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Can thermal storage assist with the electrification of heat through peak shaving?

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Abstract

The majority of heat in the UK comes from the combustion of natural gas, and heat is responsible for 37% of the nation's carbon emissions. Thus the decarbonisation of heat is a major challenge. Electrification is one possible approach to decarbonisation; however, huge increases in the electrical grid's generation and transmission capacity would be needed to meet the peaks in space heat demand during cold winter weather. Thermal energy storage (TES) may have a role to play in alleviating this problem, by shifting heat demand by hours or longer periods, enabling peaks to be shaved.

This work considers the utility of two varieties of thermal energy storage for this application. Adsorption thermal storage (ATS) is a technology offering long term storage at a high energy density, but is a costly and relatively immature option. By contrast, storage of sensible heat in hot water tanks is already widespread, although it has relatively short storage duration and lower density.

Here, we simulate the deployment of these technologies in a small residential neighbourhood, in tandem with demand-side management (DSM), to attempt the reduction of peaks in demand. With no storage or DSM, electrification causes peaks to increase by a factor of 2.36. Results so far suggest that both TES technologies have potential to reduce peaks, with a 14% decrease achievable by either 5 m^3 of hot water storage, or 0.25 m^3 of ATS, in each dwelling. However, it is thought unlikely that adsorption storage is attractive for a purely peak shaving application, given its cost and complexity.

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Keywords: Thermal storage; Adsorption storage; Sensible heat storage; DSM; Heat pumps; Peak shaving; Electrification of heat

1. Introduction

1.1. The challenge of heat decarbonisation

Heat is responsible for 37% of the UK's greenhouse gas emissions [1]; space heating by itself represents over 28% of the nation's entire energy consumption [2]. At present the great majority of heat comes from the combustion

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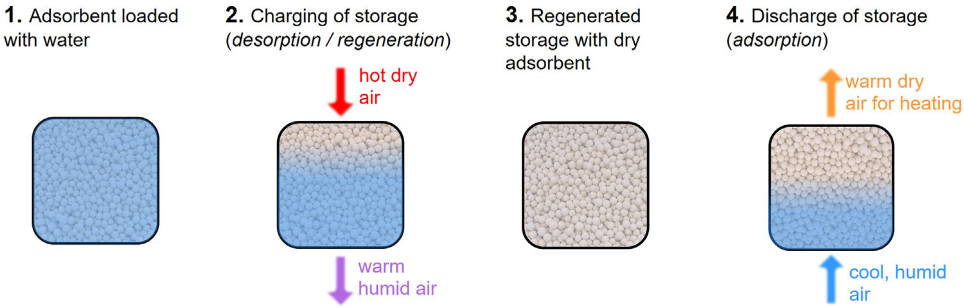

Fig. 1. Thermal storage cycle for an open adsorption store. Note that the storage period between stages and 4 can be indefinitely long.

of natural gas [1,2]. The decarbonisation of heat is thus a central challenge if the UK is to meet its targets for emissions reduction.

One possible approach to decarbonisation is electrification, with gas boilers replaced by heat pumps. However, the sheer scale of heat demand raises questions as to the ability of the electrical grid to absorb this load. Overall annual demand for heat is approximately double that for electricity, with respectively 692 TWh and 353 TWh consumed in 2017 [2]. A recent UKERC report [3] points out that in the winter of 2017–2018, the largest hourly demand for natural gas was 214 GW, compared to 53 GW for electricity. Furthermore, the demand for heat was seen to increase rapidly in the early mornings, with gas supply often ramping by 100 GW between 5 and 8 am. Thus, widespread electrification of heat is currently beyond the capability of the grid to deliver.

Thermal energy storage (TES) technologies have the potential to shift heat demand by hours or longer periods, smoothing peaks in demand, and thus reducing the increased electricity generation/transmission capacity required for electrification. In this work, we explore how thermal storage coupled with demand side management (DSM) can reduce the peak electrical demand for a residential neighbourhood. Two thermal storage technologies are considered: hot water storage, and adsorption thermal storage.

1.2. Brief introduction to the thermal storage technologies

Hot water thermal storage (HWTS), the storage of thermal energy in hot water tanks, is the simplest and most prevalent form of thermal energy storage. The high volumetric heat capacity of water (4190 kJ m^3 K^{-1}) makes it an attractive medium for storage of sensible heat [4,5]; this equates to 35 kWh/m^3 thermal storage density, for a 30 °C temperature range. HWTS can readily be integrated with traditional central heating systems, and can be charged via renewable technologies including heat pumps and solar thermal collectors. The main limitation, as with any storage of sensible heat, is the inevitability of heat losses over time.

Adsorption thermal storage (ATS) relies on the binding of an adsorbate, usually water vapour, onto a solid adsorbent. Supplying heat 'regenerates' the adsorbent, driving water off. Reintroducing water vapour to the adsorbent triggers adsorption, releasing heat [6,7]. Provided the adsorbent is kept dry in between these stages, there are no storage losses over time. The storage cycle is illustrated in Fig. 1. Energy density is also high (100–200 kWh/m^3 [6]) suggesting potential for long term storage applications. Challenges for ATS as a technology include the need for high temperatures of regeneration, typically well above 100 °C [8], and low cycle efficiency, with the heat extracted typically not exceeding 60% of the heat invested [9–11]. ATS is a relatively immature technology with costs still uncertain but possibly an order of magnitude higher than HWTS [12,13].

1.3. Thermal storage for peak shaving – existing work

As already commented above, to switch the UK's heat demand across from the gas to the electricity network would be an immense challenge. References [14,15] both suggest that wide adoption of heat pumps across the UK could cause peak electricity demand to more than double. Part of the solution will doubtless involve improving the thermal performance of building stock, but there is also interest in the use of TES for load levelling. For instance Arteconi et al. [16] concluded that HWTS with heat pumps could be used for load levelling, although

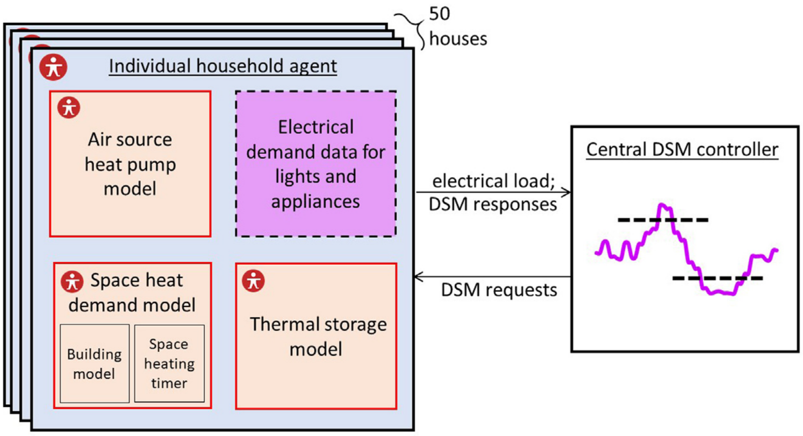

Fig. 2. Schematic of the neighbourhood simulation implemented in AnyLogic.

some heating systems may have enough inherent thermal inertia to make additional TES redundant. Cooper et al. [15] studied the impact of heat pumps on peak demand for dispatchable power on the GB grid. They found that building improvements and the use of DSM could keep the increase in peak demand to 15.9%; with the further addition of 640 l of HWTS in each house, the increase was predicted to be only 11.2%. Baeten et al. [17] found that the addition of 500 000 heat pumps to the grid in Belgium could be achieved with negligible increase in peak demand, through the use of DSM and 1 m^3 of HWTS in each dwelling. Brunner et al. [18] found that heat pumps with HWTS, replacing resistive storage heaters, could be effective for electrical peak shaving in a German neighbourhood of 1000 houses.

2. Methodology

Here, we have used AnyLogic [19] to simulate a residential neighbourhood, with electrified space heating and thermal storage controlled by DSM. The AnyLogic software enables the combination of *agent-based*, *system dynamics* and *discrete event* simulation approaches; in this work individual dwellings are represented by agents, which interact with a DSM controller. Each dwelling also contains sub-agents for space heating, ASHP and thermal storage — see the schematic shown in Fig. 2. The various sub-models present in the simulation will now be discussed.

2.1. Space heating demand model

The building model is adapted from CREST's demand model [20]. Two lumped thermal capacitances represent external building fabric, and building contents. Heat flows representing conduction and ventilation losses are calculated according to various coefficients of heat transfer. Passive solar gains are also estimated from insolation data. Three building archetypes are adopted from the CREST model, representing detached, semi-detached and terraced houses, all with upgraded insulation. The building model gives rise to a system of ODEs which is solved by AnyLogic using a fourth-order Runge–Kutta method with fixed time step 3.6 s, using the dynamic systems modelling capability.

2.2. ASHP model

ASHPs are modelled using a coefficient of performance (CoP) dependent only on the temperature difference ΔT across which the ASHP is operating. This relationship is given by the following quadratic fit based on data from Kelly and Cockroft [21].

$$CoP = \left(8 \times 10^{-4}\right) \cdot (\Delta T)^2 - 0.117 \cdot \Delta T + 6.0277 \quad (1)$$

In practice this results in CoPs of around 2.

2.3. HWTS

Hot water storage tanks are modelled as a single perfectly mixed thermal mass. Thus the rate of temperature change over time is simply governed by the heat flow $\dot{Q}_{ASHP}$ from the heat pump, the heat flow $\dot{Q}_{SH}$ to the space heating, and the thermal losses, as follows:

$$\frac{d}{dt}\left(\rho \cdot V \cdot c \cdot T_{HW}\right) = \dot{Q}_{ASHP} - \dot{Q}_{SH} - \frac{kA}{L}\left(T_{HW} - T_i\right) \tag{2}$$

Here ρVc and T_{HW} are respectively the thermal mass and the temperature of the hot water. Heat losses flow from the tank to the internal thermal mass of the building model at temperature T_i. Insulation is assumed to have thickness L = 0.3 m., with conductivity k = 0.02 W m^{-1} K^{-1}. The model is implemented in AnyLogic in the same manner as the building model (see 2.1).

HWTS tanks are presumed to operate between 45 and 65 °C. A thermostat is used to control the temperature of the tank within this range. The storage tanks are considered to be positioned in series between the heat pump and the heat demand, so that all heat must flow through the storage.

Hot water tank volumes considered are 0.25, 0.5, 1, 2 and 5 m^3.

2.4. Adsorption thermal storage model

The adsorption thermal storage system that we attempt to characterise here is an open system (meaning it operates at atmospheric pressure, and the purged water vapour is vented into the ambience rather than retained) similar to the systems described in [22] and [11]. A zeolite 13X adsorbent is assumed to be used. To prevent excessive consumption of energy by blowers, the storage is assumed to be segmented as in [23].

To model such a store, we use a simple characterisation in terms of energy density, thermal cycle efficiency and achievable power output. The heat released/stored when loading and unloading the adsorbent is calculated using Gondre's approximation for the differential heat of adsorption of water on zeolite 13X [24], and Wang and LeVan's Toth isotherm fit for the mass concentration of water on Z13X at different temperatures and partial pressures of H_2O [25]. This enables the calculation of thermal storage density at different regeneration temperatures; for regeneration at 180 °C, this is calculated to be 131 kWh/m^3.

The power output of the storage is calculated on the assumption that 10 g of H_2O is adsorbed per cubic metre of air passed through the adsorbent [7,23,26]. For regeneration at 180 °C, this is calculated to give a temperature uplift of around 29 °C for air passed through the store during adsorption. The stores are segmented to allow a sufficient airflow to achieve 5 kW_{th} output without unduly high electrical consumption by blowers.

The inefficiencies of the storage are assumed to arise during desorption, owing to the dissipation of sensible heat during and after regeneration. As regeneration temperature T_{des} rises, regeneration efficiency η_{des} tends to fall. Here we estimate this efficiency by a linear interpolation of results published in [22]:

$$\eta_{des} = 0.68 - 0.0016 \cdot \mathrm{T}_{des} \tag{3}$$

Resistive heat is needed to obtain sufficiently high regeneration temperatures. If the amount of resistive heat supplied is Q_{des} the stored heat is then given by $\eta_{des}.Q_{des}$. No other inefficiencies or balance of plant losses are considered, other than the consumption of blowers. The storage volumes considered here were 0.125, 0.25, 0.5, 1, 2 and 5 m^3.

2.5. DSM strategy

In contrast to the work by Brunner et al. [18] and Cooper et al. [15] we define *two* demand thresholds for DSM signals to be sent (see Fig. 3). When demand rises above an upper threshold, houses are switched to peak-shaving mode. When demand falls below a lower threshold, houses are switched to trough-filling mode. In between these points, houses operate in a neutral mode. Parameter variation in AnyLogic is used to ascertain sensible values for these thresholds. HWTS responds to DSM signals by adjusting its thermostat, keeping the temperature high for trough filling, or allowing it to fall for peak shaving. For ATS, trough filling/peak shaving are respectively accomplished by charging/discharging the storage.

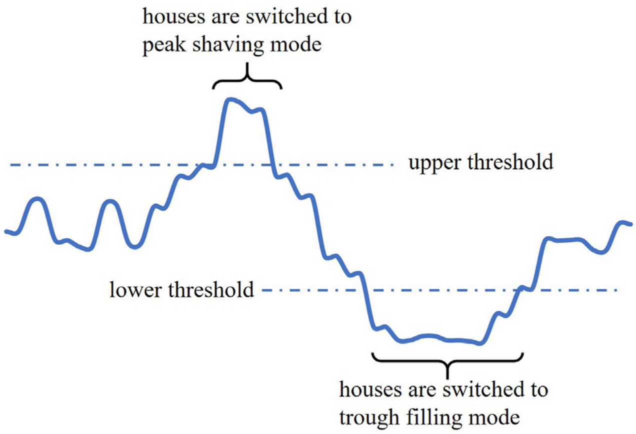

Fig. 3. Illustrates the approach to DSM using two thresholds (the vertical axis is electrical demand).

2.6. Case study details

The model described in 2.1–2.5 has been used to simulate a small neighbourhood of 50 dwellings, notionally located in South East England. Electricity demand data is sourced from a UK Power Networks smart metre trial in London [27], and has a half hour time resolution. For this data, mean electricity consumption of a dwelling is 4.12 MWh per annum, standard deviation 2.07 MWh; demand for the neighbourhood peaks at 44 kW. Climate data was recorded by UKECN at Rothamsted [28].

3. Results

The addition of heat pumps to the electrical load for the simulated neighbourhood increased peak demand from 44 kW to 104 kW, an increase of 136% - similar to the findings in [14,15]. These peaks occurred during particularly cold January weather. Overall annual consumption for the neighbourhood increased from 205 to 498 MWh.

Further simulations investigated the impact of the TES technologies in conjunction with the DSM control described above. Simulations with ATS storage ran for a full year to ensure that the seasonal storage capability could be realised; simulations with HWTS ran for 17 days, with the coldest weather occurring from around halfway through the period.

Fig. 4 exemplifies how the DSM/TES responded to conditions on the grid during a simulation using 1 m^3 of HWTS per house. 2(b) shows the DSM states of the 50 houses; the switching of houses to trough-filling or peak-shaving modes in response to valleys/peaks in demand can be seen. 2(c) shows the aggregate state of charge for storage across all houses, as a proportion of the total storage capacity. In this case (1 m^3 HWTS) peak demand was cut from 104 to 99.7 kW, a reduction of 4.5%.

Fig. 5 illustrates the degree to which peak demand could be curtailed, for the different storage technologies and volumes. As expected, ATS can achieve more peak shaving for a given volume. Indeed, 250 l per house of ATS could reduce the peaks to around 90 kW; 5 m^3 of HWTS would be needed to accomplish the same. The advantage of the ATS derives from both its greater energy density and longer storage duration.

However, use of the ATS was associated with a pronounced increase in energy consumption overall. This is inevitable given that the ATS must be charged using resistive heat, and also has low cycle efficiency. These increases, given in Table 1, are unlikely to be acceptable except for the smallest storage volumes. In practice it may well be possible to make use of some of the heat that dissipates following regeneration; this could be a matter for future investigation.

In contrast to the work of Cooper et al. we do find that enlarging the volume of HWTS beyond the hundreds of litres can enable further peak reductions. Possibly this was enabled by the use of two thresholds for DSM. However, storage as large as 5 m^3 is unlikely to be acceptable in many houses.

It should be noted that a smooth decline in peaks with increasing storage volume was not observed, which is likely due to stochastic elements in the simulation.

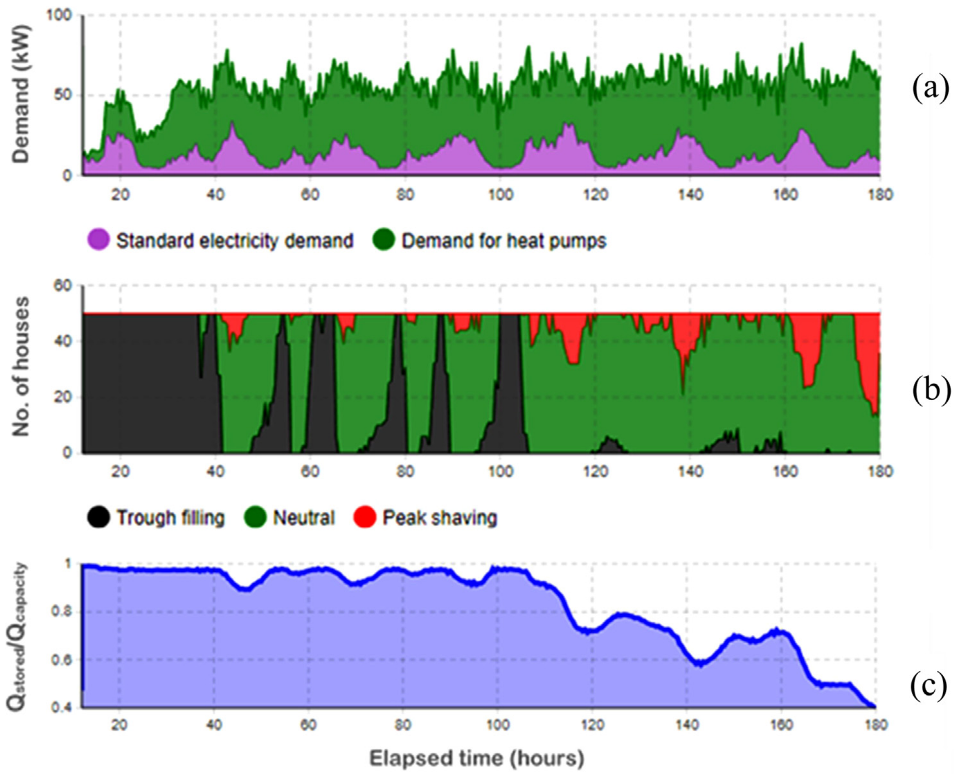

Fig. 4. Simulations of 1 m^3 of HWTS per house. 2(a) Electricity demand for neighbourhood. 2(b) DSM states of the 50 houses. 2(c) State of charge of the HWTS as an aggregated whole; total stored heat Q_{stored} as a proportion of total TES capacity $Q_{capacity}$.

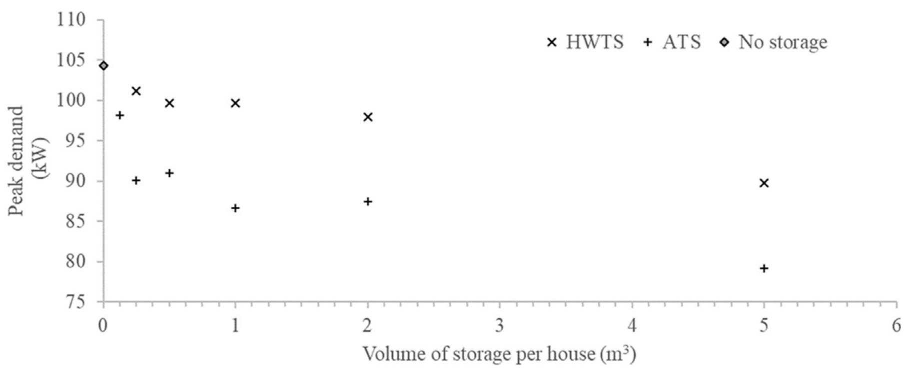

Fig. 5. Peak demand for the simulated neighbourhood, with different volumes of TES installed in each house.

Table 1. Increased electricity usage due to adsorption thermal storage, relative to case with ASHP only.

Volume of ATS (m^3)	0.125	0.25	0.5	1	2	5
Increase in annual electricity consumption	5.5%	7.5%	15.8%	24.7%	37.0%	61.6%

4. Conclusions

AnyLogic has been used to simulate the impact of ASHPs on the electrical load of a small neighbourhood of 50 houses. Two thermal storage technologies – sensible storage with hot water and adsorption thermal storage – have been added to the simulation, with DSM used to charge/discharge storage during troughs/peaks in demand.

With no DSM or thermal storage, peak loads increased by a factor of 2.36 to 104 kW. 250 l of ATS was able to reduce these peaks to 90 kW; 5 m^3 of hot water storage would be needed to match this. However, the use of resistive heat to charge ATS systems incurs a heavy penalty on overall energy consumption, so customers would need to be appropriately incentivised and compensated. Taken together with the higher cost and complexity of such systems, the attractiveness of ATS for a purely load levelling application seems doubtful.

Future work using this model may address some of the following:

- DSM strategies using only building thermal mass with no TES;
- smarter DSM strategies, e.g. incorporating model predictive control;
- the impact of space heating user behaviour;
- integration of distributed renewable generation into the model;
- correct sizing of TES for the different building archetypes;
- simulations with higher numbers of houses for better repeatability;
- addition of domestic hot water demand model;
- consideration of other TES technologies, such as phase change materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Timothy D. Hutty: Conceptualization, Data curation, Methodology, Validation, Investigation, Formal analysis, Writing - original draft, Visualization. **Natasha Patel:** Methodology, Investigation, Formal analysis. **Siyuan Dong:** Methodology. **Solomon Brown:** Conceptualization, Supervision, Writing - review & editing, Funding acquisition.

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