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Energy flexible building through smart demand-side management and latent heat storage

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HIGHLIGHTS

- Novel energy flexible building based on smart demand-side management.
- Integration of heat pump, latent heat storage and smart demand response.
- Smart integration able to operate at optimal times for electricity grid and consumers.
- Economic and environmental benefits are achieved.
- Energy flexible buildings can have a positive impact on the heating decarbonisation.

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ABSTRACT

One of the greatest challenges for long-term emissions reduction is the decarbonisation of heating and cooling due to the large scale, seasonal variation and distributed nature. Energy flexible buildings with electric heating, smart demand-side management and efficient thermal energy storage are one of the most promising strategies to deploy low-carbon technologies which can benefit the electricity system by reducing the need of reinforcing existing networks and their ability to use electricity in times of low demand and high supply. Combined with spot price contracts, in which the electricity tariff changes every half-hour depending on supply and demand, they can effectively reduce on-peak demand periods, achieve economic profits for end-users and retailers, and reduce the environmental impact of the electricity grid by operating in periods with lower CO_2 emissions rate. To achieve these benefits, it is crucial to develop accurate models for energy flexible buildings as well as control strategies to optimise the complex system operation. This paper proposes a novel flexible energy building concept, based on smart control, high density latent heat storage and smart grids, able to predict the best operational strategy according to the environmental conditions, economic rates and expected occupancy patterns. The smart integration model, carried out in TRNSYS for a Scottish case study, solves a multi-criteria assessment based on future energy demand prediction (learning machine model supported by end-user's predefined occupancy by Internet of Things, present and forecast weather data, and building load monitoring), electricity tariff evolution and building performance. The results show that end-user's electricity bill savings of 20% are obtained and retailer's associated electricity cost is reduced by 25%. In addition, despite an increase in final energy consumption of up to 8%, the environmental impact remains constant due to operation at times with lower CO_2 emissions rate in electricity generation. The developed tools enable the design of smart energy systems for energy flexible buildings which can have a large positive impact on the building sector decarbonisation.

1. Introduction

The greenhouse gas emissions reduction targets set by many countries and agreed as part of the Paris agreement require almost the complete decarbonisation of the building sector. One of the greatest challenges to achieve these emissions reductions is decarbonising heating and cooling. Heating and cooling is responsible for around 50% of final energy consumption in the European Union [1]. While there has been significant progress in the decarbonisation of the heating and cooling sector, 75% of the current fuel consumption still comes from

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Nomenclature

Abbreviations

ASHP	air source heat pump
AWHP	air-to-water heat pump
c_p	specific heat, kJ/kg K
COP	coefficient of performance
DH	district heating
DHW	domestic hot water
DR	demand response
DSM	demand-side management
E7	Economy 7
Fn	correction factor according to demand prediction
h	latent heat per unit mass, kJ/kg
HDD	heating degree days
HP	heat pump
HVAC	heating, ventilation and air-conditioning
HX	heat exchanger
LT	limit tariff, £/kWh
IoT	internet of things
$P_{specific}$	buildings' specific heat loss rate, W/K
PCM	phase change material
t	time
T	temperature, °C
TL	limit electricity tariff price
TES	thermal energy storage
WWHP	water-to-water heat pump

Greek letters

λ	thermal conductivity, W/m K
ρ	density, kg/m^3

Subscript

l	liquid
s	solid

Superscripts

aux	auxiliary heater
cond	heat conduction
hx	immersed heat exchanger
loss	loss with the environment

fossil fuels (nearly half from gas) [1].

The main challenge towards a low-carbon building sector consists of the large deployment of renewable energy sources along with most efficient generation technologies. Current policies enforcing decarbonisation in the electrical grids will result in an increasing electrification of building systems [2]. Thus, considering typical operating efficiencies and carbon footprint of heating technologies for buildings [3,4], different authors state that most promising solution for the future building sector would be a combination of TES solutions linked to efficient solar district heating (DH) networks and individual heat pumps in the remaining houses [5], involving the decarbonization of electricity networks [6]. This integration was previously identified by Lund el al. [7], Handy et al. [8] and Lizana et al. [9,10], who showed that the implementation of efficient and renewable DH systems, along with local efficient heat pumps (HPs), could play an important role in the successful deployment of a sustainable building sector.

Heating, cooling and the electricity system can support each other in the effort to decarbonise. It is essential to recognise the links between them and exploit synergies. Part of the challenge involves decarbonising electricity supplied from the national grid, and then electrifying heating and cooling, by replacing most of the oil and gas boilers used to heat buildings today with technologies such as heat pumps which run on electricity [6]. However, the electrification of heat is expected to be a difficult task. It could cause a significant increase of electricity peak demand, which could have adverse consequences on the electricity system, in particular on the low-voltage distribution networks that deliver power from the substations along cables down residential streets [11]. This might be worsened by the future deployment of electric vehicles which might lead to high uncoordinated plug-in concentrations, significantly increasing on-peak electricity demand [12–14]. The cost of having to reinforce existing electricity networks to accommodate these new loads, heat pumps and other low-carbon technologies could be very considerable and therefore it is important to make best use of existing network assets, and ensure that any reinforcement is based on an accurate assessment of need.

Energy flexible buildings through smart demand-side management (DSM) or smart demand response (DR) using efficient energy storage are one of the most promising options to deploy low-carbon technologies in the electricity networks without the need of reinforcing existing networks [15,16]. Most common DSM strategies consist of the shifting of electrical loads (or demands) from on-peak to off-peak electricity tariff hours, and the improvement of energy performance of systems through the implementation of operational strategies by avoiding partial load operation or operating at other sub-optimal times [5]. Different studies based on DSM strategies have demonstrated their high economic savings due to the advantage of electricity prices along off-peak tariff hours. Main DSM strategies are based on the implementation of thermal energy storage (TES) units using sensible, latent or thermochemical heat storage, the use of passive thermal storage of the building to shift the electricity demand, and the deployment of distributed electrical storage using electrical batteries at the building level.

As DSM applications based on sensible storage, Renaldi et al. [17,18] evaluated the economic performance of an air source heat pump (ASHP) linked to a water tank to shift electrical load from on-peak to off-peak electricity tariff periods. In [17] the results showed that the integration of a storage tank of 180 L was able to shift approximately 13% of on-peak demand to off-peak time, achieving an operational cost reduction of 21.8% in comparison with using a conventional ASHP without TES. In [18] they assessed a storage tank of 300 L, achieving an annual operation cost reduction between 26.6% and 29%. They demonstrated that annual operational cost decreases as storage capacity is increased. Arteconi et al. [19] evaluated an air-to-water heat pump (AWHP) linked with a water tank for heating purpose through a DSM strategy to shift the on-peak demand to off-peak times. Two different heating distribution systems were assessed: underfloor heating and radiators. The results showed that the underfloor heating system (always on), operating by a DSM strategy, reduced the electricity bill by around -9%. However, annual energy consumption was slightly higher (around +3–4%). For radiators, operating 8 h per day, the DSM strategy did not reduce the electricity bill (around +4%) and the annual energy consumption was higher (around +8–9%). They concluded that using TES and a DSM strategy no reduction of energy consumption is achieved, but if a time-of-use tariff is available and an effective DSM strategy is implemented, the electricity bill could be cut down. In other research, Arteconi et al. [20] evaluated water-to-water heat pumps (WWHPs) coupled with a water tank for cooling purposes through a DSM strategy (TES charged by the heat pumps during off-peak hours). The integration saved 54% of energy cost and over 42% of energy compared with normal HPs operation. Yan et al. [21] evaluated a novel air-conditioning system with proactive demand control for daily