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

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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 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 of the 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.

Keywords: Thermal energy storage, Phase change materials, Low-carbon energy, Energy flexible buildings, Demand-side management, Demand response

Contents

Nomenclature and 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
Fn   correction factor according to demand prediction
h latent heat of fusion 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
PCM   phase change material
t   time
T   temperature, ºC
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

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 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 to 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 180l 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 300l, 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 hours 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.

As DSM applications based on latent heat storage and thermochemical storage, Cui et al. [21] evaluated the performance of a DSM strategy in commercial buildings based on a chiller and an air handling unit, integrated with cold phase change material (PCM) storage. The results showed that cool TES implementation for shifting peak demand achieved significant annual net cost savings, as well as providing longer duration and larger capacity for demand response. This resulted in a payback period of 8-9 years. Finck et al. [22] quantified the demand flexibility of an office building using different storage tanks. They identified that using a water tank, a phase change material tank or a thermochemical material tank integrated for heating needs in buildings through an optimal control can supply high energy demand and provide power flexibility along with economic savings.

As DSM application based on building thermal mass storage, Romero et al. [23] analysed the performance of a HP and PV panels integrated with different dynamic electricity pricing strategies in a German case study using TRNSYS. A smart controller was implemented to automatically manage the activation of the HP in response to day-ahead electricity pricing changes with the aim of cost savings and reducing the overload of the grid during peak periods. The energy was stored in the thermal mass of the building envelope, offering a passive thermal storage to shift the electricity demand. The heat pump is connected directly to the underfloor heating manifold, and the heating tank is located on the return flow. This uncommon configuration had the advantage of focussing on the thermal storage capacity of the building, not on the thermal tank. Cost savings up to 25% were achieved for scenarios where HP operation was limited to lower electricity price periods.

As DSM application through distributed electrical storage, Sandoval et al. [2] evaluated the electricity demand flexibility of using different electric batteries at the residential levels. They highlighted the need of the active role of the building as a coordinator between the electricity utility and the final consumers and observed that the battery component capital cost is more than twice as large as the PV capital cost.

Many reported case studies show that small-scale TES units are feasible and technically attractive solutions. The performance of low-carbon energy technologies through TES implementation is clearly enhanced following DSM strategies. Furthermore, higher volumetric TES density with reduced heat losses will allow greater benefits. However, previous DSM studies based on night consumption periods using fixed off-peak electricity tariff cannot effectively represent the situation in electricity grids with ever increasing renewable generation capacities. For example, in the UK the net demand, i.e. total demand minus renewable generation, is sometimes higher during the night due to high solar PV output [24].

As a step forwards, the integration of HPs and high-density TES combined with smart DSM strategies based on real-time and predictive electricity data can efficiently support the transition towards a low-carbon energy sector. This smart integration is able to operate at optimal times from the point of view of electricity grid and consumers, getting high environmental and economic benefits. The building sector can play an important role in the final electricity demand profile, and can have significant impact on the existing and projected electrical system infrastructure. Their ability to control the timing and magnitude of the aggregate electricity consumption acquires critical relevance. Thus, with the aim of assessing the potential benefits of smart energy flexible buildings, this research evaluates a novel application of smart DSM based on the integration of a HP, an efficient and high density latent heat thermal energy storage (LHTES) unit and a smart controller. The smartest operational strategy is managed by a controller which solves a multi-criteria assessment based on future energy demand prediction (learning machine model supported by end-user's predefined occupancy, present and forecast weather data, and building load monitoring), electricity tariff evolution and building performance. The paper is structured as follows. First, the smart low-carbon heating application is further described, and the case study and scenarios

are characterised. Afterwards, the methodology for numerical simulation, which was carried out in TRNSYS, is detailed. It was divided into three groups: building modelling, energy system modelling and controller. Finally, energy balance, and economic and environmental performance are presented and discussed.

2. Description of research

2.1. Definition of smart low-carbon heating solution in electricity network

The smart integration of DSM strategies in domestic buildings has the potential to flatten the electricity demand profile throughout the day as illustrated in Fig. 1
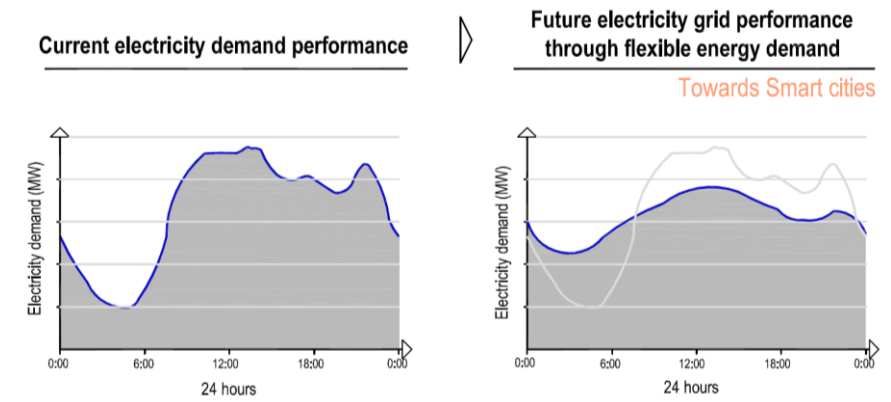

Figure 1. Future electricity grid performance through smart flexible energy buildings.

A smart system able to predict the best available operating schedule according to the environmental conditions, renewable generation, economic rates and expected occupancy patterns can generate an efficient building energy system with benefits for the consumer, the electricity grid and the environment. It would require the support of efficient TES systems, developed and conceived for full integration in buildings. This manuscript assesses the proposed smart and novel low-carbon integration which is illustrated in Fig. 2.
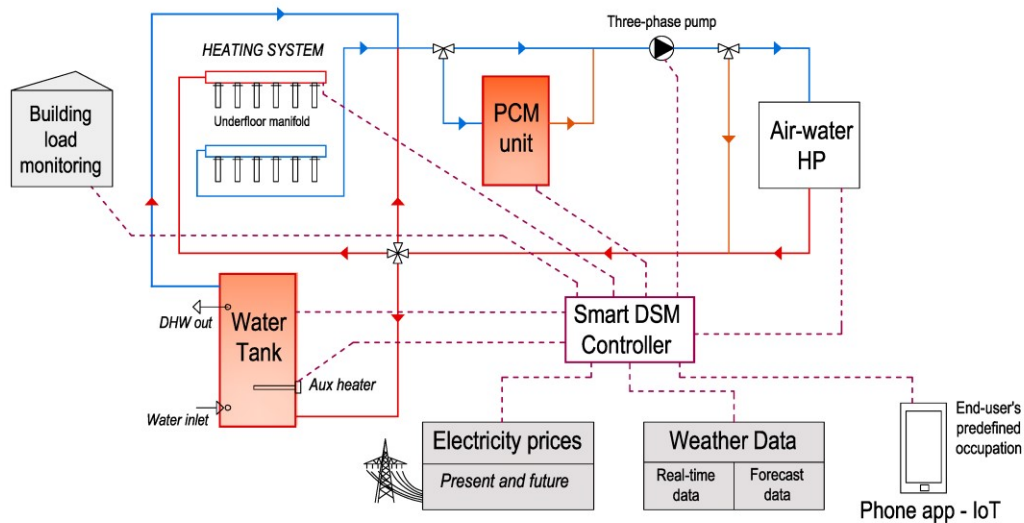

Figure 2. Smart heating and DHW integration towards flexible energy buildings.

It consists of a heat pump providing heat for heating and domestic hot water (DHW), a latent thermal energy storage unit and a smart DSM controller. The controller decides the most favorable way of energy management, using a latent heat storage unit as support system, which enables the heat pump to operate at optimal times, with the aim of reducing the energy bill. For example, the heat pump is operated when exterior conditions are better for increasing the coefficient of performance (COP) of the system, or when the electricity tariff is lower due to low-energy demand and/or high renewable generation. The smart DSM controller assesses the future energy demand according to end-user's predefined occupancy by a phone app based on Internet of Things (IoT), weather data (present and forecast) and building load monitoring. Thus, the system stops the charging period if no future energy demand is required, or if stored energy is enough to supply energy needs. In addition, electricity tariff evolution is considered to decide the most favorable economic period for electricity consumption.

This integration linked to spot price contracts, in which electricity tariff change every half-hour depending on supply and demand, leads to flexible energy buildings able to get high economic and environmental benefits by operating at low tariff periods with low CO_2 emissions rates. Fig. 3 shows the technical and economic structure of the electricity market [25].
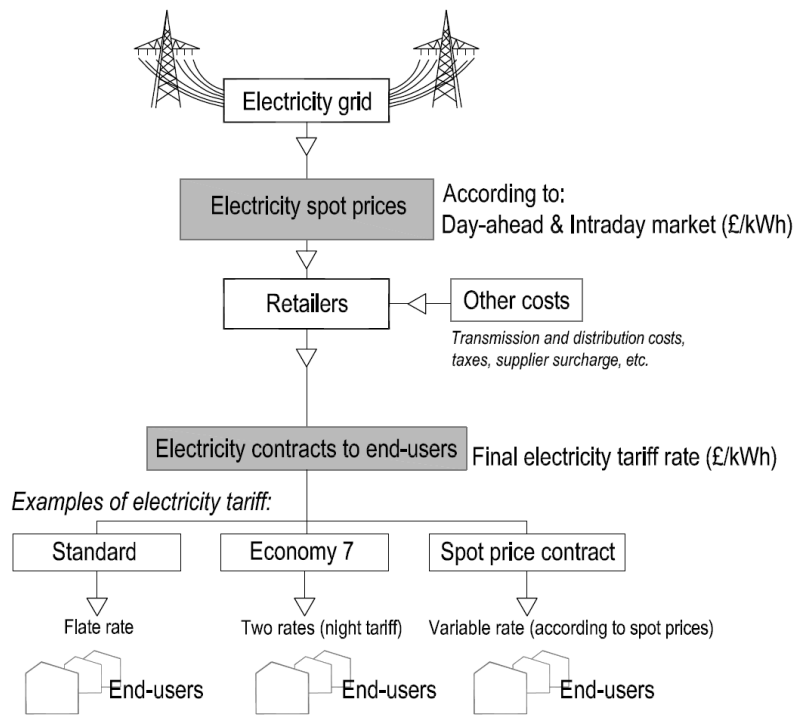

Figure 3. Technical and economic structure of electricity market.

Electricity spot price is the price retailers pay when they buy electricity from the wholesale market. Most electricity retailers charge customers a flat rate. This means you pay the same rate for the electricity you use regardless when you use it, and regardless of the spot price your retailer paid. The flat rate should range between 3.3 and 3.6 higher than the annual average cost of electricity spot price since it involves other additional costs, such as transmission and distribution costs, taxes or supplier surcharge, along with final retailers' profits. Thus, through a large deployment of the new concept of spot price contract, retailers could reduce the cost of buying electricity in the day-ahead and intraday market by moving end-user's consumption to off-peak periods. This enables a more competitive electricity cost for end-users as well as a better utilisation of the grid infrastructure.

2.2. Scenarios for environmental and economic assessment

Fig. 4 shows a conventional assembly schematic of an air-to-water heat pump for space heating and hot water. It has been used as reference scenario for evaluating the economic profitability and environmental performance of the proposed low-carbon heating solution. This conventional heating and DHW system operates with standard electricity tariff, which cost rate is defined in Table 1.
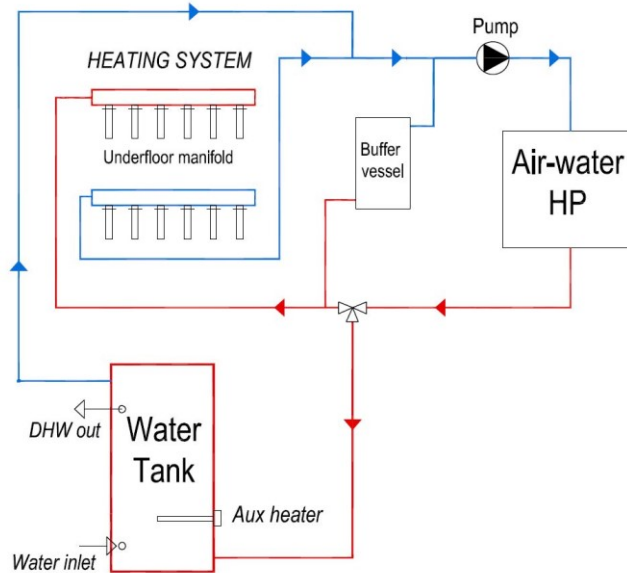

Figure 4. Conventional heating and DHW system.

Table 1. Electricity tariffs

Tariff	On-peak (£/kWh)	Off-peak (£/kWh)
Standard	0.144	0.144
Economy 7	0.1747	0.0765
Electricity spot price contract	Changeable every half-hour depending on supply and demand	

Along with the reference scenario, two smart DSM integrations are assessed, following the model illustrated in Fig. 2: one based on Economy 7 tariff and another based on spot price contract.

A new detached 2-storey house in Lochearnhead, Scotland, has been selected for assessing the proposed DSM strategies. Scottish climate is characterised by warm summers, and cold and wet winters. Heating is the main energy demand in Scottish energy sector, responsible for 53% of energy consumption, followed by transport (25%) and electricity (22%) [26]. Main primary heating fuel is gas, covering 79% of heating needs, followed by electricity (12%) and oil (7%) [26]. For an average household, hot water and space heating represent approximately 87% of total energy use [27].

Table 2 shows the main fabric parameters and compares the values with limiting standards for the properties of the fabric elements of the building, according to UK Building Regulations [28]. This case study consists of a highly-insulated, low-energy demand house. The characterisation of the building energy system is reported in Table 3. Case study is equipped with a heat recovery ventilation system with an effective recovery rate of 93% and an efficient air-to-water HP with a COP of 4.14, which provide heat for heating and hot water.

Table 2. Characterisation of fabric parameters of the case study.

Element	Definition	Characterisation	Limiting values
Window	Triple glazing system with wooden frame	U-value: 1.00 W/m^2 K	U-value: 2.00 W/m^2 K
Facade	Cement-bonded wood fibre blocks containing insulating foam and concrete, and plywood	U-value: 0.16 W/m^2 K	U-value: 0.30 W/m^2 K
Roof	Soil (green roof), insulation and plywood	U-value: 0.23 W/m^2 K	U-value: 0.20 W/m^2 K
Floor	Floating floor concrete slab, insulation and concrete slab foundation.	U-value: 0.25 W/m^2 K	U-value: 0.25 W/m^2 K

Table 3. Characterisation of the building energy systems.

System	Definition	Characterisation
Ventilation	Heat recovery ventilation system	Effective heat recovery rate: 93%
		Power consumption: 0.24Wh/m^3
		Supply: 215 m^3/h
		Extract: 220 m^3/h
Space heating and hot water	Air-to-water heat pump	COP: 4.14
		Capacity: 5 kW
		Consumption: 1.22 kW

3. Methodology for numerical simulation

The numerical simulation has been carried out in the energy system simulations software TRNSYS (Transient System Simulation) v18 [29]. TRNSYS is a flowsheet simulator with a graphical interface which facilitates the decomposition of complex problems into various interconnected model components. TRNSYS implements algebraic and first-order ordinary differential equations describing physical components into software subroutines (called types) with a standard interface. The TRNSYS model library includes components for the calculation of building thermal loads, specific components for heating/cooling, ventilation and air-conditioning (HVAC), heat pumps and circulating pumps, sensible thermal storage units, as well as climatic data files, which make it a very suitable tool to model a complete air-conditioning/ heat pump installation to provide heating and cooling to a building. Also, new components were created and written in Fortran and compiled into a dynamic link library file (also called DLL).

The numerical simulation process is divided into three stages: building modelling, energy system modelling and smart control implementation. Fig. 5 illustrates the global numerical simulation model developed in TRNSYS with identification of components associated to each stage. The next section describes the methodology used in each working stage.
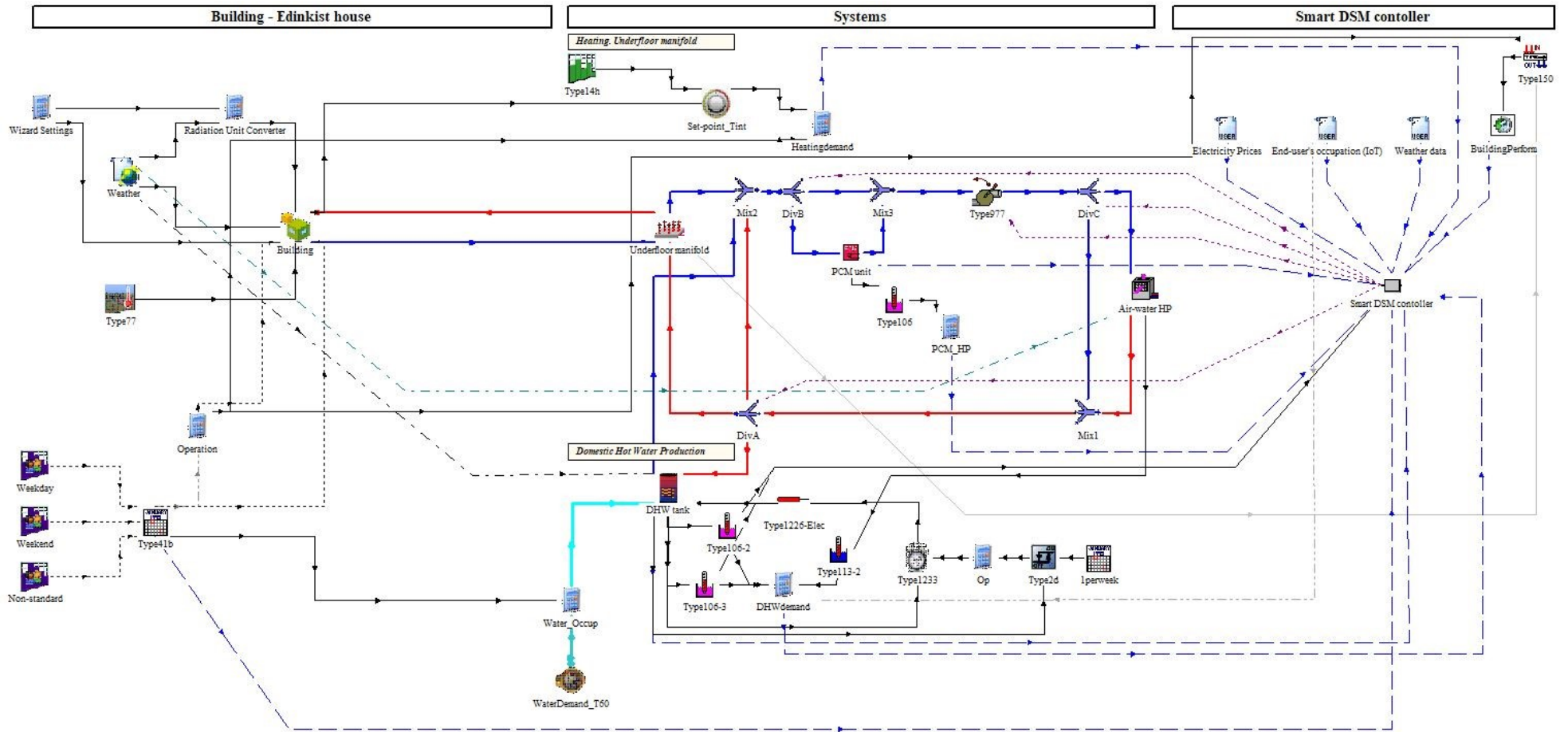
Figure 5. Process flowsheet of the numerical simulation model developed in TRNSYS *v18.*

3.1. Building modelling

The case study, previously defined in section 2.2, was modelled as a component of TRNSYS Simulation Studio (Type 56). Firstly, the geometric information of the building model was detailed using a plug-in called TRNSYS3d for Goggle SketchUp. A multi-zone 3D building shown in Fig. 6 was created, with identical form, window surfaces and shading objects as the existing building.
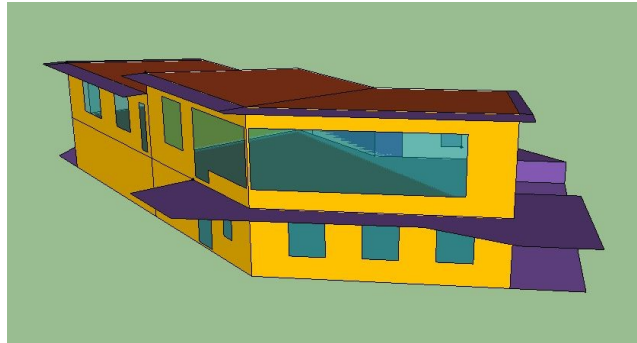

Figure 6. Building modelling in TRNBuild v18.

Secondly, building geometry model (*.IDF file) was imported to TRNSYS Simulation Studio as a 3D Building project, generating a Type 56 linked to the SketchUp file. Finally, Type 56 was further characterised through TRNBuild v18, defining building elements (walls, floors, ceilings, roofs and windows), operating and occupancy schedules, infiltration and ventilation rates, internal gains, etc.

Three different occupancy and operating schedules were implemented: weekday profile, weekend profile and non-standard profile for holiday periods. As non-standard days, 13 holiday days along the year were considered. Climate data for case study simulation were collected from Dunstaffnage station [30], which was selected as the most representative and close climate station. Data file was implemented using a standard TRNSYS weather data reader (Type 15-6).

3.2. Energy system modeling

Hot water and heating systems in the different assembly schematics were modelled using components (or types) in TRNSYS Simulation Studio. The hot water system supplies water to the whole house. The heating area is linked to the HP and the underfloor manifold is covering only 145m^2 of the house area, situated in the ground floor. In addition, the house has a wood stove to supplement the heat pump. Description and characterisation of modelling methodology of different system elements are as following:

Air-to-water HP (AWHP) was modelled using Type 941. The performance of a heat pump is characterised by capacity and coefficient of performance (COP). The nominal HP heating capacity is 5.00 kW with a COP of 4.14. As these data refer to rated operating conditions (Eurovent certification values), correction functions are used to correct rated operation data at nominal conditions, to building operating conditions. So, final energy consumption of the HP system will depend on load factor, environmental conditions, temperature lift and equipment control strategies.

Water storage tank was modelled using Type 156. The domestic water tank has a volume of 200 L, with a loss coefficient of 1.24W/m^{2}K, according to reference commercial data. Heat loss rate of modelled water tank is approximately 1.5 kWh/day, considering 24h temperature decay from 60-55ºC with an ambient temperature of 20ºC. Stratification was considered through three tank nodes. Mains water temperature was taken from climate file data (Type 15-6), with an inlet temperature ranging from 7 to 12ºC along the year. Thermal energy storage capacity of water tank for a temperature difference (ΔT) of 35ºC is 8kWh. An hourly water demand profile was defined according to different occupancy schedules. Water consumption ranges between 80 and 90 L/day, for weekday and weekend profiles, respectively.

Latent heat storage unit, as currently there is no existing component in the TRNSYS library, was modelled through a new TRNSYS component developed within this work. It is written in Fortran and compiled with the Fortran compiler. The developed model, illustrated in Fig. 7, follows the structure of TRNSYS Type 156 based on a stratified fluid tank for sensible storage, in which two flow streams that pass into and out of the storage tank were eliminated, and sensible storage capacity was changed into latent heat storage.
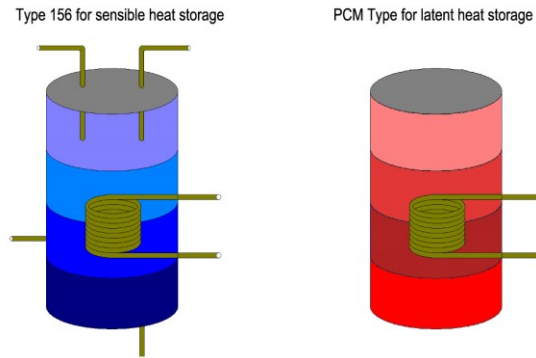

Figure 7. Diagram of LHTES model adaptation from standard type156 in TRNSYS.

The tank is divided into isothermal temperature nodes where the user controls the degree of stratification through the specification of the number of "nodes". Thus, for each node (i) defined in the new latent heat component, the energy balance (Q_i) is defined by Eq. 1:

$$Q_i = Q_i^{hx} + Q_i^{aux} + Q_i^{cond} + Q_i^{loss} \hspace{2cm} \text{Eq. 1}$$

Where (hx) is the heat transfer with the immersed heat exchanger, (aux) the heat input from an auxiliary heater, (cond) is the heat conduction to adjoining storage nodes, and (loss) is the loss with the environment (through thermal losses from the top, bottom and sides).

The latent heat performance is based on a mathematical procedure reported in the Report C5 of subtask C within the Task 32 of IEA Solar Heating and Cooling programme, about Simulation Models of PCM Storage Units [31], which has been tested and widely used in different PCM model proposals, such as LHTES units based on PCM modules plunged into water tanks [32–34] or bulk PCM units [33,35]. This mathematical model is based on an enthalpy approach, in which the enthalpy is a continuous and invertible function of the temperature. It means that for a given volume and material, a continuous and reversible function can be calculated which will return the temperature *T* depending on the calculated enthalpy *h.*

Fig. 8 shows this function, which is modelled by a succession of 3 straight lines: two for the sensible heat in solid or liquid phase and one straight line in the phase change temperature region. This latent heat model requires six input parameters: specific heat capacity in solid and liquid stage (Cp_s and Cp_l, kJ/kg K), temperature range limit of phase change (T1 and T2, ºC), heat of fusion (h, kJ/kg) and average thermal conductivity (λ, W/m K). Subcooling has been neglected in material performance as it is a drawback of pure compounds that can be further reduced by a number of techniques.
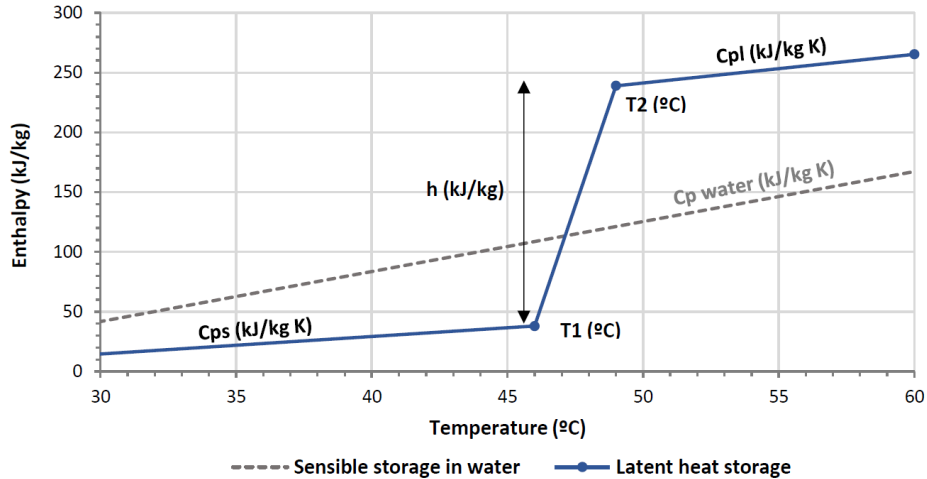
Figure 8. Characterization process of enthalpy curve implemented in new TRNSYS LHTES type.

PCM selected for latent heat storage unit is sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5H_2O$). This salt hydrate has been widely studied for heating building applications [36–41]. Thermo-physical properties of the selected PCM are reported in Table 4 according to Abhat [36].

Table 4. Thermo-physical properties of sodium thiosulfate pentahydrate.

Properties	Characterization
Melting temperature (ºC)	48.0
Latent heat (kJ/kg)	201
Thermal conductivity (W/m K)	0.5
Specific heat in solid phase (kJ/kg K)	1.46
Specific heat in liquid phase (kJ/kg K)	2.39
Density in solid phase (kg/m³)	1730
Density in liquid phase (kg/m³)	1670

Design of LHTES unit is characterised by a volume of 200 L, with a loss coefficient of 0.58W/m² K. Heat loss rate of modelled water tank is approximately 0.8 kWh/day, considering 24h temperature decay from 50ºC with an ambient temperature of 20ºC. Stratification was considered through three tank nodes. Thermal energy storage capacity of PCM unit for a temperature difference (ΔT) of 10ºC along phase change temperature is 20 kWh.

Other used components were a radiant Slab Model (Type 653), circulating pumps (Type 977), diverting and mixing valves (Type 647 and 649), and different standard controllers and utilities. The simulation time step was fixed at 5 minutes.

3.3. Conventional and smart demand-side management controller modelling

Two controllers were defined for energy performance assessment of different assembly schematics: one for conventional operating mode and another one for smart DSM mode towards flexible energy buildings.

3.3.1. Conventional controller

The conventional controller was based on current operating modes of HP for heating and hot water. Operation modes are: hot water heating using HP, auxiliary hot water heater as assistance to increase stored water above 60ºC, and direct HP heating through underfloor manifold. Assembly schematic is illustrated in Fig. 4.

Heating parameters. Two heating set-point temperatures were implemented at which the system maintains the thermal comfort in occupied spaces: 17ºC at night and 21ºC along the day. Underfloor heating system operates with water flow temperature close to 35ºC. To avoid the heat pump from short cycling, a buffer vessel is used. It also absorbs peak temperatures when water flow temperature is higher than 40ºC.

Hot water parameters. Hot water system operates with a set-point temperature of 55ºC when only the HP is running. With the aim of legionella prevention, the system increases the temperature of the stored water above 60°C to inhibit legionella bacterium growth. This is done at regular intervals, using the assistance of the electric heater to supplement the energy input of the heat pump, when heat pump capacity is not able to provide the required outlet temperature.

These operation modes were implemented in the reference scenario creating a new type in TRNSYS, which was written in the Fortran language. This reference scenario was evaluated using a standard electricity tariff without any DSM control.

3.3.2. Smart DSM controller towards flexible energy buildings

The Smart DSM controller was designed using novel operating strategies taking into account a multi-criteria assessment, in which the TES unit is crucial for efficient energy management. It was carried out to determine the most favourable operating mode according to the following parameters:

Heating parameters. As in the reference scenario, two heating set-point temperatures were implemented in occupied spaces taking as reference the recommended values of ISO 7730 [42], EN 15251 [43], and ASHRAE Standard 55 [44] 17ºC at night and 21ºC along the day. Also, for periods with on-peak electricity tariff prices, the temperature set-point is considered as 17ºC with the aim of shifting consumption towards lower electricity tariff periods.

Hot water parameters. Charge level of the hot water tank is evaluated through two set-point temperature bands: a short temperature dead band ranging from 40ºC to 55ºC, and a large temperature dead band ranging from 35ºC to 55ºC. The HP is used to keep the temperature in the short band during off-peak electricity price times, while it is kept in the large band during on-peak electricity cost periods. Following this configuration, low-tariff period is used most of the time. In addition, at regular intervals the electric heater is used to increase the temperature of the stored water above 60°C to inhibit legionella bacterium growth.

LHTES parameters. Charge level of LHTES unit is evaluated through a temperature set-point band, ranging from 45 to 50ºC. Also, storage level in kWh is monitored with the aim of assessing if the stored heat is sufficient for future energy demand prediction.

Future heating demand prediction ($Future\ Q_{heating}$) in kWh is calculated for the next 24 hours based on an iterative self-learning procedure (or machine learning) through Heating Degree Days (HDD). HDD is a common and simple metric that allows quantifying the amount of heating or cooling that buildings in a specific location need over a certain period. It is calculated with a base temperature of 20°C. Given the number of HDD, to calculate the energy required by a building, heat needs to be provided to the building at the rate at which it is being lost to the environment. This value is almost constant over a short period of time for each building, and is defined as buildings' specific heat loss rate ($P_{specific}$), generally given in Watts per Kelvin (W/K). So, final future energy need is calculated according to Eq. 2.

$$Future\ Q_{heating,t} = P_{specific,t} \cdot \left(\sum_{day\ 1}^{day\ 6} HDD_{future}\ /6 \right) \cdot \int_{t}^{t+96} Occup_{future} \Big/ 4 \cdot 1000 \quad (\text{kWh}) \qquad \text{Eq. 2}$$

Where HDD_{future} is the average value of Heating Degree Days for future 6 days (144 hours) and it is estimated by means of weather forecast data. In the simulation model, this value is obtained from the weather data file. $P_{specific,t}$ is the building's specific heat loss rate, and is calculated according to past building performance of last 6 days (144 hours), according to Eq. 3, as a function of energy consumed, hours occupied and past weather data. When a shorter performance assessment period is considered, the results are not as representative due to the occasional peak temperature oscillation. The predictive model works better with an average value along a reasonable period. On the other hand, $Occup_{future}$ is the future occupancy hours along future 4 days since the storage unit is able to provide energy for 4 days along low demand periods. Following reported criteria, the predicted heating demand ranges from 90% to 110% of the actual heating demand.

$$P_{specific,t} = \left[\int_{t-144}^{t} Q_{consumed} \cdot 1000 \right] \Big/ \left[\int_{t-144}^{t} Occup_{hours} \cdot \left(\sum_{day-6}^{day-1} HDD\ /6 \right) \right] \quad (\text{W/K}) \qquad \text{Eq. 3}$$

Present and future electricity tariff values. The smart DSM controller has to be able to decide when electricity should be consumed as a function of present and future electricity tariff evolution. Two types of electricity tariffs are considered for DSM strategies: Economy (E7), and Electricity spot price contract. They are summarised and compared with Standard electricity tariff, which was used for reference scenario assessment, in Table 1.

Standard is a one rate tariff for the entire day. **E7** is a two rate tariffs with off-peak duration of 7 hours, from 00.00 to 07:00. **Electricity spot prices** change every half-hour and can vary quite dramatically depending on supply and demand. It is the price retailers pay when they buy electricity from the wholesale market. It means that consumers will pay a variable rate according to the spot price that the retailer pays. Electricity tariff rates (Standard and Economy 7) are compared with electricity spot prices in Fig. 9. The average value of spot price throughout the year is 0.04 £/kWh, with minimum and maximum values of 0.007 and 0.99 £/kWh, respectively. Fig. 9 shows that the maximum spot price profile has two high cost or on-peak periods from 9am to 11am and from 4pm to 9pm.
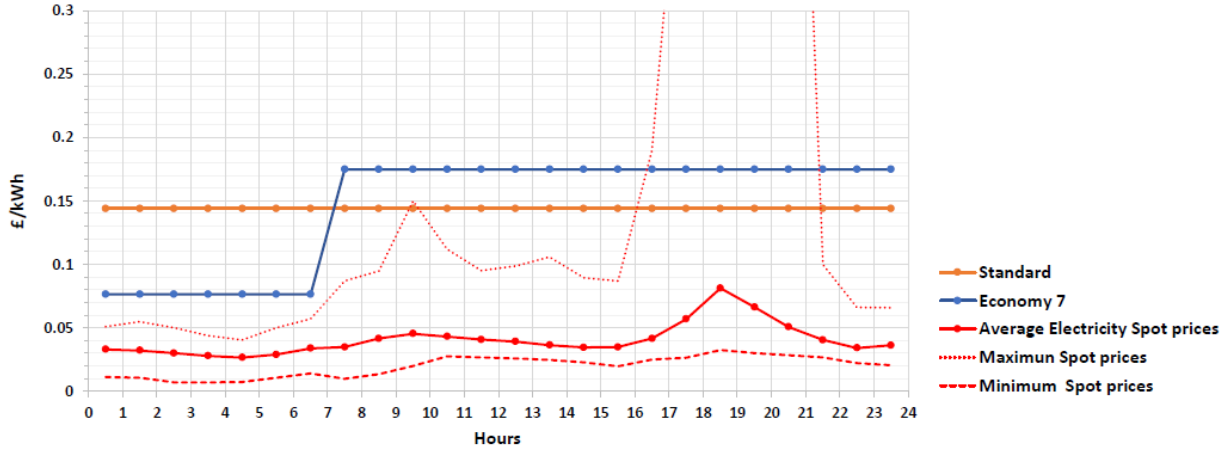
Figure 9. Selected electricity tariff values per hour calculated along a year.

Buying electricity through spot price contract has advantages. When spot prices are low, you could pay substantially less for electricity than you would on a traditional retail contract where the price is the same all the time. But, the same is true in reverse. If spot prices increase above the flat rates charged by retailers, you may pay substantially more than you would on a traditional retail contract.

As the electricity price changes over time, the smart DSM controller divides the electricity price rates into 3 ranges (A, B and C), in which it implements a priority order of operation modes. Tariff period A consists of a lowest cost range, tariff period B is a medium cost range, and tariff period C involves the high cost range. So, the system supplies or stores as much energy as possible at lower electricity price periods, avoiding consumption at on-peak periods with high electricity prices.

Electricity price ranges (A, B and C) are limited by two limit prices over time (t), LT1 and LT2, which are assessed according to Eq. 4.

Tariff period A – Low cost:

$$£/kWh_t \le TL1_t = \left(2 \cdot \sum_{t}^{t+24} Tariff \Big/ 24 + 7 \cdot \min_{t \to t+12}(Tariff) \cdot Fn \right) \Big/ 10$$

Tariff period B – Medium cost:

Eq. 4

$$TL1_t > £/kWh_t \le TL2_t = \sum_{t}^{t+24} Tariff \Big/ 24$$

Tariff period C – High cost:

$$£/kWh_t > TL2_t$$

TL1 is calculated as a fraction between the average electricity price in the next 24 hours (from day-ahead prices) and the minimum electricity price in the next 12 hours. This fraction ensures a limit electricity cost covering an adequate daily period to supply required energy with the lowest electricity tariff. As the required daily time of electricity consumption oscillates between winter (5-8h) and summer (1-3h due to no heating demand), a correction factor is introduced (Fn). It adjusts the

lower tariff period A with the aim of consuming electricity in the lowest off-peak period. Fn oscillates between 1.15 and 1.25 as a simple linear regression based on future heating demand prediction (kWh). TL2 is calculated as the average electricity price throughout future 24 hours.

The smart DSM controller considers all reported variables to decide the most favourable procedure of energy management. Operation strategies are illustrated in Fig. 10. They have been grouped in three sets: hot water supply, indirect heating supply and direct heating mode.

OPERATION MODES

MODE 1a - Hot water heating
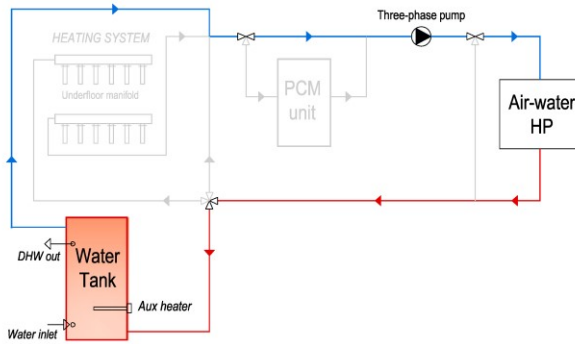
MODE 1b - Auxiliar hot water heater
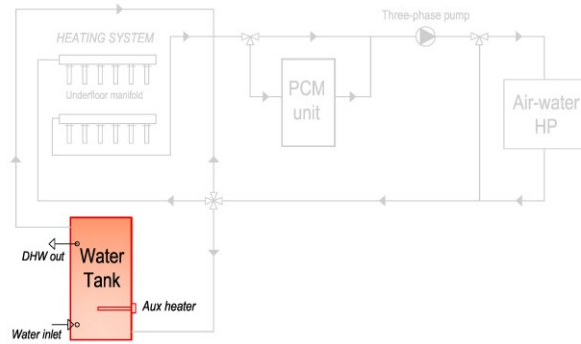
MODE 2a - Charging PCM unit (Indirect heating)

MODE 2b - Discharging PCM unit (Indirect heating)

MODE 3 - Direct heating (underfloor system)

Figure 10. Operating modes of smart heating and DHW system.

Hot water supply is divided into two operation modes, using HP linked to the water tank (mode 1a) or using electric heater placed at the bottom of the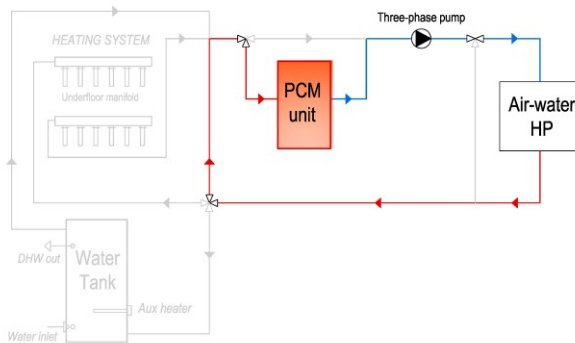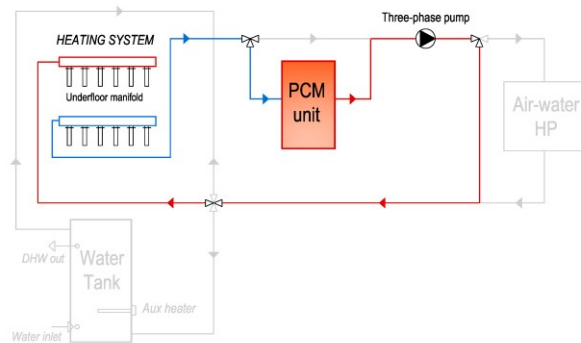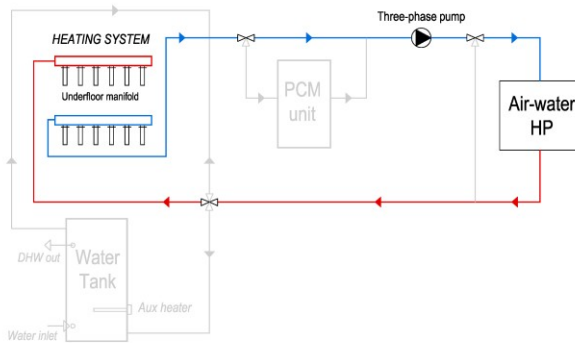 tank (mode 1b). Indirect heating supply is divided into two operating steps, charging LHTES unit and discharging LHTES unit for underfloor heating. Direct heating mode consist of HP directly running with underfloor heating system.

Programming of operational strategies and priority of operating modes are based on three steps which are summarized in Table 5. First step consist of the electricity tariff range in which energy demand is produced, second step refers to the priority of operating strategies implemented in the controller, and finally the compliance conditions for each operating mode according to parameters previously defined. The smart DSM controller update each parameter along each simulation time step (5minutes), changing operation mode according to operational strategies implemented.

Table 5. Linear operating structure of smart DSM strategies.

Step 1: Electricity tariff range	Step 2: Priority of operation modes	Main compliance conditions
£/kWh ≤ LT1	Mode 1a. HP & Water tank	-Short dead band of 40-55ºC
	Mode 1b. Auxiliary water heater	-At regular intervals after operation mode 1a
	Mode 3. HP & Underfloor heating	-Heating set-point of 17 or 21ºC
		-Occupancy and operating schedules
	Mode 2a. HP & LHTES unit	-DHW tank dead band of 45-50ºC
		-Future heating demand > 20kWh
		-LHTES level < 0.75 · Future heating demand
		-Future 24h occupancy profile > 5 hours
LT1 < £/kWh ≤ LT2	Mode 1a. HP & Water tank	-Large DHW tank dead band of 35-55ºC
	Mode 3. HP & Underfloor heating	-Heating set-point of 17 or 21ºC
		-Occupancy and operating schedules
	Mode 2a. HP & LHTES unit	-Dead band of 45-50ºC
		-Future heating demand > 20kWh
		-LHTES level < 0.75 · Future heating demand
		-LHTES level < 8kWh
LT2 < £/kWh	Mode 1a. HP & Water tank	-Large DHW tank dead band of 35-55ºC
	Mode 2b. LHTES unit & Underfloor heating	-Heating set-point of 17 or 21ºC
		-Occupancy and operating schedules
		-LHTES level > 3.5 kWh
	Mode 3. HP & Underfloor heating	-Heating set-point of 17ºC
		-Occupancy and operating schedules

3.5. Application example of smart DSM controller along a week with spot price contract.

As an example of smart DSM operation, Fig. 11 illustrates the main operating parameters along a week in the building scenario using electricity spot price contract. Fig. 11 is divided into four sections which illustrate the occupancy and operating rate (%); the energy balance of LHTES unit (kWh), water tank (kWh) and future heating demand predication (kWh); the power consumption of HP (kW) and electric water heater (kW); and day-ahead electricity prices at real time, ranged by two limit prices over time, LT1 and LT2.

Different marks have been placed to show how the operational controller responds to different parameter changes:

-Mark 1: Building is occupied (Fig. 11A) but no energy input is required.

-Mark 2: The electricity spot price is below LT1 (Fig. 11D), the HP is run to keep the DHW tank in the short temperature DHW dead band, using off-peak spot prices. Storage level of water tank increases up to approximately 8kWh (Fig. 11B).

-Mark 3: Building is occupied (Fig. 11A) and electricity spot price is over LT2 (Fig. 11D), so LHTES unit provide heating supply to the underfloor heating system, discharging LHTES level (Fig. 11B).

-Mark 4: As electricity spot price is below LT1 (Fig. 11D), and future heating demand is close to 30kWh (Fig. 11B), HP charges LHTES unit, increasing storage level up to 23 kWh.

-Mark 5: Same as mark 3.

-Mark 6: After charging water tank (Fig. 11B) using off-peak spot prices (Fig. 11D), electric heater starts running (Fig 11C) to increase the water temperature above 60°C to inhibit legionella bacterium growth.

-Mark 7: Heating is directly provided by HP to the underfloor heating system.

-Mark 8: The electricity spot price was below LT1 (Fig. 11D), and the HP was run to keep the DHW tank in the short temperature DHW dead band. Then, electricity spot price increases over the limit L1 value, and HP stops.

-Mark 9: As electricity spot price is below LT1 (Fig. 11D) and no energy is required for hot water and heating, HP charges LHTES unit up to future heating need predicted, which is approximately 20kWh (Fig. 11B).
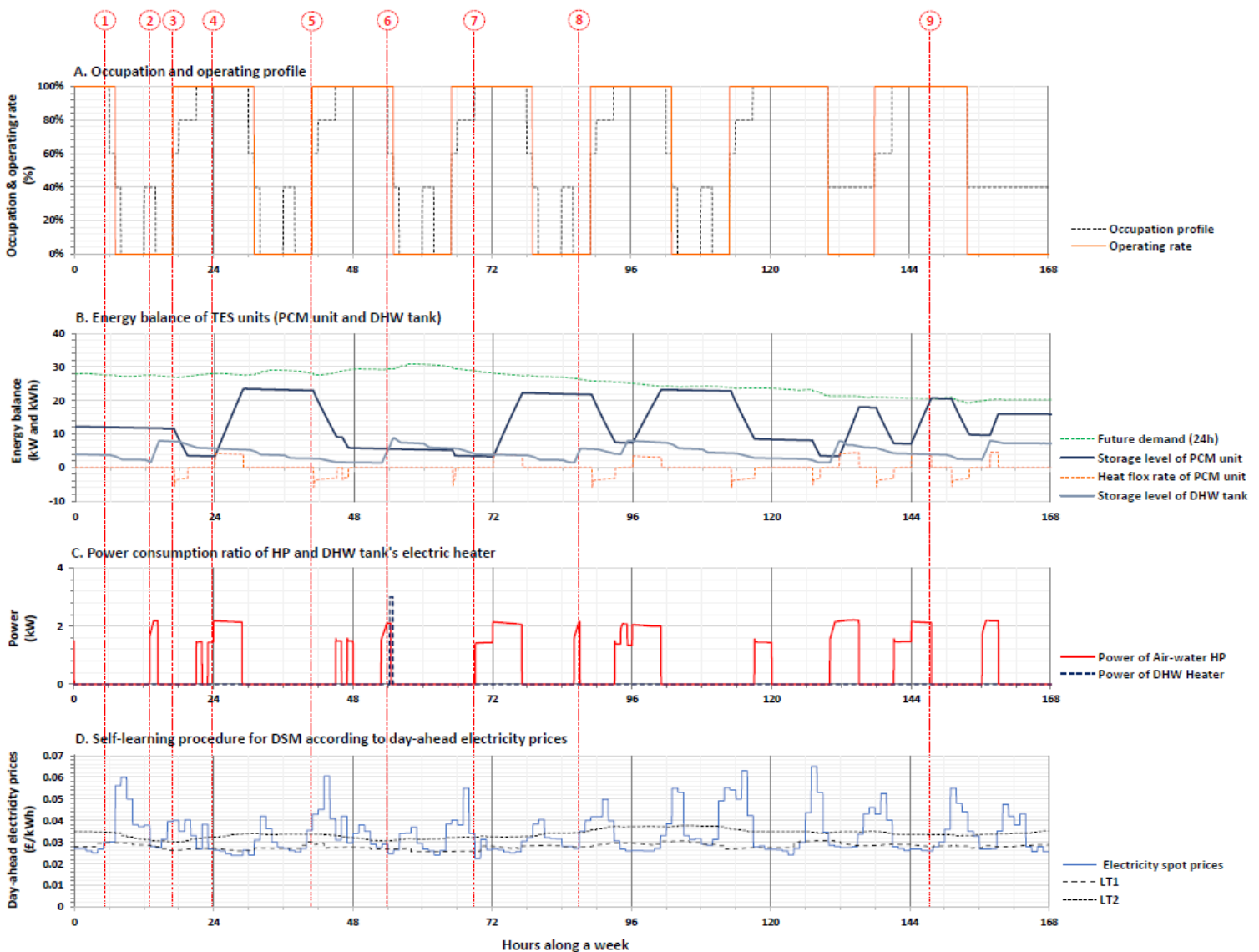

Figure 11. Visualisation of smart operational strategies along a week with spot price contract.

4. Simulation results and discussions

Energy balance, economic performance from the point of view of different agents (end-user's and retailers) and environmental impact of three scenarios (conventional operating mode, smart DSM operating mode with E7 tariff, and smart DSM operating mode with spot price contract) are assessed and discussed in this section.

4.1. Energy balance

Energy performance for the three scenarios was calculated using the simulation output with a time resolution of 5 minutes. Table 6 shows the results of monthly energy consumption achieved for each operating strategy. The energy consumption is divided into electricity consumed by HP, and electricity consumed by electric heater placed in water tank to achieve 60ºC once a week.
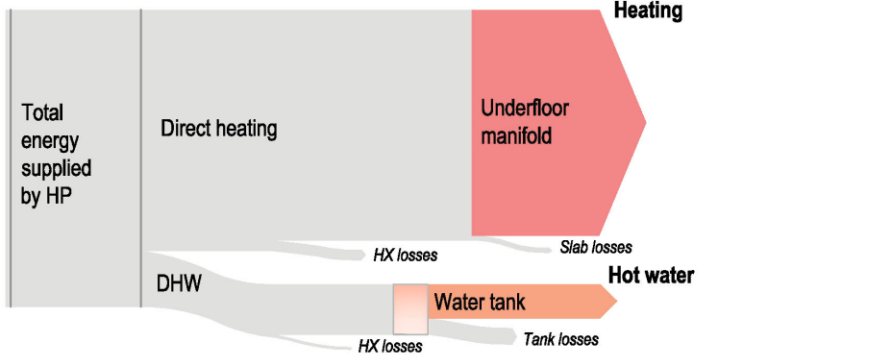
Table 6. Electricity consumption balance of each operating strategy.

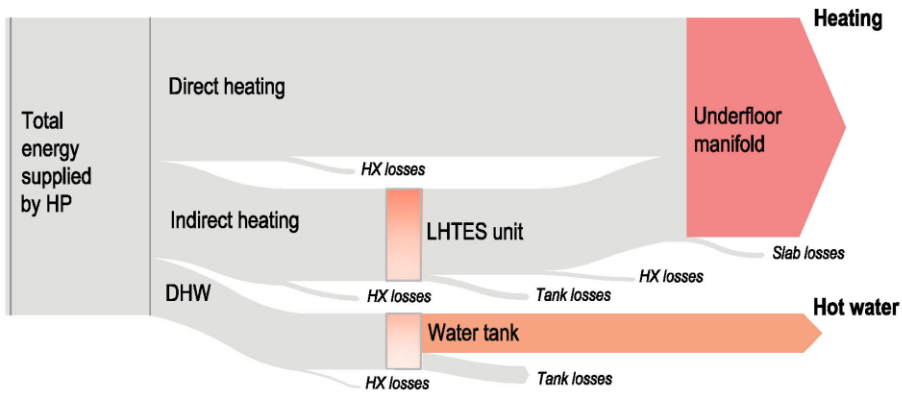| Months	Conventional mode		Smart DSM operating mode (E7 tariff)		Smart DSM operating mode (Spot price contract)	
	HP (kWh)	Electric heater (kWh)	HP (kWh)	Electric heater (kWh)	HP (kWh)	Electric heater (kWh)
January	429.9	9.0	507.6	6.2	474.4	5.4
February	408.9	7.7	475.9	6.2	461.2	5.9
March	408.9	7.2	487.1	6.0	460.1	6.0
April	308.8	8.3	407.6	5.7	347.7	6.5
May	152.9	4.2	184.7	6.5	154.7	5.1
June	69.2	6.0	75.7	4.8	64.7	3.3
July	59.3	5.7	65.7	4.4	58.9	3.5
August	57.1	6.5	60.2	4.4	50.4	5.7
September	198.2	7.7	230.8	4.8	212.3	5.0
October	312.4	8.9	377.6	6.3	349.5	6.9
November	375.6	8.4	417.0	5.6	364.4	6.0
December	399.2	7.2	486.1	5.6	449.3	6.3
Total	3180.4	86.6	3775.9	66.2	3447.6	65.4

The electricity consumption of the reference case (conventional operating mode) is 3266.9 kWh, considering heat pump and electric heater in DHW tank. Following the DSM strategies previously defined in methodology, electricity consumption increases by 18% through smart DSM operating mode with E7 tariff, and by 8% in DSM operating mode with spot prices. The E7 tariff strategy and the spot price contract strategy shift the heat consumption by 40% and 29%, respectively. Thus, higher energy shifting is leading to higher final electricity consumption.

Main reasons of the increasing energy consumption are related to heat exchanger losses (charging and discharging LHTES unit) and storage losses. They are characterised in Fig. 12, which illustrates the Sankey diagrams of the reference scenario (conventional operating mode) and two smart DSM scenarios assessed. DHW tank losses are similar in all three scenarios, ranging from 28 to 30% of heat supplied from HP for DHW. LHTES loss ratio for both smart DSM scenarios are lower than DHW tank due to more efficient storage unit with higher insulation, being situated between 5 and 8% of heat supplied from HP for indirect heating. Heat exchange losses of the conventional operating mode are 2-3% of total heat supply from HP. However, heat exchange losses of both smart DSM operating modes are higher, around 4-5%, which are associated to higher number of charging and discharging processes.

A. Reference scenario: conventional operating mode

Total energy supplied by HP

Direct heating

Underfloor manifold

Heating

HX losses

Slab losses

DHW

Water tank

Hot water

HX losses

Tank losses

B. Smart DSM operating mode with E7 tariff

Total energy supplied by HP

Direct heating

Underfloor manifold

Heating

HX losses

Indirect heating

LHTES unit

Slab losses

HX losses

DHW

HX losses

Tank losses

Hot water

Water tank

HX losses

Tank losses

C. Smart DSM operating mode with Spot price contract

Total energy supplied by HP

Direct heating

Underfloor manifold

Heating

HX losses

Indirect heating

LHTES unit

Slab losses

HX losses

DHW

HX losses

Tank losses

Hot water
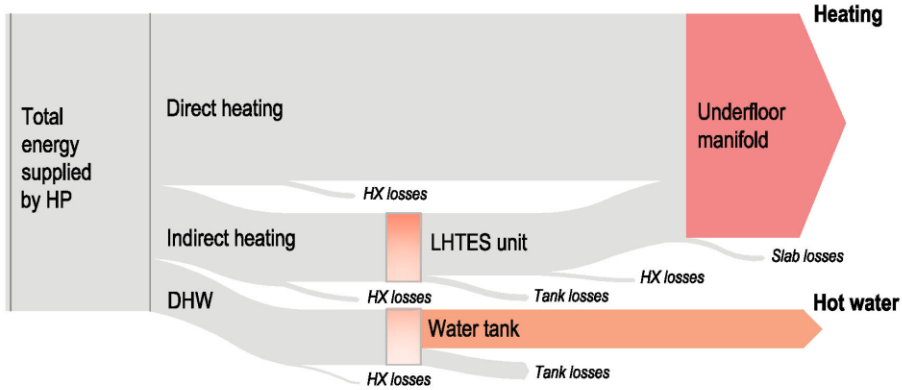
Water tank

HX losses

Tank losses

Figure 12. Sankey diagrams of the three different scenarios

Fig. 13 illustrates electricity consumption per hour over the whole year for different smart operational strategies and compared with the reference operating mode (conventional heating system).
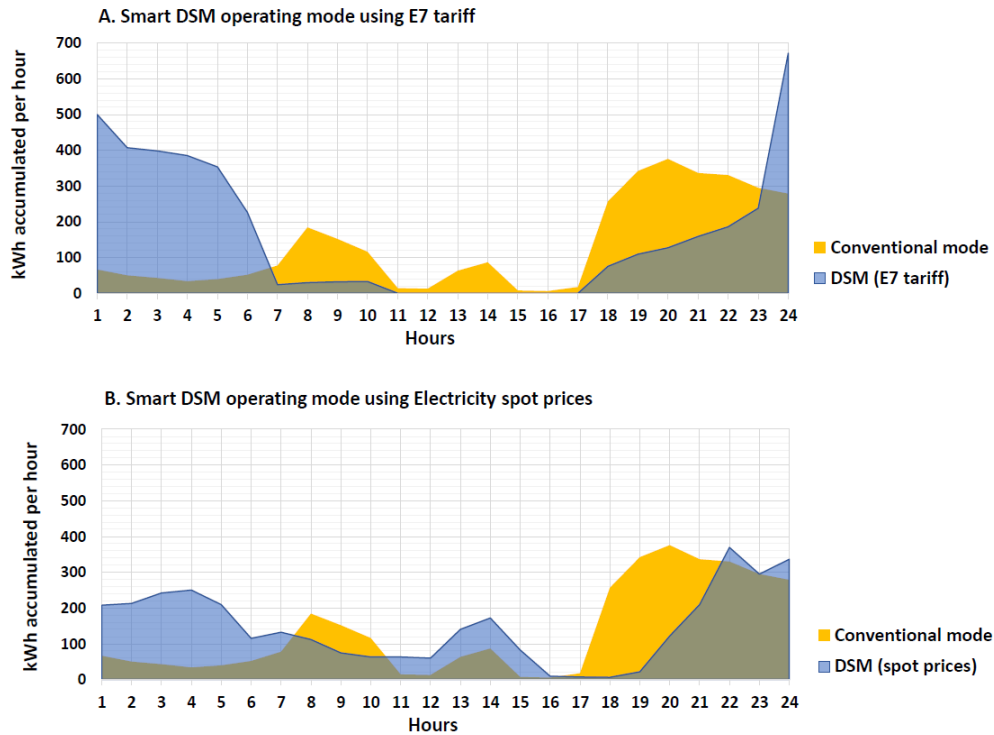

Figure 13. Electricity consumption accumulated per hour along a year for different Smart operational strategies.

Following the smart DSM strategy with E7 tariff (Fig. 13A), electricity consumption is shifted from on-peak period (from 7:00 to 0:00) to off-peak period along the night. Using the smart DSM strategy with an electricity spot price contract (Fig. 13.B), electricity consumption is shifted from two on-peak periods previously identified in Fig. 9 (from 8:00h to 11:00h and from 16:00h to 10:00h) to off-peak periods with lower electricity spot prices along the day (along the night and from 12:00h to 15:00h). Despite spot prices changing every half-hour, daily profiles are very similar.

4.2. Economic performance

The economic performance of two smart DSM strategies are assessed from the point of view of end-users and retailers, and compared with the reference scenario (conventional operating mode). Smart demand shifting can reduce the electricity bill of end-users due to lower electricity tariff periods, and provides electricity flexibility when electricity spot prices are higher to achieve lower electricity cost for retailers. Table 7 summarizes final electricity cost and consumption of end-users and retailers for each assessed scenario.

Table 7. Economic performance of different operating strategies.

	Conventional mode	DSM operating mode (E7 tariff)	DSM operating mode (Spot price contract)
Retailer's electricity cost	£ 166.82 (100%)	£ 147.53 (88%)	£ 125.19 (75%)
End-user's electricity bill	£ 470.43 (100%)	£ 452.61 (96%)	£ 375.57 [a] (80%)
End-user's electricity consumption	3266.9 kWh (100%)	3842.0 kWh (118%)	3513.0 kWh (108%)

[a] *Final electricity bill using spot price contract was calculated by multiplying the electricity spot price by three. This value was fixed considering that the average value of spot price throughout the year is 0.04 £/kWh.*

From the point of view of retailer's electricity cost, the smart DSM control reduces energy cost by 12% in E7 tariff scenario and by 25% in spot price contract scenario. These results show that electricity spot price contracts together with smart flexible energy buildings can lead to a promising smart management of energy sources, with high economic profits and reducing on-peak demand periods in electricity network.

From the point of view of end-user's electricity bill, the smart DSM control reduces the energy bill by 4% in E7 tariff scenario and by 20% in spot price contract scenario. Thus, despite an increase in energy consumption by 18% and 8% in both scenarios, respectively, economic savings are achieved. However, we should consider that annual economic saving of the best scenario, associated to the electricity spot price contract, is approximately £95, which means that the investment cost of smart integration along with LHTES unit should be lower than £950 to achieve a payback period of approximately 10 years.

Along with the economic profits for retailers and end-users, there are additional benefits such as better utilisation of the electricity grid and the renewable resource, reduced need to curtail renewable generation and no requirement of upgrading the grid to support new electricity heating systems.

4.3. Environmental performance

Energy flexible buildings not only allow operating when electricity cost is lower, but can also reduce the environmental impact of the building sector since electricity is consumed when low-carbon generation technologies are providing most of the energy.

With the aim of calculating the environmental impact of each operational strategy, hourly CO_2 emissions of the electricity grid were calculated considering the CO_2 emissions rate of UK network according to [45]. Table 8 shows the results of environmental impact for the three scenarios.

Table 8. Environmental performance of different operating strategies.

	Conventional mode	DSM operating mode (E7 tariff)	DSM operating mode (Spot prices)
End-user's energy consumption	3266.9 kWh (100%)	3842.0 kWh (118%)	3513.0 kWh (108%)
CO_2 emissions	1015.84 kgCO$_2$ (100%)	1078.37 kgCO$_2$ (106%)	1028.71 kgCO$_2$ (101%)

The results show that despite increasing energy consumption for energy shifting from on-peak electricity periods to off-peak periods, the environmental impact is constant for DSM operating mode using spot prices, and only 6% higher for DSM operating mode using E7 tariff. It is expected that the environmental impact of energy flexible buildings will decrease with the further deployment of non-dispatchable, low-carbon electricity generation.

5. Conclusions

This paper assesses a novel smart integration of low-carbon heating technology towards flexible energy buildings. A smart heating system based on an efficient HP combined with a high density latent heat storage unit and smart demand-side management (DSM) integrated with smart grids is carried out. It provides heating and domestic hot water, in which the smart DSM controller decides the most favorable procedure of energy management, using the thermal energy storage unit as support system, to enable operation at optimal times from the point of view of electricity grid and consumers, getting high environmental and economic benefits. Smart DSM controller assesses the future energy demand according to end-user's predefined occupancy by a phone app using Internet of Things (IoT), present and forecast weather data, and building load monitoring information. In addition, electricity tariff evolution is evaluated to decide the most favorable economic period for electricity consumption. Thus, the system is able to charge during the most favorable periods, and stops charging if no future energy demand is required, or if stored energy is enough to supply energy needs. The results show that:

- Building sector's on-peak electricity consumption periods can be effectively shifted to off-peak periods through the proposed low-carbon heating system. Large deployment of this technology towards smart flexible energy buildings would allow effective electrification of heating and cooling demand in buildings without increasing the need for additional, dispatchable electricity generation capacity. Moreover, current electricity networks could accommodate these low-carbon heating systems with lower or even without any reinforcement of existing network assets. This proposal, along with decarbonising electricity grid, results promising towards the transition to a low-carbon energy sector.
- Two DSM strategies were assessed, using Economy 7 tariff or spot price contract. Despite of higher energy consumption in both strategies due to thermal losses in storage and heat exchange, both achieve economic profits due to the use of lower tariff periods, getting economic savings of 4% and 20% for end-users, and 12% and 25% for retailers, respectively.
- The results of smart DSM through spot price contract are promising. Despite an 8% higher energy consumption, smart energy management achieves high economic profits compared with the reference scenario. Reduction in retailer's electricity cost is 25%, and end-user's electricity bill savings are 20%, due mainly to the fact that the smart DSM controller consumes energy along lower off-peak electricity spot prices. In addition, environmental impact is constant in spite of the higher electricity consumption, which is associated to consumption at times of lower CO_2 emissions rates in electricity production.
- As technical and economic challenge, the results indicate that smart DSM integration should cost between £900 and £1000 more than reference heating application to get a payback period of approximately 10 years in small-scale application in residential buildings. Thus, as reference ratio, latent heat storage unit cost should range between £40-£45 per kWh of storage capacity.

Future research activities will focus on developing design criteria to achieve required economical and technical performance in latent heat storage units. Investment cost of commercial latent heat storage units should be approximately less than £900, and phase change material performance should ensure feasible technical properties with the aim of achieving practical solutions with high storage capacity, high thermal reliability and stability for long-operation periods.

Acknowledgments

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