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Design and operational optimisation of an integrated thermal energy storage ground-source heat pump with time-varying electricity prices

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Abstract

A detailed methodology is proposed to design and optimise the operation of a ground-source heat pump (GSHP) coupled to a phase-change material (PCM) thermal battery. The objective is to minimise the cost of supplying space heating and hot water to a medium-demand house in the UK during a typical winter day with fluctuating electricity prices. A bespoke 8-kW GSHP is designed and used to optimise the charging schedule of the thermal battery to minimise daily operational costs while meeting the heat demand. If no limit is imposed on the size of the thermal battery, in the best scenario, a 41-kWh thermal battery is required to achieve costs as low as 1.85 £/day. However, large PCM batteries mean high upfront costs and little space restrictions. Therefore, a constraint is imposed on the thermal store capacity to identify the optimal trade-off that can be achieved between PCM battery size and daily power consumption costs. Operational costs strongly depend on the battery size, increasing from 1.85 £/day for a 41-kWh thermal battery to 3.50 £/day for a 6.3-kWh store.

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1. Introduction

Delivering near- and long-term international environmental objectives likely requires significant changes in the way heat is supplied to residential buildings [1]. The ambition to phase out the installation of new natural gas boilers in many countries implies remarkable infrastructural and regulatory changes in the upcoming years [2, 3]. Electricity-driven vapour-compression heat pumps are a proven technology [4] associated with a considerably better thermodynamic performance than gas boilers [5]. Although they are widely recognised as a sustainable alternative to conventional heating systems, the share of heat pumps in the market remains low in most countries [6]. This is mainly due to the high investment cost required [7], the high price of electricity when compared to that of natural gas [8] and the low uptake of control mechanisms that can be used to heat homes in a smart and flexible way [9].

Vapour-compression heat pumps involve many possible design options and heat sources [10]. Common types are air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs). The former uses ambient air as low-temperature heat source, while the latter draws heat from the ground. GSHPs require heat collector tubes to be buried underground. Therefore, they are associated with higher installation costs than ASHPs [4]. However, since the temperature of the ground experiences smaller fluctuations throughout a year compared to the ambient air, GSHPs can often be operated more efficiently on average than ASHPs. Especially in winter, when the demand for domestic hot water (DHW) and space heating (SH) is the highest, GSHPs typically show superior performance.

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The cost competitiveness of vapour-compression heat pumps can be potentially improved by using thermal energy stores (TES) in conjunction with smart control strategies [11–16]. TES can be used to decouple demand and supply. Smart controllers can shift some of the electricity consumption from high- to low-electricity-price periods, leading to notable economic savings for homeowners while at the same time benefiting the wider energy system by providing demand-side flexibility [11].

As countries progress in decarbonising their electricity sector, the capacity of intermittent renewable generation sources is increasing significantly in many systems, while firm generation capacity from, e.g., coal- and gas-fired power plants is decreasing. Therefore, it is widely recognised that the value of demand flexibility is ever increasing. The UK aims to install 600,000 heat pumps per year from 2028 and up to 1.7 million heat pumps per year from 2035 [12], for a total of 7 to 11 million heat pumps in 2035 [13]. These heat pumps, if used with conventional controllers, will significantly add to peak electricity demands. However, if coupled with TES and smart controllers, they can potentially provide significant demand flexibility.

Sensible-heat storage in the form of hot-water cylinders is currently the most widely used TES method in residential applications, as it is cheap and safe. However, latent-heat storage systems based on phase-change materials (PCMs) have experienced significant development and have recently entered the market for residential applications [14]. The main advantages of PCM-TES compared to hot-water cylinders are the potential for higher energy densities and the fact that they can work within smaller temperature ranges. This results in potentially lower required hot-water delivery temperatures and thus higher heat pump system efficiencies.

Most of the recent literature on smart operation of domestic heat pumps has focused on ASHPs. Several studies have examined the potential of shifting the operation of heat pumps from high- to low-electricity-price periods. Some of these studies concluded that a very large TES volume can prove beneficial for homeowners. For example, in the work of Arteconi et al. [15] a 500-L hot-water cylinder was shown to minimise the electricity consumption of an ASHP during high-electricity-price afternoon hours in Northern Ireland. Le et al. [16], also focusing on Northern Ireland, showed that hot-water cylinders with volumes in the range of 600 to 1100 L are optimal, depending on the investigated scenario. Furthermore, Kelly et al. [17] concluded that a 1000-L hot-water cylinder or a 500-L PCM thermal store would be required to shift ASHP operation to off-peak periods for a typical UK household. However, since TESs are typically installed within the internal space of houses, such storage volumes are not viable for many households that have limited space.

In addition to the aforementioned studies, Renaldi et al. [18] predicted that smart ASHP operation in a London house can lead to slightly reduced operational cost (by 6%) compared to a gas boiler. Fischer et al. [19] concluded that the use of model predictive control can reduce operating costs for a multi-family home in Germany by more than 10% compared to simple rule-based control methods. In their most recent work, Olympios et al. [20] identified that the operational optimisation of an ASHP for a single-family dwelling in the UK and Germany can lead to operational cost savings higher than 20% compared to simple heat pump control mechanisms based on temperature sensors. In that work, price and demand forecasts were assumed to be known with perfect accuracy.

Less effort has been devoted to optimising the operation of integrated thermal energy storage ground-source heat pump (GSHP-TES) systems. Salpakari et al. [21] studied cost-optimal and rule-based control strategies for buildings with a PV system, a GSHP, a hot-water cylinder, electrical storage and shiftable loads. They showed that, for a low-energy house in Finland, cost-optimal control can lead to 13–25% savings in the yearly electricity bill compared to an inflexible reference control strategy. Yang et al. [22] proposed operation strategies of a hybrid GSHP system with double-cooling towers for a hotel building, but results are not applicable to domestic buildings. Kajgaard et al. [23] estimated that economical savings achieved by time-shifting the operation of a GSHP heat pump in a typical Danish house can be up to 12%. However, none of the studies focusing on GSHPs considered PCM-TES.

In this work, the operation of an GSHP-TES is optimised for a typical UK household. The novelty lies not only in the development of comprehensive thermodynamic models and their use to perform an operational optimisation of a GSHP system integrated with a PCM-TES for domestic applications, but also in the identification of the optimal trade-off that can be achieved between PCM battery size and daily power costs. The developed heat pump and TES models, as well as the description of the optimisation framework, are presented in Section 2. The results and conclusions are provided in Sections 3 and 4, respectively.

2. Design and operational optimisation of an integrated thermal store ground-source heat pump

An optimisation framework has been developed in-house based on comprehensive first-law thermodynamic and component-costing models with a view to perform simultaneous design and operational optimisation of domestic ground-source heat pumps with integrated thermal energy storage (GSHP-TES). In this paper, we

present a preliminary study aimed at optimising the charging schedule of a phase-change material (PCM) thermal store coupled with a ground-source heat pump to supply both space heating and domestic hot water demands during a typical winter day for a medium-demand house in the UK, as detailed in Figure 1.

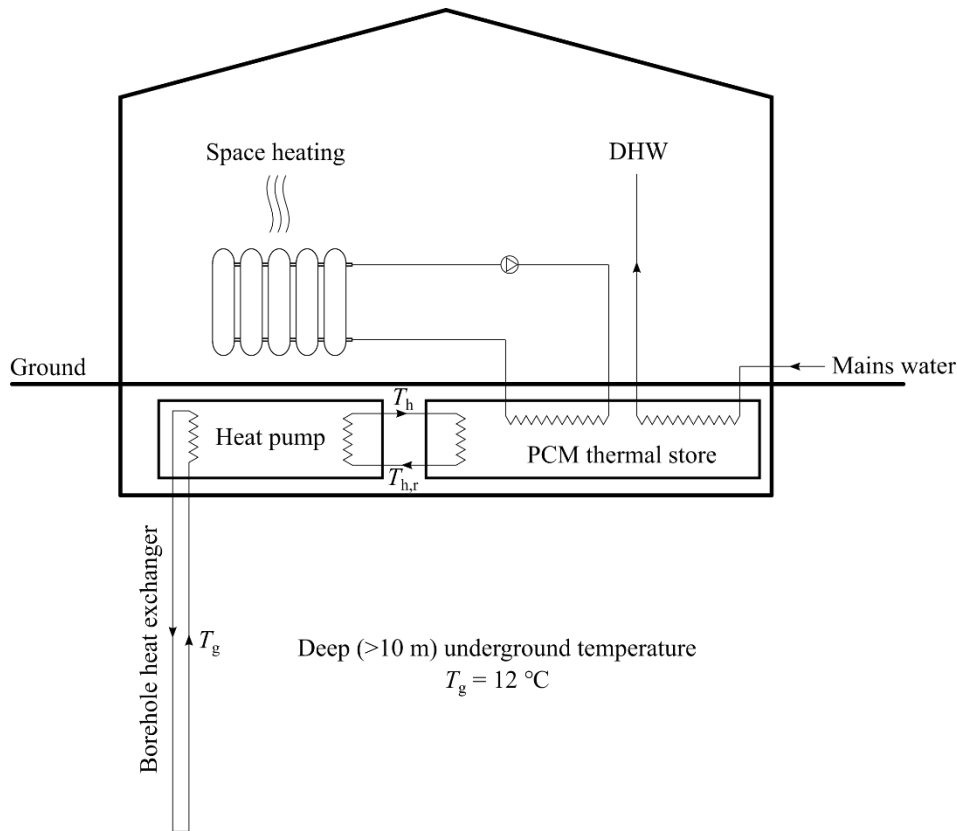


Fig. 1 - Schematic of a domestic ground-source heat pump with integrated latent-heat thermal energy storage.

Heat demand profiles and time-varying electricity prices used for this case study are presented in Section 2.1. The heat pump is first designed for a set heating capacity and prescribed pinch-point constraints for both condenser and evaporator units, as detailed in Section 2.2, while a simplified model is used to predict the PCM thermal battery performance, as detailed in Section 2.3. The charging schedule of the PCM thermal battery is then optimised for various thermal store sizes (ranging from 7 to 60 kWh), as detailed in Section 2.4.

2.1. Case study definition

This study is performed using the hourly heat demand profile of a typical UK household in a typical year. The typical household was identified by applying a kmedoids clustering algorithm to the Cambridge Housing Model dataset [24], which contains a representation of the UK building stock. Since the model only provides annual demand values for SH and DHW, the method developed by Watson et al. [25] was used to determine the hourly SH demand based on the ambient temperature, while the daily DHW demand profile was taken from Herrando et al. [26]. To eliminate any potential bias from choosing a specific year, the weather data was taken from a typical meteorological year, provided by the PVGIS tool [27].

Time-varying electricity tariffs offer end-users an opportunity to shift their electricity usage to low-price periods, which can be achieved with adequate-size thermal batteries coupled to heat pump units. In the current study, we selected the Octopus Agile tariff, which exhibits a high-price period between 4 and 7 pm [28].

Both hourly-defined electricity price and aggregated heat demand profiles for a typical winter day for a medium-demand house in the UK, presented in Figure 2, are used for this study.

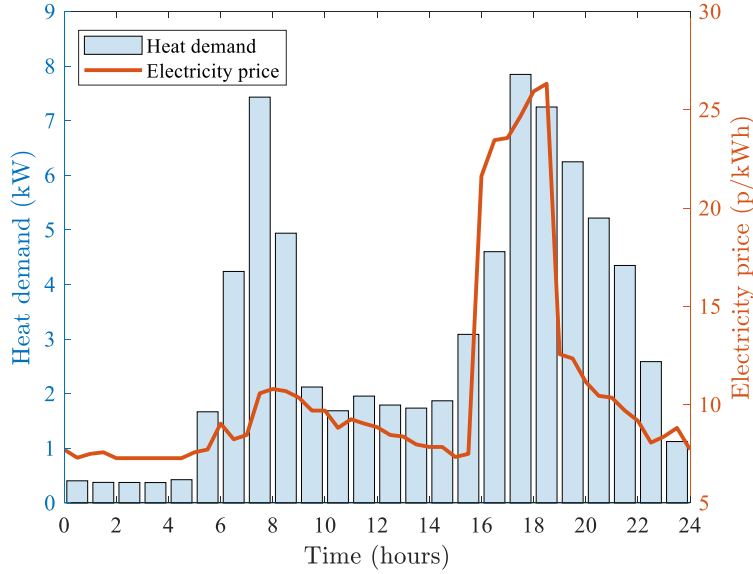


Fig. 2 - Hourly-defined electricity price and heat demand profiles for a typical winter day for a medium-demand house in the UK.

2.2. Ground-source heat pump (GSHP) design

The GSHP used to supply both space heating and DHW demands is a standard electricity-driven vapour-compression heat pump (VCHP) made of 4 main components, namely: a compressor, a condenser, an expansion valve, and an evaporator, as shown in Figure 3, operated with R32 as a working fluid, which exhibits a relatively low 100-year global warming potential of 675, as found in the IPCC 4th Assessment Report.

The GSHP is designed to extract heat from a ground-source water stream entering the evaporator unit at a constant $T_g = 12\text{ }^\circ\text{C}$ and rejecting heat at $T_h = 60\text{ }^\circ\text{C}$, with imposed 5-K pinch-point temperature difference in both the condenser and evaporator units. The return temperature from the PCM thermal store is determined from a heat balance as a function of both the PCM melting temperature, $T_m = 48\text{ }^\circ\text{C}$, and the water-to-store heat transfer effectiveness ($\varepsilon = 0.8$), as detailed in Section 2.3. In addition, the compressor is assumed to have a 60% isentropic efficiency and the expansion valve is set to maintain a constant 6-K superheat at the compressor suction. The working fluid equilibrium and transport properties are obtained using the open-source thermophysical property library Coolprop [29].

The thermodynamic performance of the VCHP unit is assessed with a comprehensive first-law thermodynamic model based on a set of widely accepted assumptions:

- No pressure losses in pipes
- No heat losses
- Zero subcooling at the condenser outlet (which can be achieved with a liquid receiver)
- Dynamic effects are neglected (i.e., cycle assumed to operate under steady conditions)
- Counter-current heat exchangers

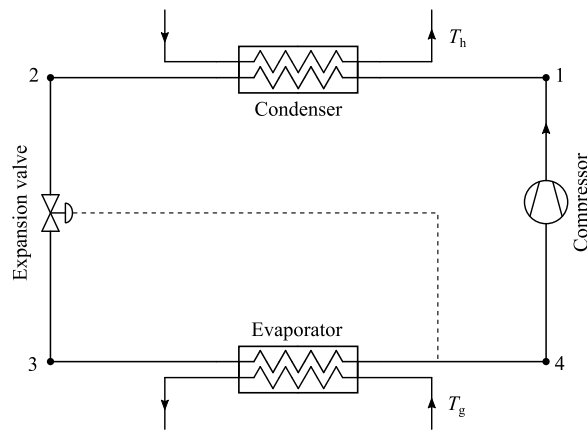


Fig. 3 - Schematic of the domestic vapour-compression heat pump (VCHP) design.

The VCHP cycle and the corresponding performance can then be determined by the condensing pressure, P_{cond} , and evaporating pressure, P_{evap} . With the zero-subcooling assumption at the condenser outlet, the thermodynamic state of the working fluid state in point ‘2’ – as defined in Figure 3 – is fully defined and both equilibrium and transport properties are calculated using Coolprop. The saturated liquid leaving the condenser then undergoes an isenthalpic throttling through the expansion valve, which allows us to calculate the vapour quality and properties of the two-phase mixture resulting from the Joule-Thompson expansion, thus fully defining state ‘3’. State ‘4’ is also fully defined from the evaporating pressure, P_{evap} , and the prescribed 6-K superheat at the evaporator outlet. The compressor discharge (state ‘1’) is obtained from the assumed 60-% compressor isentropic efficiency, which accounts for various loss mechanisms, including: pressure losses through the intake and exhaust valves, mass leakage through the piston ring and heat transfer.

Finally, both evaporating and condensing pressures are optimised to minimise the power consumption, \dot{W}_c , to provide a given heating capacity, \dot{Q}_h , while respecting pinch-point constraints in the condenser and evaporator units. This non-linear problem is solved using the sequential least squares programming (SLSQP) implemented in the Python open-source SciPy library [30]. The coefficient of performance (COP), denoted φ , is then defined as the ratio of the heating power to the power input: $\varphi = \dot{Q}_h / \dot{W}_c$.

The design of evaporator and condenser units is then determined using spatially resolved models. Brazed-plate heat exchangers (BPHXs) are used for both units as they offer compact and efficient designs for both water-cooled condensers and water-source evaporators. Heat exchanger units are discretised in equal enthalpy-step nodes and the conjugate heat transfer through the heat exchanger plates are solved for each element to determine the overall required area. Single-phase convective heat transfer is predicted using Bogaert & Böles correlation [31], which is also used to predict the convective-boiling contribution to the heat transfer in the two-phase region of the evaporator unit, while the pool-boiling contribution is estimated with Cooper’s correlation [32]. The fluid-to-wall heat transfer in the two-phase region of the condenser unit is predicted using the model proposed by Thonon & Bontemps [33]. No further detail is provided on these models nor is the choice of these correlations further discussed here, as this study focuses on the operational optimisation of GSHP-TEs and on the trade-off between the thermal battery size (or capacity) and the daily operational costs. However, interested readers may refer to recent publications where these models are presented in more detail [5, 34]. The following research questions will be addressed in future studies: (i) whether high-spec high-cost heat pumps perform better than low-spec low-cost ones from an economic point of view; or (ii) whether a large heat pump coupled with a small thermal battery outperform a small heat pump with large thermal stores.

For stated assumptions and component performance indicators, an 8-kW heat pump has been designed, and the corresponding geometry and performance characteristics are detailed in Table 1. The stated performance matches that of real-world ground-source heat pump systems, the price and performance of which are detailed in the online technology library proposed by Olympios et al. [35].

Table 1. Detailed characteristics of an 8-kW heat pump (with R32) designed to extract heat from a water stream at $T_g = 12$ °C and rejecting heat at $T_h = 60$ °C, with imposed 5-K pinch-point temperature difference in both the condenser and evaporator units.

Heat pump performance	
Power consumption	2.64 kW
Coefficient of performance	3.0
Pressure ratio ($P_{\text{cond}}/P_{\text{evap}}$)	4.8
Working fluid mass flowrate	27.10^{-3} kg/s
Condenser design	
Total heat transfer area	0.15 m ²
Number of plates	3
Channel width	50 mm
Channel length	970 mm
Evaporator design	
Total heat transfer area	0.08 m ²
Number of plates	2
Channel width	79 mm
Channel length	508 mm

2.3. PCM thermal battery design and performance

The latent-heat thermal battery proposed for domestic applications is based on an existing phase-change material, namely the PCM-A48 from PCM Products Ltd., which has a melting temperature $T_m = 48\text{ °C}$, which is deemed adequate for the mid-size dwelling selected for this investigation and for modern radiators. Further details on the selected PCM are provided in Table 2. Underfloor heating installations with proper insulation would require lower melting temperatures, which would obviously benefit the thermodynamic performance of the heat pump by reducing the source-to-sink temperature lift and using the building thermal mass as an additional thermal storage medium, which is though beyond the scope of this study.

Heat transfer to and from the latent-heat thermal battery is represented using a simple fixed-effectiveness method ($\varepsilon = 0.8$), from which the return temperature to the heat pump unit, $T_{h,r}$, is calculated:

$$T_{h,r} = T_h - \varepsilon(T_h - T_m). \quad (1)$$

Table 2. Thermo-physical properties of the organic phase change material PCM-A48 from PCM Products Ltd.

Material	Melting temperature	Density	Latent heat	Specific heat capacity	Thermal conductivity
PCM-A48	48 °C	810 kg/m ³	230 kJ/kg	2.85 kJ/kg/K	0.18 W/m/K

2.4. PCM thermal battery charging schedule optimisation

The charging schedule is defined as a set of on/off times spanned throughout the day to decide when and for how long the heat pump is turned on to charge the thermal battery. Instead of allowing an unlimited number of charges a day, which would be highly computationally expensive, we decided to impose and increase the number of charges a day incrementally until no further improvement is noticed. The optimisation exercise then boils down to decide, for a given number of charges a day, when and for how long should each charge occur to minimise the daily operational expenditure (OPEX). A couple of constraints have been imposed to ensure feasibility and control the size of the thermal battery: (i) the heat demand must always be met; and (ii) the storage capacity of the thermal battery cannot exceed a prescribed value. The latter constraint is first lifted to measure the maximum savings that can be achieved through smart control of the thermal battery charging schedule (results in Section 3.1), while a range of constrained battery sizes are imposed to identify the optimal trade-off between the thermal battery capacity and the daily operational costs (see Section 3.2).

This optimisation problem was formulated in the Python open-source SciPy library [30] and solved using a differential evolution algorithm, which consists of iteratively improving a population of candidate solutions.

3. Results

3.1. Optimised charging schedules without constraint on the thermal battery size

The charging schedule of an unlimited-size thermal battery is first optimised using the 8-kW heat pump designed in Section 2.2. The results are presented in Figure 4, where the optimum charging profiles are shown for 1-to-4 charges per day along the heat demand and electricity prices throughout the typical winter day selected for this investigation, while the associated daily operational costs (i.e., electricity consumption costs) are detailed in Table 3 along with the required battery size for each scenario.

It appears clearly that, for each scenario, low-price periods are favoured to charge the thermal battery, while the peak-price period is avoided. Increasing the number of charges does lead to significant additional savings, with the daily OPEX reducing from 2.01 £/day for a single charge to 1.85 £/day for 3 or more charges per day. It is worth noting that, although the 3-charge-a-day charging schedule differs from that of the 4-charge-a-day scenario, as shown in Figure 4, similar daily costs are achieved. The battery required to achieve the former schedule (46 kWh) is however larger than that needed to deliver the heat demand following the 4-charge-a-day schedule (41 kWh). Increasing the number of charges per day is thus needed to identify a better trade-off between battery size and daily costs, which is explored further in the next section.

Finally, for the unlimited-size battery optimisation exercise, no improvement is noticed when further increasing the number of charges per day.

Table 3. Daily operational cost (OPEX) and required battery capacities associated with optimised charging schedules with an 8-kW heat pump without constraint on the thermal battery size.

Number of charges a day	1	2	3	4	5
Required battery size (kWh)	53	47	46	41	41
Daily OPEX (£/day)	2.01	1.86	1.85	1.85	1.85

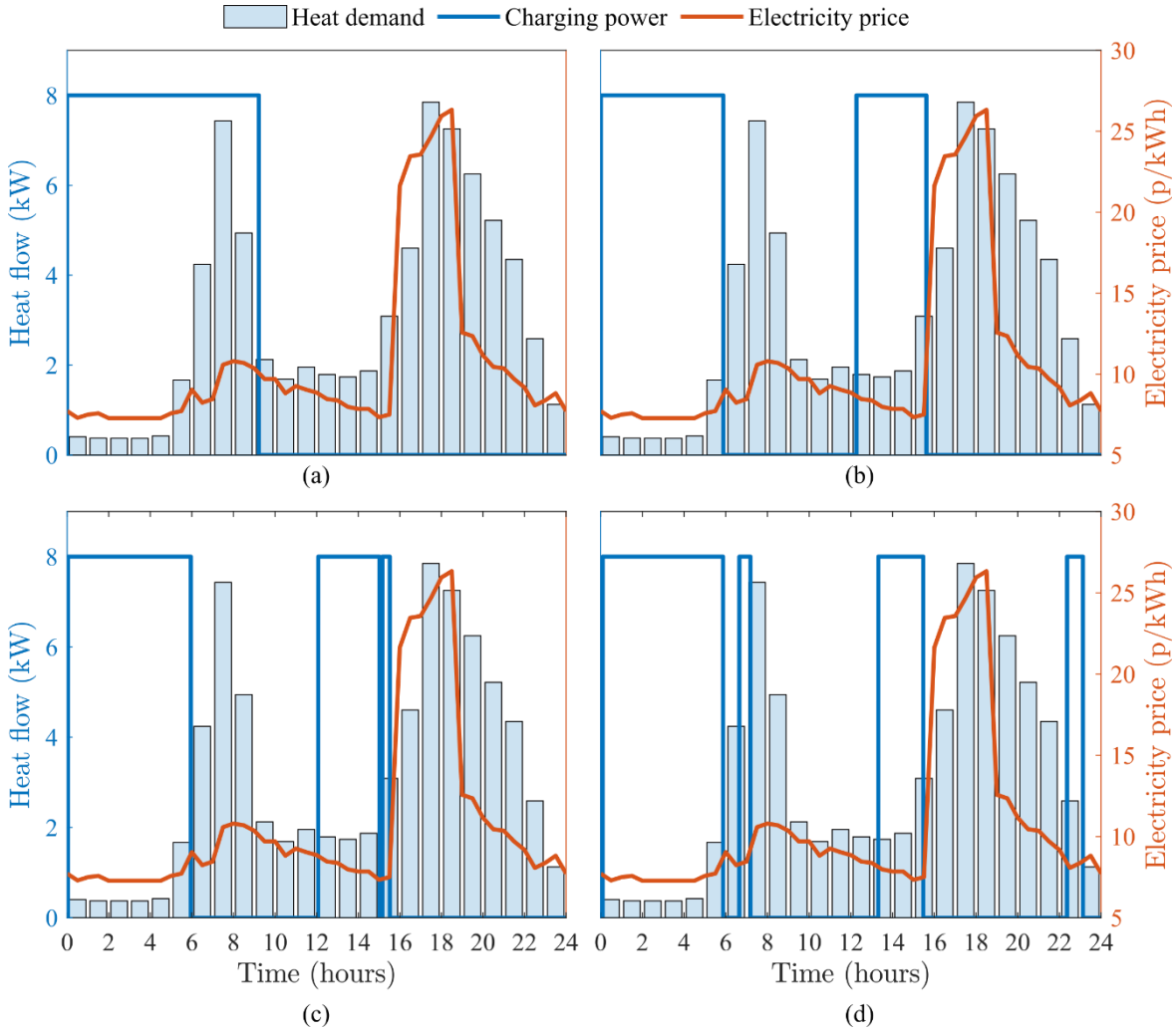


Fig. 4 - Optimised charging schedules with an 8-kW heat pump (design detailed in Table 1) without constraint on the thermal battery size for: (a) 1 charge a day; (b) 2 charges a day; (c) 3 charges a day; and (d) 4 charges a day. Corresponding daily operational and required battery sizes are detailed in Table 3.

3.2. Multi-objective optimisation: trade-off between thermal battery size and daily OPEX

Increasing the thermal storage capacity comes at a cost. First, from an economic standpoint, upfront costs for a large-scale thermal battery are very significant, as the specific cost of PCM batteries typically ranges from 200 to 400 £/kWh. Second, space restrictions are to be considered and several end-users simply will not have enough space to fit large-capacity thermal batteries. Therefore, a multi-objective optimisation has been conducted, whereby a constraint is imposed on the thermal store capacity to measure how the potential savings are impacted and identify the optimal trade-off that can be achieved between PCM battery size and daily costs.

The results of this investigation are presented in Figure 5, where the daily operational costs are plotted against required thermal store capacity for a range of optimised charging schedules. These results have been obtained by varying the number of charges per day and the constraint imposed on the battery size to explore the design/operational space. This allows us to identify the optimal trade-off, which is given by the Pareto

frontier plotted in Figure 5. This curve provides the end-user or installer with a direct relationship between how much savings can be expected by fitting a larger thermal battery.

As expected, higher daily power costs are to be paid with smaller thermal stores. The fact that the evening peak demand coincides with the peak electricity prices, as shown in Figures 2 and 4, explains why operational costs so strongly depend on the battery size, with daily OPEX increasing from 1.85 £/day for a 41-kWh thermal battery to 3.5 £/day for a 6.3-kWh thermal store. Indeed, it becomes impossible to avoid charging the battery during the peak-demand/peak-price period with smaller thermal batteries.

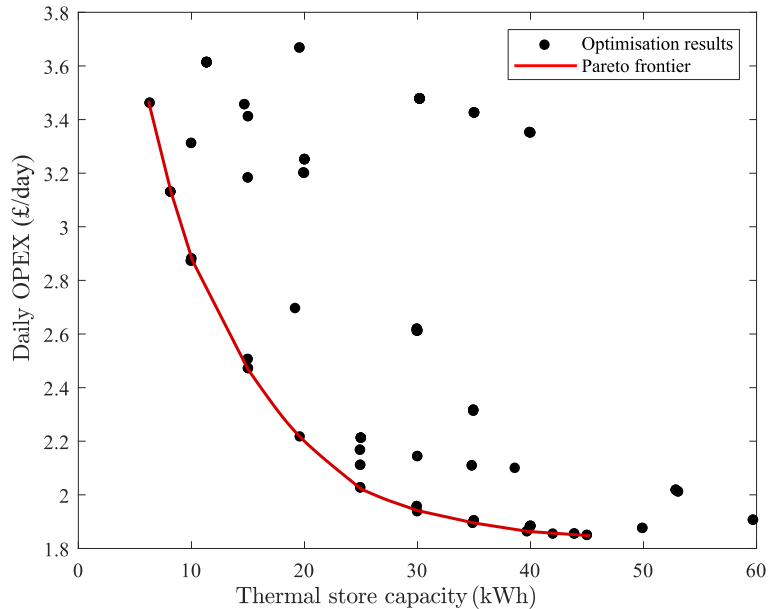


Fig. 5 - Daily operational costs (OPEX) plotted against required thermal store capacity and associated Pareto frontier. Each point corresponds to an optimised charging schedule with specific number of charges per day and constraint on the battery size.

4. Conclusions

Quantifying the savings in the yearly electricity bill that can be achieved through smart control strategies of heat pumps integrated with thermal energy storage is key to promote the uptake of clean heating technologies and help heat decarbonisation. In this paper, a detailed methodology is proposed to design and optimise the operation of a ground-source heat pump (GSHP) coupled to a phase-change material (PCM) thermal battery. The objective is to minimise costs of supplying both space heating and hot water to a medium-demand house in the UK during a typical winter day with fluctuating electricity prices.

Time-varying electricity tariffs offer end-users an opportunity to shift their electricity usage to low-price periods, which can be achieved with adequate-size thermal batteries coupled to the heat pump unit. After designing a dedicated 8-kW GSHP fitted with brazed-plate heat exchangers, charging schedules of the thermal battery have been optimised to minimise daily operational costs (OPEX) while meeting the heat demand.

First, no limit was imposed on the size of the thermal battery. By increasing the number of charges allowed per day from 1 to 5, it was found that increasing the number of charges does lead to cost savings, with the daily OPEX reducing from 2.01 £/day for a single charge to 1.85 £/day for 3 or more charges per day. In the best scenario, a 41-kWh thermal battery is required to achieve costs as low as 1.85 £/day.

However, large-scale thermal stores are costly. First, from an economic standpoint, as higher upfront costs are to be paid for larger thermal batteries. Second, space restrictions are to be considered and several end-users do not have enough space to fit large-capacity thermal batteries. Therefore, a multi-objective optimisation has been conducted, whereby a constraint is imposed on the thermal store capacity to measure how the potential savings are impacted and identify the optimal trade-off that can be achieved between PCM battery size and daily power costs. As expected, higher daily power costs are to be paid with smaller thermal stores. Operational costs strongly depend on the battery size, with daily OPEX increasing from 1.85 £/day for a 41-kWh thermal battery to 3.50 £/day for a 6.3-kWh thermal store. This is largely due to the concomitance of the evening peak heat demand and peak electricity prices as it becomes impossible to avoid charging the battery during the peak-demand/peak-price period with smaller thermal batteries.

Three main research pathways are being explored to extend the findings of this investigation.

- Simultaneous design and operational optimisation are being performed, whereby the size and performance of the heat pump system will be optimised along with yearly charging schedules to minimise the levelised cost of heat using ground-source energy systems.
- The assumption made in the current study to impose a constant return temperature from the underground borehole heat exchanger, although acceptable for a daily performance estimation, is no longer valid for yearly operation. A collaboration with a geotechnics research team is currently ongoing to address this limitation and determine year-round temperature variations associated with heat dissipation and accumulation in the ground.
- The omniscient point of view taken in the current study provides us with an upper bound for potential savings through smart control of the thermal battery charging schedule. At best, a real-life smart meter can be fed with inaccurate electricity prices, weather, and heat demand forecasts, which will lead to sub-optimal charging schedules as compared to those presented in this paper. We are currently investigating how close a smart-meter control strategy can approach this upper bound and what & how many data are needed. In other words, how smart does a smart meter need to be?

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