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UK Electrical Energy Storage: Quantifying the Impact of Policy Barriers on the Residential Investment Case

By

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A report submitted in partial fulfilment of the requirements for the MSc.

8th September 2017

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Acronyms and Glossary

BEIS	Department of Business, Energy and Industrial Strategy
BTM	Behind The Meter
C&I	Commercial and Industrial
CAGR	Compound Annual Growth Rate
CfE	Call for Evidence
CoC	Cost of Capital
DNO	Distribution Network Operator
DSR	Demand Side Response
EES	Electrical Energy Storage. Used interchangeably with “storage”
EFR	Enhanced Frequency Response
EV	Electric Vehicles
FiT	Feed in Tariffs
FRS	Frequency Response Service
HHS	Half Hourly Settlement
kW	Kilowatt = 1,000watts, a measure of power
kWh	Killowatt hour. A measure of energy – 1kW of power sustained for an hour
kWp	Kilowatt peak. A measure of maximum power output of a system eg solar system
MVA	Mega Volt Amp. A measure of “apparent” power.
NPV	Net Present Value
PHS	Pumped Hydro Storage
PV	Photo Voltaic. Used interchangeably with “solar”. Energy used to charge the battery
SGIP	Self-Generation Incentive Programme
STOR	Short Term Operating Reserve
ToU	Time of Use Tariff
VAT	Value Added Tax. Currently 20% in the UK for most products but 5% for solar panels

Abstract

This study examines the impact of policy issues on the investment case for UK homeowners adding electrical energy storage (EES) to existing solar systems. Interviews were conducted with EES providers and energy policy experts to establish the major policy issues. A techno-economic model of a lithium-ion battery was created to evaluate the investment case and quantify the impact of policy on annual income and return on investment.

Six policy issues were identified: (1) lack of ToU tariffs, (2) VAT rate uncertainty (3) the level and eligibility for subsidy (4) "deeming" (5) the absence of a market for network savings and (6) finance costs. Analysing the impact of these issues on the investment case highlights the significant boost incremental income provides returns, suggesting that enabling storage to access multiple revenue streams ("revenue stacking") should be the focus of current policy. Reducing the initial capital cost (either via subsidies or a lower VAT rate for example) has a much bigger benefit to the investment case as losses reduce.

A review of current policy suggests it appears to recognise the importance of revenue stacking and is focussed on tackling the major barriers. These initiatives may take time and interviewees were concerned about implementation in some areas. More significantly, the model suggests existing measures may prove insufficient to make residential EES an attractive investment much before 2025. This study suggests that additional policy measures such as low cost loans, a "light" subsidy and publicly stated deployment targets, used in combination, could accelerate adoption relatively cost effectively. Accelerating residential EES deployment could reduce the cost of intermittency in the electricity system, savings which could be passed onto consumers, and well as benefit the UK's industrial and decarbonisation strategies.

1. Introduction

Most academic and industry experts agree that electrical energy storage (henceforth EES or "storage") has a critical role to play in the electricity system of the future (Few, et al., 2016). To limit global warming to below 2°C, generation from variable renewable sources such as wind and solar must rise from 5% of global electricity in 2016 (REN21, 2017) to 28% by 2050 (International Energy Agency, 2014a) and from 14% to 47% in the UK (National Grid, 2017). However a fundamental property of electricity is that demand must match supply at all times. The intermittent output and distributed location of these sources poses significant challenges for electricity systems (Heptonstall, et al., 2017). Intermittency requires additional (often expensive) reserve capacity to cover any supply shortfalls while excess output on particularly sunny or windy days can overload distribution networks. EES can address these issues. By storing excess electrical energy when supply (generation) exceeds demand (consumption) for use when demand exceeds supply, the contribution of renewable generation can be managed more effectively.

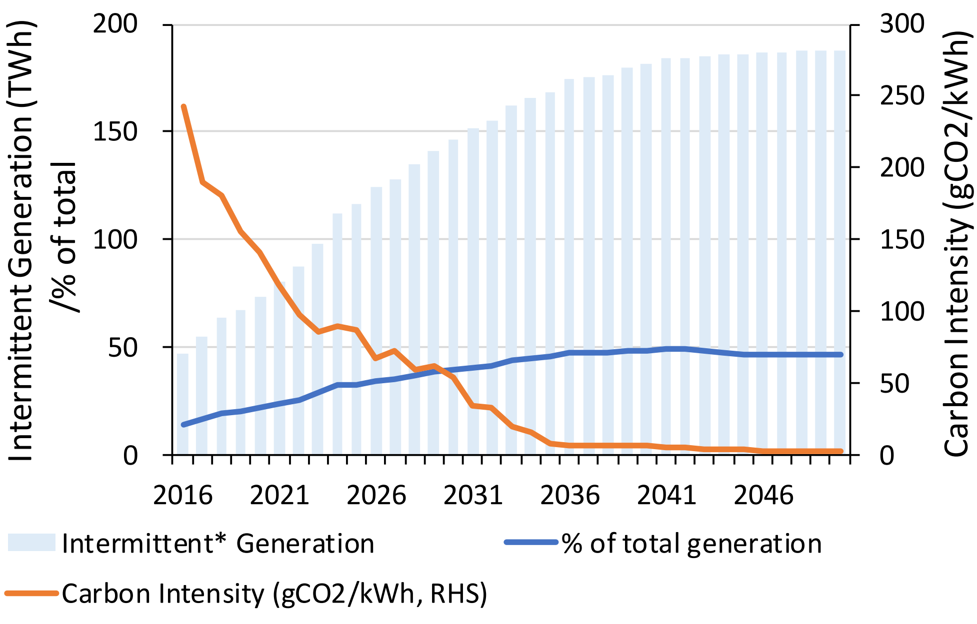


Figure 1: Growth in Intermittent Generation and Impact on Carbon Intensity

*Based on National Grid (2017) Two Degrees Scenario. * Intermittent Generation is defined as Wind (onshore and offshore) plus Solar*

Yet defining the role of storage precisely is complex. In addition to smoothing the contribution of renewables, EES can provide a number of other services. These services vary both over time and based on how and where it is deployed. Effectively EES can be a generator when electricity is needed and a consumer when generation exceeds demand. It can be deployed at scale centrally, on the distribution grid alongside intermittent renewable generators, or at industrial/residential premises. This flexibility enables it to target multiple different revenue streams and is arguably its distinguishing characteristic.

Despite its many attributes, deployment remains relatively modest. At the end of 2016 storage capacity stood at 167GW globally, 6% of average electricity demand and growth appears to be slowing even in the face of rising variable renewable penetration (US Department of Energy, 2017; BP, 2017). Today over 96% of EES is provided by PHS (Pumped Hydro Storage), large scale facilities which are expensive to build, have environmental impacts and require very specific topology and geology (US Energy Information Administration, 2012). The IEA (2014b) estimates that to limit global warming to below 2°C, grid-connected storage capacity must nearly treble to 450GW by 2050. New technologies and models need to emerge to fill this gap.

This study focusses on the potential of distributed EES, specifically the residential or Behind the Meter (BTM) model using lithium-ion. Tesla’s Powerwall addresses this segment and has attracted much publicity in recent years. Over 50,000 German consumers already have residential batteries and lithium-ion prices are falling steadily (Enkhardt, 2017).

Despite the excitement this model still faces considerable economic challenges. For the average household the potential savings to the electricity bill from EES do not come close to justifying the cost of the investment (eg. Davis & Hiralal, 2016). Growth in Germany has been largely driven by state subsidies. There is still a legitimate debate as to whether costs will ever fall low enough to drive adoption in the volumes needed.

It is generally believed that this challenge can be overcome by allowing batteries to capture more of the value they provide to the electricity system (see Eyer & Corey, 2010; Battke & Schmidt, 2015; Stephan, et al., 2017). The flexible nature of EES enables it to generate income for the homeowner while also providing services to the grid. While increasing the Self-Consumption of PV, a residential battery can also alleviate the strain on the distribution network caused by peak evening demand and be available to balance grid frequency. This "revenue stacking" is, according to Eyer & Corey (2010), "the most important topic" influencing the EES investment case.

However enabling EES to be rewarded for all the services it can potentially provide is not straightforward. In some cases markets for these services have yet to be established. In other cases, payments require complex interlinkages between the battery owner, an aggregator, the network owner and the system operator to be created. This requires co-ordination, usually by a regulator. Many studies have highlighted policy as the key obstacle to revenue stacking (Committe on Climate Change, 2016; International Energy Agency, 2014b; Bhatnagar, et al., 2013).

This study seeks to identify which policy issues pose the most significant obstacles to the residential EES investment case in the UK. This is approached by:

1) Interviewing industry experts and providers of residential storage to identify the most prominent policy issues
2) Building a techno-economic model of a residential battery to quantify the impact of different policies on the investment case

It is concluded that existing policies may prove insufficient to make residential EES an attractive investment in the near term but that there are some relatively straightforward and cost-effective policy actions that could accelerate adoption.

2. Background

This section establishes a working definition of storage, reviewing both the range of available technologies and services it can provide. It then summarises current storage policy in UK, placing it in the context of broader energy and industrial strategy in the UK and international experience. Finally conclusions from previous analysis of the residential investment case are presented.

2.1. An Overview of Electrical Energy Storage (EES)

2.1.1. A Definition of EES

This study focusses on Electrical Energy Storage (EES). The definition developed by The Electricity Storage Network "the conversion of electrical energy into a form … which can be stored, the storing of that energy, and [its] subsequent reconversion … back into electrical energy" provides a generic functional definition which distinguishes electrical energy storage from other forms of energy storage (ie. heat) and has been adopted by BEIS & Ofgem (UK Government, Department of Business, Energy and Industrial Strategy & OFGEM, 2016). This is the definition used in this study.

In the UK EES is primarily seen as a form of "flexibility" (see UK Government, Department of Business, Energy and Industrial Strategy and Ofgem, 2017). Alongside measures like demand side response (DSR), increased interconnectivity and flexible generation, it helps balance demand and supply in the grid. A legal classification as a "distinct subset of generation" is expected to be introduced into primary legislation in due course. This aims to provide long-term clarity for the planning regulations, licence terms and network charges applicable to EES without the additional legislation needed to establish it as a separate asset class.

Within EES, this study focusses exclusively on the stationary, Behind-the-Meter (BTM), deployment in residential properties. BTM is distinguished by the "on-site" location of the battery and in a residential application its primary function is the reduction of the electricity bill for the end customer. EES primarily designed and used for grid level applications, consumer electronics and electric vehicles are likely to influence the development of the residential BTM market but are outside the scope of this study.

2.1.2. Technology

EES can be provided by a range of technologies (see Table 1). This study does not attempt to evaluate their relative strengths and weaknesses in detail (Few, et al., 2016; IEA, 2014b; and Zakeri & Syri, 2015, provide excellent summaries) but it is important to highlight that no technology outperforms the others across the board. Distinct technical and economic attributes make them suitable for different services and asking a battery to provide multiple services usually compromises performance (International Energy Agency, 2014a).

EES technology	Power range (MW)	Discharge time (ms–h)	Overall efficiency	Power density (W/kg)	Energy density (Wh/kg)	Storage durability	Self-discharge (per day)	Lifetime (yr)	Life cycles (cycles)	Capital cost of power (€/kW)	Capital cost of capacity (€/kWh)
Mechanical											
PHS	10–5,000	1–24 h	0.70–0.82		0.5–1.5	h–months	Negligible	50–60	20,000–50,000	1,406	137
CAES (underground)	5–400	1–24 h	0.7–0.89		30–60	h–months	Small	20–40	>13,000	893	92
CAES (aboveground)	3–15	2–4 h	0.70–0.90			h–days	Small	20–40	>13,000	1,315	263
Flywheel	Up to 0.25	ms–15 m	0.93–0.95	1,000	5–100	s–min	100%	15–20	20,000–100,000	867	4,791
Electrochemical											
Lead–acid	Up to 20	s–h	0.70–0.90	75–300	30–50	min–days	0.1–0.3%	5–15	2,000–4500	2,140	437
NaS	0.05–8	s–h	0.75–0.90	150–230	150–250	s–h	20%	10–15	2,500–4,500	2,254	343
$NaNiCl_2$(ZEBRA)	50	2–5 h	0.86–0.88	150–200	100–140	s–h	15%	15	2,500–3,000	1,160	1,095
Ni–Cd	Up to 40	s–h	0.60–0.73	50–1,000	15–300	min–days	0.2–0.6%	10–20	2,000–2,500	3,376	699
Li-ion	up to 0.01	m–h	0.85–0.95	50–2,000	150–350	min–days	0.1–0.3%	5–15	1,500–4,500	2,512	546
VRFB	0.03–3	s–10 h	0.65–0.85	166	10–35	h–months	Small	5–10	10,000–13,000	1,360	307
Zn–Br	0.05–2	s–10 h	0.60–0.70	45	30–85	h–months	Small	5–10	5000–10,000	1,132	220
Fe–Cr	1–100	4–8 h	0.72–0.75					10–15	>10,000	1,400	569
PSB	15	s–10 h	0.65–0.85			h–months	Small	10–15	2000–2500	1,093	1,147
Electrical											
SMES	0.1–10	ms–8 s	0.95–0.98	500-2,000	0.5–5	min–h	10–15%	15–20	>100,000	218	6,090
Capacitors	Up to 0.05	ms–60 m	0.60–0.65	100,000	0.05–5	s–h	40%	5–8	50,000	229	765
SCES	Up to 0.3	ms–60 m	0.85–0.95	800–23,500	2.5–50	s–h	20–40%	10–20	>100,000		
Chemical											
Hydrogen (fuel cell)	0.3–50	s–24 h	0.33–0.42	500	100–10,000	h–months	Negligible	15–20	20,000	3,243	540

Table 1: Technical and Economic Characteristics of EES based on Zakeri & Syri, 2015

Abbreviations: PHS = Pumped Hydro Storage, CAES = Compressed Air Energy Storage, NaS = Sodium Sulfur, $NaNiCl_2$(ZEBRA) = Sodium Nickel Chloride, Ni Cd = Nickel Cadmium, Li ion = Lithium-ion, VRFB = Vanadium-Redox Fow Battery, Zn Br = Zinc Bromine, Fe Cr = Iron Chromium, PSB = Polysulfide Bromid, SMES = Superconducting Magnetic Energy Storage and SCES = Supercapacitor Energy Storage.

This study chose to focus exclusively on lithium-ion batteries for three reasons:

1) It is the most relevant technology for residential storage. Lithium-ion accounted for over 96% of US EES deployments in 1Q2017 (Greentech Media, 2017) and all UK suppliers of residential EES appear to be focussed on this technology. Greater deployment also means more cost and performance information is available.
2) Lithium-ion can provide a wide range of services. Dunn, et al. (2011) highlights lithium-ion's high power, high energy density and rapid response characteristics make it suitable to provide a range of services.

3) Further cost declines are likely. Its current dominance of both stationary and electric vehicle (EV) EES is likely to lead to scale benefits that will reduce costs further and make it even more attractive (Schmidt, et al., 2017).

2.1.3. Storage Services

EES has the flexibility to provide a wide range of services within the electricity system. Its use can vary by time (over a day or by season) or depending on where it is being deployed and who is deploying it. Battke & Schmidt's (2015) review of EES application classifications highlights both the variation in the number of services recognised (Chen, et al., 2009, identified 16, The Electricity Storage Association, 2017, found 13) and a lack of common definitions. Typically services are segmented by duration, speed of response or the part of the electricity system benefitting.

End-user Services	Self-Consumption	Excess PV generated during the day is stored and used to offset charged consumption from the grid.
End-user Services	Arbitrage	Off-peak electricity is stored and used to offset demand during peak hours. Requires a Time of Use (ToU) tariff and value is dependent on the spread between off-peak and peak rates.
Grid Services (accesible to a residential storage asset only via an aggregator)	<u>Network Services (NS)</u>	
	- Curtailment	A residential battery could reduce PV exported and/or potentially charge from the excess on the grid on particularly sunny or windy days. This would reduce the risk of overloading the distribution grid and the need for the grid to "curtail" (ie. reduce) renewable electricity generation. Estimating the value of a service is difficult as no market exists currently.
	- Peak Shaving	DNO/DSOs may be willing to pay an aggregator of residential storage to reduce peak demand on the network by discharging during peak hours. Reducing the peak could help DNOs potentially avoid costly network upgrades. Estimating the value of a service is difficult as no market exists currently.
	<u>Generation Services (GS)</u>	
	- Peak Generation Deferral	Residential EES could be used to reduce the need to run expensive "peak" generators or invest in new generation. Estimating the value of a service is difficult as no market exists currently.
	- Capacity Market	The capacity market is a payment designed to incentivise the construction of new (low carbon) generation. EES is participating in the capacity market currently via grid scale installations, receiving £22.50 per kW-year for 3.2GW in 2016 T-4 auction*. Over time it may be possible for this service to be provided by aggregating distributed EES capacity.
	<u>Ancillary Services (AS)</u>	
	- Frequency Management	NG aims to maintain grid frequency within ±0.2 of 50Hz and is obliged to maintain it within statutory limits of ±0.5Hz. Services are sgmented by response time: Enhanced FR is <1 sec, Primary FR (~5-30 secs.) and Secondary (30 secs. - 20mins). Lithium-ion is well positioned to provide EFR given its rapid response time. ll the EFR capacity auctioned in Sep-16 was awarded to EES at a price between £7-12 per MWh**
	- Voltage Management	Voltage must be controlled within a ±5% at 400kV and ±10% at lower transmission voltages.
	- Reserve	Supply (/demand) offer a specific level of power (/reduction of demand) in the event of unforeseen circumstances. The service is segmented into Fast Reserve capable of responding within 2mins and providing at least 25MW per minute for at least 15 mins. Short Term Operating Reserve (STOR) must be capable of responding within 4 hours and provide 3MW for at least 2 hours. NG paid £28m between Apr-14 and Mar-15 for STOR, equivalent to £120 per MWh***

Table 2: Service Segmentation for Residential EES

*Ancillary Services definitions based on Energy UK, 2017. Other sources: * Deign, 2016,** KPMG, 2016. *** Davis & Hiralal, 2016.*

The service segmentation and associated definitions used in this study are shown in Table 2. Rather than providing an exhaustive list (National Grid defines 21 separate ancillary services [Energy UK, 2017]) it highlights just the main services potentially relevant to residential EES investment case. The principal distinction is between "end-user" services that directly benefit the individual or "grid" services where the battery provides benefits to the wider system which are accessed via an aggregator. Grid services are segmented into three categories: network services, generation services and ancillary services reflecting the principal part of the electricity system benefitting. Figure 2 uses this segmentation to show how stacking revenue could capture value from these services via an aggregator.

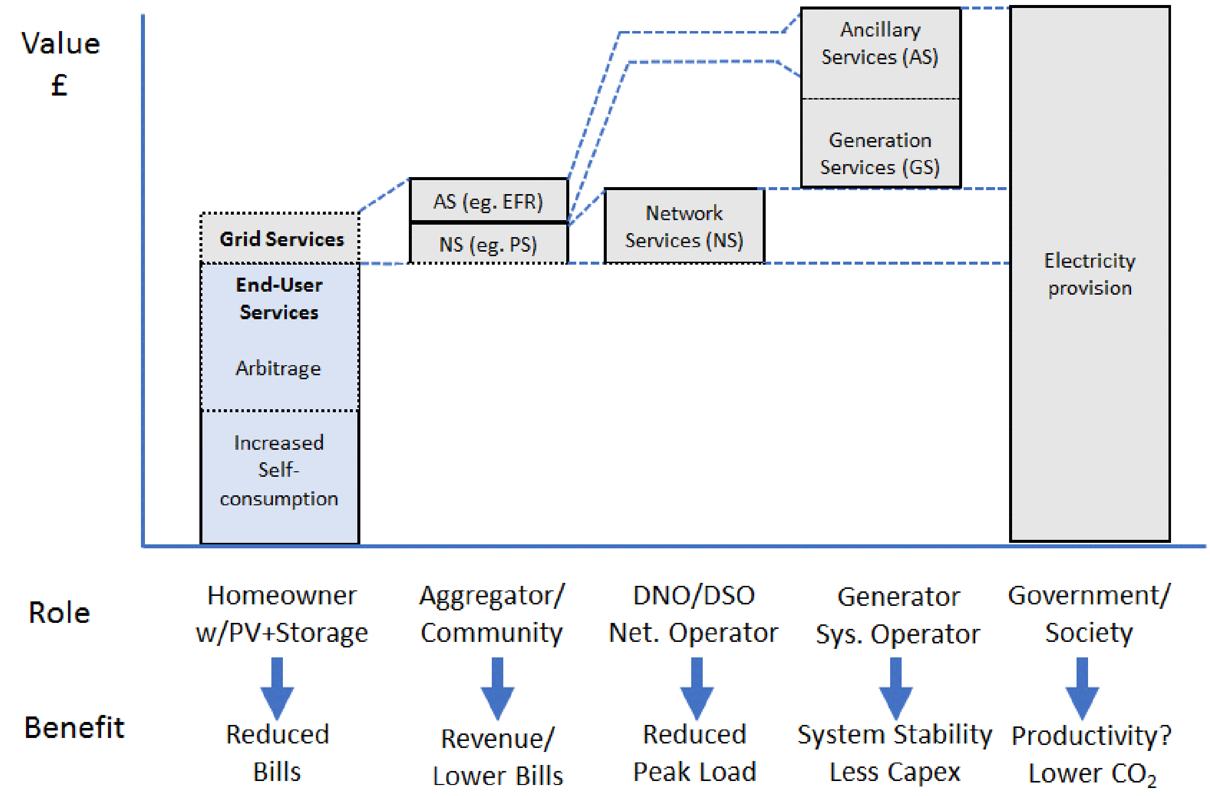


Figure 2: Revenue Stacking with a Residential Battery.

Homeowners can supplement the direct income they receive from EES (the reduction in their electricity bills) with income from Grid Services. A definition of ancillary services is included in Table 2.

2.2. UK Storage Policy

2.2.1. Aims and Objectives

A coherent UK storage policy was set out by BEIS and Ofgem for the first time in "Upgrading Energy System: Smart system and Flexibility Plan" published in July 2017 (UK Government, Department of Business, Energy and Industrial Strategy and Ofgem, 2017). The policy aims, the guiding principles and the actions needed to deliver them are shown in Figure 3. The plan attempts to establish a policy framework that will encourage storage, alongside other "flexible" options such as DSR (Demand Side Response), to meet the needs of a future energy system with greater intermittent, distributed electricity generation.

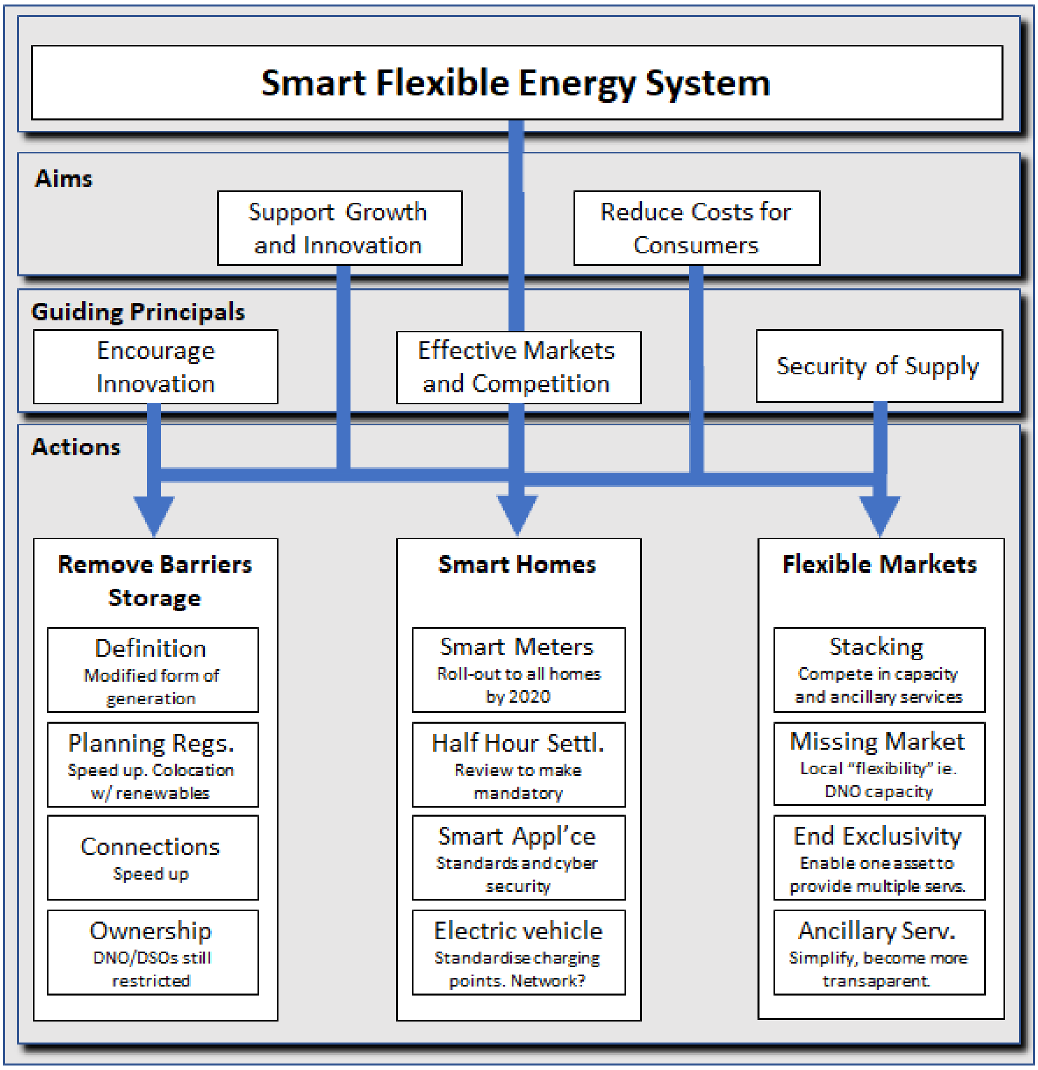


Figure 3: BEIS and Ofgem's "Smart System and Flexibility Plan".

Based on UK Government, Department of Business, Energy and Industrial Strategy and Ofgem, 2017

A stated objective of this policy is reducing costs to consumers and businesses. Over the next decade significant investment in the electricity system is needed to replace aging generators and increase renewable capacity. Greater intermittent generation imposes costs on the system such as the need for additional short term reserves and sufficient peak generating capacity (Heptonstall, et al., 2017). Analysis by Lehmann, et al. (2016) suggests these costs can be more than offset if "flexible" storage assets can be deployed concurrently and the opportunity to pass these savings on to billpayers is politically very attractive. Encouraging EES is also seen as a way of stimulating greater competition that could lead to lower prices.

Additionally the policy aims to encourage innovation. It was announced alongside increased storage R&D funding designed to accelerate investment in next generation batteries (predominantly for EVs) with ancillary benefits to jobs, growth and exports.

Policy actions to deliver these ambitions are set out in three areas:

1) Remove (policy) barriers to smart technologies
2) Enable smart homes (and businesses)
3) Making markets work flexibly

The policy barriers identified (1) are mostly amendments to existing policies designed to smooth the process of integrating storage into the network. Few of these measures have direct relevance to the residential model. Enabling the smart home (2) re-commits the government to smart meter roll out and delivering half hourly settlement (HHS). The "four-tariff" cap on the number of tariffs a supplier can offer was also lifted in June 2017 (see Ofgem, 2017a). These initiatives are predominantly designed to encourage suppliers to offer ToU tariffs – opening up the opportunity for residential EES to provide Arbitrage – and were presented alongside evidence that the complexity of ToU is not a significant barrier to consumer adoption. Making markets work flexibly (3) explicitly aims to ensure storage providers can "stack" revenue streams from multiple markets and be rewarded for the services they provide to the system. Removing the "exclusivity" clause will allow a single battery to provide multiple Ancillary services and the lack of an established market in "local flexibility" is also identified. Most of these measures are not targeted at the residential market but access to these grid services (via an aggregator) could provide additional income for residential storage.

In addition to this work Ofgem is also reviewing “residual” distribution and transmission charges (Ofgem, 2017b). These charges recover the fixed costs of running the network and generate the bulk of network operator (DNO) revenue. DSR, storage and distributed generation have the potential to reduce the variable (per unit) revenue for DNOs, so raising the level of the residual charge could compensate. Cutting variable charges could, if reflected in consumer tariffs, reduce the savings that storage can offer (CMS, 2017).

2.2.2. The UK Energy Policy Context

Storage policy should be understood within the context of the UK’s energy policy “trilemma” where considerations of cost must be balanced against both the sustainability and security of supply (Hardy, 2016). These competing objectives encourage a “systematic” approach to energy policy which seeks to avoid measures which benefit one objective at the expense of others (Heptonstall, et al., 2017). As EES addresses the challenges associated with intermittent renewable generation, it potentially benefits both the sustainability and security of the system. The major concern is cost. Initial capital outlays are significant while markets have yet to be established for many of the services it can provide including its contribution to cutting CO_2 emissions. Supporters argue that for these reasons storage justifies explicit policy support (Staffell, 2017).

2.2.3. The Historical Context

Previous policies to encourage consumers to adopt environmentally friendly technology have included explicit financial support. Residential solar was subsidised through the use of Feed in Tariffs (FiTs); payments that compensated consumers for the high initial capital cost with a guaranteed 20 year income. FiTs were justified by the wider environmental objective and the economies of scale demonstrated by technology (Jaffe, et al., 2005). The Green Deal aimed to encourage energy efficiency improvements by providing a homeowners with a loan.

However these “green” subsidies have become increasingly controversial politically. The Green Deal spent £240m improving just 1,815 homes (Energy Post, 2016) and the FiT is increasingly associated with higher consumer bills. Dramatic cuts to the FiT also damaged the solar installation industry. There is no mention of subsidies for storage in the current policy.

2.2.4. The Broader Policy Context

Storage policy is relevant to a number of other major strategic objectives across government (see Figure 4) particularly in the area of industrial strategy. Investment is seen as a critical part of both the plan to upgrade national infrastructure (see UK Government, National Infrastructure Commission, 2016a), support EV manufacturing, drive growth and jobs and, via lower energy costs, improve productivity. R&D funding support of £246m, available over four years through three separate programmes, aims to ensure the UK "leads the world in [EV] batteries". This funding is also anticipated to put "UK businesses in a leading position to export smart energy technology and services to the rest of the world" (UK Government, Department of Business, Energy and Industrial Strategy and Ofgem, 2017).

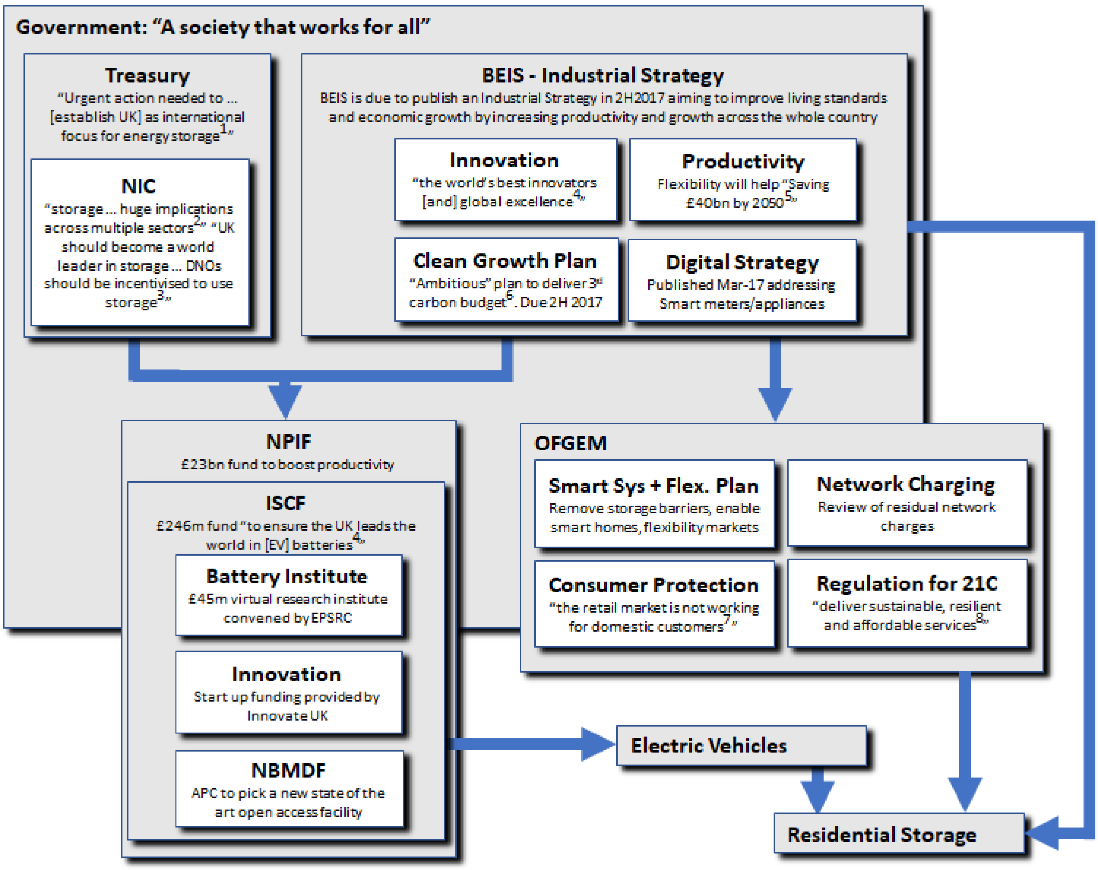


Figure 4 Storage in a UK Policy Context

NPIF = National Productivity and Investment Fund, ISCF = Industrial Strategy Challenge Fund, NBMDF = National Battery Manufacturing Development Facility 1. Osborne, 2012 2. UK Government, National Infrastructure Commission, 2016a 3. UK Government, National Infrastructure Commission, 2016b 4. Clarke, 2017 5. Sanders, et al., 2016 6. Business Green, 2017 7. Ofgem, 2013 8. Ofgem, 2017

2.2.5. The International Context

UK policy is also influenced by experience in other countries, particularly those already coping with higher levels of intermittent generation.

The US dominates non-PHS EES deployment with an estimated 0.6GW installed at the end of 2016 and a further 0.5GW expected to be added by the end of 2017 (Greentech Media, 2017)). Much of this installation has been in California which, in 2013, established a target to install 1.3GW by 2020 backed by a SGIP (Self-Generation Incentive Programme) policy. Approximately 80% of SGIP's current $566m budget is allocated to EES (California Public Utilities Commission, 2017) and 15% of its capacity target is allocated to BTM. Overall the policy has been successful but most of the BTM funding has gone to commercial and industrial (C&I) projects with batteries greater than 10kWh. Despite a $400 per kWh upfront payment and a 30% a tax credit (the tax credit stipulates storage must be used to predominantly to increase Self-Consumption of PV) residential EES adoption appears negligible (Itron, 2016). In November 2016 the US national regulator (FERC) addressed the issue of revenue stacking. Its proposals aim to ensure system and network operators give EES, including batteries of just 100kW, access all wholesale markets (US Department of Energy. Federal Energy Regulatory Commission, 2016).

Germany's rapid growth in residential PV has led to significant reductions in daytime demand and use of network charges. As a result it has also been keen to promote storage. Changes to the regulatory framework exempt it from the renewable energy levy as well as network and grid tariffs (Moore & Shabani, 2016). Unlike California there is greater focus on the residential market. The state backed development bank KfW has been providing subsidies and low cost loans for EES since 2012. The current subsidy programme makes €30m available annually and runs until 2018. The proportion of capital cost subsidised is based on an estimated €2,000 per kWp cost and is expected to fall from 25% in 2016 to just 10% by 2Q 2018 (ie. a 4kWp system would have received a €2,000 subsidy in 2016, [DNV GL, 2016a]). The scheme appears successful with 20,000 home batteries installed during 2016 bringing the total 52,000. Over 40% of residential solar installations in 2015 were fitted with a battery (STA, 2016).

Australia is another potentially attractive market for residential storage. Nearly 25% of homes have PV installed (one of the highest penetration rates of PV globally [Agnew & Dargusch, 2017]), electricity is expensive and consumers appear dissatisfied with electricity suppliers

(Moore & Shabani, 2016). In 2015 the Australian Energy Market Commission (AEMC) publication "Integration of Energy Storage" established a review of rule changes and guidelines to recognise the benefits storage brings to the grid (Australian Energy Market Commission, 2015). In addition to tackling lower system utilisation this policy seeks to address the issue of network defection and the financial burden this places on residual customers and operator finances. By ensuring grid services are accessible to residential storage these reforms aim to ensure that homes remain connected to the grid (Moore & Shabani, 2016).

2.3. Studies of the Residential EES Investment Case

A number of academic studies have looked at the economics of residential EES in different countries, with various technology and service configurations. Möshevel, et al. (2015) studied the potential grid benefits provided by Self-Consumption in Switzerland highlighting the role of accurate weather forecasting in optimising performance. Also in Switzerland, Parra & Patel (2016) highlighted the impact of different tariffs on the economics on Self-Consumption. Zheng studied Arbitrage and Peak Shaving in the US in successive papers (Zheng, et al., 2014; Zheng, et al., 2015) respectively) using a range of EES technologies. Both studies highlighted the significant potential savings on the electricity bill but did not comment on investment returns. In the UK, Davis & Hiralal (2016) compared the returns generated by different batteries providing Arbitrage using an Economy 7 tariff, concluding all were highly uneconomic. A study of Arbitrage in the UK conducted by DNV-GL for BEIS also highlighted significant losses (DNV GL, 2016b).

Reflecting the poor economics of single application deployment, there has been a growing focus in recent years on the potential for stacking in residential applications. Some of this work has looked at the engineering challenge associated with developing dispatch algorithms capable of maximising revenues multiple revenues under uncertainty (Yoon & Kim, 2016). Pena-Bello, et al., (2017) studied the Swiss residential market, highlighting that: "combined applications have not yet been explored in detail for residential batteries." The study concluded that batteries are not yet economic even when combining applications.

Teng & Strbac (2016) modelled income from residential storage in the UK in 2030 based on National Grid's "gone green" scenario and detailed demand data from Low Carbon London trials. They estimated annual Self-Consumption income between £30-40 per kWh dependent on household rising to £40-50 per kWh when combined with Arbitrage and up to £80 per kWh if Peak Shaving income is included. However commentary on returns or the actual combinability of the services was limited. Specifically there was no mention of the dispatch model used or the regulatory reform needed to offer multiple services.

Several studies examine the relationship between policy and revenue stacking. Battke & Schmidt (2015) looked at the implication of storage's multi-purpose nature on subsidy levels using a vanadium redox battery in the German market. Stephan, et al., (2017) focussed on the residential application in Switzerland using lithium-ion. It highlighted that storage economics are transformed by combining applications and also examined the impact of different cost of capital assumptions. Different applications have different risk profiles and should therefore attract different types of investors. Both papers concluded that a focus on enabling revenue stacking would minimise public subsidy. However neither sought to quantify the impact of alternative policy options or identify the measures needed to enable revenue stacking.

3. Methodology

Two lines of inquiry were followed to address the research question:

(1) Interview policy experts and providers of residential storage to identify the most prominent policy issues

(2) Build a techno-economic model of residential storage to quantify the impact of different policies on the investment case.

The twin track process reflected the nature of the evidence needed to answer the research question. Policy decisions are often informed by detailed quantitative analysis but ultimately involve reconciling a range of factors, competing interest groups and overarching political agendas (see Figure 4) – a process that is not easily captured quantitatively. It was considered that, while the BEIS and Ofgem's CfE (Call for Evidence) generated a wealth of information, only by directly interviewing experts directly could the nuances of the issues be fully understood. In contrast the residential EES investment case was best understood by financial modelling. Only a quantitative approach could enable the impact of policy measures to be assessed and compared against each other. It was recognised early on that not all policy issues would be quantifiable. These two approaches are outlined below sequentially but the research was conducted in parallel. It was considered that learning in each was beneficial to the other.

3.1. Qualitative

Six semi-structured interviews with representatives from the energy industry were conducted including three policy "experts" from trade bodies, two from residential EES providers and one expert from the commercial market. Their roles and background are shown in Table 3.

The ambition was to identify the prominent policy issues currently facing EES in general and residential storage specifically. To get a diverse perspective, most of the major parts of the industry are represented. While BEIS or Ofgem did not participate directly, its CfE (2016) and "Smart Systems and Flexibility Plan" (2017) adequately sets out its view. National Grid did not participate but its views on many of the topics are partially captured by its "Future Energy Scenarios" document (2017) and it is not directly involved in residential storage.

Each interview broadly followed the same structure. Interviewees were asked to:

1. Briefly describe their organisation, their role within it and the main challenges it faces
2. Outline their perspective on the threats/opportunities created by EES in the UK
3. Indicate how important they considered policy to the development of EES
4. Identify the policy issues they saw as most significant and how they could be resolved

This semi-structured approach allowed answers to be compared whilst maintaining sufficient flexibility to focus on areas of expertise and interesting responses with additional questions. Care was taken to ensure that the phrasing of the principal semi-structured questions was not leading, with prompts only provided as follow up questions. All interviews were carried out over the phone during July 2017 and were recorded and transcribed for analysis.

POWERVAULT	**Nick Wood, Commercial Analyst, Powervault** Powervault developed the UK's lowest cost and easiest to install residential battery based on lead acid. It now offers a lithium-ion product which provides emergency power, cuts bills by increasing self-consumption of PV. As the roll out of smart meters enables 'smart tariffs', arbitrage will expand the addressable market and the company is developing other services. Before joining Powervault Nick was policy lead at the STA on the smart solar energy future.
REA RENEWABLE ENERGY ASSOCIATION	**Frank Gordon, Senior Policy Analyst, Renewable Energy Association (REA)** REA was established in 2001 as a not-for-profit trade association representing renewable energy producers and promoting the use of renewable energy in the UK. With c.700 members it is now the UK's largest renewables trade association and particularly active in the decarbonisation of the heat, transport and power sectors. Frank specialises in storage policy.
moixa	**Simon Daniel, Founder and CEO, Moixa** Moixa is the UK's leading residential battery provider with nearly 1,000 systems installed. Part owned by the "big six" it has been selected by housing associations and utilities as well as installers. Its pioneering GridShare service aggregates batteries to provide frequency response and its partnership with Good Energy also enables its batteries to generate arbitrage income. Simon is also a director of the Energy Pension Company and developed an award winning consumer battery "USBCell".
Energy UK	**●, Senior Policy Manager, Energy UK** Energy UK is the trade association for the UK energy industry representing over 90 suppliers and generators of electricity (and gas). Its membership includes all the big six but new, growing, suppliers now make up over half of its membership. ●'s current role within the generation team focuses on renewable energy, environmental regulation, distribution network codes, market liquidity and Electricity Market Reform. ● has over five years experience in regulation and policy.
ena energynetworks association The Voice of the Networks	**●, Head of Innovation & Development, Energy Networks Association (ENA)** ENA represents the electricity (and gas) transmission and distribution network operators (DNOs) in the UK and Ireland. It actively engages with government, regulators and the EU Commission on the impact of regulation and new technologies on its members. ● joined the ENA early in 2017 following three years as a consultant at AECOM.
res	**●, Head of Energy Storage Business Development, RES** RES (Renewable Energy Systems Ltd) is a leading independent specialist in renewables which has developed and/or built over 12 GW of renewable energy capacity worldwide. As head of business development ● has originated >80 MW of energy storage contracts from initiation to secured contracts including a 35MW Enhanced Frequency Response (EFR) service contract in the 2016 National Grid tender.

Table 3: Interviewees' Role, Company and Background

Analysis was conducted by carefully reading the transcripts, looking for common policy themes (King & Horrocks, 2010). For Powervault, REA and Moixa the response to Ofgem's CfE was also analysed to give additional breadth and detail. To feed this information into the techno-economic model this analysis needed to identify:

1) Which policy issues are the most significant?
2) Can this issue be quantified?
3) What are the main parameters?

3.2. Quantitative

To quantify the impact of policy on residential storage a techno-economic model of a battery investment (retro-fitted to a domestic PV system) was constructed in Excel. The structure of this model is highlighted in Figure 5. In summary information from three input modules (PV generation, battery assumptions, and consumption) was fed into a dispatch algorithm. This evaluated which service would be the most profitable to run on a daily basis in different revenue stacking scenarios. An annual revenue figure is fed into a financial model which uses assumptions on operating costs, performance degradation of the battery, and real-terms price increases to calculate the income of the investment over its lifetime. The financial model also enables the starting date of the investment to be varied to assess the impact of falling cost of storage over time. Finally returns on investment calculated by dividing the net present value (NPV) of the lifetime income by the cost of the battery.

These stages are described in sections 3.2.1 to 3.2.4. Although not presented here the structure of the model was designed to be sufficiently flexible to evaluate a range of different storage scenarios including a C&I deployment with a business consumption profile combined with a larger PV array.

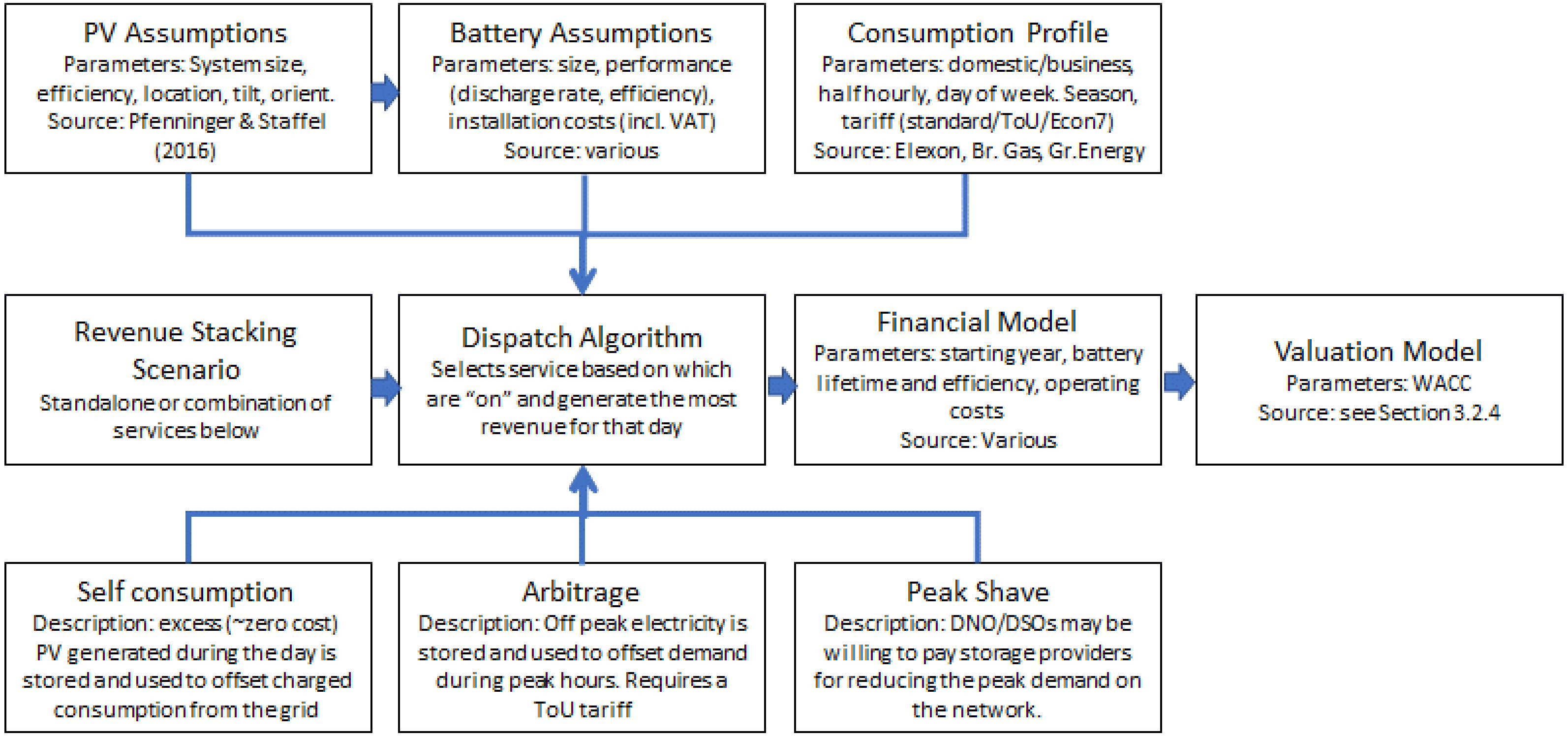


Figure 5 Techno-economic Model of Residential Storage

3.2.1. Review of Input Modules

To test the performance of the model and establish an appropriate "base case", the impact of four key inputs was assessed:

1) PV Assumptions: varying PV output according to the location, tilt and direction of the solar panels was assessed to establish a realistic scenario.
2) Optimal Battery Size: varying the size of the battery, consumption levels and the size of PV system enabled the optimal battery size to be identified.
3) Time of initial investment (Battery Cost). Varying the starting date allowed the impact of falling battery costs on the investment case to be identified.

PV Assumptions

PV inputs were taken from www.renewables.ninja using MERRA-2 radiance dataset for 2014 (Pfenninger & Staffell, 2017). This estimates PV generation in kW per m^2 taking account of tilt and orientation of the panels and inverter efficiency (see Pfenninger & Staffell, 2016). Hourly outputs were converted into half hours using a spline function. No assumption on shading or faulty panels was included. The per m^2 output was multiplied by the size of the array (assumed to be 16 x 1.5m^2) and fed into the battery model.

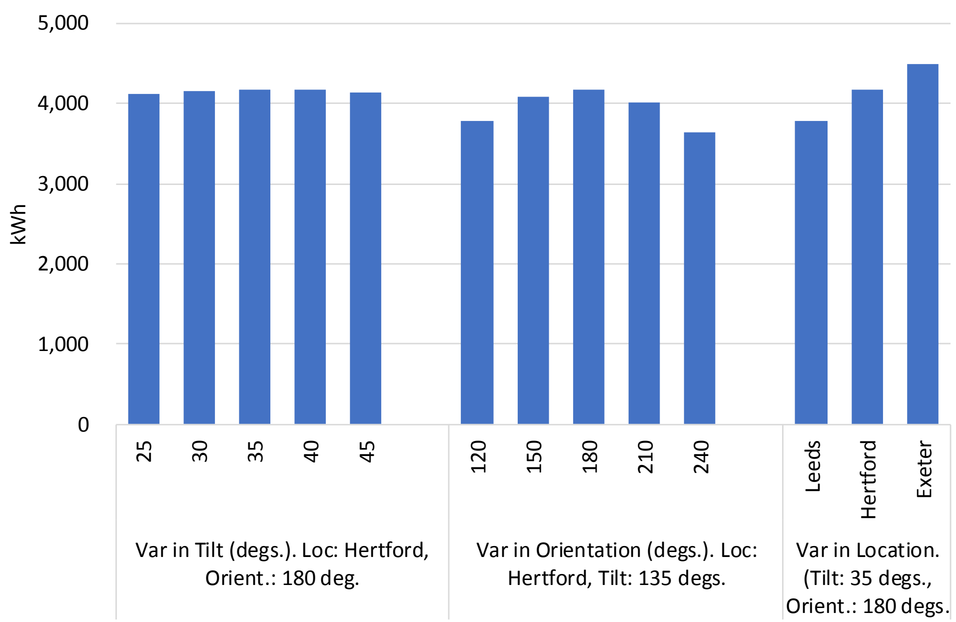


Figure 6: Impact of Variation in Tilt, Orientation and Location on Annual PV Output

Based on a 4kWp residential solar system using Pfenninger & Staffell, 2016; 2017

The PV output (4,544kWh or 1,136 per kWp assuming a Hertford based system with a 35° tilt and 180°) initially appeared high relative to historic data (800kWh per kWp [UK Government. Department of Trade and Industry, 2006]) and industry "rule of thumb" (the eco experts, 2017). Adjusting for the bias identified in Pfenninger & Staffel (2016) the output was reduced by 9.2%. The impact of different panel assumptions (location, tilt and orientation) was also tested. Figure 6 highlights only modest variation in annual PV output between panels with different tilts (<2%), with a larger impact from different orientations and different locations (+/- 8-13%).

Battery Assumptions

Table 4 highlights the principal battery assumptions used in the model and the sources for those assumptions. As set out in section 2.1.2 lithium-ion was chosen as the most suitable technology and a 4kW system was established as a base case as it generated optimal returns in our modelling (see Figure 21) and is a suitable product for medium sized residential house with a standard 4kWp PV solar system.

Parameter	Value	Source
Install cost		
- 2017 lithium-ion battery cost ($/kWh)	1,431	Price for first kWh, subsequent $/kWh cost a third as much based on published prices and academic sources (see text)
- 2017 Bi-directional AC-coupled inverter and other electronics ($/kW)	900	Price for first kWh, subsequent $/kW cost half as much based on published prices and academic sources (see text). 1:1 ratio with battery kWh assumed
- Installation costs (£)	350	Respondent elicited (annon). Flat rate per installation. RMI (2015) breakdown suggests a standalone install cost between £500 - 750
- Installation margin (%)	10.0	Respondent elicited (annon). Only applied to installation costs (assume hardware sold at zero margin)
- VAT rate (%)	20.0	Based on standard VAT rate. See section 4.5.2
- $/£ Exchange rate	1.30	As on 22-July 2017
- Annual cost decline (%)	12.4	Based on Schmidt, et al., (2017)
Performance assumptions		
- Single Trip efficiency (%)	90.0	ie round trip = 81%. In the middle of the range of 75 - 90% round trip efficiency estimated by EPRI (2010)
- Minimum battery charge (%)	10.0	BRE (2016) state a typical lithium-ion residential battery has a 75% Depth of Discharge to preserve lifespan. In 2015 Sonnenbatterie claimed to have developed a long lasting battery (see below) that had 100% DoD
- Lifetime	15	According to BRE (2016) manufactures generally state: 'Life expectancy = 10 years or 10,000 cycles, whichever is the sooner'. However battery life is improving all the time. In 2015 Sonnenbatterie claimed to have developed a battery with a 10,000 cycle lifespan. The 15 year assumption implies 5,500
- Annual decline in battery performance (%)	1.0	Expressed as an annual decline in revenue using an average taken from Xu, et al., (2016)

Table 4: Base Case Battery Cost and Performance Assumptions.

Based on Rocky Mountain Institute, (2015); EPRI, (2010); BRE, (2016); Xu, et al, (2016). See also Table 8

System cost (battery plus inverter and other electronics) was estimated from an amalgamation of sources. Schmidt, et al., (2017) estimated a battery cost of $1,634 per kWh of a 3kWh for residential lithium ion system in 2016. Assuming a further 12.4% annual price decline suggests a price of $1,431 or £1,102 in 2017 using a $/£ exchange rate of 1.30. To enable the battery to provide Arbitrage and Self-Consumption services a bi-directional AC coupled inverter is needed. Inverter cost was assumed to be £600 per kW based on the review of academic studies of 6kWh systems conducted by Ardani, et al., (2017) discounted by 10% to reflect a further year of cost declines. Adding battery and inverter cost suggested a total system cost of £5,106 for a 3kWh system. However comparing this to both the currently published (pre VAT/installation) UK prices from Tesla (2017), Sonnen (CCL, 2017) and Moixa (2017) this figure appears high. Using $1,800 as the cost of the first kWh of our 4kWh system, with subsequent kWhs costing $716 generated a cost function closer to that observed in the market and used by Ardani, et al., (2017). Modelling assumptions published by DNV GL (2016c) suggest a lower price but a similar cost per additional kWh.

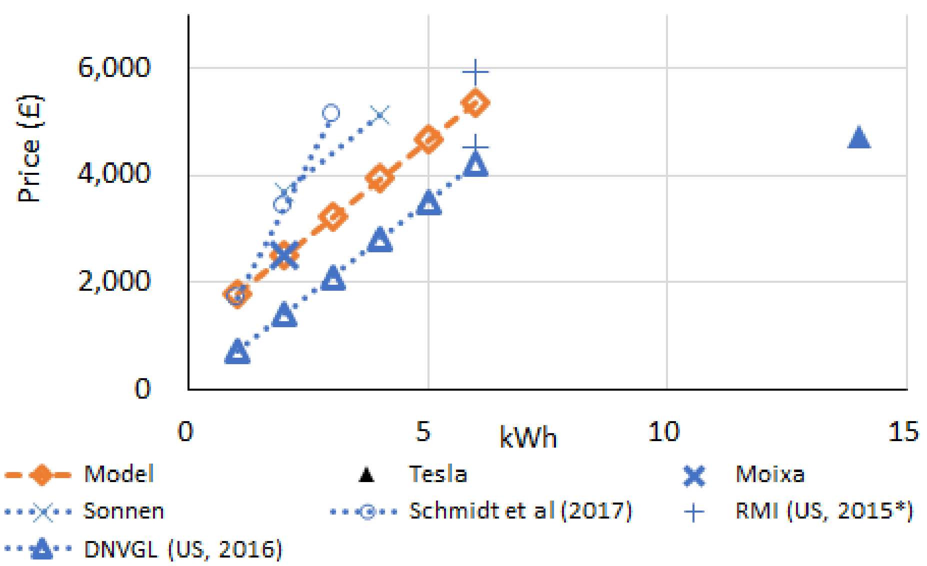


Figure 7: Published Residential Storage System Prices in the UK

*Tesla and Moixa prices from company websites (see Tesla, 2017; Moixa, 2017), Sonnen from distributor (CCL, 2017). Prices include battery and inverter but exclude installation and VAT. Prices compared with costs modelled by Schmidt et al., (2017), RMI (Rocky Mountain Institute, 2015), DNV GL (2016) and our modelling assumptions. * RMI's 2015 prices discounted by 10% to reflect an additional year of cost declines.*

The £337 ($438) price per kWh implied by Tesla's 14kWh Powerwall, nearly a third of the average of competing systems, is notable. This data point was not considered sufficiently representative to incorporate in the cost per kWh curve calculations used in this model. With a minimum 14kWh size, it is too big for most residential properties (see Figure 21), the headline metric may be misleading and it may be being sold below cost (Lin & Klipperstein, 2015). Nevertheless if Tesla is able make a profit at this price it suggests scale economies which, if applicable to its rivals and smaller systems over time, could significantly boost the residential storage investment case.

Starting Year (Battery Cost)

The choice of starting year for the model has a big impact on returns due to falling system costs. Figure 8 highlights the fall in costs over time expected for a 4kWh battery system based on the cost per kWh model described above and the 12.4% annual cost decline observed by Schmidt, et al., (2017). The $440 per kWh battery cost in 2020 compares to the $500 cost projected by Sauer (2016). By 2024 cost per KWh is expected to be half 2017 levels.

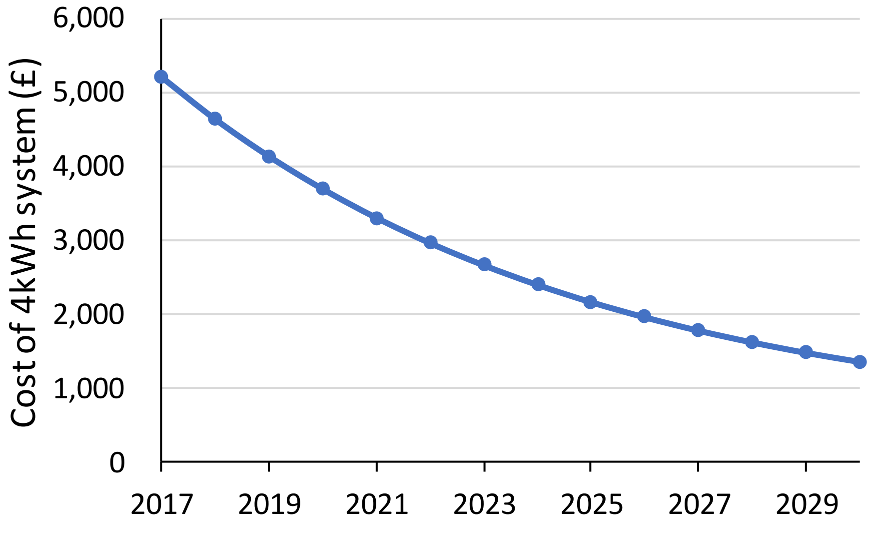


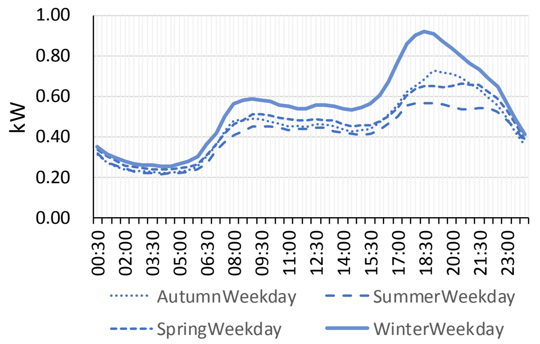
Figure 8: Cost Decline of a 4kWh System

Based on Figure 7 and the 12.4% annual decline observed by Schmidt, et al., (2017)

The base case year was chosen as 2020 to allow sufficient time for the current policy environment to change. In this way modelling the impact of different policy environments could be seen as more plausible. Different starting years were selected to assess the sensitivity of various stacking scenarios to declining system costs. Policy interventions could then be measured by the extent they "bring forward" breakeven.

Tariffs and Consumption Profiles

The default consumption (demand) profile was the "Domestic Standard" from Elexon (2017). As Figure 9 and Figure 10 highlight, this profile has a pronounced evening peak which varies by day of the week and season. Annual consumption in this profile is 4,074kWh which compares to the 3,800kWh estimated by BEIS (2017). Variations of the model using Economy 7 and business demand profiles were run but the results are not presented.



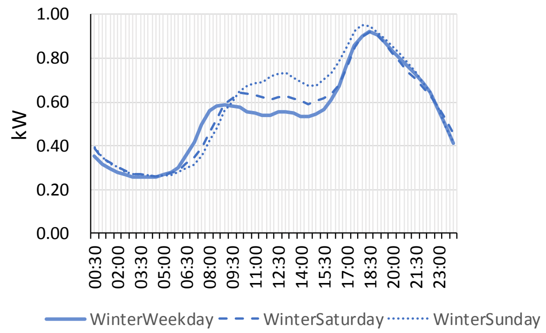


Figure 9: Seasonal Consumption Profiles
Based on Domestic Standard" from Elexon (2017).

Figure 10: Consumption by Day of the Week
Based on Domestic Standard" from Elexon (2017).

The default setting of the model was a "flat rate" standard tariff with no variation between peak and off-peak residential price per kWh charges. The rate was set at 14.24p per kWh (13.56p + VAT at 5%) based on a British Gas direct debit Eastern region tariff effective 15th September 2017 (see British Gas 2017). Based on supplier market share (see Ofgem (2017c)) and the tendency for consumers to choose the standard tariff by default, this rate is arguably the most common in the UK. In the base case no price increase took place before 2020 and prices were assumed to be stable throughout the investment lifetime although sensitivities reflecting "real terms" (ie. inflation adjusted) price increases were also run.

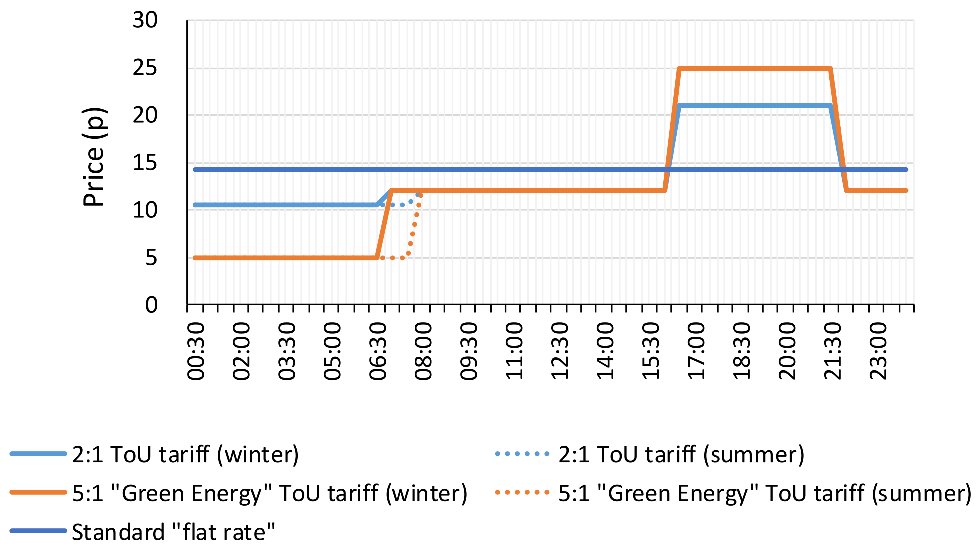


Figure 11: Electricity Consumption Tariffs

Based on British Gas direct debit Eastern region tariff effective 15th September 2017 (2017) and TIDE tariff from Green Energy (2017)

To assess the potential Arbitrage income a residential battery could provide two Time of Use (ToU) tariffs were also modelled. The prices for three rates ("peak", "medium" and "off-peak") and the time at which they would apply could be varied by hour and by season. In the first ToU tariff the spread between "peak" and "off-peak" prices was set at 10p. The second was based on the TIDE tariff from Green Energy (2017) with a 20p spread and was similar to the one modelled by Teng & Strbac (2016). In both ToU scenarios a demand elasticity assumption was applied (a 15% increase to off-peak demand offset by a 9% decrease in peak demand) to ensure the total annual bill was equivalent to the original flat rate and assume some demand side response. Other studies (Zheng, et al., 2014) have not adjusted for this effect.

Export of solar PV was deemed to be 50% of total PV production in the base case and the tariff was set at 4.1p as the default position, consistent with industry practice and the currently published rate.

3.2.2. Storage Services Chosen: Rationale and Description

Three storage services were modelled: increased Self-Consumption, Arbitrage and Peak Shaving. The services could be switched on in any configuration.

The choice of services primarily reflected their "accessibility" to a residential storage owner. Both Self-Consumption and Arbitrage are "end-user" services directly accessible to residential EES owner. Self-Consumption is available to any EES owner with PV and Arbitrage is available to all homeowners on a ToU tariff. The exception is "Peak Shaving", a "grid" service, which is not yet established and cannot be directly accessed by a storage owner today. Aggregation of individual residential storage capacity to provide services for the grid is realistic (see Section 5.3) and it was considered necessary to show the potential for residential storage to access grid revenue stream. Unlike other grid services, the reduction in peak consumption using storage (which drives the value of the service) could be modelled, therefore it was possible to build into the dispatch model and examine constraints of using one asset to provide three services could be observed.

Self-Consumption

For the nearly 1m households with PV systems in the UK adding a battery enables the excess electricity generated during the day (particularly in summer) to be stored and used to reduce metered consumption of electricity from the grid (see Figure 12). In the model the battery begins discharging as soon as PV generation falls below electricity consumption, without differentiating between peak and off-peak periods. However as the greatest reduction consumption often occurs during the evening peak the value of Self-Consumption typically increases with ToU tariffs in operation.

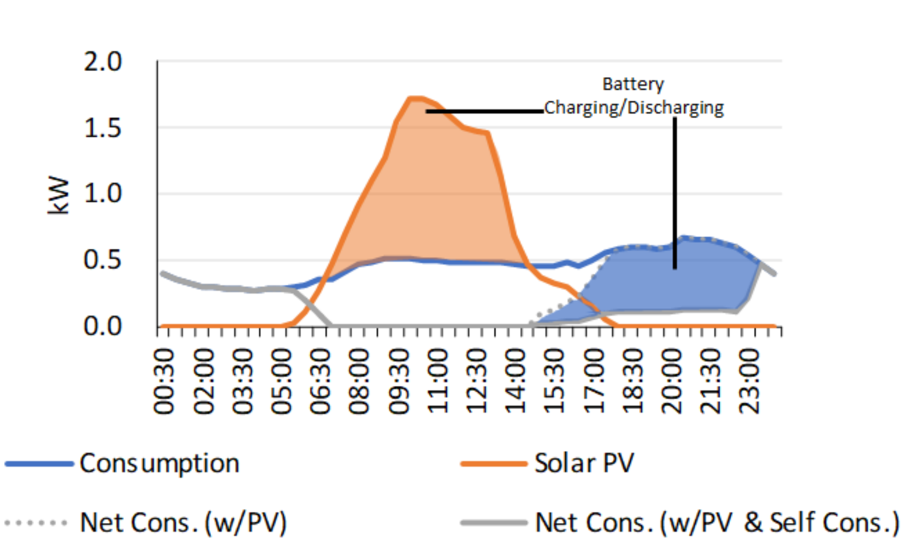


Figure 12: Daily Profile of Battery Operating in Self-Consumption Mode (6-April)

In Self-Consumption mode, adding storage reduces excess PV exported to the grid. As most export payments are based on a “deemed” rate (assumed to be 50% of PV production) rather than metered this does not impact our estimate of Self-Consumption income in the base case. This effect is discussed in more detail as a policy uncertainty in section 4.5.4.

Arbitrage

While the majority of households are on flat-rate tariffs today the roll-out of smart meters and HHS is anticipated to lead to greater availability of Time of Use (ToU) tariffs. In this mode the battery stores up cheap off-peak electricity to reduce the consumption of expensive electricity during peak periods. Overall consumption rises modestly to reflect losses in conversion (calculated to be 8%) but this is more than offset by the lower average price. In this mode the spread between buying and selling price has a significant impact on the economics.

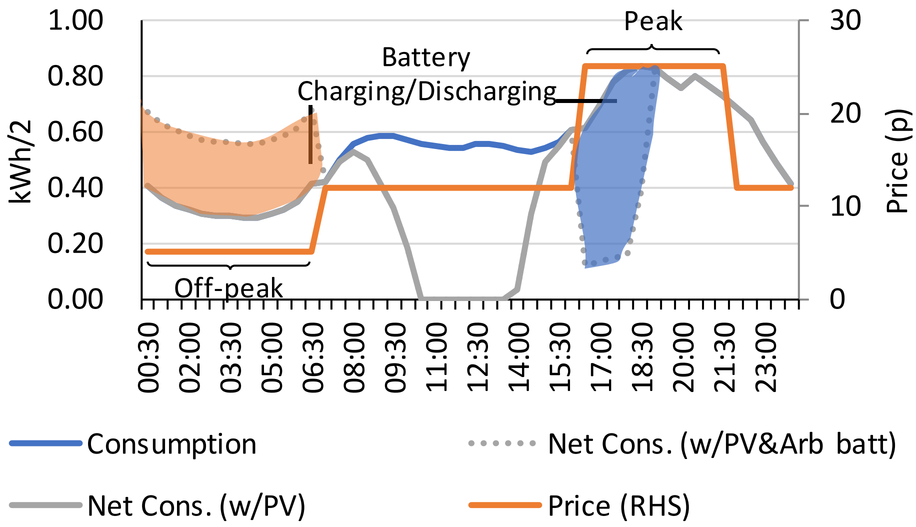


Figure 13: Profile of Battery Operating in Arbitrage Mode (2-January)

Peak Shaving

Peak Shaving is the reduction in demand for power at periods of peak consumption (see Figure 14). Supplying peak power is problematic as:

1) It is expensive as it is typically met by “peak generators”, power stations that have higher marginal costs and, because they only run for short periods in a day, can only recover these costs through charging high prices.

2) It is often particularly environmental damaging as these peak generators are typically old, inefficient fossil fuel power stations (Zheng, et al., 2015).
3) It also stresses the distribution network. All elements (transformers/cables) must be sized to ensure they can safely cope with an annual peak that may only be a few hours in duration. Growth in this peak forces DNOs to make expensive network upgrades significantly increasing overall system costs.

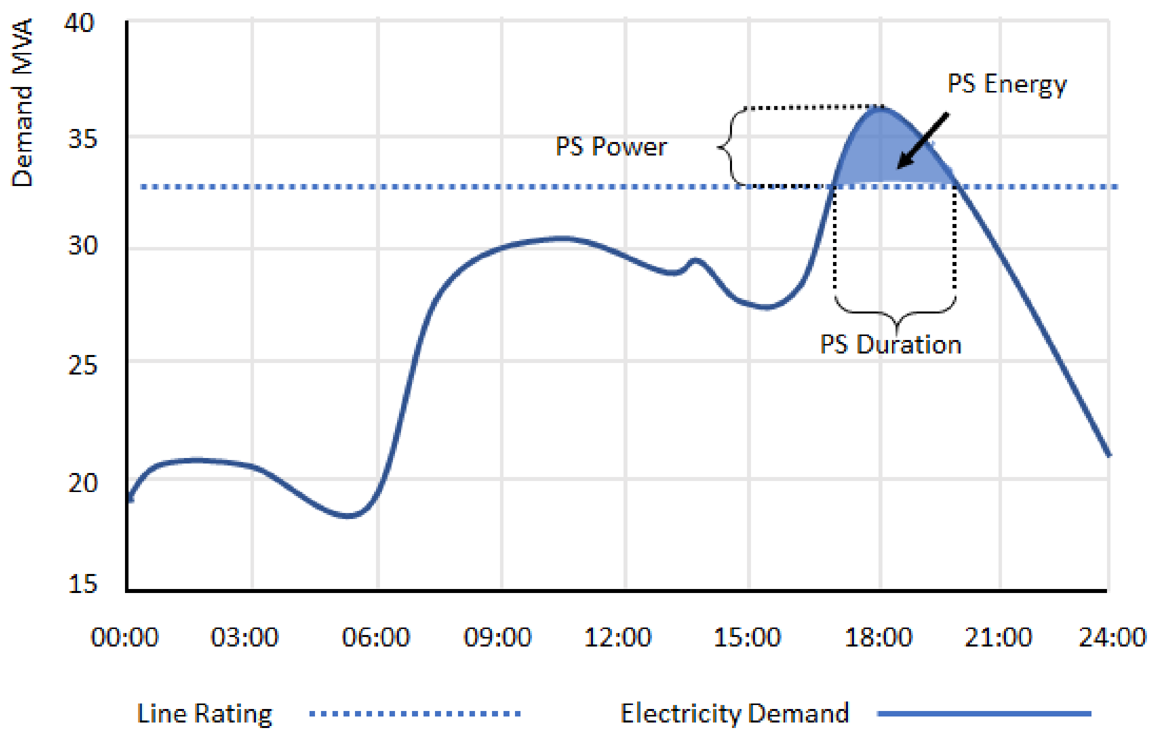


Figure 14: A Peak Shaving (PS) Service.
Peak Shaving could reward both energy and power savings. Adapted from Greenwood & Wade, 2016

For all these reasons reducing peak demand could cut significant cut system costs. Residential EES could be used to limit or even lower household demand during the peak period, replicated across enough households this effectively “shaves” the top off of the demand profile, reducing the need to run expensive, “dirty” generation and helping DNOs defer investment costs. Several recent trials of storage in the UK have at least been partially motivated by desire to defer network upgrades (UK Power Networks, 2017a) (Western Power Distribution, 2016). In the US, some consumer electricity bills include a “demand tariff”, a price per kW based on the maximum power demanded in any one-month billing period (Zheng, et al., 2014).

Peaks in distributed intermittent generation can cause similar problems. On particularly windy or sunny days the load on the distribution network can exceed the carrying capacity, forcing curtailment and restricting the ability to add renewable capacity (Joos & Staffell, forthcoming). Although this service was not directly modelled, theoretically residential storage owners with PV could also be paid to reduce the supply of PV generation to the grid during peak periods.

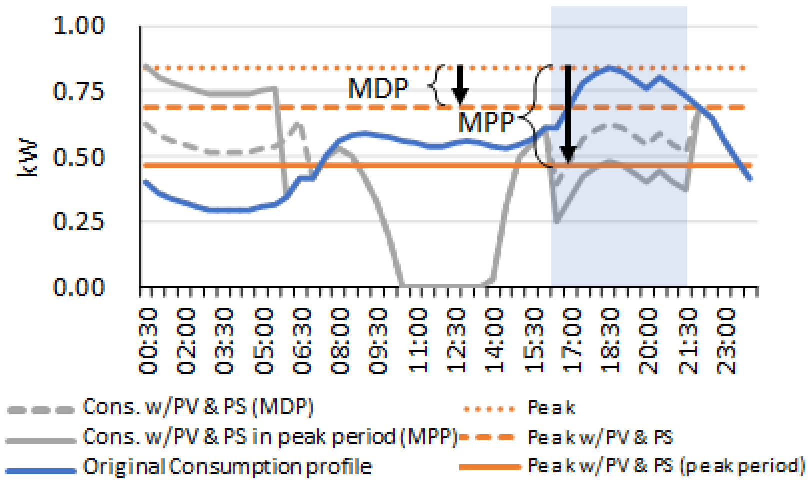


Figure 15: Reducing Power Consumption with Different Peak Shaving Modes (2-January)

A Peak Shaving service provided by residential EES could work by either:

1) Reducing maximum daily power demand (MDP – "flattening the daily profile") or
2) Reducing maximum peak power demand (MPP)

As Figure 15 highlights this choice has a big impact on battery operation and the size of the reduction. Focussing exclusively on reducing demand in the peak (MPP) causes a pronounced spike in off-peak demand as the battery charges to full capacity. This gives more energy to discharge during the peak and consequently MPP is much lower than MDP. This is potentially problematic – it would increase charges under a US style demand tariff and widespread adoption would ultimately create a pronounced off-peak spike that would raise system costs. However as storage uptake is likely to be gradual, it is argued that is effect is unlikely to significantly impact aggregate demand (Davis & Hiralal, 2016).

Consequently the model focuses on maximum peak power (MPP) rather than MDP. The annual impact of a residential battery providing a Peak Shaving service in MPP mode is shown in Figure 16 (the oscillations reflect greater peak consumption at weekends). The battery nearly halves maximum demand in the winter peak period. As demand reduction is calculated annually and demand in peak periods outside of winter is so much lower, the battery is free to provide other services (if enabled) throughout the rest of the year. Analysis by Zheng, et al., (2015) modelled the peak reduction on seasonal basis. With US style demand tariff the reduction would need to be calculated monthly.

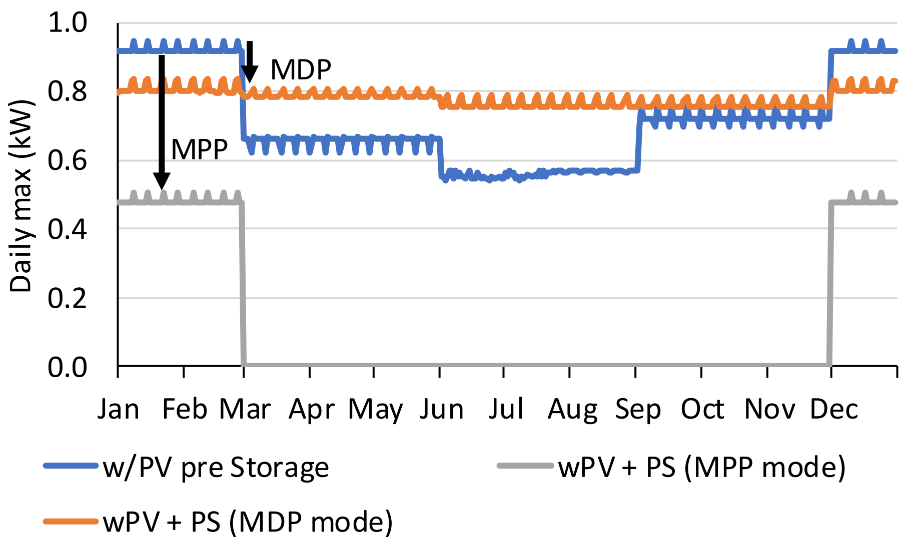


Figure 16: Reducing Peak Demand in MDP and MPP Peak Shaving Modes (Annual)

A further uncertainty in modelling a Peak Shaving service is the value placed on reducing peak power. In the US, where some residential tariffs include a power component, there is a direct mechanism linking reductions in maximum power demand to revenue. conEdison's Rate I is \$20.11/24.36 per month per kW, based on the maximum demand in that month (Consolidated Edison Company of New York, Inc, 2015). RMI's (2015) review of US estimates of the annual value of network deferral by storage suggested a range of £39 – £693 per kW, Adjusting for an outlier[1], this represents an average of £85.

[1] Use Case II was based on 12% Carrying Cost Assumption on \$1bn in infrastructure spend.

There is a similarly wide range of estimates for the potential value of Peak Shaving in the UK. Using a residential battery to reduce peak energy consumption looks unlikely to be lucrative. In 2017 Ofgem announced cuts of over 90% to its "triad" payments (made to generators to supply in the three ½ hour periods in the year with the highest demand) to £3 per kWh (Coyne, 2017). Assuming a 20% reduction in peak demand this price generates an annual income of just £0.78 (£3 x 0.44kW x 20% x 3). UK Power Networks's (2017a) SNS project paid £0.03 per kWh to a third party to reduce demand in 200 peak hours using storage produces a similarly low figure (£1.02). The potential benefit from reducing power might prove more lucrative. UK Power Networks, which distributes electricity to 8.2m homes, generates revenue of c. £600m and spends and c. £320m in capex annually, implying distribution charges/capex of ~£70/£40 per household per year, approximately 12%/7% of the average electricity bill (UK Power Networks, 2017b). Given these figures (particularly capex) are driven by the cost of upgrading the network, a cost which storage can defer, they give some indication of the potential value of storage to the system. Teng & Strbac (2016) suggests "network support" could have an annual value of c. £50 per kW.

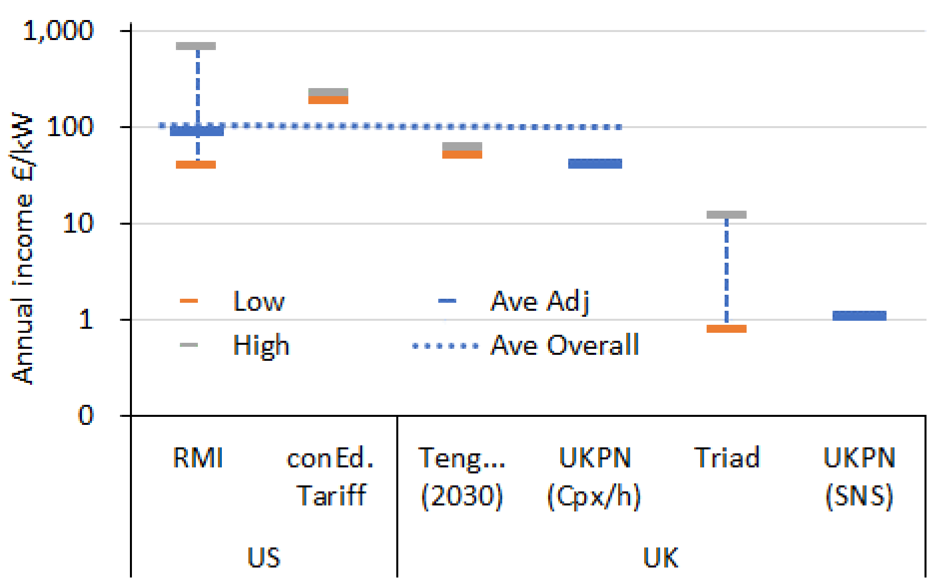


Figure 17: Estimates of Annual Income per kW for a Peak Shaving Service

Based on RMI (2015), conEdison (2015), Teng & Strbac (2016), DNO Capex (UK Power Networks, 2017b), UK Triad payments (Coyne, 2017) and SNS values UK Power Networks (2017a) (see text). Average of power derived estimates of £100 shown by blue dashed line

The estimates of annual income derived from these data points is summarised in Figure 17. As RMI (2015) highlights the network deferral costs is highly location specific, so the wide range of values probably reflect this as well as different methodologies. Taking the average of the power methods suggests a value of £100 per kW year.

Finally it is not clear how much of this value would be passed onto the residential storage asset owner. Demand reductions would have to be aggregated to make a meaningful impact on peak load. How much of the "system value" the buyer (National Grid, a generator or DNO) might pass onto an aggregator is not clear, nor is the aggregator's cut. We assume the owner of the residential storage battery receives 75% of the value created.

3.2.3. Dispatch Algorithm

A dispatch algorithm was developed to enable the model to switch between the three services (see Figure 18). The optimal schedule was defined as the one that maximised the income for the battery owner. To do this three variables were tested:

1) which services are available
2) the relative value of Self-Consumption and Arbitrage income on a given day
3) if it is a winter day

The first test logically limits the ability of the model to only switch between services that are enabled. The ability to configure this was necessary to test different revenue stacking scenarios and reflect the fact that not all services are currently available. Arbitrage is not available without ToU tariffs which are not yet widely adopted and Peak Shaving payments to residential storage owners (from a DNO via an aggregator) has not been established as a service yet. It also allowed the scenario where the battery just provides income from Arbitrage and is not tied to existing PV to be tested.

In the configuration where both Self-Consumption and Arbitrage are available the second test evaluates, on a day by day basis, which service generates the most income by comparing the next diurnal cycle. In winter when PV is generally low, the battery will predominantly operate in Arbitrage mode, charging up overnight at off-peak rates and discharging during the evening peak. During the rest of the year, the battery will wait to be charged up with "free" excess PV generation. Obviously given the model uses historical data it is able to choose which service to run with 100% accuracy but it is assumed that a high degree of accuracy in real life is plausible given advances in 24 hour weather forecasting (see Moshövel, et al., 2015).

Finally if Peak Shaving is enabled alongside other services, the model evaluates which service to run based on the season. In winter it always prioritises Peak Shaving. The Elexon consumption profile used in the model varies according to whether it is a weekday, Saturday or Sunday but is otherwise the same throughout the season. So to maximise the payment, consumption in the peak period must be reduced to the same amount throughout the season (in reality consumption might vary significantly day to day). Peak consumption periods predominantly overlap with peak pricing so if a ToU tariff is available, the operation of the battery in Peak Shaving mode also creates Arbitrage income.

Figure 18: The Dispatch Model

3.2.4. Measuring Financial Performance

Two indicators were chosen to analyse the financial performance of the battery. The Initial Year Income *(IYI)* shown in Equation 1 adds together the electricity costs avoided through the use of the battery through Self-Consumption *(SC)* and Arbitrage *(Arb)*, any payments the battery owner receives for services like Peak Shaving *(PS).* This is potentially reduced by the impact the battery might have on PV export revenues *(Exp)* where $Exp_{pvstorage}$ is the income generated from PV after storage is installed and Exp_{pv} is the original PV export income.

$$1)\quad IYI \quad = SC + Arb + PS + (Exp_{pvstoraage} - Exp_{pv})$$

The income generated in the initial year *(IYI)* is unlikely to be constant in subsequent years. Degradation of the battery (assumed to be 1% per annum in the base case, see Table 4) reduces capacity over the investment lifespan of the while real terms growth in electricity prices (assumed to be zero in the base case) can potentially increase annual income.

In addition a return on investment based metric is provided *(Return or R)*. Shown in Equation 2 *R* primarily indicates whether the investment is profitable. If *R > 0* the battery is profitable: the net present value (NPV) of the cashflow *(CF)* generated over the battery lifespan *(n)* is greater than the initial costs *(IC)*. If *R < 0* the battery loses money: the cash generated by the battery does not recoup the original investment. *IC* includes all hardware costs (battery plus inverter), installation charges, VAT and any subsidy. Dividing the net cash generated by the initial investment *(IC)* enables the performance of investments of different sizes to be compared equally.

$$2)\quad Return\ (R) \ = \ \frac{\sum_{i=1}^{n} \frac{CF_i}{(1+r)_i} - IC}{IC}$$

This returns metric is the same as the "NPV per Unit of Capex" used by Pena-Bello, et al., (2017) and similar to the PI (Profitability Index) one used by Stephan, et al., (2017).

R is presented with different cost of capital assumptions. The debate around the appropriate discount rate *(r)* to apply to projects that have wider social benefits remains unresolved (see Nordhaus, 2014) and is not a focus of this study. Papers in this area have used cost of capital assumptions ranging from zero (Lehmann, et al., 2016) to 10% (UK Government, Department of Energy & Climate Change, 2013). Work by Stephan, et al., (2017) suggests the appropriate rate should vary by service, debt equity mix and investor. The range chosen in this study (0 – 10%) reflects the debate within the literature with the 5% mid-point close to the 4% used by Pena-Bello, et al., (2017).

The combination of a returns and annual income was considered the most appropriate way to analyse the investment case based on a review of existing literature and the belief these metrics are ultimately the most relevant to homeowners. Other studies (Parra & Patel, 2016) also employed a levelized cost metric which would help compare the efficiency of residential EES based on lithium-ion with other storage models and other technologies. As this study predominantly focusses on policy impacts this metric is not presented here.

4. Results

The results are presented in five sections:

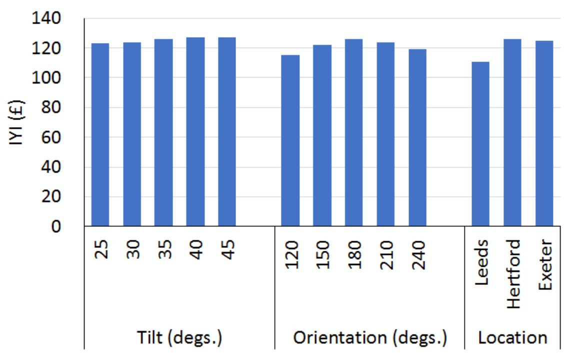
1) Optimal Parameters: results from running the model in a variety of configurations (PV input, system size, year) to establish a plausible base case scenario are shown
2) Individual services: the financial performance (*IYI* and *R*) was calculated for individual services and some sensitivities highlighted
3) Stacked Services: the financial performance (*IYI* and *R*) was calculated and compared for different stacking scenarios
4) Key Policy Issues: the salient policy issues emerging from the interviews are identified and discussed
5) Impacts of Policy Issues: the financial performance (*IYI* and *R*) were calculated for six different policy variables.

4.1. Establishing Optimal Parameters for a Base Case Scenario

The impact of different input parameters (battery size, PV input, year) was analysed to understand the sensitivity of the model and establish a realistic base case scenario. A plausible base case scenario is needed to consistently measure the impact of policy changes. A single service scenario (Self-Consumption) was chosen to model these effects. This was initially considered the most attractive revenue stream as it is an end-user service accessible by a residential battery owner with PV. A full list of the base case assumptions identified is shown in Table 8.

4.1.1. Variation in PV Input

The impact of variation in PV input on the Self-Consumption model are presented in Figure 19 and Figure 20. A panel based in Hertford (51.7957°N, 0.0785°W) with 35° tilt and 180° orientation was selected as the base case. The Self-Consumption of PV units (before any utilisation of the battery) is 38% slightly above the high end of the 20 – 35% range identified by Moshövel, et al., (2015).



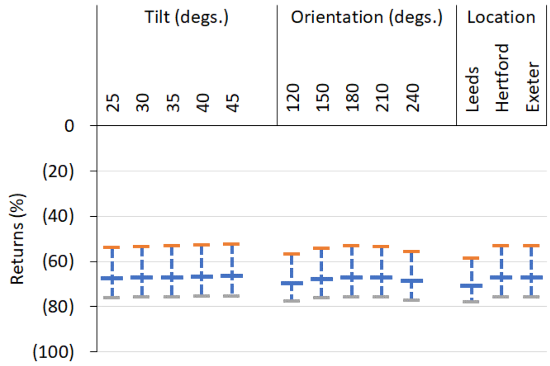


Figure 19: Impact of Variation in Tilt, Orientation and Location of PV System on IYI

Based on a 4kWp PV system and a 4kWh residential battery. Default tilt = 35°, orientation = 180°, location = Hertford

Figure 20: Impact of Variation in Tilt, Orientation and Location of PV System on Returns

Based on a 4kWp PV system and a 4kWh residential battery. Default tilt = 35°, orientation = 180°, location = Hertford

Figure 19 and Figure 20 highlight that variation in PV output has relatively little impact on either the revenue or negative returns on residential storage investment. Although a positive relationship between PV input and profitability can be observed the range and number of PV input values were too small to test the relationship statistically. Not all PV configurations with higher PV inputs generated better returns.

4.1.2. Variation in Battery Size

The variation in returns on with the size of the battery was then tested to establish the optimal size of a residential battery coupled with a 4kW PV system (Figure 21). A range of systems between 0.5kWh and 6kWh were tested in both Self-Consumption and Arbitrage mode with all other assumptions the same as for the previous test.

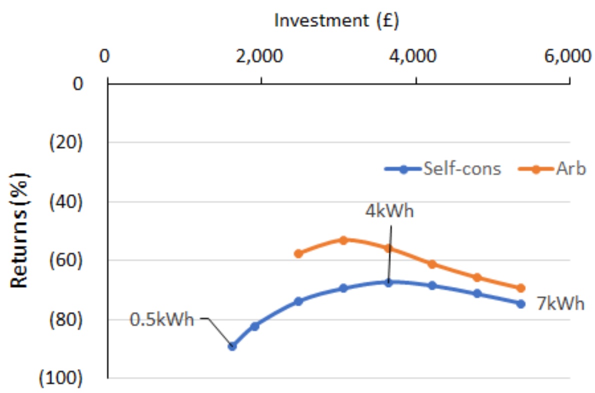


Figure 21: Impact of Variation in Battery Size on R in Self-Consumption and Arbitrage Modes

Figure 21 again highlights negative returns on residential storage investment all scenarios but the size of the system does exert a more significant influence on profitability. Small systems (<2kWh) suffer from relatively high initial capital cost as the installation cost (£380) is fixed and the initial kWh of capacity is more expensive (see Table 4). The ability for larger systems to generate incremental income is limited in winter by insufficient PV and in the summer by lower consumption and higher PV. A 4kWh system was established as optimal.

4.1.3. Variation in the Installation Year (Battery Cost)

Next the influence of the year of installation was tested. Battery costs were assumed to decline by 12.4% annually (see Figure 8) so the further into the future the investment is made the more profitable it will be.

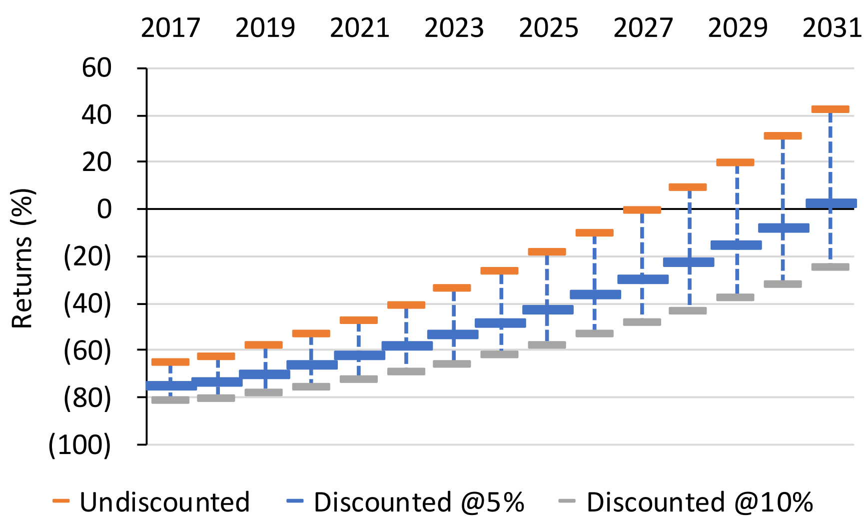


Figure 22: Variation in Self-Consumption Returns by Installation Year and Cost of Capital

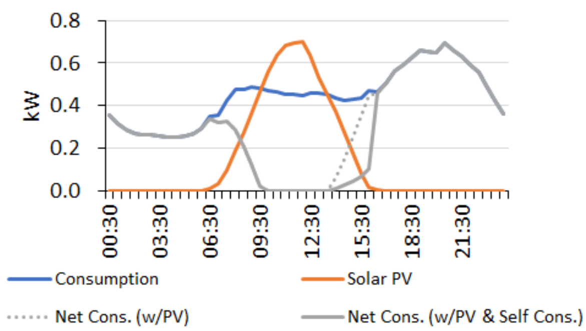
The year of the investment, through its likely impact on system costs, has a more significant impact on returns than either system size or PV levels. The steady reduction in battery costs delivers ever greater improvements in returns until profitability is achieved in 2031. While it was not modelled directly, substantially positive returns are expected beyond that point. Using the £337/$438 hardware price per kWh implied by Tesla's Powerwall, roughly a third of the rivals' prices, suggests returns of -20% (@5%CoC). Using this as the starting cost in 2017 and applying a 12.4% reduction from this level, brings break even forward to 2020.

4.2. Individual Services

Having established a base case scenario of a 2020 investment in a 4kWh residential battery paired with a 4kWp Hertford located PV system, the performance of individual services was then tested in detail. Results were compared and some sensitivities examined.

4.2.1. Self-Consumption

Figure 23 – 26 contrast the operation of the Self-Consumption model at different times of year. On a day of modest PV generation (23-October), excess PV occurs for just a few hours, therefore the battery only charges to a maximum of 24% (Figure 24) and daily income is just 8p. As the battery quickly discharges it has no impact on reducing consumption during the evening peak. On a summer day (3-June), the combination of greater PV and lower consumption results in excess PV generation from 06:00hrs until 17:00hrs allowing the battery to reach full charge. By steadily discharging in the evening consumption of 3.2kWh of metered electricity from the grid is avoided. The total daily saving is 46p.



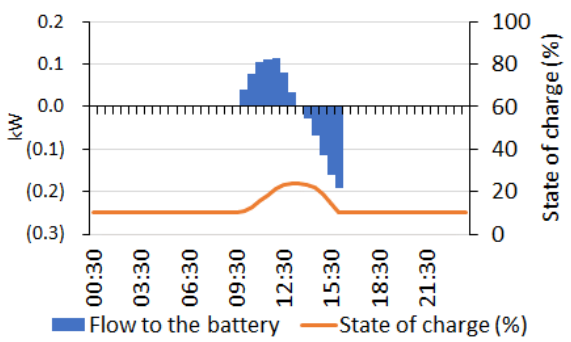
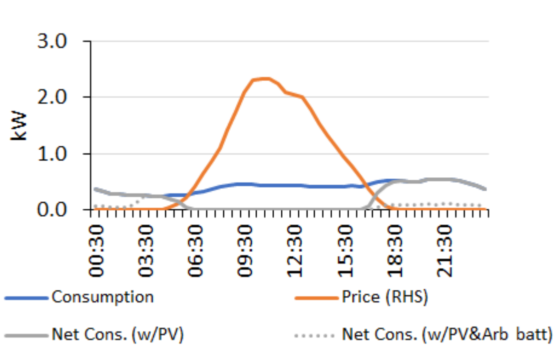


Figure 23: Consumption, PV Generation and Net Consumption with and without Battery

Based on 23-October in Self-Consumption mode

Figure 24: Battery Operation on 23-October in Self-Consumption mode



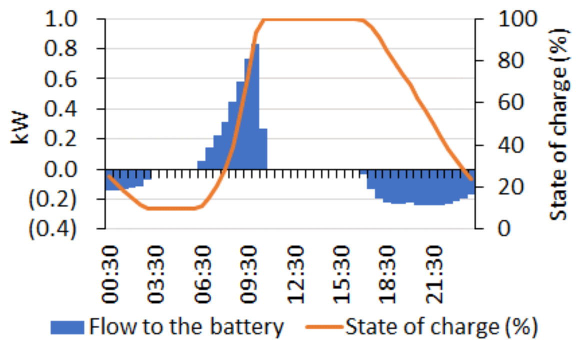


Figure 25: Consumption, PV Generation and Net Consumption with and without Battery (3-Jan)

Based on 3-June in Self-Consumption Mode

Figure 26: Battery Operation on 3-June in Self Consumption Mode

The distribution of income across the year is shown in Figure 27. Revenue generation is concentrated in the months with higher PV between February and November. Income in summer is effectively limited by the combination of PV generation and lower consumption.

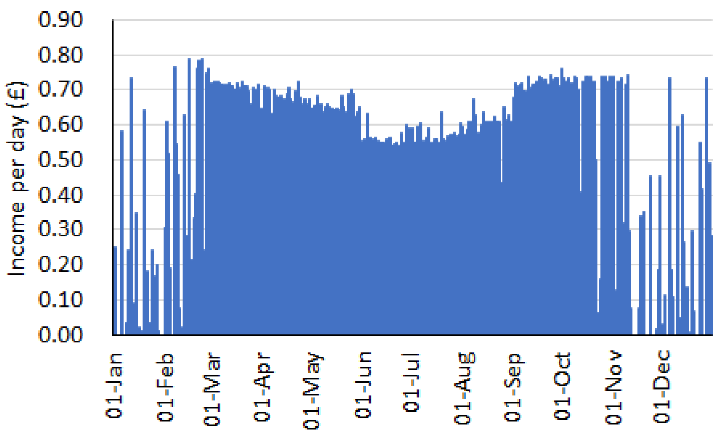
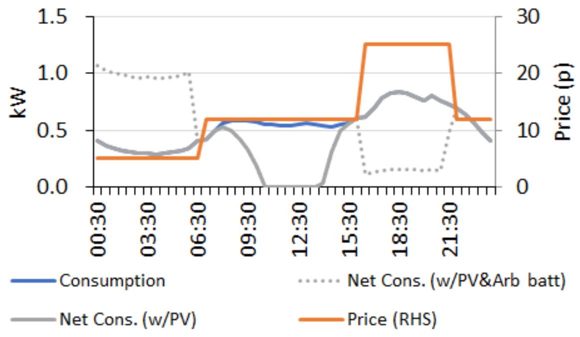


Figure 27: Distribution of Self-Consumption Income per Day

Self-Consumption saves £126 per year (IYI = £126), equivalent to 22% of an average residential bill. This figure compares closely to the £140 per year modelled by Teng & Strbac (2016) with a 2kWp PV system. The 21ppts rise in the proportion of PV units self-consumed (from 38% to 51%) is consistent with the (13-24ppts) range identified by Luthander, et al., (2015). In this mode the total income generated over the 15 year lifespan of the battery is £1,759. Adjusting for operating costs and dividing by the initial cost of investment (£3,638) generates an undiscounted return (R) of -53.1%. Applying a discount of 5% R falls to -67.3%.

4.2.2. Arbitrage

The value of an Arbitrage model was then tested. Figure 28 – 31 contrast the operation of the Arbitrage model at different times of year using a ToU tariff with 20p peak/off peak spread. A full cycle in winter (charging up to 100% and discharging to 10%) generates 61p per day. During the rest of the year performance is more variable and partially constrained by the impact of higher PV on addressable net consumption in peak periods. Arbitrage generates income more consistently throughout the year.



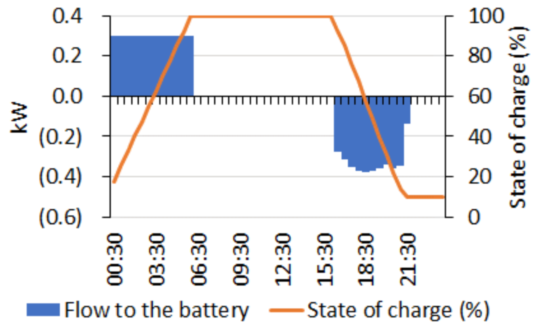
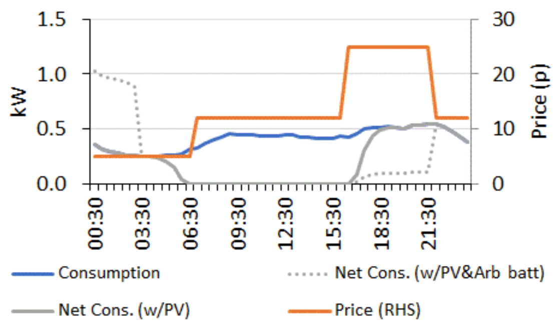


Figure 28: Consumption and Net Consumption with PV and Battery

Based on 2-January in Arbitrage mode with 20p peak/off peak spread

Figure 29: Battery Operation on 2-Jan. in Arbitrage Mode with 20p peak/off peak Spread



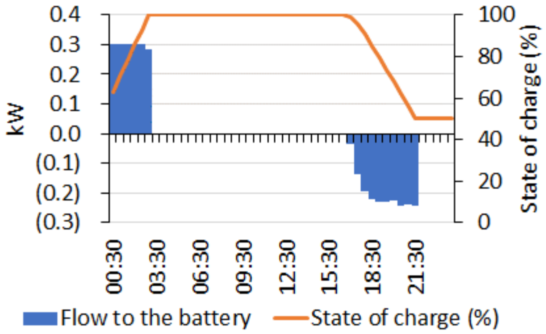


Figure 30: Consumption and Net Consumption with PV and Battery

Based on 5-July in an Arbitrage mode with a 20p peak/off peak spread

Figure 31: Battery Operation on 5-July in Arbitrage Mode with a 20p peak/off peak Spread

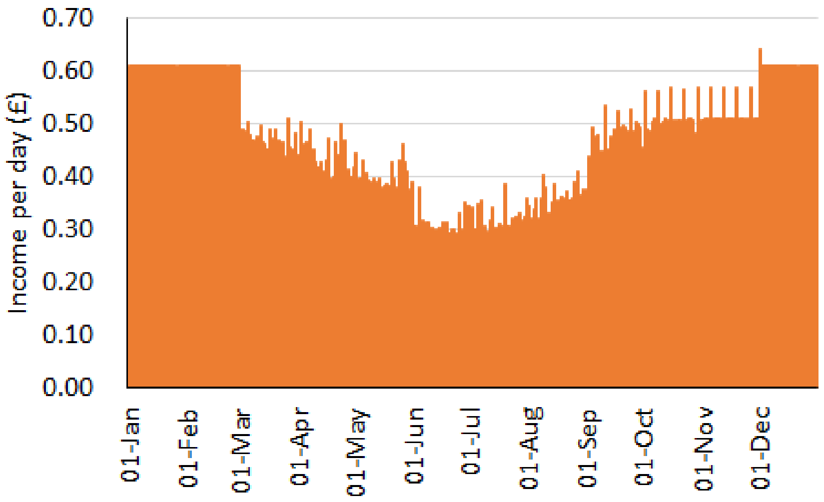


Figure 32: Distribution of Arbitrage Income per Day with 20p peak/off-peak Spread

With a 20p spread between peak and off-peak prices, Arbitrage generates IYI of £170, a 28% saving on the average residential bill. This compares to £130 saving estimated by Davis & Hiralal (2016) using an Economy 7 tariff (10p spread) from Southern Electric and a 7kWh Tesla Powerwall. Over the lifetime of the battery this generates undiscounted returns of -37% and returns @5% cost of capital of -56%.

Reducing the spread to 10p cuts IYI to £73 and returns @5% CoC to -81%. Different charging/discharging rates were also tested to establish optimum levels (Figure 33 and 34). A base case was set at 50% discharge per hour. Returns for Arbitrage as a standalone service are higher than Self-Consumption but are highly sensitive to the peak/off-peak spread.

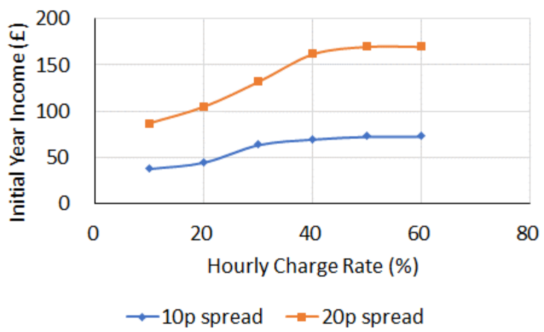


Figure 33: Impact of Price Spread and Charging Rate on Arbitrage IYI

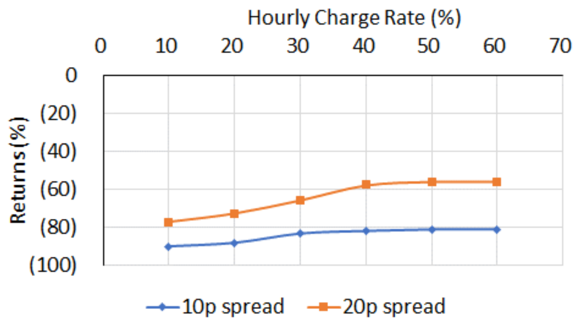
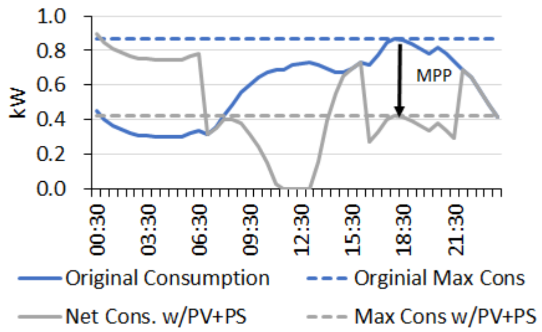


Figure 34: Impact of Price Spread and Charging Rate on Arbitrage Returns

4.2.3. Peak Shaving

The operation of a Peak Shaving service was then tested. Income was estimated by calculating the reduction in maximum power consumption during the peak period (MPP mode) and applying a £100 per kW year charge (see Section 3.2.2). Figure 35 shows the battery reducing maximum demand in the peak period on a winter day by 440W or 47%. Ledbetter & Swan (2012) observed peak demand reductions of between 42-49% for 4kW batteries in Canada. Applying the £100 per kW charge to this generates an IYI of £33, a 6% reduction to the average domestic electricity bill This compares to 23% reduction noted by Zheng, et al., (2015). At -91% returns were the lowest of all the services tested.



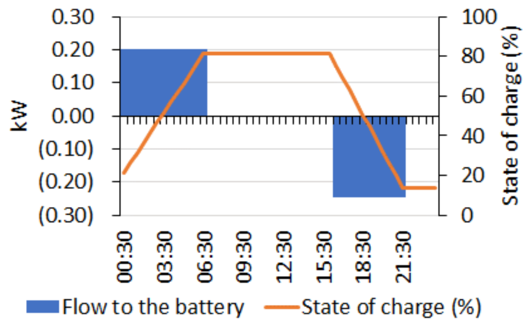
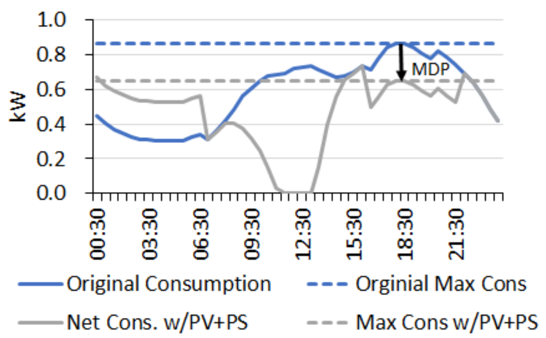


Figure 35: Reduction in Maximum Peak Power (MPP mode) with Peak Shaving on 8-Jan.

Figure 36: Battery Operation on 8-January in Peak Shaving (MPP mode)

As discussed in section 3.2.2 it is possible to configure the battery to focus on reducing maximum daily demand (MDP), essentially flattening the overall consumption profile rather than just focussing on demand in the peak period (MPP). Ultimately this service may prove more valuable to the grid as EES and EVs become more widespread but it is likely to be less lucrative to a residential storage owner at least initially. Figure 39 shows the battery operating in MDP mode. The need to restrict daily maximum limits ability to charge off-peak and therefore the reduction of the peak period is lower. In MDP mode peak demand is reduced by only 220W or 23% and therefore IYI falls to £16.



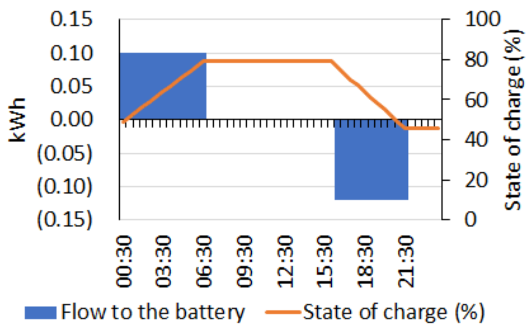
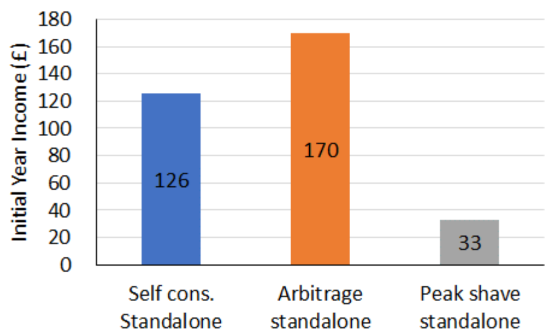


Figure 37: Reduction in Maximum Daily Peak (MDP mode) with Peak Shaving on 8-January

Figure 38: Battery Operation on 8-January in Peak Shaving (MDP mode)

4.2.4. Comparing Individual Services

Finally the financial performance of individual services was compared (Figure 39 and 40). Arbitrage is the most attractive service but returns remain strongly negative.



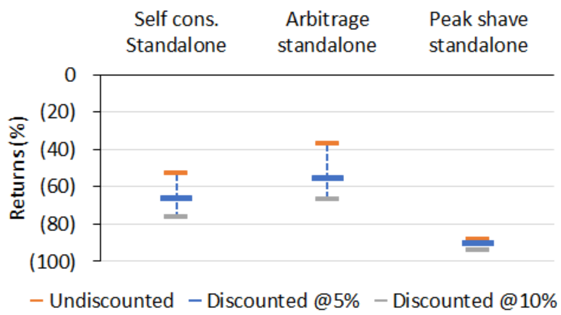


Figure 39: Comparing IYI for Individual Services

Figure 40: Comparing Returns for Individual services.

4.3. Revenue Stacking Scenarios

The results of three revenue stacking scenarios are presented:

1) Self-Consumption and Arbitrage
2) Arbitrage and Peak Shaving
3) Self-Consumption, Arbitrage and Peak Shaving

The financial performance of these scenarios, along with stacking Self-Consumption and Peak Shaving, is then compared.

4.3.1. Self-Consumption and Arbitrage

The results presented in section 4.2.1 and 4.2.2 (Figure 23 to 32) shows Self-Consumption generates higher daily income than Arbitrage for most of the year but income declines sharply during winter months. By forecasting PV and consumption 24 hours in advance, days of low excess PV where Self-Consumption income could be predicted and the battery could switch to Arbitrage mode. In this way Arbitrage could boost the Self-Consumption income provided by the battery. This is effectively the “winter” and “summer” modes described by Moixa (UK Government, House of Lords, 2016) and is shown in Figure 41. However it is important to highlight that the battery cannot operate in both modes simultaneously and therefore the IYI generated by the two services in combination is significantly less than the sum of the individual services.

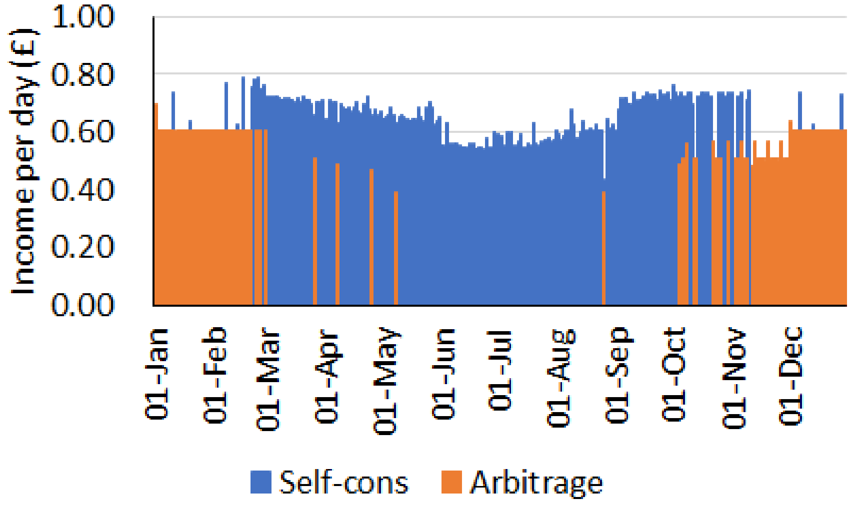
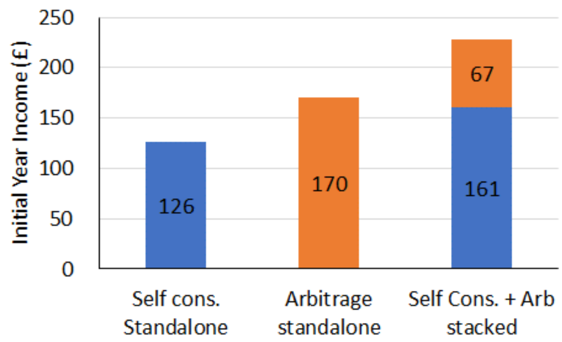


Figure 41: Combining Self-Consumption and Arbitrage

The combination generates IYI of £228, comprising £161 of Self-Consumption income plus £67 of Arbitrage income. Self-Consumption income increases from £126 in the standalone scenario as, to enable Arbitrage service to function, a ToU tariff is assumed. The combined income is an 81% increase from Self-Consumption as a standalone service and a 34% increase from Arbitrage. Returns improve to -41% (see Figure 43). Implying income per kW of £57 the result is close to the £50 per kW level identified by Teng & Strbac (2016).



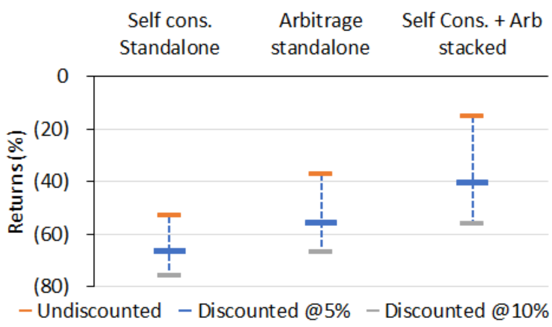


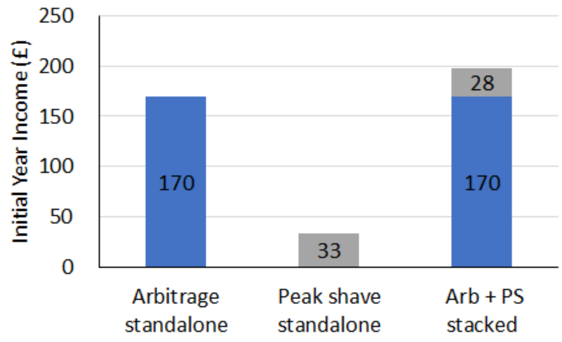
Figure 42: Increase in IYI from Stacking Self-Consumption and Arbitrage

Figure 43: Reduction in Losses from Stacking Self-Consumption and Arbitrage

4.3.2. Arbitrage and Peak Shaving

A residential battery providing both Arbitrage and Peak Shaving services operates in a similar way, charging up in the off-peak period (overnight) to reduce household demand in the evening peak. Consequently, unlike stacking Self-Consumption and Arbitrage, the revenue streams, particularly when Peak Shaving is in MPP mode, are largely complimentary. Essentially Peak Shaving provides an additional “grid” payment for the Arbitrage function the battery is already providing.

Figure 44 suggests this combination could generate IYI of £198, including £170 from Arbitrage and £28 annual payment Peak Shaving. The combined income is 16% increase from Arbitrage as a standalone service and a fivefold increase from Peak Shaving. Losses on investment reduce to 48% (see Figure 45).



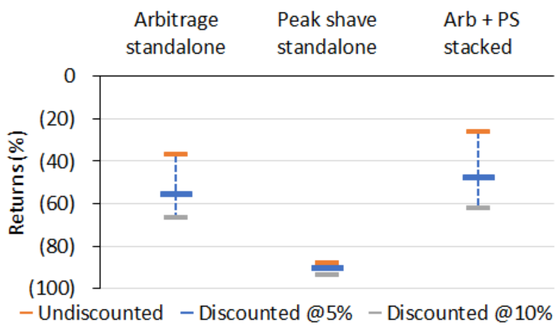


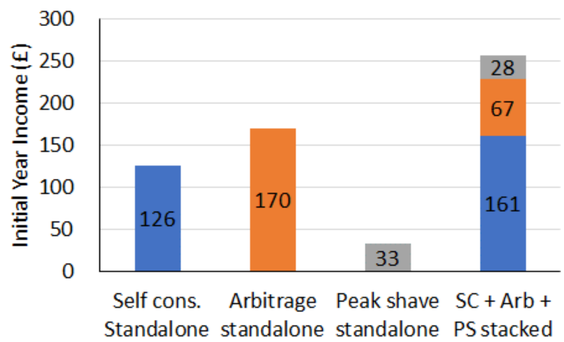
Figure 44: Increase in IYI from Stacking Arbitrage and Peak Shaving

Figure 45: Reduction in Losses from Stacking Arbitrage and Peak Shaving

Combining Peak Shaving and Arbitrage does require the battery to adjust its operation slightly. Arbitrage maximises revenue by ensuring it charges/discharges as much as possible during the peak and off-peak periods. Peak Shaving needs demand to be reduced across the whole peak period – ie the battery cannot discharge too quickly. This is particularly an issue if Peak Shaving income is generated by reducing maximum daily peak (MDP). If the battery charges up too quickly off-peak it can force up MDP.

4.3.3. Self-Consumption, Arbitrage and Peak Shaving

With all three services switched on, the dispatch algorithm choses Peak Shaving in the winter (which also generates Arbitrage income) and predominantly Self-Consumption for the rest of the year. Figure 46 suggests the battery generates IYI of £257, £161 from Self-Consumption, £67 from Arbitrage and £28 from Peak Shaving. Income in a stacked scenario is 50% higher than the most lucrative standalone service. Losses on investment fall to 34% (Figure 47).



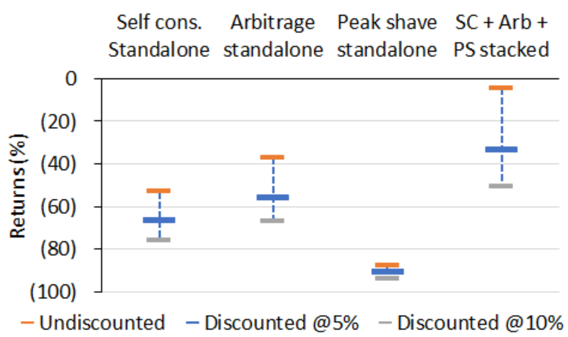
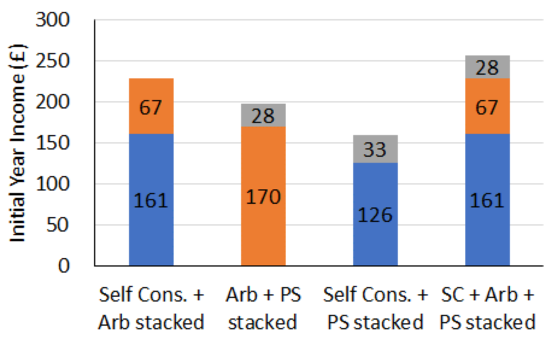


Figure 46: Increase in IYI from Stacking Self-Consumption, Arbitrage and Peak Shaving

Figure 47: Reduction in Losses from Stacking Self-Consumption, Arbitrage and Peak Shaving

4.3.4. Comparison of Stacked Services

Finally the operation of all four stacking scenarios was compared (Figure 48 and 49). Adding Peak Shaving to Self-Consumption is the least profitable stacking scenario. Arguably it is also the least realistic. Any scenario where grid payments are available for reducing consumption during peak periods is likely to be one where ToU is available and heavily promoted.



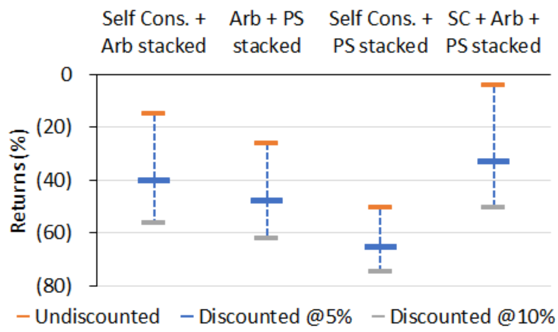


Figure 48: Comparison of IYI in all Stacking Scenarios

Figure 49: Comparison of Returns in all Stacking Scenarios

4.4. Qualitative Analysis

Table 5 shows six most important "quantifiable" policy issues identified by the interviewees. Policy was explicitly stated as a central factor for EES overall (REA: "Policy is key"). However there was suggestion that it was perhaps more important to the commercial or grid scale applications than the residential market where cost considerations were preeminent. Powervault's comment: "[Policy is] hugely important. It's not as important as cost though" was echoed by Moixa: "nothing to stop me putting swarms of batteries on the system today … the question is will I get paid for it?"

There was remarkable consistency in the issues identified. All respondents saw HHS and smart meters as critical to making ToU tariffs more widely available and thereby creating an Arbitrage opportunity for residential EES. All three respondents from a residential EES background identified the lack of a mechanism for capturing the benefits distributed storage provides to the network as an issue. Powervault was particularly optimistic about the potential of EES here: "Essentially the outlook is that it is a huge money maker … it's a win-win-win situation". All three also saw the significant code review of network tariffs as an important issue. While both REA and Moixa did not expect it to impact the residential model directly, Powervault was concerned that it may be a precursor to a flattening of tariffs that would ultimately reduce the ability to provide BTM Arbitrage. Moixa highlighted the negative impact introducing ToU tariffs with potentially low daytime rates could have on PV Self-Consumption revenue.

The uncertainty created by policy deliberations, rather than the policy environment itself, emerged as a key issue. In the debate around network charging most respondents (REA/Powervault) appeared willing to sacrifice some near term visibility by engaging in a fundamental review to establish a stable long term framework. However in most cases policy uncertainty was considered negative. The issue around the applicable VAT rate appeared particularly significant to Powervault: "VAT has a tangible impact … the upshot is uncertainty"[2]. Uncertainty was also highlighted in the debate around the future of deeming and the lack of long term ancillary service contracts with consistent definitions. In these cases respondents explicitly linked uncertainty to the ability to access low cost financing.

All residential EES interviewees offered solutions to the current policy issues via their written submissions to Ofgem's CfE. Often these referenced international developments. Both the REA and Moixa highlighted the recent policy changes in the US (FERC RM16-23 and 157 respectively) as examples of "levelling the playing field" for storage. International markets also offered lessons of what not to do. For Moixa the impending 80% rise in T&D (transmission and distribution) charges in Germany underlined the impact inadequate preparation for growth in intermittent generation could have on the network. Interestingly there was no explicit call for a large EES subsidy as seen in these markets. Powervault's comments: "they are great when they last but when they are cut they do enormous damage" were echoed by the REA. However a "light" subsidy that incentivised the installer/owner to register the system and ensure both the installer and device were accredited was seen as important by Moixa.

For solving the "missing market" in distribution network savings Moixa proposed the use of mandated targets and DNOs to provide low cost asset financing. REA suggested the current CfD framework for guaranteeing generation returns could be extended to incorporate a "market stabilisation" element:

[2] On the 15th August 2017 HMRC confirmed that a 20% VAT rate is applicable to retro-fit EES installations. This removes the uncertainty but the differential treatment between retro-fit installations and those bundled with PV remains. Arguably this distorts the market and increases system costs (see section 4.5.2)

“If storage could also truly stack revenues and play into ancillary services markets, then this could in theory lead to lower strike prices for colocated projects and … savings for consumers … For example, using entirely theoretical figures, a solar farm able to bid at £70/MWh without storage revenues could bid in at £65/MWh when the on-site storage revenues are included in the business model” (REA, 2017)

Regulatory Action	Policy Issue	Evidence to Support Change	Potential Barriers to Implementation	Impact on modelling
1) Introduce ToU tariffs	Most UK residential customers are currently on flat rate tariffs - they pay the same price for electricity in peak as in off-peak*. Without peak and off-peak price variations EES cannot be used to provide Arbitrage and Self-Consumption benefits are reduced.	REA - "A lot of our members want ToU tariffs ... its a simple way of monetising the benefit to the consumer ... ToU tariffs would be really useful." Moixa - "Smart Batteries ... can deliver an immediate ToU benefit and a customer benefit to households"	Powervault - "A few suppliers offering ToU but it is not genuinely HHS - just buying blocks of power at an average. Speeding up the move to HHS, real time trading, is a big issue... Balancing and settlement code an urgent priority" Moixa - "There is a real potential issue to consumers ... that bills will become uncertain and confusing by adding a new 'time' dimension. Such billing complexity strategies have been used effectively in the mobile industry to systemically raise prices"	Model different ratios of peak/off-peak tariffs
2) Reduce VAT Rate	Retrofit EES projects are currently charged VAT at a standard 20% vs 5% on PV with battery (based on current rate of VAT applying to PV). However the ECJ ruled the UK needed to take items off the discount VAT list and solar was offered to be removed. Current system arguably makes EES expensive, disadvantages standalone providers and creates uncertainty.	Powervault - "We think we can argue fairly objectively, that this is putting us, as a standalone storage provider, at a considerable disadvantage ... tangible impact ... which creates uncertainty" Moixa - "needs to be harmonized and ... a 5% rate on installing solar with a battery could negate the EU legal case on discounted VAT rates"	Powervault - "... unlikely to be resolved soon. ECJ ruled that we need to take items off the VAT list and solar was offered to be bumped up to full rate. But there is no decision yet and with the current hiatus there is unlikely to be one soon.	Model 5% vs 20% scenarios
3) Introduce a subsidy	The high cost of storage makes it uneconomic for consumers currently. Deployment of solar in the UK was originally supported by FiT (Feed in Tariffs) and export payments that reward homeowners for generating electricity. Other markets such as Germany and California have similar support mechanisms for storage	Moixa - "A light government 'subsidy' would be the cheapest way for UK to ensure convergence and consistent delivery in the UK System ... creating clear tracking of such distributed resources and location. Innovative solutions cannot scale up domestically so lose out to US or other markets with temporal subsidy." Powervault - "The [solar] FiT has been cut so low, there is huge underspend in the budget currently, there would be budget available for that its more a question of the political will to do that".	Powervault - "i think there is a view in the industry that we don't want a [low cost loan/subsidy] given the history of FiT. When they are cut it does enormous damage to the industry" Moixa: "No or low subsidies ... is ironically helpful in enabling companies and technologies to deliver 'subsidy free' solution	Model different levels of subsidy
4) Reform solar export tariffs ("deeming")	Currently homes with solar are "deemed" to export 50% of PV to the grid. Adding storage reduces the level of PV exported but homeowners are currently still paid the deemed 50% export rate ie. they are paid for electricity they are not exporting.	REA - "surprised ... that the fit tariff reforms in February 2016 didn't mandate everyone to get a smart meter but that was probably good for the storage sector" Powervault - "BEIS start thinking about ... full price export tariff ... once the FiT runs out in 2Q2019"	REA - "Storage devices are ... benefitting the system as a whole. Deeming is a big motivation to get storage – you get an extra payment for that 50% ... don't change it until you have something sustainable in its place."	Model impact of removing deeming
5) Create a market for Peak Shave	~ 26% of the average electricity bill is network charges. Residential demand in the evening and solar peaks during the day are putting pressure on the network in some areas forcing DNOs to invest in the network.	Powervault - "storage has already come onto the network and we have seen decreased demand in the peaks ... Setting up markets for [deferring network spending] will see immediate and tangible savings for the consumers. It's a sort of a win-win-win situation that one" Moixa - "reduced stress on network is not correctly monetized ..." Could be addressed by 1) Mandates/targets under RIIO (eg California) or a separate incentive to DNOs 2) Flexible connection payments for BTM installers or contractual income for benefits in reducing peaks 3) Enable storage to be an allowable measure to cut network charges 4) Reduced network charge obligation for new towns built with reduced peak 5) Encourage asset finance provision by DNOs in congested areas	Powervault - " ... the networks have spotted that they don't actually need to upgrade this any more so Ofgem has cut their funding"	Model the introduction of Peak Shaving
6) Financing	The high upfront capital cost combined with a long payback lifetime means that cost of capital assumptions have a big impact on the value of the investment. Different investors in the market will have very different cost of capital eg operators with 1% vs consumers or equity investors at 7-9%	Moixa - finance a "critical factor" ... "NIC (National Infrastructure Commission) also needs to play a role in helping to address systemic asset financing issues" REA - "UK businesses have consistently faced a 'Valley of Death' in the commercialisation ... good support for R&D ... for projects which are near to market ... there has been a lack of adequate financing"	Moixa - provision of finance might need a separation in the role of "Battery Asset Provider" and "Battery Operator" REA - "key to this is sorting out ... longer term revenue streams"	Model returns with different cost of capital

Table 5: The Six Quantifiable Policy Barriers Identified by Interviewees

4.5. Policy Cases Modelled

Section 4.4 identified six policy issues capable of being tested by the techno-economic residential storage model. Change in these policies were compared to a "policy neutral" base case scenario to establish which impacted the investment case most. In the "policy neutral" base case scenario the current policy and market conditions remain unchanged and EES is only able to provide Self-Consumption income (a full list of parameter settings is shown in Table 8).

4.5.1. Increasing the Availability of ToU tariffs

For residential storage to generate Arbitrage income ToU tariffs must be available. However adoption of ToU is currently restricted by the lack of HHS and smart meters. To understand the potential benefits greater availability of HHS and smart meters could have on the residential storage market, Arbitrage income was stacked with Self-Consumption (as in section 4.3.1). Using a 20p peak off peak spread generates a 81% increase in IYI from a policy neutral scenario (Figure 50) and boosts returns by 26ppts (Figure 51).

As highlighted earlier, the ability to generate income from ToU tariffs is heavily dependent on the spread between peak and off-peak prices. Any changes to the current electricity charging regime that narrows this spread, either directly or by rebalancing higher standing charges with lower unit prices at all times of day, could significant impact on returns. A 10p spread only leads to an 50% uplift in IYI and 13ppt rise in returns.

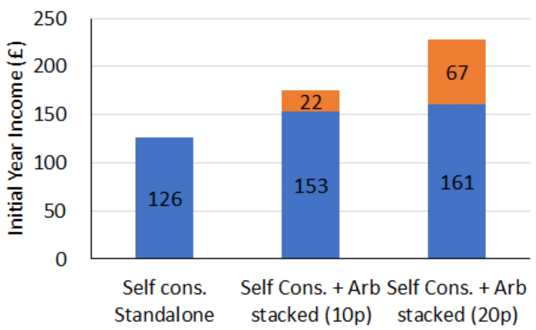


Figure 50: Increase in IYI from Stacking Arbitrage with Self-Consumption with both a 10p and 20p peak/off-peak Spread

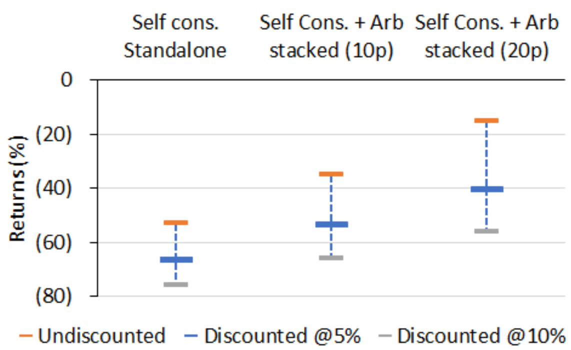


Figure 51: Reduction in Losses from Stacking Arbitrage with Self-Consumption with both a 10p and 20p peak/off-peak Spread

4.5.2. Applying a 5% VAT Rate for Retro-Fit Installation

Cutting the VAT rate applicable to a battery fitted to an existing PV system (ie not installed alongside PV simultaneously) from 20% to 5% has only a modest impact on the investment case (see Figure 52). Income generation is unchanged but the initial outlay is reduced by 12.75% from £3,638 to £3,183. This improves returns by just 4.7ppts (@5% CoC) and the investment remains heavily loss-making.

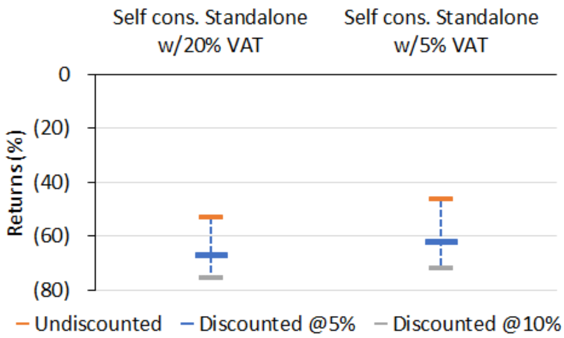


Figure 52: Reduction in Losses from Cutting the Applicable VAT rate from 20% to 5%

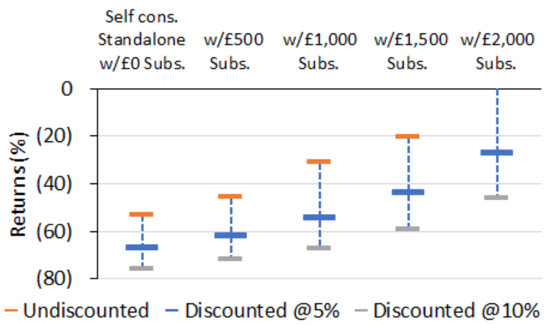


Figure 53: Reduction in Losses from Introducing Subsidies

4.5.3. Introducing a Subsidy Programme

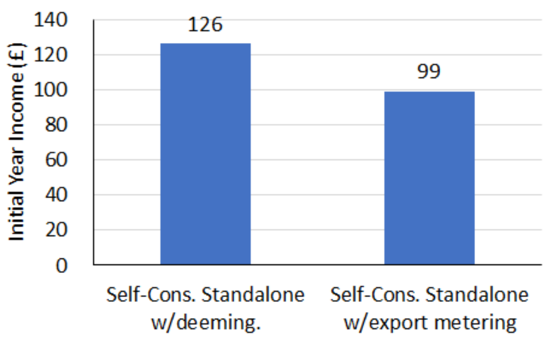
Residential EES subsidy programmes in California and Germany have experienced contrasting fortunes. In 2016 Germany's KfW programme added 20,000 households with an average subsidy for a 4kWh system equivalent to c.£1,500. California's SGIP currently pays a subsidy equivalent to £1,230 for a for 4kWh system but has failed to stimulate significant residential demand.

Figure 53 highlights that introducing a £500 subsidy in a single service scenario has a similar impact to cutting the VAT rate, improving discounted returns by just 5ppts (@5% CoC). Even a £1,500 subsidy only reduces losses by 23ppts to -44%. It requires a £2,000 subsidy, significantly more than international programmes, before the net investment costs fall below discounted cashflows.

4.5.4. Removing Deeming

Moving from "deemed" to metered PV export is the only policy change modelled which hurts residential storage economics. In the current policy environment 50% of PV production is "deemed" to be exported. This equals 2,063kWh in our model, generating annual PV export income of £101. Adding a battery (operating in Self-Consumption mode) electricity exported to the grid falls to 1,520kWh, 26% below the deemed rate.

In a scenario where export payments remain "deemed" at 50% of PV production, the reduction in electricity exported does not impact income. However as smart meters are rolled out (they could be potentially mandated with residential storage) exports to the grid can be measured directly. The model suggests a move to metered export would significantly impact storage economics for PV owners, reducing IYI by £27 (21%) and lowering returns by 10ppts (see Figure 54 and Figure 55). In this scenario undiscounted income from residential storage would recover less than 30% of the initial capital outlay over the lifetime of the project.



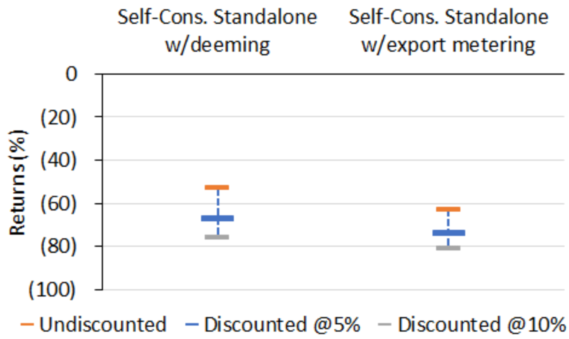
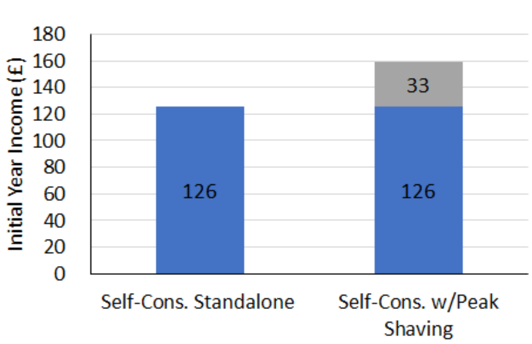


Figure 54: Impact of Removing Deeming on IYI

Figure 55: Removing Deeming Reduces Returns

4.5.5. Enabling A Peak Shaving Service

Figure 56 Figure 57 highlight that enabling a Peak Shave service only modestly improves storage economics. The £33 increase in IYI translates into a 2ppt increase in returns.



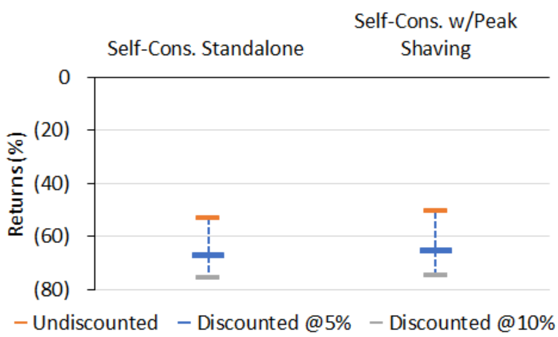


Figure 56: Increase in IYI from Stacking Self-Consumption and Peak Shaving

Figure 57: Reduction in Losses from Stacking Self-Consumption and Peak Shaving

4.5.6. Cost of Financing

Given the assumed battery lifespan of 15 years, unsurprisingly the cost of capital has a significant impact on returns. Capitalising on current near record low borrowing rates, the government could offer consumers low or zero cost loans to finance storage, with the loan paid back from electricity savings over time. Moixa suggests co-ordinating storage roll-out is needed to ensure system wide benefits are available. As Figure 40 highlights reducing the cost of capital from 5% to 0% improves Self-Consumption returns by 14ppts, from -67% to -53%.

5. Discussion

5.1. Single Service Residential EES is an Uneconomic Investment

These results suggest that Arbitrage is the most attractive service on a standalone basis, generating 35% more annual income than Self-Consumption. This is arguably positive as it has the greatest addressable market (less than 1m or 4% of UK homes currently have PV installed). Nevertheless an investment in residential EES in the UK in 2020 that just provides Arbitrage is highly loss-making. Despite assuming a 33% fall in system costs (from £984/$1,247 per kWh in 2017 to £659/$835 by 2020) and a ToU tariff with a 20p spread, Arbitrage returns are -56% (@5% CoC). Effectively over half the money invested is wasted.

A sensitivity analysis (Table 6) of an "Arbitrage only" scenario, varying the base case parameters individually, suggests that achieving breakeven by 2020 with a 5% CoC requires either a sustained 8.8% per annum growth in electricity prices or a subsidy of £2,030. A trebling in the rate of annual system cost declines (ie. 12.4% to 38%), or applying a 12.4% annual reduction to the 2017 £337/$438 per kWh price implied by Tesla's Powerwall, could also bring break even forward to 2020. Without a big fall in initial capital costs, an investment in EES providing just a single service, is unlikely to generate positive returns until 2028.

Investment Input	Base case Arbitrage only	'alue in Arbitrage only scenario needed to reacl breakeven		
		Undiscounted	5% CoC	10% CoC
Annual h/ware cost decline (%)	(12.4)	(27.0)	(38.0)	(47.0)
Annual electricity price rise (%)	0.0	4.6	8.8	13.0
Level of subsidy (£)	-	1,340	2,030	2,450
Start of investment	2020	2025	2028	beyond 2030

Table 6: Changes to Key Investment Inputs Needed to Reach Breakeven in an Arbitrage only Mode.

5.2. Revenue Stacking has the Biggest Impact on Returns

An investment in residential EES that can stack revenue is also likely to be uneconomic (R = -34%). This conclusion appears largely consistent with the existing academic literature. The IYI per kW generated by the model for Self-Consumption and Arbitrage are similar to that predicted by Teng & Strbac (2016) for 2030. Both Pena-Bello, et al., (2017) and Davies & Hiralal (2016) found significantly negative returns for investments in 2016.

While revenue stacking might not, in isolation, turn the investment case positive, it does significantly improve returns. Figure 58 highlights that adding Arbitrage and Peak Shaving to Self-Consumption income boosts returns by 34ppts (with a 5%CoC) – an impact nearly three times greater than introducing a £1,000 subsidy and 8x greater than cutting the VAT rate.

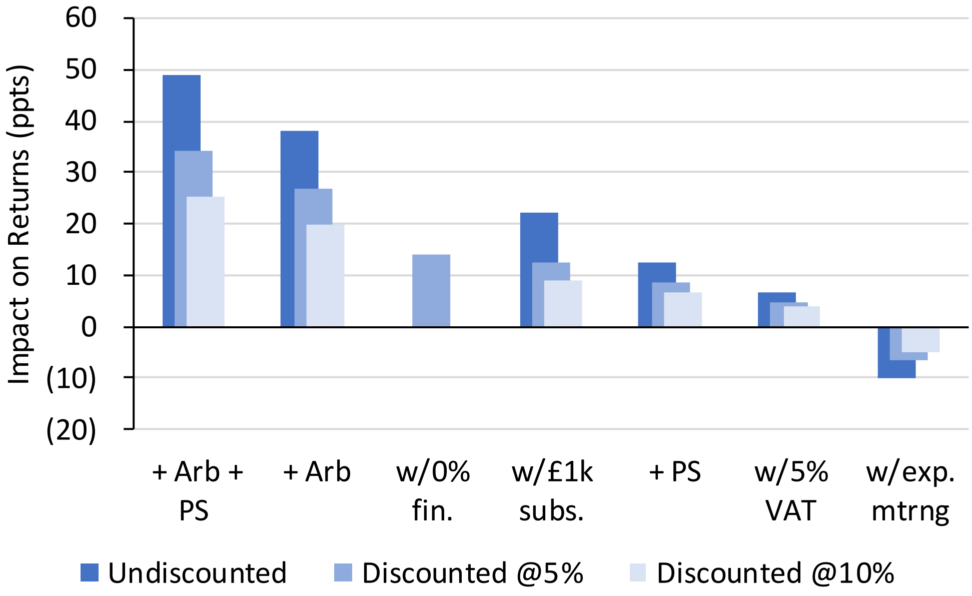


Figure 58: The Impact of Revenue Stacking on Returns vs Other Policy Issues

This finding puts the policy debate around the VAT rate and subsidies in context. Without revenue stacking a c. £2,500 subsidy is needed to generate a positive return. This study suggests little enthusiasm for an intervention of this size even from residential EES providers. The uncertainty about the VAT rate is unhelpful and the differential between standalone (retro-fit) and bundled installation potentially distorts competition (see Table 5). However a positive resolution is unlikely to be game changing. In isolation, neither a subsidy or VAT cut appear likely to transform the EES investment case.

Analysis of the results also show that changes to annual income impact returns differently from changes to initial capital costs. Figure 59 highlights that in a 2020 scenario with relatively high capital costs (£3,638), incremental annual income (created by revenue stacking for example) leads to a linear improvement in returns – every £50 of additional income improves R by 13ppts. In contrast, reductions in capital cost (either falling battery prices, higher subsidies or a lower VAT rate) have an increasing effect on returns. Figure 60 describes how improving returns by 13ppts from -87% requires a large (£1,800) reduction in capital cost but a similar 13ppts improvement from -22% costs just £90. This simply reflects whether the change is predominantly impacting the numerator (discounted annual income) or the denominator (initial capital costs) of the returns calculation. However this effect has important implications for how storage returns could evolve over time and the design of any policy incentivising storage (see Section 5.3 – 5.5).

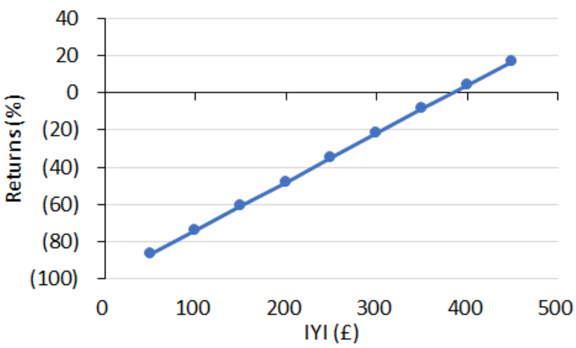


Figure 59: Impact of Rising IYI on Returns

Based on a @5% CoC and capital cost of £3,638

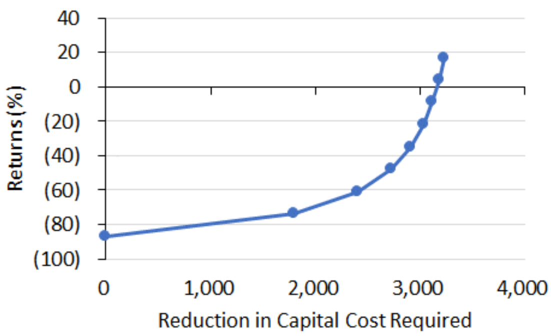


Figure 60: Impact of Lower Capital Cost on Returns

Based on @5%CoC, IYI of £50 and £3,38 capital cost

This effect can also be seen in the sensitivity analysis of a revenue stacking scenario (see Table 7). A relatively modest "real terms" price increase of 14% by 2020 (a 4.6% CAGR sustained through the battery lifespan) increases IYI by £30 and makes an EES investment profitable in 2020 (ie. a 34ppt increase in R). The observation that tariff levels have a significant impact on returns was also made by Parra & Patel (2016) and is particularly relevant in light of recent price rises from British Gas[3] and the current political debate in the UK about capping energy bills (Pratley, 2017). Interestingly the issue of overall electricity pricing was not highlighted by any of the interviewees as major issue for storage policy.

Not only does stacking have a big impact on returns, access to multiple income streams also de-risks the investment. Moixa and Powervault both highlight that grid EES income has remained remarkably constant even as the constituent income streams have altered substantially, helping Dinorwig secure cheap financing. All these points suggest revenue stacking should be the primary focus of any residential storage policy.

[3] On the 1st August 2017 British Gas announced a 17% increase in price per kWh for its standard electricity tariff. The first increase in the standard tariff in four years, it effectively implied a 4% per annum increase in prices between 2013 and 2017 (2% per annum rise in "real terms"). The standing charge was unchanged.

Investment input	Value in Stacking Scenario Base Case	Value in a Stacking Scenario (Self-Cons, Arb + PS) needed to reach breakeven		
		Undiscounted	5% CoC	10% CoC
Annual h/ware cost decline (%)	(12.4)	(14.0)	(25.3)	(33.0)
Annual electricity price rise (%)	0.0	0.5	4.6	8.8
Level of subsidy (£)	-	150	1,200	1,850
Start of investment	2020	2021	2024	2027

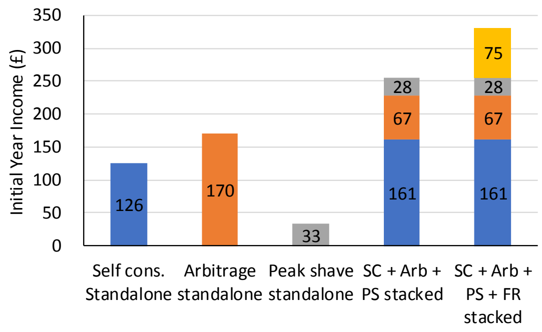
Table 7: Changes to Key Investment Inputs Needed to Reach Breakeven with Self-Consumption, Arbitrage and Peak Shaving All Enabled.

In contrast a significant reduction in capital cost is required to reach breakeven even in a revenue stacking scenario. Table 7 suggests a subsidy of £1,200 would needed with a 5% CoC – roughly half the amount needed bring a single service scenario to breakeven. Alternatively an acceleration in system cost declines could bridge the gap. The price of Tesla's Powerwall ($337 per kWh) and the experience of other renewable technologies suggests scope for costs to fall faster than the 12.4% annual decline factored into the model. Table 7 suggests that the current rate of decline must double to reach breakeven by 2020. Tesla's cost per kWh suggests a revenue stacking scenario would be substantially profitable, generating returns of more than 100%.

5.3. More Ambitious Revenue Stacking Scenarios (Adding Ancillary Services)

Table 7 showed how in a stacking scenario relatively modest increases to income assumptions (through tariffs) could make residential EES economic. The same effect could be achieved by stacking additional services. Lithium-ion is well suited to the quick response time needed for FRS (see Dunn, et al., 2011; Parnell, 2017). Teng & Strbac's (2016) analysis suggests FRS could be worth more than £100 per year in 2030 if aggregated by a local community. Moixa's GridShare pays residential storage owners £75 per year to use their capacity to provide FRS. Alternatively National Grid spent £28m procuring 233GWh of Short Term Operating Reserve (STOR) between April 2014 and March 2015 (National Grid, 2016). Equivalent to 12p per kWh this could generate annual income of £170 for a 4kWh battery. Unlike Peak Shaving both FRS and STOR are also likely to be valued consistently nationally.

Figure 62 suggests adding £75 to the existing 2020 revenue stacking scenario boosts returns by 20ppts to -14% (assuming @5% CoC) and brings breakeven forward by two years to 2022. This analysis again highlights the value of revenue stacking to the investment case.



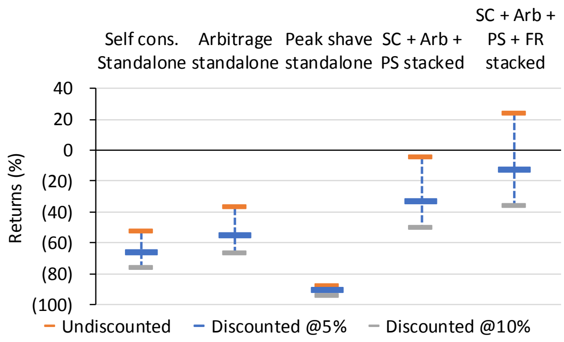


Figure 61: Increase in IYI from Stacking FRS with Peak Shaving, Self-Consumption and Arbitrage

Figure 62: Fall in Losses from Stacking FRS with Peak Shaving, Self-Consumption and Arbitrage

5.4. The Barriers to Revenue Stacking: Policy or Market?

If revenue stacking is the biggest driver of returns what determines their availability? Section 4.5.1 and 4.5.5 considered revenue stacking as a function of policy. However Moixa already offers three services (Self-Consumption, Arbitrage and FRS). If Moixa can do it today, is policy really such a big barrier?

5.4.1. Stacking Arbitrage

Policy appears unlikely to remain a major restriction on stacking Arbitrage with Self-Consumption for long. The "four-tariff" restriction has already been lifted and the availability of HHS and smart meters, both identified as crucial issues by our respondents, are being addressed. A decision on mandatory HHS for domestic customers is expected in 2019 (Ofgem, 2017d), and the roll out of smart meters to all homes (that want one) by 2020. Both REA and Powervault expressed concern about the interoperability of current smart meters and HHS reform has been delayed by a year already (Utility Week, 2017). Nevertheless policy initiatives in this area should make ToU tariffs more widely available.

Whether they will be adopted by consumers is another question. ToU tariffs such as Economy 7/Economy 10 have been around for many years, and new ones are becoming available. There is no restriction on residential EES owners switching to these tariffs. BEIS & Ofgem highlighted consumer interest in ToU in its "Smart Systems and Flexibility Plan" (2017) but over two thirds of households remain on poor value standard plans (Ofgem, 2016), and BEIS suggests just 10% of consumers would definitely switch to a ToU tariff (UK Government, Department of Business, Energy and Industrial Strategy, 2016).

5.4.2. Stacking Peak Shaving

The situation appears different with Peak Shaving. The lack of a defined market in reducing distribution costs via accessing storage was identified by all the interviewees and acknowledged by Ofgem. Actions to address this include:

> "open up the delivery of network requirements to the market so new solutions such as storage or demand-side response can compete directly with more traditional network solutions [and] actively consider what further evolution of parties' roles may be required" (UK Government, Department of Business, Energy and Industrial Strategy and Ofgem, 2017)

While stating it expects to make "swift" progress in this area, the language suggests a solution is not imminent. Part of the problem is the wide range of potential solutions. Adding a power component to residential bills might be one relatively straightforward "cost reflective" approach to creating a market (albeit one with significant implications for consumer bills). The two alternative initiatives suggested by the interviewees also appear viable. It will take time to identify consensus.

How significant this policy obstacle will ultimately prove to be is not clear. The analysis presented here suggest rewards for Peak Shaving may prove to be modest (see Figure 40) and this is not the only study to reach that conclusion. As the ENA (trade body representing the network operators) highlighted in its submission to BEIS and Ofgem's CfE: "We do not know if the commercial market place can provide viable storage services in the highly location specific manner networks may need" (Energy Networks Association, 2017). The Smart Network Storage (SNS) study undertaken by UKPN looked at a Peak Shaving service based on the deferral of £6m of network investment. Even in this case, where there was a large quantifiable benefit from delaying investment, Peak Shaving was not commercially viable (UK Power Networks, 2017a). A similar conclusion was reached by Western Power Networks from its SoLa Bristol project:

> "we are firmly of the view that the benefits for DNO's to take SoLa Bristol forward do not currently exist. SoLa Bristol produced some interesting insights [but] the perceived benefits for DNOs that we envisaged could materialise, did not occur" (Western Power Distribution, 2016).

5.4.3. Stacking Ancillary Services

The policy issues around using residential EES to provide Ancillary services are also significant. Ofgem's approach, simplifying the Ancillary services market, ending exclusivity and opening up the capacity market (see Figure 3) appear to have identified the main issues raised by the interviewees. However like Peak Shaving, tackling these issues is at a relatively early stage.

Commercial value is also a big uncertainty in the area of Ancillary grid services. The most recent EFR (Enhanced Frequency Response) auction achieved a value per kWh less than half the FRS value used in Teng & Strbac's (2016) study (0.7-1.2p per kWh vs 2p). Demand for ancillary services may increase with the growth in intermittent generation but residential storage will be just one model competing to address the opportunity.

The technical feasibility of adding Ancillary services is another. Figure 61 simply added FRS income without modelling the impact on dispatching other services (Teng & Strbac (2016) adopted a similar approach). A more complex dispatch algorithm is needed to incorporate FRS, particularly alongside additional ancillary services. Optimal battery size might also need to be re-considered (FRS is a much shorter duration service so a larger battery capable of faster discharge might be ideal (Dunn, et al., 2011)). Integrating Ancillary services into the model is an area where this study could be extended.

5.4.4. Barriers to Stacking: A Summary

The boost stacking provides to returns (relative to measures which reduce investment cost), highlights why it should be the primary focus of any residential storage policy. Overall Ofgem appears to have identified most of the major policy barriers and established initiatives to address them. Removing barriers to Arbitrage look addressable by 2020, even acknowledging concerns about delivery. There are bigger obstacles to accessing Peak Shaving and Ancillary services. Here preferred policy has not been identified and no timeframe for delivery set.

However even with a policy environment that fully enables stacking, residential EES is likely to be an uneconomic investment in 2020. Figure 62 shows that combining FRS, Peak Shaving, Arbitrage and Self-Consumption, R is -14%. The commercial value of FRS and Peak Shaving functions included in this analysis is highly uncertain and arguably generous. A residential EES policy that prioritises stacking is sensible but the results suggest further support may be needed encourage deployment by 2020.

5.5. Policy Options Beyond Revenue Stacking

Financing is one area where additional policy support could be considered. As Figure 62 highlights a 5ppt reduction in the cost of capital assumption (from 5% to 0%) boosts returns by +20ppts, equivalent to £75 of additional annual income (IYI).

Policy can influence financing costs for residential EES in two ways. All respondents highlighted the negative impact of uncertainty on finance costs. Guaranteeing residential EES access to income streams could reduce this uncertainty. Alternatively the government and/or return regulated entities such as DNOs, could exploit their access to near zero cost finance to provide low-cost loans to consumers. With a zero cost of capital assumption, residential EES is breakeven in 2020 stacking income from just three services.

Unfortunately the policy debate on financing in the UK appears tarnished by the Green Deal debacle, the effect cutting FiT rates (government support) had on the solar industry and the perceived impact on consumer bills (see section 2.2.3). As Powervault states - " we don't want a [low cost loan/subsidy] given history of FiT. When they are cut it does enormous damage to the industry". Most of the issues associated with the Green Deal appear eminently fixable and Germany's KfW and EnEv programmes (see 2.2.5) show providing loans can be successful (Energy Post, 2016).

The political appetite for subsidies may have diminished, and they may be an expensive way to improve low returns, but this study suggests they still have a role to play. The "light" subsidy for the residential ESS proposed by Moixa, essentially a payment for registering the system which ensures only accredited systems are fitted by vetted suppliers, appears prudent (a fire caused by poorly fitted battery could damage public confidence enormously). More fundamentally, registering ensures that both the total available storage capacity is known and that installed systems are compatible for aggregators.

In addition Figure 60 highlighted that subsidies have an increasing benefit as returns approach breakeven. So in a scenario where revenue stacking (FRS, Peak Shaving, Arbitrage and Self-Consumption) has reduced losses to -14%, a subsidy of under £500 would bring residential EES to profitability (assuming a 5% CoC). A more proactive version of this policy, where a £150 "registration incentive" is combined with a low (zero) cost loan for the balance of the investment costs, transforms residential EES into a very profitable investment (R = 29%).

Alternatively a subsidy could be varied to reflect the severity of local network issues, effectively substituting for the missing market in Peak Shaving until regulation can be established.

These measures could be accompanied by a publicly stated target for storage deployment. The use of a target to signal long-term policy intentions has been cited as a reason for the success of California's storage policy (Peterman, 2017). Procurement targets have also been used in Ontario and Italy. The Electricity Storage Network has called for a 2GW target by 2020 to be established for the UK (ESN, 2014).

5.6. Justifying a More Proactive EES Policy

Section 5.2 to 5.4 highlighted that existing storage policies are focused on reducing barriers to revenue stacking but look insufficient in isolation to encourage widespread adoption of residential EES in the near term. Section 5.5 identified additional policies which could arguably bring forward adoption relatively cost effectively. In this section justification for additional policy support, based on evidence collected in this study, is set out briefly.

The timing of residential EES deployment is the key issue. Assuming battery costs continue falling at the current rate and no radical change in electricity market structure, residential EES looks likely to become a profitable, if not highly profitable, investment within the next 15 years, suggesting widespread deployment is likely at some point. So the question of whether to provide additional support for residential storage is effectively what value does bringing forward residential EES deployment have? This value can be summarised as:

1. **The value of storage to the system is greater if deployed earlier.** Reducing the cost of electricity is a stated objective of both energy and broader industrial strategy. Studies by both Lehmann, et al., (2016) and Heptonstall, et al., (2017) emphasise that the value of storage, and therefore the potential savings to customers, is greater if deployed earlier.

2. **Environmental benefits.** Meeting future carbon budgets will require a re-acceleration in intermittent (renewable) generation deployment, adoption of EVs and the electrification of heating. Residential EES will making integrating these technologies into the system easier (Radcliffe, 2015).

3. **Meets needs of broader industrial strategy.** EES, particularly its application to EVs, has been heralded as an important part of the UK's industrial strategy and backed by significant government R&D funding (see section 2.2.2). Sustainably encouraging a viable domestic market could enable UK companies to establish themselves, generating jobs, growth and potentially exports.

4. **Other flexibility options could fall short.** Storage is part of a "flexibility" portfolio that includes DSR, interconnection and flexible generation. Interconnection with Europe may be complicated by Brexit and recent issues with the French nuclear fleet (The Economist, 2016). As much of the UK's pronounced evening winter peak is driven by consumer lighting and cooking demand the role of DSR may also be limited. Accelerating EES deployment could address this contingency.

It is beyond the scope of this study to quantify the value of these benefits, or the cost of the measures set out in section 5.5 that might deliver them. Nevertheless this analysis suggests that accelerating residential EES deployment could create significant value for multiple stakeholders and the additional policy support needed could be provided relatively cost effectively. The announced R&D funding signals there is money available for EES but also indicates a possible misconception that the technology is still at a pre-commercialisation phase. As Few, et al., (2016) states, it is the commercialisation of established storage technologies, rather than the development of new ones that look likely to be relevant to addressing the energy system issues in the next 15 years. As Figure 63 highlights the UK is already well behind other countries in (non-PHS) storage deployment. If it wants to establish itself as a genuine leader in this technology, what it is missing, based on evidence from this study and echoed by REA, is policy support for domestic producers trying to commercialise the technology.

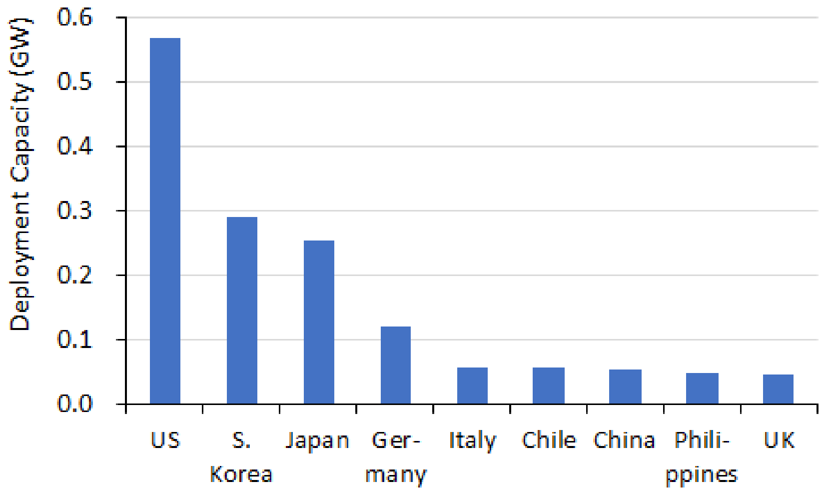


Figure 63: Deployment of Electro-chemical EES by Country (based on US Department of Energy, 2017)

6. Conclusion

The rising proportion of intermittent renewable generation needed to decarbonise the UK electricity system creates an increasing need for the deployment of electrical energy storage (EES). This thesis attempts to quantify the impact of current policy barriers on the investment case for residential EES in the UK. The principal policy barriers were identified by interviews with industry experts and representatives from residential EES providers. Issues capable of being quantified were fed into a techno-economic model using projected costs for a 4kWh lithium-ion battery in 2020 added to an existing 4kWp residential PV system. The impact on the investment case was assessed using annual income and returns based metrics.

The results suggest that residential EES is likely to remain an uneconomic investment for some time to come. Using the battery to increase Self-Consumption of PV generates annual income (in the first year) of £126 but a return of -67% (based on a 5% CoC). Providing Arbitrage is more lucrative, generating income of £170 per annum but returns remain negative (R –56%). Only by 2028 have battery costs fallen sufficiently far for the investment to become economic.

Some sensitivities on these results were conducted. The impact of system size and different levels of PV input on investment returns was relatively modest. The impact of hardware cost was more significant. The current £337/$438 system price per kWh implied by Tesla's Powerwall (nearly a third that of competitors – see Figure 7) was not considered sufficiently representative to be used as a basis for cost assumptions in this study. However applying a 12.4% annual reduction from this level would bring forward Arbitrage break even by eight years to 2020.

Using the battery to provide multiple services was more lucrative, but the investment remained loss making. Adding Arbitrage to Self-Consumption enables greater utilisation in the winter months, raising annual income to £228. A Peak Shaving service, payment for reducing demand during peak periods, could lift annual income to £257, but returns remain negative (R= -34%). By stacking three services together the date of breakeven is brought forward to 2024. Adding an Ancillary service like FRS could bring break even forward to 2022.

Six key quantifiable policy issues were identified by interviewees:

1. the introduction of ToU tariffs

2. the appropriate VAT rate for retro-fit installations
3. whether residential EES should receive a subsidy
4. the potential removal of "deeming" of PV export tariffs with smart meter roll-out
5. the need to establish a market for network savings.
6. financing costs.

Overall the barriers that prevented revenue stacking were most significant to the investment case. Without ToU tariffs (Issue 1) residential EES cannot provide Arbitrage and without a way of rewarding network savings (Issue 5) there can be no Peak Shaving service. A review of BEIS and Ofgem's "Smart Systems and Flexibility Plan" (2017) suggests current policy recognises the importance of revenue stacking and is focused on removing barriers. These initiatives may take time and interviewees were concerned about implementation in some areas. Mandating HHS and Smart Meter roll out should enable ToU and Arbitrage; plans to remove barriers to widespread and consistent availability of Peak Shaving and Ancillary services look less advanced.

Modelling these policy impacts highlights the different effect measures boosting income and those reducing initial investment costs have on the investment case. In this study each incremental £50 increase in annual income improves returns by 13ppts. This underlines the importance of revenue stacking in raising returns and also explains why higher overall electricity prices also have a significant impact on returns. While the relationship between tariffs and residential EES returns was not raised by interviewees it is arguably particularly relevant in light of the current political debate in the UK about price capping.

In contrast measures reducing initial investment cost increasing benefit the investment case as returns improve. Operating in a single service mode only very large (c. £2,500) subsidies bring the investment to breakeven in 2020. With stacking enabled, subsidy levels fall below £500 (80%). This effect underscores the importance of prioritising revenue stacking in policy design. It also highlights that, assuming no radical change in electricity unit prices and falling battery costs continue, residential storage will transition from being an uneconomic to highly profitable investment relatively quickly. This suggests that, at some point, perhaps beyond 2025, widespread deployment is likely.

Policy may be focussed on the right areas but, given residential EES appears likely to remain loss making even with revenue stacking until 2024, current policy measures look insufficient in isolation to deliver widespread consumer adoption in the near term. Additional measures could include providing low cost loans, a “light” subsidy and publicly stated deployment targets. Initial analysis suggests these measures, used in combination, could potentially bring forward adoption substantially and relatively cost effectively. Accelerating EES roll out could be justified by greater reduction to system costs which, in turn, could be passed onto consumers. These measures could also hasten the deployment of low carbon generation and begin the transition to a system capable of supporting electrification of heating and widespread EV adoption. Finally they could also bring significant benefits to industrial strategy. Strategic policy announcements (Osborne, 2012; UK Government, National Infrastructure Commission, 2016a; and Clarke, 2017) continue to highlight the importance of the UK establishing a leadership role in advanced EES. By focussing more on deployment, policy could help close the substantial gap already opening up between the UK and international deployment and between rhetoric and reality.

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8. Appendix

Parameter	Value	Notes
PV Model		
Location/tilt/orient.	ninja_hertford_35_1	data source, location, tilt and orientation
number of panels	16	
System Size (kWp)	4	
Inverter losses (%)	10.0	
Half hourly random variation	off	a randomise function (+/-10% from splined value) was built into PV model
Shaded/Correction factor (%)	9	a factor to correct the proportion of sunlight not reaching panels due to structural shading (buildings/trees etc). Has been used to adjust the correction factor identified in Pfenninger & Staffell (2016) instead.
Efficiency factor (%)	0	Adjust for inverter efficiency. Not used
Output		
- kWh generated	4,126	
- Capacity factor (%)	13.0	
- Annual output	1,032	
Tariffs		
- FiT (p per kWh)	41	
- Export metered	no	
- Export assumption (%)	50	
- Export price (p per kWh)	4.9	
Battery assumptions		
Battery size (kWh)	4	
Inverter cost (kWp)	4.0	paired
Install cost		
- 2017 Lithium-ion system cost per $	1,431	Price for first kWh, subsequent $/kWh cost 1/3 based on published prices and academic sources (see section 3.2.1)
- Inverter ($ AC-coupled)	900	Price for first kWh, subsequent $/kW cost 1/2 based on published prices and academic sources (see section 3.2.1). 1:1 ratio with battery kWh assumed
- Installation costs (£)	350	Respondent elicited (annon). Flat rate per installation. RMI breakdown suggests a standalone install cost between £500 - 750
- Installation margin (%)	10.0	Respondent elicited (annon). Only applied to installation costs (assume hardware sold at zero margin)
- VAT rate (%)	20	Based on standard VAT rate. See section 4.5.2.
- Subsidy	0	
- Exchange rate	1.30	As on 22-July 2017
Performance assumptions		
- Trip efficiency (%)	90.0	ie round trip = 81%. In the middle of the range of 75 - 90% round trip efficiency estimated by EPRI (2010)
- Minimum battery charge (%)	10	BRE (2016) state a typical lithium ion residential battery has a 75% Depth of Discharge to preserve lifespan. In 2015 Sonnenbatterie claimed to have developed a long lasting battery (see below) that had 100% DoD
- Lifetime	15	According to BRE (2016) manufactures generally state: 'Life expectancy = 10 years or 10,000 cycles, whichever is the sooner'. However battery improving all the time. In 2015 Sonnenbatterie claimed to have developed a battery with a 10,000 cycle lifespan. The 15 year assumption implies 5,500 daily cycles
- Annual decline battery capacity	1.0	Expressed as an annual decline in revenue using an average taken from Xu, et al., (2016)
Half hour Charging/Discharge Rate (%)		
- +ve SC	7.0	
- -ve SC	40.0	
- +ve Arb	15.0	
- -ve Arb	30.0	
- +ve PS	10.0	at least 14 off peak periods
- -ve PS	6.2	
Consumption/Tariff assumptions		
Customer	Domestic	
Usage profile	Standard	**Needs to be set to ToU for Arbitrage to work**
Pricing profile	Flat Rate	**Needs to be set to ToU for Arbitrage to work**
Tariffs (p)		
Flat Ratemedium	14.24	British Gas (2017), based on single rate, direct debit, Eastern Region
Economy 7medium	18.0	
Economy 7off-peak	10.0	
ToUpeak	25.0	
ToUmedium	12.0	
ToUoff-peak	5.0	
Flat rate flexer	1.0	should be set at 1
Inflation rate (%)	0.0	should be set at 0
ToU Winter Peak (on)	16:00	
ToU Winter Peak (off)	22:00	
Financial/Valuation assumptions		
year of start	2020	
Rate of cost decline	(12.4)	Based on Schmidt, et al., (2017) residential battery system (-12.4%)
Operating costs	3.0	
Tax rate	0.0	
Cost of capital	5.0	
Peak Shave assumptions		
Type of peak shave service	MPP	MDP = Maximum daily Peak, MPP = Maximum in Peak Period
Peak kW pre storage (incl. PV)	0.87	
Peak kW w/Peak Shave	0.49	
Reduction (kW)	0.38	
Price per kW per year (£)	100.0	
Revenue share (%)	75.0	

Table 8: Base Case Modelling Assumptions