
Assessing the Benefits of Installing Energy Storage in a Household Equipped with Photovoltaic Panels

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Abstract: This paper evaluates the technical and financial impact of installing energy storage in a house equipped with Photovoltaic (PV) panels subject to the Feed-In Tariff (FIT). An additional benefit of installing energy storage is the possibility to purchase electricity off-peak (overnight) at a cheap rate and replace consumption during day/peak time and for this reason, the Economy7 tariff is considered.

The studies carried out are using real data of PV generation and household consumption continuously recorded over a week for each of the four seasons, from a UK installation. A functional model of the battery system is implemented that includes voltage dependency versus state of charge and maximum charging and discharging currents, that account for the limitations of the amount of charge - size dependant and current that can reflect the power capability of the battery to preserve high conversion efficiencies and lifetime.

As initial investigations point to a rather large battery system to maximize the synergy between PV and energy storage, the paper investigates how the performance indicators vary with the battery size. It is found that there may be a critical battery size up to which the peak rate consumption and the PV energy export decrease more rapidly. Above this critical point which in this study lies at around 25-30% of the battery size that would allow full local use of PV energy generated, the impact of increasing the battery size reduces, therefore the return of investment as a percentage decreases.

Keywords: battery sizing, energy storage, off peak tariff, photovoltaics

1. INTRODUCTION

Renewable energy is considered the main tool we have for reducing greenhouse gas emissions that cause climate change. Wind power is typically exploited in large wind farms consisting of multi-MW turbines whilst solar power can be converted directly into electricity via photovoltaic (PV) panels or into heat. Whilst some large pilot solar power plants exist in the world, it is widely accepted that small-scale (few kW) roof mounted installations deployed in tens of million houses have the capability to become a major contributor for reaching the 2020/2050 renewable energy production targets. [1] The reasons why the government supports this trend is that it can create a competitive market in the medium term. Also producing renewable energy closer to the point of consumption reduces the losses associated with transporting and distributing electrical energy. The size of the installation remains low as there are limitations on the amount of power generated this way due to the fact that today's distribution systems are not designed to handle power travelling upstream.

Energy storage is seen as the critical technology to complement the unpredictability of renewable energy. In the particular case of PV generation installed at the point of load, the use of energy storage may help prevent export of solar energy and therefore defer the upgrade of the distribution grids to allow bidirectional power flow. Regarding the energy storage technologies, electrochemical energy storage in the form of secondary (rechargeable) batteries is perhaps the most convenient way of storing PV energy. Various technologies exist and they have various applications and specific prices. Lead-acid batteries are still used in solar energy storage due to their low cost and also due to the predictable charging power that cannot exceed the PV panel power/current. They are, however, quite heavy and bulky. For this reason, Lithium-Ion batteries, primarily used in transportation [2], have also been evaluated due to their small size and higher power/current capability but they are quite expensive which means these installations are less affordable and overall may not reach a wide deployment.

A power electronic interface is needed between the energy storage and the power grid [2]-[4] which is typically characterised by the voltage and current rating. This means that the power processed by the power electronic interface is limited for a particular design and higher power means larger power semiconductors and costs. When summarising the capability of the power electronic interface in terms of maximum power with the capability of the battery in terms of energy storage capability and maximum charging and discharging current as a percentage of the capacity current, it becomes quite clear that an energy storage system (ESS) comprising both components, needs to be specified in terms of both maximum energy stored and power which influence both the cost of the system. The other important aspect when designing an energy storage system is the roundtrip efficiency which quantifies the percentage of energy that is retrieved back from the energy that was sent into the storage. In order to maximise the roundtrip efficiency, performant battery technologies are needed. But also the choice for the power rating of the power electronic interface is very important. A large installed power means the system is able to supply a wide range of powers but operation at reduced loading (20-50%) which is the situation the ESS will operate for most of the time, will result in significantly lower conversion efficiency, affecting therefore the roundtrip efficiency. More importantly, a higher power rating means higher cost. For these reasons, it makes sense that the power rating of the ESS will be chosen not to cover the largest load power. Also, it may be more feasible that the size of the battery is chosen significantly smaller than the maximum weekly energy span.

This paper explores the optimum size of the battery for complementing the benefits of PV generation of a UK household. Simple algorithms have been implemented when controlling the ESS, in terms of cancelling power consumption under the ESS ratings and imposing a constant state of charge level upto which the ESS recharges overnight with off-peak energy. It is shown that a higher rate of the revenue/kWh installed is achieved at moderate battery size and the breakpoints where this behaviour changes are determined.

2. THEORETICAL POTENTIAL OF ENERGY STORAGE USED IN PV GENERATION

This study case is based on power data acquired from a UK household having installed PV generation [5]. The weekly power consumed and generated by PV for each of the four seasons that are used as input data for this evaluation are shown on the left side of Figure 1. These are derived from energy data that were sampled every 5 minutes. It is possible to calculate an average power export/import that can cancel the energy excess/deficit at the end of the week. When this is added to the excess power (PV-consumption), the resulting energy variation can be used to estimate the required size of the energy storage system that would prevent any additional export of PV energy due to ESS size limitation. The energy consumed and the one generated by PV are shown in the right side of Figure 1.

Table 1 summarises the weekly energy consumed, generated and the weekly energy excess for each of the four seasons. It can be seen that only during summer, an energy excess is produced. Table 2 summarises the energy costs and the associated feed in tariff (FIT) used as assumptions in the following financial cost/benefits estimations [6]-[7].

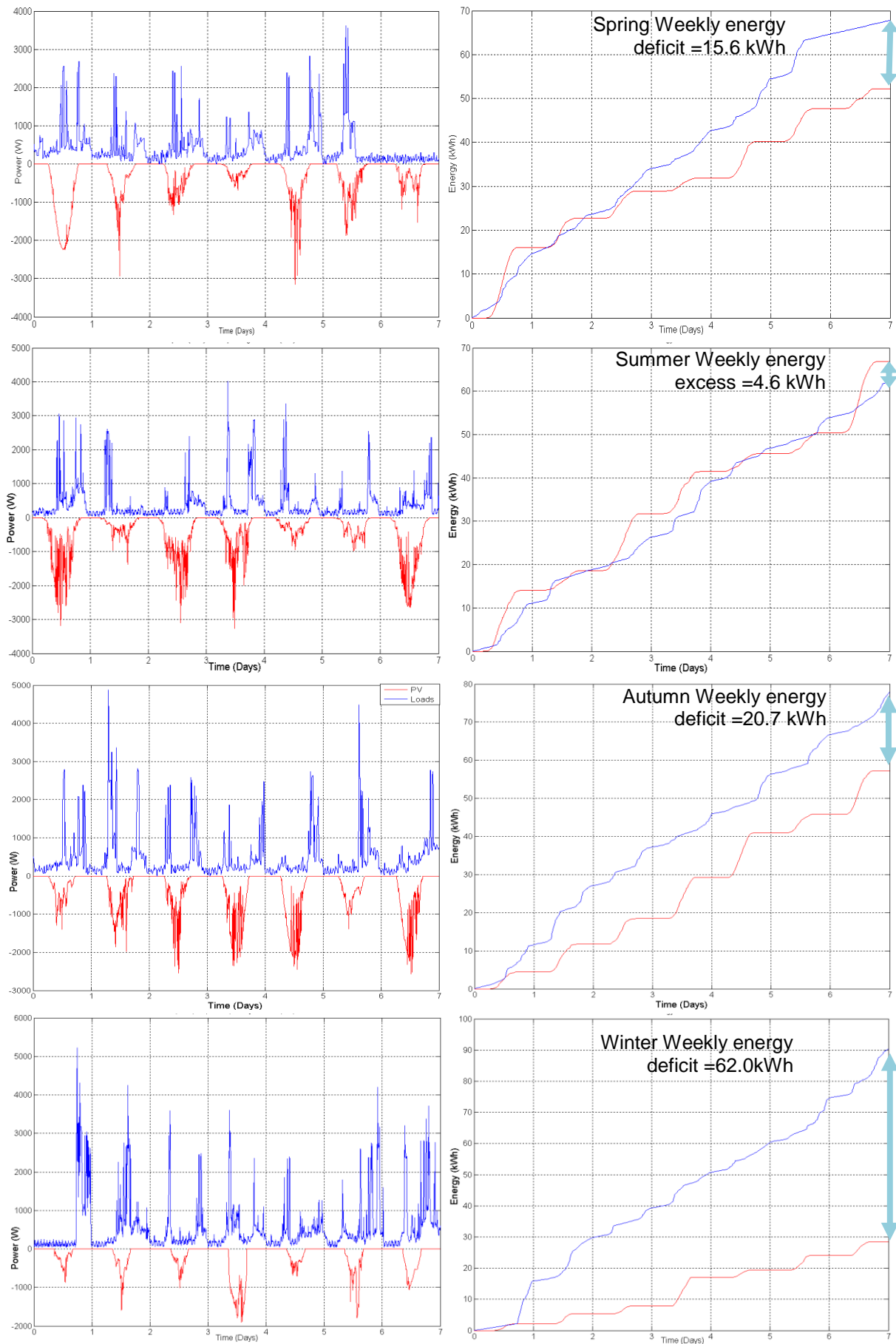


Figure 1: Left side: Power(W) consumed (positive quantities) and PV power generated (negative quantities) over a week for each season (spring =top; winter = bottom); Right side: the corresponding energy (kWh) consumed and generated with the weekly energy excess/deficit highlighted. Time: 1day/div

Table 1: Summary of the weekly seasonal consumption of a household with PV generation [5]

	Energy Consumed	PV Energy generated	Excess(+)/Deficit(-)
Spring week	67.8kWh	52.2kWh	-15.6kWh
Summer week	62.3kWh	66.9kWh	+4.6kWh
Autumn week	77.9kWh	57.2kWh	-20.7kWh
Winter week	90.4kWh	28.4kWh	-62.0kWh
Annual (13x4week Sum)	3879.2kWh	2661.1kWh (68.6% of yearly energy consumption)	

Table 2: Electrical energy price scheme consumed and generated considered in this study (spring 2014) [6]

Single tariff	13.6p/kWh	
Econo7	Peak: 15.32p/kWh	Off peak: 6.92p/kWh
Feed in Tariff	14.9p/kWh	
Excess PV exported	4.64p/kWh	

By assuming the energy cost scheme highlighted in Table 2, it can be concluded that:

- A. The cost of electricity for the household assuming that no PV is installed and that the electricity is charged at the single tariff is £527.57. We may consider this case as our noPV&no storage benchmark;
- B. If the energy generated by the PV panels is considered, and it is assumed that the household is equipped with two meters, one counting the consumption on a single tariff as above and the second to count the generation according to a FIT scheme including all PV as exported, the annual cost of energy becomes £527.57 - £519.98= £7.59 with the £519.98 benefit due to FIT counting as the yearly Return on Investment (ROI) for the PV equipment and installation;
- C. It can be imagined that another situation is possible, where some of the PV energy generated during the day is used to cancel out in real time energy consumption. If a bidirectional single metering solution would be available, to detect each direction of electrical power and assign to it the corresponding energy tariff, it will be therefore possible to only count as energy export/import for the power excess (consumption – PV generation). If under these conditions, the PV generation premium would still be awarded, a higher ROI would be possible. If consumption data with high sampling rate would be available, it may be possible to predict the overall financial aspects. However, the energy consumption data that were available were sampled over a 5 minute interval which means accuracy is lost which may result in power consumed not being actually cancelled by PV generation. On the other hand, the behaviour of the inhabitants and their energy consumption pattern will change significantly and for this reason, data from a house not equipped with PVs cannot be used to estimate the financial outcome of the household after PV installation;
- D. It is possible to estimate the potential to maximise the ROI by using energy storage to store the PV energy generation during day time and displace energy consumption during the evening and also be able to benefit from shifting peak loads to the off peak tariff. This means that if the energy storage is large enough to facilitate buying only the weekly deficit at cheap tariff, the amount of electricity that needs to be acquired (all seasons except summer when there is an excess) becomes 1277.9kWh and its cost is £88.43, whilst during the three months of summer an energy excess of 59.8kWh is produced. If in this situation the premium for the PV energy generation but consumed locally is still awarded, the total energy cost becomes £88.43 – 2661.1kWh x 14.9p/kWh + 59.8kWh x 4.64p/kWh = -£310.85. This means a yearly ROI of £832.42 when compared to the noPV&no storage benchmark, which now has to pay for both the installation of PV and the storage system, or when compared to the PV only case, an additional yearly ROI of £318.44 that could theoretically pay back for the installation of the energy storage system;
- E. If the FIT will not be paid for the PV energy that is generated but consumed locally, the ROI will dramatically reduce, as this accounted for -£399.28 whilst the real export accounted only for -£2.77 making the situation significantly less economically viable compared to the PV only case. And this is the reason why energy storage needs to be considered under FIT conditions if it is chosen to encourage the wide deployment of energy storage.

The energy prices and the potential ROI quoted above are the maximum theoretical achievable that may be available when a very large energy storage system/battery is used that can deliver any power/current in order to cancel the export of PV energy. In practice, this may result in an unreasonable size and costs. For this reason, it is recognised that it may be possible to find a higher ROI (in % of the investment) when exploring the trade-off between reduction/optimisation of the energy storage size/cost vs the decrease in the financial benefits due to battery limitations (state of charge, and current with impact also on lifetime).

It can be seen that a fairly large size for the energy storage is needed. Also whilst the hypothesis of importing/exporting the excess as a small constant continuous quantity may have an effect in smoothing the

variation of the energy, it does not capitalise on the possibility to buy cheap electricity overnight and displace additional consumption during daytime typically charged at a higher rate when enrolled in an Economy 7 tariff.

The second problem is that setting up a converter to handle in particular a low power level of continuous nature, has a negative effect on the overall energy efficiency where shorter bursts of power set at the power level where the converter efficiency is the highest, leads to better overall energy efficiency.

The last issue is that varying the size of energy storage may lead to poorer retention of the PV energy but it is expected that in relative figures (savings vs investment) smaller battery size may, in fact, offer a better Return on Investment (ROI) and the following investigation is designed to identify this optimum design point from the point of view of ROI.

3. METHODOLOGY

The energy storage (ES) system is assumed that it behaves as a simplified model of a 12.5V battery of variable capacity that assumes a voltage that is linearly dependent on the State of Charge (SOC) but neglecting internal resistance:

$$V_{\text{batt}}(\text{SOC}) = 10\text{V} + 5\text{V} \cdot \text{SOC}(\%) / 100\% \quad (1)$$

Following the update of the battery capacity and consequently of its SOC at the end of the previous sampling interval, the new battery voltage is determined using (1). This allows for the battery current to be calculated based on the power requirement for the energy storage. A limitation of the maximum charging and discharging battery current has also been implemented by assuming two situations: a cheap battery (lead acid) and a more expensive power battery (Li-ion). When the required battery current exceeds the battery limit, the battery current will be limited to its maximum and the resulting power difference will be covered by the grid power.

Table 3: Type of batteries used in this study

	Max charging current	Max discharge current
Cost-effective battery	0.2 C	0.5 C
Power dense battery	1.0 C	2.0 C

Also, in order to capitalise on the cheap rates of the Economy7 tariff, the energy storage system will perform battery charging overnight starting at midnight. The initial SOC for the night recharge is the residual SOC at the end of the previous day. The recharge will end at 5AM when the chosen target SOC for the battery is reached, a level that is maintained constant for the week. Two levels were tested: 35% SOC @5AM which works well for the seasons with energy excess or small deficits (spring, summer and autumn) and 70% SOC @5AM which seem to work better for seasons with larger deficits (winter).

Figure 2 shows the battery power versus the excess (consumption – PV) power when simulating the autumn week with a 12.5V/200Ah battery. On the left side, the battery considered is a cost-effective type whilst on the right side, the battery has same capacity but is of a power dense type (has significantly higher charge (5x) and discharge (4x) current capability), both limits being stated in Table 3.

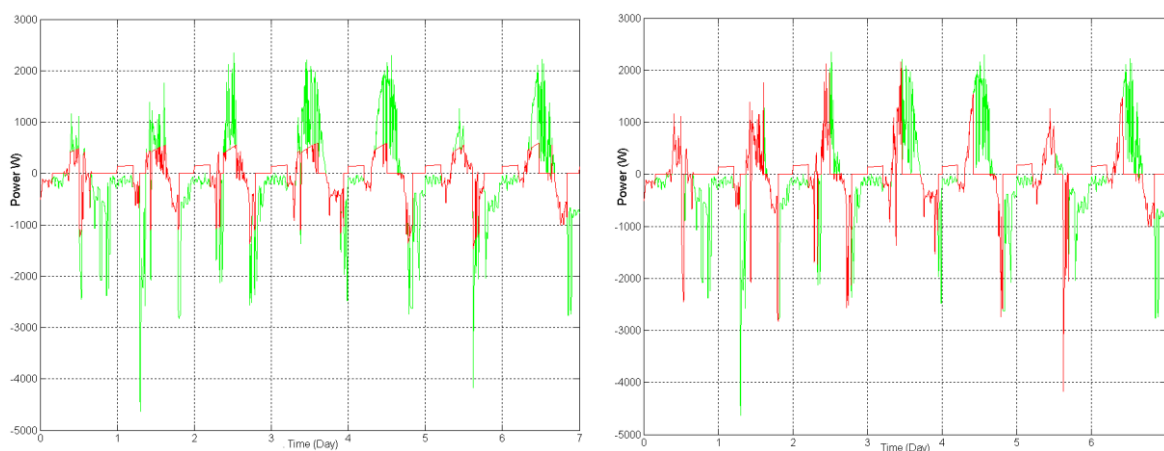


Figure 2: Power (W) of the energy storage system (red) and the excess (consumed – PV) power (light green) showing the difference in ESS behaviour when the battery has a weak (0.2C charging/0.5C discharging) current capability (left) vs power dense (1C charging/2C discharging). Battery parameters: 12.5V/200Ah; Season: Autumn. Time scale: 1day/div.

Ideally, the power of the energy storage system should overlap the excess power at any time. It is clear however that that is not always the case. First, there are moments when the energy storage power drops to zero and the reason is that the battery becomes fully charged whilst the excess power points towards continuing the charging, or is fully discharged but the excess power points towards extracting power out of the battery. The second mismatch is in amplitude and may be due to the forced overnight charging (midnight to 5AM) or is due to the excess power causing a battery current that would exceed the current limits stated in Table 3. Typically, smaller battery sizes would be quite often subject to reaching the SOC limits due to lower energy storage capability, but they can also be affected by current limitation, as the current limits are also linked to capacity current/battery size.

Figure 3 shows the simulation of the household + PV + 12.5V/400Ah cost effective battery during a week of all four seasons. On the left side, the evolution of battery SOC is shown revealing that the overnight charging is equivalent to creating another charge/discharge partial cycle with impact on increasing profitability, but decreasing the lifetime. On the right side, the evolution of the energy bought at off—peak/cheap and peak rates are shown. The strategy of pre-charging the battery overnight at a predefined level compensates for any use of grid power before the sunlight is powerful enough to give sufficient PV power. This results in the minimisation of expensive energy purchases. This is obvious in the beginning and end of the spring week and also in the middle and end of the summer week. The reason is that UK weather tends to change significantly over 2-3 days in these two seasons. During autumn and winter, the weather seems steadier/ more consistent and therefore imports of electricity are mainly due to the limited storage capability of the battery that cannot supply power for the whole evening. Further optimisation of the target SOC@5AM for the overnight recharging may further reduce the peak time energy consumption based eventually on the weather forecast. This was not considered here as the aims of this study was first to determine the benefits of the system whilst using a very simple control that do not require regular user interventions.

4. COMPARATIVE ANALYSIS

Figure 4 shows the percentage of PV energy exported out of the weekly PV energy generated. First, it suggests that without energy storage (extrapolate the curves for 0Ah battery, a large proportion (40+ to 60+ %) of the weekly energy generated by the PV is not met by instantaneous consumption by the household loads, having, therefore, to be exported. The curves show a steeper decaying slope until 250-300Ah battery capacity which means differential gains are higher at lower battery capacity. The PV energy export percentage can be reduced to under 30% of the energy generated when using a 325Ah battery or it can be reduced at 20% by using a 500Ah battery. It should be noted that in a summer week, there is a PV energy generation excess of 6.9% = 4.6kWh/66.9kWh which means the PV energy export cannot be canceled completely, irrespective of battery size). During winter, the loads typically consume more power whilst the PVs are generating less energy and this is why the household utilisation of the PV generated energy looks so much better. There is a significant difference between the spring and the autumn curves even though the circumstances for the two seasons seem very similar (consumption and PV generation). However, the 20% difference in the PV energy utilisation which remains constant, down to a 50Ah battery capacity is perhaps due to a better synchronicity between PV generation energy availability and loads. This may be in fact the result of the initial awareness and enthusiasm of the house inhabitants following PV panels installation and their desire to use locally as much of the PV generation as possible. It is expected that this initial enthusiasm will wear out with time and would have been interesting to check if the same significant difference in the utilisation of PV energy during the following year's spring and autumn week remains.

Looking at the curves in Figure 5 that shows expensive (red) and cheap (blue) energy purchased for each of the four season weeks, it can be noted that their slope changes significantly above a critical battery size which means that above this critical battery size, a given increase in battery capacity will result in smaller gains.

Increasing the battery size from 50Ah to 300Ah reduces to less than half the amount of expensive energy that has to be purchased at peak times in the spring. Above 300Ah battery size, the slope showing the amount of energy bought at peak time reduces which means lower gains are reached with the same increase in battery size. The slope showing the PV energy sold due to limitations of the battery falls quicker from 21kWh(40% of total PV energy captured) @50Ah to approx. 8kWh(18%)@300Ah. At higher battery capacity, the slope (relative gains) reduces visibly. The energy bought at cheap /off-peak rate raises fast from 10kWh @50Ah to 16.5kWh@350Ah above which the slope reduces. The battery capacity where the returns in percentage are higher seems to be in the range of 300-350Ah for the spring week data.

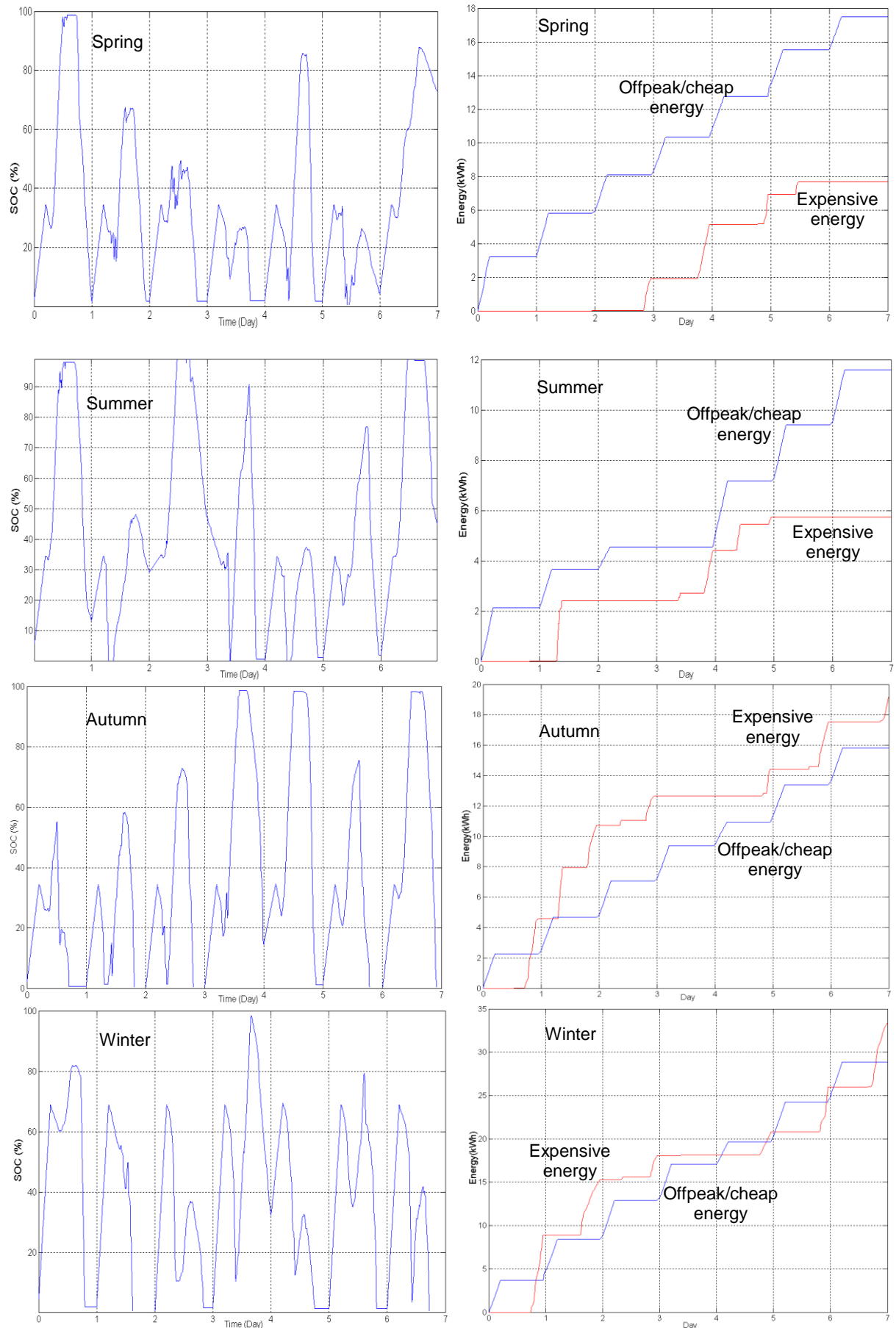


Figure 3: Weekly battery state of charge (left side in %) and expensive (red) vs off-peak/cheap (blue) purchased energy (right side in kWh) for a 12.5V/400Ah battery system controlled to recharge overnight up to 35% SOC at 5AM of each day of spring (top) – summer (2nd from top) – autumn (3rd from top) and up to 70% SOC at 5AM of each winter day. Time scale: 1 day/div.

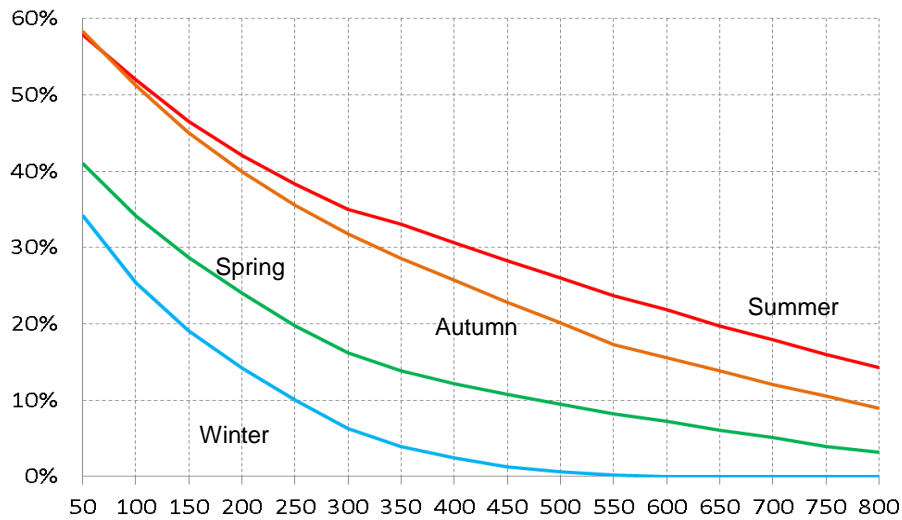


Figure 4. Export of PV energy as a percentage of overall weekly PV energy generation versus the 12.5V battery capacity (in Ah). (green=spring; red= summer; amber=autumn; blue=winter).

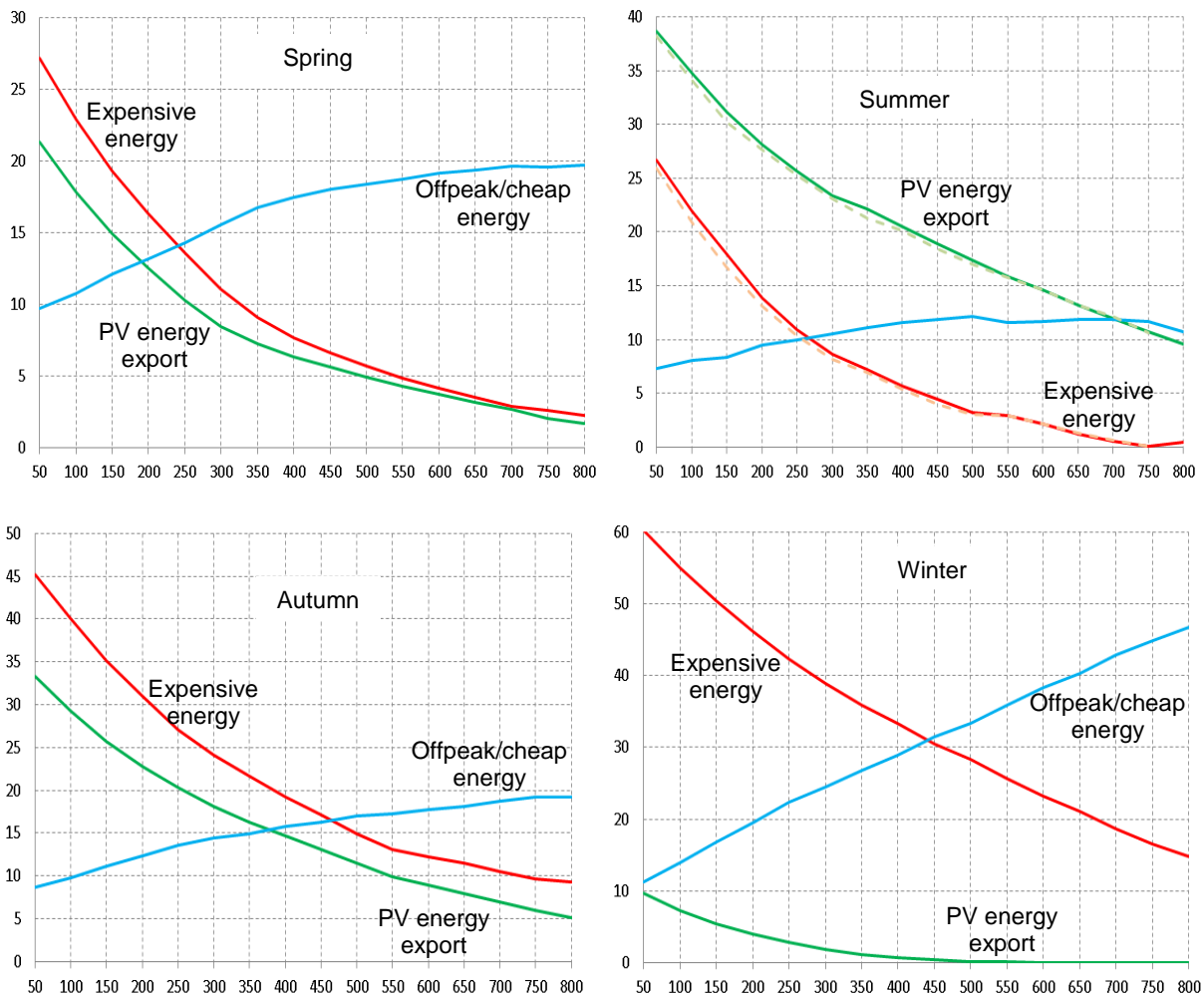


Figure 5: Weekly variation of the weekly energy (kWh) (red= expensive; green= PV exported and blue=cheap off-peak) as a dependency on the 12.5V battery capacity [Ah] for the four considered seasons. Top -left: spring; -right: summer (dotted lines = curves corresponding to power dense battery); Bottom -left: autumn; -right: winter.

Vertical axis: Energy [kWh]; Horizontal axis: Capacity [Ah] of the 12.5V battery stack.

The results corresponding to the summer week data show two set of curves. In addition to the cost-effective battery (solid lines shows the battery that charges at 0.2C and discharges at 0.5C), the characteristics of a more powerful battery (charging at 1C and discharging at 2C) are shown. As expected at higher battery capacities, there is no difference between the two curves as the battery current limits are large enough even for the cost effective battery. But when the battery capacity is below 200Ah, there are some slight gains in terms of being able to handle the desired power. However, due to size limitation, the capacity limits are triggered quicker and this explains the small differences. The critical battery size below which the slope of expensive/peak price range drops quicker is between 250-300Ah. The slope of the cheap energy curve rises slowest and above 450Ah, there is no visible gain. The autumn season shows a similar behaviour with the spring, with two critical points placed at 250Ah and 550Ah where the slope of the expensive/peak energy price reduces visibly twice. The other two curves show a fairly constant slope.

For the winter season, it can be noticed that increasing the battery size above 300Ah enables the full utilisation / disables the export of the PV energy generated by the household. In addition, by being able to charge overnight, it allows the reduction of electricity bought at peak time by a third (from 60kWh to just under 40kWh). The reductions seen in the PV energy that was exported and the energy purchased at peak time are compensated by the increase in energy bought at night and stored for use during morning. The amount of off-peak/cheap energy, shows a 2.5 times increase (from 10kWh to 25kWh) for battery capacities ranging from 50-300Ah. Further increase of the battery size is possible, but since there is no further improvement possible in utilisation of PV energy, the only mechanism for increasing the ROI is to buy energy overnight cheap and displace expensive consumption during peak time. This is also reflected by the slightly slower decaying slope of the expensive energy curve above 250Ah battery capacity. It can be noted that in order to completely avoid purchasing expensive energy during the winter week under investigation, a battery capacity of 1500Ah is necessary.

Finally, it is possible to assign the price tag for each of the components in the energy bill. The cumulated variation of the financial benefits as a function of the battery size is shown in Figure 6. It is possible to compare this against the theoretical values calculated in Case B/Section 2 of the paper. The financial benefit from operating the PV + 50Ah battery is £570.83 which includes the FIT and the limited gains due to buying cheap overnight electricity and replacing expensive electricity, thanks to the Econo7 dual tariff. Compared to the benefit of having only a PV system, which resulted in £519.98, this offers an addition of £50.85 to pay towards an energy storage system based on a 12.5V/50Ah battery. The financial benefit that corresponds to a 1000Ah battery reaches £768.69 which is smaller than the theoretical gain of £832.42 as calculated in Case D in Section 2 of the paper. But this last figure represents the maximum available that could be achieved only with prior knowledge of the PV energy evolution and synchronisation of power consumption to prevent purchasing energy at the peak tariff .

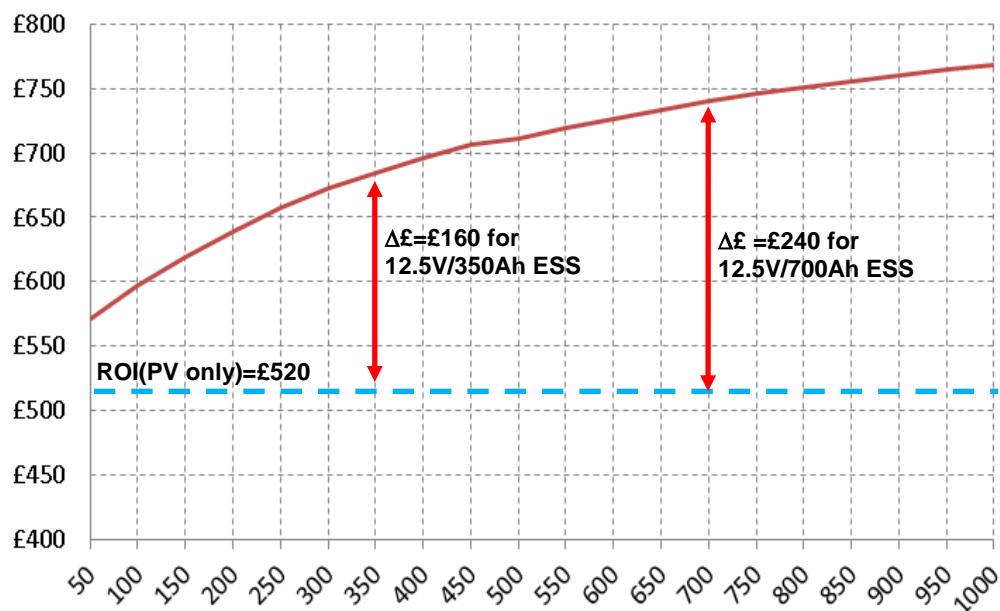


Figure 6: Financial benefit of PV+ESS versus battery capacity assuming a 12.5 V battery

Looking at the financial benefit curve versus the size of the battery it can be seen that the slope rises faster initially but the slope is continuously reducing and is not possible to identify a clear critical battery capacity. However, it can be concluded that a battery capacity between 300-400Ah would offer the highest relative benefit (financial benefit related to cost/size of the battery). In Figure 6 two cases are highlighted: the case of a 350Ah battery that gives an extra ROI of approx. £160 and the case of a 700Ah battery (twice larger) that gives an extra ROI of approx. £240. It can be noticed that the extra ROI increases by only 50%.

5. CONCLUSION

This paper investigated the benefits that can be achieved by the addition of an energy storage system to a PV system installed in a UK household. Initially, the theoretical financial gains are derived based on idealistic assumptions. Then a realistic energy storage system based on a battery is modelled that can realistically model battery limitations in terms of size/capacity and current capability. A control algorithm based on a simple assumption of performing overnight charging to a predefined and constant state of charge level to be achieved at 5AM, of 35% (spring-autumn) and 70% (winter), is implemented. The simulation model then quantifies separately the amount of PV energy that has to be exported due to limitations of the state of charge or current/power handling. The energy consumed during peak time and off-peak time are also separately quantified and represented as dependence of the battery capacity. Interesting trends emerge, that point to the possibility to achieve better financial benefits relative to the size of the battery (investment). This is finally confirmed by estimating the financial benefits versus battery capacity and comparing the ends of the range with the two theoretical values determined initially in Section 2 or the paper, showing reasonable consistency.

Overall it could be concluded that these models may help determine a cost effective sizing of the energy storage system. The resulting size will not fulfil the needs of storing all available PV energy that is generated in the sunniest day/week of the year but it may result in a smaller/optimal size/cost that offers a faster and highest percentage of Return on Investment. Future work will include considering the losses in the battery and also the restriction in operation for the energy storage system emerging from the need to preserve high roundtrip efficiency which may require disabling the operation of the Energy Storage System at very low power levels.

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