fraction) increased, as it implied a lower set-point, and thus a higher cooling load. Consequently, the overall energy used by the heat pump increased. Moreover, the lower P_{min} implied that the control allowed to activate the heat pump even if the PV output was not enough to offset the energy demand, hence, the "solar fraction" of the energy used decreased, despite the higher "charge mode fraction".

Finally, higher P_{min} limited the use of the "charge mode", and then the PV output was not exploited for cooling. Moreover, as the cooling load was not fulfilled by the "charge" mode, the heat pump was required to use the "comfort". This event usually happened in the afternoon periods, when the indoor space was affected by the heat wave, which was delayed by the thermal mass of the wall. As a result, the heat pump was activated when the PV output was very low. Therefore, the "solar fraction" decreased sharply despite the energy demand did not decrease significantly. The energy results directly translated into the operational cost. As shown in Figure 7, the minimum operational cost matched the cases with higher solar fraction.

Table 3. "Solar following" concept sensitivity analysis results (best results in bold)

PV nominal power [W]	P_{min} [W]	HP energy [kWh]	Solar fraction [%]	Charge mode fraction [%]
504 W	125	327.61	47.05	100.00
	250	303.01	56.64	99.63
	375	**274.63**	**65.76**	**91.01**
	500	220.01	47.47	33.78
	625	191.40	23.40	2.41
	750	189.77	22.70	0.04
756 W	125	331.82	63.30	100.00
	250	320.16	71.89	99.49
	375	303.01	79.17	99.63
	500	284.54	85.02	97.48

	625	**258.39**	**86.55**	**74.75**
	750	220.01	64.69	33.78

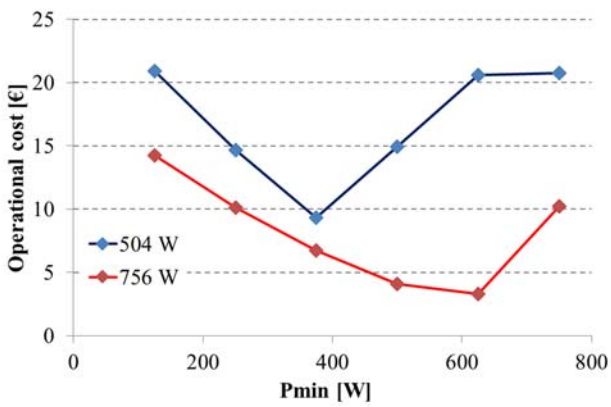

Figure 7. Operational cost in solar following mode depending on P_{min} for different nominal PV power.

3.2 Sensitivity analysis of "peak load shifting" concept

The results of the sensitivity analysis on the "peak load shifting" concept favoured longer pre-cooling periods, as summarized in Table 4. The 4-hours cases had lower operation cost than the 2-hours counterparts at the same periods. Moreover, doubling length of the "charge" period did not imply a significant increase in energy use despite theoretically having a higher cooling demand. Furthermore, even it resulted in a decrease in the energy use at the midnight pre-cooling case. Instead, allowing longer "charge" periods increased the fraction of energy used in this mode, meaning the system successfully shifted the energy use to off-peak periods. Furthermore, the results were influenced by the performance of the heat pump, which had a better COP when the outdoor temperature was lower, with the best results just before sunrise. Operating at the longest "charge" period at sunrise led to the highest "charge" mode fraction and lowest operation cost.

Table 4. "Peak load shifting" concept sensitivity analysis results (best result in bold)

Period	Length [h]	Schedule [hh:mm]	Cost [€]	HP energy [kWh]	Charge mode fraction [%]
Midnight	2	0:00 – 2:00	19.62	223.81	74.63 %
Midnight	4	0:00 – 4:00	15.90	222.60	94.84 %
Sunrise	2	5:30 – 7:30	17.04	200.26	77.81 %
Sunrise	**4**	**4:30 – 8:30**	**14.78**	**218.51**	**99.51 %**
Noon	2	11:00 – 13:00	16.73	219.41	86.17 %
Noon	4	9:00 – 13:00	15.73	233.77	98.55 %

3.3 Optimization of control parameters

Table 5 and Figure 8 compare the results of the optimized “solar following” and “peak load shifting” concepts against the cubicle controlled just under “comfort” mode. For the “solar following” concept the optimized value of P_{min} is presented for different PV nominal powers, while the optimized h_{start} and h_{end} are shown for “peak load shifting” concept.

First, the results showed that the cost of controlling the cubicle just with “comfort” mode decreased if PV was installed, although the energy use of the heat pump remained constant. As expected, the higher the PV surface the higher the operation cost savings. However, optimized “solar following” had much higher cost savings.

The key to the better performance of “solar following” concept was the maximized solar fraction. While the “charge” mode implied an increase of the cooling demand, and thus an increase of the energy use, the high solar fraction resulted in very low operational cost. In order to achieve this, the P_{min} was optimized depending on the PV installed capacity.

The optimized P_{min} was not proportional to the PV installed capacity. At the case with nominal power 252 W the optimal solution was to skip “charge” mode, and thus only operate under “comfort” mode conditions. In the other cases, increasing the installed capacity increased the optimal P_{min}, however, the increase was not linear with the PV installed capacity. With PV installed capacity of 356 W or more the energy use of the heat pump stabilized, meaning that P_{min} was stabilized in order to meet the cooling load while maximizing the “solar fraction”.

On the other hand, the optimization of the “peak load shifting” favoured charging the cubicle at sunrise and early morning for a period about 4.5 hours. This optimized operation resulted in cost reduction of 46 % compared to “comfort” mode without PV. Moreover, the operational cost was similar to “comfort” mode with nominal power of 1008 W. Noticeably, the energy use of the heat pump under “peak load shifting” was only 10 % higher than in comfort mode, showing a better performance of the system during the night-time, when the COP was higher.

Table 5. Optimization results

Control concept	PV nominal power [W]	Optimized parameters: Parameter [units]	Optimized parameters: Value	HP energy [kWh]	Charge mode fraction [%]	Solar fraction [%]
Comfort	0	n/a		190.3	n/a	n/a
Comfort 252 W_{PV}	252	n/a		190.3	n/a	11.3 %
Comfort	504	n/a		190.3	n/a	22.5 %
Comfort	756	n/a		190.3	n/a	33.8 %
Comfort	1008	n/a		190.3	n/a	45.0 %
Comfort	1260	n/a		190.3	n/a	56.2 %
Solar following	252	P_{min} [W]	max*	190.3	0 %	11.3 %
Solar following	504	P_{min} [W]	409.4	261.6	68.9 %	65.9 %
Solar following	756	P_{min} [W]	571.9	273.5	80.5 %	87.3 %
Solar following	1008	P_{min} [W]	765.6	273.0	78.5 %	94.9 %
Solar following	1260	P_{min} [W]	909.4	277.6	81.7 %	97.9 %
Peak load shifting	0	Schedule	6:00 – 10:30	209.3	97.5 %	n/a

* With PV nominal power of 252 W the optimization sets a P_{min} high enough to skip "charge" mode completely

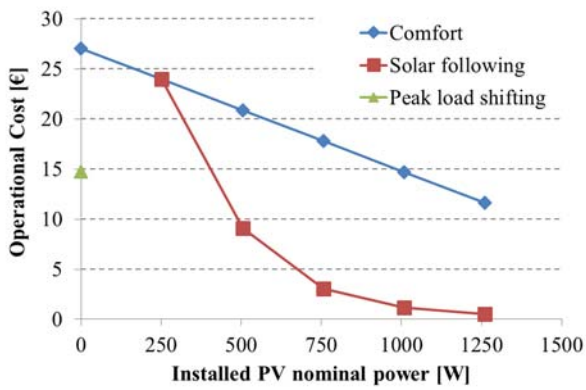

Figure 8. Operational cost for each optimized control strategy with different installed PV power.

4 Discussion

The results clearly showed the capability of the radiant wall to act as a TES system. This allowed shifting the cooling production to periods with availability of solar energy, better efficiency of the heat pump, or low electricity cost. However, in order to fully exploit these periods, the system required using control concepts that "charged" during high efficiency periods conditions. On that point, two control concepts were studied. On one side, "solar following" concept focused on exploiting the solar energy obtained with the PV panels, while "peak load shifting" attempted to exploit off-peak periods and the higher efficiency of the heat pump during the night,

The optimization highlighted that in terms of operation cost of the heat pump, the advantages of the PV array were only harnessed under specific solar control concepts. If not, the optimization of the "peak load shifting" concept resulted in a lower operational cost than controlling just under "comfort" mode with a system up to PV installed capacity of 1008 W. Furthermore, once the "solar following" control concept was optimized, the operation cost were improved by 57% with a PV nominal power of 504 W and up to 96 % with 1260 W in comparison to the respective cases under "comfort" mode. However, the results also implied that "solar following" concept was only profitable if a minimum of PV installed capacity was available, requiring at least 504 W in the tested conditions. Finally, optimizing the "solar following" concept even with this minimum PV installed power yielded better results than optimized "peak load shifting" concept or operation under "comfort" mode with any of the cases studied.

While the results of the optimization reduced significantly the operational cost, the control concepts could be further improved. In this study, only a single value of the control parameters was used for the whole summer season, despite the cooling demand clearly changed along the period of the simulation. Additionally, a single climatic area was studied, hence the influence of different solar radiation and cloud coverage was not taken into account. Therefore, the independent variable influencing the control parameters was the PV installed capacity. However, the storage capacity of the radiant wall, the performance of the heat pump, and the cooling demand should also affect the optimal control set-up. Noticeably, supply temperature was constant in the current study. However, this parameter directly affects the performance of the heat pump, hence it can potentially be a control variable for optimization. Moreover, the supply temperature determines the heat transfer rate with the radiant wall, affecting the length of the charging cycle. On the other hand, it limits the storage capacity of the system, as this is directly related to the temperature difference. Finally, all these mentioned parameters can have a synergistically effect on the cost reduction, as shown on a study of the influence of the storage capacity of a TES system and installed capacity of PV in an industry [35].

As mentioned above, the results of the optimization could be improved. One simple example would be to optimize the control parameters for shorter periods, i.e. monthly or weekly. Moreover, a more realistic case would be to optimize the control in real time, forecasting the weather conditions instead of using perfectly known data. However, this implies more complex control strategies, which are currently an important area of research. Considering examples in which the building structure was used as TES or buffer, adaptive predictive control was applied to radiant floor [23], model predictive controls were applied to radiant ceiling for heating and cooling [36] or to concrete core activation [37], cooperative fuzzy model predictive control was applied to concrete activated floor [38], and model predictive control for thermally activated systems was applied with additional integration of blinds control [39].

In contrast, the present study showed that a very simple control could already improve the performance of the system. The results clearly highlight the relevant aspects of the control strategies, which were either to maximize the "solar fraction" of the energy use or to shift the energy use to low cost and heat pump high efficiency periods. The control concepts proposed can be easily implemented, without requiring an important investment in equipment, as these only require monitoring indoor ambient temperature, solar radiation, and time. Moreover, the control concepts can be optimized, which might significantly improve their performance. The results of this study provide guidelines on the trends of optimization when being used under different conditions.

Finally, the study showed the capability of the proposed system to improve the demand side flexibility of the buildings. The TES capacity of the radiant wall allowed shifting the energy usage, which could reduce the peak demand requirement of the building as well as also be useful to absorb the peaks of production of a highly renewable energy grid. In this aspect, the integration of renewable energies, such as PV in the current case, helped in achieving buildings that produce enough energy that meets their own demand. In addition, the solar control concept proposed even improved this objective, as it also reduced the absolute imported energy for cooling by exploiting the PV production, which in consequence reduced the exported energy to the grid.

5 Conclusions

The present study analysed the performance of the configuration consisting of a PV array coupled to a heat pump that supplied cooling to a radiant wall. This last component actuated as both thermal energy storage and heat sink system for cooling a room. Two main control concepts were considered in order to exploit the capabilities of the set-up, one focused on exploiting the solar energy and the other one focused on shifting the energy use to low cost periods. These control concepts were compared against standard operation of the heat pump under different scenarios of PV installed capacity.

The results showed that in terms of operational cost, simple peak load shifting control concept had better results than investing in PV without using a specific control. Moreover, a simple solar control significantly reduced the operational cost just by charging the system if the PV output exceeded a threshold. With the optimization of this parameter, the minimum PV power output, the solar following control concept showed the best results in all the studied cases.

Finally, the research presented in this study showed the potential of the presented set-up to increase the renewable energy share for space cooling in buildings. The storage capacity of the radiant wall allowed demand side management, reducing the peak demand requirements. This improved the integration of the PV array, which did not only help in compensating the energy demand of the building, but together with the improved control concepts achieved a reduction of absolute imported/exported energy of the building.

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