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Research Paper

Assessing domestic heat storage requirements for energy flexibility over varying timescales

John Allison[a], Keith Bell[b], Joe Clarke[a], Andrew Cowie[a], Ahmed Elsayed[c], Graeme Flett[a], Gbemi Oluleye[d], Adam Hawkes[d], Graeme Hawker[b], Nick Kelly[a,*], Maria Manuela Marinho de Castro[e], Tim Sharpe[e], Andy Shea[c], Paul Strachan[a], Paul Tuohy[a]

[a] Energy Systems Research Unit, University of Strathclyde, Glasgow G1 1XJ, UK
[b] Institute for Energy and Environment, University of Strathclyde, Glasgow G1 1XW, UK
[c] BRE Centre for Innovative Construction Materials, University of Bath, BA2 7AY, UK
[d] Sustainable Gas Institute, Imperial College, London SW7 2AZ, UK
[e] Mackintosh Architectural Research Unit, Glasgow School of Art, G3 6RQ, UK

HIGHLIGHTS

- Feasibility of load shifting over diurnal, weekly and seasonal periods assessed.
- Storage capacity for range of load shift periods, house types, occupancy and climates quantified.
- Encapsulated storage volumes for different four materials quantified.
- Thermal storage sizing method and algorithm developed and described.
- Diurnal – weekly load shifts feasible using encapsulated stores, seasonal storage impractical.

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ABSTRACT

This paper explores the feasibility of storing heat in an encapsulated store to support thermal load shifting over three timescales: diurnal, weekly and seasonal. A building simulation tool was used to calculate the space heating and hot water demands for four common UK housing types and a range of operating conditions. A custom sizing methodology calculated the capacities of storage required to fully meet the heat demands over the three timescales. Corresponding storage volumes were calculated for a range of heat storage materials deemed suitable for storing heat within a dwelling, either in a tank or as an integral part of the building fabric: hot water, concrete, high-temperature magnetite blocks, and a phase change material. The results indicate that with low temperature heat storage, domestic load shifting is feasible over a few days. Beyond this timescale, the very large storage volumes required make integration in dwellings problematic. Supporting load shifting over 1–2 weeks is feasible with high temperature storage. Retention of heat over periods longer than this is challenging, even with significant levels of insulation. Seasonal storage of heat in an encapsulated store appeared impractical in all cases modelled due to the volume of material required.

1. Introduction

In the United Kingdom (UK), flexibility in heat demand is seen as a key component of a future energy system in which all the major energy end uses such as heating and transportation are decarbonised [1–3]. The domestic sector accounts for approximately 29% of UK final energy consumption, of which 80% is heating demand [4]. So, any large-scale, decarbonisation needs to include domestic space heating and hot water. In the UK, the electrification of heat and use of decarbonised grid electricity from zero-carbon generation is seen as the most likely pathway to decarbonise domestic heating. However, this could significantly increase electrical demand variability and peak demands [5], potentially requiring significant upgrading of the electrical infrastructure. Thermal storage could help mitigate the more acute impacts of demand growth from electrified heating by decoupling when energy is drawn from the network and when heat is supplied inside a dwelling.

* Corresponding author.
E-mail address: nick@esru.strath.ac.uk (N. Kelly).

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Table 1
Functionality afforded by different heat load shifting time scales.

Shifting timescale	Functions
Diurnal (up to 8-hours)	Local plant capacity reduction, scheduled load shifting - off peak heat demand; reduced grid interaction (connection capacity management); responsive load - peak clipping, diurnal opportune charging with renewable energy (e.g. PV, wind at a local and grid scale) for voltage and frequency control
Weekly (up to 7-days)	Renewables "lull" ride-through, e.g. high-pressure system in winter; medium-term opportune charging with low-carbon grid and local renewable electricity; and medium term heating autonomy
Seasonal (up to 3-months)	Autarkic zero-carbon heating; seasonal load shifting (grid scale) and long-term opportune charging; and long-term heating autonomy

However, a key question is the quantity of storage needed to provide demand flexibility in support of a future low carbon electricity network: this is of importance because dwelling sizes are reducing in the UK [6] and the space penalty associated with conventional thermal storage may act as a barrier to its uptake.

1.1. Aims and contribution

The aim of the paper is to identify the quantity of encapsulated thermal storage required to support domestic heat load shifting over a range of timescales for a variety of key UK housing types, climates, occupancy characteristics and housing conditions. This is done for a range of material types, as future thermal storage may need to migrate away from the traditional hot water tank at seen at present, towards alternative media such as phase-change materials and storage that makes better use of existing space and thermal mass in and around buildings.

The contributions of the paper are as follows. Firstly, it applies state-of-the-art building energy modelling techniques to generate realistic, domestic space heating and hot water demand profiles. Secondly, storage requirements are determined from these profiles using a novel storage sizing methodology for a range of timescales. Finally, the storage volumes required to support heat load shifting are quantified for the different storage materials.

2. Review

The concept of using thermal storage 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 need for flexible demand has become more pressing, as large-scale renewables now account for around 25% of the UK's electricity supply [8] and over 750,000 small, renewable generators including photovoltaics (PV) and small-scale wind power have been installed since 2010 [9]. Grid-coupled thermal storage allows the re-shaping of demand to better match the more variable supply from renewable sources and many authors have studied its performance. For example, Callaway [10] and Wang et al. [11] examined the potential for large populations of resistive heating loads to be thermostatically controlled for supply matching. Arteconi et al. [12] looked at fabric integrated thermal storage in commercial buildings and assessed how it could be used to manipulate demand without adversely affecting comfort. Literature focusing on the domestic sector is rarer and those studies that try to quantify storage requirements or demand flexibility tend to focus on specific cases. Hong et al. [13] attempted to quantify demand flexibility for a range of house types with heat pumps, but no dedicated thermal buffering. Kelly et al. [14] and Arteconi et al. [15] quantified hot water buffering requirements for diurnal domestic load shifting.

3. Method

This paper quantifies the quantity of storage material required to *fully* meet the total heating needs of typical house types over a range of timescales and operating conditions. The approach taken was as follows.

(a) The ESP-r building simulation tool [16] was used to determine the space heating demand profiles associated with key UK housing archetypes. Corresponding hot water demand profiles were generated using a calibrated stochastic model [17].
(b) The combined heat demand profiles were processed to determine the storage capacity (kWh) required when storing heat over a range of time periods and operating contexts, accounting for losses.
(c) The calculated energy storage capacities (kWh) were converted to physical volumes (m^3) and normalised volumes for (m^3/m^2 of heated floor area) for four different storage 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 load shift periods examined were diurnal (up to 8-hours), weekly (up to 7-days), and seasonal (up to 3-months). Diurnal load shifting for a few hours offers the potential for a wide range of short-term functions (Table 1) to enhance the operation of a building's heating system and to provide services to the wider electricity network, if the heating is electrified. Storage for load shifting over longer time scales is physically more onerous but offers some additional functionality, e.g. storage for weekly load shifting offers the possibility of using grid-coupled heat storage to absorb surplus electricity during periods of high wind speeds and supplying heat when low-carbon renewable electricity is not available for an extended period [18]. Storage for seasonal load shifting could be employed to limit the huge variation seen in demand for heat between summer and winter in northern latitudes: a variation which would appear in electrical demand with electrified heating [5].

4. Models and demand simulation

A set of four thermodynamic UK house models[1] were developed for the ESP-r building simulation tool: a detached dwelling, semi-detached dwelling, terraced dwelling and a flat (apartment); these types constitute some 90% of the UK housing stock [19]. The model geometries are illustrated in Fig. 1. ESP-r is a long-established building simulation tool that allows the energy and environmental performance of the building and its energy systems to be calculated over a user-defined time interval (e.g. a day, a year, etc.). The tool explicitly calculates the transient energy and mass transfer processes underpinning building performance. The technical basis of ESP-r is detailed by Clarke [16].

Each model comprises a 3-D building geometry, coupled with explicit details of constructions, internal heat gains and hot water draw profiles, and heating control requirements (set points). These generic models can be customised to accommodate variations in the stock such as insulation levels, air tightness, occupancy, and floor area.

4.1. Quantifying heating demand

To quantify heating demand over a range of conditions, 64 annual

[1] The ESP-r tool and the models used in this paper are available for download from http://fits-lcd.org.uk.

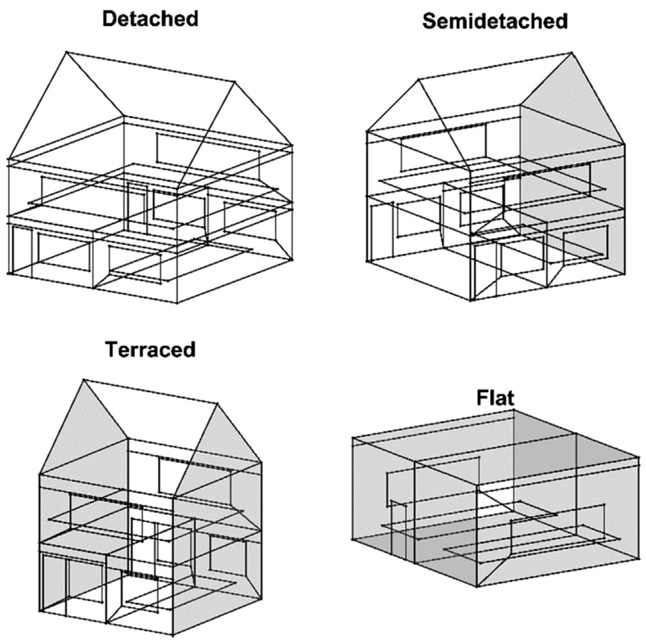

Fig. 1. ESP-r Housing types models (shaded surfaces represent those bounded by another dwelling).

Table 2
basic dwelling geometrical data.

	Floor area (m^2)	Heated volume (m^3)
Detached	136	286
Semi-detached	87	186
Terraced	57	142
Flat	56	140

Table 3
Construction thermal characteristics [19,21].

Construction	Basic U-value ($W/m^2\,K$)	Improved U-value ($W/m^2\,K$)
External wall	0.45	0.11
Floor	0.6	0.10
Ceiling	0.25	0.13
Glazing	2.94	0.7
Average uncontrolled infiltration (air changes per hour)	0.5	0.06[a]

[a] This model features mechanical ventilation heat recovery – the figure is therefore an energy equivalent air change rate for heat exchanger with 90% effectiveness.

simulations were run for all permutations of the following model variants: 4 UK climatic regions: North East (NE), North West (NW), South West (SW) and South East (SE); 2 insulation levels - typical and future; and 2 occupancy levels – high and low. Climate, occupancy and insulation have been shown to have the most significant impact on heat demand [20], and the modelled variants therefore provide a broad range of conditions within which domestic thermal storage could be expected to operate in future.

For each case simulated and at each time interval over the simulated period, ESP-r calculates the heat required to maintain the desired set point temperature in the dwelling. This is modelled as a heat flux input into the heat balance of each heated space in a dwelling model. The heating system and its effects are therefore modelled generically, rather than explicitly modelling a specific system type.

4.1.1. House types

The geometries of the dwelling models are shown in Fig. 1 and basic geometric data is given in Table 2.

4.1.2. Insulation

The two fabric insulation levels represent contemporary and future building performance, which is equivalent to the Passive House building standard [21]. The thermal characteristics are summarised in Table 3.

4.1.3. Occupancy

High and low occupancy cases were generated for each model using a profiling tool described by Flett and Kelly [22], which builds on the profile generation method developed by Richardson et al. [23]. This tool uses correlations derived from the UK Time Use Survey [24] and other datasets to generate time varying occupancy, hot water demand and electrical demand profiles, and corresponding heat gain profiles, which were then integrated with the building models. The various occupancy-dependent profiles generated are summarised in Table 4, with an example heat gain profile shown in Fig. 2.

4.1.4. Climate

The four climate datasets used in this study characterise the UK's basic climatic regions (Fig. 3). Each dataset holds hourly values of direct and diffuse solar radiation (W/m^2), wind speed (m/s), wind direction (°), air temperature (°C) and relative humidity (%).

4.1.5. Simulations

Using ESP-r, the heating and hot water demands of each house variant were calculated for a one-year period at 15-min time intervals. The space heating control set point was assumed to be 21 °C, typical of that seen in UK housing [25], with heating following occupancy between 07:00 and 23:00. Example output is shown in Fig. 4.

The calculated space heating demand is the energy required over

Table 4
Summary characteristics of occupancy and internal gains.

House type	Occupancy 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

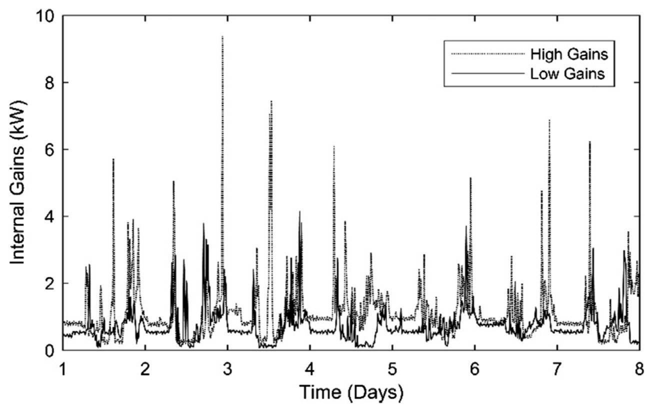

Fig. 2. typical 1-week period of high and low occupancy gain profiles.

Fig. 3. basic UK climatic regions.

each time interval to bring the heated space air point temperature up to the set point temperature. This is dependent on a range of factors including external climate, heat gains from occupants and equipment, infiltration solar penetration into the building and heat transfer and storage in the building fabric. A full description of the process for the calculation of heat demands in ESP-r is provided by Clarke [16]. The calculation process for hot water profiles is detailed by Flett and Kelly [22].

4.2. Determining storage capacity

The required storage capacities (in kWh) to support load shifting were determined as follows. Firstly, a heat demand matrix was constructed with the simulated domestic profiles, where each column holds

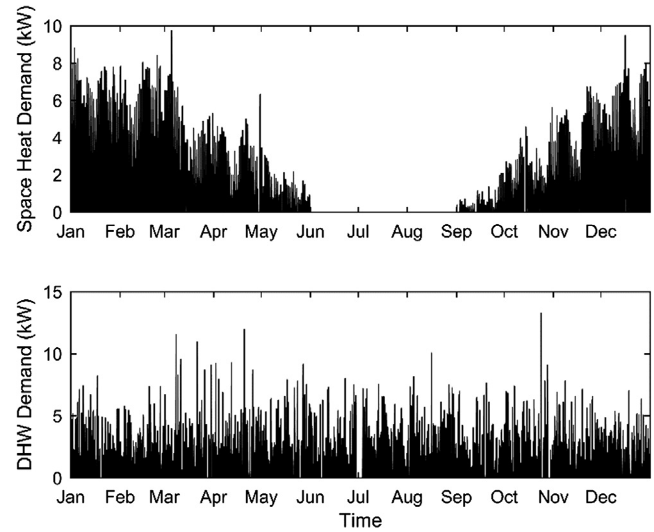

Fig. 4. simulated space heating and hot water demand profiles.

Table 5
Desired load shift period and data segmentation.

Period	Segments
Diurnal	1095
Weekly	52
Seasonal	4

all the thermal demand values from an annual simulation:

$$\boldsymbol{P}_{\text{dem}} = (P_{\text{dem},ij}) \in \mathbb{R}^{n_{\text{ts}} \times n_{\text{var}}} \tag{1}$$

Here, $P_{\text{dem},ij}$ is the heat demand of building j at time-step i, n_{var} is the number of simulated cases and n_{ts} is the total number of time-steps in the simulation. Each profile holds 35,040 (8769 × 4) demand values and there were 64 modelled cases. Consequently, $P_{\text{dem}} \in \mathbb{R}^{35040\times 64}$.

The heat demand data from each building simulation was then reshaped into equal segments (Table 5) corresponding to the desired load shift period.

To check if the data could be divided into equal segments, the following logical variable was defined

$$\breve{b}_{\text{even}}: =\text{mod}(n_{\text{ts}},n_{\text{seg}}) = 0, \tag{2}$$

where mod(·) is the modulo operation[2] (remainder after division) and n_{seg} is the number of segments from Table 5. Subsequently, the thermal demand vector for a single dwelling as $\boldsymbol{p}_{\text{dem},j}: =\text{col}_j \boldsymbol{P}_{\text{dem}}$. For $\breve{b}_{\text{even}} = 1$ (i.e. even segments) was defined and the demand data reshaped as

$$\hat{\boldsymbol{P}}_{\text{dem},j} \in \mathbb{R}^{n_{\text{ts,seg}} \times n_{\text{seg}}} = \text{reshape}(\boldsymbol{p}_{\text{dem},j},[n_{\text{ts,seg}},n_{\text{seg}}]), \tag{3}$$

where reshape(·) is the reshaping array function and $n_{\text{ts,seg}} = (31536000/n_{\text{seg}})/t_s$ is the number of time steps in each segment. When $\breve{b}_{\text{even}} = 0$ excess time steps from the end of the vector were removed so that all segments are even.

An energy balance was enforced for each time period to determine the amount of energy the store would need to supply during each segment. Consider the demand from a single building j during one time-segment q, $\boldsymbol{p}_{\text{dem},j,q}: =\text{col}_q \hat{\boldsymbol{P}}_{\text{dem},j}$. The continuous time energy balance is given by

$$\frac{\mathrm{d}P_{\text{tes}}(t)}{\mathrm{d}t} = P_{\text{gen}}(t) - P_{\text{dem}}(t) - P_{\text{losses}}(t), \tag{4}$$

[2] This function can be expressed as $b = \text{mod}(a,m) = a - m\lfloor a/m \rfloor$.

Table 6
Total annual heat demand (space heating and hot water) for each case simulated.

House type	Fabric insulation	Occupancy	Climatic zone			
			NE	NW	SW	SE
			Total annual heat demand (kWh)			
Detached	Average	High	10,694	10,083	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

where P_{gen} is any heat input to the store, P_{dem} is the thermal demand on the store, and P_{losses} are the energy losses from the store. To use the profiles generated from the simulations, the energy balance was expressed in discrete time as

$$\frac{P_{tes}[k+1]-P_{tes}[k]}{t_s} = P_{gen}[k]-P_{dem}[k]-P_{losses}[k], \tag{5}$$

where k is the k-th time step of the simulation. It was assumed that there was no heat input to the store, so the store would have to be large enough supply the entire demand for each time segment i.e. $P_{gen}[k] = 0, \forall k$.

$$E_{tes}[k]-E_{tes}[k+1] = E_{dem}[k] + E_{losses}[k]. \tag{6}$$

The amount of energy required in the store is then

$$Q_{tes}[k] = E_{tes}[k]-E_{tes}[k+1] = E_{dem}[k] + E_{losses}[k]. \tag{7}$$

The required size of store for each q-th time segment is then the sum of all elements in the segment:

$$Q_{tes,q} = \sum_{k=1}^{n_{ts,seg}} E_{dem}[k] + \sum_{k=1}^{n_{ts,seg}} E_{losses}[k] \tag{8}$$

It is now possible to determine the maximum required storage capacity by taking the maximum value from all time segments i.e.

$$Q_{tes} = \max(Q_{tes,q})q = 1,...,n_{seg}. \tag{9}$$

where Q_{tes} is the maximum storage capacity (kWh). The storage capacity calculated using this approach ensures that space and hot water heating demand are be met under *all* circumstances during the period considered.

The storage capacity is a function of the (currently unknown) losses at each time step. Therefore, the algorithm first calculates the required size of store for each q-th time segment with no losses as

$$Q^{*}_{tes,q} = \sum_{k=1}^{n_{ts,seg}} E_{dem}[k] \tag{10}$$

where $Q^{*}_{tes,q}$ is the storage capacity required to ensure that thermal demands are fulfilled during the time segment q for a perfectly insulated thermal store. The losses over a period are then

$$E_{losses,24h} = f_{losses} Q^{*}_{tes,q} \tag{11}$$

where f_{losses} is the fraction of capacity lost from the store over a period.

A separate storage heat loss analysis was undertaken by the authors indicating that a worst-case loss rate of around 5%/day was appropriate for the materials and storage geometries considered.

The losses at each time step k are then

$$E_{losses}[k] = \left(\frac{365}{n_{seg} n_{ts,seg}}\right) E_{losses,24h} \tag{12}$$

Substituting Eqs. (10)–(12) into (8) and rearranging gives

$$Q_{tes,q} = \left(1 + \left(\frac{365}{n_{seg} n_{ts,seg}}\right) f_{losses}\right) \sum_{k=1}^{n_{ts,seg}} E_{dem}[k]. \tag{13}$$

5. Modelling results

5.1. Heat demands

The aggregate heat demands (for space heating and hot water) calculated for each building type and for each case simulated are summarised in Table 6.

5.1.1. Verification

ESP-r has been extensively validated along with other with regards to its ability to predict building heating and cooling loads. These validation efforts are summarised by Strachan et al. [26]. Flett and Kelly [22] detail the calibration and validation of the process for calculation of occupancy dependent profiles.

Focusing on the predicted heat demands for this study, verification against specific housing demand figures is not practicable as the models are generic archetypes. However, the predicted demands for the dwellings with average insulation given in Table 6 can be compared to figures from the UK Office for Gas and Electricity Markets (OFGEM), who provide ranges for UK domestic gas demands [27].

The ESP-r space and hot water heating predictions (for the contemporary dwellings) can be converted to an equivalent gas consumption, assuming that 96% of domestic gas consumption is for space heating and hot water [4] and that a typical gas heating and hot water system efficiency is 75% [28]. Fig. 5 contrasts the annual gas demand predictions from the ESP-r models with the OFGEM's high and low median demands.

The simulation results from the average dwelling models produce gas consumptions slightly lower than the median values provided by OFGEM; this would be expected, as the OFGEM figures include many older and less energy efficient properties. It can be concluded that the ESP-r average models used here produce heat demand estimates that are broadly representative of those seen in contemporary or improved UK housing.

5.2. Storage capacities

Energy storage capacities (kWh) required to support load shifting were calculated using the approach described in Section 4.2 for each case simulated and for the three storage durations (diurnal weekly and seasonal). Note that these capacities assume the worst-case scenario – where the heat load is *fully* met by the store with no additional heat input. This provides a prudent estimate of the store size, capable of meeting the heat demand under all circumstances. Additional heat input from local zero-carbon sources could potentially reduce the size of store required but may not always be available.

Table 7 shows that the computed thermal storage capacities vary by up to three orders of magnitude. For example, the flat in the SE climate with passive house insulation levels and low occupancy requires 8 kWh for diurnal storage, whilst the detached house with average insulation levels in a NE climate with high occupancy levels would require over

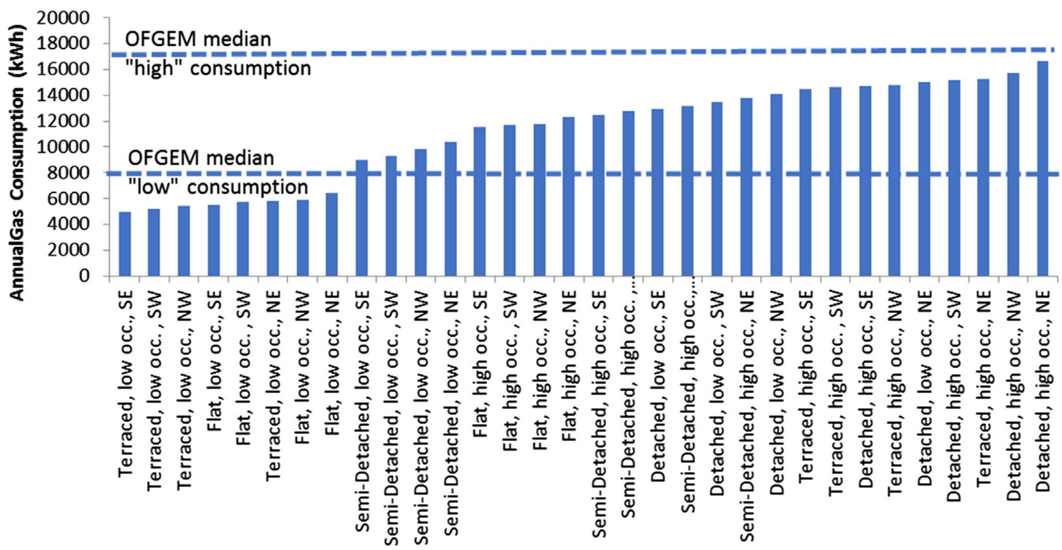

Fig. 5. simulated annual domestic gas demands and OFGEM high and low median gas demand values.

Table 7
Calculated storage capacities (kWh).

House type	Insulation level	Occupancy	NE Diurnal	NE Weekly	NE Seasonal	NW Diurnal	NW Weekly	NW Seasonal	SW Diurnal	SW Weekly	SW Seasonal	SE Diurnal	SE Weekly	SE Seasonal
Detached	Average	High	44	687	41,405	39	616	38,502	38	616	37,086	43	627	36,203
		Low	45	661	41,684	40	599	38,711	44	606	37,248	42	611	36,412
	Passive	High	15	160	7289	13	168	7150	14	146	6830	15	155	6611
		Low	12	117	5634	10	128	5729	10	106	5065	10	116	4791
Semi-detached	Average	High	38	476	29,005	37	446	27,007	33	453	26,102	33	465	25,568
		Low	36	482	29,097	31	455	27,286	32	457	26,171	33	442	25,591
	Passive	High	15	150	7164	15	156	7238	15	141	6930	15	152	6862
		Low	15	110	5362	15	117	5525	15	109	4930	15	106	4633
Terraced	Average	High	34	421	24,337	30	402	23,111	28	404	22,349	28	403	22,056
		Low	27	260	15,752	25	248	14,660	25	246	14,128	24	263	13,708
	Passive	High	22	229	11,878	22	229	11,836	22	229	11,846	22	229	11,834
		Low	8	54	2041	7	53	2088	6	45	1862	6	52	1793
Flat	Average	High	28	351	19,579	24	303	18,123	28	306	17,928	26	327	17,756
		Low	21	251	16,179	20	236	14,730	19	242	14,372	23	255	14,031
	Passive	High	19	184	9414	19	176	9122	20	180	9087	19	180	9059
		Low	8	50	2311	8	46	2150	8	46	2030	8	56	1979

41 MWh for seasonal heat storage.

Corresponding storage volumes were calculated for the four storage materials: hot water, heavy weight concrete, magnetite brick and an organic phase change material, Paraffin (C_{28}). This materials selection is not intended to be comprehensive, but to provide contrasting examples of the volumes required to store the heat energy indicated in Table 7.

The usable temperature ranges for the materials were assumed to be 20 °C for hot water (70–50 °C) and concrete (50–30 °C) [29], and 500 °C for magnetite brick (600–100 °C) [29]. The value of latent heat of fusion (h_{fg}) for the paraffin was taken as 253 kJ/kg, with a melting temperature of 61.6 °C [30] (see Table 8).

The storage volume was calculated as follows, where V is the volume (m^3) and c is the specific heat (kJ/kgK) and ρ is the material density (kg/m^3):

$$V_{tes,q} = \frac{3600.\ Q_{tes,q}}{\rho c \Delta T} \quad \text{(sensible heat)} \quad \text{Or } V_{tes,q} = \frac{3600.\ Q_{tes,q}}{h_{fg}} \quad \text{(latent heat)} \tag{14}$$

As the heating system is not explicitly modelled in this study, it is assumed that a particular store would be matched to an appropriate heat source and working fluid e.g. high temperature storage would typically be combined with air cooling and a predominantly convective heating system.

The storage volumes (m^3) are shown in Tables 9a–9c for diurnal, weekly and seasonal storage, respectively.

Table 8
Properties of heat storage materials [29,30].

Material	Density (kg/m^3)	Specific heat c (kJ/kg K)	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)
Paraffin (C_{28})	900.0 (solid)	253.0	61.6

Table 9a
Storage volumes (m^3) for different materials to support diurnal heat load shifting.

House type	Fabricinsulation.	Occupancy	Climatic region															
			NE				NW				SW				SE			
			Storage material															
			Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin
Detached	Average	High	1.896	3.753	0.06	0.411	1.675	3.314	0.053	0.363	1.652	3.27	0.053	0.358	1.869	3.699	0.06	0.405
		Low	1.933	3.825	0.062	0.419	1.707	3.378	0.054	0.370	1.912	3.785	0.061	0.414	1.812	3.586	0.058	0.393
	Passive	High	0.663	1.313	0.021	0.144	0.58	1.149	0.018	0.126	0.591	1.17	0.019	0.128	0.646	1.279	0.021	0.140
		Low	0.499	0.988	0.016	0.108	0.439	0.868	0.014	0.095	0.442	0.874	0.014	0.096	0.44	0.871	0.014	0.095
Semi-detached	Average	High	1.62	3.207	0.052	0.351	1.588	3.144	0.051	0.344	1.422	2.814	0.045	0.308	1.412	2.795	0.045	0.306
		Low	1.556	3.08	0.05	0.337	1.343	2.658	0.043	0.291	1.376	2.724	0.044	0.298	1.41	2.79	0.045	0.305
	Passive	High	0.664	1.314	0.021	0.144	0.655	1.296	0.021	0.141	0.655	1.295	0.021	0.141	0.654	1.295	0.021	0.141
		Low	0.633	1.253	0.02	0.137	0.633	1.253	0.02	0.137	0.633	1.253	0.02	0.137	0.633	1.252	0.02	0.137
Terraced	Average	High	1.467	2.903	0.047	0.318	1.305	2.583	0.042	0.283	1.187	2.349	0.038	0.257	1.223	2.421	0.039	0.265
		Low	1.158	2.292	0.037	0.251	1.058	2.094	0.034	0.229	1.067	2.112	0.034	0.231	1.015	2.009	0.032	0.220
	Passive	High	0.937	1.855	0.03	0.203	0.937	1.855	0.03	0.203	0.937	1.855	0.03	0.203	0.937	1.855	0.03	0.203
		Low	0.324	0.641	0.01	0.070	0.281	0.556	0.009	0.060	0.271	0.537	0.009	0.058	0.27	0.535	0.009	0.058
Flat	Average	High	1.212	2.398	0.039	0.262	1.048	2.075	0.033	0.228	1.187	2.35	0.038	0.257	1.101	2.178	0.035	0.238
		Low	0.919	1.819	0.029	0.200	0.871	1.725	0.028	0.189	0.822	1.628	0.026	0.178	0.999	1.978	0.032	0.217
	Passive	High	0.838	1.659	0.027	0.181	0.819	1.621	0.026	0.178	0.844	1.67	0.027	0.182	0.82	1.622	0.026	0.178
		Low	0.347	0.687	0.011	0.076	0.347	0.687	0.011	0.076	0.347	0.687	0.011	0.076	0.347	0.687	0.011	0.076

Table 9b
Storage volumes (m^3) for different materials to support weekly heat load shifting.

House type	Fabric insulation	Internal gains	Climatic zone															
			NE				NW				SW				SE			
			Storage material															
			Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin
Detached	Average	High	29.57	58.53	0.94	6.410	26.53	52.5	0.84	5.751	26.52	52.49	0.84	5.751	27.01	53.45	0.86	5.848
		Low	28.46	56.33	0.91	6.161	25.8	51.06	0.82	5.589	26.08	51.61	0.83	5.654	26.32	52.1	0.84	5.708
	Passive	High	6.87	13.59	0.22	1.489	7.25	14.35	0.23	1.575	6.28	12.44	0.2	1.360	6.67	13.19	0.21	1.446
		Low	5.04	9.98	0.16	1.090	5.53	10.94	0.18	1.198	4.58	9.06	0.15	0.993	4.99	9.87	0.16	1.079
Semi-detached	Average	High	20.51	40.59	0.65	4.446	19.22	38.04	0.61	4.165	19.51	38.61	0.62	4.230	20.04	39.66	0.64	4.338
		Low	20.75	41.07	0.66	4.500	19.61	38.81	0.62	4.251	19.66	38.91	0.63	4.262	19.04	37.68	0.61	4.122
	Passive	High	6.45	12.77	0.21	1.403	6.71	13.29	0.21	1.457	6.08	12.04	0.19	1.316	6.55	12.97	0.21	1.424
		Low	4.75	9.41	0.15	1.025	5.05	9.99	0.16	1.090	4.68	9.27	0.15	1.014	4.56	9.02	0.15	0.993
Terraced	Average	High	18.12	35.85	0.58	3.928	17.29	34.21	0.55	3.744	17.39	34.42	0.55	3.766	17.37	34.38	0.55	3.766
		Low	11.19	22.14	0.36	2.428	10.67	21.13	0.34	2.309	10.59	20.96	0.34	2.298	11.31	22.39	0.36	2.449
	Passive	High	9.88	19.55	0.31	2.137	9.87	19.54	0.31	2.137	9.87	19.54	0.31	2.137	9.87	19.54	0.31	2.137
		Low	2.33	4.61	0.07	0.507	2.28	4.52	0.07	0.496	1.94	3.84	0.06	0.421	2.22	4.39	0.07	0.486
Flat	Average	High	15.1	29.89	0.48	3.270	13.06	25.84	0.42	2.827	13.16	26.04	0.42	2.849	14.09	27.88	0.45	3.054
		Low	10.81	21.39	0.34	2.342	10.15	20.08	0.32	2.201	10.44	20.66	0.33	2.266	10.97	21.7	0.35	2.374
	Passive	High	7.94	15.72	0.25	1.726	7.6	15.05	0.24	1.651	7.74	15.32	0.25	1.673	7.76	15.36	0.25	1.683
		Low	2.17	4.3	0.07	0.475	1.99	3.94	0.06	0.432	1.98	3.92	0.06	0.432	2.39	4.74	0.08	0.518

Table 9c
Storage volumes (m^3) for different materials to support seasonal heat load shifting.

House type	Fabric insulation	Internal gains	Climatic zone															
			NE				NW				SW				SE			
			Storage material (m^3)															
			Hot Water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin	Hot water	Concrete	Magnetite	Paraffin
Detached	Average	High	1783	3529	56.8	386.4	1658	3281	52.8	359.3	1597	3162	50.9	346.2	1559	3085	49.6	337.7
		Low	1795	3553	57.2	389	1667	3300	53.1	361.4	1604	3175	51.1	347.7	1568	3103	49.9	339.8
	Passive	High	313.9	621.2	10	68	307.9	609.4	9.8	66.7	294.1	582	9.4	63.7	284.7	563.5	9.1	61.7
		Low	242.6	480.1	7.7	52.5	246.7	488.2	7.9	53.4	218.1	431.6	6.9	47.3	206.3	408.3	6.6	44.7
Semi-detached	Average	High	1249	2472	39.8	270.7	1163	2303	37.1	252.2	1124	2225	35.8	243.6	1101	2180	35.1	238.7
		Low	1253	2480	39.9	271.5	1175	2325	37.4	254.7	1127	2231	35.9	244.3	1102	2182	35.1	238.9
	Passive	High	308.5	610.6	9.8	66.9	311.7	616.9	9.9	67.5	298.4	590.6	9.5	64.6	295.5	584.9	9.4	64
		Low	230.9	456.9	7.4	50.1	237.9	470.9	7.6	51.6	212.3	420.1	6.8	46	199.5	394.9	6.4	43.3
Terraced	Average	High	1048	2075	33.4	227.2	995.2	1969	31.7	215.6	962.4	1904	30.7	208.6	949.8	1879	30.2	205.8
		Low	678.3	1342	21.6	147	631.3	1249	20.1	136.8	608.4	1204	19.4	131.9	590.3	1168	18.8	127.9
	Passive	High	511.5	1012	16.3	110.8	509.7	1008	16.2	110.4	510.1	1009	16.2	110.5	509.6	1008	16.2	110.4
		Low	87.9	174	2.8	19.1	89.9	178	2.9	19.5	80.2	158.7	2.6	17.4	77.2	152.7	2.5	16.7
Flat	Average	High	843.1	1668	26.9	182.7	780.4	1544	24.9	169.1	772	1527	24.6	167.3	764.6	1513	24.4	165.6
		Low	696.7	1378	22.2	151	634.3	1255	20.2	137.5	618.9	1224	19.7	134.1	604.2	1195	19.2	130.9
	Passive	High	405.4	802.3	12.9	87.8	392.8	777.4	12.5	85.1	391.3	774.5	12.5	84.8	390.1	772	12.4	84.5
		Low	99.5	196.8	3.2	21.6	92.6	183.2	2.9	20.1	87.4	172.9	2.8	18.9	85.2	168.6	2.7	18.5

6. Discussion

6.1. Heat demand

The results for the heat demand across the different dwellings show very significant variations, with occupancy and insulation levels having the most pronounced effect. For example, the terraced dwelling with average insulation levels in a NE climate gas a heat demand of 3.7 MWh in the low occupancy case rising to 9.8 MWh with higher occupancy; the detached dwelling, in an NW climate with low gains with average insulation levels has a total heat demand of about 9 MWh. The same building with passive house insulation levels has a total heat demand of 2.1 MWh. In the most extreme case, the terraced house insulated to passive house standard with low occupancy has almost no space heating load, with most of the heat demand being for hot water.

The strong linkage between demand and household occupancy could cause potential problems in storage systems design. For example, higher levels of occupancy than anticipated could result in a thermal store failing to provide enough heat due to higher levels of demand than the store was sized for. Conversely, thermal storage could be over sized if occupancy and demand were less than anticipated.

6.2. Diurnal storage

Table 9a shows the volume of storage required to facilitate diurnal load shifting, with the store alone meeting all heating and hot water loads, typically this would require heat being stored for up to 8-hours. The variation in storage volume is most pronounced when considering the different storage materials and temperatures. For example, the terraced dwelling in a NE climate, with average insulation levels and low occupancy requires 1158 L of hot water storage for diurnal load shifting, or 2.3 m^3 of concrete, 251 L of phase change material (PCM) and 0.037 m^3 of magnetite block heated to around 600 °C. All these storage options pose challenges. For the first two options, (water and concrete, $\Delta T = 20$ °C) it could be problematic be to find the space to accommodate the volume of material. With PCM, challenges include achieving sufficient rates of heat absorption and recovery; and with the high-temperature store, the challenge is providing sufficient levels of insulation to prevent excessive heat leakage which could cause overheating in the dwelling.

For illustration purposes, Fig. 6a shows the different storage materials (represented as a cube) scaled against the host dwelling for the smallest and largest computed volumes – typically associated with the SE climate + passive house insulation + low occupancy or the NE climate + average insulation + high occupancy, respectively.

6.3. Weekly storage

Table 9b shows the volume of store required to facilitate load shifting for up to a week, with the store meeting all the heat demand. 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 56 m^3 of high density concrete, 6160 L of phase change material or 0.91 m^3 of magnetite block at 600 °C. With reduced heat load through improved insulation and a smaller heated volume, the picture is slightly different: 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 4.3 m^2 concrete, 475 L of PCM or 0.07 m^3 of high-temperature magnetite block. Whilst substantial, these latter volumes could feasibly be accommodated within the footprint of a dwelling.

Fig. 6b shows smallest and largest storage sizes scaled against the host dwelling for weekly storage.

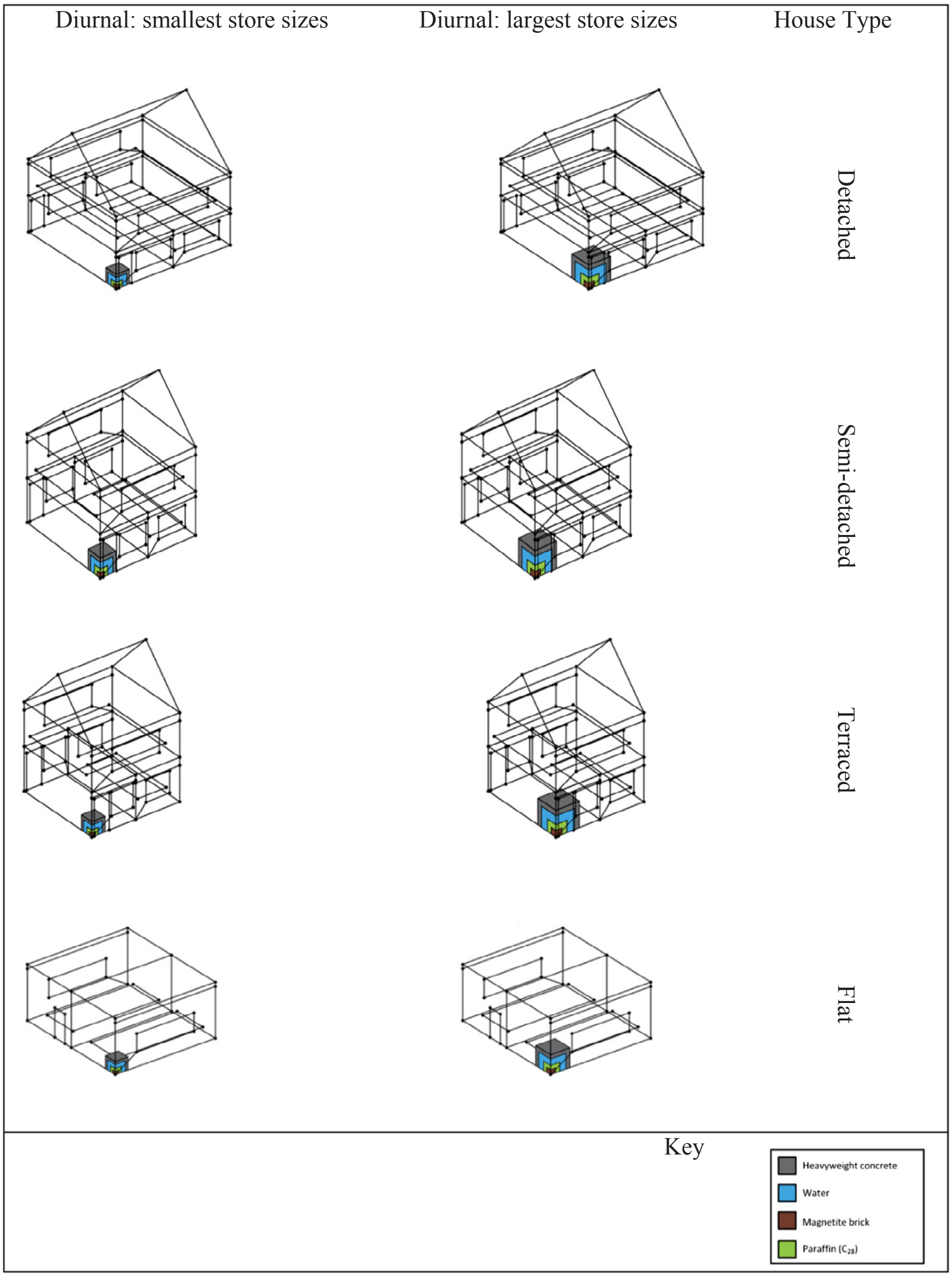

Fig. 6a. scaled illustration of the best and worst case diurnal store sizes contrasted to the dwelling size.

6.4. Seasonal storage

The results for seasonal storage sizes in Table 9c and Fig. 6c illustrate that with low storage temperatures, sensible or latent storage volumes approach or significantly exceed the volume of the host building in all cases. High temperature storage volumes are an order of magnitude lower and could potentially be housed inside the building volume. However, a sensitivity analysis indicated that even with up to 300 mm of low conductivity (0.03 W/m K) insulation around the store and no heat draws, much of the initial heat charge would be lost within two weeks (Fig. 7), this illustrates the inefficiency of high temperature storage over long durations.

6.5. Normalised storage volumes

Storage volumes, normalised against the heated floor area of the different dwelling types (shown in Table 10) illustrate that the storage material type, storage temperature and duration of the load shift have by far the largest influence on the physical quantity of storage required. For example, to support load shifting over a diurnal period in concrete at low temperatures (c. 50 °C) required between 0.006 and 0.05 m^3 of material per m^2 of heated floor area. By contrast between 0.0001 and 0.0008 m^3 of magnetite at high temperature (c.500 °C) per m^2 of heated floor area was required. To support seasonal load shifting, between 2.7 and 36.4 m^3 of low-temperature concrete per m^2 of heated floor area

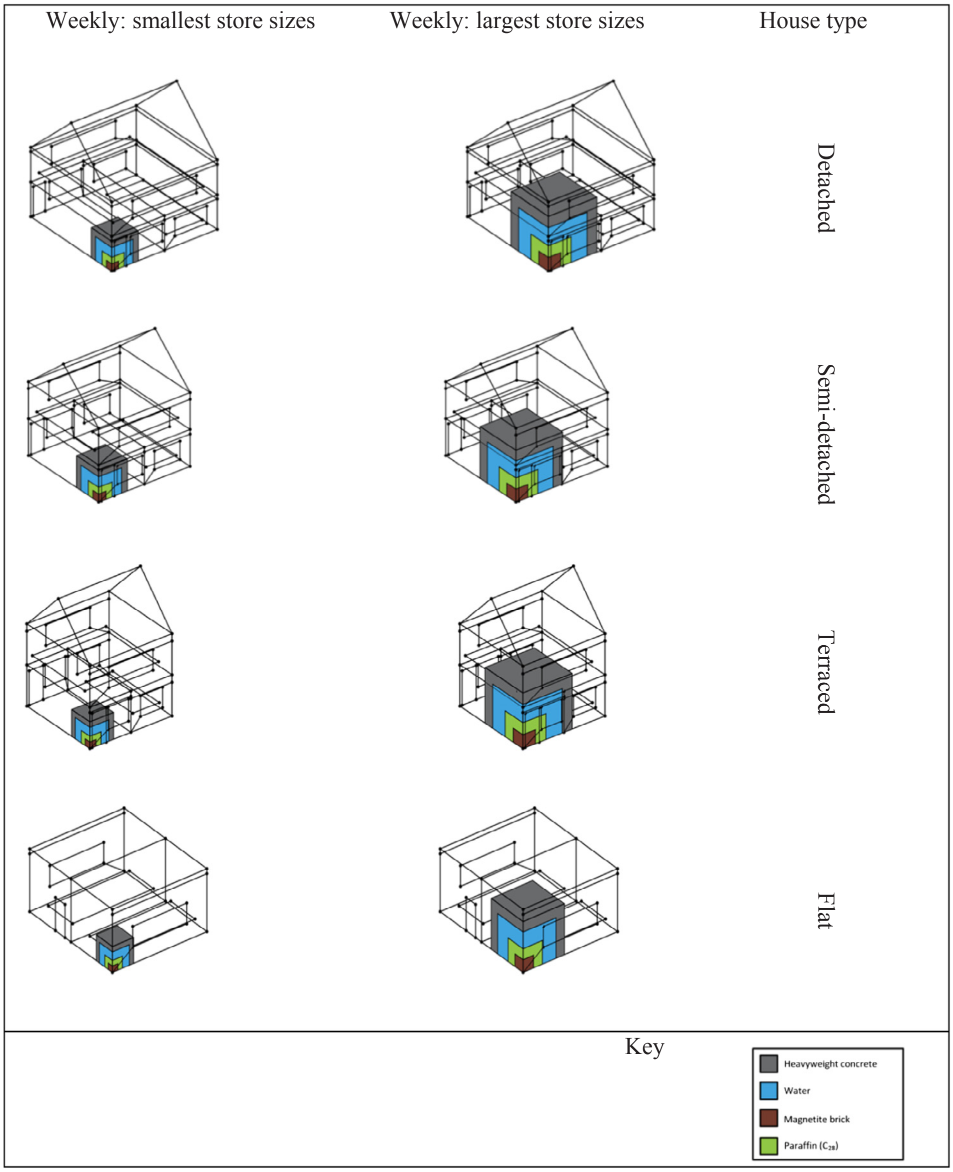

Fig. 6b. scaled illustration of the best and worst case weekly store sizes contrasted to the dwelling size.

was required and between 0.044 and 0.59 m^3 of high-temperature magnetite per m^2 of heated floor area was required. These numbers show that there is significant variability, even in the normalised values of storage for the same material type; this indicates that floor area is only one of a number of determinants for the volume of heat storage material required for load shifting. Occupancy, climate and insulation levels also have a major influence. Indeed, for dwellings insulated to passive house standard, occupancy and by extension, hot water use, become more influential on storage requirements than space heating and floor area.

7. Conclusions and final remarks

Simulation models of four key UK house types have been presented. These enable the dynamic thermal demand (heating and hot water) of each house to be quantified over a range of different operating conditions. Occupancy and insulation levels were key determinants of heat demand and consequently storage requirements.

A heat storage sizing methodology has also been presented, which enables storage sizes to be computed for any simulated space heating and hot water demand profile over any load-shifting timescale.

The models and sizing methodology were used to determine the storage capacities (kWh) required to support load shifting in each simulation. The storage volumes (m^3) were then computed for four contrasting heat storage materials – low temperature hot water, concrete, a phase change material and high temperature magnetite brick. Absolute storage volumes varied widely and were primarily dictated by the storage material, storage temperature and the timescale over which heat needs to be load-shifted. Storage volumes normalised by heated floor area were also calculated, indicating that floor area was not the

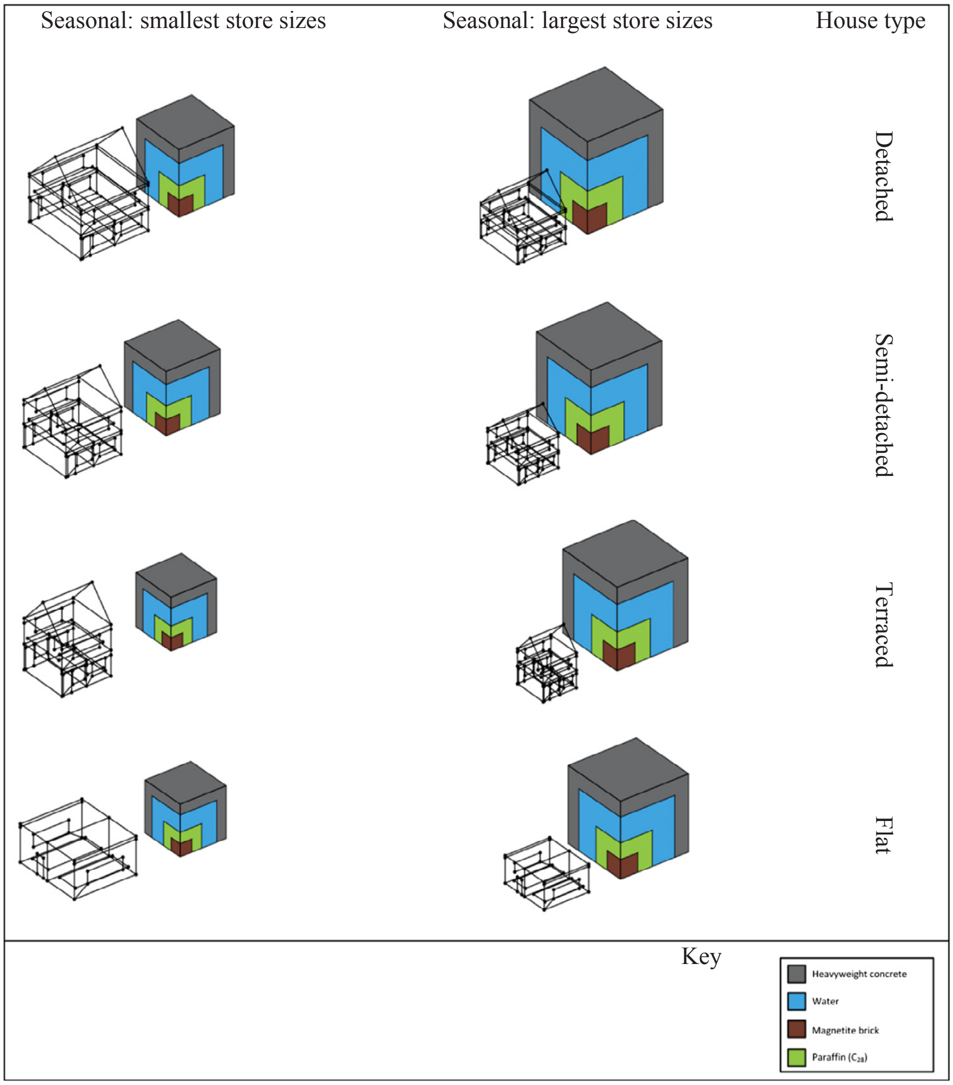

Fig. 6c. scaled illustration of the best and worst case seasonal store sizes contrasted to the dwelling size.

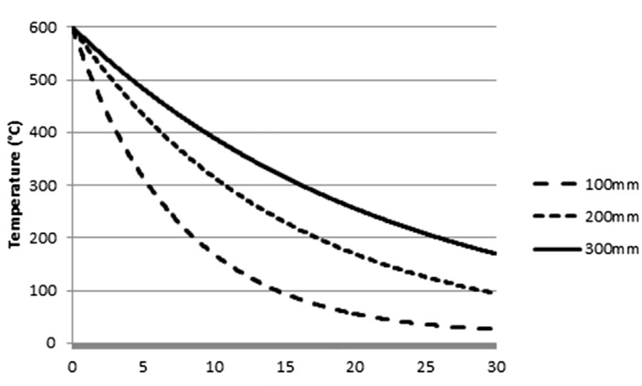

Fig. 7. Temperature decay of a high temperature store due to losses only with different insulation thicknesses.

sole determinant of required storage volume: occupancy and insulation levels were also influential parameters.

Fabric-integrated storage over shorter, diurnal timescales was (in the main) physically practical, as store volumes for all the material types assessed were a small fraction of that of the host building size. However, extensive demand reduction would be highly desirable, to minimise store sizes.

High-temperature heat storage could feasibly be used to store heat over time scales up to 1–2 weeks, with store sizes that could be integrated into the host building, but beyond this timescale the majority of the stored the heat would be lost to the environment even with significant insulation thickness. Weekly storage could also be feasible at lower temperatures, but only for small, well insulated dwellings with small heat demands.

Storing heat with encapsulated, low temperature heat stores, over seasonal timescales appears infeasible as storage volumes approach or significantly exceed that of the host building.

Consequently, if or until robust, ultra-low conductivity insulation materials appear on the market or technologies such as absorption heat storage evolves beyond laboratory and demonstrator systems [31], long term, seasonal thermal storage for housing only appears feasible using ground-coupled heat exchangers and heat pumps.

Table 10
Normalised storage volumes - expressed in m^3 per m^2 of heated floor area to support load shifting.

Storage period	House type	Fabric insulation	Occupancy	UK Climatic region							
				NE	NW	SW	SE	NE	NW	SW	SE
				Storage material m^3 per m^2 of floor area							
				Concrete				Hot Water			
Diurnal	Detached	Average	High	2.76E−02	2.44E−02	2.40E−02	2.72E−02	1.39E−02	1.23E−02	1.21E−02	1.37E−02
			Low	2.81E−02	2.48E−02	2.78E−02	2.64E−02	1.42E−02	1.26E−02	1.41E−02	1.33E−02
		Passive	High	9.65E−03	8.45E−03	8.60E−03	9.40E−03	4.88E−03	4.26E−03	4.35E−03	4.75E−03
			Low	7.26E−03	6.38E−03	6.43E−03	6.40E−03	3.67E−03	3.23E−03	3.25E−03	3.24E−03
	Semi-detached	Average	High	3.69E−02	3.61E−02	3.23E−02	3.21E−02	1.86E−02	1.83E−02	1.63E−02	1.62E−02
			Low	3.54E−02	3.06E−02	3.13E−02	3.21E−02	1.79E−02	1.54E−02	1.58E−02	1.62E−02
		Passive	High	1.51E−02	1.49E−02	1.49E−02	1.49E−02	7.63E−03	7.53E−03	7.53E−03	7.52E−03
			Low	1.44E−02	1.44E−02	1.44E−02	1.44E−02	7.28E−03	7.28E−03	7.28E−03	7.28E−03
	Terraced	Average	High	5.09E−02	4.53E−02	4.12E−02	4.25E−02	2.57E−02	2.29E−02	2.08E−02	2.15E−02
			Low	4.02E−02	3.67E−02	3.71E−02	3.52E−02	2.03E−02	1.86E−02	1.87E−02	1.78E−02
		Passive	High	3.25E−02	3.25E−02	3.25E−02	3.25E−02	1.64E−02	1.64E−02	1.64E−02	1.64E−02
			Low	1.12E−02	9.75E−03	9.42E−03	9.39E−03	5.68E−03	4.93E−03	4.75E−03	4.74E−03
	Flat	Average	High	4.28E−02	3.71E−02	4.20E−02	3.89E−02	2.16E−02	1.87E−02	2.12E−02	1.97E−02
			Low	3.25E−02	3.08E−02	2.91E−02	3.53E−02	1.64E−02	1.56E−02	1.47E−02	1.78E−02
		Passive	High	2.96E−02	2.89E−02	2.98E−02	2.90E−02	1.50E−02	1.46E−02	1.51E−02	1.46E−02
			Low	1.23E−02	1.23E−02	1.23E−02	1.23E−02	6.20E−03	6.20E−03	6.20E−03	6.20E−03
Weekly	Detached	Average	High	4.30E−01	3.86E−01	3.86E−01	3.93E−01	2.17E−01	1.95E−01	1.95E−01	1.99E−01
			Low	4.14E−01	3.75E−01	3.79E−01	3.83E−01	2.09E−01	1.90E−01	1.92E−01	1.94E−01
		Passive	High	9.99E−02	1.06E−01	9.15E−02	9.70E−02	5.05E−02	5.33E−02	4.62E−02	4.90E−02
			Low	7.34E−02	8.04E−02	6.66E−02	7.26E−02	3.71E−02	4.07E−02	3.37E−02	3.67E−02
	Semi-detached	Average	High	4.67E−01	4.37E−01	4.44E−01	4.56E−01	2.36E−01	2.21E−01	2.24E−01	2.30E−01
			Low	4.72E−01	4.46E−01	4.47E−01	4.33E−01	2.39E−01	2.25E−01	2.26E−01	2.19E−01
		Passive	High	1.47E−01	1.53E−01	1.38E−01	1.49E−01	7.41E−02	7.71E−02	6.99E−02	7.53E−02
			Low	1.08E−01	1.15E−01	1.07E−01	1.04E−01	5.46E−02	5.80E−02	5.38E−02	5.24E−02
	Terraced	Average	High	6.29E−01	6.00E−01	6.04E−01	6.03E−01	3.18E−01	3.03E−01	3.05E−01	3.05E−01
			Low	3.88E−01	3.71E−01	3.68E−01	3.93E−01	1.96E−01	1.87E−01	1.86E−01	1.98E−01
		Passive	High	3.43E−01	3.43E−01	3.43E−01	3.43E−01	1.73E−01	1.73E−01	1.73E−01	1.73E−01
			Low	8.09E−02	7.93E−02	6.74E−02	7.70E−02	4.09E−02	4.00E−02	3.40E−02	3.89E−02
	Flat	Average	High	5.34E−01	4.61E−01	4.65E−01	4.98E−01	2.70E−01	2.33E−01	2.35E−01	2.52E−01
			Low	3.82E−01	3.59E−01	3.69E−01	3.88E−01	1.93E−01	1.81E−01	1.86E−01	1.96E−01
		Passive	High	2.81E−01	2.69E−01	2.74E−01	2.74E−01	1.42E−01	1.36E−01	1.38E−01	1.39E−01
			Low	7.68E−02	7.04E−02	7.00E−02	8.46E−02	3.88E−02	3.55E−02	3.54E−02	4.27E−02

(*continued on next page*)

Table 10 (*continued*)

Storage period	House type	Fabric insulation	Occupancy	UK Climatic region							
				NE	NW	SW	SE	NE	NW	SW	SE
				Storage material m^3 per m^2 of floor area							
				Concrete				Hot Water			
Seasonal	Detached	Average	High	2.59E+01	2.41E+01	2.33E+01	2.27E+01	1.31E+01	1.22E+01	1.17E+01	1.15E+01
			Low	2.61E+01	2.43E+01	2.33E+01	2.28E+01	1.32E+01	1.23E+01	1.18E+01	1.15E+01
		Passive	High	4.57E+00	4.48E+00	4.28E+00	4.14E+00	2.31E+00	2.26E+00	2.16E+00	2.09E+00
			Low	3.53E+00	3.59E+00	3.17E+00	3.00E+00	1.78E+00	1.81E+00	1.60E+00	1.52E+00
	Semi-detached	Average	High	2.84E+01	2.65E+01	2.56E+01	2.51E+01	1.44E+01	1.34E+01	1.29E+01	1.27E+01
			Low	2.85E+01	2.67E+01	2.56E+01	2.51E+01	1.44E+01	1.35E+01	1.30E+01	1.27E+01
		Passive	High	7.02E+00	7.09E+00	6.79E+00	6.72E+00	3.55E+00	3.58E+00	3.43E+00	3.40E+00
			Low	5.25E+00	5.41E+00	4.83E+00	4.54E+00	2.65E+00	2.73E+00	2.44E+00	2.29E+00
	Terraced	Average	High	3.64E+01	3.45E+01	3.34E+01	3.30E+01	1.84E+01	1.75E+01	1.69E+01	1.67E+01
			Low	2.35E+01	2.19E+01	2.11E+01	2.05E+01	1.19E+01	1.11E+01	1.07E+01	1.04E+01
		Passive	High	1.78E+01	1.77E+01	1.77E+01	1.77E+01	8.97E+00	8.94E+00	8.95E+00	8.94E+00
			Low	3.05E+00	3.12E+00	2.78E+00	2.68E+00	1.54E+00	1.58E+00	1.41E+00	1.35E+00
	Flat	Average	High	2.98E+01	2.76E+01	2.73E+01	2.70E+01	1.51E+01	1.39E+01	1.38E+01	1.37E+01
			Low	2.46E+01	2.24E+01	2.19E+01	2.13E+01	1.24E+01	1.13E+01	1.11E+01	1.08E+01
		Passive	High	1.43E+01	1.39E+01	1.38E+01	1.38E+01	7.24E+00	7.01E+00	6.99E+00	6.97E+00
			Low	3.51E+00	3.27E+00	3.09E+00	3.01E+00	1.78E+00	1.65E+00	1.56E+00	1.52E+00

Storage period	House type	Fabric insulation	UK Climatic region							
			NE	NW	SW	SE	NE	NW	SW	SE
			Storage material m^3 per m^2 of floor area							
			Paraffin				Magnetite			
Diurnal	Detached	Average	3.02E−03	2.67E−03	2.63E−03	2.98E−03	4.41E−04	3.90E−04	3.90E−04	4.41E−04
			3.08E−03	2.72E−03	3.04E−03	2.89E−03	4.56E−04	3.97E−04	4.49E−04	4.26E−04
		Passive	1.06E−03	9.26E−04	9.41E−04	1.03E−03	1.54E−04	1.32E−04	1.40E−04	1.54E−04
			7.94E−04	6.99E−04	7.06E−04	6.99E−04	1.18E−04	1.03E−04	1.03E−04	1.03E−04
	Semi-detached	Average	4.03E−03	3.95E−03	3.54E−03	3.52E−03	5.98E−04	5.86E−04	5.17E−04	5.17E−04
			3.87E−03	3.34E−03	3.43E−03	3.51E−03	5.75E−04	4.94E−04	5.06E−04	5.17E−04
		Passive	1.66E−03	1.62E−03	1.62E−03	1.62E−03	2.41E−04	2.41E−04	2.41E−04	2.41E−04
			1.57E−03	1.57E−03	1.57E−03	1.57E−03	2.30E−04	2.30E−04	2.30E−04	2.30E−04
	Terraced	Average	5.58E−03	4.96E−03	4.51E−03	4.65E−03	8.25E−04	7.37E−04	6.67E−04	6.84E−04
			4.40E−03	4.02E−03	4.05E−03	3.86E−03	6.49E−04	5.96E−04	5.96E−04	5.61E−04
		Passive	3.56E−03	3.56E−03	3.56E−03	3.56E−03	5.26E−04	5.26E−04	5.26E−04	5.26E−04
			1.23E−03	1.05E−03	1.02E−03	1.02E−03	1.75E−04	1.58E−04	1.58E−04	1.58E−04
	Flat	Average	4.68E−03	4.07E−03	4.59E−03	4.25E−03	6.96E−04	5.89E−04	6.79E−04	6.25E−04
			3.57E−03	3.38E−03	3.18E−03	3.88E−03	5.18E−04	5.00E−04	4.64E−04	5.71E−04
		Passive	3.23E−03	3.18E−03	3.25E−03	3.18E−03	4.82E−04	4.64E−04	4.82E−04	4.64E−04
			1.36E−03	1.36E−03	1.36E−03	1.36E−03	1.96E−04	1.96E−04	1.96E−04	1.96E−04

(*continued on next page*)

Table 10 (*continued*)

Storage period	House type	Fabric insulation	UK Climatic region							
			NE	NW	SW	SE	NE	NW	SW	SE
			Storage material m^3 per m^2 of floor area							
			Paraffin				Magnetite			
Weekly	Detached	Average	4.71E−02	4.23E−02	4.23E−02	4.30E−02	6.91E−03	6.18E−03	6.18E−03	6.32E−03
			4.53E−02	4.11E−02	4.16E−02	4.20E−02	6.69E−03	6.03E−03	6.10E−03	6.18E−03
		Passive	1.09E−02	1.16E−02	1.00E−02	1.06E−02	1.62E−03	1.69E−03	1.47E−03	1.54E−03
			8.01E−03	8.81E−03	7.30E−03	7.93E−03	1.18E−03	1.32E−03	1.10E−03	1.18E−03
	Semi-detached	Average	5.11E−02	4.79E−02	4.86E−02	4.99E−02	7.47E−03	7.01E−03	7.13E−03	7.36E−03
			5.17E−02	4.89E−02	4.90E−02	4.74E−02	7.59E−03	7.13E−03	7.24E−03	7.01E−03
		Passive	1.61E−02	1.67E−02	1.51E−02	1.64E−02	2.41E−03	2.41E−03	2.18E−03	2.41E−03
			1.18E−02	1.25E−02	1.17E−02	1.14E−02	1.72E−03	1.84E−03	1.72E−03	1.72E−03
	Terraced	Average	6.89E−02	6.57E−02	6.61E−02	6.61E−02	1.02E−02	9.65E−03	9.65E−03	9.65E−03
			4.26E−02	4.05E−02	4.03E−02	4.30E−02	6.32E−03	5.96E−03	5.96E−03	6.32E−03
		Passive	3.75E−02	3.75E−02	3.75E−02	3.75E−02	5.44E−03	5.44E−03	5.44E−03	5.44E−03
			8.89E−03	8.70E−03	7.39E−03	8.53E−03	1.23E−03	1.23E−03	1.05E−03	1.23E−03
	Flat	Average	5.84E−02	5.05E−02	5.09E−02	5.45E−02	8.57E−03	7.50E−03	7.50E−03	8.04E−03
			4.18E−02	3.93E−02	4.05E−02	4.24E−02	6.07E−03	5.71E−03	5.89E−03	6.25E−03
		Passive	3.08E−02	2.95E−02	2.99E−02	3.01E−02	4.46E−03	4.29E−03	4.46E−03	4.46E−03
			8.48E−03	7.71E−03	7.71E−03	9.25E−03	1.25E−03	1.07E−03	1.07E−03	1.43E−03
Seasonal	Detached	Average	2.84E+00	2.64E+00	2.55E+00	2.48E+00	4.18E−01	3.88E−01	3.74E−01	3.65E−01
			2.86E+00	2.66E+00	2.56E+00	2.50E+00	4.21E−01	3.90E−01	3.76E−01	3.67E−01
		Passive	5.00E−01	4.90E−01	4.68E−01	4.54E−01	7.35E−02	7.21E−02	6.91E−02	6.69E−02
			3.86E−01	3.93E−01	3.48E−01	3.29E−01	5.66E−02	5.81E−02	5.07E−02	4.85E−02
	Semi-detached	Average	3.11E+00	2.90E+00	2.80E+00	2.74E+00	4.57E−01	4.26E−01	4.11E−01	4.03E−01
			3.12E+00	2.93E+00	2.81E+00	2.75E+00	4.59E−01	4.30E−01	4.13E−01	4.03E−01
		Passive	7.69E−01	7.76E−01	7.43E−01	7.36E−01	1.13E−01	1.14E−01	1.09E−01	1.08E−01
			5.76E−01	5.93E−01	5.29E−01	4.98E−01	8.51E−02	8.74E−02	7.82E−02	7.36E−02
	Terraced	Average	3.99E+00	3.78E+00	3.66E+00	3.61E+00	5.86E−01	5.56E−01	5.39E−01	5.30E−01
			2.58E+00	2.40E+00	2.31E+00	2.24E+00	3.79E−01	3.53E−01	3.40E−01	3.30E−01
		Passive	1.94E+00	1.94E+00	1.94E+00	1.94E+00	2.86E−01	2.84E−01	2.84E−01	2.84E−01
			3.35E−01	3.42E−01	3.05E−01	2.93E−01	4.91E−02	5.09E−02	4.56E−02	4.39E−02
	Flat	Average	3.26E+00	3.02E+00	2.99E+00	2.96E+00	4.80E−01	4.45E−01	4.39E−01	4.36E−01
			2.70E+00	2.46E+00	2.39E+00	2.34E+00	3.96E−01	3.61E−01	3.52E−01	3.43E−01
		Passive	1.57E+00	1.52E+00	1.51E+00	1.51E+00	2.30E−01	2.23E−01	2.23E−01	2.21E−01
			3.86E−01	3.59E−01	3.38E−01	3.30E−01	5.71E−02	5.18E−02	5.00E−02	4.82E−02

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