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

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HIGHLIGHTS

- Radiant wall used as TES for a heat pump coupled to a PV array.
- Deterministic control concepts were optimized for radiant wall pre-cooling.
- Investment in PV panels was fully exploited only under solar control strategies.
- A minimum of PV nominal power was required for optimizing solar controls.
- Best solar control had lower operation cost than best peak load shifting control.

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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.

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 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,

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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. 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 [27,28]. 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 [29]. 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 Fig. 1. The room had an internal size of 5.25 × 2.7 × 2.7 m and radiant walls on each of its surfaces, as shown in Fig. 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 [27,28] 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].