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Energy self-sufficiency, grid demand variability and consumer costs: Integrating solar PV, Stirling engine CHP and battery storage

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HIGHLIGHTS

- Simulation of integrated solar PV, Stirling engine CHP and battery system.
- Grid demand variability significantly reduced but incentives to install required.
- Electricity self-sufficiency reaches 72% with a 6 kWh battery.
- The 6 kWh battery reduces grid ramping requirements by 35%.
- System only financially viable for households with electricity demand >4300 kWh/yr.

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ABSTRACT

Global uptake of solar PV has risen significantly over the past four years, motivated by increased economic feasibility and the desire for electricity self-sufficiency. However, significant uptake of solar PV could cause grid balancing issues. A system comprising Stirling engine combined heat and power, solar PV and battery storage (SECHP–PV–battery) may further improve self-sufficiency, satisfying both heat and electricity demand as well as mitigating potential negative grid effects. This paper presents the results of a simulation of 30 households with different energy demand profiles using this system, in order to determine: the degree of household electricity self-sufficiency achieved; resultant grid demand profiles; and the consumer economic costs and benefits. The results indicate that, even though PV and SECHP collectively produced 30% more electricity than the average demand of 3300 kWh/yr, households still had to import 28% of their electricity demand from the grid with a 6 kWh battery. This work shows that SECHP is much more effective in increasing self-sufficiency than PV, with the households consuming on average 49% of electricity generated (not including battery contribution), compared to 28% for PV. The addition of a 6 kWh battery to PV and SECHP improves the grid demand profile by 28% in terms of grid demand ramp-up requirement and 40% for ramp-downs. However, the variability of the grid demand profile is still greater than for the conventional system comprising a standard gas boiler and electricity from the grid. These moderate improvements must be weighed against the consumer cost: with current incentives, the system is only financially beneficial for households with high electricity demand (>4300 kWh/yr). A capital grant of 24% of the installed cost of the whole micro-generation system is required to make the system financially viable for households with an average electricity demand (3300 kWh/yr).

1. Introduction

Global demand for solar PV in residential dwellings has increased rapidly in the past decade, resulting in 138 GW of installed capacity by 2013 [1]. This has been driven by government incentives such as Feed-in Tariffs (FITs) [e.g. 2] and the rapid reduction in manufacturing costs: PV module costs reduced by 62% between 2011 and 2013 [3]. In the UK, there is presently 2 GW of installed capacity [4]. However, UK FIT rates for solar PV were cut in half in 2012, reducing the financial motivation to install and has slowed uptake significantly [5]. If uptake is to increase again, the consumer motivation to install must be improved: research on the motivations and barriers affecting

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Nomenclature

t_{CHP}	duration of SECHP operation (s)
D_{heat}	total heating requirement (kJ)
P_{heat}	power requirement for heating during the morning or evening (kW)
C_{PV}	the installed cost of the solar PV system (£)
P	the rated peak capacity of the system (kWp)
Q	the total charge required (Ah)
B_T	total battery capacity (kWh)
V	system voltage (V)
C_{op}	total yearly operating cost (£)
E	cost of electricity imported from the grid (£)
G	cost of natural gas (£)
M_{PV}	maintenance cost of solar PV (£)
M_{CHP}	maintenance cost of SECHP (£)
M_B	maintenance cost of battery (£)
FIT_{PV}	FIT earnings from electricity generated by the solar PV (£)
FIT_{CHP}	FIT earnings from electricity generated by the CHP (£)
FIT_{exp}	FIT earnings from exporting unused electricity to the grid (£)

consumer adoption suggests uptake would increase further if higher levels of self-sufficiency were achieved, such as by incorporating battery storage [5].

Additionally, the UK National Grid has reported that the installed capacity of solar PV above 10 GW feeding into the grid would present difficulties in the operation and balancing of the electricity transmission system [6]. The intermittent and diurnal nature of PV generation increases the ramping requirements of variable load power plants, such as combined cycle gas plants [6,7]. The ramping requirements are the rates at which the electrical output of variable-load plants must change to meet demand. Furthermore, with 22 GW of uncontrolled solar PV feeding into the grid, the summer peak PV generation together with anticipated baseline generation from nuclear could exceed demand [6]. It has been suggested that battery storage could be used to help towards aleviating the these grid issues [6,8,9] Whilst centralised battery storage remains unappealing owing to low energy densities and financial constraints [10], decentralised lead-acid battery storage local to solar PV generators is more common [11]. However, local battery storage represents an additional upfront cost to the consumer, which is already an important barrier for most who consider installing it [5]. Batteries are currently not cost effective [12], although smaller capacity systems are perhaps close to being so [13–15], particularly lead-acid batteries [16]. Additionally, there is a growing expectation that local battery storage will become cost effective in the near future [17,18].

Furthermore, adding a Stirling Engine combined heat and power (SECHP) unit to a system with solar PV and battery storage would further improve the household's electricity self-sufficiency, and reduce the required battery capacity (and cost). SECHP systems are intermittent electricity generators, only generating whilst there is a household heat demand similarly to a standard gas boiler, therefore mainly during the winter. This provides a useful contrast to solar PV, which generates most during the summer owing to higher insolation. SECHP could deliver improved economic and environmental impacts over a gas boiler but is highly dependent on the way in which it is operated by the household [19,20]. High system efficiencies are achieved only when the system is operated for long periods as the high operation temperatures (approximately 500 °C) require startup and shutdown periods where gas is consumed but no electricity is generated [21–23].

Thus, a combined household system comprising solar PV, SECHP and battery storage could help to mitigate potential grid balancing and ramping issues, whilst significantly improving household electricity self-sufficiency. A number of studies have modelled the potential for battery storage installed with microgeneration to reduce variability of household grid demand, thus mitigating grid balancing issues, finding that some degree of smoothing (10–50% reduction in grid energy demand oscillations) is possible with mid-sized batteries (3–8 kWh) [e.g. 24–26]. Additionally, many studies have simulated different combinations of microgeneration technologies with battery storage to provide household self-sufficiency; for example, with solar PV [27–29], SECHP [30,31], fuel cells [28,32,33], or wind turbines [34]. Most studies indicate that the degree of self-sufficiency achieved is limited without very large battery capacities. To the authors' knowledge, none has investigated the combination of solar PV, SECHP and battery storage and none has studied both self-sufficiency and grid demand smoothing effects.

Therefore, the aim of this research is to determine the impact of using a combined solar PV, SECHP and battery household system on electricity self-sufficiency, the variability of grid demand and household economic costs. This paper presents the results of a simulation of energy supply and demand for 30 households using the PV-SECHP-battery system as well as a consumer cost-benefit analysis. In particular, the study demonstrates the effects of the following variables on the above research outputs:

- the variation in household electricity and gas demand;
- different battery storage capacities; and
- the efficiency of SECHP operation.

The work strives to provide a greater understanding of the potential benefits and economic costs of decentralised battery storage systems to contribute to mitigating future electricity grid operation and balancing difficulties associated with increased solar PV uptake. This would give policy makers and grid operators a sound basis for deliberating on the pathways to mitigate this future risk to the grid and capital cost implications. Recommendations regarding system improvements and policy are also made. The study is based in the UK but the analysis is generic enough to be applicable to other countries.

The following section describes the methodology for the simulation. This is followed in Section 3 by the results of the self-sufficiency, grid demand profile and the cost-benefit analyses. A discussion of the results relating to financial incentives is given in Section 4 and conclusions are made in Section 5.

2. Methodology

The operation of the household energy system comprising solar PV, SECHP and battery storage was simulated over a year for 30 dwellings in detached, semi-detached and terraced houses with different heat and electricity demands and solar PV generation. The simulation provides energy performance data which are then compared to a household using currently predominant energy sources, i.e. gas boiler for heating and electricity from the grid. The following sections describe how the simulation was carried

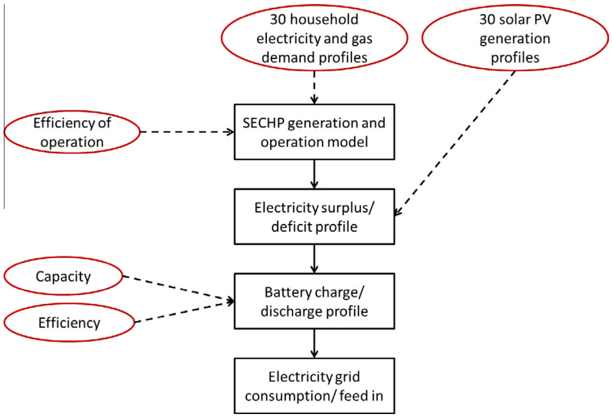

Fig. 1. Simulation steps for the solar PV, SECHP and battery system. The boxes represent the stages and the circles indicate simulation variables.

out, the analysis of household electricity self-sufficiency, the assessment of the effect of the system on the electricity grid and the cost-benefit analysis.

2.1. Household simulation

Fig. 1 gives an overview of the simulation steps. Real household energy demand and solar PV generation profiles are used for the simulation input data. The SECHP operation profile is modelled using the heat demand data with a control variable for the efficiency of operation. Combining this with the PV generation and electricity demand profiles allows an electricity surplus/deficit profile to be generated for each household (and each control variable value). The battery storage can then be simulated, using the surplus/deficit profile and defining the battery capacity and discharge efficiency variables. Various values for battery capacity and discharge efficiency are used to create a set of scenarios of battery profiles. Lastly, the electricity grid import and export profiles are generated for each scenario. A detailed description of these simulation steps is given in Section 2.1.2; prior to that, the data used to conduct the simulation are described next.

2.1.1. Simulation data

The simulation is based on 30 household electricity and gas demand profiles from the UKERC Energy Database Centre (EDC) [35]. The UKERC EDC is an open source database, containing data from the Milton Keynes Energy Park with 94 household hourly demand profiles from 1990. Although this dataset is now 24 years old, it remains the only openly available dataset with coincident gas and electricity demand of sufficient quality to conduct a household simulation and continues to be used for energy-related simulations [e.g. 20,36,37]. The 30 profiles were selected based on the completeness of the data set (i.e. electricity and gas profiles with at least one year's data), to include range of detached (DH), semi-detached (SDH) and mid-terraced (MTH) house types and a broad range of electricity and gas demand profiles. In addition, three average UK household electricity profiles were also used [38]: average electricity demand profiles for typical urban, suburban and rural households, replacing the UKERC EDC data for three households with similar annual electricity demands.

Solar PV generation profiles were sourced from the open-access PVoutput.org database, a website where solar PV users can upload 5-minutely generation data [39]. Data were selected based on their completeness and to be representative of UK installation capacities [40] with a range of capacities of 1–4 kWp. Allocation of each PV profile to a demand profile was carried out by ranking the PV data by peak capacity and the household data by floor area, and matching the ranking numbers (assuming that greater floor area implies greater roof space availability for solar PV). A summary of the household demand and PV generation data is given in the Appendix (Table A1).

As the simulation is based on hourly electricity and gas demand data and 5-minutely PV data, the demand data were split and assumed constant over 5 min divisions within the hour. Thus, the simulation estimated SECHP and battery usage on a 5-minutely scale. However, the smoothing effect of using the hourly demand data, in particular for electricity demand, may have resulted in lower instantaneous power variations [41,42]. Higher resolution data is preferable for investigations into network voltage variations, but this is deemed acceptable for investigating the impact on the central grid as this demand is likely to be smoothed out over the large number of households that the grid supplies.

The SECHP system was modelled using data from the only SECHP system approved by the Microgeneration Certification Scheme [43]: the Baxi Ecogen [44], with a variable output of 3.4–6.4 kW heat and 0.3–1 kW electricity using 3.7–7.7 kW natural gas [45]. For periods when heat demand is greater than the maximum output, 6.4 kW, an auxiliary burner is used to supply the additional requirement. This burner delivers 3.6–17.6 kW heat output, consuming 3.8–19 kW of natural gas [45].

Note that the 30 simulations are all specific household case studies, designed to reflect a broad range of dwelling types, demand and generation profiles. The simulation results are not necessarily representative of the UK housing stock, but an example of the potential impact such a household system would have on self-sufficiency and grid demand. In order to give some detail on the representativeness of the households, Fig. 2 shows the electricity and gas demand for each household together with the UK average (low, medium and high, from [46]). The graph shows a broad spread across the electricity demand axis and two clusters around low and high gas demands. However, to the authors' knowledge there is no available data on the distribution of UK household demand for different dwelling types, thus the representativeness of the data is not known.

The PV data collected are representative of the UK PV stock as illustrated by Fig. 3, showing the proportion of PV installation capacities for the UK [40] and for the simulation data.

It is important to note that this study assumes that the household energy demand patterns are not affected by installation of the PV-SECHP-battery system: the simulation involves mapping historical household demand profiles, using grid electricity and a standard gas boiler, on to modelled generation and storage patterns. In reality, both the time-varying pattern of generation and the change in marginal electricity cost throughout the day may have an impact on the demand patterns. For example, as PV generates more electricity during the middle of the day, households may alter their consumption patterns to maximise usage of PV electricity. Some studies suggest that demand may shift in order to reduce cost or maximise self-generated electricity [47,48], although a change is not guaranteed and may depend on a number of other social factors [49]. In this study, the assumption that heat and electricity demand does not change is conservative with respect to self-sufficiency.

2.1.2. Simulation design

Household heat demand was derived from the gas demand data by applying an assumed boiler efficiency of 80%, based on average UK boiler efficiencies and the UKERC EDC stated average boiler SEDBUK[1] (Seasonal Efficiency of Domestic Boilers) efficiency of

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[1] SEDBUK is the UK standard measurement of boiler efficiency, used within the UK government's Standard Assessment Procedure (SAP) of household efficiency ratings [50].

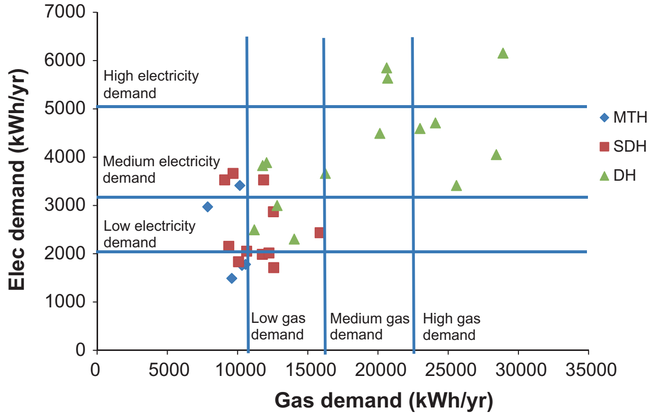

Fig. 2. Annual gas and electricity demand for each household simulation. Vertical lines indicate UK average household gas demand and horizontal lines indicate average electricity demand [46]. [DH – detached house; SDH – semi-detached house; MTH – mid-terraced house].

75–90% [35,50]. The operation of the SECHP system was modelled in two different ways to investigate the impact of the efficiency of operation:

1. 'inefficient' SECHP mode 1: operating the SECHP system in the same way that a standard boiler is used (turned on whenever there is a heat requirement); and
2. 'efficient' SECHP mode 2: operating the SECHP to deliver the total heat requirement for each day within two on/off cycles (morning and afternoon).

The study assumes a startup and shutdown sequence of 2 min of maximum natural gas consumption (7.7 kW gas input for 2 min = 0.26 kWh), where no useful energy output is generated, based on discussion with the Baxi Ecogen Technical Department (pers. comm., 18 September 2013).

Under the efficient SECHP operation (mode 2), the system is switched on twice per day: in the morning (05:00) and in the evening (16:00). These are the times with the most commonly occurring demand peaks, based on observations of the heat profile data. Therefore, this mode of operation is more efficient in terms of the ratio of useful energy output to the quantity of natural gas consumed as there are fewer startup/shutdown cycles compared to mode 1.

The SECHP heat output for each cycle is equal to the total heat demand and the power output is equal to the maximum hourly demand for each part of the day (morning or evening), in order to maximise electricity power output during that period. The duration of the SECHP operation for each part of the day is consequently determined by:

$$t_{CHP} = \frac{\sum D_{heat}}{MAX(P_{heat})} \tag{1}$$

where t_{CHP} is the duration of the SECHP operation, $\sum D_{heat}$ is the total heating requirement and $MAX(P_{heat})$ is the maximum heat power requirement during the morning or evening.

The household system is operated such that the consumption of locally generated electricity is maximised, maximising self-sufficiency. Thus, when electricity generation by SECHP or solar PV coincides with demand, the electricity is consumed. When local generation exceeds demand, the battery is charged until full, at which point the surplus is exported to the grid. Likewise, when demand exceeds local generation, the battery supplies the deficit until the minimum battery capacity is reached, at which point grid electricity is imported. For each 5-minutely time point, the simulation determines the state of battery charge and the quantity of residual electricity that is imported from, or exported to, the grid.

Six different battery capacities were simulated for each household: 2, 4, 6, 10, 20 and 40 kWh, as well as a 'no battery' scenario which is used for comparison. These storage capacities were selected based on sizes used in similar battery simulation studies [e.g. 51]. The battery is operated to be discharged to only 50% of full capacity in order to prolong battery life, based on a conservative estimate from literature [13,52,53]. Thus, the usable capacity is half the total capacity: 1, 2, 3, 5, 10 and 20 kWh. This paper refers only to the usable capacity from here on.

The efficiency of the battery system was modelled by applying a constant discharge efficiency, defined as the ratio of useful energy output to energy input. In reality, battery efficiency is variable and depends upon the ambient temperature, operating voltage and state of charge [12,24,25,27,54,55]. This study adopts the simpler approach of modelling power flows with a constant battery discharge efficiency [as per 29,56–58], instead focussing on the impact of different battery capacities and the degradation of discharge efficiency over time. A number of discharge efficiency scenarios are considered for each household to reflect the broad range of efficiencies cited in literature [59,60]: 40%, 60%, 80% and 100%.

In summary, the simulation was carried out for each combination of each parameter shown in Table 1, using Stata, a database analysis and statistics software package. Two additional scenarios are also considered in this study in order to understand the contribution of each technology: a solar PV only system (with a gas

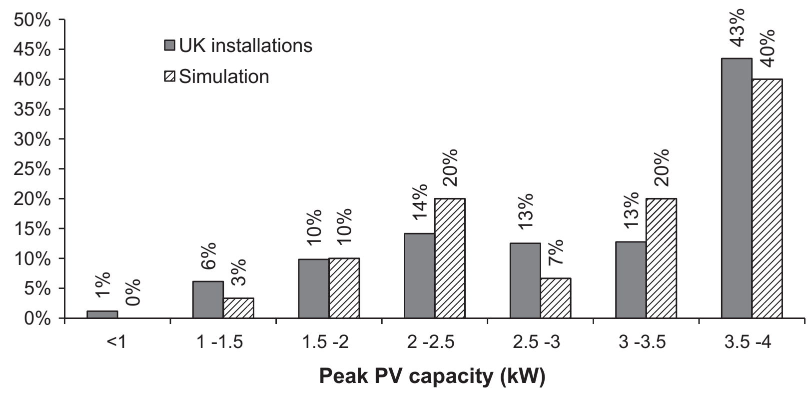

Fig. 3. Graph of the range of PV capacities for UK installations <4 kWp and for the simulation data [40].

Table 1
The simulation parameters, their units and range of values, as well as the base case values.

Parameter	Units	Values	Base case
Battery efficiency	%	40, 60, 80, 100	80
Battery capacity	kWh	1, 2, 3, 5, 10, 20	3
SECHP operation mode	N/A	Inefficient, efficient (0, 1)	Efficient
Electricity demand	kWh/yr	1491–6276 (30 profiles)	Not applicable
Gas demand	kWh/yr	7901–29174 (30 profiles)	Not applicable
PV generation	kWh/yr	692.2–4556 (30 profiles)	Not applicable
Total number of simulations	1440	$4 \times 6 \times 2 \times 30$[a]	Not applicable

[a] The total number of simulations equals the product of the number of values considered for each parameter.

boiler) and a PV with SECHP system (without the battery). Owing to the large number of parameter combinations (1440), a base case scenario was selected for analysis (as shown in Table 1). The efficient SECHP mode was selected for the base case as this offers energy efficiency and economic benefit. A battery (usable) capacity of 3 kWh was selected for the base case as this was the most cost-efficient capacity. Further, a base-case battery discharge efficiency of 80% was used as it most closely reflects battery efficiency found in literature [61–63].

2.2. Household electricity self-sufficiency

The degree of household electricity self-sufficiency is defined by the proportion of demand met by local generation, i.e. not imported from the grid. Thus, the annual proportion of imported electricity is determined for each household simulation and the impact on self-sufficiency of each parameter listed in Table 1 is analysed. The individual contribution of PV, SECHP and the battery is also investigated.

2.3. Electricity grid demand profiles

The effect of the household system on the variability of grid electricity demand is determined by creating and analysing a series of daily grid demand profiles. Average demand profiles are generated for each simulation and each quarter of the year, showing the variation in grid electricity imports and exports across the course of a day. A comparison between the simulation profiles and the conventional system (grid electricity and gas boiler for heating) is made using the following profile parameters:

- the mean daily demand;
- the daily variation in electricity demand, from maximum to minimum;
- the maximum hourly ramp-up rate (i.e. maximum hourly gradient of electricity demand over time); and
- the maximum hourly ramp-down rate (minimum hourly gradient).

Other studies investigating the variability of electricity demand profiles often use common statistics such as mean, standard deviation, variance and the coefficient of variation [56,64], or instead focus on the reduction in peak demand [e.g. 51]. This study creates the additional 'ramping' indicators (ramp-up and ramp down as described above) in order to describe more intuitively the potential change in ramping duty placed on the centralised generation plants. The 'variation' indicator compliments the hourly ramping figures by illustrating the daily magnitude in 'swing' between the peak export and peak demand.

2.4. Cost-benefit analysis

A cost-benefit analysis was conducted for a 30 year period, based on the longest expected lifespan of the system component: solar PV panels. This lifespan was based on literature figures of 25–50 years [65]. Component lifespans are described further in Section 2.4.3. Household costs were estimated based on 2013 values, thus no inflation over time was considered. The calculation comprised the summation of capital, operating and equipment replacement costs for each year. All costs and benefits (e.g. FIT incentives) considered are from the household perspective, thus no other costs/benefits (e.g. the 'social' benefit of reducing greenhouse gas emissions) are included. The difference in net-present value (NPV) between the SECHP–PV–battery system and the conventional gas boiler and grid system was used to indicate financial feasibility: the former system is financially viable for households with an NPV difference above zero. The calculation of NPV is defined in the Appendix. The payback time and undiscounted lifetime costs were also estimated for each combination of parameter values given in Table 1. Payback time is defined here as the time it takes to pay back the capital cost of the SECHP–PV–battery system by way of lower operational (energy) costs, including the consumer discount rate. 'Simple payback time' is also estimated, which is the payback time without accounting for the consumer discount rate (i.e. the discount rate is zero).

The consumer discount rate used to calculate NPV and payback time was 5%, but a range of 0–50% was used as part of a sensitivity analysis, as consumer discount rates are notoriously difficult to predict and vary significantly for different forms of investment [66]. Estimated discount rates are often based on the opportunity cost of the capital (i.e. equal to the rate of return of the best alternative investment) [67,68]; therefore, 5% was selected as a base case as this is a typical savings account interest rate (before the economic recession). Additionally, 5% is approximately the rate of return achieved for a solar PV system [5].

2.4.1. Capital costs

Different solar PV capital costs were found in the literature, ranging from £1500 to £13,859 for capacities of 1–4 kWp (see Table A2). The installation cost was estimated based on the Parsons Brinkerhoff's 'medium' estimate (as opposed to 'low' and 'high'), defined as [65]:

$$C_{PV} = £1127 + £1621xP \qquad (2)$$

where C_{PV} is the installed cost (£) of the whole solar PV system and P is the rated peak capacity of the system (kWp).

Various installation costs for were also found for SECHP systems, ranging from £3500 to £10,000 (see Table A3 for full list). A median value of £5500 was assumed in the study. The lead-acid battery capital cost includes costs of battery cells, inverter, charge controller, cabling and installation cost, and varies with battery capacity. Table 2 shows the assumed cost for each component of the battery system, based on quoted prices from online microgeneration equipment distributors [69,70] as well as estimates in the literature [12,27]. The required number and specification of battery cells for each capacity is also included in Table 2. A battery system voltage of 24 V was assumed [71] and the required rated charge of the battery cells was estimated according to Eq. (3):

Table 2
Capital cost and specification of the battery system components [12,27,69,70].

Component	Specification[a]	Cost (£)
Battery cells 1 kWh	12 V 90 Ah ×2	480
Battery cells 2 kWh	12 V 90 Ah ×4	960
Battery cells 3 kWh	6 V 460 Ah ×4	1120
Battery cells 5 kWh	12 V 220 Ah ×4	2000
Battery cells 10 kWh	6 V 460 Ah ×12	3360
Battery cells 20 kWh	6 V 460 Ah ×20	5600
Charge controller	N/A	100
Inverter	24 V 3 kW	1500
Cabling	N/A	100
Installation cost	N/A	1000

[a] The multipliers in the ‘Specification’ column show the number of cells needed to give the required quantity of energy storage (1–20 kWh usable capacity).

Table 3
Total capital cost for different battery usable capacities.

Battery usable capacity (kWh)	Cost (£)
1	3180
2	3660
3	3820
5	4700
10	6060
20	8300

$$Q = \frac{B_T}{V} \tag{3}$$

where Q is the total charge required (Ah), B_T is the total battery capacity (twice the usable battery capacity in this case because of the 50% required depth of discharge) and V is the system voltage. The resultant total battery system costs were estimated between £3180 and £8300 and are shown in Table 3.

2.4.2. Operating costs

The net annual operating costs were estimated based on the following equation:

$$C_{\text{op}} = E + G + M_{\text{PV}} + M_{\text{CHP}} + M_B - \text{FIT}_{\text{PV}} - \text{FIT}_{\text{CHP}} - \text{FIT}_{\text{exp}} \tag{4}$$

where:

C_{op} total yearly operating cost
E cost of electricity imported from the grid
G cost of natural gas
M_{PV} maintenance cost of solar PV
M_{CHP} maintenance cost of SECHP
M_B maintenance cost of battery
FIT_{PV} FIT earnings from electricity generated by the solar PV
FIT_{CHP} FIT earnings from electricity generated by the CHP
FIT_{exp} FIT earnings from exporting unused electricity to the grid.

With the exception of the electricity and gas unit costs, operating costs remain constant over the time period and the values used are listed in Table 4.

Table 5
Yearly electricity unit cost increase above inflation ordered from lowest to highest, alongside gas cost inflation rate and the source of the estimate.

Electricity cost inflation rate	Gas cost inflation rate	Source
−0.11%*	−0.48%[a]	[77]
1.35%*	−0.71%[a]	[76] (‘low’)
2.12%*	0.99%[a]	[76] (‘ref’)
2.60%	5.80%	[78]
2.7%*	2.32%[a]	[76] (‘high’)
2.94%*	3.11%[a]	[77]
3.65%	N/A	[73]
5%*	5%*	[77]

[a] The inflation rates are derived average rates over the 30 year period, but do not reflect the shape of the cost increase over time (i.e. they are not necessarily exponential).

The solar PV maintenance cost estimates varied from £42/yr to £110/yr [65,74] and the figure of £63/yr was based on the ‘medium’ estimate from the Parsons Brinckerhoff cost review. The SECHP maintenance cost of £110/yr was based on the high estimate from the CEPA and PB cost review [65]. Estimates for battery maintenance cost were not found and an assumption of £50/yr was made. FIT tariff payments were all based on 2013 current rates [75].

The initial electricity and gas costs (Table 4) were taken from the DECC average estimates of 2013 UK domestic energy bills [72]. The electricity unit cost was assumed to be constant throughout each year, whilst yearly changes were modelled on a series of projection scenarios. The constant unit cost was used for simplicity, to limit the scope and size of the model. Electricity and gas costs in the UK are often variable within time periods, either depending on the time of day (for example ‘Economy 7’) or the quantity of electricity consumed (higher price for the first unit of electricity, lower for all electricity consumed thereafter). This may have some impact on the total energy cost (and potentially time-varying demand) but is outside the scope of this study.

There are various projections of future electricity and gas unit costs that vary considerably, as shown in Table 5. The DECC ‘high’ annual inflation of 2.7% for electricity and 2.3% for gas were used as a base case as this was the median projection for both electricity and gas prices [76]. The effect of the other cost projections is included within the sensitivity analysis.

2.4.3. Equipment replacement costs

The cost-benefit analysis was conducted for a 30 year period, which is the expected life span of the solar PV system. Other major system components must be replaced over this time. Table 6 lists major components that need replacing, their expected lifespans and cost of replacement.

2.4.4. Disposal and residual asset value

The disposal cost is dependent on the installation of a replacement system (e.g. boiler replacement services often include disposal), which is unknown. Additionally, owing to the different

Table 4
Costs associated with each operating cost component.

Operating cost type	Cost	Source
Electricity (at year 0)	15 p/kWh	DECC [72]; McKinsey & Co. [73]
Gas (at year 0)	5 p/kWh	DECC [72]
Solar PV maintenance	£63/yr	Parsons Brinckerhoff [74]
CHP maintenance	£130/yr	CEPA and Parsons Brinckerhoff [65]
Battery maintenance	£50/yr	Assumption
FIT solar PV generation tariff	15 p/kWh	Ofgem [75]
FIT SECHP generation tariff	10 p/kWh	Ofgem [75]
FIT export tariff	5 p/kWh	Ofgem [75]

Table 6
Expected lifespan and installation cost of each replacement item.

Component	Lifespan (yr)	Replacement cost (£)	Source
Solar PV inverter	11	1000	Electricians Forums [79]; Rudge [80]
Battery inverter	11	1500	Electricians Forums [79]; Rudge [80]
SECHP system	10	5500	Parsons Brinckerhoff [81]
Battery cells	10	See Table 2	See Table 2

operational lifespans of the components, some components will still have an asset value at the end of the 30 year period considered. For simplicity, it is assumed that there is zero net-cost to the consumer associated with disposal and asset value of the system.

2.4.5. Reference system

The reference system, as previously stated, consists of a gas boiler which provides heat and electricity from the UK grid. The installation cost of the boiler is assumed to be £2500 [21] with an operational lifespan of 15 years (one replacement over the 30 year period considered here). No cost of connection to the electricity grid is considered, as this would be required for both household systems. Similarly, no cost of the heating distribution systems (radiators and pipework) is considered. The annual maintenance cost of the boiler is assumed to be £120 [21].

3. Results

The results of the simulation and analysis presented in this section discuss the level of household self-sufficiency achieved (Section 2.1), the variability of grid demand (2.2) and the consumer cost-benefit analysis (2.3).

3.1. Electricity self-sufficiency

Table 7 summarises the average energy demand and the generation by each technology, estimated through the simulation. On average, the total solar PV and SECHP electricity generation over a year is 30% higher than household demand. However, imports still account for 28% of electricity supply, as shown in Table 8. The reason for the high level of imports is because the generation profiles of PV and SECHP do not match the household demand profile, and the base case battery capacity is not large enough to store the excess electricity required.

The contributions toward electricity supply from each source are shown in Table 8. Solar PV and SECHP make similar contributions but account for less than half of the electricity supply in total (45%). The battery storage increases consumption of household-generated electricity by 27%. This finding is similar to that of Li and Danzer [24], who add 3.3 kWh battery storage to a household solar PV system, reducing imports by approximately 25% and exports by 10%.

Table 7
Summary of base case annual household generation and consumption figures across the 30 simulated households.

Variable	Mean	Standard deviation	Minimum	Maximum
Electricity demand (kWh/yr)	3265	1320	1491	6276
Heat demand (kWh/yr)	11,773	4943	6321	23,339
PV generation (kWh/yr)	2772	1087	692	4557
SECHP electricity generation (kWh/yr)	1477	637	715	2946
SECHP gas use (kWh/yr)	13,963	5413	7680	26,034
Battery contribution (kWh/yr)	797	126	401	958
Imported electricity (kWh/yr)	982	663	218	2882
Exported electricity (kWh/yr)	1965	952	136	3662

Table 8
Contribution of each energy source as a percentage of total household demand for the base case, averaged over the 30 households.

Source	Mean	Standard deviation	Minimum	Maximum
Grid	27.6%	10%	9%	49%
Solar PV	22.8%	5%	12%	33%
SECHP	22.2%	5%	13%	31%
Battery	27.4%	9%	14%	42%

Table 9
Average proportion of consumed PV and SECHP electricity for the base case, both directly and indirectly (through the battery).

Source	Mean	Standard deviation	Minimum	Maximum
Instantaneous PV consumption	27.8%	9%	19.1%	64.9%
PV consumption from battery	23.4%	7%	14.5%	36.2%
Total PV electricity consumption	*51.2%*	*13%*	*36.1%*	*97%*
Instantaneous SECHP consumption	49.4%	11%	32.5%	66.9%
CHP consumption from battery	30.8%	8%	17.6%	48.0%
Total SECHP electricity consumption	*80.1%*	*8%*	*62.1%*	*98%*

They represent the total sum of the values in the two rows above.

Although contributions by the solar PV and SECHP are similar, the proportion of total SECHP generation consumed by the households is far greater than that of solar PV: 80% vs 51%. Table 9 shows the consumption of electricity generated by solar PV and SECHP, as a percentage of the total generation from each technology. This value is split into instantaneous consumption and consumption via the battery. Consumption from solar PV is somewhat smaller than expected: it is normally assumed that 50% of electricity generated from solar PV is consumed [82,83], whereas this study shows only half of this (28%) is achieved on average, albeit with a range of 19–65% across all households. Even with battery storage, only 51% PV electricity is consumed, although this figure varies significantly with different battery capacities. Consumption from SECHP is somewhat higher: 49% is consumed instantaneously, rising to 80% with battery storage. The instantaneous SECHP consumption is broadly in line with other similar studies: Fubara et al. [20] estimate 47–64%, whilst Peacock and Newborough [84,85] estimate 21–63%, both with similar SECHP systems. The daily generation profile of SECHP makes it much more effective in meeting demand than solar PV. SECHP generation is governed by the household heat profile, which is likely to be a closer match to the electricity demand profile than the solar PV generation profile. Thus, SECHP is more effective than solar PV for providing electricity self-sufficiency.

Overall, there was a large variation in reliance on imported electricity across households: from 9% to 49% for the base case as shown in Table 8. This is mainly due to the large variation in electricity demand, as well as the time of use of electricity in relation to the time of local generation.

The change in battery capacity has a significant impact on the amount of electricity imported from the grid. As shown in Fig. 4, increasing battery capacity to 20 kWh decreases imports to 12%. However, the reduction in imports above 5 kWh is marginal.

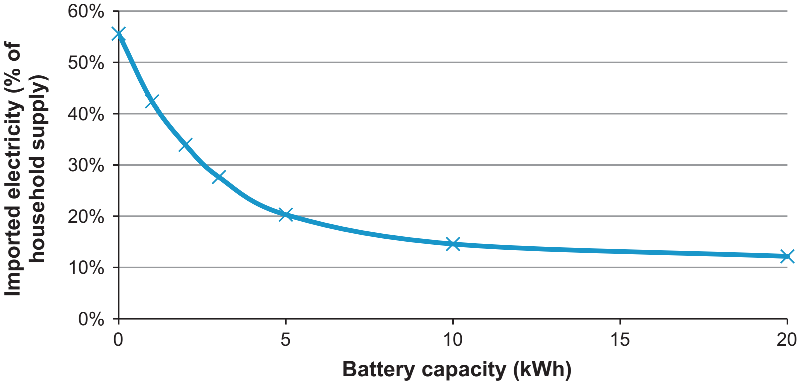

Fig. 4. The percentage of imported electricity for different installed battery capacities, with 80% battery efficiency and efficient SECHP operation, averaged across all households.

The impact of different battery discharge efficiencies on imports is somewhat smaller than battery capacity. At 100% efficiency, the mean imports are 23% but increase to 40% with 40% efficiency. Additionally, the SECHP operation efficiency has little impact on self-sufficiency, with an average import of 25.9% for inefficient operation (mode 1) and 27.6% for efficient operation (mode 2). This is because very similar quantities of electricity are generated in both modes of operation, albeit whilst consuming different quantities of natural gas.

Therefore, this part of the simulation suggests that, whilst some degree of self-sufficiency is achieved for the base case (72% for 3 kWh battery), there are only marginal improvements for the battery capacity above 5 kWh. Additionally, the SECHP is far more suitable for providing electricity self-sufficiency than solar PV, because of the far better correlation between the generation profile and household demand.

3.2. Variability in grid demand profiles

In addition to reducing annual electricity imports, the SECHP–PV–battery system significantly alters the daily grid demand profile. Fig. 5 summarises the average daily demand properties for the reference system, PV only, SECHP–PV–battery for all battery sizes considered. The graph clearly shows an increased daily variation in demand when PV and SECHP are added to the household: solar PV increases the maximum ramp-down and ramp-up rates by a factor of 2.5 and 1.6, respectively. Somewhat surprisingly, the addition of SECHP increases ramping requirements even further, by 3.9 for ramp-down and 2.2 for ramp-up relative to the reference system. This corroborates the findings of Peacock and Newborough [86], who suggest that the electricity grid profiles increase in variability if the SECHP system is operated as a heat-led system, as is currently the case for the Baxi Ecogen considered here. The addition of battery storage reduces ramping requirements and variation considerably: 1 kWh storage reduces ramp-down by 43% and ramp-up by 22% relative to the PV + SECHP scenario. This result broadly agrees with that of Purvins et al. [56] who find that a 0.6 kWh battery reduces household grid demand variation by 35%. As battery capacity increases, grid ramping requirements and variation in demand are reduced further. Although the addition of battery storage reduces the impacts significantly compared to the PV-SECHP system without the battery, the variation is still greater than for the reference system, even with a 20 kWh battery. Thus, the addition of a battery may not prevent grid balancing problems.

The effect of the negative impact of solar PV on grid demand is shown in greater detail in Fig. 6. The reducing PV generation in the afternoon for Q2 and Q3, combined with increasing demand in the evening, produces a prolonged ramp-up in grid import, demonstrating very clearly the increase in demand variation that concerns the National Grid (as described in Section 1).

As indicated in Fig. 7, the contribution of SECHP and a battery is to decrease peak demand and peak exports, whilst adding a trough at 16:00, due to the SECHP system being switched on Although during the winter months (Q1 and Q4) the demand curve is visibly flattened, there is higher variation in demand during the summer months (Q2 and Q3). The 3 kWh battery system is unable to negate the greater summer PV generation rates, causing the sharp rise from mid-afternoon export to high evening demand.

Thus, these results show the impact of each technology on the variation in grid demand: both solar PV and SECHP significantly increase grid demand variation and the effect is cumulative when both installed, particularly during the summer months, whilst battery storage provides some reduction in grid ramping requirements.

3.3. Cost-benefit analysis

The results of the cost-benefit analysis consider payback time and NPV difference compared to the reference system (for details, see Table A4 in the Appendix). The results show that the payback for the base case is achieved for 9 out of 30 households within the lifespan of the system (30 years). The simple payback time, which excludes the consumer discount rate, is achieved for 17 of the households. There is a very large variation in NPV across the 30 households, with NPV difference ranging from £8542 to −£11,379, largely because of the varying household energy demand. Payback times range from 15 years to never paying back the investment. Those households which achieve positive NPV difference have higher electricity demand (greater than 3600 kWh/yr). For these, the SECHP–PV–battery system provides more electricity and heat at lower cost than the reference system, resulting in an improved operating cost reduction.

3.3.1. Factors affecting the cost benefit analysis

The results suggest that only the installations without battery storage (PV only and PV with SECHP) have a positive NPV difference relative to the reference system (Fig. 8). The NPV difference remains roughly constant for battery capacities of 1–3 kWh, implying that the marginal increase in capital cost is nullified by the marginal decrease in electricity import cost. At capacities above 3 kWh, the NPV decreases much more significantly, reaching −£12,077 for the largest battery capacity of 20 kWh. Thus, the addition of any size battery storage tends to decrease the relative

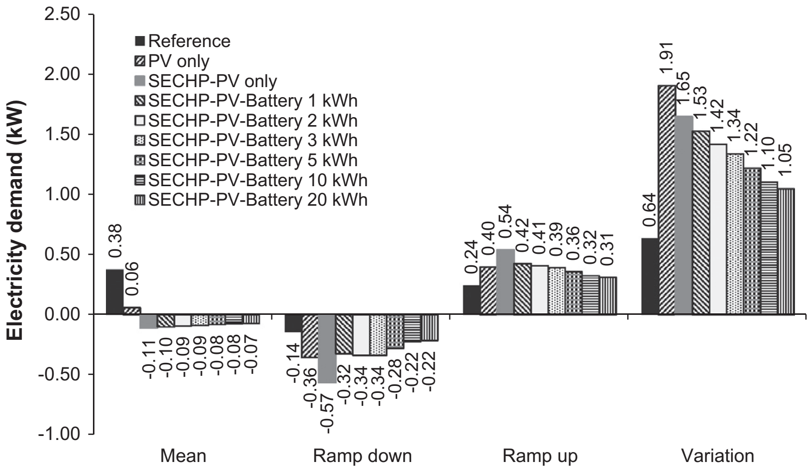

Fig. 5. Daily household demand properties for the reference system, PV only, PV + SECHP and all battery sizes, averaged across all households for 80% battery efficiency and efficient SECHP operation (where applicable).

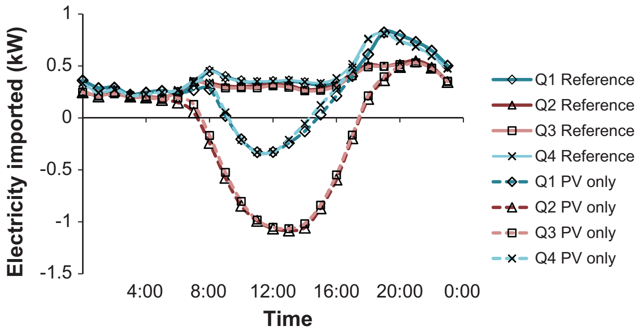

Fig. 6. Daily demand profile for different quarters of the year for the reference and solar PV only systems, averaged across all households.

NPV, which is consistent with the findings of McKenna et al. [12]. This means that, if local battery storage is seen as beneficial to the electricity grid, it must be incentivised to increase uptake.

The decrease in NPV at larger battery capacities is due to the increase in capital and, in particular, equipment replacement costs. The total undiscounted lifetime cost breakdown shown in Fig. 9 for different scenarios shows that the effect of increasing battery capacity on reducing operating costs is minimal: a battery capacity of 20 kWh decreases operating costs by less than 20% relative to a battery capacity of 1 kWh, whereas capital costs are 36% higher and replacement equipment costs are 65% greater.

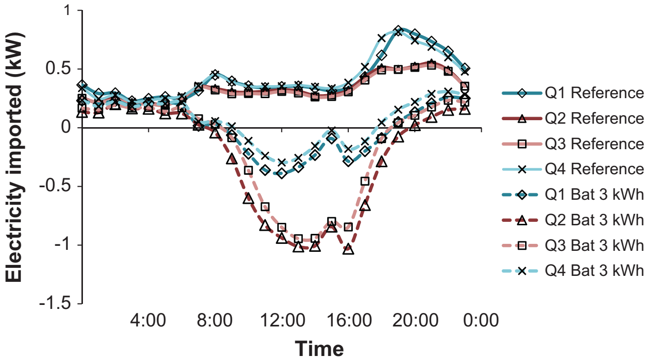

Fig. 7. Daily demand profile in different quarters of the year for the reference and base case SECHP–PV–battery systems, averaged across all households.

Operating costs are not reduced significantly by large battery capacities because these costs are dominated by gas costs, as shown in Fig. 10. Although electricity cost is reduced significantly (approximately by 40% from 1 kWh to 20 kWh battery capacity), the high gas cost is over 200% of the net total operating cost (including FIT credits).

As seen in Table A4, the NPV varies significantly across the households. The main contributor to this difference is electricity demand. Fig. 11 shows the NPV difference against household electricity demand and indicates that NPV difference is significantly improved as household electricity demand increases. A household demand of above 4300 kWh/yr would make the base case financially viable relative to the reference system. This is above the average UK household electricity demand of 3300 kWh/yr [46], but nevertheless accounts for approximately 40% of the UK housing stock [87]. There is also a significant difference between dwelling types, with only detached houses obtaining a positive NPV difference, as shown in Fig. 12. This is because larger households generally have higher energy demands because of increased floor area and a higher average number of occupants.

The impact of SECHP efficiency on the cost is also substantial, as previously suggested by The Carbon Trust [21]. This study estimates that an inefficient operation decreases the NPV difference a factor of two in the base case (−£6900 compared to −£3600 for the efficient operation). Thus, operating the SECHP efficiently will save a significant amount of money for the household. More efficient gas usage reduces operating costs significantly as gas cost represents such a high proportion of the total operating costs and a higher quantity of electricity is generated.

3.4. Sensitivity analysis

As seen in Fig. 9, equipment replacement costs represent a large proportion of the undiscounted lifetime cost (25–40%). The SECHP system contributes the most to these costs: 40–65%. At 20 kWh battery capacity, the replacement of battery cells becomes the highest cost. This study assumes an operating life of 10 years for both SECHP and battery cells, resulting in two replacements each for the 30 year period considered. However, other estimates of SECHP lifespan range between 8 and 15 years [81], which would mean 1–3 replacements. The lifespan of the battery cells also varies widely [27,88].

As the SECHP has such a large replacement cost (£5500), the effect of prolonging or shortening its lifespan is large, as shown

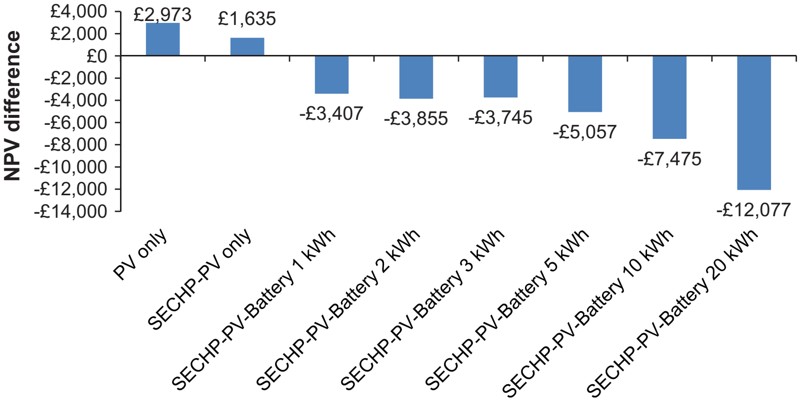

Fig. 8. NPV difference (relative to the reference system) for PV only, PV and SECHP and SECHP–PV–battery for different battery sizes, averaged across all households for 80% battery efficiency and efficient SECHP operation (where applicable).

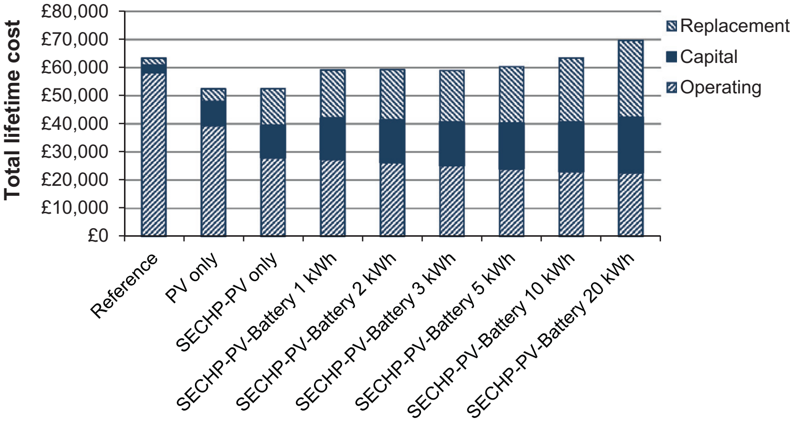

Fig. 9. Breakdown of lifetime costs for systems with different battery capacities in comparison to the reference system, averaged across all households with 80% battery efficiency and efficient SECHP operation (where applicable).

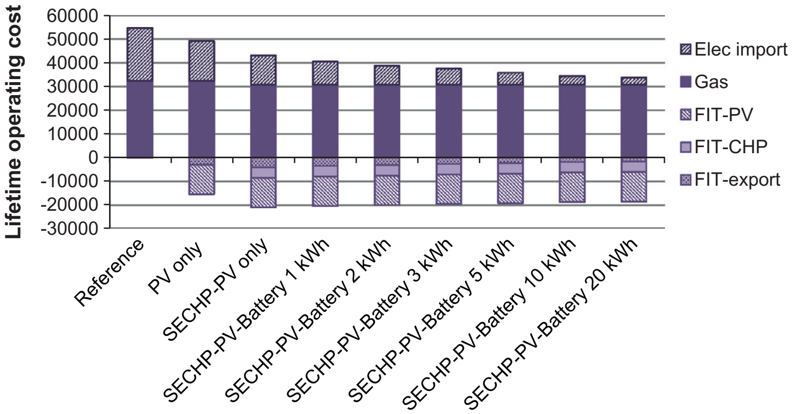

Fig. 10. Selected operating costs across different battery capacities in comparison to the reference system, averaged across all households with 80% battery efficiency and efficient SECHP operation (where applicable).

in Fig. 13. If it lasted for 15 years, the SECHP–PV–battery system would approach financial feasibility. The lifetime of the battery cells is also important, although less so than the SECHP system, except for the largest battery capacities. Shortening the lifespan to five years decreases the NPV difference by 46% but a 15-year lifespan is only marginally different (15%) to a 10-year lifespan.

The impact of different consumer discount rates on the NPV of the household system relative to the reference system is stark, as shown in Fig. 14. As the operational savings of the household system are discounted at a higher rate, the impact of the higher capital cost becomes stronger, increasing the financial gap between the system and the reference system. Note that the NPV difference

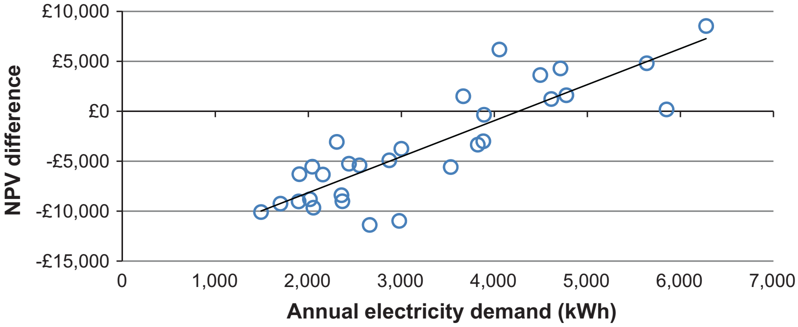

Fig. 11. NPV difference for each household for the base case plotted against the household annual electricity demand.

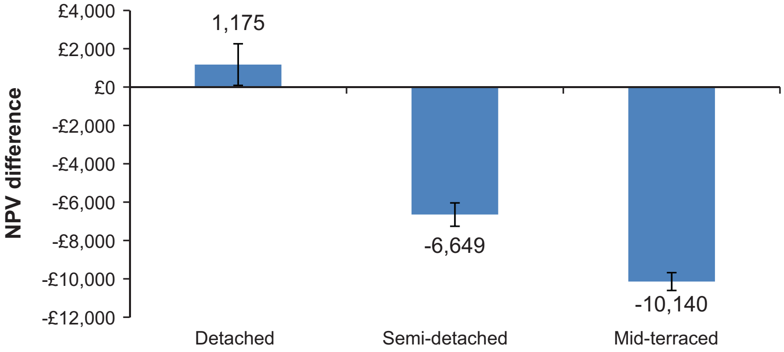

Fig. 12. Average NPV difference for each dwelling type for the base case, relative to the reference system.

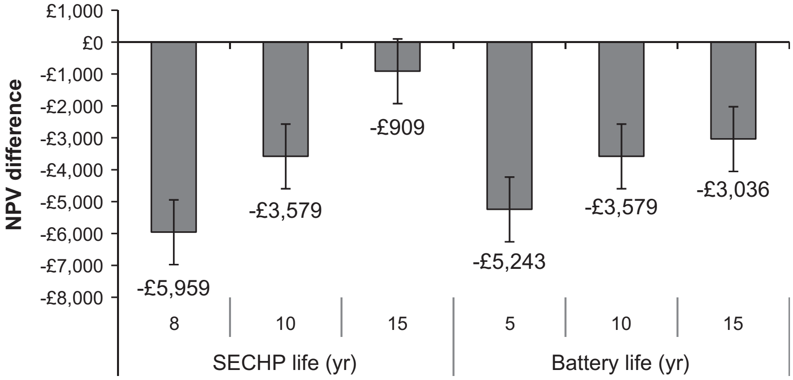

Fig. 13. NPV difference for different lifespans of the SECHP–PV–battery system for the base case, relative to the reference system.

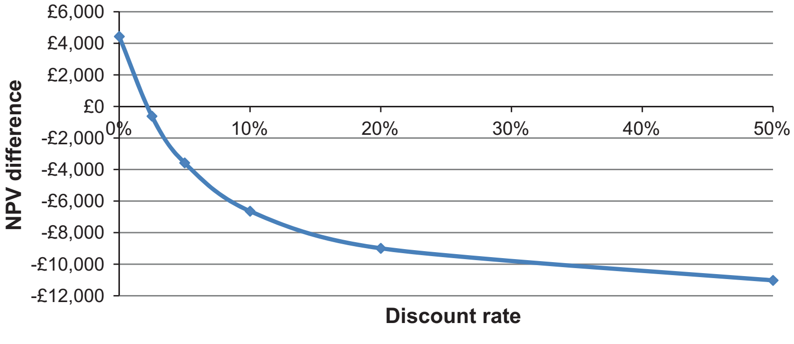

Fig. 14. Annualised NPV difference for base case for different consumer discount rates.

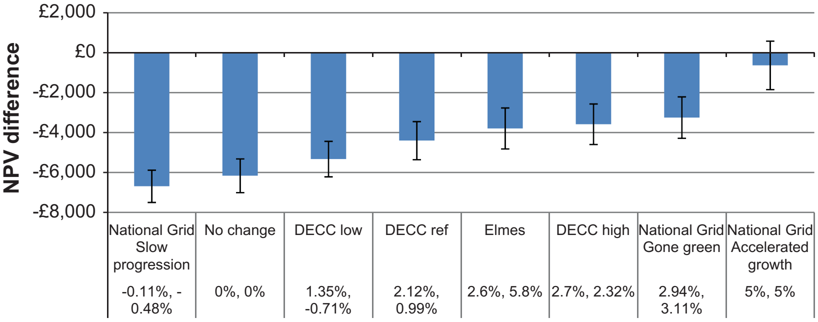

Fig. 15. Average NPV difference for the base case for different future energy cost projections. The different categories represent the source and equivalent electricity and gas price inflation rates, respectively [76–78].

becomes positive for the average household at discount rates of 3% and below.

As previously mentioned, the system is more financially viable for households with higher electricity demand. Thus, as electricity and gas prices increase over the 30 year period, the relative operational savings of the system increase. Eight future cost projections were used to estimate the effect that could have on NPV; these results are shown in Fig. 15. The only cost projection that comes close to producing a positive NPV difference is the highest, a 5% year on year increase in both electricity and gas over 30 years.

4. Discussion

The results have shown that the SECHP–PV–battery system provides some reduction in the variability of the grid demand relative to households with solar PV only or with PV and SECHP without battery storage. Households with both PV and SECHP exhibit even greater import ramp-downs (59%) and ramp-ups (36%) than those with PV only. Whilst SECHP electricity generation more closely coincides with household demand, there is still an excess in electricity generation from SECHP that causes increased variability. The addition of a 1 kWh battery store reduces these ramp-downs by 63% and ramp-ups by 22% and greater reductions occur with increasing battery capacity. Thus, battery storage offers an option to mitigate the intermittency-related impacts associated with microgeneration. However, this reduction in demand variability is limited: even a 20 kWh battery system is still worse than the reference system. Additionally, the overall level of electricity self-sufficiency achieved with this system is limited to approximately 70% (with 30% of electricity imported) for a 3 kWh battery.

Clearly, a larger capacity battery system provides greater benefits, both in reducing variation in grid demand and increasing household self-sufficiency. However, battery capital and replacement costs increase linearly with increasing capacity owing to their modular nature (doubling the number of battery cells doubles the capacity), whereas the marginal benefit decays. Even with a small battery capacity (3 kWh), the household system is only financially feasible for households with high electricity demand (>4300 kWh/yr). This minimum electricity demand for which the system is viable increases to 4500 kWh/yr for a 5 kWh battery, 5000 kWh/yr for 10 kWh and 5900 kWh/yr for 20 kWh. The total undiscounted lifetime costs are very similar between the microgeneration and the reference system, but equipment costs (capital and replacement) contribute to 70% of the total costs in the base case, compared to 11% for the reference system. The high replacement costs associated with the base case are due to the expected short lifespan of the SECHP unit and battery cells.

This system is not currently financially viable for the majority of UK households (60% of households have electricity demand lower than 4300 kWh). In order for it to become financially appealing to the majority of consumers, capital (and replacement) costs must be reduced or gas and electricity costs must increase substantially. A capital grant was applied to the cost-benefit calculation in order to determine at which point the base case system becomes financially viable across the households studied. Fig. 16 shows the average NPV difference relative to the reference case across all households for different levels of capital cost grant (as a proportion of the total installed cost). The error bars show the mean standard error for each value, indicating the range of 'financial cross-over' points across the households. The figure shows that, assuming a consumer discount rate of 5%, a 24% capital grant is required in order to make the SECHP–PV–battery system financially beneficial to the average household with an electricity demand of 3300 kWh/yr. This is equal to £3690, close to the cost of the 2 kWh battery (£3660). It is important to note that this average household in the simulation is not necessarily representative of the average UK household: whilst the annual electricity demand is similar (3265 kWh/yr vs. UK average of 3300 kWh/yr), the average gas demand across households in this study was lower than the UK average: 14,700 kWh/yr compared to 16,500 kWh/yr [46]. However, households with higher heat demand are likely to benefit more from the PV-SECHP-battery system, therefore this estimated grant requirement is a conservative value for the average UK household. Additionally, 17% of British homes are not heated by mains gas [89], meaning they are unsuitable for this PV-SECHP-battery system and are thus excluded from the findings of this study.

There are currently no incentives available in the UK for household battery storage. In fact, Germany is currently the only country to subsidise small-scale battery storage [90], whilst Japan and California are subsidising larger-scale storage (1.3 GW target by 2020 for California and various multi-megawatt facilities in Japan) [91–93]. In 2013, the German government committed 25 m Euro towards capital grants for battery storage systems, applicable to households that have already installed a solar PV system smaller than 30 kWp [94]. The incentive offers up to 660 Euro/kWp of solar PV capacity installed and is aimed at mitigating the country's electricity grid balancing problems, which is expected once 40% of renewable electricity generation is reached [90]. Similarly to the case of solar PV [95], it is expected that the grants and low interest loans will increase demand for battery storage and trigger global manufacturing

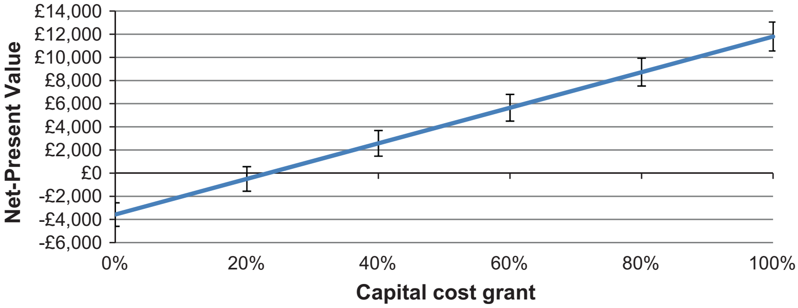

Fig. 16. Average NPV across all households for the base case for different contribution of grants for the total capital cost.

cost reductions [96]. Indeed, a number of interest groups are suggesting that battery costs will decrease dramatically in the near future and could transform the energy industry towards decentralisation [17,18].

One other option to incentivise battery storage with microgeneration systems is to eliminate the export tariff associated with the FIT incentives. Currently, microgeneration owners are paid 5 p/kWh for every unit of electricity exported to the grid, in addition to the standard FIT tariff. If this was reduced, or the gap between importing and exporting costs increased, there would be a greater financial incentive to maximise consumption of the locally generated electricity [5,83].

If battery storage is to be incentivised in the short term, an economic impact assessment must also consider other options able of providing grid stability and reliability. Such options are to increase the capacity of centralised variable-load generation, such as by gas and coal power, to provide greater interconnection of electricity with neighbouring countries, or to limit the feeding of solar PV electricity into the grid using local terminals and smart meters. Each of these options carries a large cost burden and, in the case of limiting solar PV feeding into the grid, reducing the contribution of renewable electricity generation. The latter may negatively impact upon the UK 2020 renewables target of 15% [2]. An impact analysis for each of these options is required to identify the best options, which must include environmental and energy security-related issues, in addition to costs.

5. Conclusions

The results of this research indicate that even with solar PV, SECHP and battery storage, on average 28% of electricity demand still has to be met by imports from the grid, even though the average combined generation from solar PV and SECHP across all simulations was 4190 kWh/yr, 30% greater than the average household electricity demand. Battery capacities above 5 kWh provide only marginal improvements in self-sufficiency relative to their large cost.

Consumption of electricity generated by solar PV is somewhat smaller than is typically assumed in literature: 28% as opposed to 50%, compared to 49% from SECHP. The SECHP generation profile is far more suitable to achieving self-sufficiency because of the better correlation between the generation and household demand profiles.

The impact on the grid demand profile of a PV installation and a PV with SECHP without a battery is stark, drastically increasing the variation, ramp-up and ramp-down in daily grid demand. Battery storage reduces ramping-down rates by 40% and ramping-up by 28% for a 3 kWh capacity. Thus, battery storage offers an option to mitigate PV grid balancing problems. However, the profiles are still not an improvement on the reference system even with large battery capacities of 20 kWh, which carries a high capital cost.

The base case SECHP–PV–battery system is only financially viable for those with an electricity demand above 4300 kWh/yr, which encompasses 40% of UK households. This is much higher than the average demand of 3300 kWh/yr. The capital and replacement costs of the battery cells and SECHP have the largest impact on the financial viability of the system. Because of this, the financial impacts are highly sensitive to the assumed lifespan of these components as well as the assumed consumer discount rate. Operating the SECHP more efficiently (continuous operation rather than frequent on/off cycles) is shown to be significantly more cost-effective.

With a capital cost grant equal to a small battery (2 kWh), the system would be financially feasible for the average household and would provide significant benefits in terms of grid balancing, equivalent to a reduction in ramp-ups and downs of 28% and 40%, respectively. Small battery storage systems are the subject of increasing attention in global energy policy owing to the rapid rise in renewable electricity generation so that capital costs may be reduced in the near-term future. A capital cost grant for batteries applicable to households with microgeneration installations would serve to increase demand and could help to reduce manufacturing costs with a maturing market. A comparative impact analysis between this option and others to achieve grid stability and reliability should be a subject of future research.

Another option to provide greater motivation for microgeneration owners to install batteries is to reduce or eliminate the Feed-in Tariff (FIT) electricity export rate. This would create a greater price differential between importing and exporting electricity and would serve to promote greater consumption of self-generated electricity. In the longer term, this price differential is likely to increase anyway considering the current projections of high future grid electricity costs.

Finally, whilst the PV-SECHP-battery system provides benefits relating to grid demand variability and household self-sufficiency, the associated environmental impacts should also be considered. This was the subject of the related research by the authors, details of which can be found in Balcombe et al. [97].

Acknowledgements

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Appendix A

NPV is estimated according to the following equation:

$$NPV = \sum_{t=0}^{t=30} \frac{C_t}{(1+i)^t} \tag{A1}$$

where C_t is the total cost associated with year t and i is the consumer discount rate. The total cost C_t is estimated as:

$$C_t = C_{cap\ t} + C_{op\ t} + C_{rep\ t} \tag{A2}$$

where $C_{cap\ t}$ is the capital cost, $C_{op\ t}$ is the operating cost and $C_{rep\ t}$ is the equipment replacement cost, all in year t. The difference in NPV between the household system and the reference system is used as the indicator of financial performance:

$$\Delta NPV = NPV - NPV_r \tag{A3}$$

where NPV_r is the NPV of the reference system.

Table A1
Summary profile data associated with each household, including dwelling type, floor area, gas demand, electricity demand, PV capacity and PV generation.

Household ID	Dwelling type	Floor area (m^2)	Gas demand (kWh/yr)	Electricity demand (kWh/yr)	PV capacity (kW)	PV generation (kWh/yr)
1	DH	183.9	29,173	6276	4	3896
2	DH	139.1	11,573	3880	4	3729
3	DH	139.1	12,064	3888	4	4224
4	DH	136.1	25,270	4611	4	2959
5	DH	136.1	20,616	5851	4	3201
6	DH	134.7	16,247	3665	4	4130
7	DH	128	22,931	4773	4	3167
8	DH	128	24,088	4710	4	4368
9	DH	128	20,130	4493	4	4557
10	DH	125.1	28,423	4053	3.9	3779
11	DH	104.8	20,687	5637	3.8	4135
12	DH	76.2	14,034	2305	3.5	3448
13	DH	76.2	11,320	2550	3.4	3037
14	DH	76.2	12,812	2999	3.4	3251
15	SDH	74.3	11,848	3821	3.3	3178
16	SDH	74.3	11,929	2870	3.3	2907
17	SDH	74.3	9,371	2155	3	2806
18	SDH	74.3	10,385	2042	3	2993
19	MTH	68.8	7,901	2976	2.8	1563
20	MTH	68.8	10,904	2365	2.6	1875
21	SDH	64.8	13,395	1903	2.5	2281
22	SDH	64.8	10,229	1895	2.4	1771
23	SDH	64.8	9081	3530	2.2	2269
24	SDH	64.8	9655	2355	2.2	1700
25	SDH	64.8	10,642	2054	2.1	1387
26	SDH	62.8	15,876	2436	2	1762
27	SDH	62.8	12,233	2017	1.8	1467
28	MTH	60.3	10,280	1700	1.6	1450
29	MTH	60.3	8790	2659	1.5	692
30	MTH	60.3	9585	1491	1.1	1169

Table A2
Low, medium and high capital cost estimates for a set of solar PV capacities [65].

Solar PV capacity (kW)	Low cost (£)	Medium cost (£)	High cost (£)
1	1500	2748	5096
2	2400	4369	8017
3	3300	5990	10,938
4	4200	7611	13,859

Table A3
Various estimates of SECHP installed capital cost, alongside the source of the estimate.

Installation cost (£)	Source
3500	Low estimate: (Cambridge Economic Policy Associates Ltd and Parsons Brinckerhoff, 2011)
5000	(Carbon Trust, 2011)
5000	Low estimate: (Parsons Brinckerhoff, 2012)
5500	High estimate: (Cambridge Economic Policy Associates Ltd and Parsons Brinckerhoff, 2011)
6500	Conversation with distribution company
7500	Medium estimate: (Parsons Brinckerhoff, 2012)
10,000	High estimate: (Parsons Brinckerhoff, 2012)

Table A4
A summary of the base case costs for each household, in descending order for NPV difference (relative to the reference system).

HH ID	Electricity demand (kWh/yr)	PV capacity (kW)	Capital cost (£)	Operating cost (£/yr)	Reference operating cost (£/yr)	NPV difference[a] (£)	Payback time (yr)	Simple payback time (yr)
1	6276	4	16,931	50,308	110,717	8542	15	8
10	4053	4	16,801	38,641	93,939	6186	16	9
11	5637	4	16,607	35,367	87,633	4817	17	9
8	4710	4	16,931	37,104	88,831	4296	17	9
9	4493	4	16,931	28,194	78,616	3632	18	15
7	4773	4	16,866	40,264	86,706	1609	20	15
6	3665	4	16,866	18,295	64,408	1510	20	15
4	4611	4	16,923	44,957	90,767	1235	27	15
5	5851	4	16,915	45,281	88,926	188	30	15
3	3888	4	16,931	14,189	56,690	−344	None	16
2	3880	4	16,931	18,364	55,554	−3000	None	18
12	2305	3.5	16,121	14,835	50,269	−3060	None	18
15	3821	3.3	15,845	21,288	55,758	−3340	None	18
14	2999	3.4	16,023	18,395	52,295	−3750	None	19
16	2870	3.3	15,780	18,271	49,465	−4907	None	28
26	2436	2	13,689	28,761	55,231	−5249	None	None
13	2550	3.4	16,023	15,347	45,941	−5411	None	29
18	2042	3	15,310	11,541	40,421	−5549	None	30
23	3530	2.2	14,046	21,159	47,668	−5582	None	None
21	1903	2.5	14,435	20,412	46,124	−6294	None	None
17	2155	3	15,310	11,597	38,955	−6331	None	None
24	2355	2.2	14,013	20,155	40,943	−8401	None	None
27	2017	1.8	13,365	25,658	44,332	−8807	None	None
20	2365	2.6	14,637	22,991	43,770	−9010	None	None
22	1895	2.4	14,337	18,957	39,079	−9023	None	None
28	1700	1.6	12,976	20,849	37,863	−9247	None	None
25	2054	2.1	13,819	23,200	41,072	−9652	None	None
30	1491	1.1	12,230	21,072	34,907	−10,088	None	None
19	2976	2.8	14,999	23,666	41,296	−10,974	None	None
29	2659	1.5	12,879	28,436	41,099	−11,379	None	None

[a] NPV difference estimated as the NPV of the base case minus the reference NPV.

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