Solar PV with Energy Storage

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Solar with storage has been examined on multiple levels in this project. Energy stores can be used to smooth the output from a PV farm and also shift the supply to fit the demand. The roles storage can be implemented on both the demand and utility sides and have been analysed. The requirements from the storage unit are very different for these two applications. It has been concluded that for the storage unit to be economically viable on the utility side it must perform additional tasks such as frequency support or price arbitrage. Implementation of storage with solar has been hindered by the introduction of Contracts for Difference and a policy change or addition is needed before large scale uptake can be seen. Subsidy implementations or financing deals are likely to lead uptake on the demand side when combined with demand charges and existing solar arrays.

Introduction

There can be no doubt that the threat of climate change is real and grave. Many countries across the world are combatting this threat by reducing carbon emissions. The UK has legislated an 80% reduction in emissions from the 1990 baseline by 2050. This will require a revolutionary change to the generation mix in the UK. Undoubtedly distributed solar PV generation will play a part in this.

Solar PV installations have seen a huge growth in the last year, the overall PV capacity in the UK stood at 5095MW at the end of 2014, this is a 79% increase on that point in 2013 [1]. It is unclear whether this extreme growth will continue as subsidy levels are decreasing, but the module price is also decreasing. However, the scene is set for widespread PV uptake and a driver for an effective policy framework and improved infrastructure of enabling technologies is in place.

Solar power is a variable electricity source though, we have very little control over when the PV plant is producing electricity. A typical daily irradiance profile has a peak at 12-1pm and decreases until the sun sets. In addition to this, clouds passing over cause significant fluctuations in electricity generated. Strategies to increase the correlation of solar power with electricity demand have concluded that a key technology in solving these issues is energy storage [2]. This enables the shifting of PV power to when it is most needed and can smooth out the rapid fluctuations in production. The applications of energy storage with solar power are examined in this report, as well as an assessment of modeling parameters and policy considerations.

Current Projects

Current solar PV with storage projects in the UK are limited. The use of energy storage on a micro-grid, where part of the generation is a PV array, has been seen on some Scottish Isles. However, there are only two examples of the use of energy storage with a PV farm in the UK.

The first storage unit was installed at Slepe Farm solar park in Dorset during October 2014. This is a relatively small solar farm with a rated power of 498.4kWp. The energy storage device installed was a 250kWh battery, the chemistry and maximum power rating were not disclosed. However, the press-release stated that energy will be "released when it is more needed by the grid". This implies that the battery is not only improving power quality from the PV farm but also providing a service of frequency response to the local grid.

The second UK PV with storage project was announced in February 2015. This will be located at Willersey Solar Farm which has a rated power of 3.8MWp. This project forms part of the Enhanced Frequency Control Capability (EFCC) project which is lead by the National Grid and is run by the UK arm of Belectric. It is intended to provide frequency stability. The results from this project will be compared with the grid balancing effects of a similar battery unit, installed by the same company, but not connected to a PV farm.

From the limited information available, it would suggest that both of these projects do not just provide ramp-rate control for increased power quality but also provide stability to the grid through frequency response. This approach makes the PV farm a stabilising feature in the local grid, thus the funding mechanism for the battery system comes through this rather than the changes it makes to the PV farm output.

Germany has seen a large growth in the solar with storage market since mid-2013, this is largely due to a government subsidy of domestic battery systems. In the first year, this accounted for €66m in low-interest loans and €10m in grants [3]. Germany has historically had issues with an unstable electricity spot price market due to high levels of renewable penetration, most notably leading to negative prices for electricity on some occasions. Thus, a large driver exists to increase the stability of the grid during high levels of wind and solar generation. Crucially the subsidy is given per kWh of installed battery capacity, as such the policy is aimed at increasing the overall energy stored in the system rather than simply providing short term grid stability through high power batteries.

In the UK, two initial projects looking into domestic storage with solar are underway. Very little information on their findings exists at the moment, however, by their existence it can be seen that there is a growing trend towards domestic solar with storage. The funding for these projects is provided by the Department for Energy and Climate Change (DECC) and as such, if they show successful results it would not be unfeasible to see the UK Government implement a domestic battery subsidy policy akin to that in Germany.

In the United States a large growth in solar with storage has been seen in the commercial sector, this largely is without subsidy but due to the high electricity costs in states such as California and commercial customers receiving large penalties for peak usage [4]. This gives an energy store which can supply electricity at peak times a high value. Very similar conditions exist in the UK, though. The key difference is the funding mechanism through which American companies are offering Solar with Storage projects. A "No-Money-Down" policy has been very successful as used by companies such as SolarCity, Sunrun, Clean Power Finance, Vivint and SunPower. These companies offer battery technology, or solar with storage packages at little or no cost but with an agreement that they will take a share of the savings. The falling cost of large Lithium-Ion batteries has created the opportunity for economic viability behind the meter. With the cost of Lithium-Ion batteries predicted to fall further and the demand for solar with storage to rise significantly the size of the distributed storage market is predicted to rise to $1bn by 2018 [5].

Literature Review

Solar power is one of the most predictable sources of renewable generation. The sun only shines during the day, however, the highly unpredictable nature of cloud movement leads to large variation in the output of a PV farm in a short period of time.

Large and quick variations in the power output of any generator will cause issues in the electrical grid. In an isolated system, as a PV plant's output reduces when a cloud passes over, a heat generator must ramp up at the same rate and to the same amplitude to maintain a constant system frequency. This introduces inefficiencies and promotes spillage and curtailment of renewable generation to protect the less flexible heat generation infrastructure [6].

The flexibility of the existing electricity generation stock is the limiting factor of PV penetration. Flexibility is measured as the percentage of peak-load to which the generation fleet can reduce supply [6]. As such, a grid with a large proportion of nuclear energy, such as France, will only be able to tolerate a very small amount of PV generation without interconnectors or energy storage to avoid curtailment. However, a more flexible grid system with a high level of gas turbine or hydropower such as the UK or Norway can sustain a high level of PV integration without the need for enabling technologies.

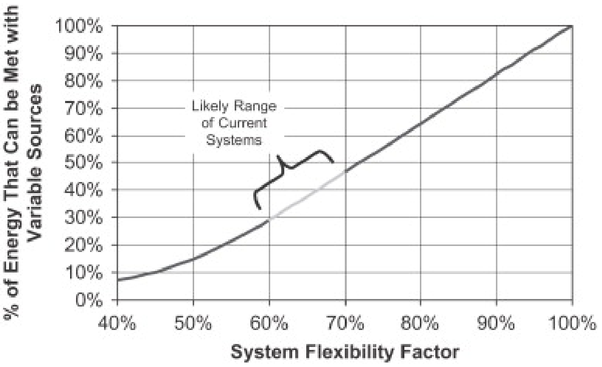

Figure 1: *Limits of energy produced by renewable sources compared to overall system flexibility [6].*

Denholm and Margolis suggest that under current system flexibility factors of 65-70% a maximum penetration of renewable power would account for 30-40% of the energy provided, this is shown in Figure 1. However, at this level of penetration a huge cost of curtailment is incurred, equaling up to double the installation cost. So a case for energy storage can easily be made when accompanied by these high levels of penetration.

Ramp-rate Control

The main aim of ramp-rate control is to improve power quality under intermittent solar irradiance conditions, where this has been stipulated by the District Network Operator (DNO) or otherwise. The role of the battery is to reduce the ramp rate (Ws^{-1}) to an acceptable level. This need is due to the very large swings in power which can be observed on a cloudy day. The literature suggests ramp-rates of up to 90% change in output power from a PF farm in just 1 minute [7] at a 1MWp plant. The maximum ramp-rate reduces with increasing plant size.

The possible methods for controlling ramp-up and ramp-down events are different. There are two strategies for reducing the ramp-up rate. Firstly, the power gap can be used to charge a battery, this minimises energy loss and provides the capability for support at a ramp-down event. Secondly, the inverter can be set to only provide the ramp-rate which is desired and the excess power is wasted, has been observed to be up to 9% of overall output [8]. The ramp-down event, however, always needs an energy store in order to mitigate.

In the UK, Engineering Recommendation G83 details the guidelines for small scale embedded generators. The maximum ramp-up rate is $333Ws^{-1}$ for one phase and $860Ws^{-1}$ for 3 phase [9]. This does not give limitations on the ramp-down rate and as such, there is no legal requirement which promotes energy storage implementation.

There is a growing trend of regulation of maximum allowable ramp-rates. Mexico, in particular, has seen a regulation of 1%/min to 5%/min maximum ramp rate output [10]. The driver for this level of regulation is a large renewable penetration or a weak grid. With increasing renewable penetration in the UK, it is not unreasonable to assume that in coming years increasingly stringent ramp-rate controls will be implemented.

Ramp rate control can implemented by geographical grouping of PV farms [11]. It is claimed by Mills that a consistent output with no greater than 25% per 15 minute can be achieved 99.7% of the time with the aggregation of 100 PV farms. The effects can be seen in Figure 2. There are geographical and power-line transmission limitations to this, further study is needed to assess these limitations in the UK. There is also an associated cost of electrical transmission dependent on geographical location and distance between farms, as such a cost analysis is recommended to assess economic viability in comparison to paired energy storage.

The examples of implementation of storage with solar in the UK provide grid services in addition to the improvements made to the output of the PV farm. This enables the economic viability since the ESS has an alternative revenue stream. The need for fast grid support is growing and batteries are one of the major contenders for supplying the need [12]. At ref [12] a complex model of the behavior of a battery for fast grid response is presented, but it is beyond the scope of this report to discuss it in detail.

Supply Demand Mismatch

The issue of supply-demand mismatch is central to energy storage growth and a move to a zero carbon

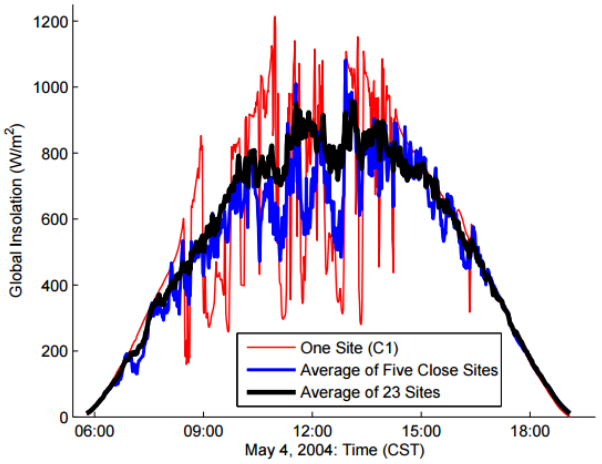

Figure 2: *PV farm output with aggregated 5 and 23 PV farms overlayed. [11].*

economy. Since solar power follows predictable and regular cycles it pre-disposes itself for use with storage. Bortolini et al. [13] suggest that for effective supply-demand mismatch mitigation a control strategy where power flow between the battery and the grid is two way. Thus, the battery can store excess energy at night and leveling the output during the day.

The size of a battery which effectively matches the supply with the demand is based on the size of the evening peak in demand. The demand should be normalised such that it is equal to the net output energy from the PV. The size of the battery, in relation to the PV array size, can then be found as the area between the PV output and demand profile.

The control strategy shown in Figure 3 forces a match between the supply from the PV array and demand, if the PV and battery system cannot meet the demand, power is bought in from the grid. However, the system can easily be specified to provide the demand under normal conditions.

If there is to be a significantly higher level of renewable penetration onto the grid, the allowable ramp rate for distributed embedded generators will need to be reduced to almost zero. This would enable the supply from renewables to follow demand. However, there is currently no driver for this change. At a simple level, for the energy storage system to be economically viable the initial capital cost and ongoing maintenance costs must be counteracted by the revenue achieved through supply shifting to peak times. Thus, a framework must be set up for this to occur through a tariff system or through PV farm exposure to electricity spot prices. This would incentivise PV farms to invest in energy storage in order to sell electricity at the highest price.

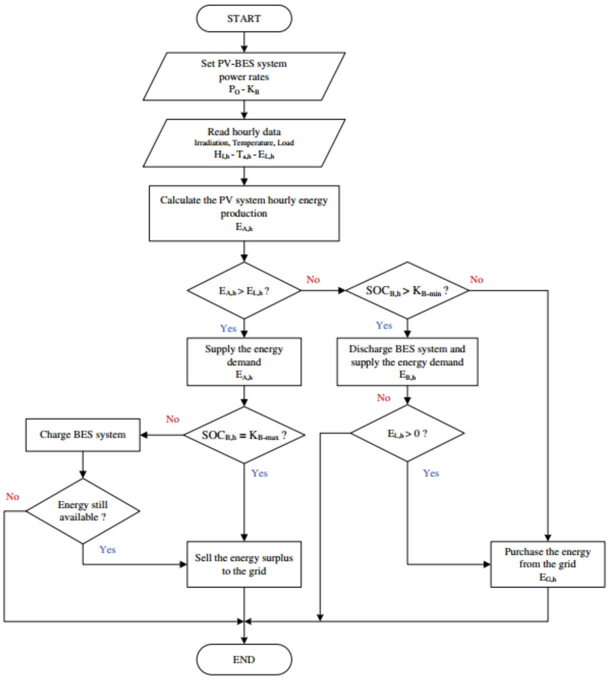

Figure 3: *Proposed control strategy for supply demand control [13].*

Thus, the revenue stream for this method of battery management is quite different to that used for ramp rate control. Price arbitrage would provide an alternative funding mechanism for the energy store [14]. The battery needs for price arbitrage are very similar to that for supply shifting. In effect, they follow the same principle of supplying electricity when it is most expensive to achieve the highest revenue. However, for price arbitrage, electricity is bought from the grid rather than provided by the PV array. Since electricity is cheapest at night, when no solar power is available, it can be seen that these two revenue generation mechanisms could run in conjunction. This is similar to the intention of the project proposed by Bortolini et al. [13]. A model could be used in order to specify the system under certain electricity market conditions and assess profitability. A concern with the price arbitrage is that if it is effective it will cannibalise its own market. This is due to its reliance on the volatility of the electricity market, and the addition of energy storage will increase stability due to matching the supply with demand more effectively. It is a matter for further study to assess the predicted effects of arbitrage cannibalisation when used in conjunction with solar, since intermittent generation will always promote price volatility. In the short and intermediate timescales there is little chance that price arbitrage would become obsolete.

A behind the meter application, as suggested in the literature [15], [16], [17], could lead to economic viability through supply shifting and price arbitrage since large customers are subjected to variable tariffs and TRIAD charges.

Literature Modelling Methods

The models found in the literature can be classified into two main fields; demand side models to maximise energy reduction or economic benefit for an energy user, and utility side models which calculate the benefit for providers of electrical services.

Nottrott et al. [15] [16] looks at the benefit for customers with installed PV arrays with ESS. This focuses on demand charge management and tactics to reduce extra costs from the energy supplier, such as TRIAD avoidance. A linear model has been developed which uses forecast data for load and supply to calculate the best charge or discharge strategy for the battery. It is limited due to its reliance on a variable tariff. But the matching of forecast supply and demand data could be useful when programming battery dispatch strategies for PV farms. Hanna et al. [16] concluded that the algorithm developed for maximum demand charge management reduction caused higher battery degradation levels than can currently be allowed for economic viability.

Gitizadeh and Fakharzadegan proposed a model which can be used to optimize the capacity of a battery system for a given PV storage application [17]. In their model the degradation properties of the lead-acid battery system were taken into account and the model was created around the US tariff system. The sizing of the battery was decoupled from the dispatch optimisation model. It was concluded in this paper that the sizing of the battery greatly depends on the electricity tariff and battery aging characteristics. In addition to that, the paper concluded that it is not currently economically viable to use a lead-acid battery for PV energy storage behind the meter. Parra et al. [18] performs a similar economic analysis over the lifetime of the battery system but when operating in the UK. The model agrigates domestic PV systems in a community energy store, this led to a decrease in the effective cost of the system however, economic viability was still not reached. These models do not take into account the potential revenue streams through offering grid services with the ESS.

On the utility side, a main driver for research is a need to improve the power quality of the output by ramp-rate control. This is usually driven by either a desire to minimise the capacity of the battery necessary, or minimise the aging effects of the dispatch strategy.

The size of the required energy store per ramp-up/down event can be calculated as such:

$$\frac{C_{batt}}{\eta_{batt}} = \int P_G dt - \int P_{PV} dt \tag{1}$$

Where C_{batt} is the required capactiy of the battery, P_G describes the maximum power ramp rate which can be supplied to the grid, and P_{PV} is the maximum power ramp rate provided from the PV array. This is doubled for the non-inverter controlled ramp-down event if the battery is held at 50% SOC when not in use.

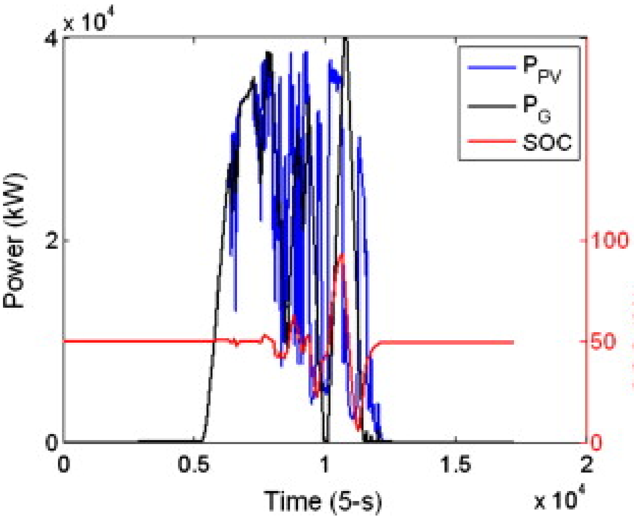

Figure 4: *Graph of SOC of the battery, PV output power and output power to the grid for battery storage on ramp-up and ramp-down events where the battery is held at 50% SOC when not in use [8].*

However, in ref [8], it is suggested that a more optimal control strategy is used which can provide battery storage for both ramp-up and ramp-down events without the need to double the battery capacity. This is achieved by comparing the maximum and minimum PV generation at a given moment with the actual generation and relating that to desired SOC of the battery. In this situation, the desired SOC of the battery is simply given as:

$$SOC = \frac{P_{PV} - P_{MIN}}{P_{MAX} - P_{MIN}}$$

If the PV array is producing near peak power then the battery is not needed to absorb power on a ramp-up event, as such, the SOC can be increased, the converse is true for low PV generation where the battery is not needed to provide power for a ramp-down event. In this case, the battery capacity needed to provide effective ramp-up and down support is significantly reduced and is theoretically equal to that given in Equation 1.

However, a third method further minimises the capacity of the battery needed but requires a geographical dispersion of PV farms, this was proposed by Marcos et al. [7]. It is called “Step Rate Control” and produces a stepped response to a ramp down event, this can be seen in Figure 5.

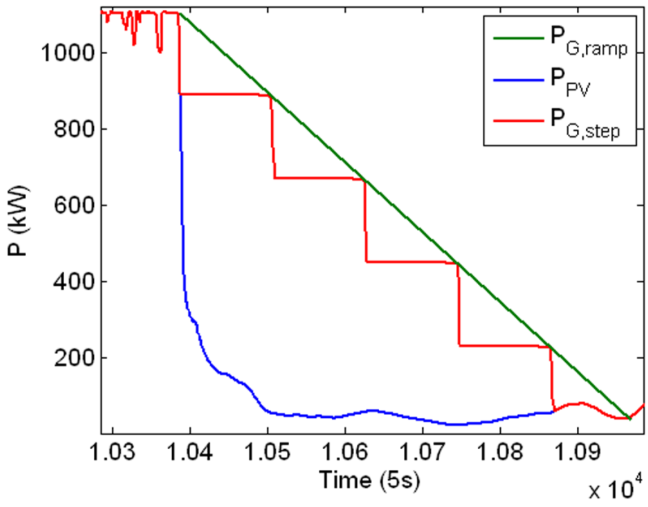

Figure 5: *Proposed control strategy for step rate control [7].*

When this response is present in a group of associated PV farms the overall ramp down takes a much smoother profile. This has the advantage of cycling the ESS far fewer times than the moving average model, and a smaller capacity is needed due to the shape of the step response. However, this tactic is only needed when only a very low ramp-rate is allowable. The pooling of PV farms in a local area provides a significant amount of ramp-rate control without the utilisation of an ESS.

Modeling considerations

In order to assess the benefits of an ESS intervention and degree of economic viability a modeling procedure is key. An effective model will take into account all revenue streams and operating conditions to find optimum operating conditions for profitability or battery life.

To identify whether a favorable economic situation exists for the deployment of storage with solar, the method of utilisation is very important and as such ESSs for providing ramp-rate control and supply shifting are discussed separately here.

Modelling Ramp-Rate Control

For the case of an energy storage system being used to provide ramp rate control and frequency response to the grid, profit will be through four avenues. Firstly there is a mechanism through which the national grid pays for frequency response services. A grid connected battery would fall into the ‘Fast Reserve’ category where power must be delivered within 2 minutes and sustained for a minimum of 15 minutes. Fore this service the National Grid pays 145/MWh which is utilised and 3.88/MWh as an availability payment [19]. In addition to this the National Grid pays for the reduction of demand, traditionally through demand management, however, a battery could be used to absorb energy in this situation and as such could receive 35.49/MWh for storing energy when the frequency rises [20]. The revenue stream for profit from ramp rate control is not as well established yet in the UK. Current regulations from Engineering Recommendation G83 [9] specify only a maximum ramp-up rate from embedded generators. This can be absorbed in the inverter and so does not promote energy storage use or provide a revenue stream. As the penetration of renewables on the grid increases it can be anticipated that ramp-rate restrictions will be imposed as has been the case in Mexico, Puerto Rico and Spain. This will impose a penalty on embedded generators which deliver a power distribution which exceeds the maximum allowable ramp rate. An energy storage system would enable the avoidance of these possible penalties. In addition, an energy store could avoid the PV farm exposure to imbalance charges. These occur when the amount of energy delivered to the grid differs from the amount of energy sold in the previous 30 minute settlement period. An energy store could absorb excess or provide extra energy when it becomes apparent a difference will occur. This is quite likely to happen with a PV farm due to changing weather conditions.

In order to model the revenue available from an energy store operating in the above conditions a significant amount of data is needed. The frequency and nature of the grid services which the energy store could provide need to be addressed. This would need to be matched with the generation profile of the PV array and the frequency of ESS interactions with ramp-rate control and imbalance charge avoidance assessed. This would provide the information needed in order to correctly size the battery necessary for the roles which it is expected to fulfill.

A control strategy would be designed to provision for all the services which the battery could be used for in order to maximise profit. It is anticipated that the two key stages which would form part of this control strategy, would be an assessment of whether a service is needed from the battery, and whether it would be profitable to provide this service. The ability of the battery to respond to service requests would be dependent on such factors as the SOC, the time of the day, the weather forecast and the possible profit. This information would enable a decision to be made as effectively as possible. There must be a thorough assessment of the data available from the national grid and from existing PV farms in order to specify the control strategy for maximal profit. Once this has been completed, this model could then be used with the data in order to assess the profitability of the system.

Policy Considerations

The main goal of supply shifting with PV systems is to minimise the selling of electricity at cheap prices and maximise selling at expensive times. Due to zero generation during the night, the ESS can be charged with cheap off-peak power in these hours to provide a price arbitrage revenue stream. A renewable generator's ability to do this is highly dependent on the policy framework in which it operates due to the continued need for subsidy.

The Renewables Obligation (RO), used by the British Government since 2002, gives subsidy to large scale renewable generators (less than 5MW) through the award of Renewable Obligation Certificates (ROCs) and obligating energy suppliers to obtain a certain number of ROCs in a given year. They do this by buying the ROCs from the renewable generator and as such subsidising the renewable industry [21]. This allows the renewable generator to operate on the standard energy market and as such it is exposed to electricity price fluctuations, the same as any other generating facility. Contracts for Difference (CfD) are now being used to phase out the RO as the main funding mechanism [22], this scheme is designed to offer more stability to renewable investors by guaranteeing that the electricity sold by the renewable generating plant will always achieve the same price and will not be subject to ROC price volatility or wholesale electricity volatility. This removes the economic driver for a supply shifting ESS linked to solar PV farm since the same revenue will be achieved per kW generated no-matter what the time or demand.

The Capacity Market [23] is designed to prevent electricity shortages during key peak times. In this framework any electricity generator can bid to guarantee a certain amount of electricity generation during the peak times. The generator which bids at the lowest price gets the contract. The subsidy provided through this capacity market does not drive flexible renewable generation since distributed generators are immediately priced out of the market by the large coal and gas providers who can bid much lower due to cheaper running costs and then modify their maintenance plans around the new commitment. This has the effect of subsidising large heat plants which have low flexibility. The money used to subsidise the capacity market would be much better used in an addition to the contracts for difference in a mechanism deisgned to add flexibility to the renewables sector since the plants recieving the subsidy are not, in most cases, altering their planed generation anyway.

The addition of a second tier strike price in the CfD policy framework could provide the stimulus for energy storage. This would operate under the same structure, however a higher strike price would be available to a renewable generator which pairs the generation with energy storage. The renewable generator would obligated to sell the electricity at times where the spot price is high, thus the subsidy recieved from the 'Low Carbon Contracts Company' to remain roughly the same.

A model to estimate the profitability of an ESS operating under the RO could be achieved through comparing the profit from selling the electricity when generated with the profit of selling at peak price. This must then be compared with the ESS efficiency and the capital cost to calculate a payback period. The capacity of the ESS can be calculated as that which reduces the variance of the difference between the generation and normalised demand data sets to an acceptable level.

Recommended Work

A model including the use of ESS for PV ramp rate control and grid services could be novel, it would enable informed decision making for paired energy storage. The model must assess all revenue streams and combine that with an effective battery dispatch schedule which maximises profit.

Energy storage with solar has become a popular "behind the meter" solution in Germany and the USA, further study which focuses on the policy structure which makes those markets succesful and finds how it could be replicated in the UK could provide an avenue for increased energy storage investment in the UK. This could look into the agricultural sector PV investors to find whether a “no-money-down” programme would be popular with existing commercial PV owners.

It is clear that the UK needs a policy framework for energy storage which works with CfD if we are to see any development of ESS linked to renewable generators for Supply Shifting. Future work could look into the policy sector and assess where changes can be made in order to make energy storage an economically viable option for renewable generators.

Conclusions

This report has presented the different methods for providing energy storage with solar power. This has focussed on two main types; Ramp-rate control and supply-demand shifting. On the utility side there is little room for profitability under the current UK policy framework. Ramp-rate control is not yet enforced and as such there is no incentive for a PV farm to reduce the ramp-rate of their output. This is liable to change in the future as renewables form a larger part of the market, this has been seen in Mexico, Spain and Puerto Rico. Supply-demand shifting on the utility side has been dis-incentivised by the introduction of Contracts for Difference as the main funding mechanism for large renewable projects since the same price is achieved for the electricity produced regardless of the demand for that electricity.

Matching the energy stores used for ramp-rate control and supply shifting with grid services could provide a path to economic viability on the utility side. Frequency response imposes similar battery demands to ramp-rate control and price arbitrage on the electricity spot market could be achieved with a large capacity batter linked to a PV farm. Frequency response has a specified revenue stream, however, the same cannot be said for price arbitrage and integrating that within the contracts for difference framework could prove prohibitively difficult. However, both of these methods have the benefit of reduced to zero electricity purchase costs due to linked generation.

Behind the meter energy storage has fewer barriers to economic viability. This is due to variable tariffs and peak demand charges placed upon commercial customers. If demand charges continue to rise, and prices for lithium-ion batteries fall to a sufficient level a widespread uptake of PV with storage could be seen in the commercial sector. This has begun in the US, aided by “No-Money-Down” financing schemes.

Domestic batteries, linked to PV arrays is another behind the meter approach to energy storage which could see some traction in coming years. DECC has funded two projects on the subject and a subsidy policy in Germany has proven very popular. The roll-out of smart meters and variable tariffs could lead to an increase in demand for this, especially if combined with a subsidy policy.

CfD has removed driver for paired storage, however, continued investment in the UK renewable sector will reduce stability. The government response to this is the Capacity Market, however this has just seen subsidy given to large heat plants rather than increasing overall grid flexibility levels and reducing carbon emissions. There must be a policy shift if the UK is going to move towards promoting flexible and sustainable generation.

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