Domestic thermal storage requirements for heat demand flexibility

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Abstract

Future changes to the UK's energy system, specifically radically increasing the deployment of renewable energy sources at all scales, will require much more flexibility in demand to ensure system stability. Using dynamic building simulation, this paper explores the feasibility of using thermal storage to enable flexibility in heat demand over a range of timescales: diurnal, weekly and seasonal. Time-varying space heating and hot water demand profiles for four common UK housing types were generated, accounting for different occupancy characteristics and various UK climates. These simulated heat demand profiles were used to calculate the necessary storage volumes for four heat storage options: hot water, concrete, high-temperature magnetite blocks and an inorganic phase change material. The results indicated that without first radically improving insulation levels to reduce heat demands, even facilitating diurnal heat storage would require low-temperature, sensible heat storage volumes well in excess of 1000L, in many cases. Storage of heat over more than a few days becomes infeasible due to the large storage volumes required, except in the case of dwellings with small heat demands and using high-temperature storage. However, for heat storage at high temperature, retention of heat over longer time periods becomes challenging event with significant levels of insulation.

Keywords: thermal storage; sizing; flexible demand; housing; building simulation

1 Introduction

There are frequent statements made in energy strategy and planning documents that demand flexibility will play a key role in the stable operation of a future, low-carbon energy system in which major demands such as heat and transport are decarbonised [1,2,3]. The built environment is the biggest UK energy end-user and the main component of this is housing. Around 80% of domestic demand is hot water and space heating [4], so any large-scale, flexible demand capability should encompass domestic heat. Temporal flexibility in heat demand will be essential if heat is decarbonised through electrification - uncontrolled, this has the potential to significantly increase electrical demand variability and peak demands [5]. However, many questions arise as to the feasibility and acceptability of widespread heating flexibility. Moving the timing of heat demand without adversely affecting the comfort of householders and the availability of hot water requires thermal storage (e.g. hot water tanks, electric storage heating, etc.). Storage increases the cost and complexity of domestic energy systems, uses valuable space and increases energy use due to parasitic losses. It also runs contrary to the trends in housing which have seen a huge rise in gas central heating and the replacement of hot water storage with combination gas boilers [6]. Consequently, there is uncertainty over whether heat storage could be deployed extensively in the housing sector and hence the degree to which flexible heating could be relied upon as a means to support the operation of a future power system.

It is against this background that the EPSRC Fabric Integrated Thermal Storage in Low Carbon Dwellings project (FITS-LCD, http://fits-lcd.org.uk) is examining alternative approaches to the deployment of storage in housing. Specifically, the project looks at whether the intrinsic thermal mass in a building's fabric could be better utilised (either passively or actively) or modified to provide heat demand flexibility. The project is making use of both modelling and demonstration to explore the feasibility of fabric-integrated storage concepts.

1.1 Aims and objectives

This paper addresses demand flexibility in the domestic sector. Specifically, the paper identifies the storage capacities required for domestic heat load shifting over a range of timescales. This is done for a variety of key housing types, climates, occupancy characteristics and housing conditions. The calculated capacities are converted to physical sizes for a range of materials; this is done to assess the feasibility of a wide range of integrated storage options.

2 Review

The concept of thermal storage being used as a means to improve the operation of electricity networks is not new, with off-peak storage heating designs being patented in the late 1920s [7]. However, the operating context and potential end use for heat storage coupled to the electricity network has changed significantly as heterogeneous sources of electrical energy have been introduced into the power system including photovoltaics (PV), wind power, micro combined heat and power (μCHP), and more exotic concepts such as organic Rankine cycles and hydrogen fuel cells. Thermal storage can perform multiple roles such as enabling the integration of disparate low-carbon energy sources; temporally decoupling the supply and demand for energy and providing a more favourable operating environment for devices such as heat pumps. However, the most useful feature of grid-coupled thermal storage is still its ability to re-shape demand to better match the available supply. At the micro and macro scale, this becomes more important as the production of electricity from stochastic renewable resources such as PV and wind increases significantly. Several authors have looked at the potential benefits of grid coupled thermal storage. For example, Callaway [8] and Wang *et al.* [9] examined the potential for large populations of electrical heating loads to be thermostatically controlled for the purpose of supply matching. Arteconi *et al.* [10] looked at fabric integrated thermal storage in commercial buildings modelling the performance of thermally activated building systems (TABS) and assessing how they could be used to manipulate demand without impacting on comfort. Literature focusing on the domestic sector is rarer and those studies that do look at storage capacities tend to focus on specific cases. For example, both Kelly *et al.* [11] and Arteconi *et al.* [12] quantified buffering requirements for diurnal load shifting for specific system and building types. Hong *et al.* [13] attempted to quantify storage for a range of house types, but the work was focused on heat pumps and assessed a narrow range of operating conditions.

This paper adds to the literature, looking strategically at the housing stock as a whole and quantifying the storage capacity required to store heat over a range of timescales and a variety of building types, conditions and operating contexts.

3 Method

The approach taken to determine possible storage sizes is as follows. A) The ESP-r building simulation tool [14] was used to determine the space heating demand profiles associated with key housing archetypes found in the UK. Corresponding hot water demand profiles were generated using a stochastic model based on the work of Flett [15] B) The combined heat demand profiles were analysed to determine the storage capacity required when storing heat over a range of periods and operating contexts, accounting for losses. C) The calculated storage capacities were converted to storage volumes for four different materials. D) Based on the range of calculated storage volumes, an assessment was made as to the practicality of integrating the different storage options into housing.

The heat storage periods examined were diurnal, weekly, and seasonal (3-months). Diurnal heat storage for a few hours offers the potential for a wide range of short-term functions to enhance the operation of a building's energy system and provide services to the wider electricity network. Storage over longer time scales is technically more onerous but offers additional functionality. For example, weekly storage opens the possibility of using grid-connected heat storage to absorb surplus electricity during periods of high wind speeds and supplying heat when renewable supplies are limited, for example when a winter high-pressure system results in low wind speeds and low temperatures for an extended period of time [16]. Longer-term storage could also improve resilience in buildings allowing them to ride through periods when power might be unavailable. Seasonal thermal storage would be deployed if the goal was to achieve autarkic heating systems operation. At scale, seasonal storage could be employed to limit the huge seasonal variation seen in demand for heat, a variation which would appear in electrical demand if heat was electrified [5]. The potential range of local and network functions that network-coupled domestic thermal storage could provide for increasing storage time scales are illustrated in Table 1.

Table 1: Functionality afforded by different storage time scales.

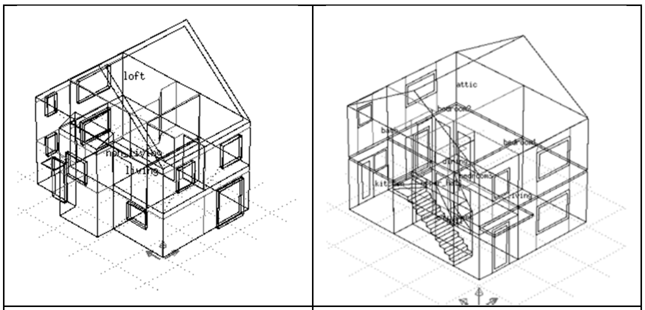
Storage Timescale	Functions
Hourly to diurnal	Local plant capacity reduction, scheduled load shifting - off peak heat demand; reduced grid interaction (connection capacity management); responsive load - peak clipping, opportune charging with renewable energy (e.g. PV, wind at a local and grid scale) for voltage and frequency control.
Diurnal to weekly	Opportune charging with grid and local renewable electricity; renewables "lull" ride-through, e.g. high-pressure system in winter.
Weekly to seasonal	Autarkic zero-carbon heating; seasonal load shifting (grid scale) and opportune charging.

4 Models and simulation

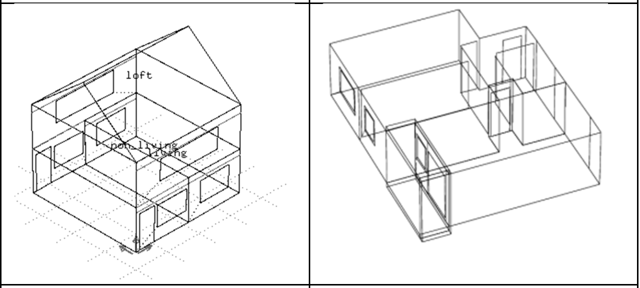
In order to gain a picture of heat storage requirements across the UK housing stock, a set of four building simulation models was employed to calculate typical energy demands under various operating contexts. The four building types were: detached, semi-detached, terraced and a flat; together these constitute some 90% of the UK housing stock [17]. The house types are illustrated in Figure 1. The models of these housing types were developed for the ESP-r building simulation environment [14].

ESP-r allows the energy and environmental performance of the building and its energy systems to be determined over a user defined time interval (e.g a day, a week, a year). The tool explicitly calculates all of the energy and mass transfer processes underpinning building performance. These include: conduction and thermal storage in building materials, convective and radiant heat exchanges (including solar processes), air flows and interaction with plant and control systems. To achieve this, a physical description of the building (materials, constructions, geometry, etc.) is decomposed into a number of 'control volumes'. In this context, a control volume is an arbitrary region of space to which conservation equations for continuity, energy (thermal and electrical) and contaminant species can be applied and one or more characteristic equations formed. A typical building model will contain thousands of such volumes, with sets of equations extracted and grouped according to energy system. The solution of these equation sets with real-time series climate data, coupled with control and occupancy-related boundary conditions yields the dynamic evolution of temperatures, energy exchanges and fluid flows within the building and its supporting systems. The validity of the ESP-r tool is reviewed by Strachan et al. [18].

Each ESP-r model comprises a representation of the building geometry, coupled with explicit representations of the different constructions (Figure 1) internal heat gains and temporal hot water draws, along with space and water heating control requirements. The models can be customised to accommodate variations in the stock: floor area, building materials, insulation levels, air tightness, occupancy, heating system, etc.



Model of typical detached house. | Model of typical terraced house and model.



Model of typical Semi-detached dwelling. | Model of typical suburban flat.

Figure 1: Housing types and geometric details.

In order to quantify the overall heating demand for each dwelling over a range of operating contexts, a total of 64 simulations were run. In each, the performance of a building was simulated over the course of a calendar year for all permutations of the following variants:

- Representative climate for 4 UK climatic regions: NE, NW, SW and SE;
- 2 insulation levels - typical and future; and
- 2 internal gains levels – high and low.

The two insulation levels used within the models (Table 2) represent contemporary building performance, and possible future building performance which is equivalent to the passive house building standard [19]. These models, therefore, span the range of envelope performance characteristics, within which domestic thermal storage could be expected to operate.

Table 2: Construction thermal characteristics.

Construction	Basic U-value (W/m^2K)	Improved U-value (W/m^2K)
External wall	0.45	0.11
Floor	0.6	0.10
Ceiling	0.25	0.13
Glazing	2.94	0.7
Average uncontrolled infiltration	0.5	0.06*

* model features mechanical ventilation heat recovery.

Two levels of internal gains were investigated: a high internal gains case and low internal gains case; these took the form of time varying profiles of occupant, equipment and lighting heat gains. The profiles were derived using a verified, stochastic modelling approach described by Flett and Kelly [20], which is a refined version of the commonly-used profile generation approach developed by Richardson et al [21]. The profile modelling approach used UK time use survey [22] data as the basis for its calibration. Examples high and low gains profiles are shown in Figure 2.

The basic data used for the generation of the profiles was the number of household occupants and their characteristics (i.e. working, family, retired, etc.). The model automatically generates related equipment and lighting profiles based on this information. The occupant characteristics used for each household are shown in Table 3.

Table 3: Summary characteristics of internal gains.

House Type	Gains Level	Number of Occupants	Occupant Characteristics	Mean Appliance Gains (W)	Mean Active Occupancy as % of Day	Mean Hot Water Use (litres/day)
Terrace	Low	1 adult	Part-time employment	160.4	35.8%	51.4
Terrace	High	3 adults	2 x full-time employment + 1 x non-working	503.8	54.0%	125.7
Detached	Low	2 adults/ 2 children	1 x full-time employment + 1 x non-working	272.0	48.2%	50.0
Detached	High	2 adults/ 3 children	1 x full-time + 1 x part-time employment	456.0	55.8%	251.6
Semidetached	Low	1 adult/1 child	Non-working	199.1	45.0%	85.5
Semidetached	High	2 adults	Both retired	582.2	54.8%	146.9
Flat	Low	1 adult	Non-working	115.4	41.2%	42.3
Flat	High	2 adults/1 child	1 x full-time employment + 1 x non-working	228.2	46.2%	82.7

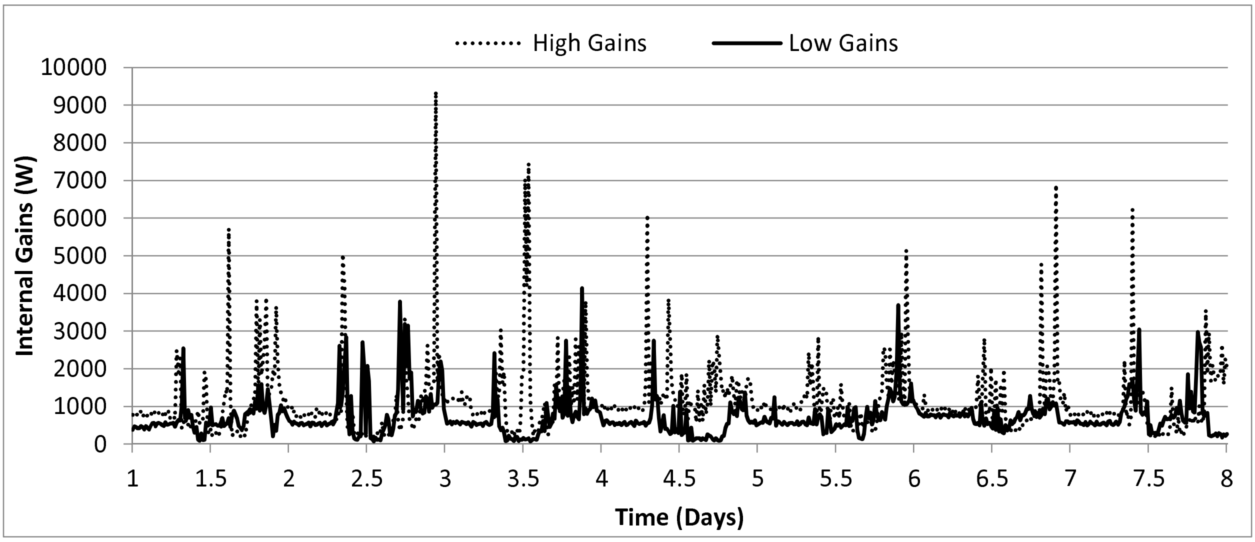


Figure 2: typical week from the high and low gains profiles used with the detached house.

In all simulations, the space heating set point was assumed to be 21°C, and heating followed active occupancy between 07:00 and 23:00 - i.e. space heating was switched on when the house was occupied and the indoor temperature was below the set point and switched off when the house was unoccupied. The exceptions to this rule were if a period of occupancy lasted less than an hour, then the heating would remain off. Similarly, if the space heating was switched off due to lack of active occupancy, then the minimum time within which it could be switched back on again was one hour. The heating system was assumed to be off at night between 23:00 and 07:00.

The ESP-r building simulation tool and all of the models (which includes the occupancy and heat gain profiles) used in this paper are available for download from http://fits-lcd.org.uk.

Each of the 64 simulations provided data on the space heating and hot water demand at 15 minute time intervals for a calendar year (35,040 data points). Note that the spikes in demand correspond to days with larger hot water draws and the obvious low demand period corresponds to a holiday when the house was unoccupied.

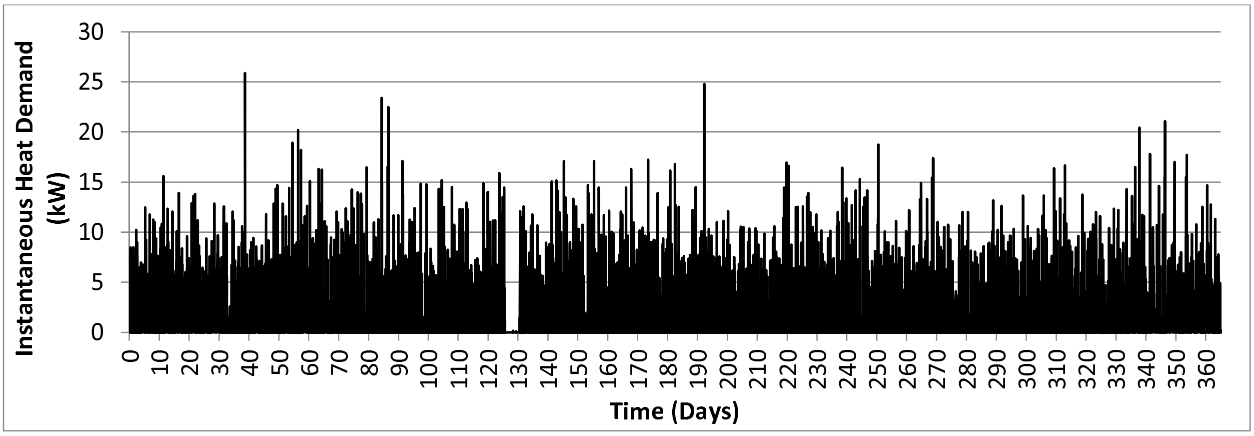


Figure 3: An example of a simulated heat demand profile (space heating + hot water).

4.1 Determining storage size

The storage requirements (in kWh) for each case simulated were determined by scanning each demand profile using a running summation of energy requirements - the sum of the heat demand over the desired storage time period being the calculated storage size. At the end of this scanning process the maximum storage size required over the course of the simulated year was identified from all of the calculated values. This value was then modified to account for 5% assumed thermal loss from the store. A separate analysis was undertaken to assess the insulation requirements for different loss levels from a range of thermal store geometries. This indicated that obtaining loss levels below 5% would require infeasible thicknesses of insulation; a 5% loss rate in itself represents a challenging engineering target.

The maximum storage capacity calculated using this approach was effectively the store size capable of ensuring that space and hot water heating was supplied under all circumstances. To check that these maximum capacities were not data outliers, the computed maximum size was compared to that of the mean store capacity + 3 standard deviations (that encompasses 99.9% of the sample population). In all cases, the difference between both numbers was relatively small.

5 Results

The calculated storage capacities were converted into an indicative storage volume for four materials: hot water, heavy weight concrete, magnetite brick and a phase change material – hydrated sodium hydroxide ($NaOH.H_2O$). The usable temperature ranges were assumed to be 20K [23] for hot water and concrete, and 500K for magnetite brick [24]. The value of latent heat of fusion (h_{fg}) for the hydrated salt was 273 kJ/kg, with a melting temperature of 65.3°C [23]. The key thermal properties are shown in Table 4.

Table 4: Properties of heat storage materials [24, 25].

Material	Density (kg/m^3)	Specific heat (kJ/kgK)	Temperature range (K)
Water	1000.0	4.18	20.0
Heavyweight concrete	2400.0	0.88	20.0
Magnetite brick	3500.0	1.5	500.0
		h_{fg} (kJ/kg)	Melting temp. (°C)
$NaOH.H_2O$	1525.0	273.0	65.3

Note that as the focus of this paper was the thermal storage rather than the balance of plant which services the store, the assumption was made that the energy to charge the store would always be available, either from the network or from local low-carbon generation. Also, note that the only feasible low-carbon heating source for the high temperature store is electricity (if from a low-carbon source). The optimisation of storage accounting for local generation will be analysed in a later paper.

The aggregate energy demands calculated for each building type and for each case simulated are summarised in Table 4, and the computed storage sizes (m^3) are shown in Tables 6a-6c for diurnal, weekly and seasonal storage, respectively.

Table 5: Aggregate annual energy demand (in kWh) for each case simulated.

House type	Fabric insulation	Internal gains	Climatic zone			
			NE	NW	SW	SE
Detached	average	high	10694	10083	9735	9416
		low	9630	9048	8625	8316
	passive house	high	3660	3615	3572	3526
		low	2070	2053	1953	1894
Semi-detached	average	high	8848	8437	8192	7988
		low	6674	6296	5981	5769
	passive house	high	4259	4236	4202	4178
		low	1617	1617	1526	1471
Terraced	average	high	9795	9487	9369	9273
		low	3716	3467	3326	3194
	passive house	high	7333	7324	7326	7323
		low	904	904	866	850
Flat	average	high	7905	7560	7502	7384
		low	4121	3783	3672	3523
	passive house	high	5658	5587	5598	5572
		low	1123	1094	1072	1059

Table 6a: Storage sizes for different heat storage materials for diurnal heat storage.

House type	Fabric insulation.	Int. gain	Climatic zone															
			NE				NW				SW				SE			
			Storage material (m^3)															
			Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$
Detached	average	high	1.896	3.753	0.060	0.381	1.675	3.314	0.053	0.336	1.652	3.270	0.053	0.332	1.869	3.699	0.060	0.375
		low	1.933	3.825	0.062	0.388	1.707	3.378	0.054	0.343	1.912	3.785	0.061	0.384	1.812	3.586	0.058	0.364
	passive house	high	0.663	1.313	0.021	0.133	0.580	1.149	0.018	0.117	0.591	1.170	0.019	0.119	0.646	1.279	0.021	0.130
		low	0.499	0.988	0.016	0.100	0.439	0.868	0.014	0.088	0.442	0.874	0.014	0.089	0.440	0.871	0.014	0.088
Semi-detached	average	high	1.620	3.207	0.052	0.325	1.588	3.144	0.051	0.319	1.422	2.814	0.045	0.285	1.412	2.795	0.045	0.284
		low	1.556	3.080	0.050	0.312	1.343	2.658	0.043	0.270	1.376	2.724	0.044	0.276	1.410	2.790	0.045	0.283
	passive house	high	0.664	1.314	0.021	0.133	0.655	1.296	0.021	0.131	0.655	1.295	0.021	0.131	0.654	1.295	0.021	0.131
		low	0.633	1.253	0.020	0.127	0.633	1.253	0.020	0.127	0.633	1.253	0.020	0.127	0.633	1.252	0.020	0.127
Terraced	average	high	1.467	2.903	0.047	0.295	1.305	2.583	0.042	0.262	1.187	2.349	0.038	0.238	1.223	2.421	0.039	0.246
		low	1.158	2.292	0.037	0.233	1.058	2.094	0.034	0.212	1.067	2.112	0.034	0.214	1.015	2.009	0.032	0.204
	passive house	high	0.937	1.855	0.030	0.188	0.937	1.855	0.030	0.188	0.937	1.855	0.030	0.188	0.937	1.855	0.030	0.188
		low	0.324	0.641	0.010	0.065	0.281	0.556	0.009	0.056	0.271	0.537	0.009	0.054	0.270	0.535	0.009	0.054
Flat	average	high	1.212	2.398	0.039	0.243	1.048	2.075	0.033	0.211	1.187	2.350	0.038	0.238	1.101	2.178	0.035	0.221
		low	0.919	1.819	0.029	0.185	0.871	1.725	0.028	0.175	0.822	1.628	0.026	0.165	0.999	1.978	0.032	0.201
	passive house	high	0.838	1.659	0.027	0.168	0.819	1.621	0.026	0.165	0.844	1.670	0.027	0.169	0.820	1.622	0.026	0.165
		low	0.347	0.687	0.011	0.070	0.347	0.687	0.011	0.070	0.347	0.687	0.011	0.070	0.347	0.687	0.011	0.070

Table 6b: Storage sizes for different heat storage materials for weekly heat storage.

House type	Fabric insulation	Internal gains	Climatic zone															
			NE				NW				SW				SE			
			Storage material (m^3)															
			Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$
Detached	average	high	29.57	58.53	0.94	5.94	26.53	52.50	0.84	5.33	26.52	52.49	0.84	5.33	27.01	53.45	0.86	5.42
		low	28.46	56.33	0.91	5.71	25.80	51.06	0.82	5.18	26.08	51.61	0.83	5.24	26.32	52.10	0.84	5.29
	passive house	high	6.87	13.59	0.22	1.38	7.25	14.35	0.23	1.46	6.28	12.44	0.20	1.26	6.67	13.19	0.21	1.34
		low	5.04	9.98	0.16	1.01	5.53	10.94	0.18	1.11	4.58	9.06	0.15	0.92	4.99	9.87	0.16	1.00
Semi-detached	average	high	20.51	40.59	0.65	4.12	19.22	38.04	0.61	3.86	19.51	38.61	0.62	3.92	20.04	39.66	0.64	4.02
		low	20.75	41.07	0.66	4.17	19.61	38.81	0.62	3.94	19.66	38.91	0.63	3.95	19.04	37.68	0.61	3.82
	passive house	high	6.45	12.77	0.21	1.30	6.71	13.29	0.21	1.35	6.08	12.04	0.19	1.22	6.55	12.97	0.21	1.32
		low	4.75	9.41	0.15	0.95	5.05	9.99	0.16	1.01	4.68	9.27	0.15	0.94	4.56	9.02	0.15	0.92
Terraced	average	high	18.12	35.85	0.58	3.64	17.29	34.21	0.55	3.47	17.39	34.42	0.55	3.49	17.37	34.38	0.55	3.49
		low	11.19	22.14	0.36	2.25	10.67	21.13	0.34	2.14	10.59	20.96	0.34	2.13	11.31	22.39	0.36	2.27
	passive house	high	9.88	19.55	0.31	1.98	9.87	19.54	0.31	1.98	9.87	19.54	0.31	1.98	9.87	19.54	0.31	1.98
		low	2.33	4.61	0.07	0.47	2.28	4.52	0.07	0.46	1.94	3.84	0.06	0.39	2.22	4.39	0.07	0.45
Flat	average	high	15.10	29.89	0.48	3.03	13.06	25.84	0.42	2.62	13.16	26.04	0.42	2.64	14.09	27.88	0.45	2.83
		low	10.81	21.39	0.34	2.17	10.15	20.08	0.32	2.04	10.44	20.66	0.33	2.10	10.97	21.70	0.35	2.20
	passive house	high	7.94	15.72	0.25	1.60	7.60	15.05	0.24	1.53	7.74	15.32	0.25	1.55	7.76	15.36	0.25	1.56
		low	2.17	4.30	0.07	0.44	1.99	3.94	0.06	0.40	1.98	3.92	0.06	0.40	2.39	4.74	0.08	0.48

Table 6c: Storage sizes for different heat storage materials for seasonal heat storage.

House type	Insulation level	Internal gains	Climatic zone															
			NE				NW				SW				SE			
			Storage material (m^3)															
			Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$	Hot water	Concrete	Magnetite	$NaOHH_2O$
Detached	average	high	1783.	3529.	56.8	358.1	1658.	3281.	52.8	333.0	1597.	3162.	50.9	320.8	1559.	3085.	49.6	313.0
		low	1795.	3553.	57.2	360.5	1667.	3300.	53.1	334.9	1604.	3175.	51.1	322.2	1568.	3103.	49.9	314.9
	passive house.	high	313.9	621.2	10.0	63.0	307.9	609.4	9.8	61.8	294.1	582.0	9.4	59.0	284.7	563.5	9.1	57.2
		low	242.6	480.1	7.7	48.7	246.7	488.2	7.9	49.5	218.1	431.6	6.9	43.8	206.3	408.3	6.6	41.4

Semi-detached	average	high	1249.	2472.	39.8	250.9	1163.	2303.	37.1	233.7	1124.	2225.	35.8	225.8	1101.	2180.	35.1	221.2
		low	1253.	2480.	39.9	251.6	1175.	2325.	37.4	236.0	1127.	2231.	35.9	226.4	1102.	2182.	35.1	221.4
	passive house.	high	308.5	610.6	9.8	62.0	311.7	616.9	9.9	62.6	298.4	590.6	9.5	59.9	295.5	584.9	9.4	59.3
		low	230.9	456.9	7.4	46.4	237.9	470.9	7.6	47.8	212.3	420.1	6.8	42.6	199.5	394.9	6.4	40.1
Terraced	average	high	1048.	2075.	33.4	210.6	995.2	1969.	31.7	199.8	962.4	1904.	30.7	193.3	949.8	1879.	30.2	190.7
		low	678.3	1342.	21.6	136.2	631.3	1249.	20.1	126.8	608.4	1204.	19.4	122.2	590.3	1168.	18.8	118.5
	passive house.	high	511.5	1012.	16.3	102.7	509.7	1008.	16.2	102.3	510.1	1009.	16.2	102.4	509.6	1008.	16.2	102.3
		low	87.9	174.0	2.8	17.7	89.9	178.0	2.9	18.1	80.2	158.7	2.6	16.1	77.2	152.7	2.5	15.5
Flat	average	high	843.1	1668.	26.9	169.3	780.4	1544.	24.9	156.7	772.0	1527.	24.6	155.0	764.6	1513.	24.4	153.5
		low	696.7	1378.	22.2	139.9	634.3	1255.	20.2	127.4	618.9	1224.	19.7	124.3	604.2	1195.	19.2	121.3
	passive house.	high	405.4	802.3	12.9	81.4	392.8	777.4	12.5	78.9	391.3	774.5	12.5	78.6	390.1	772.0	12.4	78.3
		low	99.5	196.8	3.2	20.0	92.6	183.2	2.9	18.6	87.4	172.9	2.8	17.5	85.2	168.6	2.7	17.1

6 Discussion and conclusions

As stated, the aim of this paper was to assess the feasibility of different storage concepts for the domestic sector. Consequently, the computed storage volumes were assessed with a view to their integration into buildings. Other factors affecting feasibility such as temperature and losses were also considered.

6.1 Heat demand

The simulated results for the heat demand across the different dwellings and operating contexts are summarised in Table 5 and show a large variation in heating requirements.

The type of dwelling has a significant impact on demand. For example, the detached dwelling in the NE climate, with average insulation levels and low internal gains has an annual heat demand of 9.6 MWh, whereas the equivalent flat has a demand of around 4.1 MWh; this is due to the flat's significantly lower heated volume and external surface area.

Insulation levels have the most pronounced effect on heat demand. For example, the detached dwelling, in an NW climate with low gains with average insulation levels has a demand of about 9 MWh. The same building with passive house insulation levels has a total heat demand of 2.1 MWh. Insulation also lessens the impact of climate, for example, the demand of the detached house with high gains with average insulation levels varies between 10.7 MWh to 9.4 MWh between NE and SE. The range for the building insulated to passive house levels is 3.7 MWh to 3.5 MWh. In the most extreme case, the terraced house insulated to passive house standard with low internal gains has almost no heating load, with the vast majority of the heat demand being for hot water.

In all cases, low gains scenarios have lower heat demands, due to less occupancy and hence less time heated. However it is interesting to note that for the detached and semi-detached models with average insulation, the store sizes sometimes do not reflect this trend. Indeed for these conditions, the store size for low gains is in some cases larger than for high gains, though by a very small margin. This is due to the fact that store sizes are more dependent on peak demand rather than total demand, and is an indication that peak demands between the high and low gains scenarios for these house types are similar. As shown in Table 3, the differences in the number of occupants between the high and low gains scenarios for the terraced house and flat is greater than for the detached and semi-detached, so it makes sense that these should exhibit greater differences in peak demand between gains scenarios.

6.2 Diurnal storage

Table 6a shows the volume of storage required to facilitate diurnal load shifting, whilst meeting all heating and hot water loads. Diurnal storage allows load shifting between periods of more expensive and cheap electricity or captured solar heat being used later in the evening or next morning; typically these uses would require heat being stored for around 6-12 hours. This amount of storage also facilitates responsive demand, allowing interruption of store charging (from the network) or commencement of store charging without impacting on the comfort of the end user. Analysis of the modelling results shows a huge variation in the size of store volume required – varying with the level of heat demand, but more significantly with the form of the store. Focusing solely on the differing heat demands – the detached house with the NE climate, insulated to average levels and low internal gains, requires around 1930 L of hot water storage. By contrast the flat insulated to passive house levels requires approximately 350 L; note that both of these storage volumes are substantial in comparison to standard hot water tanks, which range between 60 and 200 L.

However, variation in storage volume is far more significant when considering the different storage materials and conditions. For example, the terraced dwelling with average insulation levels and low internal gains requires 1158 L of hot water storage for diurnal load shifting, or $2.3m^3$ of concrete, 233 L of phase change material and 0.037 m^3 of magnetite block heated to 600^oC. All of these storage options pose engineering challenges. For the first two options, (water and concrete, $\Delta T=20K$) this would be to find the space to accommodate the volume of material. With phase change material, challenges include encapsulation and rates of heat absorption and recovery; and with the high-temperature store, the challenge is suitable levels of insulation to prevent excessive heat leakage. Heat leakage becomes more of an acute problem when storage is inside a well-insulated dwelling, in this case, the parasitic losses could give rise to overheating.

6.3 Weekly storage

Table 6b shows the volume of store required to facilitate load manipulation over periods of time of up to a week. The results indicate the scale of the engineering challenge associated with storing sufficient heat over this period of time. For example, to supply the heat demands of the detached house, with average insulation levels and low internal gains in the NE climatic region would require around 28,460 L of hot water or $56m^3$ of high density concrete, 5710 L of phase change material or $0.91m^3$ of magnetite block at 600^oC. All of these storage volumes, with the exception of the high-temperature store, would be far too large to accommodate within a dwelling. With the high-temperature store, the key issue would be to keep heat losses to a level such that the stored heat was not lost before it could be utilised.

With reduced heat load through improved insulation and a smaller heated volume, the picture is slightly different. For example, to service the heat load of the flat insulated to passive house levels with low internal gains and located in the NE climatic region for a week would require a store comprising 2170 L of hot water storage or $4.3m^2$ concrete, 440 L of PCM or $0.07m^3$ of high-temperature magnetite block. Whilst these volumes are substantial, they could be accommodated within the footprint of the building, though a water tank greater than 2000 L (plus insulation and balance of plant) would take up a very significant amount of floor area.

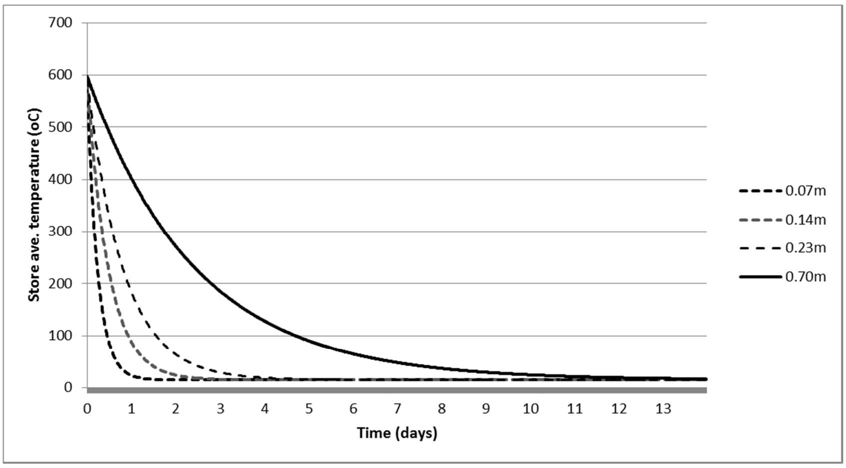


Figure 4: Temperature decay of high temperature thermal store with different insulation thicknesses.

6.4 Seasonal storage

The results for seasonal storage sizes in Table 6c illustrate the immense difficulties in storing large volumes of heat over long time scales. Low temperature (sensible and latent) storage volumes approach or significantly exceed the volume of the host building. High temperature storage volumes are large, but an order of magnitude lower. However, a key problem with high temperature stores is preventing the stored heat dissipating before it could be used. Analysis of a cubic storage geometry undertaken by the authors indicated that even with 600mm+ of ultra-low conductivity insulation and no heat demand from the store, most of the initial heat charge would be lost well within a 1-week period (Figure 4).

6.5 Final remarks

Based on the analysis undertaken for the range of building types and operating conditions, integrated diurnal storage, in the main, is physically practical. Store sizes are a small fraction of the volume of the host building. However, storage integration would not be without its challenges, particularly when considering larger, less well-insulated dwellings. In these cases, the size and mass of low-temperature stores are significant and indicates that insulation improvements would be highly desirable, prior to or in combination with the roll-out of local diurnal heat storage for demand flexibility. Storing heat over longer time scales (weeks - months) is a far less feasible proposition. Low-temperature sensible and latent heat store volumes approach or significantly exceed the volume of the host building and only with very high-temperature heat storage does the storage volume reduce to manageable proportions. However, the challenge with a high-temperature store then becomes minimisation of losses to prevent the vast majority of the heat being lost before it can be used and overheating of the host building. Consequently, if or until robust, ultra-low conductivity insulation materials appear on the market and absorption heat storage evolves beyond laboratory and demonstrator systems, long term thermal storage for housing is really only feasible using ground-coupled heat exchangers and heat pumps.

7 Future work

This paper has assessed the capacity and physical characteristics of a variety of domestic thermal storage options, storing heat for different building types over increasing periods of time. Within the FITS-LCD project, the results will be used to focus effort on those storage options which offer the best potential for fabric-integration (e.g. integrated into the foundation slab, intermediate floor or wall structures). Specifically, options to investigate further include low-temperature diurnal storage systems coupled with improved insulation; and weekly storage for small-passive-house-type dwellings at high temperature or featuring phase change materials.

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