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Building-level energy storage: reducing consumer bills to deliver zero-emissions heat

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Executive summary

This report examines the extent to which building-level energy storage technologies could help to reduce household energy costs when installed alongside zero-carbon heat technologies. We also present results from a simulation exercise to determine the cost effectiveness of electric batteries, heat batteries and thermal storage installed alongside heat pumps.

Decarbonising heat in buildings is likely to involve widespread electrification of heat (for example, through the use of heat pumps). This will require additional flexibility within the electricity grid. Enabling energy storage is one way of creating flexibility as it allows for the decoupling of consumption from generation. Storage will be required at both grid-scale and building-level in order to store electricity over a range of timescales.

The findings within this report show that currently there is little commercial benefit to the householder installing storage without localised electricity generation. However, the potential role of domestic storage in smoothing peak demand periods on the grid indicates that building-level storage will be required to support the decarbonisation of heat through electrification.

Key findings

The findings in this report are based on an evidence review, interviews with stakeholders and the development of a simulation tool. The findings relate to the cost savings which can be achieved through the installation of electric batteries, heat batteries, and thermal storage when installed alongside heat pumps.

How storage technologies can reduce energy costs

- The research explains how bill savings can be made by pairing storage technologies with self-generation, and by storing off-peak electricity for later use.

- In addition to storing cheap or free electricity, electric batteries can export electricity to the grid and provide grid balancing services[1]. This is an additional source of revenue for consumers which cannot be provided by heat batteries or thermal storage.
- It is not feasible or recommended to use thermal storage to fully shift heat pump operation to off-peak periods. This is due to the size of thermal store required, and the likelihood of increasing consumer bills.
- Pairing phase change material (PCM) heat batteries with heat pumps will result in lower efficiencies due to the required flow temperature being above 55^{o}C.

Availability of evidence

- Due to limited evidence, it is not possible to draw wide-reaching conclusions on the potential role of storage technologies in reducing consumer bills. There is limited monitoring data or evidence of cost savings for consumers across all storage types reviewed. However, more evidence is available for electric batteries than heat batteries and thermal storage.
- Although domestic thermal storage is fairly ubiquitous, we found no monitoring data or case studies for thermal storage paired with a heat pump.
- Due to this lack of quantitative evidence, we have used case studies to illustrate some of the potential ways in which storage technologies have been used to reduce consumer bills. However, the conclusions and comparisons we can draw from these case studies is limited.
- The simulation tool provides the opportunity to model the savings that can be achieved for each storage technology by altering the variables of tariff type, property size, and electrical and heat demand.
- The simulated scenarios across different property archetypes and demand profiles show that without pairing storage with electrical generation the return on investment is usually longer than the expected lifespan of the technology. In certain scenarios where the return would be within the lifespan, there would be limiting factors such as space requirements. This corresponds with the findings from the evidence review and stakeholder interviews.

Quantifying bill savings

- The case studies illustrate that, in some instances, bill savings have been achieved, and also instances where householders' bills have increased.
- Case study 1 demonstrates that pairing electric batteries with a solar photovoltaic (PV) system resulted in average savings per household between £44 and £67[2].
- Case study 2 illustrates that using electric batteries with off-peak electricity tariffs resulted in estimated annual savings of between £208 and £436, dependent on tariff type. However, the savings of £436 were short-lived as these were based on a dynamic time-of-use (ToU) tariff[3] which subsequently increased. Tenants' bills then increased to higher than their bills prior to the battery installation.
- Case study 5 illustrates a huge range in heating bills as a result of the installation of heat batteries with heat pumps (replacing solid fuel heating). The impact on

[1] Grid balancing services are mechanisms used to help match supply and demand and support provision of a secure and reliable energy supply

[2] Annual figures have been extrapolated based on the average household savings from case study 1 of £37.06 and £55.80 over a 10-month period.

[3] See Table 3 for explanation of tariff types

bills ranged between a £326 increase to a £360 saving across four households. The main reason for this range is the different types of tariffs being used. Householders made savings if they were able to switch to a dual rate tariff. One householder could not access a dual rate tariff and their bills increased as a result of switching from solid fuel heating to a heat pump with a heat battery.
- Where savings have been achieved in the case studies, they represent significant bill savings for those in fuel poverty.

Trade-offs, risks and sensitivities

- Where savings have been achieved, the savings figures are a small proportion of the current capital costs of most storage technologies. In most cases, the financial savings will not cover the cost of installing storage technologies; additional grant funding will be required.
- The instances where householder bills have increased illustrate the risks of relying solely on off-peak electricity without self-generation.
- Due to the volatility of dynamic tariffs, it can be difficult to predict bill savings for consumers. Dynamic tariff prices track the wholesale electricity price and there is a risk that consumer bills may increase. The use of static tariffs provides more predictable savings. However, the potential for bill savings is lower due to the lower price differential between peak and off-peak electricity rates.
- We found evidence of difficulties accessing ToU tariffs due to metering arrangements. This occurred in households unable to get a smart meter or with double Meter Point Administration Number (MPAN) setups (two electricity meters, such as dynamic teleswitch meters). Without microgeneration or the ability to switch to a dual rate or smart ToU tariff, the installed batteries in these instances were redundant.
- Where housing providers install storage technologies and rely on electricity tariffs to provide cheap electricity there is a risk of tenants inadvertently switching away from a ToU tariff and on to a standard (not flexible) tariff. This could negate bill savings.
- The case studies provide examples of some of the sensitivities to error when pairing storage solely with tariffs. A small error in Case study 5 caused a heat battery to charge for one hour a day at peak prices. This error would have cost an estimated £125 over a year.

Mitigations

- Pairing storage technologies with microgeneration such as solar PV can go some way to mitigating the risks associated with relying solely on off-peak electricity tariffs. For this reason, several electric battery installers noted that they would not recommend installing a battery without onsite generation.
- However, the use of solar PV does not guarantee that bill savings will be significant enough to recoup investment in storage technologies.
- Recent research published by Solar Energy UK[4] concluded that currently the additional cost of installing a battery with a solar PV system outweighs the savings enabled through storing surplus generation.
- The cost of installing electric batteries can also be partially offset through the provision of grid services. The current financial benefit for consumers of providing

[4] Solar Energy UK (2021) The Value of Solar Property

grid services is around £50 per year, although it can be up to £120 per year. This is significant in the context of anticipated total savings from battery use. However, some grid service contracts limit this annual income to two or three years.

Recommendations

As a result of our findings, we recommend that:

- Once published, the monitoring results from ongoing projects with building-level storage should be reviewed for evidence of financial savings for consumers. This includes the UK Department for Business, Energy and Industrial Strategy (BEIS) electrification of heat pilot, OVO Energy's trial with Powervault[5] and various Scottish Government funded projects[6].
- Ensure the Distribution Network Operators (DNOs) in their transition to District Systems Operators (DSO) actively provide support for local and national flexibility markets by engaging with aggregators when planning for the increased future demand on the grid.
- Where feasible, installers and property owners should be encouraged to pair thermal storage with heat pumps. Although there is limited evidence of the direct financial savings that this can provide for consumers, the benefits of improved system efficiencies, heat pump longevity and the ability to ease pressure on the grid during peak periods will provide indirect financial benefits.
- Grant funding or some form of financial incentive may be necessary to encourage the installation of thermal storage with heat pumps.
- Further research is conducted to understand what the identified savings from existing and ongoing research might mean for rates of fuel poverty.

[5] Ovo Energy Ovo Smart Home (last accessed 29 Nov 2021)
[6] For example, Changeworks are conducting M&E for the LCITP funded project in Moray and two Decarbonisation Fund projects in Edinburgh and Midlothian

Contents

1 Introduction

The Scottish Government has ambitious climate change and fuel poverty targets. Achieving net-zero emissions by 2045[7] while ensuring no more than 5% of Scottish households are in fuel poverty by 2040[8] will both require affordable domestic heating for consumers. The deployment of electric heating systems, such as heat pumps and resistive heating, in the absence of fabric measures risks increasing household energy costs. As outlined in the Heat in Buildings Strategy[9], there is a role for storage technologies such as electric batteries, thermal water stores or heat batteries to reduce the cost of heat for consumers transitioning to electrically-fuelled heating technologies.

This report examines the extent to which building-level storage technologies could help reduce household energy costs when installed alongside zero-carbon heat technologies. The report explores the implications of using storage in combination with secondary technologies such as solar photovoltaic (PV) systems. Time-of-use (ToU) tariffs could also present opportunities to reduce household energy bills; this research examines whether there is evidence of this in practice.

An overview of electric batteries, heat batteries and thermal storage is provided in Section 1. The report then presents evidence for how these storage technologies can reduce consumer bills. Due to a lack of comparable in-situ performance data, we use case studies to illustrate how energy storage technologies can reduce costs for consumers.

Section 6 presents results from a simulation exercise to determine the cost effectiveness of electric batteries, heat batteries and thermal storage installed alongside heat pumps or electric resistive heating when paired with flexible electricity tariffs. The simulation was coded in the statistical programming language R, and is based on standard Scottish Government property archetypes and their associated heat demands. The heat demands have been seasonally adjusted using data from the National Grid, using prices taken from the Sutherland Tables and averages of the Octopus Agile tariffs.

2 Overview of storage technologies

Domestic energy storage allows consumers to capture cheap electricity or heat when it is available and store it for later use. Cheap energy can generally come from two sources: microgeneration or off-peak electricity rates (or both). The most common energy storage systems are electric batteries, heat batteries and thermal stores.

[7] Climate Change (Emissions Reduction Targets) (Scotland) Act 2019
[8] The Fuel Poverty (Targets, Definition and Strategy) (Scotland) Act
[9] Scottish Government (2021) Heat in Buildings Strategy

Table 1: A summary of the key characteristics of different energy storage technologies.

Technology	Model	Unit cost[10]	Energy storage capacity (kWh)	Warranty (years)	Estimated lifespan	Estimated efficiency
Electric battery	Alpha Smile B3	£1620 - 7350	2.9 - 17.2	10	10,000 cycles[11]	n/a[12]
	SonnenBatterie 10	£4500 - 10,000	11 - 22	10	10,000 cycles (estimated service lifetime of 20 years)	92.5% inverter efficiency, 81.6% RTE[13]
	Giv-Bat	£883 - 2244	2.6 - 8.2	10	10 years	n/a
	Powervault 3	£4740-14,820	4 - 20	10	4,500 cycles	n/a
	Puredrive Purestorage II	£5479 - 8398	5 - 10	10	10,000 cycles	95% inverter efficiency
	Moixa Smart Battery	£4450-6250	4.8 - 9.6	10	6000-10,000 cycles	n/a
	Tesla Powerwall 2	£5900	14	10	n/a	90% RTE
Heat batteries (phase change material - PCM)	Sunamp UniQ eHW (DWH only)	£1836 - 3295	3.5 - 12	10	<50 years	≤75% (ErP[14] rating C)
	Sunamp UniQ eHW + iPV (DHW + PV)	£1907 - 3366	3.5 - 14	10	<50 years	≤75% (ErP rating C)
	Sunamp UniQ HW + iLTHP (DHW + space heating)	£1972 - 2690	6.3 - 12.6	10	<50 years	≤98% (ErP rating A+)
Thermal store	Advance Appliances SFUTS Multi Fuel Thermal Store Cylinder	£2450-4560	17.5 - 35 (250 - 500L)	10	n/a	≤90% (ErP rating B)
	Mibec Hi-Spec Buffer Tank	£472 - 2013	21 - 140 (300 - 2000L)	5	n/a	n/a

[10] Excl. VAT.
[11] 1 cycle is a full charge and full discharge. E.g. 10,000 cycles of a 12kWh battery = 120,000 kWh of storage capacity.
[12] No available information
[13] Round Trip Efficiency (RTE) is the percentage of the energy put into the storage which can be retrieved
[14] Energy related Product (ErP) is statutory energy labelling required for all regulated energy related products on the UK market.

2.1 Electric batteries

Electric batteries are becoming increasingly affordable and popular, in part due to the rapid development and uptake of electric vehicles (EV)[15] which has supported technological improvement and cost reductions. They have the potential to provide both financial advantages to consumers and grid management services. Though lead-acid batteries are cheaper, most domestic electric storage installations are lithium-ion (Li-ion) batteries, owing to a greater storage capacity and higher discharge rate[16]. Li-ion batteries typically have a lifespan of between 8 and 12 years[17]. Batteries degrade over time, and battery lifespans are commonly described by the number of charge/discharge cycles. For example, the SonnenBatterie 10 has an estimated lifespan of 10,000 cycles (Table 1), after which point the battery will still be operational, though will be running at a reduced efficiency which may no longer be able to provide the same financial benefits. Warranties for Li-ion batteries are usually 10 years.

Electric batteries may be installed to allow householders to benefit from flexible energy tariffs, such as ToU, allowing energy to be stored during periods of cheaper electricity and used during more expensive peak hours. This provides the additional benefit of balancing pressures on the electrical grid. Generally, domestic battery installations in the UK have been driven by the solar photovoltaic (PV) market[18]. It is more common for batteries to be installed in tandem with solar PV, rather than used only with ToU tariffs. Installing a battery alongside solar PV increases the financial benefits of self-generation for the consumer. Solar Energy UK estimate that battery storage is now installed alongside half of all new solar PV systems in the UK[19].

Electric batteries require very little maintenance. Once installed, overheads are very low. Users control batteries either by an interface on the unit or through a web or app-based customer portal. Smart features are increasingly being integrated into battery storage systems to ensure compatibility with ToU tariffs, smart meters, and smart home appliances.

2.2 Heat batteries

Heat batteries can store heat or convert electricity to heat and store it. Therefore, heat batteries can be used in conjunction with renewable heating systems such as heat pumps and electrical microgeneration such as solar PV allowing householders to store cheap heat for later use. For example, heat pumps are designed to provide consistent low-level heat throughout the day, maintaining a comfortable temperature in the home. With the use of a heat battery, heat generated by the heat pump during warmer off-peak daytime hours day can be stored and used to supplement the heat pump during the cooler, peak hours in the evening. Currently Sunamp provides the only PCM storage products available in the UK.

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[15] Dong, S. et al. (2020) Techno-Enviro-Economic Assessment of Household and Community Energy Storage in the UK
[16] Centre for Sustainable Energy (2019) Battery Storage
[17] Beltran, H. (2020) Lifetime Expectancy of Li-Ion Batteries used for Residential Solar Storage
[18] SolarPower Europe (2020) European Market Outlook For Residential Battery Storage 2020–2024
[19] Solar Energy UK (2021) Smart Solar Homes: The Journey to Net Zero

Figure 1: In-situ Sunamp UniQ heat battery[20]

Heat batteries use a phase change material (PCM) to store thermal energy as 'latent heat'. Instead of water as the storage medium (as in thermal stores), PCM alter their physical state (i.e., melting or freezing) to store and release heat. Heat is stored while the PCM is in liquid form. Electrical energy or heat is used to alter the physical state of the PCM. Heat is then released when the PCM returns to its original solid state during battery discharge. During discharge, black water, or mains water flows through a heat exchanger within the battery, providing heated water for central heating or potable use reaching temperatures of up to 55°C.

Heat batteries using PCMs can be used for domestic hot water (DHW), space heating or a combination of both depending on the requirements of the householder. The required heat output determines the size of the heat battery. For example, Sunamp's UniQ eHW heat battery[21] is available in four sizes ranging from 3kWh – 12kWh. The smallest model can fit in a kitchen cupboard. 3kWh of stored heat supplies around 80L of hot water. This is the equivalent of the hot water demand of a single-occupant one bedroom flat. The largest 12kWh model would therefore take up four times the space and produce 320L of hot water. To work alongside a heat pump the heat battery would need to be able to store enough energy to cover the peak heat demand period of the property, which would vary depending on the property type and size.

[20] Image reproduced with permission from Biggs Heat Technologies
[21] Note that in December 2021 Sunamp's UniQ range was superseded by the 4th generation Thermino range

Sunamp heat batteries have been shown to work for up to 14,000 cycles (full charge to full discharge), equating to 35 years of use[22]. According to their technical specifications, batteries do not require regular maintenance.

PCM heat batteries differ from traditional DHW cylinders. Due to the higher volumetric density of PCM compared to water, heat batteries can be up to 3-4 times smaller than a cylinder of the same storage capacity. Heat batteries are generally better insulated than hot water cylinders, and therefore have lower heat losses[23]. Heat batteries have no moving parts, unlike hot water cylinders, and therefore require less maintenance. Finally, heat batteries have no requirement for periodic legionella cycles. Building control regulations require hot water cylinders to be heated above 60°C intermittently[24]. Unlike thermal stores and hot water cylinders, heat batteries require a set input temperature to charge the PCM. This means they are restricted to heating systems with flow temperatures above a certain point. Most Sunamp models are based at a 58°C set point. These can only be used in conjunction with high temperature heat pumps, or a small number of low temperature heat pump models from Samsung and Daikin which can produce high temperatures for short periods[25].

2.3 Thermal storage

Domestic thermal stores typically use water as the storage medium, though larger commercial applications use other materials such as sand or aluminium[26]. Most commonly, thermal storage is installed alongside domestic renewable heating systems, such as biomass boilers or ground source heat pumps. This is due to the intermittent nature of the operation of those heating systems. Biomass boilers have a time delay while they ignite and run at a higher burn efficiency when operating at nominal output, so the thermal store accumulates the heat from a burn cycle and then distributes it through the building when required. Similarly, heat pumps have a time delay when they start operation and are more efficient when operating for prolonged periods rather than 'stop-start'. A thermal store acts as a buffer (a way or storing and managing heat until it is needed) between the heat pump and distribution system to ensure more consistent heat delivery. Thermal stores have a substantial layer of thermal insulation to reduce heat loss.

Domestic thermal stores can provide:

- space heating and mains pressure hot water
- space heating only (which may be the case with a heat pump system)
- hot water only (when paired with solar thermal where there is a very high potable water requirement such as a swimming pool)

For the purpose of this research, we have not considered hot water tanks to be included as thermal stores, as they provide potable DHW only and do not contribute to space heating. Thermal stores do not contain potable water and are primarily to increase the volume of the heating system.

Thermal stores are referred to as 'accumulator tanks' when used to pool heat from multiple sources (i.e., solar water heating and a heat pump). Tanks are filled with 'black water' which circulates around a wet central heating system and are directly heated by the heat source, with no heat exchanger separating the water Thermal stores are

[22] ACArchitects (2016) Maximise your renewables: Sunamp heat batteries
[23] Stakeholder interview with a representative from Sunamp
[24] Health and Safety Executive (2014) Legionnaires' disease
[25] Sunamp (2018) UniQ Heat Storage Batteries
[26] Sarbu, I. and Sebarchievichi, C. (2017) A comprehensive review of thermal energy storage

referred to as 'buffer tanks' when used to provide more consistent heat delivery from one heat source. For example, a manually fed biomass boiler will feed into a buffer tank prior to circulation around a wet central heating system to provide more consistent space heating.

DHW can be provided in three ways alongside a thermal store:

- directly from the heat source bypassing the thermal store into a separate indirect hot water cylinder
- black water from the thermal store into a separate indirect hot water cylinder
- a coil inside the thermal store, allowing for potable water to be heated by the thermal mass indirectly

Both hot water cylinders and thermal stores can be installed with an immersion heater and PV diverter to store surplus electricity from solar PV as heat.

Manufacturer specifications suggest that servicing should be undertaken annually to check flow rates and temperature as well as inspecting moving parts such as the expansion vessel and safety relief valves.

3 Considerations for installations

3.1 Space constraints

There are practical considerations that impact the appropriateness of storage technologies for different properties. In small properties, particularly flats, space may be a constraint. Therefore, storage technologies with a higher storage density may be advantageous i.e. a heat battery rather than thermal storage.

Table 2: Size, weight, and space requirements

Technology	Size (mm)	Weight (kg)	Space requirements (mm)
Powervault 3[27] (internal, wall mounted)	**H:** 970 - 2120 **W:** 100 **D:** 250	130 - 380	100mm around perimeter of unit for ventilation
Sunamp UniQ range[28]	**H**: 429 – 1070 **W**: 575 **D:** 365	74 - 234	**Front:** 150 **Sides:** 150 (10 if no access required) **Rear:** 10 (if no access required) **Above:** 450
Cordivari EC2 Thermal Store (800-1000L)[29]	**H:** 1840 - 2130 **Ø**: 990	788 – 905 (filled)	**Sides:** 150 **Rear**: 80 **Above:** 80

[27] Powervault (2021) - Powervault 3 Technical Specifications
[28] Sunamp (2020) - Sunamp UniQ eHW +iPV & HW+iPV Heat Battery Installation and User Manual
[29] Mibec (2020) - Cordivari EC2 Datasheet

Heat batteries and most Li-ion battery models are modular and can be stacked. This could aid installations in space-constrained homes as units can be stacked in different configurations to fit in small or awkward spaces. Electric batteries can be floor or wall-mounted and can be installed in loft spaces. However, Sunamp's UniQ heat battery can weigh between 74 – 234kg (Table 2), requiring a solid and flat area for installation. Heat batteries cannot be wall mounted and may require additional reinforcement if installed on a suspended timber floor[30]. This may present a barrier to installation in mid- or top-floor flats. Specialist delivery equipment may be required if the installation location is upstairs.

Thermal stores have a relatively low energy density compared to electric or heat batteries. They therefore require more space for a similar storage capacity and are bulkier (Figure 1). Capacity ranges between 200-1000L, and a typical domestic store is 250L. Unlike heat batteries, a thermal store is lightweight during the installation process, however when filled a 250L store will weight up to 300kg. It is possible to install thermal stores in lofts, but the need for a reinforced floor and the manoeuvrability of a large cylinder may preclude this in many cases. The location of installation relative to the rest of the heating system is not a major concern. There will be some heat loss along pipe runs, and some energy required for pumps, but these will be insignificant if the thermal store is located within the fabric of the building.

Figure 2: In-situ thermal store[31]

Li-ion batteries have an ideal temperature range of between 10-55^{o}C. Charging at low temperatures can damage the battery and affect performance. However, a small number of models (such as those by Tesla and LG Chem) are rated for outdoor use. Heat

[30] Sunamp (2020) - Sunamp UniQ eHW +iPV & HW+iPV Heat Battery Installation and User Manual
[31] Image courtesy of Alto Energy Ltd. (last accessed 20 Jan 2022)

batteries and thermal stores cannot be installed outdoors unless built into weatherproofed and insulated outbuildings.

Li-ion batteries require clearances of between 10-20cm around the unit for ventilation. Battery units also have ventilation systems within the unit casing. This is to prevent overheating, which in extreme cases could lead to battery fire. There have been few recorded fires involving domestic Li-ion batteries[32]. Heat batteries and thermal stores require similar clearances of 10-20cm, although this is for accessibility rather than ventilation.

3.2 Digital connectivity

Digital connectivity is a requisite for all the storage technologies listed in this report if they are to respond to grid signals. Both smart meters and internet connections are required for most electric battery interfaces. National Energy Action (NEA) reported that connectivity to external systems and monitoring platforms was the single most important challenge across all their battery trials[33]. Every NEA battery trial has suffered from internet connectivity issues whether the setup was using WiFi, 3G, 4G, or GPRS. As well as issues with internet provision, a lack of continuous internet connection was problematic. Some battery models can only operate with basic functionality when offline, and some had to be manually reset. This could be caused by WiFi outages, householders switching off their routers overnight, or the use of WiFi range extenders which did not provide a reliable internet connection. Hardwired internet connections were the most reliable method.

4 Electric batteries

4.1 Current Scottish market

4.1.1 Cost trends and availability of technology

Li-ion costs fell by 89% between 2010 and 2021[34] due to the growth of electric vehicle (EV) applications and a rapid global increase in manufacturing capability. Installed costs for Li-ion batteries in stationary applications are higher than EVs as they require more expensive battery management systems and hardware. However, benefitting from the growth in scale of EVs, the cost for stationary applications is predicted to drop significantly by 2030[35]. This has already happened in Germany where total installed costs fell by 60% between 2014 and 2017[36].

Li-ion is anticipated to continue to dominate the battery market over the next ten years, with rapid growth for the next 5 years. Future cost reductions are anticipated based on reducing the amount of cobalt in a battery and improving energy density. Industry stakeholders predict a plateau of the Li-ion market in 10+ years, as other chemistries and technologies are developed[37].

[32] BEIS (2020) Domestic Battery Energy Storage Systems: A review of safety risks
[33] NEA (2019) Domestic Batteries: learnings from NEA's technical innovation fund field trials
[34] BloombergNEF (2021) Annual battery price survey
[35] IRENA (2017) Electricity Storage and Renewables: Costs and Markets to 2030
[36] Ibid.
[37] Zero Waste Scotland (2021) Battery use in Scotland now and in the future: Phase 2 - The future of batteries in Scotland

Against the backdrop of this price trend, stakeholders from across the supply chain in Scotland reported recent price increases over the last year. This is due to increases in raw material prices and a slowdown in manufacturing in China due to Covid-19. BloombergNEF predict that Li-ion battery prices may continue to rise in the short-term, although a long-term decreasing price trend is expected to continue[38].

Stakeholders also reported that shipping delays caused by Brexit and Covid-19 are impacting the availability of battery technology in Scotland. Lead-times from battery brands such as Tesla and SolaX are currently between 12-16 weeks. A lack of installers was also highlighted as a barrier in the Scottish market, causing long wait times and preventing a drop in the cost of installation.

Going forward, stakeholders anticipated that costs would fall again following the overall trend of increasing demand and greater economies of scale for manufacturers. However, it was also noted that insulation costs are increasing more rapidly as a result of Covid and Brexit-related material shortages, which may negate energy storage cost savings.

It is also anticipated that a market for second life EV batteries will emerge. Li-ion batteries are replaced in EVs once they have degraded to 70-80% of their original capacity. These batteries can be repurposed for stationary domestic use, with an anticipated further lifespan of 7-10 years[39]. The second life battery (SLB) market would reduce costs for consumers, however further analysis is required to estimate the selling price of SLBs[40]. Analysis by Energy Systems Catapult concluded there are unlikely to be enough second life batteries from UK-based EVs to meet peak demand until around 2040[41].

4.1.2 Property profiles

Based on stakeholder interviews, the majority of electric battery installs in Scotland have occurred within single rather than multi-occupancy buildings. A large proportion of installs are retrofitting social housing stock. Installs have predominantly been in older terraced and semi-detached houses. b

Electric batteries are generally installed in properties with solar PV, or another form of generation. Stakeholders reported rarely installing batteries to specifically support heating systems, or entirely independent of generation. Several installers noted that they would not recommend installing a battery without onsite generation.

4.1.3 Customer profiles

A large proportion of battery customers in Scotland are registered social landlords (RSLs). Many of these are based in the north of Scotland where there is a high proportion of off-gas housing. Sales to the private market tend to be to customers aged over 40 with disposable income. A large proportion of these are in remote locations in the north of Scotland and are using batteries for emergency backup power.

Some distributors are beginning to supply wholesale to energy companies. For example, E.ON offer a home battery solution for private homeowners throughout the UK with interest free payment options, as well as grant-assisted installations of solar PV and battery storage through the Highland Energy Efficient Scotland: Area Based Scheme (EES:ABS) for eligible households[42].

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[38] BloombergNEF (2021) Annual battery price survey
[39] Haram, M.H.S.M. et al (2021) Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges
[40] Ibid.
[41] Energy Systems Catapult (2020) Second Life Batteries
[42] Highland Council Energy Efficient Scotland: Area Based Scheme (last accessed 12th January 2022)

4.2 Reducing consumer bills

Electric batteries can be used to reduce consumer bills by storing self-generated electricity (‘self-consumption’) or off-peak electricity for use during peak hours. Battery storage systems can be set up to do both or either of these things. Electric batteries can also provide ancillary services to help grid operators maintain a reliable electricity system. The provision of ancillary services may also generate some financial benefits to consumers.

Battery storage can provide other non-financial benefits for consumers, although these have not been considered in detail as part of this research. Some models such as the Tesla Powerwall, can continue to provide electricity in the event of an outage (known as islanding or backup). However, this is not standard, and most Li-ion battery models do not offer backup capability.

4.2.1 Self-consumption

Storage of self-generated electricity is currently the most common application of domestic batteries. Generation is usually through solar PV systems, although any form of onsite electricity generation could fulfil this role. A battery stores any surplus electricity which would otherwise be exported to the National Grid.

Optimal battery size, and the anticipated financial benefit for householders, can be calculated based on the generation capacity available and the household demand profile. A household with solar PV and high daytime energy use may not benefit from the installation of a battery[43].

Recent research published by Solar Energy UK[44] concluded that currently the additional cost of installing a battery with a solar PV system outweighs the savings enabled through storing surplus generation. This was based on a modelling exercise and case studies from across the UK. The installation of batteries more than doubled the percentage of self-consumed electricity from PV systems. However, the additional cost of installing a battery was more than the additional savings enabled through storing surplus electricity. Solar Energy UK anticipate this will change based on falling battery prices, increasing battery lifespans and the emergence of more ToU tariffs once the UK electricity retail market moves to half-hourly metered billing from 2025.

4.2.2 Off-peak electricity

Off-peak electricity prices can be accessed through ToU tariffs. There is currently one dynamic ToU tariff available in the UK, and several static ToU tariffs. Dual rate tariffs such as Economy 10 and Economy 7 can also be used to provide cheap off-peak electricity for battery storage (see Table 3).

Tariffs for dynamically teleswitched meters could also be used to charge a battery. These tariffs provide a cheap rate of electricity for heating and hot water appliances. This set up is designed for homes with storage heaters. The storage heaters are connected to a separate circuit from lighting and electrical appliances. Therefore, a battery charged on the cheap heating rate would only provide electricity to the storage heaters. In such a scenario upgrading storage heaters to high heat retention storage heaters (HHRSH) is likely to be a more cost-effective option than using a battery to supplement the operation of storage heaters.

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[43] Pliz, M et al. (2019) On Optimal Battery Sizing for Households Participating in Demand-Side Management Schemes
[44] Solar Energy UK (2021) The Value of Solar Property

Table 3: Types of tariffs which can be used with electric batteries

Tariff type	Description	Examples
Dynamic ToU	Reflects wholesale electricity prices, usually on a half-hourly basis	Octopus 'Agile'
Static ToU	Set periods of peak and off-peak pricing	• Green Energy 'TIDE' • Octopus 'GO' • Dual rate tariffs (E7 / E10)
Storage specific SEG[45] tariffs	Currently the highest SEG rates on the market are exclusively for households with battery storage	• Tesla Energy Plan • Social Energy 'Better Together'

Relying solely on off-peak electricity prices to charge a battery (without any self-generation) is currently perceived as a high-risk option. This is because dynamic tariffs with high price differentials (the difference between peak and off-peak prices) are volatile. Bill savings are difficult to predict, and there is a risk of high electricity prices as tariffs track the wholesale energy price. For example, the Octopus Agile tariff has a potential price differential of up to 35p, however at the time of publishing the price differential is currently 0p[46]. Static tariffs are less volatile, and therefore predicted savings can be calculated more reliably. However, bill savings from a price differential of around 13p[47] will be lower than the potential savings from dynamic tariffs. With both types of tariff there is a risk that the savings will not offset the cost of installing a battery. Several installers stated that they would not recommend installing a battery without onsite electricity generation for this reason.

Stakeholders considered dynamic electricity tariffs to be unpredictable, particularly given the current energy price crisis. The introduction of half-hourly pricing across the retail electricity market from 2025[48] is likely to see more ToU tariffs available. As the ToU tariff market evolves, it may be that the business case for batteries without onsite generation improves.

4.2.3 Ancillary services

Ancillary services support the transmission and generation of electricity, and also help to maintain usability of energy throughout the system. These services are necessary for network operators to maintain stable and reliable energy networks. Ancillary services include:

- frequency control services: flexibility/balancing of the supply and demand of electricity
- network control services: used to maintain energy system security and reliability
- system restart services[49]: assets are used to assist with black starts [50]

To date, these services have generally been provided by large commercial actors who manage large generation or storage assets. There are now increasing opportunities for

[45] The Smart Export Guarantee (SEG) requires large energy suppliers to pay small-scale and domestic generators for renewable energy exported back to the National Grid.
[46] Prices are available from www.agileprices.co.uk (last accessed 17 Jan 2022)
[47] Based on Economy 7 prices from the Sutherland Tables, September 2021
[48] Ofgem (2021) Electricity Retail Market-wide Half-hourly Settlement: Decision and Full Business Case
[49] Kumar, G.V.B. (2020) A Review of Energy Storage Participation for Ancillary Services in a Microgrid Environment
[50] A black start is the process of restoring part of the electrical grid following system shutdown.

consumers to provide ancillary grid services either independently or aggregated into a larger portfolio.

4.2.4 Financial benefits to consumers

Ultimately, more stable and reliable energy networks will deliver cost savings to the end user. More directly, consumers will be able to opt-in to virtual power plants which aggregate multiple domestic batteries to provide ancillary grid services.

In addition, some manufacturers are offering incentives for customers to opt into ancillary grid services alongside purchase of their equipment. Table 4 provides information on existing incentives for householders.

Table 4: Financial incentives for consumers opting into ancillary grid services.

	Eligibility Criteria	Battery Size	Price (inc.VAT)	Annual Incentive Value	Timescale	Total Incentive Value
EDF Grid Services[51]	Powervault 3 battery	4kWh 8kWh	£5,599 £7,999	£50 £100	10 years	£500 £1000
Powervault GridFLEX[52]	Powervault 3 battery	4kWh – 20kWh	£4,740 – £14,820	£120	2 years	£240
Moixa GridShare[53]	Moixa Smart Battery + ToU tariff	4.8kWh – 9.6 kWh	£4,450 - £6,250	£50	3 years	£150
Tesla Energy Plan[54]	One or more Tesla Powerwall 2 batteries + Solar PV + total daytime consumption of <9,500 kWh per year.	14kWh	£5,900	24hr fixed energy tariff (between 10-12p/kWh	n/a	Estimated 64% saving on energy bills.

There has been considerable progress in terms of the benefits that domestic batteries can provide to network operators. In an early pilot in 2016 Western Power Distribution installed solar PV and batteries in 26 homes[55]. The aim was to manage network constraints on a low voltage network, as an alternative to network reinforcement. The financial benefit from this early pilot to the Distribution Network Operator (DNO) in terms of network investment deferral was low (less than £300).

Since that pilot, developments in aggregating domestic batteries have enabled DNOs to design network constraint schemes. For example, Western Power Distribution is now

[51] EDF Complete Guide to Home Battery Storage. (last accessed 9 Nov 2021)
[52] Octopus Energy Smart energy trial with Powervault and AgileOctopus (last accessed 3 Dec 2021)
[53] Moixa GridShare (Last accessed 3 Dec 2021)
[54] Octopus Energy Tesla Energy Plan FAQ (Last accessed 9 Nov 2021)
[55] Western Power Distribution (2016) Project SoLa Bristol Closedown Report

looking to mainstream its Sustain-H[56] pilot project. This allows the DNO to procure constraint management services from flexibility providers (aggregators). Despite this progress, the financial incentives for consumers to provide ancillary services are still limited. The value of the Sustain-H service to flexibility providers is estimated to be £5-75 per year. It is unclear how much of this revenue would be passed to householders.

The pricing and reward structure in relation to ancillary services provided by batteries requires reconsideration and improvement[57]. The current levels of remuneration available to householders for providing ancillary services do not incentivise the uptake of battery storage.

Recent developments such as the widening of access to the Balancing Mechanism market[58] signify that opportunities for revenue from domestic batteries may improve. As DNOs transition to Distribution System Operators (DSOs) they will need to procure flexibility services, some of which may be provided by aggregated domestic batteries.

4.2.5 Performance and cost savings

There is limited monitoring data available of both battery performance, and the impact on consumer bills. There are currently a number of domestic electric battery trials including OVO Energy's trial with Powervault[59] and various Scottish Government funded projects[60]. These projects involve monitoring, although no data is available yet.

Stirling Council are gradually installing solar PV and Tesla Powerwall batteries on all council housing stock (over 5800 properties). Based on current installs they estimate that self-consumption of PV-generated electricity has increased from 35-45% to around 90% with the installation of batteries. This has led to additional savings of around £200 per year on top of savings already seen from the installation of PV alone[61].

Due to the lack of comparable monitoring data, we will present a number of case studies of existing electric battery installations in order to illustrate cost savings that have been achieved.

[56] Everoze (2020) Future Flex: Sustain-H Trial Design
[57] Mexis, I. and Todeschini, G. (2020) Battery Energy Storage Systems in the United Kingdom: A Review of Current State-of-the-Art and Future Applications
[58] NationalGrid ESO (2021) Balancing Mechanism Wider Access
[59] Ovo Energy Ovo Smart Home (last accessed 29 Nov 2021)
[60] For example, Changeworks are conducting M&E for the LCITP funded project in Moray and two Decarbonisation Fund projects in Edinburgh and Midlothian
[61] Stakeholder interview with a representative from Stirling Council

Case Study 1: Batteries with Solar PV: 24/7 Solar

Partners: National Energy Action and London Boroughs of Camden, Islington and Waltham Forest

Year of install: 2016

Funded by: NEA's Technical Innovation Fund

Technology: 40 battery systems with new or pre-installed solar PV systems. Batteries were Moixa Maslow V3 (32 installs), Sonnen eco 8.2 (6) and Growatt (2).

Householder savings:

The financial benefit for residents was calculated for the solar PV (kWh of PV generation used directly * 16p/kWh) and from the battery (battery discharge * 16p/kWh). Due to connectivity issues this was only calculated for systems which had a good internet connection (10 in total). Average savings per household over a 10-month period were as follows[62]:

- Moixa (8 systems) £106.43 from solar PV, and £37.06 from the batteries
- Sonnen (2 systems) £173.76 from the solar PV, and £55.80 from the batteries

Monitoring results:

A huge range in round trip efficiencies (RTE)[63] was recorded. The eight Moixa batteries ranged between 66.9% and 87.7%, and one Sonnen battery between 13.4% and 64.9%. Little information is available regarding both expected or in-situ RTE values for the majority of battery models, though the Sonnen 10 battery has an expected RTE of 81.6% (Table 1).

Challenges:

Some systems performed poorly. In some cases, this was due to PV systems being undersized for the household's consumption. Little excess solar generation was available for the batteries, which therefore provided minimal financial benefit for the household.

The 24/7 Solar case study demonstrates fairly minimal savings for households when considering the return on investment on the capital costs of a battery and solar PV system. However, for grant funded installs the level of bill savings demonstrated in this case study could have a significant impact for households in fuel poverty. This case study highlights the importance of sizing solar PV and batteries for household consumption in order to realise financial savings.

The Moixa batteries performed better than Sonnen in terms of RTE due to differences in the inverter thresholds (250W vs 30W respectively). The inverter threshold is the level at which the battery kicks in and starts storing electricity. These levels are pre-set by manufacturers to reduce unnecessary inverter losses at low supply levels (low efficiencies). A low inverter threshold allowed the Sonnen battery to charge when solar output levels were low. Moixa batteries only charged when solar output exceeded 250W,

[62] NEA (2019) 24/7 Solar
[63] Round trip efficiency represents the percentage of the energy put into a battery which can be retrieved.

effectively missing out on some generation. However, at low power the efficiency of the inverter is lower, hence the Sonnen battery had an RTE 13.4% in January.

This highlights the need for the batteries and inverters installed to take into consideration local conditions and roof orientation of the solar panels to maximise the potential.

Case Study 2: Batteries and ToU tariffs in Dumfries and Galloway

Partners: Warmworks and Dumfries and Galloway Housing Partnership

Year of install: 2019

Funded by: SPEN Green Economy Fund

Technology: 113 Tesla Powerwall 2 batteries were installed. 89% of homes were off the gas grid.

Householder savings:

For households on a dual tariff the estimated savings from battery use were £208 per year (compared to baseline electricity use)[64].

Some households switched to the Octopus Agile tariff. The estimated savings from battery use were £331 per year for those previously on a dual tariff, and £436 per year for those previously on a single tariff. Monitoring took place during 2020, during which the average peak price ranged between 19.8 p/kWh (May) and 30.0 p/kWh (December), and the average off-peak price ranged between 4.8p (May) and 11p (December). Over the year, the price differential between peak and off-peak averaged 16.7p[65].

The highest reported saving during the project was 83% during May 2020 (when compared with the householder's bill from May 2019). This was during a period of high excess renewable generation which saw several 'price plunge' events with negative prices for Octopus Agile customers for around 30 hours (or 4% of the month). Overall, the Agile prices in May 2020 were very favourable, the average price across the month was 6.7p.

Challenges:

Multiple householders were unable to get a smart meter or change their tariff arrangements. Properties with double MPAN setups (two electricity meters, such as dynamic teleswitch meters) were particularly problematic. Without switching to a dual rate or smart ToU tariff the batteries were redundant.

This project demonstrates that savings can be made if batteries are installed without generation and charged only through off-peak electricity. The project showed some promising savings for tenants during the monitoring period. However, as Tesla Powerwall 2 batteries retail at £8-9000, these savings are not sufficient to build a business case for battery installations without grant funding.

Additionally, due to increases in wholesale electricity prices, the Octopus Agile tariff is currently at the maximum rate of 35p/kWh nearly constantly[66]. The average price per kWh for November 2021 was 32.6p, whereas Ofgem's 2021 price cap for standard variable tariffs is equivalent to 21p/kWh[67]. Warmworks reported that tenants on Octopus

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[64] Warmworks (2021) Domestic Battery Storage Project
[65] Prices for South of Scotland from https://agileprices.co.uk/ (last accessed 17 Jan 2022)
[66] Ibid
[67] Ofgem (2021) Default tariff cap level: 1 October 2021 to 31 March 2022

Agile are now paying higher bills than before the project. Warmworks are working with Dumfries and Galloway Housing Partnership to help tenants switch away from the Agile tariff to a dual rate tariff instead.

This case study illustrates the inherent risk of relying on off-peak electricity tariffs for savings without the option of self-generation. Whilst the dynamic ToU tariff market is still in its infancy Warmworks have indicated that for future projects they would only consider using dual-rate tariffs. As these have a price differential of around 13p between peak and off-peak rates the potential savings for consumer are lower but more reliable than a dynamic tariff.

The ability for self-generation of electricity would not fully mitigate the risks of volatile electricity prices, but it could reduce the risk (depending on the capacity of the battery and the output of microgeneration). Low wholesale electricity prices are normally caused by high levels of renewable generation, and therefore are likely to coincide with householder’s own periods of electricity generation.

Case Study 3: Battery Optimisation Pilot in Fife

Partners: Fife Council, AES Solar and Greencom (Aggregator)

Year of install: 2019-20

Funded by: Scottish Government Decarbonisation Fund

Technology: 52 Varta Pulse batteries were installed in properties with existing solar PV systems. These properties all have gas central heating.

Householder savings:

Monitoring data was collected over two months from 22 properties. Based on actual energy consumption and PV production values, Greencom simulated several scenarios to obtain potential cost savings on electricity bills for householders.

Table 5. Scenarios simulated by Greencom to determine potential savings on electricity bills

Scenario	Assets	Tariffs	Optimisation[68]	Electricity Bill Savings (%)
'No assets'	None	Standard tariff (not flexible)	No	Baseline
'Current set up'	PV + Battery	Standard tariff	No	35%
'Better tariff'	PV + Battery	Octopus GO	No	43%
'Better tariff + SEG'	PV + Battery	Octopus GO + SEG	No	56%
'Better tariff + SEG + optimisation'	PV + Battery	Octopus GO + SEG	Yes	78%

Challenges:

As the solar PV systems are owned by Fife Council, tenants are not eligible to receive SEG (Smart Export Guarantee[69]). The savings outlined above are purely theoretical.

This was a pilot project to produce an average cost saving figure per dwelling that could be used as a benchmark for future projects. Following the pilot Fife Council intend to procure an aggregator. The installation of PV with batteries is on average saving householders 35% on their electricity bills (based on in-situ consumption and production values). This is where the largest proportion of savings originate from. Monitoring was conducted in spring, and therefore we would expect higher % savings in summer and lower % savings in winter.

This case study also demonstrates the potential value of optimisation for consumers in terms of reducing bills. Optimisation provides a simulated average additional saving of 22%. In this simulation batteries were optimised to prioritise cost savings for householders. Optimisation could also be used for CO_2 reduction or autarky (grid

[68] The timing of battery charging is managed to maximise the economic potential.
[69] OFGEM, Smart Export Guarantee

independence). Utilising a static ToU tariff (Octopus GO) only provided an average 8% additional savings.

All properties in this case study have gas central heating. Therefore, the savings are based on domestic electrical consumption only, and householders' heating bills are unaffected. Additionally, the solar PV systems are small (mostly 2kW). This limits the potential savings which householders can make based on storing self-generated electricity. Larger solar PV systems paired with higher capacity batteries are likely to have resulted in higher savings in the 'current set up' scenario (Table 5).

4.2.6 Summary of electric battery case studies

The three case studies demonstrate that savings can be made by pairing electric batteries with solar PV and with off-peak electricity rates. However, actual savings realised were either minimal when compared to the capital costs (24/7 Solar case study and those on dual rate tariffs in Dumfries and Galloway), or unreliable (Octopus Agile tariff in the Dumfries and Galloway case study).

The savings which householders experienced in the 24/7 Solar project were lower than those experiences by householders in the Warmworks project (using only off-peak electricity to charge batteries). Given the number of variables (such as heating system, levels of household electricity consumption, electricity tariffs and prices) it is difficult to draw comparisons between case studies. However, a significant factor which may explain this is battery size. Warmworks installed batteries with a capacity of 13.5kWh, whereas the batteries installed in the 24/7 Solar project were between 1.6-3kWh.Smaller capacity batteries will store fewer kWh of energy for later use during peak hours, limiting the financial benefits.

The Fife case study demonstrated that householders made average savings of 35% using solar PV and battery storage. Predicted additional savings from battery optimisation were relatively significant, suggesting that this could be a mechanism through which to reduce consumers bills. Simulated additional savings from a ToU tariff however were only 8%.

5 Heat Batteries

5.1 Current Scottish market

5.1.1 Cost trends and availability of technology

Sunamp is the only provider of PCM heat batteries within Scotland. Technological improvements have reduced the cost of Sunamp's heat batteries to a tenth of the first heat battery system. Current costs can range between approximately £1,800 to £3,400, depending on the model, and are comparative to high-end hot water cylinders (Table 1). Sunamp aims to reduce unit costs further.

Sunamp has sold 10,000 units of the current product generation (UniQ) over the last 3.5 years in the UK. They estimated that 5-10% of those sales were in Scotland.

Unlike electric batteries, Sunamp has had no issues with the supply of chip sets or shipping of materials. Lead times have increased in recent months; however, this has not had a significant impact on the supply of heat batteries.

5.1.2 Property profiles

Installations of Sunamp heat batteries occur almost exclusively within domestic properties, although residential-scale technologies may also be installed in commercial settings. As part of the EastHeat project[70], 625 heat batteries were installed in social housing properties across a variety of flats, houses, and bungalows, ranging from one to four bedrooms.

5.1.3 Customer profiles

Sunamp no longer sells directly to customers. All sales are now through merchants or as part of retrofit projects and new build developments. As with electric batteries, many heat batteries in recent years have been installed as part of retrofit projects in partnership with RSLs.

5.2 Reducing consumer bills

Like electric batteries, heat batteries can be paired with generation and utilise off-peak electricity to reduce consumer bills. A heat battery can be paired with either electric generation (solar PV) or thermal generation (solar thermal systems).

Heat batteries can be paired with heat pumps to shift electricity consumption to off-peak rates. The PCM in a Sunamp heat battery requires temperatures of 58°C to initiate the phase change and store heat. This requires a high-temperature heat pump, or specific heat pump models from Samsung and Daikin which are capable of achieving temperatures of up to 65°C for short periods[71]. Operating at this temperature will negatively impact the efficiency of a heat pump, reducing the SPF (Seasonal Performance Factor), as in Case Study 4. There is therefore a trade-off between the efficiency of heat pump operation and the ability to store heat produced using low-cost electricity. There is a risk that the financial implications of installing a high-temperature heat pump in order to effectively service a heat battery would negate any bill savings resulting from the storage. In some cases, it could prove more cost effective to opt for a standard heat pump without storage.

We found limited monitoring data available for installed heat batteries, both from Sunamp and from RSLs in Scotland. As part of the BEIS Electrification of Heat Demonstration Project, OVO is installing heat pumps with either hot water cylinders or Sunamp heat batteries in homes in south-east England. We anticipate that monitoring data will be available from BEIS following this project.

Results from installations of Sunamp heat batteries are illustrated through the following three case studies.

[70] Sunamp (2018) EastHeat Interim Report
[71] Sunamp (2018) UniQ Heat Storage Batteries

Case Study 4: DECC Heat Pump Trial

Partners: Sunamp and Berwickshire Housing Association

Year of install: 2013

Funded by: DECC (now BEIS)

Technology: Heat batteries with air source heat pumps in 10 homes[72]. Heat pumps operate at off-peak hours on E10 tariffs. Each property received three heat batteries: two for space heating and one for hot water.

Householder savings:

The majority of trial homes were originally electrically heated, with one gas heated home included within the trial. Sunamp reported savings in running costs of 45-57%[73], and that householder energy bills were reduced to "below the cost of gas heating"[74].

Challenges:

The SPF of the heat pumps was 2.2[75] due to the requirement to provide heat at 58°C for charging the heat batteries.

The reported savings for householders in this case study are significant. However, we are unable to isolate the impact of the heat battery from the impact of installing a heat pump system on householders' bills. In this case study it is also unclear what advantages the heat batteries provide over a low temperature heat pump system paired with a normal cylinder.

The case study illustrates some of the trade-offs when considering whether to install a heat battery or DHW cylinder. Heat batteries can be installed in properties without sufficient space for a DHW cylinder. However, in this example three heat batteries were installed, at a likely cost of £1768 per unit[76], which takes up a similar footprint to a standard cylinder. The advantage of heat batteries is that they provide space heating at off-peak rates, whereas a cylinder can only provide DHW. However, as described above, pairing a heat pump with a heat battery results in a lower SPF. It is worth noting that and SPF of 2.2 from the case study is not classed as renewable, which is defined as a SPF of 2.5 or above[77].

Heat batteries are currently more expensive than cylinders, and the above trade-offs should be factored into the decision between a heat battery and DHW cylinder.

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[72] https://Sunamp.com/decc/ (Last accessed 29 Nov 2021)
[73] Sunamp (2018) Optimising Electrical Systems via Smart Heat Batteries
[74] Stakeholder interview with a representative from Sunamp
[75] Ibid.
[76] Sunamp (2018) Optimising Electrical Systems via Smart Heat Batteries
[77] The European Parliament and the Council of the European Union (2009) EU Renewable Energy Directive

Case Study 5: NEA Ongo Homes Project

Partners: National Energy Action, Sunamp, Ongo Homes

Year of install: 2016

Funded by: NEA's Technical Innovation Fund

Technology: High temperature Daikin heat pumps with Sunamp heat batteries were installed in six properties. Sunamp recommended an E10 tariff to 'charge' the heat store with off-peak electricity.

Householder savings:

Heat pumps with heat batteries were cheaper to run than the solid fuel heating systems they replaced, providing householders switched to a dual rate tariff. Four households made annual savings of between £121.54 (18% reduction) and £359.82 (30% reduction). One customer was unable to switch to an E10 tariff, and their heating bills increased by £326.46 (48%) compared to their coal costs[78].

Monitoring results:

An average heat loss[79] of 16 kWh per day was recorded across the 6 properties. On an off-peak tariff of 6p/kWh, with a CoP of 2 would cost about £180 per year.

Challenges:

One householder experienced an issue with the change to daylight saving time. The clocks on the heat battery and electricity meter became one hour out of sync. The heat battery was charging for one hour per day at a peak rate. Over 12 days this error cost £8.

Some households experienced considerable savings on their bills. However, this example illustrates the sensitivity to errors and risk of pairing storage solely with tariffs. Firstly, the household unable to switch to a dual rate tariff saw a significant increase in bills. Secondly, the error which lead to a heat battery charging for one hour at peak prices would cost nearly £125 over a year. If undetected this error would negate savings made through a dual rate tariff.

The heat loss rates recorded in the Ongo homes trial are significant. Sunamp has released two generations of heat battery products since this project[80], and presumably heat loss rates have improved. The specification for their third-generation products states a heat loss rate of between 0.48-0.84 kWh per 24 hours[81]. These figures are from laboratory conditions tests, and we have not found any in-situ evidence of the heat loss rates for Sunamp's current product generation.

5.2.1 Summary of heat battery case studies

These two case studies do not provide a useful evidence base as to the extent to which heat batteries can reduce consumer bills. Both case studies refer to installations from 2016 or earlier using old generations of Sunamp products. Sunamp was unable to provide any recent case studies or monitoring data.

[78] NEA (2018) Various heating solutions for social housing in North Lincolnshire
[79] The heat loss from a heat battery is similar to the round trip efficiency of an electric battery, it is a measure of the amount of energy that is lost in the storage process.
[80] The fourth generation 'Thermino' will be available for purchase from Dec 2021
[81] Sunamp (2021) UniQ Product Brochure

In 2016, 2042 Sunamp heat batteries were installed as part of a £4million project which was the UK's largest domestic energy storage project at the time[82]. However very little useful monitoring data is available from this project. The final report, due to present the final monitoring data and report on value for money and replicability, has not been published.

6 Thermal storage

6.1 Current Scottish market

6.1.1 Cost trends and availability of technology

Thermal stores are an established mass-market technology. Costs for domestic scale thermal stores vary due to the variety of available products and differences in quality and system sophistication. Analysis in 2016 by Delta-EE[83] found that the cost for integrated thermal storage with DHW varied from <£1,000 to nearly £3,000 (ex. VAT). This price range is consistent with the current data we have reviewed from retailers and distributors.

In addition to individual households, thermal stores are often coupled with individual biomass heating systems or heat networks. With the introduction of the Heat Networks (Scotland) Act (2021) there may be a growing commercial market for larger, shared accumulator tanks (≤10,000L) within new heat network developments to help regulate heat generation and delivery.

Thermal stores can also be paired with heat pumps and are usually referred to as a 'buffer' in this context. The typical size for a buffer tank is 100L for a domestic heat pump. This has a similar footprint to a DHW tank. One installer explained that currently about 60-70% of the heat pumps they install will include a buffer tank and this is decreasing year on year[84]. With the introduction of variable speed compressors[85] there is a reduced need to install all heat pump system with a buffer tank.

6.1.2 Property profiles

Due to their size, thermal stores are predominantly installed within detached properties with a large utility space. There are some instances of thermal stores being installed within multi-occupancy buildings to support heat networks. For example, one project in Cologne involved the installation of 12,000L of storage tank capacity alongside ground source heat pumps, solar PV and battery storage for 1,395 apartments[86]. The thermal storage was used to consolidate heat from multiple generation sources as well as buffer the supply of heat within the properties.

6.2 Reducing consumer bills

The main benefit of using thermal stores is storing excess renewable generation, either electrical or thermal. Thermal stores can be paired with solar thermal systems or biomass boilers to improve efficiency and reduce intermittency.

82 Sunamp (2018) EastHeat Interim Report
83 Delta EE (2016) Evidence Gathering: Thermal Energy Storage (TES) Technologies.
84 Stakeholder interview with heat pump installer
85 Variable speed compressors (known as inverter driven) adjust the compressor speed of a heat pump to the required heat demand.
86 Rhein Energie Stegerwaldsiedlung (last accessed 29 Nov 21)

Thermal stores can also be paired with heat pumps and are usually referred to as a ‘buffer’ in this context. Buffer tanks provide a ‘safety net’ minimum amount of heat to the system when heat demand is low. This prevents the heat pump short-cycling[87] in order to cope with low heat demand. There is a lack of in-situ monitoring which specifically investigates the performance and potential cost savings from installing buffers as part of heat pump systems[88]. The alternative to installing a buffer tank is to use some of the heat already in the heating system, essentially using radiators as a buffer tank. Although this removes the cost and space requirements of a buffer tank, it may impact the performance of the heat pump system. Several stakeholders mentioned they now install 40L buffer tanks, which are relatively new on the market. These are designed to provide a compromise between a large buffer tank and using heat from the open volume of the system.

We found no monitoring data or case studies for thermal storage in conjunction with heat pumps. As part of the BEIS electrification of heat trial, both E.ON (Newcastle) and OVO (south-east England) are installing thermal stores. We anticipate monitoring data will be available from BEIS once this trial is complete.

Like electric and heat batteries, thermal storage could enable consumers to avoid peak electricity rates when paired with a heat pump or direct electric wet heating system. A report by Energy Systems Catapult[89] discusses the necessity of thermal storage to manage the peak demand of heat pumps as uptake increases. The report provides a high-level estimate of thermal storage requirements to eliminate power draw from the heat pump during the evening peak demand period. Designing the system for peak load (very cold days) would require 20kWh of thermal storage in a typical northern UK home. This size of thermal store will not be feasible in most homes.

Theoretically a buffer tank can also be used for daily energy storage, with the heat pump operating on off-peak electricity and heating up the buffer. However, this is not feasible or recommended. Kensa has estimated the storage requirements for this to be several thousand litres[90]. A simulation[91] of this arrangement found that 1000L of hot water buffering was required to move the operation of a heat pump to the off-peak hours on an E10 tariff. This also increased the heat pump’s electrical demand by over 60%. As a result, household bills increased.

7 Simulation of storage scenarios

To analyse the financial benefits that energy storage can offer there are several factors to consider, which we combined and simulated.

We identified five standard property archetypes. Each had separate annual figures for electrical demand and heat demand covering a range from low (flat) to high (detached house). Taking data from the National Grid reports summer\winter outlooks covering 2020, we assigned each week a proportion of the annual demand for heat demand and electrical demand. This allowed us to seasonally adjust the simulation. The simulation used three tariff types, along with their associated peak and off-peak periods and prices per kWh (Table 6).

[87] Short-cycling is when a heat pump turns on and off too frequently. It adversely affects the lifetime of the compressor and other components and can reduce system efficiency.
[88] CXC (2021) Heat pump use in Scotland - an evidence review
[89] Energy Systems Catapult (2019) Pathways to Low Carbon Heating: Dynamic Modelling of Five UK Homes
[90] Kensa Heat Pumps (2016) Buff up your knowledge of buffer tanks (last accessed 29 Nov 2021)
[91] Kelly, N.J. et al. (2014) Performance assessment of tariff-based air source heat pump load shifting in a UK detached dwelling featuring phase change-enhanced buffering

Table 6: Tariff types and associated costs used

Tariff Type	Off-peak price	Peak price	Price difference
Standard single rate	£0.20	£0.20	Baseline
Octopus Agile	£0.15	£0.35	£0.20
Economy 7	£0.10	£0.23	£0.13

We created three demand profiles which could differentiate between peak and off-peak costs. Storage capacity and capital costs based on the research findings were input to the simulation to provide annual savings, annual running costs, and payback period. While some current commercial options have been coded, this exercise was not designed as a feasibility study for any specific storage solution.

Due to the complexity of the problem, a simulation was designed in R which could run through every combination of inputs and storage options to output a csv file to be viewed in Excel with all the results. Of the 1500 combinations we identified a few key scenarios which are explored in Appendix C. To make the simulation more flexible it has been coded so that the property archetypes, demand profiles and tariff prices can each be adjusted separately, and new storage technologies can be added and analysed.

The simulation in R can provide results for all possible combinations of archetype, storage type/capacity, and tariff. This section identifies the best-case scenarios across a range of archetypes and demand profiles.

The capital costs used in the simulations below for electric batteries and thermal storage were based on an aggregated median of the identified commercial options in the research. This has led to a capital cost of £740 per kWh of electrical battery storage, and the simulation runs through the potential capacity options in increments of 2 kWhs. For each of the simulated scenarios in Table 7 the ideal size of storage has been identified for two goals:

- to minimise the payback period (‘Min’)
- to maximise the annual savings (Max’)[92]

These are therefore the minimum and maximum logical levels of storage for the given scenario. Any choice of storage smaller than the lower value would represent an undersized storage solution, and any storage larger than the higher value would not result in any increase in annual savings.

For the heat batteries there is currently only one commercially available option and so the costs were from Sunamp with an allowance for installation. These costs were chosen to be £500 in the case of a ‘simple’ installation at the same time as a heat pump or £1500 to reflect the increased cost to retrofit the heat battery as a single item. This is based on the required trade persons already being on site to facilitate the installation in the ‘simple’ case, compared to being solely brought in to install the heat battery alone.

For all the simulations shown in this section the heating source is a heat pump. To simulate an installation where the heating is supplied by electric resistive heating, the conversion ratio from an annualised gas heat demand to an ASHP equivalent demand has been removed. Holding all other variables equal this will result in an increased

[92] See Appendix C: Simulation details

annual heat demand (in kWh p.a.), which drives an increase in annual heating costs equivalent to the inverse of the conversion ratio[93].

Note that this change only affects the heating demand and costs, the non-heating electricity costs are the same. If the same electrical storage solution specification (both in capacity and capital cost) is used, the annual savings will remain the same and therefore the payback period would also be unchanged from the ASHP scenario.

To consider the impact of storage heaters on the simulations shown in this section, they would be the maximum storage level for each archetype on the Economy 7 tariff. This is because they would need to store all the required heat for the property only charging during the off-peak period. Again, as there is no conversion factor, the capacity and running costs would be 2.5 times the value.

7.1 Key scenarios: electric batteries

The key difference between electrical and thermal storage is the benefit of the stored electricity also being available for a property's electrical demand outside of the heating source. To demonstrate this, a column has been included to show the proportion of the battery capacity that is used to power the heat source only.

[93] See Appendix C: Simulation details

Table 7: Best-case payback period and best-case annual savings for three archetypes, demand profiles and tariffs for electrical storage installed alongside a heat pump.

Scenario		Storage capacity and capital cost	Annual savings compared to single rate tariff	Payback period in years	Proportion of capacity used for heat	Annual heating cost
Economy 7 - low peak demand – Flat	Min	6 kWh - £4440	£284.70	15.6	0.79	£956.56
	Max	20kWh - £14,800	£591.46	25	0.34	£649.96
Agile - low peak demand – Flat	Min	2 kWh - £1280	£126.88	11.7	0.6	£1010.54
	Max	4 kWh - £2960	£162.49	18.2	0.3	£974.93
Economy 7 - medium peak demand - Mid-terrace	Min	10 kWh - £7400	£473.63	15.6	0.77	£1209.05
	Max	28 kWh - £20,720	£857.83	24.2	0.37	£824.85
Agile - medium peak demand - Mid-terrace	Min	2 kWh - £1480	£146.00	10.1	0.84	£1434.95
	Max	8 kWh - £5920	£343.68	17.2	0.34	£1237.27
Economy 7 - high peak demand – Detached	Min	16 kWh - £11,840	£757.80	15.6	0.79	£1877.53
	Max	48kWh – £35,520	£1214.44	25	0.38	£1420.89
Agile - high peak demand – Detached	Min	4 kWh - £2960	£292.00	10.1	0.86	£2238.08
	Max	16 kWh - £11,840	£708.42	16.7	0.37	£974.93

Table 7 shows a range of scenarios highlighting the minimum and maximum storage capacities across different archetypes, demand profiles and tariffs. Any capacity lower than the minimum would not store enough energy to offset any of the peak period. Any capacity higher than the maximum would have no benefit as the heat demand during the peak period would be lower than this, meaning the battery would not fully discharge. The maximum is also the point where the battery capacity would provide the highest possible annual savings.

It is important to note that the scenarios that show shorter payback periods are based on the £0.20 price differential of the Octopus Agile tariff as seen in Table 6. Although this level of differential has been seen, the volatility of the Agile tariff would mean it wouldn't be consistently this high, with a lower differential resulting in increased payback periods. In addition, the demand profile should be noted, with a high peak demand profile having a higher proportion of heating provided during peak price periods and so focussing the savings. So, these scenarios should be considered as an *absolute best case*.

It is also key to note the practical implications of the maximum battery capacity, so although the potential bill savings can be maximised with a large capacity battery, it may be physically too large to fit into the property.

The scenarios where the Economy 7 tariff have been used can be compared to case studies with confidence as it is not as volatile as the Agile tariff, but as the peak period is through most of the day the demand profile has less impact on the results. It's also notable that the storage capacity for both the minimum and maximum is increased, which again may lead to practical issues depending on space availability in the archetype.

7.2 Key scenarios: heat batteries

With the simulations for heat batteries, it was important to consider the relative impact on the SPF of the heat pump, which was identified in the research to be lower than the modelled 2.5. The savings are therefore based on a higher initial running cost assuming a lower SPF.

As the range of capacity on the Sunamp PCM batteries is significant between the two available models (5kWh – 40kWh) the larger capacity model is not shown for the low or medium demand profiles of the flat and mid-terraced house as there is no discernible benefit. This is due to the lower demand during the peak periods, compounded with the fact that heat batteries can only satisfy heat demand, rather than electric batteries which can also satisfy standard electricity demand.

Table 8: Best-case payback period and best-case annual savings for three archetypes, demand profiles and tariffs for PCM storage installed alongside a heat pump.

Scenario	Storage capacity and capital cost	Annual savings	Payback period in years	Annual heating cost
Economy 7 – low peak demand - Flat	Sunamp - 5 kWh £2200	£198.99	11.1	£1042.43
Agile - low peak demand - Flat	Sunamp - 5 kWh £2200	£88.70	24.8	£1048.72
Economy 7 - medium peak demand - Mid-terrace	Sunamp - 5 kWh £2200	£222.80	9.9	£1459.88
Agile - medium peak demand - Mid-terrace	Sunamp - 5 kWh £2200	£196.11	11.2	£1384.84
Economy 7 - high peak demand - Detached	Sunamp - 5 kWh £2200	£237.25	9.3	£2398.08
	Sunamp - 40 kWh £8000	£868.37	9.2	£1766.96
Agile - high peak demand - Detached	Sunamp - 5 kWh £2200	£293.45	7.5	£2236.63
	Sunamp - 40 kWh £8000	£432.95	18.5	£2097.13

Note that under the high demand, detached archetype combinations, the 5kWh capacity heat battery performs similarly, as they are a somewhat undersized solution given the demand under either tariff. For the 40kWh system the annual savings for the Agile tariff are around half of those under the E7 tariff. This effect is caused by the limited discharge period of 3 hours under the Agile tariff, which becomes a limiting factor in terms of the number of kWh's which can be utilised during the peak period to generate savings.

7.3 Key scenarios: thermal storage

Although thermal storage scenarios compare favourably in the cost-benefit analysis, consideration needs to be made for the space requirements. For example, in a flat with a low demand profile on an Economy 7 tariff, the maximum potential savings could be met with 11kWh of storage. However, this would be approximately 1000 litres, dependent on stored water temperature, and so unlikely to be feasible in the property due to the weight and the space requirements[94].

The simulation does highlight the relative benefit of having even a small capacity of thermal storage when installed alongside a heat pump and dual rate or flexible tariff.

Table 9: Best-case payback period and best-case annual savings for three archetypes, demand profiles and tariffs for thermal storage installed alongside a heat pump.

Scenario		Storage capacity and capital cost	Annual savings	Payback period in years	Annual heating cost
Economy 7 - low peak demand - Flat	Min	7 kWh - £1200	£266.38	4.5	£975.04
	Max	11 kWh - £1600	£322.87	5	£918.55
Agile - low peak demand - Flat	Min	2 kWh - £700	£88.70	7.9	£1048.72
	Max	As above			
Economy 7 - medium peak demand - Mid-terrace	Min	9 kWh - £1400	£363.86	3.8	£1318.82
	Max	17 kWh - £2200	£489.49	4.5	£1193.19
Agile - medium peak demand - Mid-terrace	Min	4 kWh - £900	£194.12	4.6	£1386.83
	Max	5 kWh - £1000	£196.11	5.1	£1384.84
Economy 7 - high peak demand - Detached	Min	9 kWh - £1400	£432.13	3.2	£2203.20
	Max	29 kWh – £3400	£868.37	3.9	£1766.96
Agile - high peak demand - Detached	Min	6 kWh - £1100	£353.48	3.1	£2176.60
	Max	10 kWh - £1500	£432.95	3.5	£2097.13

The table above reinforces the effect of the shorter peak price discharge period under an Agile tariff as a limiting factor on savings. Now that we are no longer constrained by there being only two options in terms of capacity, the table shows the optimised sizing, based on the median price per litre (converted to kWh) of the current commercial options. The Agile scenarios require lower capacity storage to optimise their performance as the peak period is limited to only three hours, compared to 17 hours of the higher rate tariff with Economy 7.

Although the pay back periods and savings look favourable across the scenarios, as with the electrical batteries, space constraints in the archetypes may limit the possibility of installing thermal storage alongside heat pumps. Especially as there would also be a space requirement for the DHW cylinder.

[94] See 'Energy stored in water calculation' (Appendix C: Simulation details)

8 Conclusions

8.1 Key findings

The findings in this report are based on an evidence review, interviews with stakeholders and the development of a simulation tool. The findings relate to the cost savings which can be achieved through the installation of electric batteries, heat batteries, and thermal storage when installed alongside heat pumps.

How storage technologies can reduce energy costs

- The research explains how bill savings can be made by pairing storage technologies with self-generation, and by storing off-peak electricity for later use.
- In addition to storing cheap or free electricity, electric batteries can export electricity to the grid and provide grid balancing services. This is an additional source of revenue for consumers which cannot be provided by heat batteries or thermal storage.
- It is not feasible or recommended to use thermal storage to fully shift heat pump operation to off-peak periods. This is due to the size of thermal store required, and the likelihood of increasing consumer bills.
- Pairing phase change material (PCM) heat batteries with heat pumps will result in lower efficiencies due to the required flow temperature being above 55°C.

Availability of evidence

- Due to limited evidence, it is not possible to draw wide-reaching conclusions on the potential role of storage technologies in reducing consumer bills There is limited monitoring data or evidence of cost savings for consumers across all storage types reviewed. However, more evidence is available for electric batteries than heat batteries and thermal storage.
- Although domestic thermal storage is fairly ubiquitous, we found no monitoring data or case studies for thermal storage paired with a heat pump.
- Due to this lack of quantitative evidence, we have used case studies to illustrate some of the potential ways in which storage technologies have been employed to reduce consumer bills. However, the conclusions and comparisons we can draw from these case studies is limited.
- The simulation tool provides the opportunity to simulate the savings that can be achieved for each storage technology by altering the variables of tariff type, property size, and electrical and heat demand.
- The simulated scenarios across different property archetypes and demand profiles show that without pairing storage with electrical generation the return on investment is usually longer than the expected lifespan of the technology. In certain scenarios where the return would be within the lifespan, there would be limiting factors such as space requirements. This corresponds with the findings from the evidence review and stakeholder interviews.

Quantifying bill savings

- The case studies illustrate that in some instances bill savings have been achieved, and also instances where householders' bills have increased.

- Case study 1 demonstrates that pairing electric batteries with solar PV resulted in average savings per household between £44 and £67[95].
- Case study 2 illustrates that using electric batteries with off-peak electricity tariffs resulted in estimated annual savings of between £208 and £436, dependent on tariff type. However, the savings of £436 were short-lived as these were based on a dynamic ToU tariff[96] which subsequently increased. Tenants' bills increased to higher than their bills prior to the battery installation.
- Case study 5 illustrates a huge range in heating bills as a result of the installation of heat batteries with heat pumps (replacing solid fuel heating). The impact on bills ranged between a £326 increase to a £360 saving across four households. The main reason for this range is the different types of tariffs being used. Householders made savings if they were able to switch to a dual rate tariff. One householder could not access a dual rate tariff and their bills increased as a result of switching from solid fuel heating to a heat pump with a heat battery.
- Where savings have been achieved in the case studies, they represent significant bill savings for those in fuel poverty.

Trade-offs, risks and sensitivities

- Where savings have been achieved, the savings figures are a small proportion of the current capital costs of most storage technologies. In most cases the financial savings will not cover the cost of installing storage technologies, and additional grant funding will be required.
- The instances where householder bills have increased illustrate the risks of relying solely on off-peak electricity without self-generation.
- Due to the volatility of dynamic tariffs, it can be difficult to predict bill savings for consumers. Dynamic tariff prices track the wholesale electricity price and there is a risk that consumer bills may increase. This may also result in self-funding consumers failing to recoup investment. The use of static tariffs provides more predictable savings, however the potential for bill savings is lower due to the lower price differential between peak and off-peak electricity rates.
- We found evidence of difficulties accessing time-of-use (ToU) tariffs due to metering arrangements. This occurred in households unable to get a smart meter or with double MPAN setups (two electricity meters, such as dynamic teleswitch meters). Without microgeneration or the ability to switch to a dual rate or smart ToU tariff, the installed batteries in these instances were redundant.
- Where housing providers install storage technologies and rely on electricity tariffs to provide cheap electricity there is a risk of tenants inadvertently switching away from a ToU tariff. This could negate bill savings.
- The case studies provide examples of some of the sensitivities to error when pairing storage solely with tariffs. A small error in case study 5 caused a heat battery to charge for 1 hour a day at peak prices. This error would have cost an estimated £125 over a year.

Mitigations

- Pairing storage technologies with microgeneration such as solar PV can go some way to mitigating the risks associated with relying solely on off-peak electricity

[95] Annual figures have been extrapolated based on the average household savings from case study 1 of £37.06 and £55.80 over a 10-month period.
[96] See Table 3 for explanation of tariff types

tariffs. For this reason, several electric battery installers noted that they would not recommend installing a battery without onsite generation.

- However, the use of solar PV does not guarantee that bill savings will be significant enough to recoup investment in storage technologies.
- Recent research published by Solar Energy UK[97] concluded that currently the additional cost of installing a battery with a solar PV system outweighs the savings enabled through storing surplus generation.
- The cost of installing electric batteries can also be partially offset through the provision of grid services. The current financial benefit for consumers of providing grid services is around £50 per year, although can be up to £120 per year. This is significant in the context of anticipated total savings from battery use. However, some grid service contracts limit this annual income to two or three years.

8.2 Recommendations

As a result of our findings, we recommend that:

- Once published, the monitoring results from ongoing projects with building-level storage should be reviewed for evidence of financial savings for consumers. This includes the BEIS electrification of heat pilot, OVO Energy's trial with Powervault[98] and various Scottish Government funded projects[99].
- Ensure the Distribution Network Operators (DNOs) in their transition to District Systems Operators (DSO) actively provide support for local and national flexibility markets by engaging with aggregators when planning for the increased future demand on the grid.
- Where feasible, installers and property owners should be encouraged to pair thermal storage with heat pumps. Although there is limited evidence of the direct financial savings that this can provide for consumers, the benefits of improved system efficiencies, heat pump longevity and the ability to ease pressure on the grid during peak periods will provide indirect financial benefits.
- Grant funding or some form of financial incentive may be necessary to encourage the installation of thermal storage with heat pumps.
- Further research is conducted to understand what the identified savings from existing and ongoing research might mean for rates of fuel poverty.

[97] Solar Energy UK (2021) The Value of Solar Property
[98] Ovo Energy Ovo Smart Home (last accessed 29 Nov 2021)
[99] For example, Changeworks are conducting M&E for the LCITP funded project in Moray and two Decarbonisation Fund projects in Edinburgh and Midlothian

Appendix A: Methodology

Scoping

The research team formulated specific research questions and sub-questions which addressed the aims and cross-cutting themes of this research. We produced a research framework to structure the direction, topics and prioritisation of research objectives.

The research framework contained the following research questions:

1. **Technology overview**
    a. How does each storage technology operate?
    b. What are the barriers to installation that may be prevalent across the Scottish housing stock?
2. **For each storage technology, what is the status of the current market in Scotland?**
    a. Across a range of brands / models, how many installs have there been to date or per annum in recent years?
    b. Are there clear routes for future cost reductions?
    c. What types of properties are storage technologies normally installed in?
    d. What is the usual customer profile for installs?
    e. Are there any issues with availability of the technology?
3. **In-situ monitoring data**
    a. How does each storage technology perform in-situ in terms of efficiency?
    b. What evidence is there of bill savings as a result of each storage technology?
4. **What are the costs to own and use battery storage?**
    a. What are the purchase costs for each storage technology?
    b. What are the install costs for each storage technology?
    c. What are the operational and maintenance costs for each storage technology?
5. **In theory, how can each technology reduce energy costs for consumers:**
    a. Through reducing energy use?
    b. In conjunction with solar PV or other microgeneration?

c. By shifting consumption and using ToU tariffs or optimisation?

d. Are there examples of tariffs being designed around storage in other countries?

6. What are the advantages of phase change storage?

a) What advantages do phase change storage technologies have over traditional domestic hot water cylinders?
b) Could phase change storage technologies support the installation of heat pumps in space constrained homes?

In recognition of the lack of published monitoring data for battery storage, the research team made contact with a number of stakeholders which may have unpublished performance data and figures for the market analysis. This included energy storage manufacturers, installers, distributors, aggregators, consultants, and registered social landlords (including local authorities) involved in battery storage projects.

Identification of evidence

Based on the research questions, the research team developed inclusion and exclusion criteria and search terms to guide the evidence search through identification of grey literature, published research, academic papers, and case studies on academic (Web of Science, Scopus etc.) and non-academic (Google) search engines, and through reference mining. The research team were also able to draw on Changeworks' own project records for in-situ performance and market data.

The following search terms were used to identify sources:

Table 10: List of search terms

heat	*thermal storage*	*tariff*	*shift*
electric	*buffer*	*ToU*	*aggregation*
storage	*accumulator*	*operate*	*fabric*
lithium-ion	*redox flow battery*	*battery*	*building*
Li-ion	*HHR storage heater*	*smart storage heater*	*archetype*
domestic	*Quantum*	*peak*	*property*
phase change	*bill*	*barrier*	*housing*
Sunamp	*costs*	*constraint*	*Scotland*
hot water	*biomass*	*consumption*	*solar*
cylinder	*space*	*behaviour*	*photovoltaic*
tank	*size*	*change*	*PV*
advantage	*reduce*	*microgeneration*	*surplus*
benefit	*demand*	*flexible*	*optimisation*
PCM	*multi-source*	*heat pump*	*manufacturer*
running costs	*energy storage system*	*technical specifications*	*specifications*
maintenance costs	*annual*	*stationary battery*	*BESS*

Relevant stakeholders were also recorded. Stakeholder interviews were used to gather evidence on number of installs, costs, issues around availability and viability, and the role of storage in space constrained homes. An overview of stakeholder groups can be found in Table 11.

Table 11: Stakeholder types and engagement summary

Stakeholder Type	No. Invited to interview	Information asked for	No. Interviews completed
Manufacturer	9	State of market, CAPEX, OPEX, performance data, impact on bills	3
Installer	7	State of market, CAPEX, OPEX, performance data, impact on bills	3
Distributor	3	State of market, CAPEX, performance data	2
Aggregator	7	State of market, performance data, impact on bills	3
Consultant	2	State of market, performance data, impact on bills	1
RSL	8	Performance data, impact on bills, customer experience	4
Strategic Overview	4	State of market, case studies	2
Total	**40**		**18**

Table 12: Stakeholder engagement summary by storage technology.

Storage type	No. invited to interview	No. interviews completed
Electric battery	22	9
PCM	3	1
Thermal storage	10	4
Multiple technologies	10	6
Total	**45**	**20**

Evidence review

The research team read executive summaries (or similar) from the identified evidence and screened it against the agreed inclusion / exclusion criteria:

- Initial search was limited to evidence from the last 5 years to capture the current state of storage technologies and the market. For cost data, any evidence prior to the last 12 months was excluded.
- English language papers only (for literature search).
- Evidence was limited to that from Scotland and the rest of the UK, particularly when assessing the current state of the market, and factors relevant to the Scottish building stock. Some international evidence was reviewed where it can provide insight into developments in technologies or tariff structures which are not currently available in Scotland or the UK.

The quality, strengths and weaknesses of each evidence source were assessed and sources were mapped against the research questions. This process ensured that each piece of evidence we reviewed was relevant to the research, and clearly demonstrated where there were gaps in the evidence.

Appendix B: Alternative storage technologies

The following three technologies were not included in the evidence review and analysis. Descriptions of the storage technologies are included in this appendix as they should be included when considering building-level energy storage.

Flow batteries

Flow batteries store energy in electrolyte liquids. The most common examples of this technology are rechargeable batteries in electrical devices. Flow battery technology is not as prevalent or developed as Li-ion battery technology. Current flow batteries are very large and mainly designed for grid energy storage. Widespread use is unlikely to occur for another five to ten years[100]. However, domestic-scale products have already been developed by Australian firm Redox.

Similar to electric batteries, flow batteries can be integrated with renewable generation or renewable heating systems. Flow batteries offer several advantages over Li-ion batteries:

- capable of overload and total discharge without any risk of damage[101]
- have a life span of up to 30 years and over 10,000 cycles[102]
- can provide stored energy for 6-8 hours

[100] Zero Waste Scotland (2021) Battery use in Scotland now and in the future: Phase 2 - The future of batteries in Scotland
[101] Leung, P. et al. (2012) Progress in redox flow batteries, remaining challenges and their applications in energy storage
[102] Scroggin-Wicker, T. and McInerney, K. (2020) Flow Batteries: Energy Storage Option for a Variety of Uses

We have included this description of flow batteries due to their potential as an alternative to Li-ion batteries in the future. However, flow batteries are not included in the evidence review or simulation due to their limited domestic application in the UK.

Storage heaters

We have included a brief description of storage heaters as they are an important storage asset which is already installed in numerous properties across Scotland. However, storage heaters are also beyond the scope of the evidence review or simulation exercise.

Storage heaters use electricity to heat electrical elements which transfer heat to a solid stone core. HHRSH are more efficient than standard storage heaters and up to 27% cheaper to run[103]. This is due to increased insulation, more sophisticated controls and improved heat delivery. These systems can estimate heat demand using previous heat habits and predicted climactic conditions and can be controlled remotely using smart phone apps.

Current storage heaters operate on static dual rate tariffs. Smart storage heaters will enable more dynamic use of their storage capacity, allowing storage heaters to respond to price signals. Like electric batteries smart storage heaters can be aggregated to provide grid balancing services.

Solid heat battery

Products such as Warmstone by Caldera[104] use similar technology to storage heaters. These stores are very large, insulated blocks of a solid storage material heated by electrical elements. The store can be charged through off-peak electricity or self-generated electricity, and heat is discharged via a heat exchanger to produce hot water.

Due to their size and weight, these types of storage solutions must be installed outside on a solid base. For example, the Warmstone is 1.1m diameter, 1.8m tall and weighs 1.85 tonnes. This will preclude their use in many properties without the necessary outdoor space.

Appendix C: Simulation details

Introduction

This document provides explanatory notes and information regarding the modelling aspects of the research. The model has been coded using the R programming language in order to provide a more flexible, and expandable solution than Excel would be able to offer. The model been designed to allow most inputs to be easily adjusted, or to increase the number of scenarios such as additional property archetypes or demand profiles.

The primary outputs of the code are two .csv files, (split by electric or thermal only solutions) which contain a row of results for each permutation of the inputs. There are secondary outputs within R such as plots and console printouts, but these will only be viewable on running the code.

[103] Counsell, J (2014) Running Costs of Conventional Electric Space Heating Systems
[104] www.caldera.co.uk/warmstone-heat-battery (last accessed 29 Nov 2021)

The first section of this document provides a brief summary of the model and its inputs, along with the underlying assumptions and known limitations. The second section goes into detail on each of the input types, what is currently being used, and an explanation as to why certain values have been chosen, where choices are available.

The final section gives a sample of the R outputs from the model, specifically results to explore how the potential annual savings vary based on property archetype, demand profile and maximum storage capacity. This is followed by a small sample of the console outputs.

Model parameters

Assumptions and known limitations

The model assumes that the storage solution will have one cycle per day, charging at the lowest price point and discharging during the peak period. It also does not consider any interactions with renewable generation such as solar PV or solar thermal, nor does it consider selling excess storage capacity back to the grid.

This is a necessary assumption due to the lack of detailed manufacturer\supplier data tracking storage states on a half-hourly basis, those states being charging, discharging, full or empty. Additionally, we have no data on the precise conditions under which some state changes are possible which would be necessary to model charging from generation which will happen at multiple points throughout the day.

Another limitation is that the seasonal adjustments have been applied per week to the yearly demand, but not to the demand profile level. This is due to a lack of data on how 24-hour use patterns vary throughout the year.

For standard thermal solutions (i.e., hot water cylinder) we have assumed that each 100L of hot water capacity is the equivalent of 1.11kWh of storage capacity.

Input parameters

The following are the broad categories of data which the model currently uses as inputs. The model has been coded with flexibility and expandability in mind so these should not be considered as fixed.

Table 43: Summary of input parameters used within simulation

Input Type	Required Field	Unit	Notes
Property archetypes	Annual electricity demand	kWh p.a.	
Property archetypes	Annual heat demand	kWh p.a.	Heat demand is inputted as a "gas equivalent" figure, see conversion
Demand profile	Daily peak heat proportion	Proportion (from 0 to 1)	How much of the daily heat demand is during "peak hours"
Demand profile	Daily peak electricity proportion	Proportion (from 0 to 1)	How much of the daily electricity demand is during "peak hours"
Price	Average daily low and high price	£ per kWh	
Seasonal Adjustment	Vector of weekly heat demand proportions	Proportion (from 0 to 1) of annual heat demand	Currently based on national grid data
Seasonal Adjustment	Vector of weekly electricity demand proportions	Proportion (from 0 to 1) of annual electricity demand	Currently based on national grid data
Storage Solution	Technology	Electric or thermal solution	The model separates these options and runs slightly different calculations for each
Storage Solution	Capital Cost	£	Includes VAT
Storage Solution	Maximum capacity	kWh	
Storage Solution	Installation costs	£	Thermal only, can be a single rate or vector of options

Property archetypes

Five standard property archetypes were used for the simulations, summarised below, figures in kWh.

Table 54: Agreed property archetypes with energy demand used in simulations

Property Type	Electricity	Heat (Gas)	Total
Flat	3000	9800	12800
4-in-a-block	3300	11400	14700
Mid-terrace	3600	13000	16600
End-terrace/ semi-detached	3800	15200	19000
Detached	4800	20500	25300

To convert the gas demand above to the equivalent demand of a heat pump the following calculation was used.

$$ASHP\ demand = \frac{Gas\ demand * 0.92}{2.5}$$

0.92 represents the efficiency of a modern gas boiler and 2.5 represents the scaling (rule of thumb) of heat pump efficiency.

Demand profiles

Demand profiles have been abstracted due to limited data regarding 24-hour demand profiles and how these throughout the year. Note that these values can be varied separately to consider cases where (for example) the peak heat is low, and the peak electricity is high.

For the Octopus Agile tariff scenario three demand profiles have been created, based on what proportion of their daily use will be during the peak period. The baseline is for low\constant use, and as such takes a value of 3/24 (12.5%) since the peak period covers three hours out of 24. Medium use has been assigned a value of 5/24 (21%) and high is 7/24 (29%).

Table 15: Outline of the three demand profiles used in the simulations for the Octopus Agile tariff

Demand Profile	Peak electricity	Peak heat
Low \ Constant	12.50%	12.50%
Medium	20.83%	20.83%
High	29.17%	29.17%

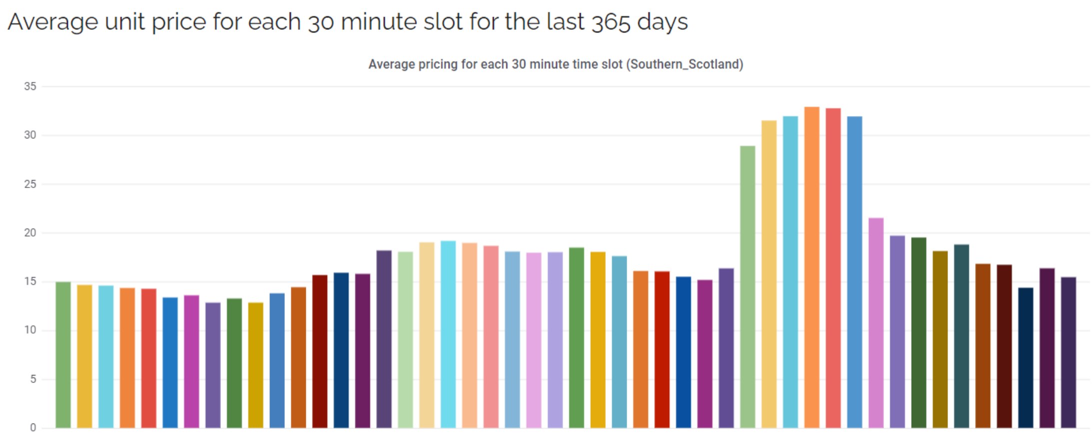
For Economy 7 tariffs where the peak period covers a larger proportion of the day the percentages above must be increased to reflect this. Given that the peak period now covers 17 out of 24 hours, the low\constant use percentage is $\frac{17}{24} \cong 71\%$ we have chosen demand profiles as follows

Table 16: Outline of the three demand profiles used in the simulations for the Economy 7 tariff

Demand Profile	Peak electricity	Peak heat
Low constant	70%	70%
Medium	80%	80%
High	90%	90%

Prices

The model assumes that the storage solution will have one cycle per day, charging at the lowest price point and discharging during the peak period. In the Agile tariff scenario this peak period is three hours, between 4pm and 7pm. Currently this is set to a £0.20 difference. This value was chosen based on the average unit price for each 30-minute slot for the last 365 days table from [Octopus Agile Southern Scotland - Energy Stats UK (energy-stats.uk)](energy-stats.uk)



For the economy tariffs the price difference used will be £0.13 per kW. This figure was taken from the latest Sutherland tables, but does not differentiate between E7 or E10 tariffs:

Off Peak - 1 Unit	
Night rate for 90% of use	10.37
Day rate for 10% of use	23.38

Figure 3 : Current Economy 7 costs from the Sutherland Tables November 2021

Seasonal adjustments

Seasonal adjustments taken from National Grid reports Summer\winter outlooks covering 2020[105].

To calculate the weekly gas demand figures, daily figures for 'non-daily metered' were summed and averaged per week. Each week was divided by the total to work out proportion of yearly heat demand for that week.

For electricity demand the calculation was similar to gas demand, but the original data was already summarised by week.

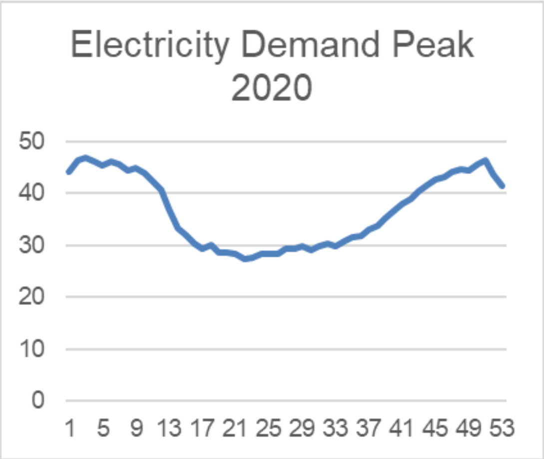


Figure 4 : Seasonally adjusted demand for household electricity

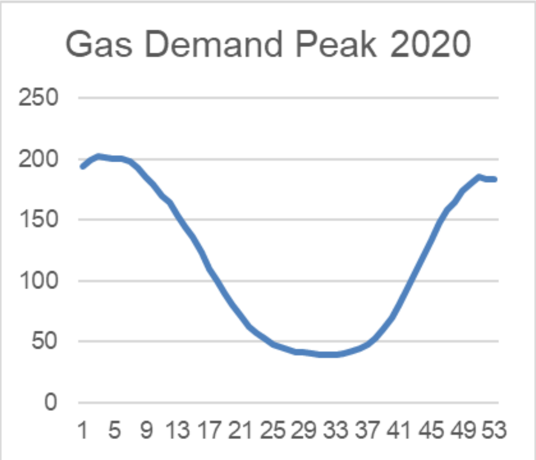


Figure 5 : Seasonally adjusted demand for household gas (heat)

The graphs above show how the simulation breaks down yearly demand figures (based on the property archetype) into seasonally adjusted weekly demand figures. As expected, heat demand throughout the year varies more than electrical demand.

[105] www.nationalgrideso.com/research-publications/summer-outlook
www.nationalgrideso.com/research-publications/winter-outlook
www.nationalgrid.com/uk/gas-transmission/insight-and-innovation/summer-outlook
www.nationalgrid.com/uk/gas-transmission/insight-and-innovation/winter--outlook

Energy stored in water calculation

To estimate the storage capacity in kWh within thermal stores expressed in litres, the following formula has been used:

$$E = c_p . \delta t . m$$

Where:

E – Energy in Kj

c_p – specific heat of water at a certain temperature ($at\ 55^oC = 4\frac{Kj}{KgK}$)

δt - temperature difference (10^oC)[106]

m – mass (100kg per 100L of capacity)

$$E = 4\ \times 10\ \times 100 = 4000Kj$$

$$kWh = \frac{Kj}{3600} = \frac{4000}{3600} \cong 1.11$$

As such any thermal solution measured in litres will be converted to kWh at a rate of 1.11kWh per 100L of storage.

Sample R outputs - theoretical storage size suitability

Using the parameters outlined above, the model is able to loop over combinations and variations. Each section below shows five outputs, one for each of the property archetypes. Each graph has three sets of results, one of each of the demand profiles. The maximum storage capacity varies along the horizontal axis, and the resulting annual saving is plotted on the vertical axis.

These graphs are independent of a specific storage solution and show how the archetype and demand profile interact with the size of storage.

[106] The assumption is that the usable energy is in the 45^oC to 55^oC range, and below 45^oC there will be no noticeable benefit on the heating system – this is variable, dependant on design flow temps etc.

Agile tariff scenario - electric solutions

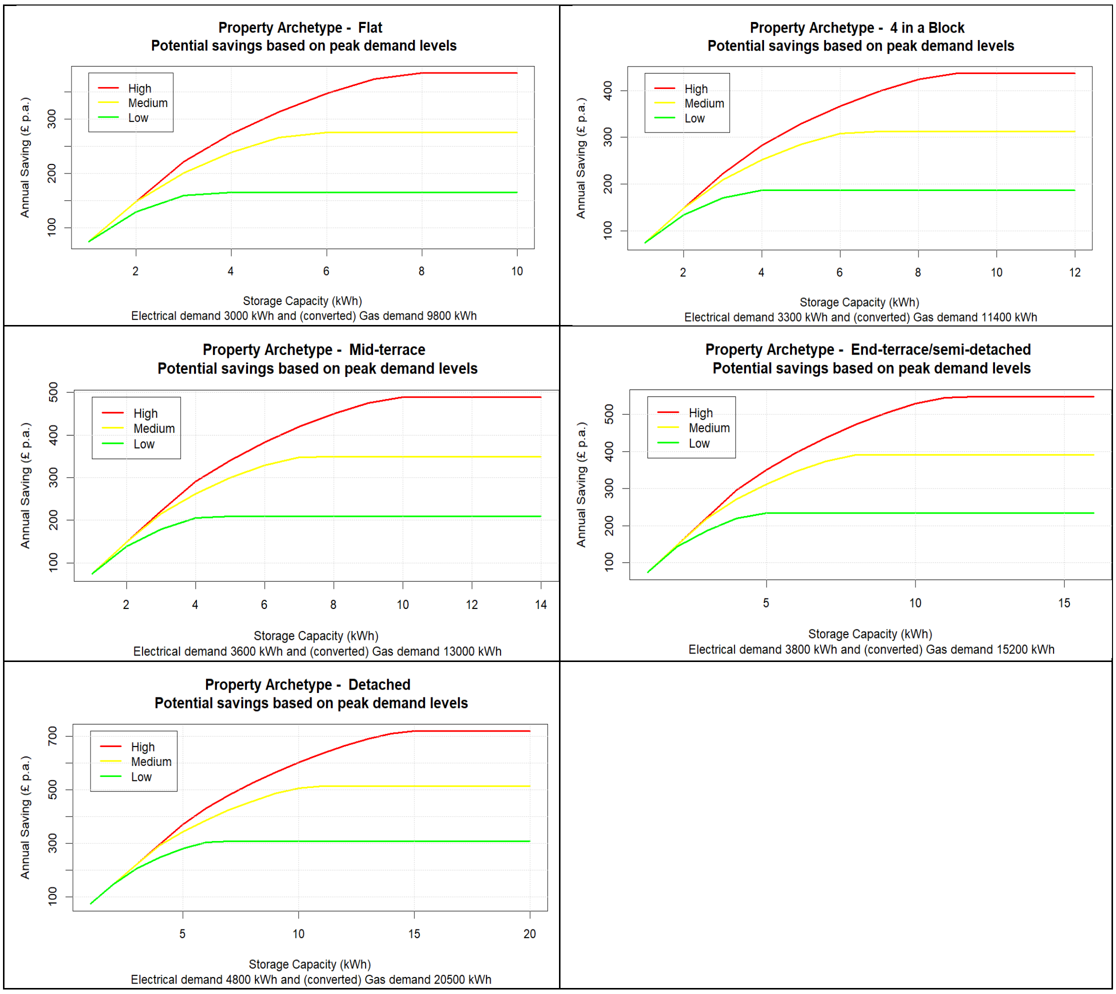
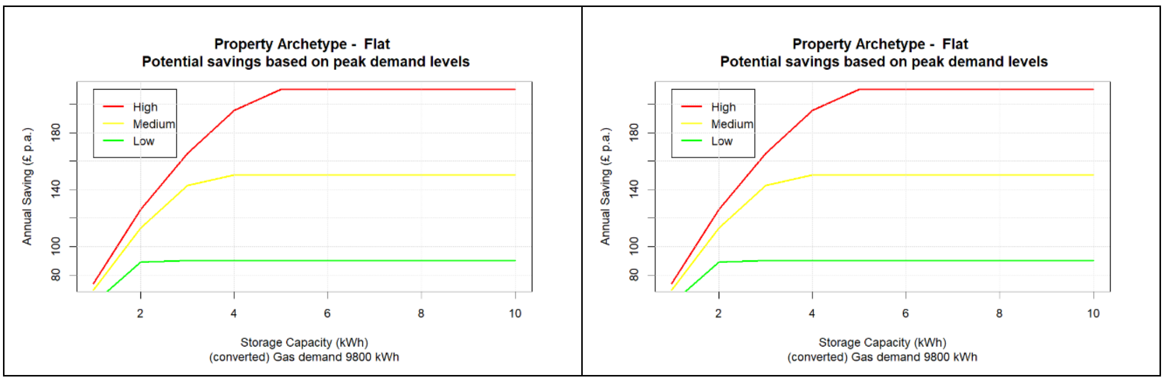


Figure 6 : Range of potential savings based on demand profile for each archetype – electrical batteries

As expected, larger properties with greater demand and more intense peak time usage will gain more benefit from a larger storage solution.

It is worth noting that the lower demand and use combinations do not benefit significantly from storage capacity increases. For example, a flat with a low peak demand profile will start to experience diminishing returns on solutions greater than 2 kWhs and will see no benefit beyond 4 kWhs.

Agile tariff scenario - thermal solutions



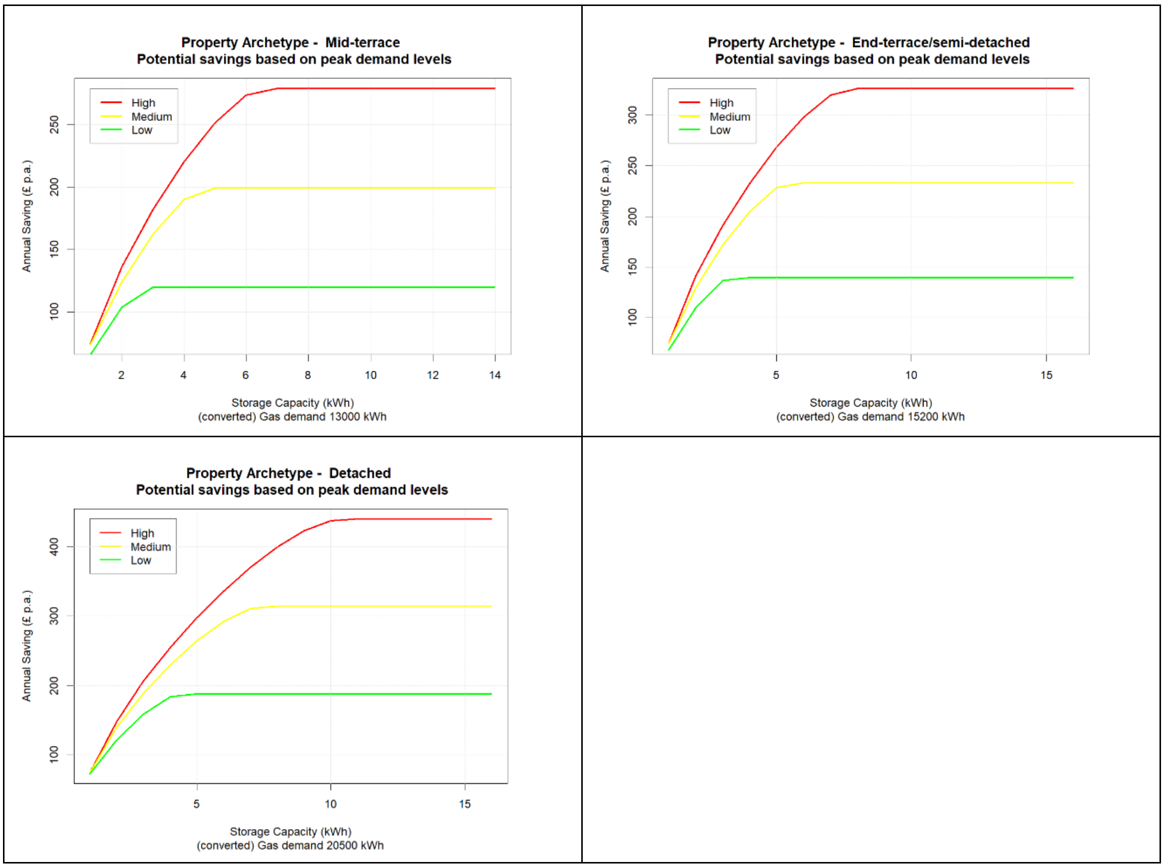


Figure 7 : Range of potential savings based on demand profile for each archetype – thermal storage

The results for the thermal only solutions are similar to electric storage, but with lower potential annual savings. This makes sense as with all other variables being equal the property will be unable to utilise the capacity for satisfying standard electrical demand. This has a particularly notable effect during the summer months, since heat demand will be significantly reduced.

Custom R simulations

This section is primarily for those who plan on interacting with the R code directly.

In section 3 of the code you will see the following:

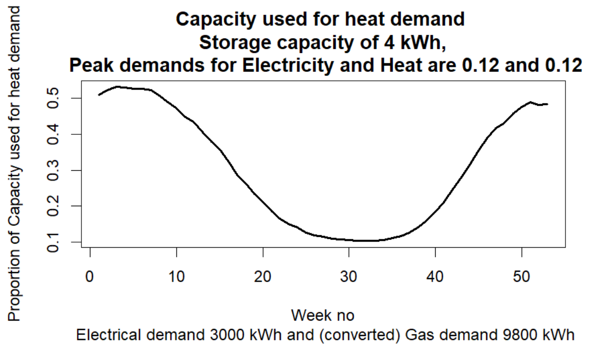
```
##########################################################################
## Section 3 - Run functions here to test out different parameters
##########################################################################

# Run main (electric) simulation for the following variables (in order):
#     Storage capacity(kWh)
#     Yearly electrical demand(kW)
#     Yearly heat demand(kW in gas equivalent)
#     Capital cost(£)
#     Electrical demand during peak hours as a proportion of daily (0 to 1)
#     Heat demand during peak hours as a proportion of daily demand (0 to 1)
# This will print a blurb in the console, return values for annual savings, ROI,
# average proportion used for heat, and plot how the capacity used for heat
# varies throughout the year

CXC_main_sim(4, 3000, 9800, 4000, 3/24, 3/24)
```

Running line 335 of the code will run the model for electric solutions with whichever values are chosen, simply overtype the values in pink and use Ctrl+Enter to execute.

The resulting console output is:

```
> CXC_main_sim(4, 3000, 9800, 4000, 3/24, 3/24)
Main simulation output
 Annual saving is £ 165.16 using yearly Electricity demand of 3000 kWh and converting
 heat required from annualised gas estimate of 9800 kWh
ROI period for this option is 24.2 years
Average proportion of capacity used for heat demand is 0.3
[1] 165.16  24.20   0.30
```

The code will generate a plot of how the proportion of capacity used for heat demand varies over the year:

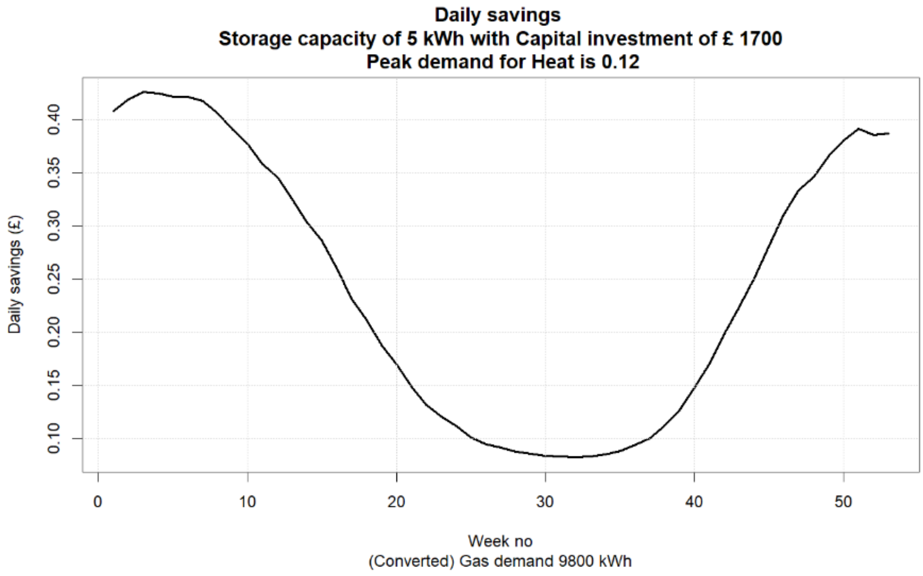


The thermal only simulation functions similarly:

```
# Run main (thermal) simulation for the following variables (in order):
#     Storage capacity(kWh)
#     Yearly heat demand(kW in gas equivalent)
#     Capital cost(£)
#     Installation cost(£)
#     Heat demand during peak hours as a proportion of daily demand (0 to 1)
# This will print a blurb in the console, return values for annual savings, ROI,
# and plot how the daily saving varies throughout the year

CXC_thermal_sim(5, 9800, 1700, 500, 3/24)
```

In the case of thermal only solutions there is no need to consider any electrical demand, since the storage cannot satisfy it. As such the plot associated with the thermal simulation shows how the daily savings vary over the year.

```
> CXC_thermal_sim(5, 9800, 1700, 500, 3/24)
Thermal storage simulation output
 Annual saving is £ 90.16 on Capital investment of £ 1700 assuming installation costs of
 £ 500 converting heat required from annualised gas estimate of 9800 kWh
ROI period for this option is 24.4 years
[1] 90.16 24.40
```



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