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Residential PV-BES Systems: Economic and Grid Impact Analysis

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Abstract

The energy industry has seen a revolutionary transformation in the growth of renewables over the past decade. With recent advances in battery storage performance, solar energy is fast becoming the focus of the global energy shift towards a more sustainable future. Photovoltaic (PV) systems integrated with Battery Energy Storage (BES) systems are expected to play an important role in the UK's future energy industry, aided in part by manufacturing cost reductions. For energy consumers, these systems can deliver considerable savings in utility costs and potentially bring a financial return via a feed-in-tariff (FIT) scheme. Such a system could also help energy suppliers and network operators ease the burden of a huge surge of future energy demand, mitigate network congestion and improve system resilience and autonomy. There is, however, limited literature that utilises simulation to investigate the influence of PV-BES system deployment at urban scale on the grid based on economic and technical analysis. In this work, a household-level model is developed that includes load demand heterogeneities, as well as BES and PV systems. The single household model can be scaled to higher levels, such as streets and community, hence the model can be applied to study the interaction between households, the wider community and the grid, in terms of electricity im/export, BES usage and network injection impact. A comprehensive analysis of both technical and economic perspectives is presented based on several key performance indicators (KPIs), such as self-consumption rate (SCR), self-sufficiency rate (SSR) and reduction in peak charges. The addition of a BES system can significantly increase the self-consumption of a home PV system, by at least 15%, however the expensive upfront cost of the BES system leads to a much longer payback time.

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Keywords: Photovaltaic, Lithium-ion Battery, Local Energy System, Energy System Simulation, Distributed Residential Storage

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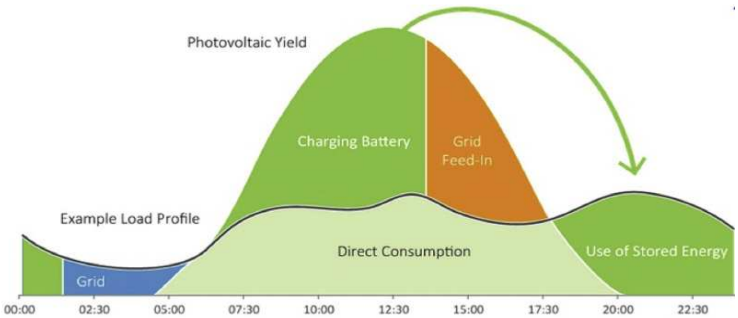
1. Introduction

The UKs legal obligation to reduce CO_2 emissions by 80% to combat climate change [1] and energy security concerns [2] mean decarbonization of the energy sector has received a great deal of attention [3,4]. It is expected that renewable energy technologies will play a primary role in this due to their low emissions. Photovoltaic (PV) systems have substantial potential to generate significant amounts of energy and, together with the decrease in unit cost of (PV) systems over the last decade [5], there has been a rapid increase in the take-up of residential PV [6]. As battery energy storage (BES) systems develop, the prospect of self-consumption, i.e. consumming and storing self-generated electricity, becomes increasingly attractive.

Most of the research on self-consumption using residential PV-BES systems has focused on individual buildings [7–11]. Luthander et al. [12] suggests that there are two alternatives to enhance the self-consumption: integrating with energy storage and demand side management. The self-consumption rate is defined as the percentage of PV generated electricity that is consumed locally against the total electricity generated by a particular PV unit [6]. The study shows that the self-consumption rate can be improved by 13-24% for a typical 1 kw PV with a 0.5-1 kwh battery storage and demand side management can contribute to an improvement of self-consumption rate by 2-15% [12]. However, most of the research used hourly or daily data, which could lead to inaccuracy due to the unpredictable change in household power consumption. Another aspect that was found to be key by Linssen et al. [10], for the assessment of the self-consumption, was the use of an individual rather than averaged load profile.



The benefits to those customers with home PV-BES units mainly rely upon subsidies, including feed-in tariffs [13], green certificates [14] or favorable metering schemes which are expected to be withdrawn in the future [15]. Another aspect raised has been the lifetime performance of such systems due to the impact of battery degradation; for example, analysis by Uddin et al. [16] found that this could lead to the investment being unviable for the customer due to the cost of replacing the Li-ion battery.

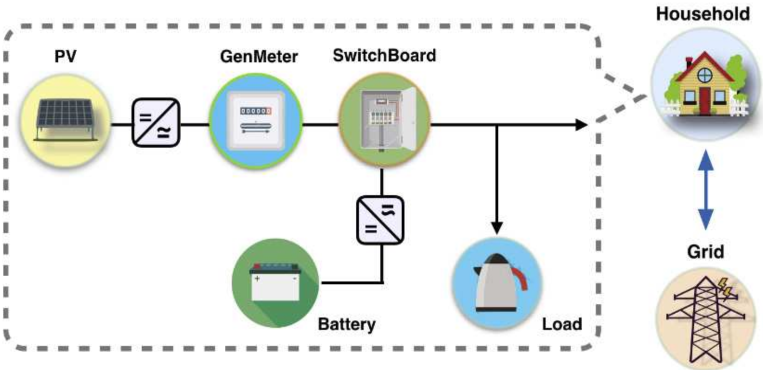
This study aims to investigate how battery storage contributes to increased self-consumption in a community with houses installed with rooftop PV systems. The second aim is to investigate the optimal arrangement of PV and BES units in the community. This study starts with a focus on single households and, using the agent-based model developed, these are then aggregated to calculate the community demand, self-consumption and other metrics.

2. Methodology

To determine the energy saving potential resulting from the implementation of on-site energy generation and storage device in a house, an agent-based model is adopted for this study. The agent-based framework developed in this work builds upon a description of a microgrid system as: a supply/demand model that consists of multiple agents, representing households, presenting supply and demand to the network based on their needs and capacities respectively, and engineering models representing the physical energy technologies that each contains. These agents are then able to interact with each other, using physical and economic rules, to determine the overall system behaviour.

2.1. Home PV-BES system configuration

Figure 2 shows a schematic representation of the household agent, along with the battery and PV generation that it contains, and its relation to the wider network. The adopted configuration of the PV system is based on an architecture using an AC bus, which can be easily retrofitted into a currently existing home PV system. The PV is connected to a DC/AC converter and a bidirectional DC/AC converter. The monitoring of the energy flux in the household considers the availability of the energy power produced by the PV field, the state of charge of the lithium-ion battery and also the consumption profiles.



2.2. Household electricity profile

The household demand data is generated from the CREST demand model [17]. In order to compare different impacts brought by the introduction of PV-BES system, load profiles of five different types of household in UK are used as inputs for the model, which are synthesized from measured load demand profiles in 1 min intervals of 34 typical household appliances. An overall annual electricity consumption of five households is shown in Table 1.

Table 1 Overview of Electrical Load Profiles of Five Exemplary Households

Household Type	Type of Occupants	Occupants	Annual Electricity Consumption (kwh)
HH1	Adult Single	1	1519
HH2	Adult Couple	2	2105
HH3	Adult Couple with A Chid	3	3215
HH4	Adult Couple with Two Children	4	2302
HH5	Retired Couple	2	3748

2.3. Photovoltaic system simulation and battery model

The PV system is modelled based on the area of the PV installation, the solar radiation received by an inclined surface taking into account the position of the sun and the system efficiency as described in [18]. The solar irradiance and temperature data is adopted from the CREST irradiance database, which provides high-resolution irradiance data recorded in Loughborough University [17]. The charging or discharging state of the battery is determined by the difference between power generated and load. In this way, the charge quantity of a battery bank at time *t* can be obtained by considering the hourly self-discharge rate, energy generated by the PV after loss in the controller, the load demand and the inverter and battery charging efficiency. Constraints are placed on the maximum and minimum charge quantity of the battery bank [19,20].

2.4. Energy management algorithm

To analyse the influence of the PV-BES system on the feed-in power, the model allows households to exist with or without either, or both, of the PV generation and batteries. Where battery storage systems exist, they can be operated with various management strategies to control the charging and discharging. In this study, the PV-BES system follows a basic management strategy, as shown in Figure 3.

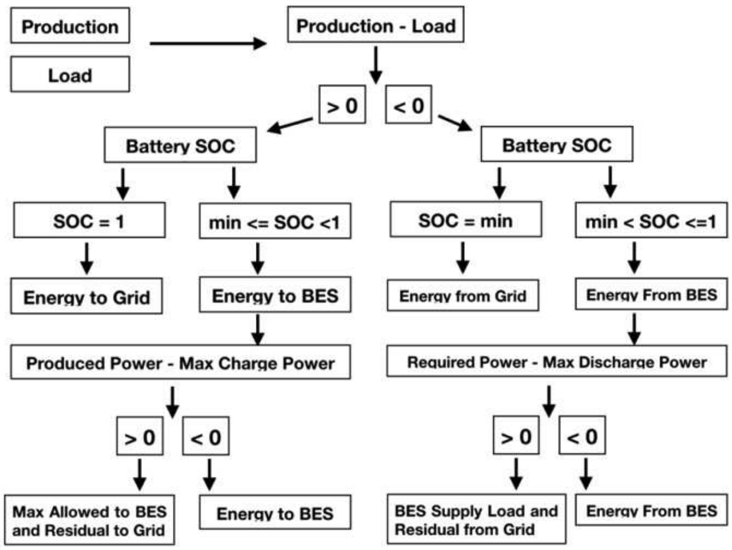


Figure 3 PV-BES power flow control strategy

The proposed management strategy aims to satisfy the energy demand of the household while optimising the use of the available PV energy. For this reason, several levels of satisfaction have been set based on the state of charge of the battery (SOC).

- 20% < SOC < 100%: The batteries supply the demand of the house and any remaining energy required is drawn from the power grid.
- SOC = 100%: The energy demand of the household is satisfied and the surplus energy is exported to the network.
- SOC <= 20%: The batteries stop working and the load demand is met the grid import.

The parameters for the PV-BES system are shown in the Table2.

Table 2 An overview of PV and battery parameters assumed for this purpose of this study [21]

Parameter	
Battery Depth of Discharge (%)	80
Battery Roundtrip Efficiency (%)	98
Battery Cycle Lifetime (cycles)	10000
Battery Degradation (%/a)	0.4
PV Installed Capacity (kW)	2
Battery System Price (£/kWh)	500
PV System Price (£/kWh)	1000
Inverter and Other Power Electronics Price (£)	1100

2.5. Evaluation criteria

Key performance indicators (KPIs) are used to evaluate the energy performance of the solar PV system, including self-consumption rate (SCR or r_{sc}) and self-sufficiency rate (SSR or r_{ss}).

The SCR (r_{sc}) is defined as the percentage of PV generated electricity that is consumed locally against the total electricity generated by a particular PV unit [23]:

$$r_{SC} = \frac{E_{DSC} + E_{Battery}}{E_{PV}} \quad (1)$$

where E_{pv} is the amount of electricity generated from the PV system, E_{DSC} is the amount of PV electricity instantaneously consumed by household and $E_{battery}$ is the amount of energy supplied by the battery.

The SSR (r_{ss}) is introduced and used to describe how much of the household load demand can be covered by a PV-BES system on site. In this way, the SSR can be calculated as:

$$r_{SS} = \frac{E_{DSC} + E_{Battery}}{E_{Load}} \quad (2)$$

where E_{load} is the load demand of a household. The economic performance of the PV-battery system is also considered and the various aspects of this including energy bill of each household, FIT generation payment and FIT export payment, are calculated for each household. The function is represented in the equation to calculate total electricity bill of household, which is shown in following equation:

$$Energy\ Bill = \sum_{(d,t)} \left(p_{export} + P_{grid(d,t)}\, p_{import} - d\, p_{standard} P_{pv(d,t)}\, p_{FIT} + P_{pv_{export(d,t)}} \right) \Delta t \quad (3)$$

where $P_{pv(d,t)}$ is the amount of PV electricity at each time step, $P_{pv\_export(d,t)}$ is the PV power sold to the grid at each time step, $P_{grid(d,t)}$ is electricity imported from grid at each time step, P_{FIT} represents FIT for generated electricity, P_{export} represents FIT of electricity exported to the grid and P_{import} represents standard retail electricity tariff, and $P_{standard}$ means a fix rate charged by energy suppliers per day. For the set (d, t), d represents the set of days in a year ($1 \leq d \leq 365$) and t is the minutes over a day ($1 \leq t \leq 1440$).

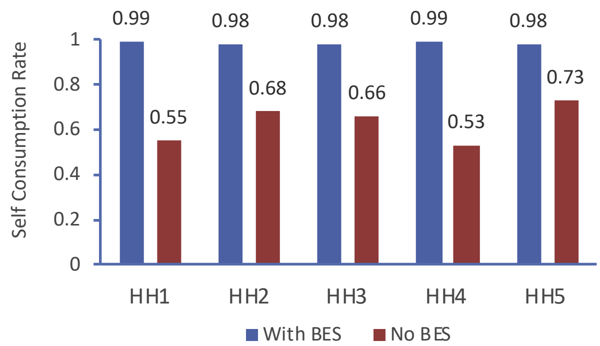
Table 3 Economic Parameter Adopted in This Study [13,21]

Economical Parameter	
Electricity Tariff (p/kWh)	15
Standard Charge (p/kWh)	17.54
FIT Generation Tariff (p/kWh)	5.04
FIT Export Tariff (p/kWh)	5.03

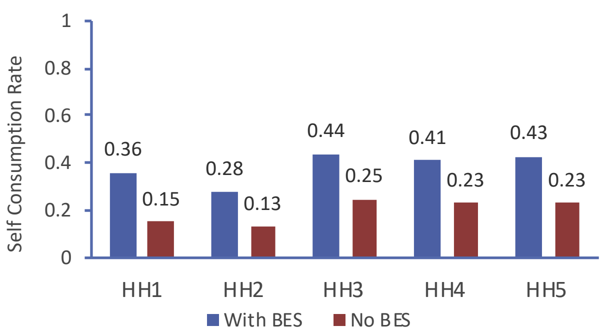
3. Results and Discussion

3.1. Household with and without BES

Figure 4 shows the SCRs of the five different types of households with and without a BES for January and May respectively. The direct self-consumption of five households are observed to be high while the SCRs are even higher, as the load demands approximately equal to the low PV generation power. The average SCRs with BES are higher than those without, indicating that the addition of BES can significantly contribute to the household use of onsite PV generation. In comparison, during the summer months both the SCR with and without BES drop significantly due to the large increase in PV electricity production, which results in export of the surplus electricity export to the grid.



a)



b)

Figure 4 Self-consumption rate for HH with and without BES in a) January and b) May

Figure 5 shows the SSRs for HH1 to HH5 both with and without BES, for January and May respectively. In all cases the SSRs for the households with BES are greater than those without. Turning to Figure 5 b), this is seen to still be the case, however the SSRs observed are substantially higher but with a wide variation in values. In summer months, PV electricity generated on-site is much more sufficient than that in January. For those household with BES, the electricity from battery and PV can meet most of the load demand, while it is extremely small compared to the load in January.

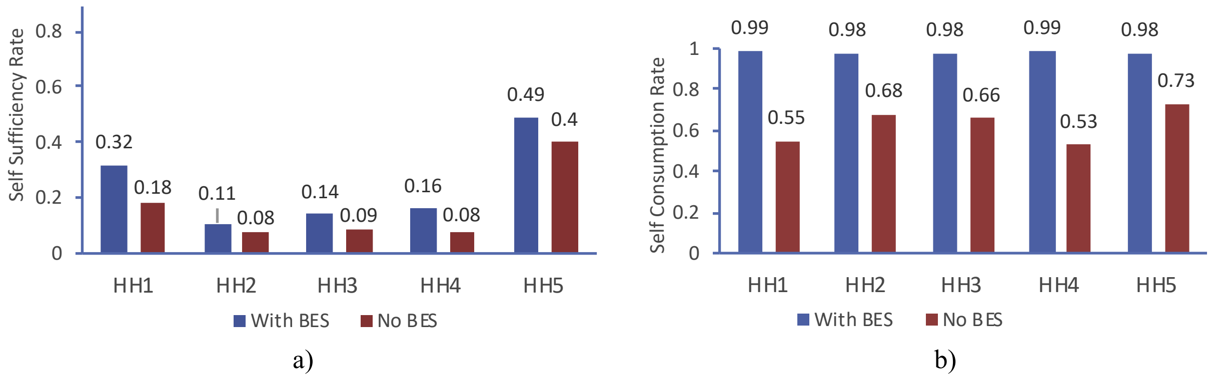


Figure 5 Self-sufficiency rate for HH with and without BES in a) January and b) May

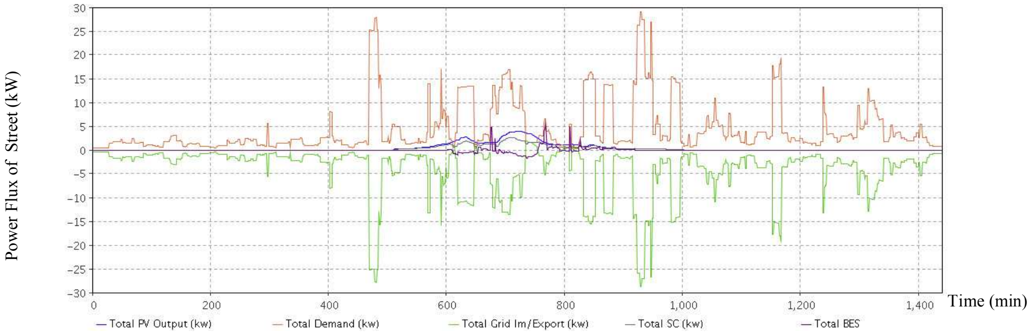
Figure 6 shows the aggregate power flux with and without battery storage in January and May respectively. As shown in the figure, the addition of a battery can significantly help the street reduce the electricity import from the grid, especially in the summer when the PV produces sufficient electricity for the street demand. However, due to the short daytime in winter, the limited PV production cannot fully charge the battery and only 10% of demand can be met by the PV production and battery, while the self-sufficiency rate is even smaller for household without BES, around 8%. This provides a potential that enables the battery to be charged from the grid, which is extremely helpful for demand-load shifting or those areas with abundant solar resources and poor grid connection [22,23]. The installation of a battery would significantly reduce the burden of the power network when an appropriate size of battery is installed. However, for hot summer months, the battery can be fully charged by the abundant PV electricity and meet the load demand of households when the PV stops producing electricity. In contrast, for those households without batteries, most of the demand can be met by the PV production, but the households still reply on power grid import once the on-site generation stops.

3.2. Energy bill savings

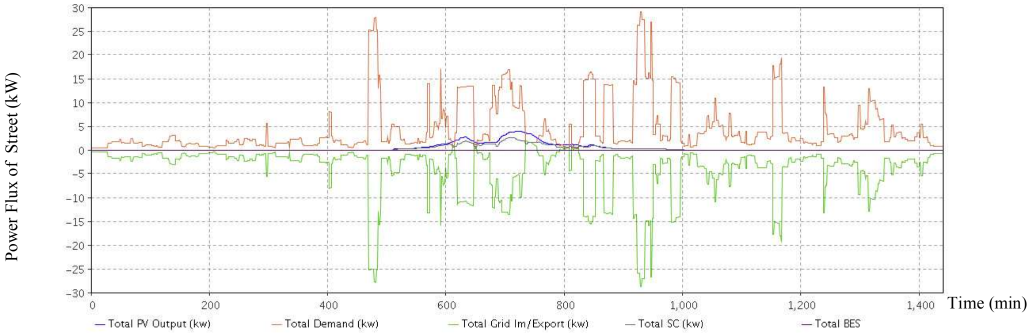
Table 3 presents a summary of the relevant economic data for the individual households, including the annual saving on energy bill and the payback time for the investment. As can be seen there is a substantial increase in the annual saving with the addition of the BES. It can also be observed, however, that the payback period for the installation of these systems is long in both instances, but significantly so with the installation of the BES. Clearly in the case of these systems at current costs, they are not economically viable. The payback period is obviously also impacted by the energy demand of the household, for example HH5 with the highest demand has the lowest payback time both with and without BES. In this way, it can be seen that the addition of PV-BES system is likely to contribute to benefits for households, especially for those with high load demand. However, the expensive upfront cost, especially BES, is the paramount factor that leads to the long payback time. To shorten the payback time, a bigger capacity will be possibly required to achieve more self-consumption on site. Furthermore, the price of both technologies also needs to be lower than the current prices adopted in the study.

Table 4 Summary of economic data for each household

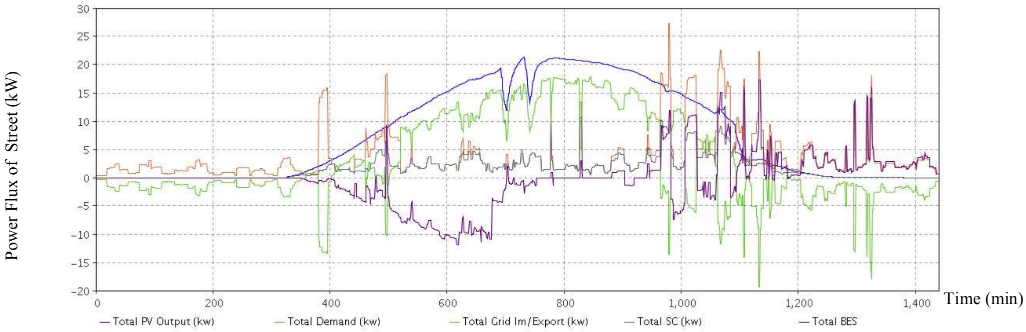
	Annual savings (£)		Payback time (yr)	
	With BES	No BES	With BES	No BES
HH1	205.45	144.85	38.33	26.56
HH2	215.48	142.51	36.54	26.99
HH3	254.33	181.98	30.96	21.14
HH4	238.40	162.74	33.03	23.64
HH5	265.30	187.66	29.68	20.50



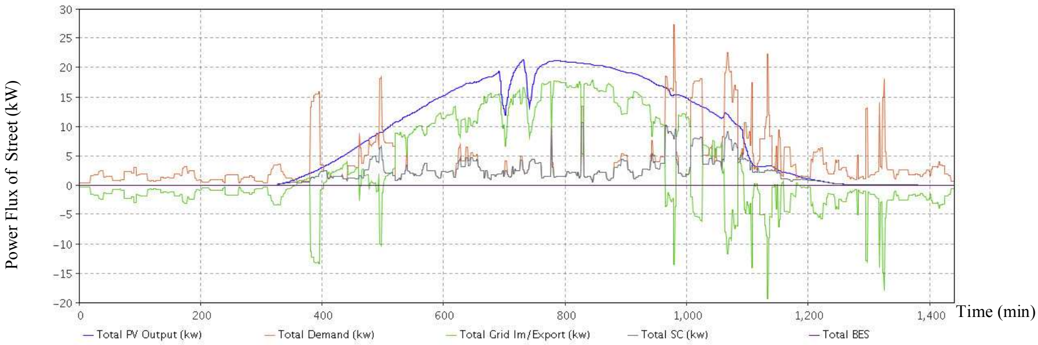
a) Power Flux of Street with Battery in January



b) Power Flux of Street without Battery in January



c) Power Flux of Street with Battery in May



d) Power Flux of Street without Battery in May

Figure 6 Power Flux of a Street with and without battery in a)b) January and c)d) May

4. Conclusion

This work presented an agent-based model developed to investigate the planning and operation of residential PV-BES systems in terms of both technical and economic metrics. Given the increased interest in such systems for demand and consumer bill reduction such an analysis is extremely timely. The model incorporated sub-models representing both the PV and battery technologies, and also the management approach taken to their interaction, as well as to the external grid. Aggregation of several household agents forming a larger "street" agent, allows the generation and simulation of populations that can be evaluated separately and at different aggregation levels.

To study the importance of the BES in the performance of such a system, a hypothetical case study, incorporating high fidelity synthetic load profiles, was developed and simulated over the course of a year. It was found, as expected, that the battery system enabled a much higher self-sufficiency rate; at times this approached, on a population aggregated basis, unity, though for individual households this could be significantly lower. Seasonal variation of PV production provides a potential to operate the battery in a different way that enables the interaction with the power grid, which is significantly helpful when a time-of-use tariff is applied. Additionally, the battery can also enhance the stability of grid when abundant electricity is produced from PV, especially during summer.

5. Acknowledgement

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