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LEM Residential BESS Utilisation Summary Report

Cornwall Local Energy Market, Centrica plc

Prepared By:

Dr David Kane*, Dr Andrew Peacock, Dr Peter McCallum

Trilemma Consulting Limited

* David.Kane@TrilemmaConsulting.co.uk

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Executive Summary

In this report, we quantified the energy utilisation of BESS at each participating site in the LEM residential trial when operated in self-consumption control mode. This also allowed the headroom capacity, not utilised for self-consumption to be quantified. A methodology was developed for assigning economic value to this headroom using arbitrage based on a published, dynamic, half-hourly data-set of time of use tariffs for the operating period. The impact of varying how BESS capacity that was apportioned between self-consumption and arbitrage was then explored to understand its impact on BESS economics. The extent to which an economic or operational performance case could be made for increasing BESS capacity at each site was investigated alongside comparison with an alternative option of deploying a community-scale BESS. The impact of these on individual dwelling CO_2e emissions was also considered.

The energy utilisation of BESS systems deployed in the LEM trial, when operated using a self-consumption control signal, returned a fleet average of 63%, ranging from 33%-90%. Energy utilisation for a given site can be approximated using estimates of Production Surplus and Production Deficit. Significant stranded capacity is therefore present in almost all sites with commensurate impact on BESS economics. Power utilisation, defined as the average power level when charging or discharging divided by BESS rated power was found to be significantly lower than energy utilisation, with fleet averages of 26% and 17% for charge and discharge respectively. Round Trip Efficiency (RTE) was found to be influenced by charge and discharge power utilisation. This is expected and is consistent with part-load efficiency curves that occur in any electronics that have been designed to meet rated power capacity.

A methodology was proposed for investigating headroom using confidence intervals that allowed quantification uncertainty to be evaluated by time of day, between seasons (winter, summer, shoulder), and within each season. This was also able to explore the proportion of BESS energy capacity that has to be reserved to achieve maximum available self-consumption and how this can be traded to provide additional headroom for monetisation.

A generic arbitrage approach was defined that used up-to 3 shifting events between 2 charge and 2 discharge time windows within each day. This illustrated how multi-objective BESS operation can increase BESS utilisation through multiple dispatch events within each day, whilst delivering economically optimal level of self-consumption. Using annual average time of use arbitrage values of £3/MWh to £87/MWh (per each shifting event), the headroom could be monetised to improve Total Value by 50%+ versus self-consumption, without appreciable detriment to self-consumption value. Further study is required to ascribe value to a definite contracting structure or trading approach, and to optimise reduced self-consumption vs increased trading; but the initial results suggest that more value can be unlocked.

The potential for increasing the BESS capacity over the value installed in the LEM trial was evaluated for 2 generic capacity upgrade scenarios; +2.5kWh per site (increases fleet capacity by 39%) and +5kWh per site (increases fleet capacity by 78%). Under self-consumption control, only a small proportion of this additional capacity is utilised and no commercial case can be made what so ever to justify the increase. Even when the capacity is monetised as headroom using the arbitrage procedure previously described still produced simple payback periods for the additional capacity that would exceed probably lifetime of systems.

A more persuasive economic case can be made for replacing discrete dwelling BESS with a community-scale system driven by the economies of scale that can be derived from load diversity. Using the confidence limit approach, it was found that a 10% reduction in BESS capacity (with commensurate impact on capital costs) would have <1% reduction on self-consumption value (this relates specifically to the 100-site fleet from these trials; a larger fleet could unlock greater potential for economies of scale). The impact on project economics may be significant, especially when considering the project mobilisation and ongoing support costs, as many 100's or 1000's of sites could be reduced to a single site. Further study is required to optimise any such sizing decisions against loss in headroom and any associated monetisation opportunities.

The impact of BESS on CO_2-equivalent footprint of the dwelling was found to be negative when compared to PV only technology deployment using a simplistic basis of displacing average grid emissions because of round trip efficiency (RTE) of the battery). In a similar vein to Time of Use tariffs, the opportunity for CO_2e arbitrage was explored, but the results clearly demonstrated that such arbitrage is of limited value, and insufficient to outweigh the losses attributable to the current fleet-average RTE of 70%.

Self-consumption operation and headroom dispatch opportunities could be leveraged to address network capacity and generation reliability constraints, allowing zero carbon renewables to be connected (or avoid constraint). When the charging electricity has a CO_2e intensity of zero, the round-trip efficiency is irrelevant from a CO_2e savings perspective; instead, the

BESS should be credited with the annual generation that it enables to be connected to the network, and the attendant displacement of marginal generation (usually at grid emission factors 2-3x higher than current grid average). This aligns with the Green House Gas [GHG] savings methodology for flexibility assets (which applies to CO_2e) discussed in a related LEM publication[1].

It is worth noting that increased RTE is still an important aspiration, as it reduces losses and hence operational and embodied costs (financial, CO_2e and materials) that are associated with generation and network.

[1] "Accounting for GHG Abatement in the Cornwall LEM Project", D. Parish, Centrica PLC, Cornwall Local Energy Market project, 26/10/2020

1. Introduction

In this report, the performance of the Battery Energy Storage Systems [BESS], as deployed during the Cornwall Local Energy Market [LEM] residential workstream is investigated. Based on an investigation of the factors that influence their technical, economic and environmental performance, alternative battery sizing and control approaches are proposed and evaluated.

Several methodologies from Trilemma Consulting Limited's Cost Function Optimised Dispatch [CFOD] suite of energy system optimisation tools are used to assess alternative sizing & optimisation strategies, namely:

- Headroom Quantification - With the existing BESS sizing, quantify the available headroom by season over the 48 settlement periods, assessing the opportunities for price arbitrage to further monetisation surplus BESS capacity (i.e. the headroom)
- Residential BESS Sizing - Upgrade existing BESS on all 100 individual homes to reduce grid export from Production Surplus that cannot be stored with the currently installed BESS capacity
- Community BESS Sizing - Leverage diversity with a community scale BESS that connects to all 100 individual homes under a "Virtual Private Metering" regime

The BESS fleet was predominantly controlled using a PV self-consumption operating strategy during the LEM project. This report provides an analysis of fleet performance under this operating strategy and posits how it may have performed using multi-objective control approaches, complementary to PV self-consumption that were designed to enhance BESS economics.

Unless otherwise stated, the report evaluates BESS performance over a 12-month period, from March 2019 to February 2019 using a combination of minutely and half-hourly datasets as appropriate to the attribute being evaluated. A cohort of the BESS fleet did participate in a frequency response investigation during this period. This performance is not included in this report, and the data used here has been modified to exclude operating behaviour prompted by the frequency response trial.

The report is split into five sections, which cover the aforementioned exploration of current and alternative BESS utilisation:

- Section 2: BESS Utilisation describes different ways in which utilisation can be defined and reports how aspects of BESS capacity and discrete dwelling consumption & PV production influence utilisation under PV self-consumption operating strategy.
- Section 3: Headroom Assessment uses a scenario-based approach to explore how operating strategies, complementary to the PV self-consumption strategy might increase utilisation. In so doing it introduces a methodology for visualizing BESS headroom and use it to describe how capacity retained for PV self-consumption can be released to meet the requirements of different control objectives. The effect of this multi-objective control approach on BESS economics is quantified.
- Section 4: BESS Sizing: Dwelling-Scale uses the outputs from **Sections 2 & 3** to investigate the impact of varying BESS capacity on utilisation and BESS economics.
- Section 5: BESS Sizing: Community-Scale explores how a community-scale BESS might be defined and provides a comparison between its estimated performance and the performance of the aggregated BESS fleet.
- Section 6: BESS CO2 Savings with Time-of-Use CO2 Intensity estimates the CO_2 impact of the aggregated BESS fleet when compared to estimated emissions for dwelling demand and dwellings with PV only.

Comprehensive appendices are provided that contain:

- Appendix A1: Headroom Analysis per Site presents charts, by site and by season, to communicate the available headroom by confidence interval, which complement the fleet-level charts in **Section 3**
- Appendix A2: Headroom Analysis per Sub-Fleet presents charts by BESS Capacity Sub-Fleet and by season, to communicate the available headroom by confidence interval, which complement the fleet-level charts in **Section 3**
- Appendix B1: Time of Use Import Tariff provides a description, with supporting charts, of the retail Time of Use [ToU] tariff used as an example in headroom assessment of **Section 3**
- Appendix B2: Flexibility Pricing provides context of flexibility value by summarising successful flexibility bids, to support the credibility of the simplified headroom value used in the headroom assessment of **Section 3**
- Appendix B3: Wholesale Price Analysis presents charts to support the analysis of the wholesale price data, which was considered when creating pricing scenarios for **Section 3Error! Reference source not found.**
- Appendix C: Economic impact of BESS capacity upgrades presents charts to visualise the economic impact of BESS capacity upgrades at each site, to complement the results presented in **Section 4**

2. BESS Utilisation

2.1 Defining Utilisation KPIs

To investigate BESS utilisation it is useful to define a series of Key Performance Indicators [KPIs}, calculated as per the equations presented in **Table 2-1.** These parameters have been calculated on an annual basis for several bases – namely;

- Site-specific
- BESS Capacity Sub-fleets (5kWh, 7.5kWh & 10kWh)
- Total Fleet (aggregation of 100 sites)

Metric	Calculation
Average Energy Utilisation	= sum(Charge Energy) / Rated Energy Capacity
Average Charge Power Utilisation	= AverageIF(Charge Power, Charge Power >20W) / Rated Charge Power
Average Discharge Power Utilisation	= AverageIF(Discharge Power, Charge Power >20W) / Rated Discharge Power

Table 2-1: BESS Utilisation Key Performance Indicators [KPIs]

BESS energy utilisation considers the annual charge energy compared with an arbitrarily-assumed target of 1 full charge cycle per day for the entire year, i.e. 100% utilisation means on average daily charge energy = rated energy capacity. In reality, a BESS may charge successively for more than 1 full cycle in a day, i.e. utilization can be higher than 100%.

The power utilisation calculations use minutely data, converted and approximated to a uniform power draw in W over each minute. A threshold of 20 W is used, below which the battery is assumed idle (i.e. managing only parasitic losses). The calculation for 'Average (Dis)Charge Power Utilisation' takes the average power during periods when the battery is not idle, dividing this by peak (dis)charge power.

2.2 Relationships

2.2.1 Energy Utilisation

The spread of BESS energy utilisation is shown for each site in **Figure 2-1**, disaggregated by BESS Type (Eco vs Hybrid) and for each type by BESS Capacity (5kWh, 7.5kWh and 10kWh). Utilisation factor tends to be higher in lower capacity BESS systems, but there are a significant number of sites anomalous to this trend. Over the entire year, under PV self-consumption control, no site reached 100% utilisation. It is interesting to reflect this finding against the description of BESS lifetime that underpin the warranty conditions. These state that lifetime is given by earliest point at which BESS reaches 10,000 cycles (where 1 cycle = full charge and full discharge) or 10 years. Clearly, residential BESS operating under self-consumption control would always exit warranty period based on the 10-year criteria based on this performance.

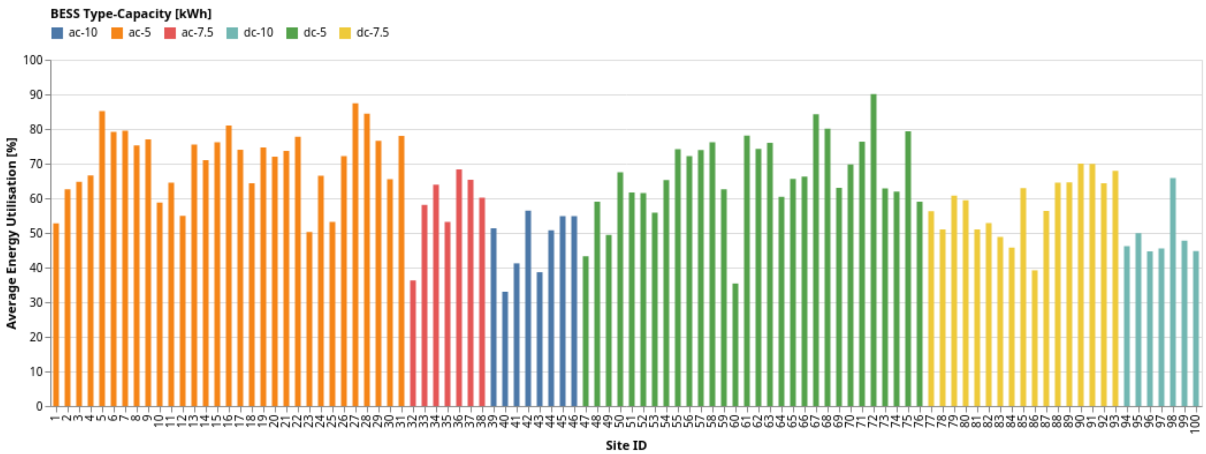


Figure 2-1: BESS Energy Utilisation [%] across all sites

That energy utilisation is not only a factor of BESS capacity can be explained by considering production surplus, i.e. that proportion of PV production not used instantaneously by the dwelling **(Figure 2-2**). As expected, a positive trend exists between production surplus and BESS energy utilisation. Since low production deficit, i.e. incidence where PV output does not meet total demand of the dwelling, tends to be coincident with high production surplus it is also a determinant of BESS energy utilisation (**Figure 2-3**). However, a balance between these two conditions does occur which is evident from the heat maps shown in **Figure 2-4**. Low levels of production surplus accompanied by high levels of production deficit results in lower BESS energy utilisation. This was displayed in both Eco and Hybrid BESS.

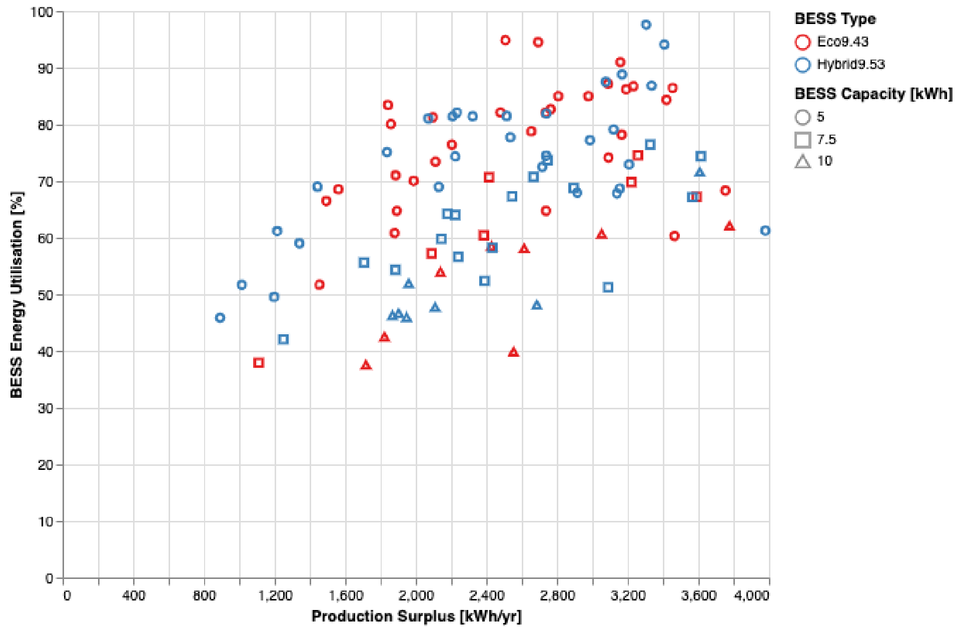


Figure 2-2: Effect of production surplus on BESS Energy utilisation

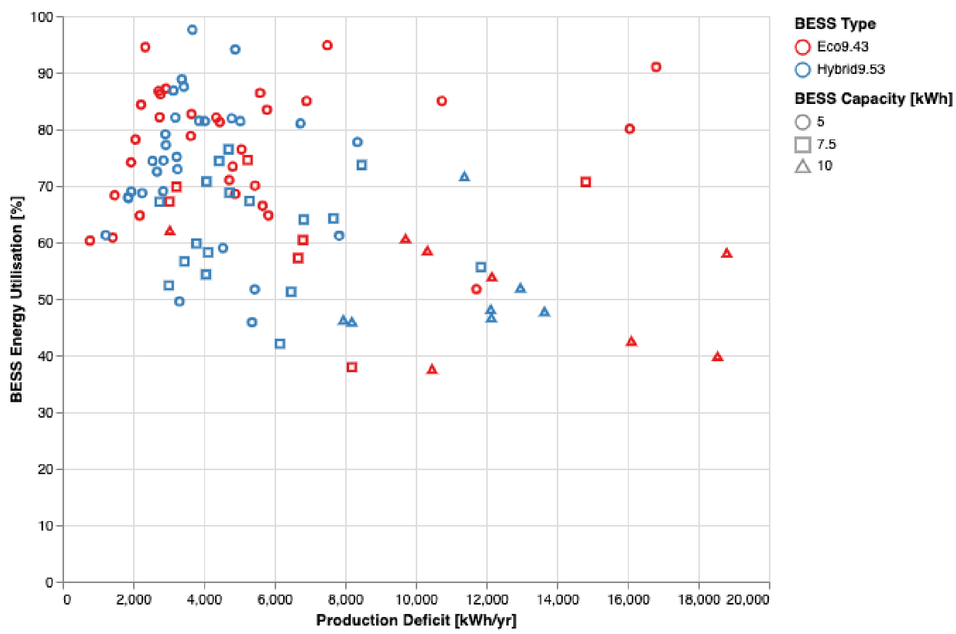


Figure 2-3: Effect of production deficit on BESS Energy utilisation

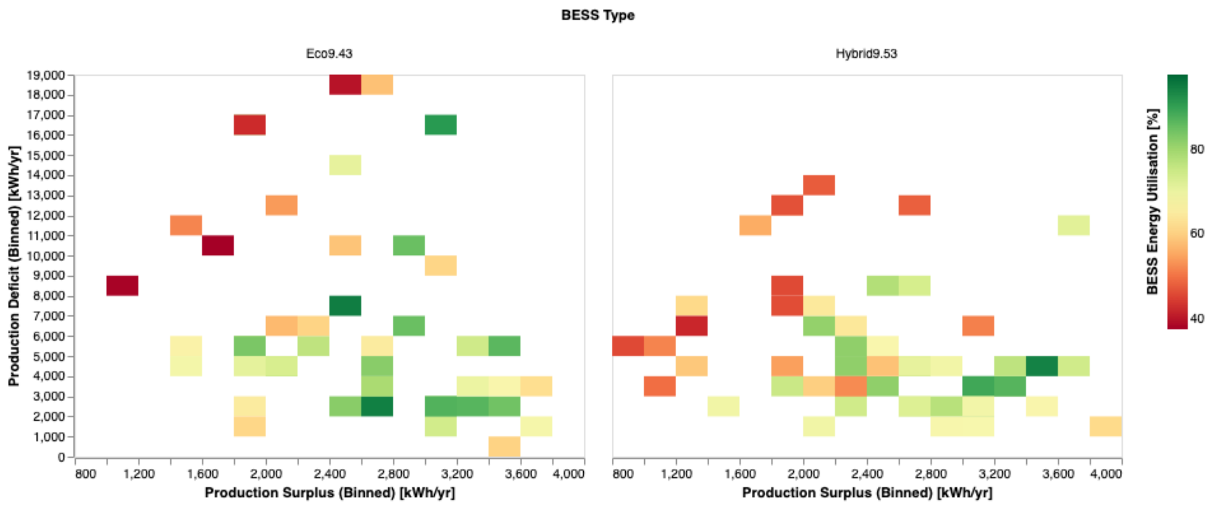


Figure 2-4: Production surplus vs production deficit expressed as BESS utilisation heat map

2.2.2 Power Utilisation

At a site level, BESS power utilisation for charge and discharge does not show the same weak trend associated with BESS capacity (**Figure 2-5** & **Figure 2-6**) as displayed by energy utilisation. Average charge utilisation is higher than discharge utilisation, reflecting the myriad of low power demand events that can occur in a dwelling. In addition to creating a high incidence of low power discharge events, it also creates the opportunity for higher power surplus (and higher charge utilisation) during periods of PV production.

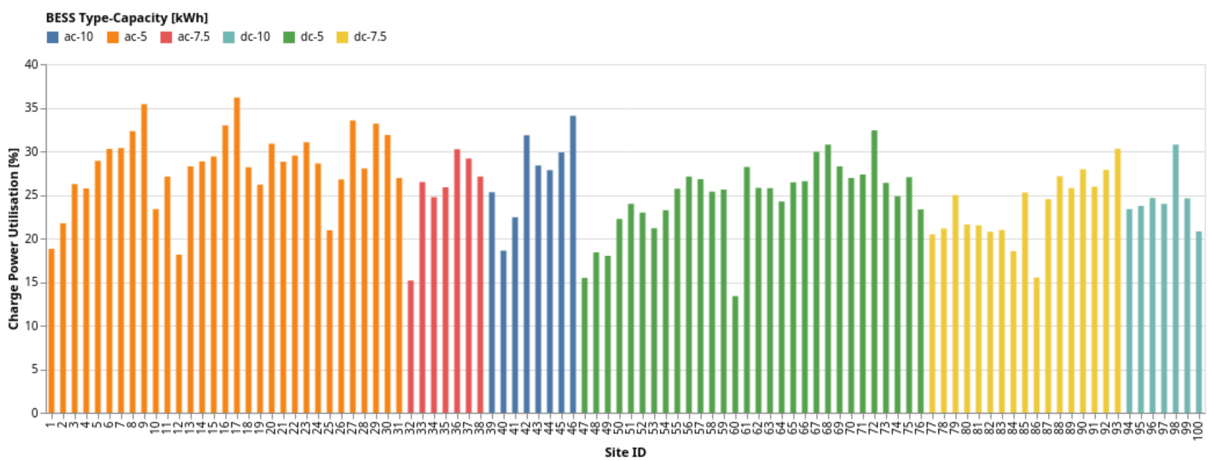


Figure 2-5: Average charge utilisation across all sites

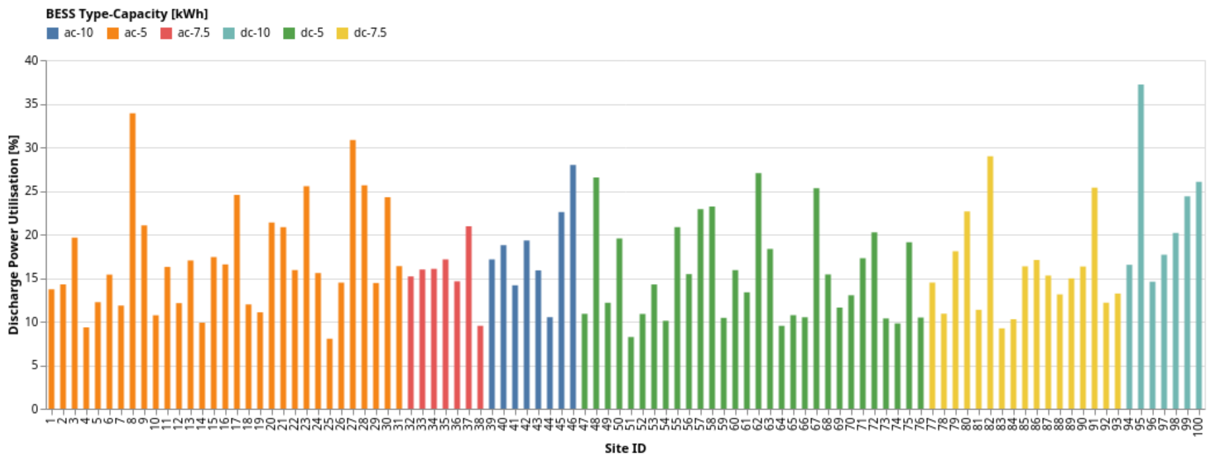


Figure 2-6: Average discharge utilisation across all sites

A weak trend is found between annual production surplus and charge power utilisation (**Figure 2-7**). This reflects the likelihood, rather than certainty that higher production surplus is accompanied by higher average surplus power. A similar weak trend is found between annual production deficit and discharge power utilisation (**Figure 2-8**). Reductions in these annual utilisation indices caused Round Trip Efficiency [RTE] to fall. This implies that their impact would be compound, i.e., those sites with low charge and discharge utilisation would have the lowest RTE.

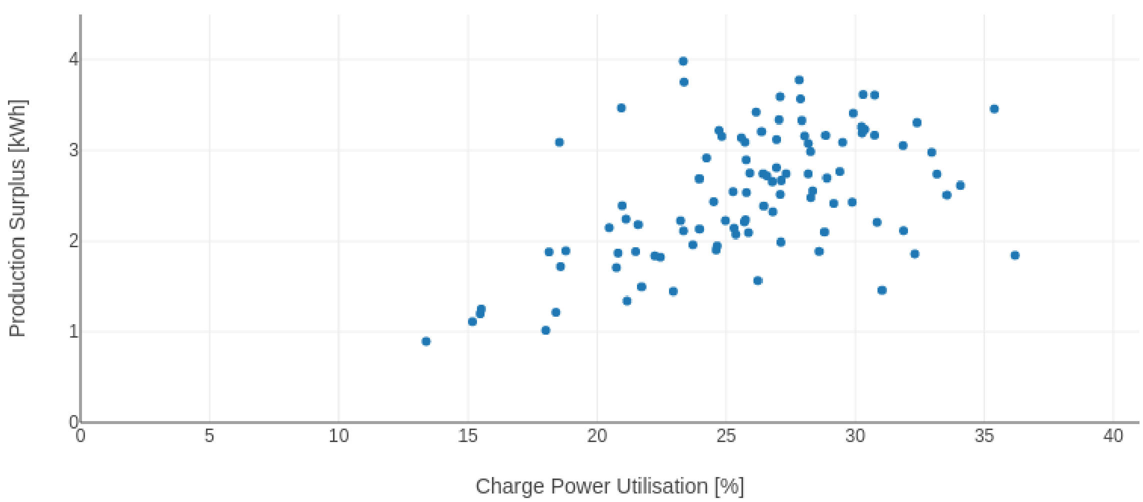


Figure 2-7: Relationship between charge power utilisation and production surplus

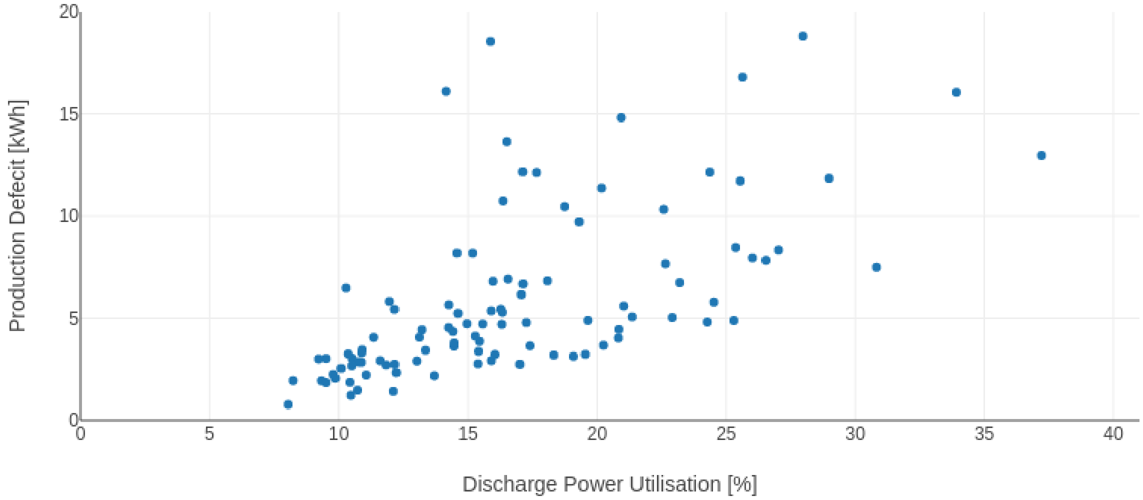


Figure 2-8: Relationship between discharge power utilisation and production deficit

2.3 Impact on Round Trip Efficiency [RTE]

Neither of BESS energy utilisation, level of PV production and level of production surplus were found to have an impact on RTE (see **Figure 2-9** and **Figure 2-10**). Rather, RTE was found to be a function of charge and discharge utilisation: sites with a lower charge/discharge utilisation resulted in lower RTE (see **Figure 2-11** and **Figure 2-12**). This raises both a control and a site/technology applicability question with respect to BESS deployment. From a control perspective there is likely to be a power cut off point on both charge and discharge cycles, below which it would be energy literate to permit grid spill/import. This would protect the RTE of the BESS, reducing losses. There will be a balance point for a given BESS technology as to where this cut off point might be and this may be something that could be usefully evaluated through a data-led AI approach after system has been installed.

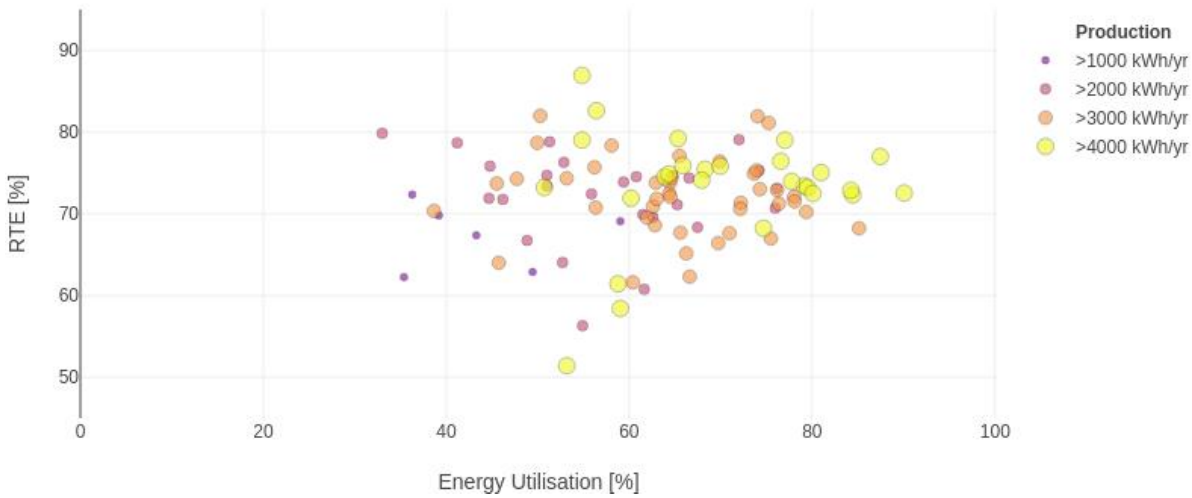


Figure 2-9: BESS Energy utilisation against Round Trip Efficiency (RTE) for all individual sites disaggregated by level of PV production

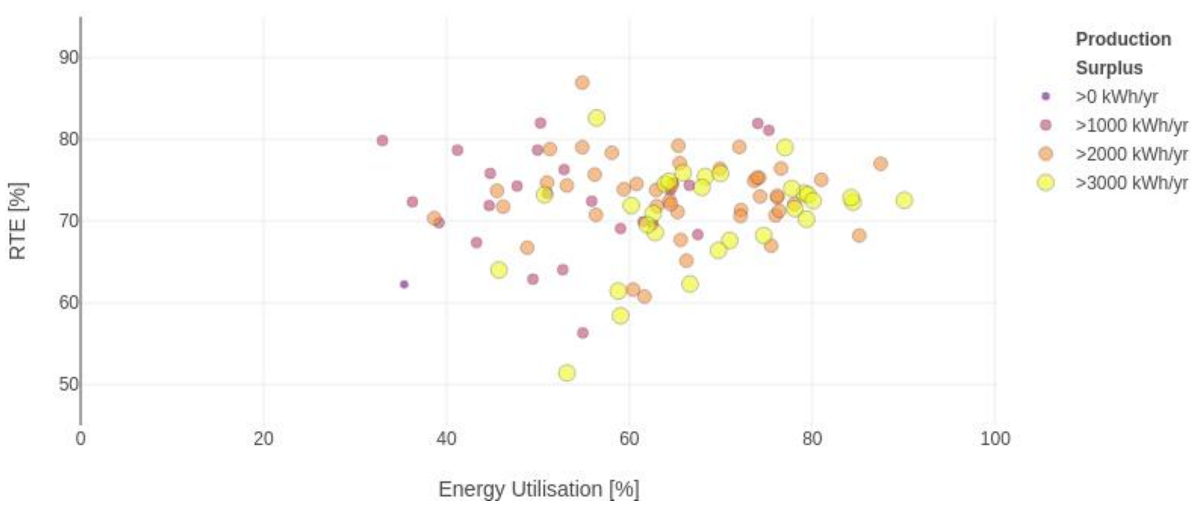


Figure 2-10: BESS Energy utilisation against Round Trip Efficiency for all individual sites disaggregated by level of production surplus

From the perspective of site/technology applicability, sites with either/and low PV capacity or low annual demand and no major power loads are likely to result in a higher proportion of low charge/discharge power cycles (see **Figure 2-11** and **Figure 2-12)**. However, as has been seen in the meta-data report these site conditions are not guaranteed to result in this outcome, and the observation should be considered more as a rule of thumb or a way of ordering installation preferences rather than a hard and fast rule.

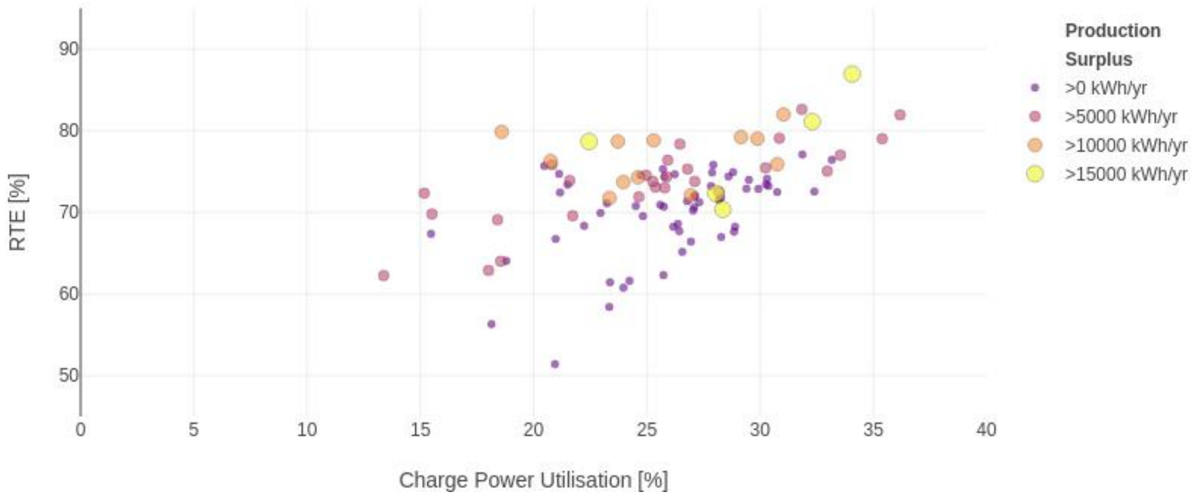


Figure 2-11: BESS Charge Power utilisation against Round Trip Efficiency for all individual sites disaggregated by level of production surplus

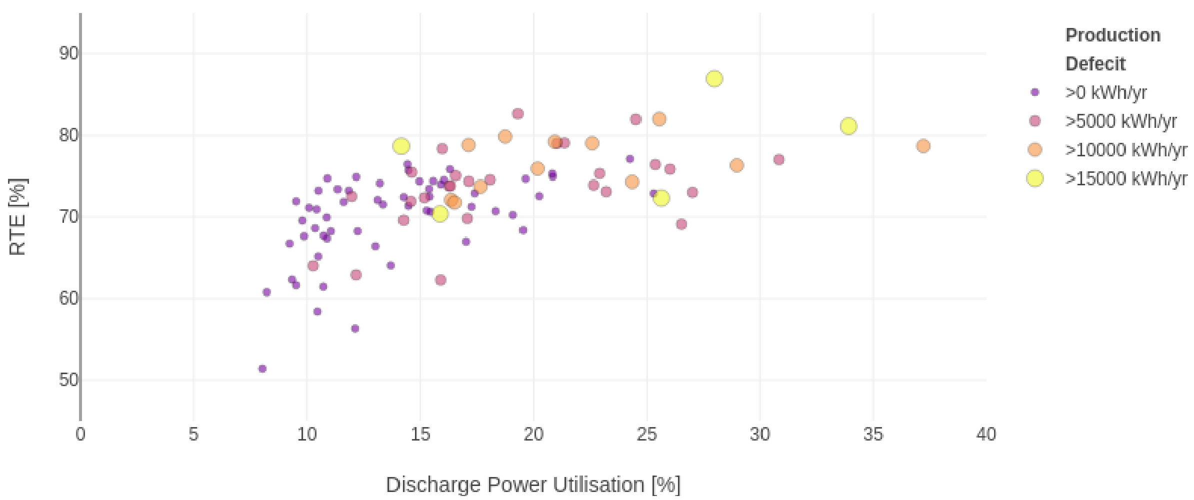


Figure 2-12: BESS Discharge Power utilisation against Round Trip Efficiency for all individual sites disaggregated by level of production surplus

3. Headroom Assessment

3.1 Methodology

3.1.1 Description of Headroom

The term *headroom* is defined here as the residual BESS energy capacity that has not participated in PV self-consumption. The purpose of assessing headroom is to reflect that PV self-consumption can only ever utilise a proportion of total BESS capacity, concentrated in the summer and to a lesser extent the shoulder season. This stranded capacity represents an economic opportunity that could be accessed if appropriate market conditions exist and alternative BESS control approaches capable of accessing this value opportunity are developed. In this manner, BESS control would be multi-objective, allowing it to access both self-consumption and headroom market opportunities. Occasions may arise where BESS economics would be better served by eschewing PV self-consumption in favour of directing additional capacity to meet the headroom value opportunity. In a full simulation of BESS performance, this could be managed by optimising multi-objective control in each time stamp to maximise revenues in that time stamp and in future time stamps within a plausible forecast horizon. Creation of a modelling environment to permit this level of complexity to be simulated was beyond the scope of this analysis.

Rather, a more iterative approach was developed here based on use of a probability function (defined here as a confidence level, CL). This determined the likelihood that headroom capacity would be available in a BESS at any given time. Using this approach, a minimum BESS capacity over a 24-hour period (BLH_{24h}) that might be reserved as headroom can be quantified. To describe this further, consider the headroom analysis of the whole 10kWh BESS fleet during the winter season (**Figure 3-1**). By setting CL = 99%, control is directed to place primacy on collection of production surplus (within power constraints). This requires that 60% of BESS capacity is made available to ensure that all production surplus is collected during the afternoon, effectively reducing the headroom capacity to 40%. If CL was reduced to 95%, the available headroom is increased from 40% to 60%, this released by allowing the energy represented by the shaded area between the 95 and 99% CL lines to be exported rather than used to charge to BESS. In this manner, it is possible to discretise BESS capacity that is assigned to self-consumption and headroom. This can be continued until CL = 1%, where in the winter time <5% of BESS capacity is now participating in self-consumption. However, in the summer this reduction of CL = 1% only results in c50% of the BESS capacity being released as headroom, an increase from c5% when self-consumption is prioritised. A clear relationship can be demonstrated between headroom availability and CL using the BLH_{24h} disaggregated by BESS capacity and each season (**Figure 3-2**). Here, the reserve capacity refers to that value required for self-consumption operation and available to headroom.

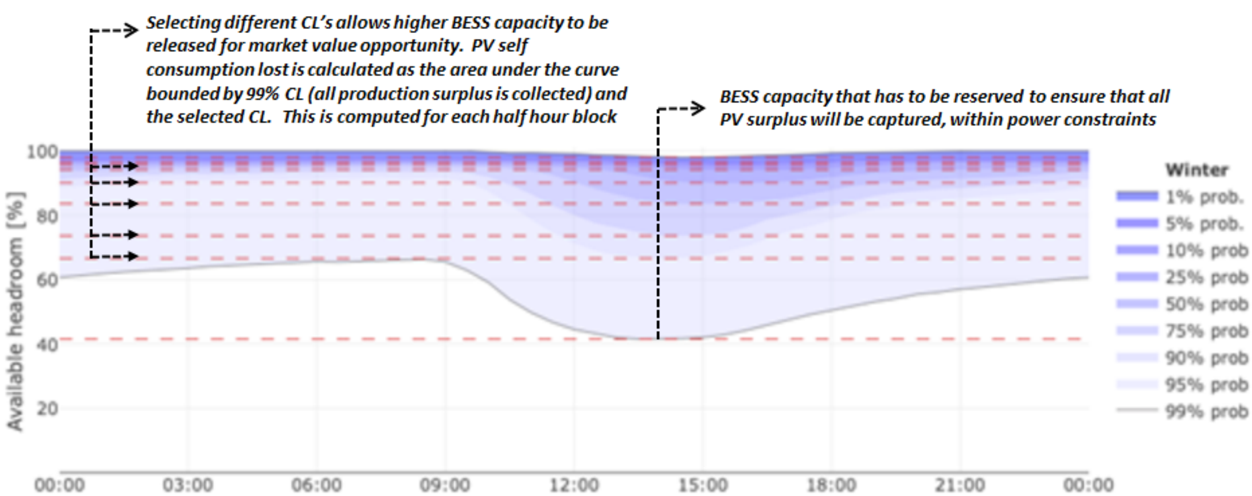


Figure 3-1: BESS headroom for the fleet during winter period showing confidence limits for reserving capacity for arbitrage

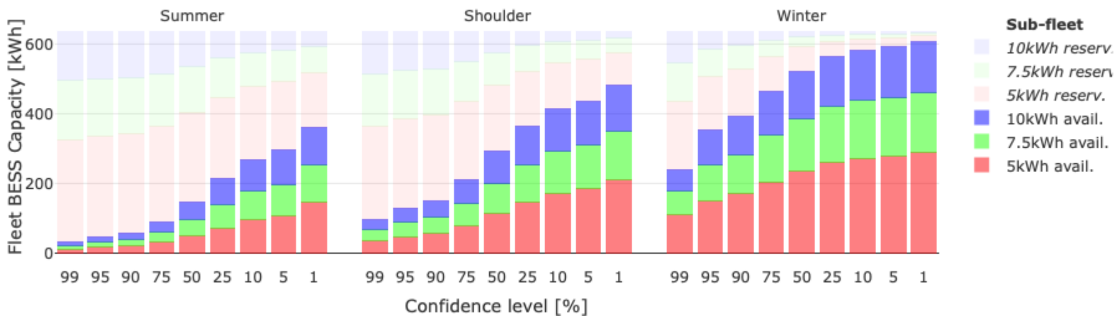


Figure 3-2: 24h Base-Level Headroom (BLH_{24h}), all seasons, all Confidence Levels (CLs), by sub-fleet

3.1.2 Method of Quantifying Headroom

Headroom was quantified at a temporal precision of 30 minutes, i.e. the unused BESS capacity in each half hour block after PV self-consumption has been accounted for dependant on the selected CL. To simplify its visualisation, headroom has been expressed as an average daily, half hourly time series for three designated seasons; namely summer (May-Aug), winter (Nov-Feb) and shoulder (Mar, Apr, Sept & Oct). Available headroom was net of RTE losses which were assumed to be constant at the average value returned for each site from analysis of self-consumption operation. Average headroom graphs for each site in each season are shown in **Appendices A1 & A2**.

3.1.3 Method of Assessing Market Opportunity

Future trading arrangements for an aggregated BESS Fleet are likely to involve response to a basket of dynamic market conditions and contracted positions. These may for instance include management of the BESS fleet to provide charge/discharge capacity to meet distribution network services and/or to ensure adequate reserve capacity is available to service contracts secured in ancillary market. The economic value of these different positions is fluid, difficult to derive with confidence and subject to substantial change in the near term as markets evolve to meet the pace of the low carbon transition.

An approach has been followed here that quantifies the economic value of BESS based on arbitrage opportunities revealed by using a public-domain dynamic time of use tariff (ToU) dataset (details of which are provided in **Appendix B1**). Based on ToU tariff fluctuations present in the dataset, four arbitrage windows were identified. These constituted two discharge periods, morning and evening and two charge opportunities, afternoon and night. The economic value of the different permutations of these arbitrage opportunities varies throughout the day and throughout the season (**Table 3-1**).

The realisation of these arbitrage values assumed that a Virtual Private Metering (VPM) model was in operation, permitting energy to be shuttled between meter points. As such, all BESS discharge was assumed to be used either in the discrete dwelling or elsewhere with negligible grid losses. Nominal charges between metering points that might be expected in a VPM arrangement of this type were ignored in this assessment. The output of an analysis of published data describing the economic value of contracted flexibility services in distribution networks is shown in **Appendix B2**. This was conducted to sense check the range of value ascribed to arbitrage in this assessment. In this context, the range from £2/MWh - £88/MWh shown in **Table 3-1** appear to be consistent with the values described in **Appendix B2** and can be used to credibly investigate the value opportunity available to BESS headroom.

Arbitrage Time Window	SUMMER	SHOULDER	WINTER	AVERAGE
Night to Morning	£ 0.002	£ 0.004	£ 0.004	£ 0.003
Afternoon to Evening	£ 0.073	£ 0.076	£ 0.076	£ 0.075
Night to Evening	£ 0.084	£ 0.088	£ 0.088	£ 0.087

Table 3-1: Net value (£/kWh) for arbitrage performed between different periods of the day disaggregated by season

A modelling approach was adopted to determine the maximum value that could be attained using these arbitrage windows constrained by the CL selected in each run of the model. Consider for instance daily average winter season headroom and CL map for a given site where these arbitrage windows are visible (**Figure 3-3**). For this candidate day, the maximum arbitrage opportunity involves charge during the night and discharge during the evening period.

The maximum overnight charge potential is governed by the minimum headroom available for a given CL choice; if CL is set to 99% for instance then the maximum headroom available for charge during the night-time window is 70%. However, it is not possible to access all this headroom. It is constrained by the minimum headroom that has to be made available during the afternoon period to accommodate production surplus, set by the CL level. This 'pinch-point' is therefore the determinant feature of arbitrage opportunity for a given CL and its influence is more acute in the summer for sites where BESS was appropriately sized (rather than over-sized). Opportunities exist for charging overnight to a value higher than this afternoon constraint to discharge the BESS during the morning window. Similarly, charging opportunities during the afternoon period above that delivered by production surplus may also occur to boost the capacity available for discharge during the evening window. The charge headroom in the night-time period is therefore a sum of these constrained, subsequent discharge–charge–discharge opportunities up to the maximum night-time charge level set by the CL choice.

These constraints and opportunities are calculated and a fiscally optimum charge/discharge schedule defined for a given BESS for each season, where the season is represented by an average day. These values are then multiplied and summed to quantify the annual arbitrage opportunity for each dwelling, and then summed to provide fleet level data.

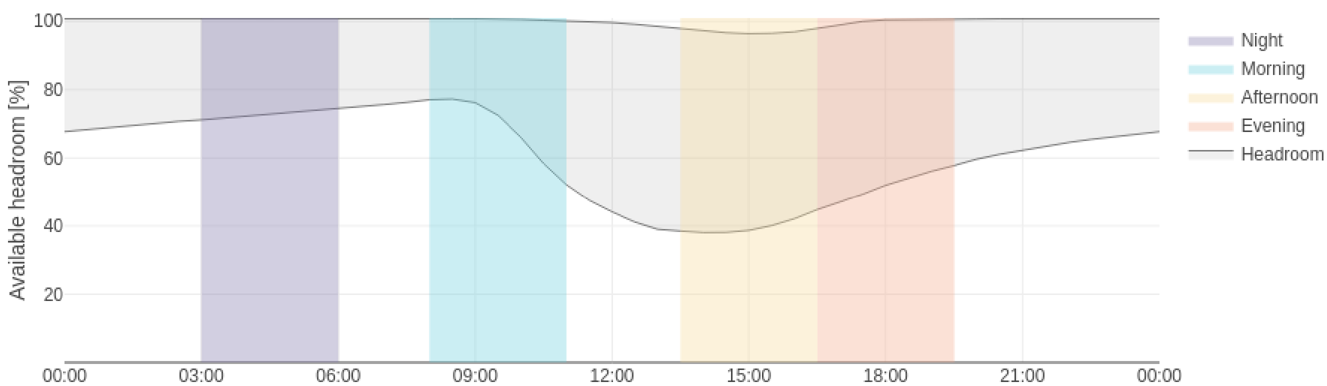


Figure 3-3: Time period opportunities for arbitrage: Night (03:00-06:00), Morning (08:00-11:00), Afternoon (13:30-16:30), Evening (16:30-19:30)

3.1.4 Power constraints for arbitrage

The rate of charge and discharge is governed by the power constraints at the various BESS sizes (**Table 3-2**). This places an additional constraint on arbitrage opportunity as all charging and discharging operations have to be located within the time windows shown in **Figure 3-3.** For example, discharge to maximise arbitrage opportunity in the evening block must take place in the 3-hour period between 16:00 and 19:00.

BESS Energy Capacity [kWh]	BESS Power Capacity [kW]	Quickest possible discharge
5 kWh	2.5 kW	2 hrs
7.5 kWh	3.3 kW	2 hrs and 16 min
10 kWh	3.3 kW	3 hrs

Table 3-2: Discharge time governed by BESS capacity and Power output during discharge event

3.2 Headroom Results with Existing LEM Sizing

Headroom capacity for the entire BESS fleet is heavily influenced by season, as might be expected (**Figure 3-4**, **Figure 3-5** & **Figure 3-6**). BESS headroom capacity available if control is determined to maximise available self-consumption was found to be 5%, 17% and 39% for the summer, shoulder and winter season respectively. However, time period over which the maximum self-consumption capacity is required is relatively short due to large daily and seasonal variance of production surplus. As a consequence, relatively large BESS capacity can be released for headroom with limited impact on self-consumption utilisation. In the summer season for instance, altering CL from 99% to 95% releases an additional c12% of headroom capacity in return for c3% reduction in self-consumption. Although outside the scope of this project, it is possible to envisage how this CL approach can be used dynamically in conjunction with forecasts of production, consumption and headroom value to dynamically set headroom capacity on a daily or intra-day basis to economically optimise BESS revenue.

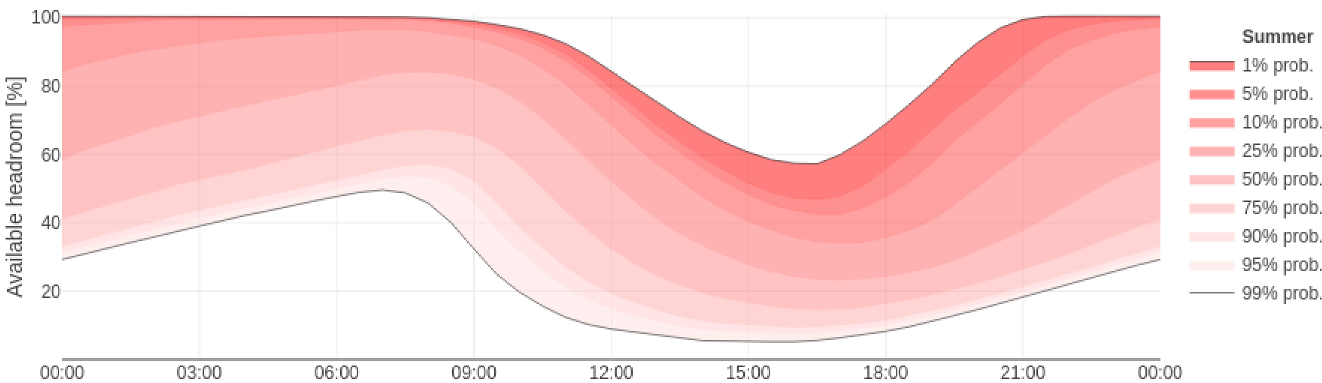


Figure 3-4: Headroom throughout the fleet, summer season daily pattern with respect to Confidence Level

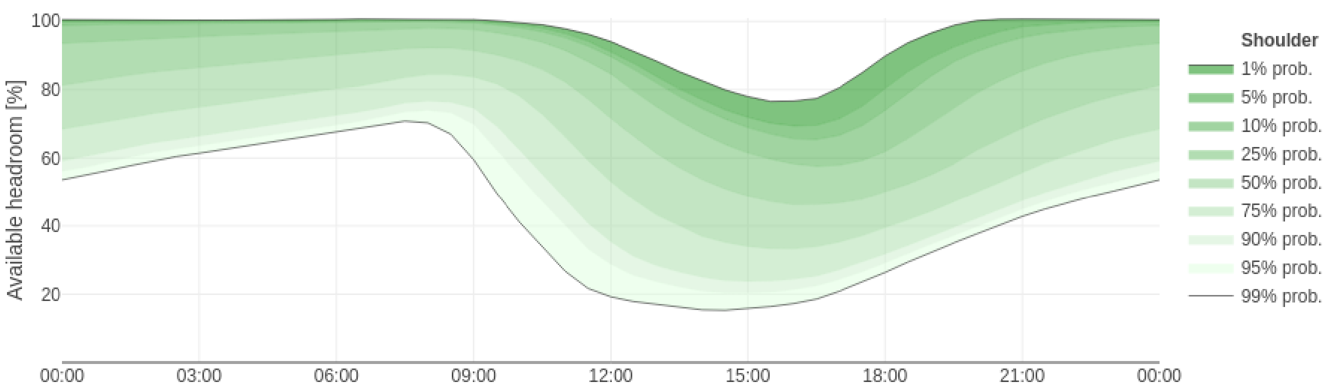


Figure 3-5: Headroom throughout the fleet, shoulder season daily pattern with respect to Confidence Level

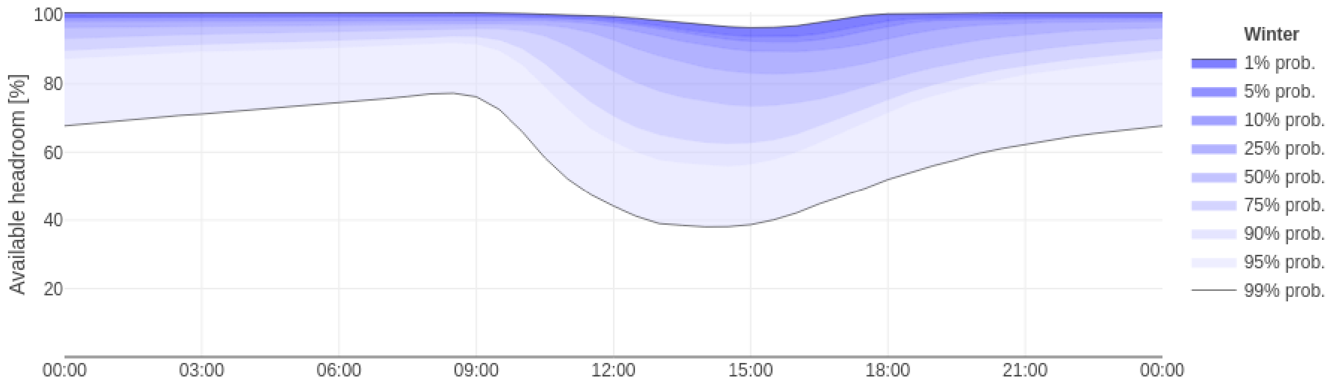


Figure 3-6: Headroom throughout the fleet, winter season daily pattern with respect to Confidence Level

The impact of selection of CL on the BESS utilisation that is assigned to headroom, disaggregated by its use in the different arbitrage time windows is shown in **Table 3-3**. The proportion of headroom ascribed to each time window varies, governed by a reduction in the constraint imposed in the afternoon window that throttles the capacity that can be assigned to the night to evening window. As this 'pinch-point' is reduced, by lowering CL increased high value opportunity is made available and the proportion of headroom ascribed to other windows relative to the night to evening window is reduced as the computation seeks the highest revenue. Total values of headroom higher than 100% appear as opportunities exist to charge in the afternoon, after morning discharge; this resulting in more than one charge/discharge cycle being operated during a 24-hour period. The point at which headroom saturates is reached more quickly in the winter season as relaxation in CL level has a more immediate impact due to lower levels of production surplus. This value does not reflect total utilisation, only headroom, and in each case shown a proportion of the BESS capacity is always retained to capture production surplus.

SUMMER	99	95	90	75	50	25	10	5	1
Night to Morning	29%	40%	42%	46%	56%	62%	59%	56%	45%
Afternoon to Evening	3%	2%	2%	1%	0%	1%	5%	8%	11%
Night to Evening	5%	7%	9%	14%	22%	33%	40%	44%	54%
Total	37%	49%	53%	61%	78%	96%	99%	108%	110%
SHOULDER									
Night to Morning	51%	48%	47%	47%	45%	41%	36%	33%	26%
Afternoon to Evening	9%	7%	7%	5%	4%	4%	8%	10%	12%
Night to Evening	14%	19%	22%	31%	43%	55%	63%	66%	74%
Total	74%	74%	76%	83%	92%	100%	107%	109%	112%
WINTER									
Night to Morning	37%	36%	31%	23%	16%	10%	8%	7%	5%
Afternoon to Evening	13%	15%	12%	7%	4%	4%	4%	4%	4%
Night to Evening	37%	54%	60%	71%	81%	88%	91%	93%	95%
Total	87%	105%	103%	101%	101%	102%	103%	104%	104%

Table 3-3: Impact of selected CL on the proportion of headroom assigned to each arbitrage window disaggregated by season, fleet view

3.3 Earning Potential with Existing LEM BESS Sizing

The results in **Figure 3-7** were calculated using fleet-level results; as such the confidence limits on the x-axis include the diversity associated with varying demand profiles, solar PV generation performance, and BESS energy capacity; as would be expected from a Virtual Power Plant [VPP]. The results estimate earning potential per kWh of fleet-wide (i.e. VPP) BESS charging energy capacity, disaggregated by both season and arbitrage time windows.

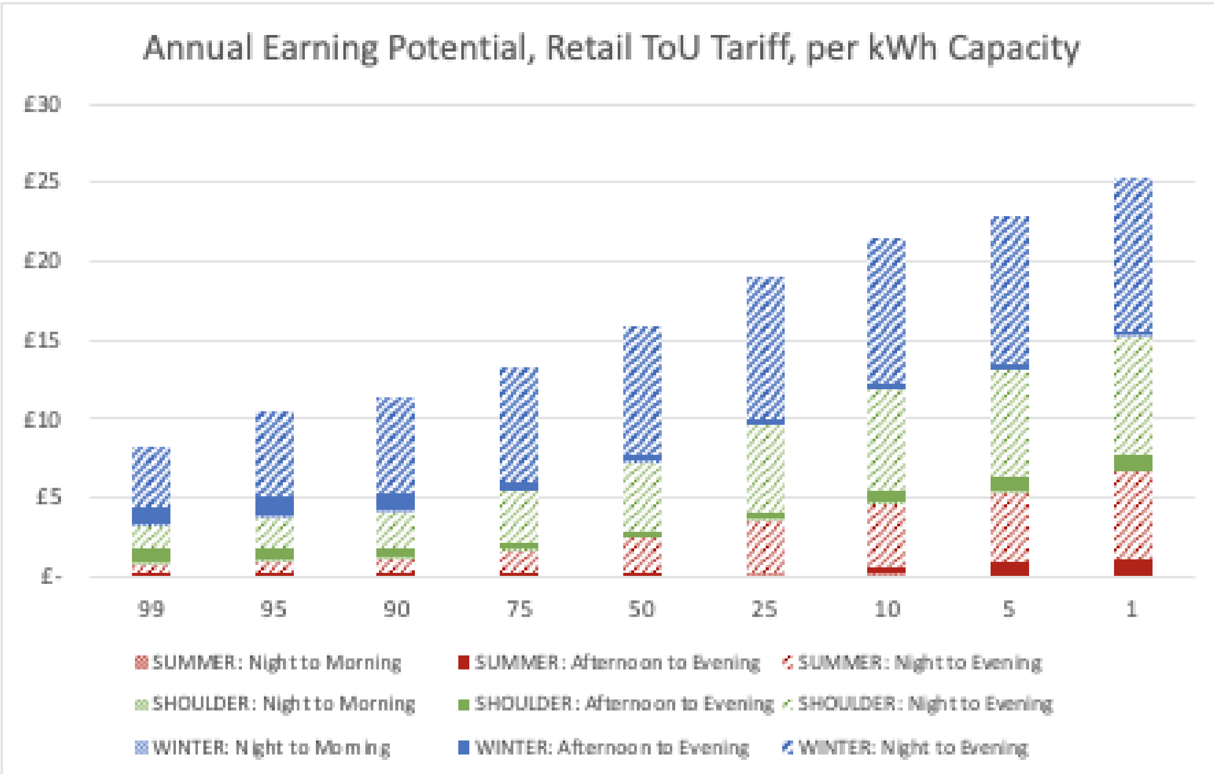


Figure 3-7: Impact of CL selection on revenue stack from arbitrage opportunity, per kWh of BESS capacity

The economic value of arbitrage can be quantified at fleet level by considering the entire 635kWh of installed BESS capacity used in the LEM residential trial, as presented in **Table 3-4**. As the CL level falls, the proportion of BESS capacity that is reserved for self-consumption falls resulting in higher proportions of production surplus being exported from the dwelling to the grid. As a consequence, the fleet revenue from self-consumption (approximately £10k at 99% CL) will fall, replaced by increasing arbitrage revenue. This £10k value can be compared with the £11.3k value at 1% CL, where self-consumption has been reduced to the lowest contribution considered here (c15% of its maximum value). Computing a balance point where multi objective control, rather than singular control is economically advantageous is made difficult as the relaxation in capacity reserved for self-consumption does not apply for every day. It is rather based on the maximum self-consumption opportunity in any half-hour window. CL relaxation will therefore only have an impact on a certain number of days. Computing the balance point was beyond the scope of this analysis and requires an optimised modelling approach involving half-hourly dataset for each site to be constructed. However, at an average level it is evident that supressing self-consumption to <30% of its maximum utilisation to allow maximum headroom opportunity is capable of more than doubling the revenue opportunity of the BESS.

Energy Capacity [kWh]	99	95	90	75	50	25	10	5	1
635 *As Installed*	£5,239	£4,725	£5,087	£5,947	£7,126	£8,463	£9,617	£10,237	£11,323

Table 3-4: Impact of CL selection on the aggregated arbitrage value ascribed by the LEM fleet

4. BESS Sizing: Dwelling-Scale

4.1 Sizing Strategy

In **Section 2**, the impact of increasing system capacity on BESS economics is investigated using self-consumption and multi-objective control. Based on the scenarios introduced in **Section 3**, two sizing upgrade strategies were investigated; namely upgrading all BESS systems by 2.5kWh and by 5kWh to arrive at the distribution of systems and overall fleet capacity shown in **Table 4-1**.

BESS System Capacity (kWh)	Deployed Original LEM trial	Deployed 2.5kWh upgrade	Deployed 5kWh upgrade
5.0	61		
7.5	24	61	
10.0	15	24	61
12.5		15	24
15.0			15
Total fleet capacity (kWh)	635	885	1135

Table 4-1: System Upgrade details

The calculations for this study do not account for power flow constraints. This daily calculation assumes that up to 2.5kWh or 5.0kWh, depending on the sizing strategy can be removed from daily export from the dwelling (in kWh) and released to defer grid import subject to the average RTE that has been calculated for the candidate site. This additional self-consumption - the Spare Potential Self-Consumption (SPSC) - is taken as the total daily export energy in kWh ($export_{24h}$), up to the maximum of the upgrade, i.e.,2.5kWh (or 5.0kWh). This is evaluated as in Equation (1).

$$\text{SPSC} = min\{export_{24h}, [2.5,5.0])$$

Equation 1: Spare Potential Self-Consumption, due to counterfactual BESS size increases of 2.5 or 5.0kWh(cap.)

Two costs adjustments were considered:

1. The lost revenue due to the reduction in export, which is re-directed to BESS charge
2. The reduction in import cost due to additional charge

The combined effect of these two cost adjustments is captured in Equation (2). The cost saving also accounted for the RTE by applying the discrete average RTE for a BESS installed on the candidate site to the SPSC discharge capacity. For instance, where SPSC = 1.0kWh, 1.0kWh of export revenue is lost at 5.5p/kWh. If the site RTE was found to be 80%, the reduction in grid import ascribed to SPSC would be 0.8kWh at 15p/kWh)

$$\text{Total savings due to BESS upgrade} = \text{SPSC} \times \eta_{\text{RTE}} \times £_{import} - \text{SPSC} \times £_{export}$$

Equation 2: Total savings due to counterfactual BESS size increases of 2.5 or 5.0kWh(cap.)

4.2 Site-Level Results

4.2.1 Impact on Charge/Discharge and BESS Energy Utilisation

The maximum additional charge throughput that is available at each site under each upgrade scenario is 912.5kWh and 1825kWh for the 2.5kWh and 5kWh scenario respectively. This assumes that accessing this additional capacity is capped at 1 cycle per day. This maximum additional throughput is constrained by availability of production surplus (charge) and production deficit (discharge).

The extent to which this additional capacity was accessed varied considerably throughout the dwelling fleet, ranging for the 2.5kWh system upgrade between 15 and 620kWh **Figure 4-1**); for the 5kWh upgrade this was 17 and 1120kWh (**Figure 4-2**). It is perhaps instructive to consider the usefulness of this additional capacity from the perspective of the additional discharge (**Figure 4-3** and **Figure 4-4**) and in terms of the charge utilisation (**Figure 4-5** and **Figure 4-6**). No site fully utilises additional capacity for self-consumption with only four sites achieving values in the 60-70% range on the 2.5kWh upgrade. Incidence of low utilisation was more common with 35 sites utilising the additional 2.5kWh by less than 30%. As expected, the utilisation of the 5kWh upgrade was lower than that of the 2.5kWh upgrade with 50 dwellings utilising the additional capacity by less than 30%.

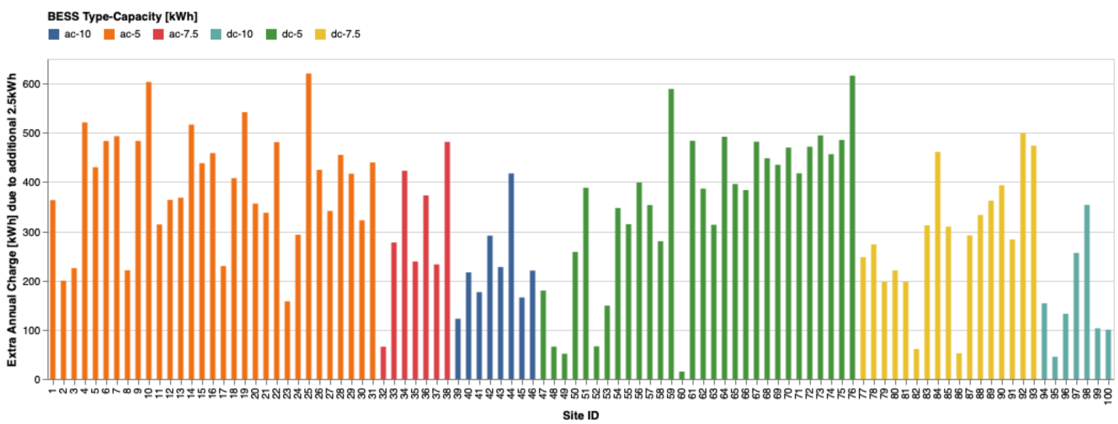


Figure 4-1: Extra annual charge, due to BESS size increase (2.5kWh)

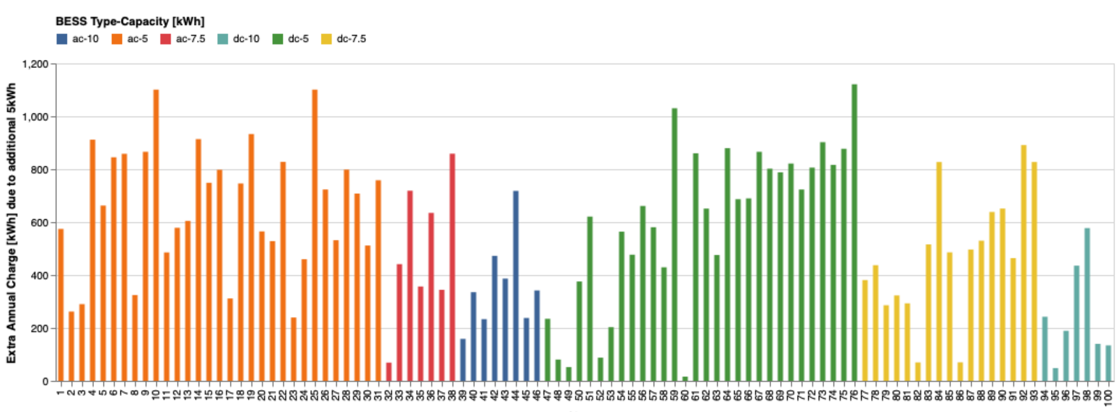


Figure 4-2: Extra annual charge, due to BESS size increase (5kWh)

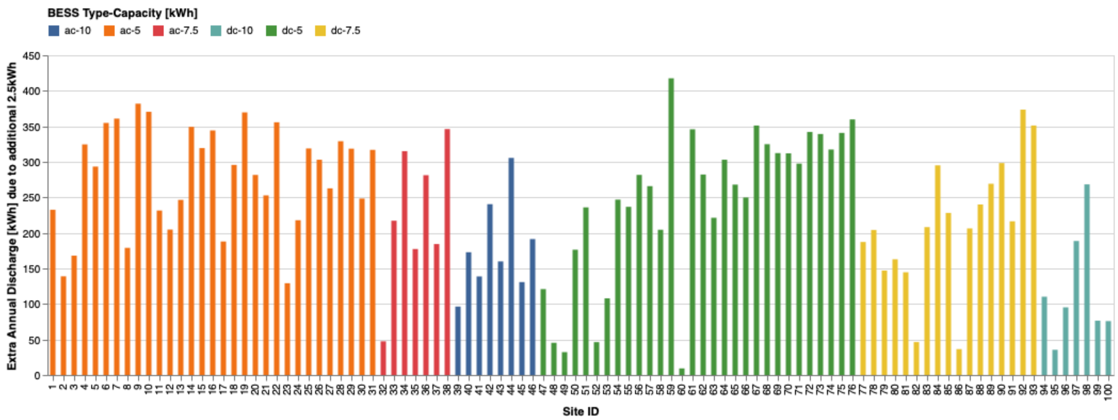


Figure 4-3: Extra annual discharge, due to BESS size increase (2.5kWh)

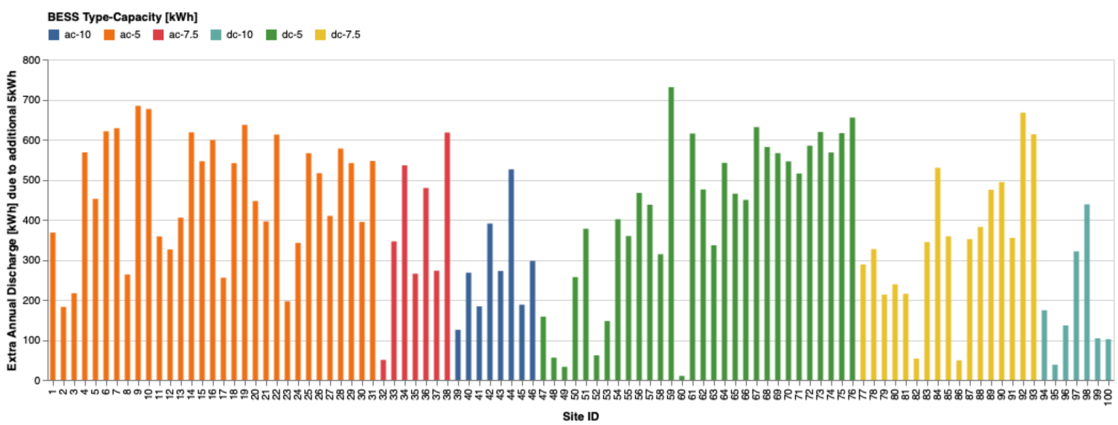


Figure 4-4: Extra annual discharge, due to BESS size increase (5kWh)

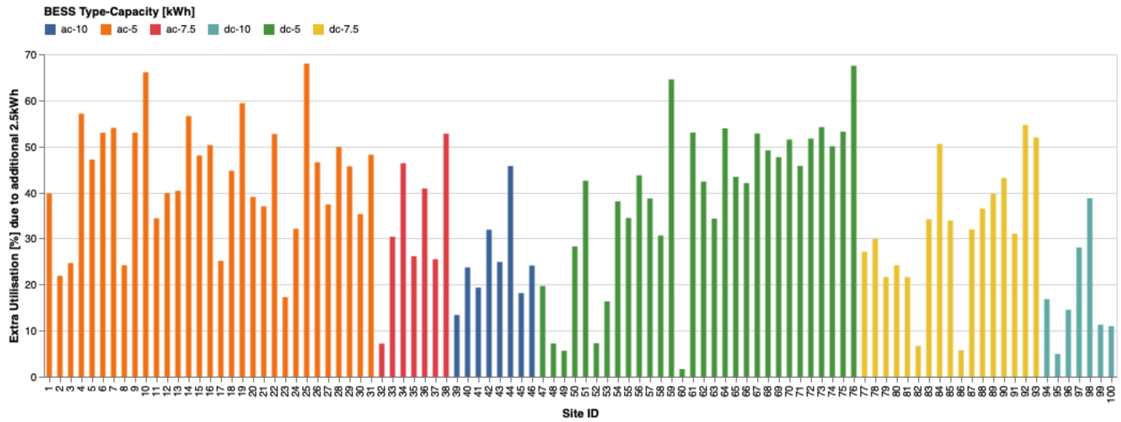


Figure 4-5: Utilisation of additional BESS capacity (2.5kWh upgrade)

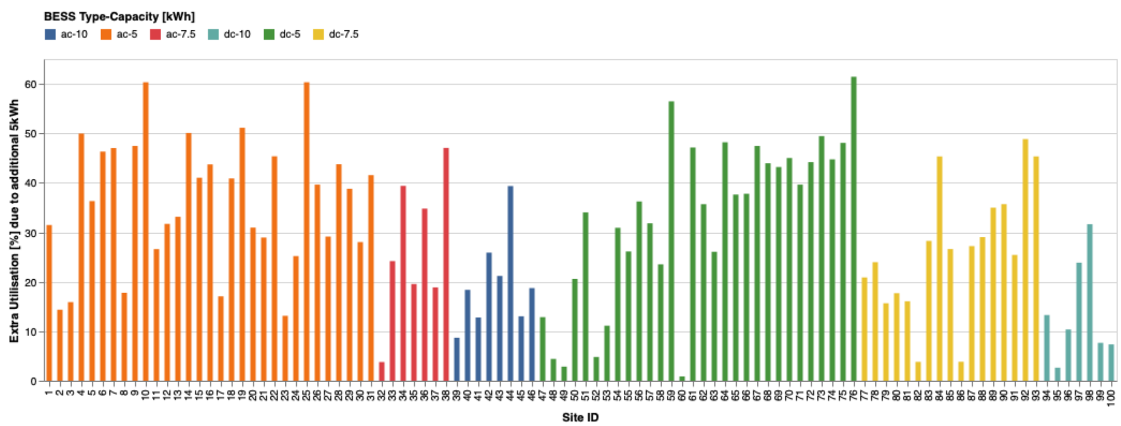


Figure 4-6: Utilisation of additional BESS capacity (5kWh upgrade)

4.2.2 Impact on Grid Import/Export

The impact of upgrading BESS on dwelling electricity import from the grid is relatively slight (**Figure 4-7**). Even in those sites where utilisation of additional capacity would be high (>70%) the resultant deferral of grid import was below 10% of dwelling electrical demand. Surveys conducted before and during the trial identified achieving grid independence as being a primary motivation for many of the participants. The limited impact that provision of additional BESS capacity has on reducing dwelling grid imports can be provided as a cautionary tale to debunk likelihood of autarky. The additional capacity was able to capture a greater proportion of grid export, i.e. production surplus (**Figure 4-8**). However, on larger PV systems, significant proportions of export still persisted, even when 5kWh upgrades were considered.

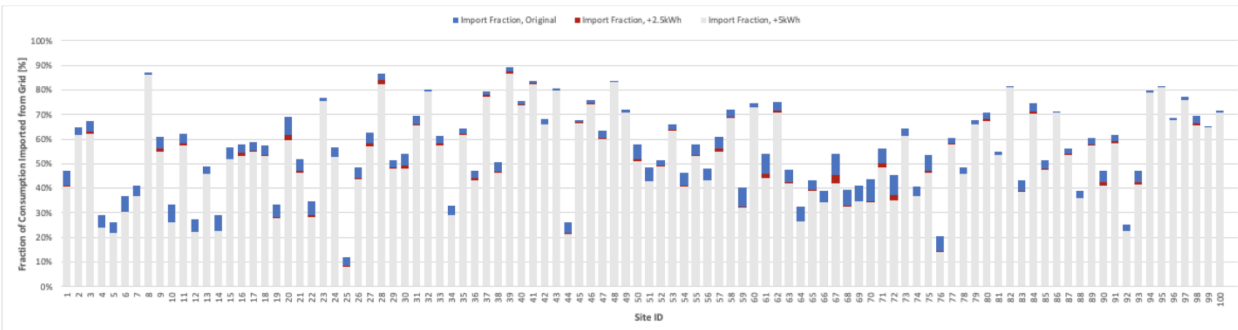


Figure 4-7: Proportion of electricity demand met by PV&BESS, disaggregated by BESS deployment (trial capacity, 2.5kWh upgrade, 5kWh upgrade)

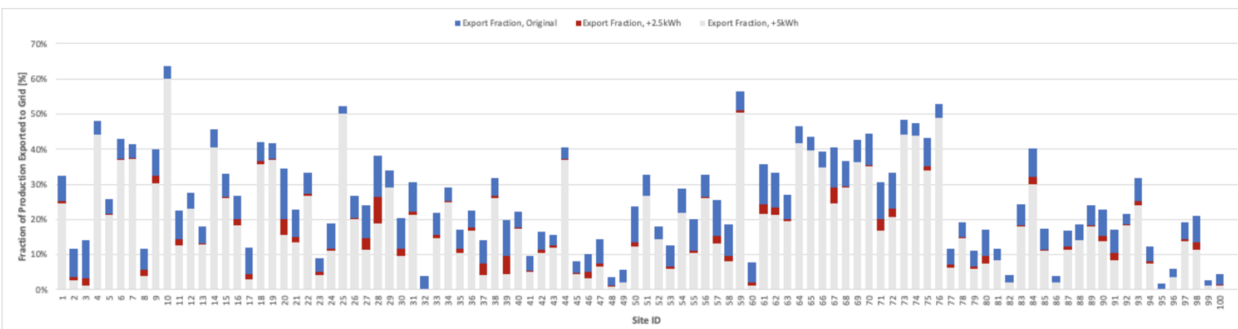


Figure 4-8: Proportion of production surplus met by BESS, disaggregated by BESS deployment (trial capacity, 2.5kWh upgrade, 5kWh upgrade)

4.2.3 Impact on Financial Value

The financial savings accrued by the PV&BESS solution ranged from just below £150 to just over £500 pa. The magnitude of savings was predominantly driven by installed PV capacity, not BESS capacity. The revenue accrued by BESS capacity upgrade can be viewed in relation to overall savings by considering the distance between the dots in **Figure 4-9**. Expanding on this to consider only incremental savings attributable to BESS system (**Figure 4-10**) it is clear that sites which performed well with the original trial capacity BESS were likely to extract the greatest benefit from capacity upgrades. This trend is clearly visible in **Figure 4-11**. In self-consumption mode, low performing sites are marked by the confluence of low production surplus and low production deficit. These attributes are a function of dwelling and PV and are not remedied by BESS capacity. From **Figure 4-11, Figure 4-12** & **Figure 4-13**, the three most improved sites invovled 10kWh BESS (as installed), increased to 12.5kWh and 15kWh. At 12.5kWh these demonstrated £170 to £180 p.a. savings specifically as a result of the battery, these increased to £180 to £190 p.a..

Considered at a fleet level the increase in self-consumption was estimated as being 23,550kWh and 39,150kWh for the 2.5kWh and 5kWh upgrade respectively **(Table 4-4**). The capital costs of different capacities of residential BESS systems were estimated using industry averages, rather than solely being based on LEM trial procurement costs (**Figure 4-14**). From these capital costs it was possible to estimate the incremental cost of additional BESS capacity as being £1,000 per 2.5kWh upgrade. The 2.5kWh and 5kWh upgrades would therefore cost £100k and £200k respectively.

Using simple payback analysis (i.e. not discounting cashflow) and assuming a 10-year product life, the cost of delivering the additional self-consumption would be 42p/kWh and 51p/kWh for the 2.5kWh and 5kWh upgrade respectively. There are no energy policy scenarios envisaged that would see electricity tariffs rising to these levels over the next decade. No economic case can therefore be made for increasing the capacity of BESS for any dwellings if the system is only to be operated in self-consumption mode.

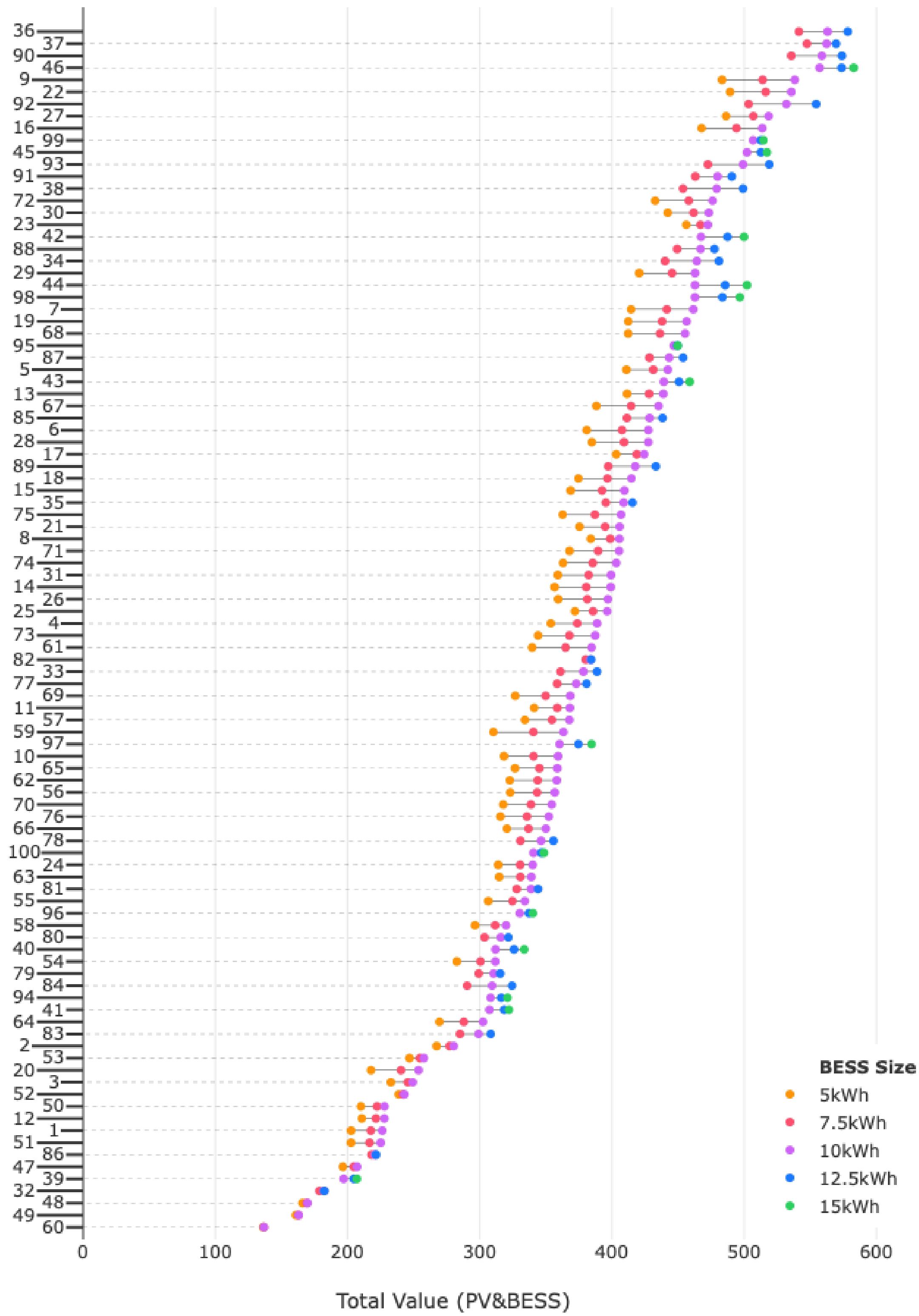


Figure 4-9: Self-consumption economic savings from PV&BESS, including BESS capacity upgrades, all sites

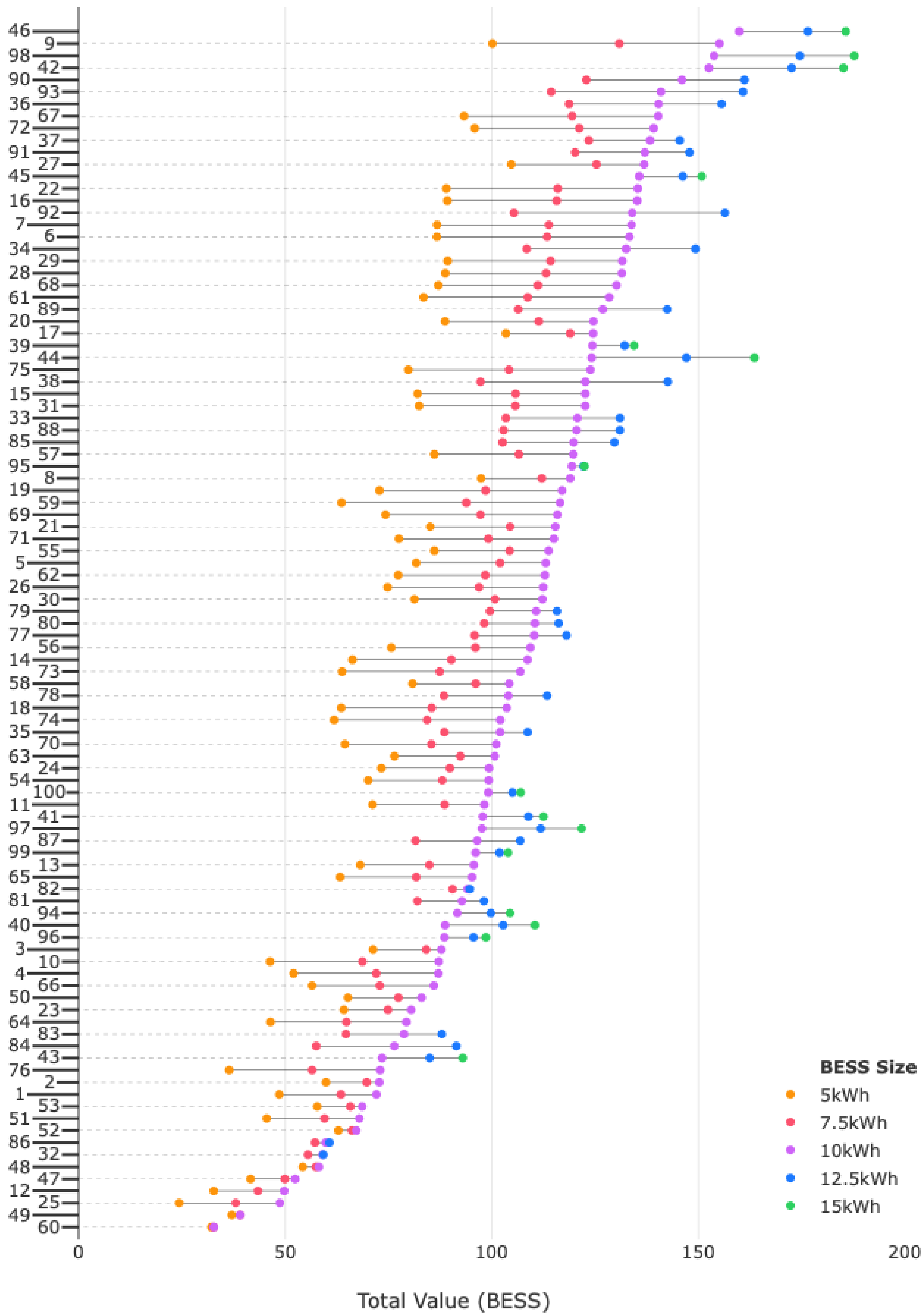


Figure 4-10: Self-consumption economic savings from BESS only, including BESS capacity upgrades, all sites

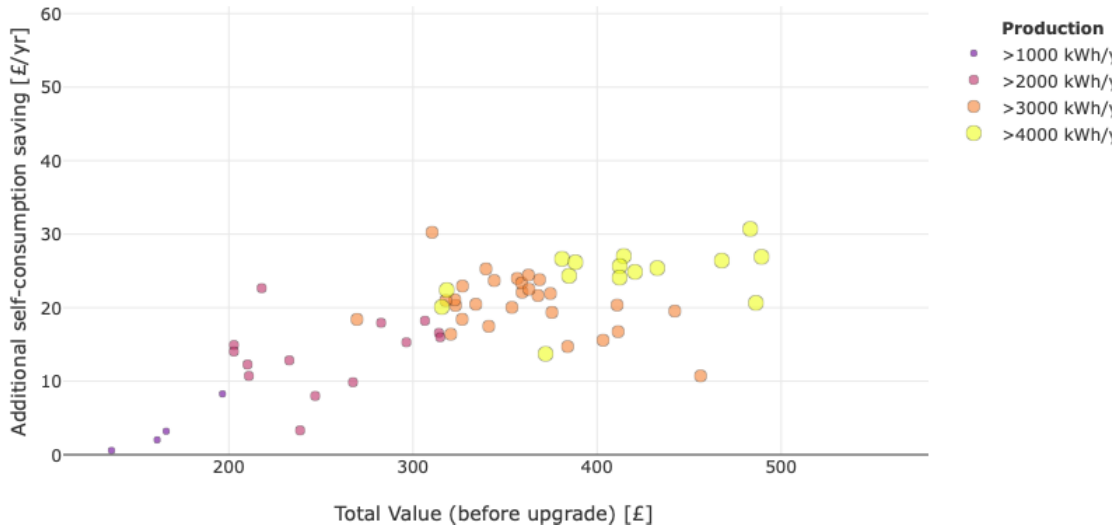


Figure 4-11: Self-consumption economic savings from BESS only, including BESS capacity upgrades, all sites

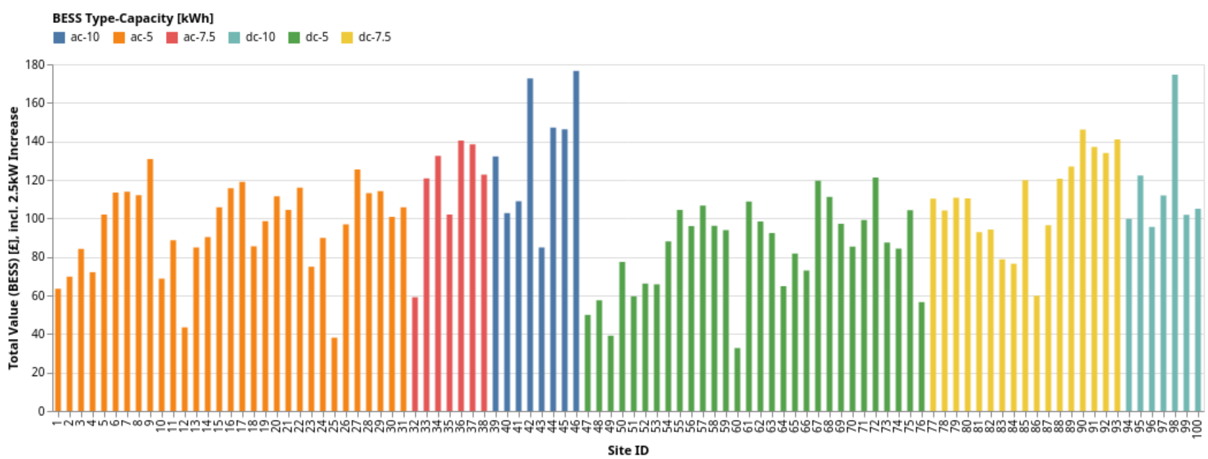


Figure 4-12: Total Value estimate from BESS only, including 2.5kWh BESS size increase

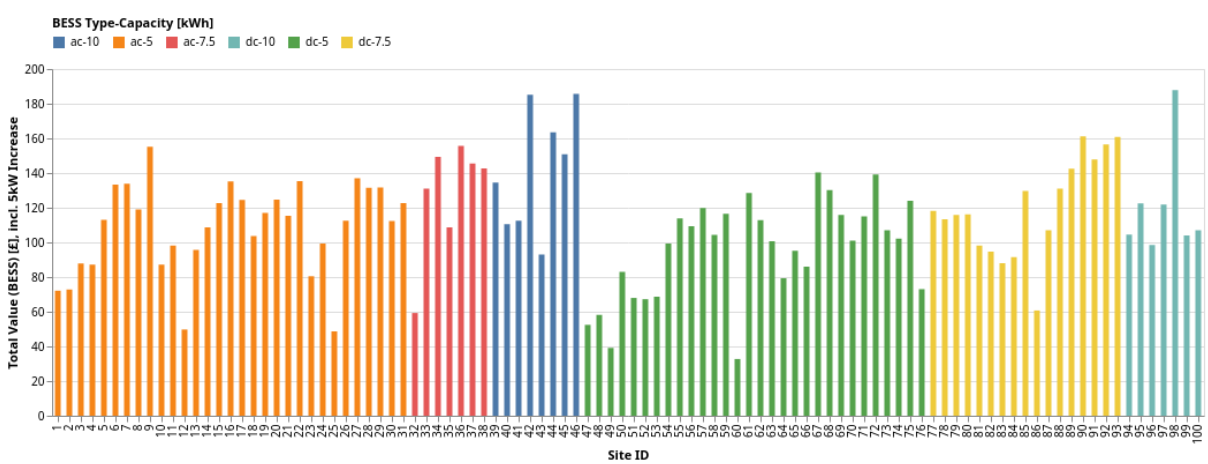


Figure 4-13: Total Value estimate from BESS only, including 5kWh BESS size increase

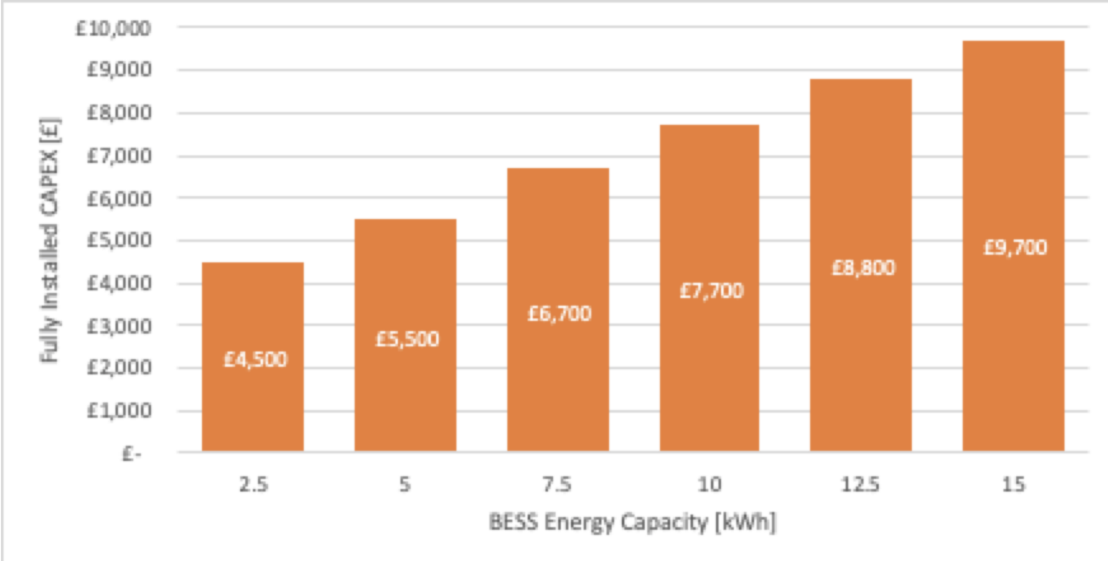


Figure 4-14: Estimated, illustrative CAPEX (Fully Installed Cost to Consumer) of BESS systems

4.3 Full Fleet Results

To provide the most appropriate measure of diversified financial performance following the theoretical size upgrades, the fleet-level aggregated CAPEX and Total Value (PV&BESS) are presented here. This relates specifically to financial benefit through self-consumption, by reducing import costs at the expense of a smaller portion of export revenue. From **Table 4-2**, the headline result is that an estimated additional CAPEX of £113,700 kWh would be necessary to increase all BESS by 2.5kWh(cap.); for the 5kWh(cap.) case, this increases to £214,600. In terms of rate of return, from **Table 4-3**, the two scenarios result in fleet-level increments of £1,700 p.a. and £2,850 p.a., respectively. This clearly demonstrates a very weak economic argument for increasing BESS capacity when the systems are configured to operate purely in self-consumption mode. This echoes the universally-accepted industry view, that it is highly inappropriate to consider any single dwelling for 100% supply-autonomy. For the additional expenditure on the 2.5kWh(cap.) and 5kWh(cap.) increases, the simple payback is 67 years, and 75 years, respectively. These diminishing returns are also illustrated in **Figure 4-15**.

Scenario	5kWh BESS	7.5kWh BESS	10kWh BESS	12.5kWh BESS	15kWh BESS	kWh	CAPEX
As Installed	61	24	15	-	-	635	£611,800
+2.5kWh/site	-	61	24	15	-	885	£725,500
+5kWh/site	-	-	61	24	15	1135	£826,400

Table 4-2: Estimated Total Value for BESS resizing scenarios (+2.5kWh and +5kWh across all sites)

Scenario	kWh	TV (BESS) [£/yr]	TV (PV&BESS) [£/yr]
As Installed	635	£8,300	£35,800
+2.5kWh/site	885	£10,050	£37,500
+5kWh/site	1135	£11,150	£38,650

Table 4-3: Estimated Total Value for BESS resizing scenarios (+2.5kWh and +5kWh across all sites)

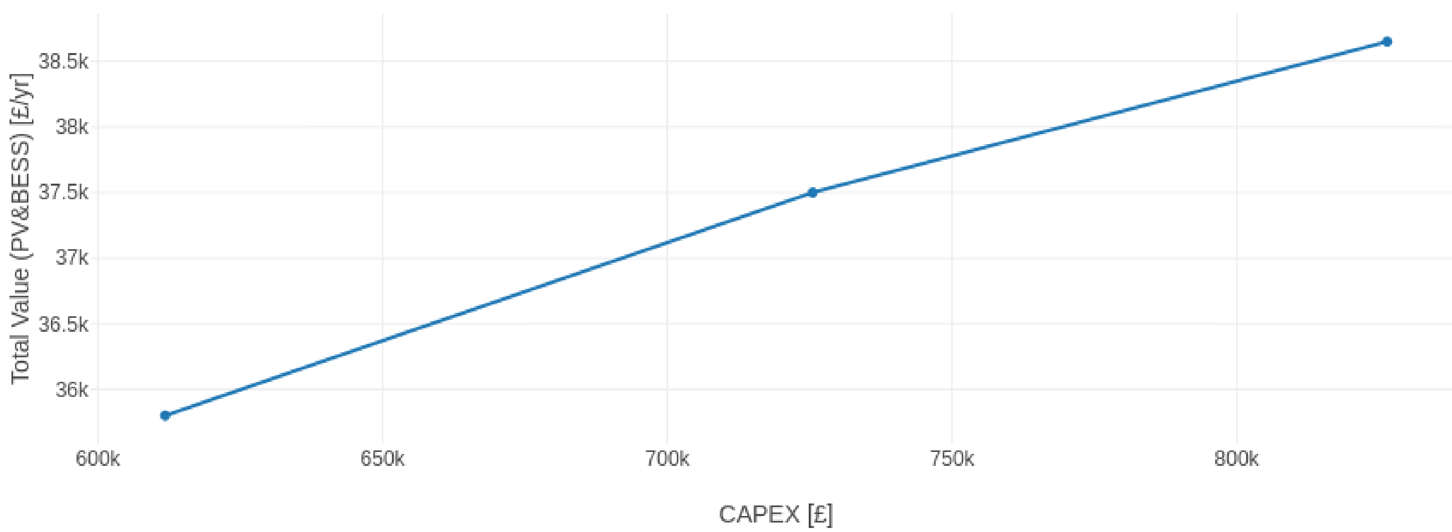


Figure 4-15: Estimated, illustrative CAPEX (Fully Installed Cost to Consumer) of BESS systems

Considering energy, the measures that directly impact bills and revenues for customers are the annual import and export totals throughout the year; these results are presented in **Table 4-4**. Export can be reduced by 34% with the additional 2.5kWh(cap.) per site, and 56% for the 5kWh(cap.) per site increment. This transpires in more limited energy retention on site following RTE; based on fleet-level import dropping from 478,200 through to 439,050kWh/yr, import charges are reduce by 5% and 8% for the two sizing scenarios. The change in imported energy between scenarios is equal to the corresponding change in self-consumption. Between the scenarios, self-consumption increased by 10% and 17%, respectively.

Scenario	kWh	Import [kWh]	Export [kWh]	Charge [kWh]	Discharge [kWh]	Self-consumption [kWh]	BESS Energy Utilisation [%]
0	635	478,200	97,600	153,400	111,650	228,650	66.2%
1	885	454,650	64,600	186,400	135,200	252,200	57.7%
2	1135	439,050	42,600	208,400	150,800	267,800	50.3%

Table 4-4: Estimated impact on self-consumption for BESS resizing scenarios (+2.5kWh and +5kWh across all sites)

The main result from **Table 4-4** is the BESS Energy Utilisation. The very modest financial value derived from these results is undermined by a significant drop in utilisation, from 66.2% to 50.5%. Given the additional CAPEX, there is no justifiable case for upgrading BESS on the basis of self-consumption alone. In contrast to self-consumption, however, there are significant opportunities to exploit headroom for the purpose of arbitrage. This is described in the following subsection.

4.4 Impact on Headroom

Given the absence of economic viability of BESS capacity upgrade arising from self-consumption control only, it is instructive to explore the impact it would have on headroom availability. This could then potentially be used to attract additional revenue using the arbitrage control scenarios described in **Section 3**. The additional headroom introduced by each upgrade scenario is presented on seasonal basis in **Table 4-5**. It is clear that - when averaged across the fleet of 100 sites - the majority of new capacity is available as trading headroom.

Of the additional capacity added in each scenario, the extended headroom is shown in **Figure 4-16**. In the most extreme cases, the additional 2.5kWh and 5kWh are almost entirely unused. Whilst this offers no additional value for self-consumption, new headroom is close to 100%. These same sites clearly result in the greatest arbitrage potential; 2.5kWh additional capacity can generate additional income close to £100 p.a. (see **Figure 4-17**), whilst 5kWh returns almost £200 p.a. for these sites (see **Figure 4-18**).

	Additional Headroom for Trading (% of new Capacity)		
Scenario	Summer	Shoulder	Winter
Add 2.5kWh x 100 siites	69%	73%	93%
Add 5kWh x 100 siites	82%	84%	96%

Table 4-5: Headroom from new capacity, disaggregated by season

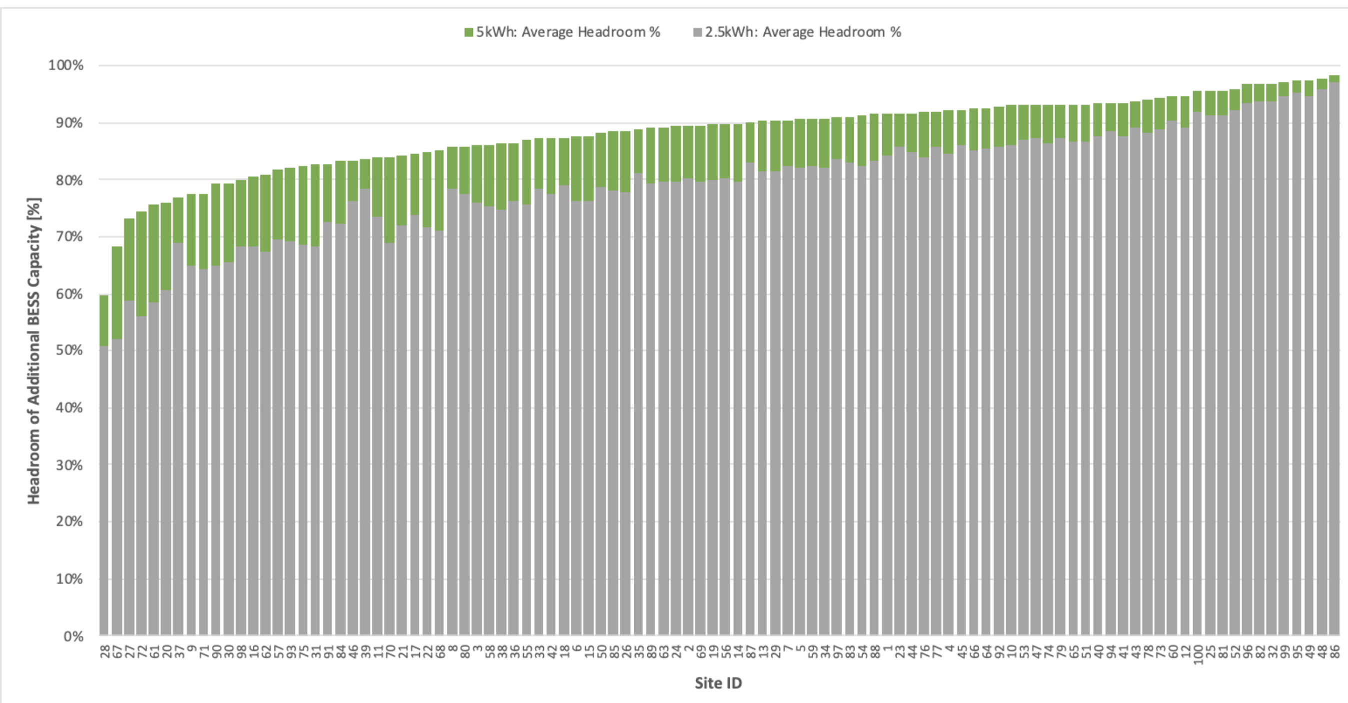


Figure 4-16: Proportion of additional capacity that can be released as headroom if self-consumption is prioritised, all sites

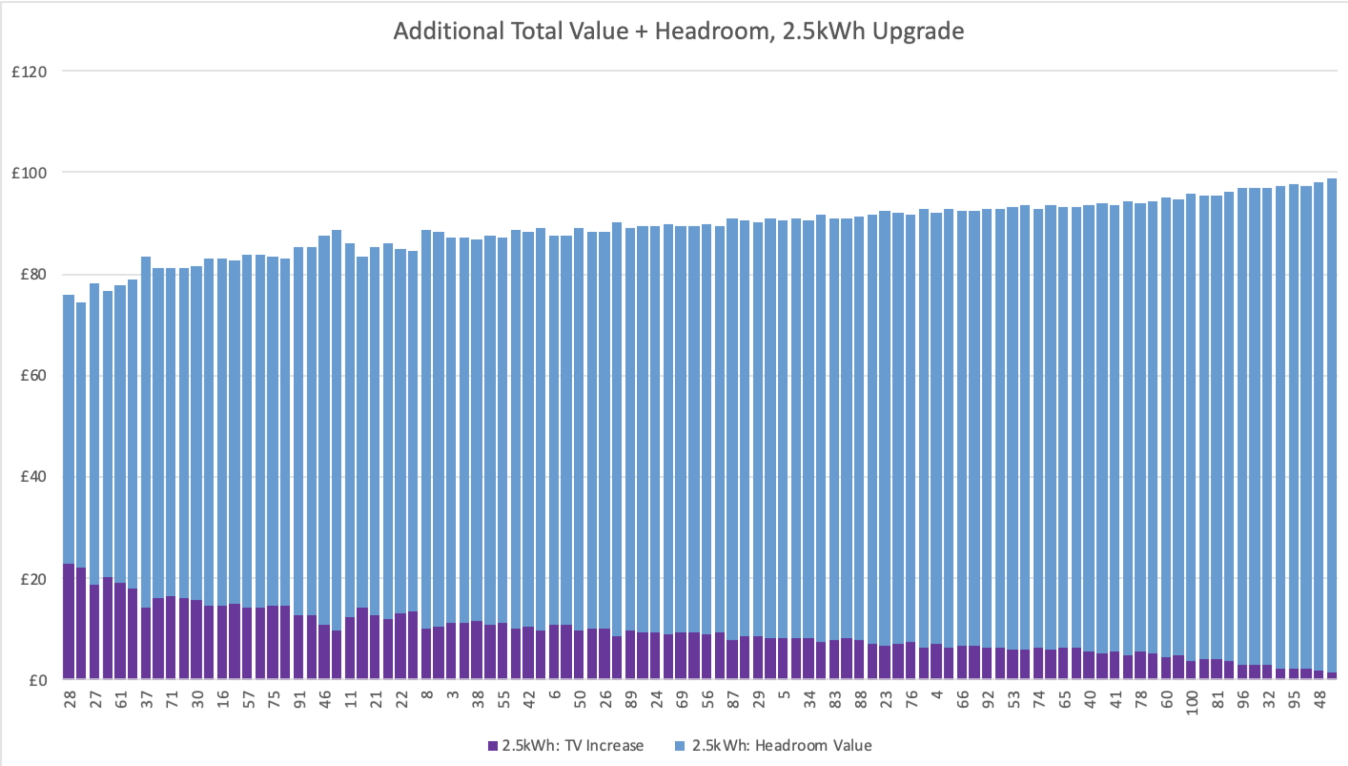


Figure 4-17: Annual revenue from self-consumption and arbitrage with remaining headroom that can be accrued from additional capacity, all sites, 2.5kWh upgrade

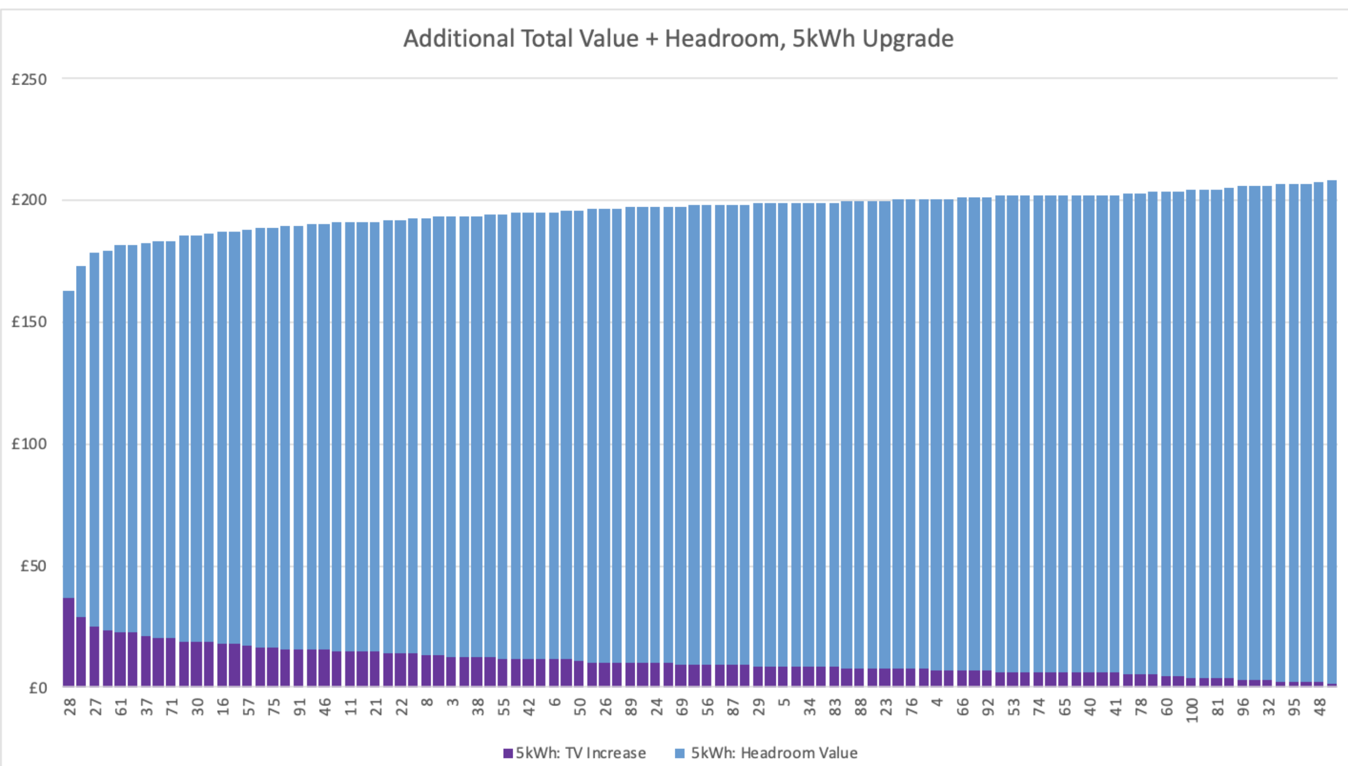


Figure 4-18: Annual revenue from self-consumption and arbitrage with remaining headroom that can be accrued from additional capacity, all sites, 5kWh upgrade

Using the methodology discussed in **Section 3**, the additional financial value associated with each upgrade scenario is presented in **Figure 4-19**. Clearly the value from additional trading - by leveraging the headroom - is likely to dominate the financial case for such upgrades. It is important to note that under the optimistic (yet realistic) time of use arbitrage scenario discussed in **Section 3**, assigning additional capacity to trading proves to be more valuable than a self-consumption & trading combined operating strategy. When considering the discharge time of the additional self-consumption throughput - i.e. late evening and overnight - the benefits of a trading approach are only likely to increase.

Assuming arbitrage control only is applied, the revenue that can potentially be accrued was estimated as being £8.4k and £16.8k for the 2.5kWh and 5kWh capacity increases respectively. Given the capital costs of these upgrades were estimated as being £100k and £200k, the simple payback using arbitrage control only would be 11.9 years, i.e. longer than the 10-year lifespan covered by typical warranties for BESS technology.

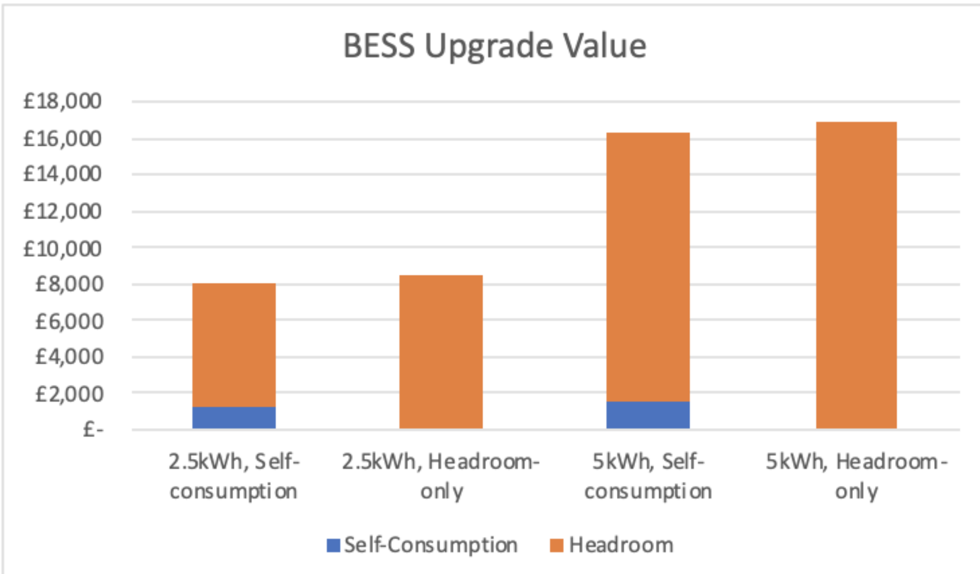


Figure 4-19: Financial Value from each BESS capacity upgrade scenario, comparing use for self-consumption & headroom, vs headroom only (under the headroom ToU trading assumptions discussed in Section 3)

5. BESS Sizing: Community-Scale

5.1 Sizing Strategy

A series of theoretical community-scale BESS were studied to explore opportunities for capacity reduction on the basis of aggregate load diversity. All scenarios studied involved community-scale BESS capacities that were equal to or less than the total installed capacity across the 100 sites (635kWh). Aside from opportunities to reduce CAPEX by reducing total installed capacity, there are clearly opportunities to exploit economies of scale. This analysis computes reduced BESS throughput in both kWh(cap.) and £/kWh(cap.).

There are a number of significant factors that affect operational performance differences between distributed behind-the-meter BESS and centralised community-scale systems. Due to the counterfactual nature of this study, the constraints envisaged for the performance of the community-scale system were theoretical; it was therefore inappropriate to perform a highly refined numerical simulation. The approach taken, however, provides substantial evidence based on the minutely site measurements that were taken during the project.

The steps taken were as follows:

1. Generate the fleet-level SoC (SoC_{fleet}), capturing the variation in BESS capacities at each site. SoC_{fleet} is then rounded to the nearest kWh. It is noted that SoC_{fleet} peaks at 95.4% (606kWh), justifying the basis for this analysis to only consider capacity reductions for the community-scale system.
2. Generate the fleet-level charge and discharge on a 1-minute basis for 1 year. These minutely values correspond to minutely values of SoC_{fleet}.
3. The total charge occurring at each rounded value of SoC_{fleet} is accumulated (irrespective of time); this is repeated for discharge. This provides a record of all charge and discharge (in kWh) that occurred against all possible values of SoC_{fleet} (in percent).
4. This record of SoC_{fleet} and corresponding charge and discharge is sorted with respect to SoC_{fleet}. Records of cumulative charge and discharge (equal to or above each SoC_{fleet} value) are then produced; this facilitates resizing calculations by omitting all charge and discharge that occurs above a certain cut-off (for a community-scale BESS sized at 90%, all charge that occurred when SoC_{fleet} was 90-100% is considered 'Missed').
5. Relative adjustments for import costs and export revenue are produced. This considers three RTE scenarios: 70% RTE (as evaluated from total fleet charge and discharge data), 80% (considering improved performance from the aggregate diversified load), and a dynamic range from 70% to 80% (decreasing at higher SoC_{fleet}).

5.2 Results

5.2.1 Impact on Total Charge/Discharge

Figure 5-1 shows the cumulative state of charge equal to or above all possible values of 'BESS Energy Capacity' (SoC_{fleet}). As SoC_{fleet} does not exceed 95.4% at any point in time, reducing the BESS Energy Capacity to 95.4% (606kWh) had no impact on performance. As the occurrence of $SoC_{fleet}>80\%$ is relatively rare, the impact on performance is limited (this corresponds to approximately 10,000kWh/yr from an unmitigated total of 141,000kWh/yr of charge). The results from various sizing strategies are provided in **Table 5-1**.

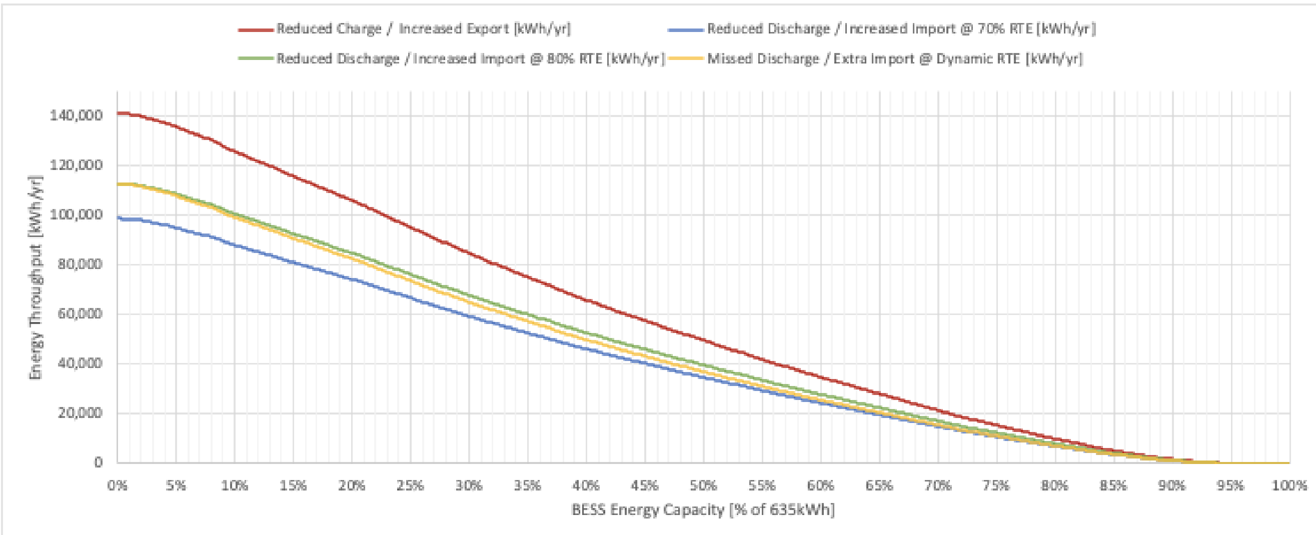


Figure 5-1: Variation of Energy Throughput of the community-scale BESS with respect to scaled capacity (%).

BESS Resizing Factor	Energy Capacity [kWh]	Charge		70% RTE	80% RTE	Dyn. RTE
		kWh Missed	**% Missed**	**kWh Missed**	**kWh Missed**	**kWh Missed**
100%	635	-	-		-	-
90%	572	1,639	1%	1,140	1,300	1,150
80%	508	9,940	7%	6,960	6,960	70,90
70%	445	21,270	15%	14,890	17,020	15,410
60%	381	34,790	25%	24,350	27,830	25,580
50%	318	49,410	35%	34,590	39,530	36,860

Table 5-1: Variation of Energy Throughput of the community-scale BESS at various installed capacities.

5.2.2 *Impact on Financial Value*

The capacity dependent reduction in financial value of the community-scale BESS is derived from the relative impact on electricity import costs and export revenues (15p/kWh and 5.5p/kWh, respectively). **Figure 5-2** shows Net Value for the 70% and dynamic (70-80%) RTE scenarios. As previously, the top 4.6% of the full-size BESS (635kWh) is unused, so can be trimmed accordingly with no impact on Total Value. These results are summarised in **Table 5-2**.

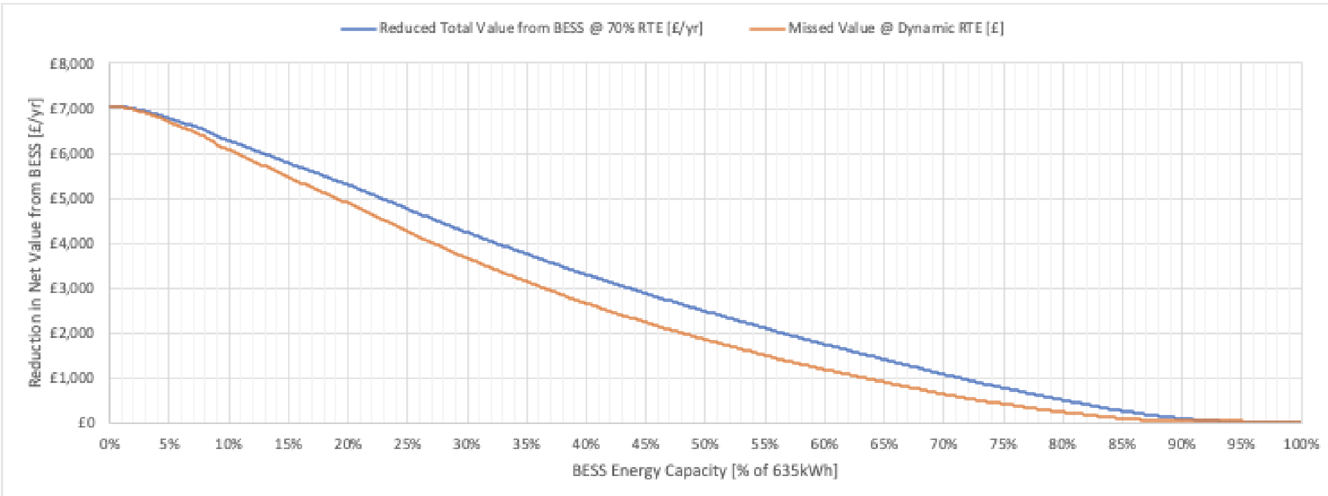


Figure 5-2: Variation of Net Value of the community-scale BESS with respect to scaled capacity (%).

BESS Resizing Factor	Energy Capacity [kWh]	Net Value	
		70% RTE	**Dyn. RTE**
100%	635	-	-
90%	572	£80	£20
80%	508	£500	£230
70%	445	£1,060	£630
60%	381	£1,740	£1,180
50%	318	£2,470	£1,840

Table 5-2: Variation of Net Value of the community-scale BESS at various installed capacities.

5.2.3 Considering CAPEX

Research from a wide range of recent BESS installations provided the empirical basis for BESS CAPEX shown in **Figure 5-3**, which demonstrated a significant downturn in £/kWh(cap.) for larger systems. This indicated that a system sized at the capacity as the distributed fleet (635kWh) would cost in the region of £100k.

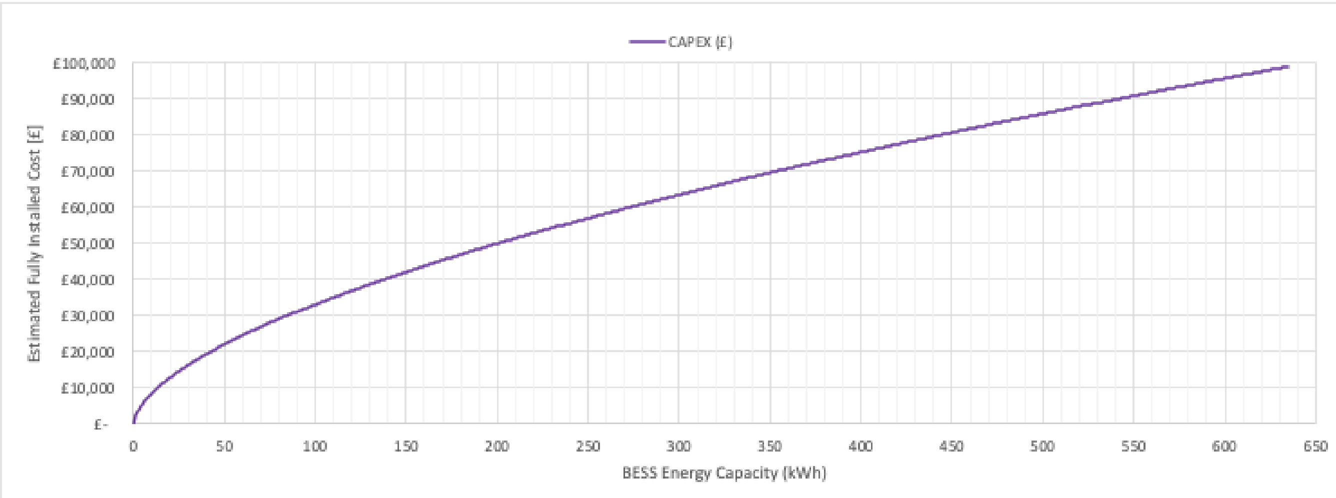


Figure 5-3: Variation of estimated CAPEX of the community-scale BESS with respect to scaled capacity (kWh).

Based on the Net Value (specifically the reduction in financial benefit) discussed above, **Figure 5-4** overlays two annualised CAPEX scenarios, based on 15 year and 10 year timeframes. By apportioning the upfront cost of additional capacity into typical payback timeframes, it is possible to consider the Net impact of different CAPEX scenarios, against the Net impact on financial value during operation. Over the 15 year period, there are intersections between the relationships for CAPEX against kWh(cap.) and Value against kWh(cap.). This occurs for both 70% RTE and dynamic RTE. When the 'Reduced CAPEX' (saving) is above the 'Missed Value' (penalty), this implies that the economics are dominated by CAPEX savings (these intersection points occur at 235kWh(cap.) and 387kWh(cap.), for 70% RTE and dynamic RTE, respectively).

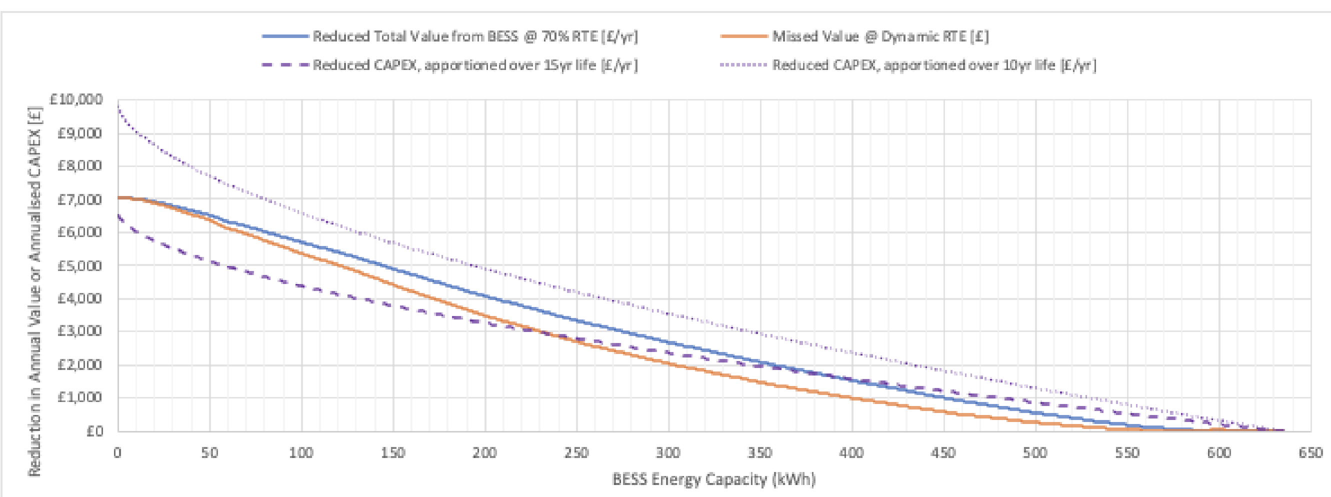


Figure 5-4: Variation of Net Value and CAPEX of the community-scale BESS with respect to scaled capacity (kWh).

6. BESS CO_2 Savings with Time-of-Use CO_2 Intensity

6.1 Methodology

The CO_2 emissions attributable to three circumstances, namely;

- dwelling demand
- dwellings fitted only with PV
- dwellings fitted with PV&BESS were compared at a fleet level

For each of these circumstances the total grid import and grid export to the dwelling was constructed as a half-hourly dataset. The CO_2 emissions in each half-hour block was calculated by using half-hourly grid emission factor (gCO_2/kWh) for the period March 1st 2019 to February 29th 2020[2].

[2] National Grid ESO (2020), https://carbonintensity.org.uk/, accessed November 2020

6.2 Self-Consumption

The CO_2 emissions from the entire 100 dwelling fleet associated with dwelling electricity consumption was calculated as being 112.7 TCO_2 during the period March 2019 to February 2020 (**Figure 6-1**). Two views of the CO_2 emissions associated with electricity consumption in the dwellings can be constructed.

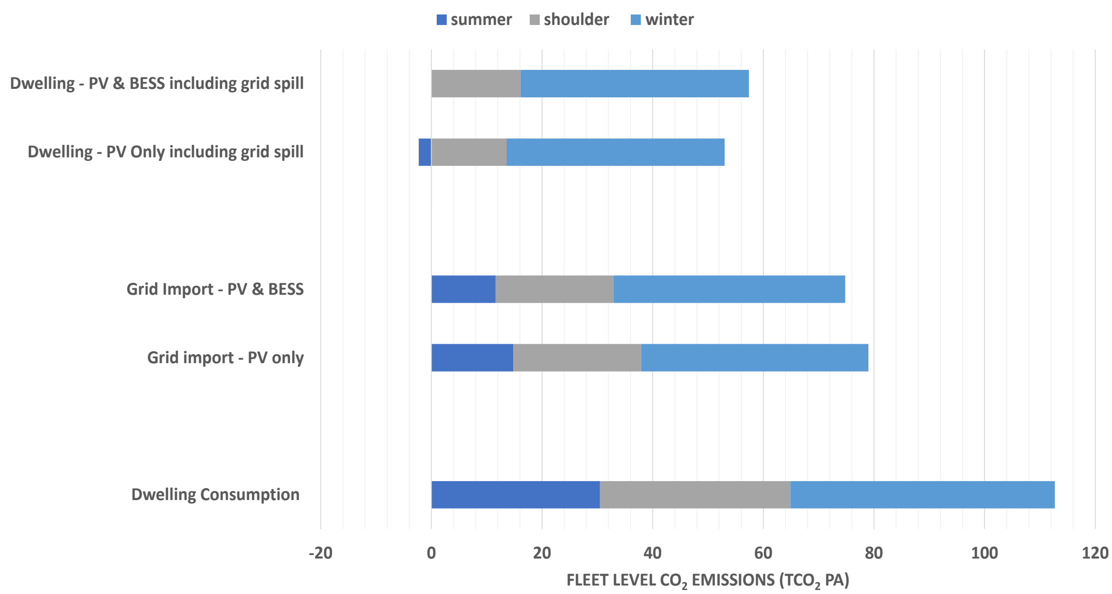


Figure 6-1: Annual, Fleet level on-site and net CO_2 emissions attributable to dwelling only, dwelling with PV and dwelling with PV & BESS

The first of these considers electricity consumed on-site only and ignores any reductions associated with electricity exported from the dwelling. Under this view, the installation of PV systems in the absence of BESS caused fleet level emissions to fall to 79.0 TCO_2, a reduction of 29.9%. The impact of BESS was to allow a proportion of electricity that would otherwise have been exported to the grid to be consumed by the dwellings. This resulted in on-site emissions at fleet level to fall to 74.8 TCO_2, a total reduction of 33.6%.

The second view accounts for on-site consumption of electricity generated by PV systems and that exported from the dwelling. Net CO_2 emissions attributable to the fleet fell to 50.7 TCO_2 when considering PV only a reduction of 55.0%. A point to note is that during the summer months (May-August) the dwellings were in effect running at below-zero emission levels with respect to electricity consumption. When PV & BESS systems were considered, net CO_2 emissions fell to 57.4 TCO_2, a reduction of 49.1%. The PV&BESS condition produces less net CO_2 emissions as a consequence of losses attributable to BESS round trip efficiency, which at fleet level had an average of 70.3%. It further assumes that all electricity that would have been exported from the dwellings under a PV only condition was used elsewhere with negligible losses in the distribution network. CO_2 emissions attributable to losses in the transmission and distribution (T&D) of electricity in the UK in 2020 were reported as being 0.02005kgCO_2 per kWh against a system annual grid emission factor of 0.233kgCO_2/kWh[3]. This implies T&D losses of 8.6%.

The total electricity exported from the dwellings in the PV only circumstance was found to be 150.0 MWh. Using the average T&D losses figure, the amount of this that can be assumed to be usefully consumed is estimated as being 137.1 MWh. The displaced CO_2 that should not be included in the net accounting figure was calculated as being 0.26TCO_2. In the PV&BESS circumstance, the amount of electricity that was exported from the dwellings fell to 56.2MWh, of which 51.4MWh can assume to have been used elsewhere. The displaced CO_2 that should not be included in the net accounting figure was calculated as being 0.096TCO_2. The benefit accrued to the PV&BESS situation in deferring electricity consumption arising from T&D losses is therefore 0.164TCO_2.

Feeding these values back into the net emission reduction estimated for the PV only and PV&BESS situations resulted in fleet emissions of 51.0TCO_2 and 57.5TCO_2 respectively.

[3] UK Government (2020), https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting, accessed November 2020

6.3 Time of day GEF

If it was imperative that this reduction in emission saving created by BESS RTE losses was obviated, a plausible approach might be to create charge/discharge control approaches that took account of the time varying nature of grid emission factors (GEF). In effect this would be akin to having the BESS running a CO_2 arbitrage control signal. The differential required to achieve neutrality in emissions at RTE of 70.3% is 142%; for instance, charging with electricity at GEF of 0.2gCO_2/kWh and discharging when GEF is 0.28gCO_2/kWh would create CO_2 emissions savings that would account for RTE losses. The proportion of the year where the required differential to achieve this carbon neutrality point is clearly a function of BESS RTE (**Figure 6-2**).

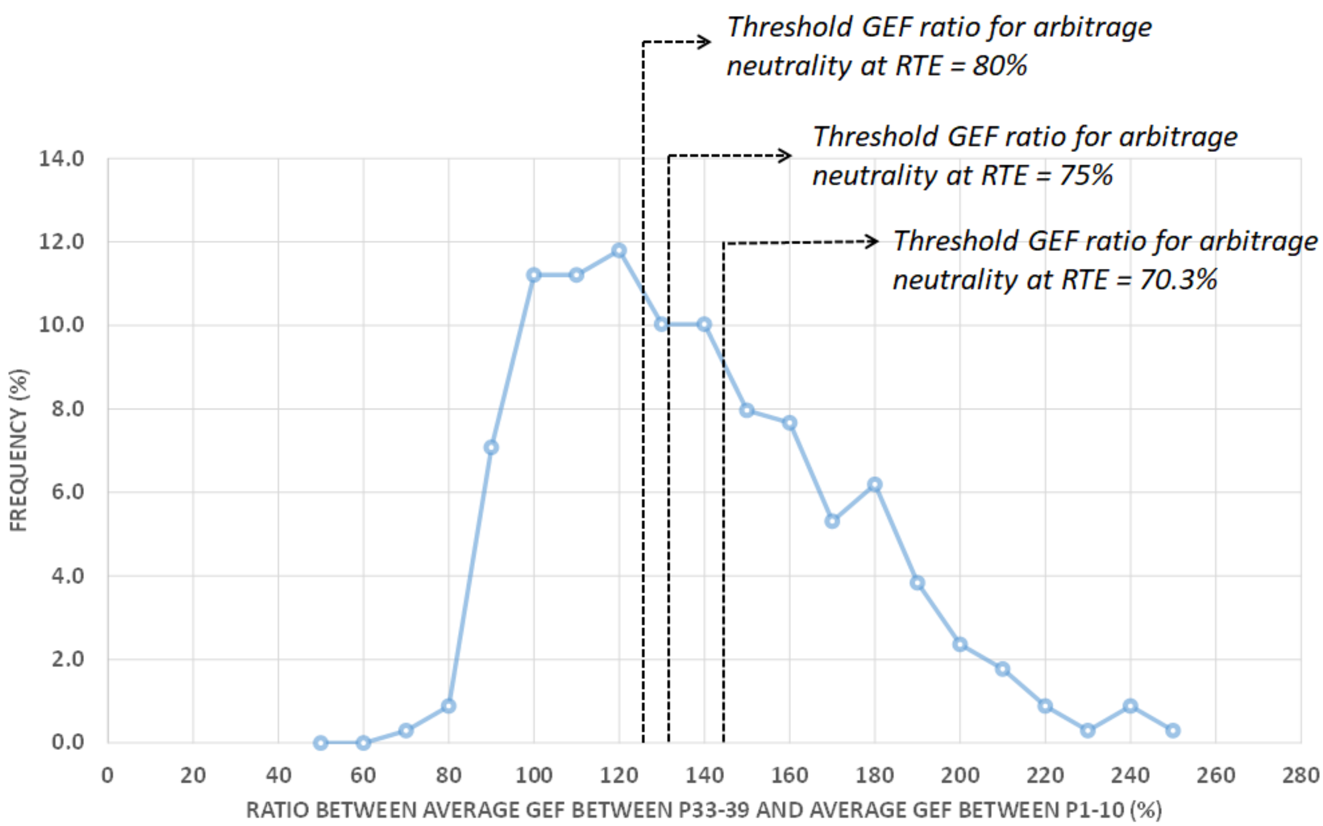


Figure 6-2: Frequency plot of peak to night time GEF for GB electricity between March 2019 and February 2020

If the BESS fleet was able to operate at the value of the highest performing systems (86% RTE) rather than the fleet average, the proportion of the year where a peak to night time ratio would result in CO_2 neutrality would be extended from 134 to 234 days of the year (**Figure 6-3**).

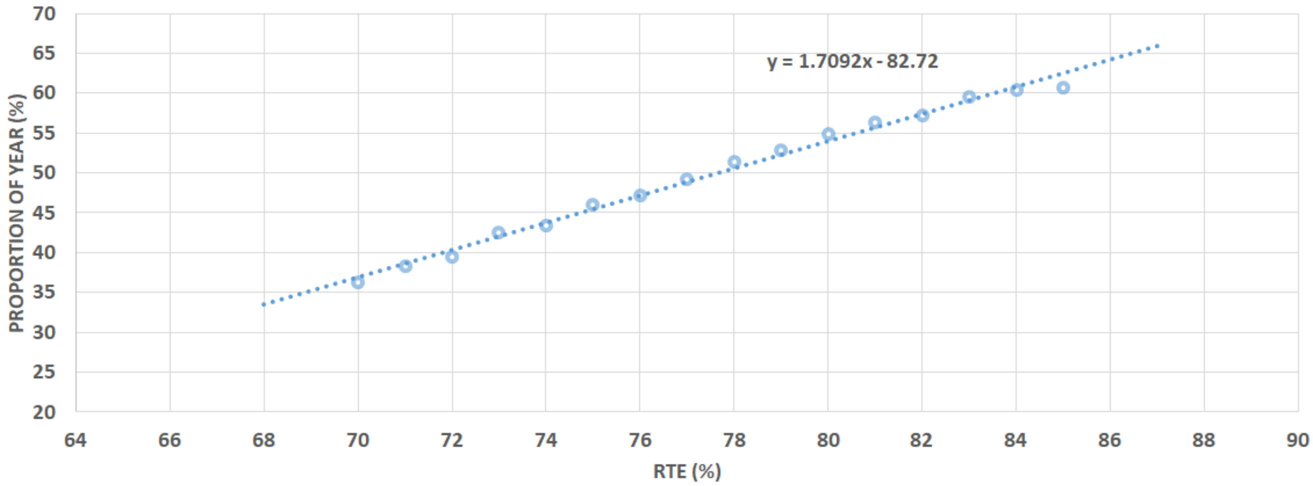


Figure 6-3: Relationship between RTE and proportion of the year where peak to night-time GEF ratio would result in CO_2 neutral arbitrage

The extent to which GEF is time variant is a function of season, with solar systems resulting in a noticeable suppression during the summer and shoulder months **(Figure 6-4)**. The maximum differential in GEF occurs in the winter between overnight period (periods 1-10) and early evening (periods 33-39) during the winter period. This was found to be between a maximum GEF of 242gCO_2/kWh and 167gCO_2/kWh; a differential of 145%. Assuming arbitrage during the same periods in summer and shoulder periods would produce differentials of 113% and 134% respectively.

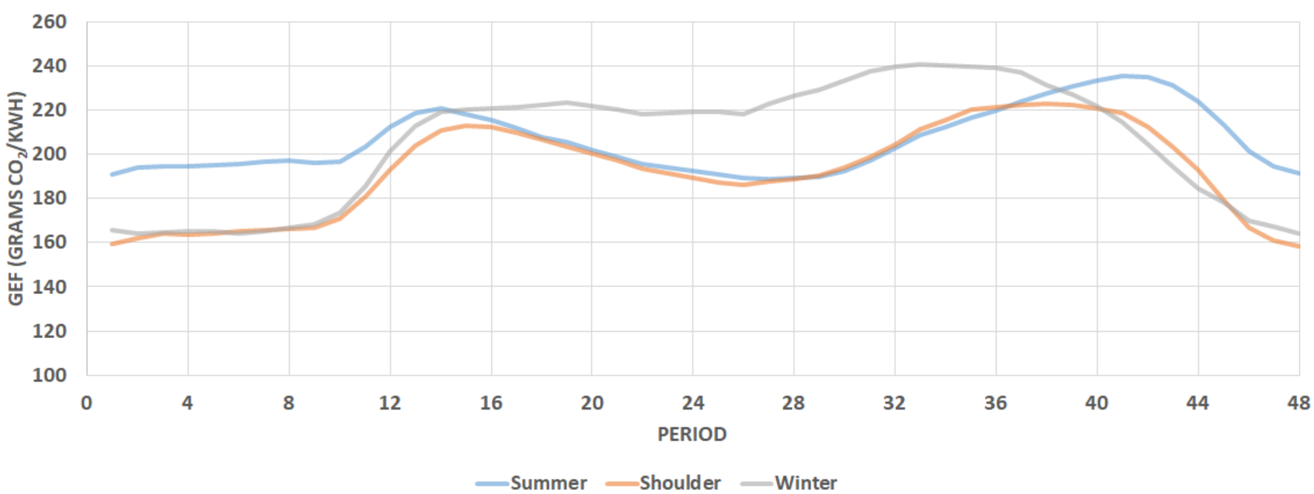


Figure 6-4: Time of day UK Grid Emission Factor [GEF] (gCO_2e/kWh) by season

6.4 Fleet Level Battery

A potential impact of deploying a fleet level sized BESS rather than dwelling discrete systems is in improving RTE of the charge/discharge cycle. This may arise as a consequence of optimised sizing made possible by (i) smoothed production and consumption load curves that would be expected by diversity and (ii) computing a sizing calculation for a single installation, rather than a series of sizing studies in each individual dwelling. As has been described above, the RTE has a substantial impact on the overall environmental efficiency of the deployed PV&BESS solution. If, for instance the fleet scale BESS is able to achieve RTE of 75%, then under self-consumption control the net CO_2 emissions attributable to the dwellings would be 56.4T CO_2 compared with 57.5T CO_2 with the discrete dwelling systems. The number of days where CO_2 neutrality could be expected from a CO_2 arbitrage night-time charge, peak time discharge would rise from 134 to 166 days pa.

6.5 Summarising Impact of BESS on CO_2 Savings

The deployment of BESS in conjunction with PV will supress CO_2 emission saving of the technology as a consequence of RTE losses. This environmental penalty is only marginally reduced by accounting for reduced T&D losses as a consequence of the higher share of PV generation that can be directed to meet on-site demand rather than exported and used elsewhere. The potential to use BESS headroom, employing CO_2 arbitrage approaches to charge BESS during periods of high GEF and discharge during low GEF periods is not plausible, given the lack of GEF variability throughout the year.

The veracity of evaluating CO_2 emissions for electricity generating and storage systems by assigning its relationship only to the discrete demand of the building to which it is deployed has to be questioned as the low carbon transition progresses. The role of embedded generation coupled with aggregated flexibility is more likely to be associated with energy system management, i.e. associated with system wide emission accounting. For instance, BESS environmental contribution might be accounted by assessing its ability to cost effectively allow increasing capacities of variable renewable energy to be connected to the grid or reduce the requirement of fossil fuel plant to be used to meet peak residual demand periods. It is likely that control signals will be developed to permit this operation using economic signals rather than derived GEF. This is based on the assumption that electricity markets will continue to evolve to reflect and encourage the overall imperative of decarbonisation.

7. Conclusions

The definition of energy utilisation used in this report is where 100% is equivalent to a full charge and discharge cycle per day. The energy utilisation of BESS systems deployed in the LEM trial, when operated using a self-consumption control signal, returned a fleet average of 63%, ranging from 33%-90%. Energy utilisation for a given site can be approximated using estimates of Production Surplus and Production Deficit; both these parameters are KPIs defined in the BESS Self-Consumption Summary Report[4].

Power utilisation (charge and discharge) is defined as the average power level when charging or discharging divided by BESS rated power. Power utilisation was found to be significantly lower than energy utilisation, with fleet averages of 26% and 17% for charge and discharge respectively. Again, Production Surplus and Production Deficit can be used to provide approximate estimates of Power utilisation, as reduced energy is likely to correlate with reduce power levels.

A number of observations relevant to BESS energy and power utilisation are pertinent:

1. Significant stranded capacity is present in almost all sites with commensurate impact on BESS economics. This stranded capacity or headroom can be used to generate additional revenue, for example by grid trading or time of use arbitrage.
2. When averaged over a year, BESS operation is constrained by energy, and not power. Significant levels of grid export occur in the summer months when BESS becomes saturated for periods of time.
3. Power constraints do occur, but their impact on dwelling energy balancing is less pronounced. When considering their impact, a suitable temporal precision commensurate with accompanying monetisation approaches should be adopted (e.g. half-hourly for ToU arbitrage).

The impact of BESS energy and power utilisation on Round Trip Efficiency [RTE] was studied, with several key findings:

1. The correlation between RTE and energy utilisation was very weak. It is likely that continuous BESS parasitic energy demands (for control & measurement systems, user interfaces, etc), are fixed regardless of operating state; most other losses (in charge and discharge cycles) are proportional to energy throughput.
2. There is a much stronger correlation of RTE with charge and discharge power utilisation. This is expected and is consistent with part-load efficiency curves that occur in any electronics that have been designed to meet rated power capacity.

When considering the headroom available for additional monetisation, it is important to consider how it varies by time of day, between seasons, and within each season. To that end, a methodology is proposed here for visualising cumulative fleet headroom using confidence intervals. These can be used to describe the likelihood of achieving a specific headroom value on the same half-hourly settlement period across the 4 months of each season. They can also be used to explore the proportion of BESS energy capacity that has to be reserved to achieve maximum available self-consumption and how this can be traded to provide additional headroom for additional monetisation.

Using a generic arbitrage approach, with up-to 3 shifting events between 2 charge and 2 discharge time windows within each day, we attempt to illustrate how optimised BESS operation can increase BESS utilisation through multiple dispatch events within each day, whilst working within the constraints of headroom "pinch-points". Using annual average time of use arbitrage values of £3/MWh to £87/MWh (per each shifting event), we can describe how headroom could be monetised to improve Total Value by 50%+ versus self-consumption, without appreciable detriment to self-consumption value.

The headroom assessment was based on simplistic logic, with unitary values that are typically less than a range of published flexibility services or other wholesale market opportunities. We assumed that a "Virtual Private Metering" scheme would allow site export to displace site import elsewhere at full import cost; which is obviously a gross simplification, but the

[4] LEM Residential Fleet Self-Consumption Summary Report

resulting £/MWh values are credible in the context of other monetisation options. The approach taken was sufficient to communicate both the value and variability of headroom on a time of use and seasonal basis.

Further study is required to ascribe value to a definite contracting structure or trading approach, and to optimise reduced self-consumption vs increased trading; but the initial results suggest that more value can be unlocked.

The potential for increasing the BESS capacity over the value installed in the LEM trial was evaluated for 2 generic capacity upgrade scenarios; +2.5kWh per site (increases fleet capacity by 39%) and +5kWh per site (increases fleet capacity by 78%). Under self-consumption control, only a small proportion of this additional capacity is utilised and no commercial case can be made what so ever to justify the increase. Even when the capacity is monetised as headroom using the arbitrage procedure previously described still produced simple payback periods for the additional capacity that would exceed probably lifetime of systems.

A more persuasive economic case can be made for replacing discrete dwelling BESS with a community-scale system driven by the economies of scale that can be derived from load diversity. Using the confidence limit approach, it was found that a 10% reduction in BESS capacity (with commensurate impact on capital costs) would have <1% reduction on self-consumption value (this relates specifically to the 100-site fleet from these trials; a larger fleet could unlock greater potential for economies of scale). The impact on project economics may be significant, especially when considering the project mobilisation and ongoing support costs, as many 100's or 1000's of sites could be reduced to a single site. Further study is required to optimise any such sizing decisions against loss in headroom and any associated monetisation opportunities.

The impact of BESS on CO_2-equivalent footprint of the dwelling was found to be negative when compared to PV only technology deployment using a simplistic basis of displacing average grid emissions - as illustrated in the BESS Self-Consumption Summary Report[5]. In a similar vein to Time of Use tariffs, the opportunity for CO_2 arbitrage was explored, but the results clearly demonstrate that such arbitrage is of limited value, and insufficient to outweigh the energy losses by the current fleet-average Round Trip Efficiency of 70%.

However, we can conclude that both the self-consumption operation and headroom dispatch opportunities could be leveraged to address network capacity and generation reliability constraints, allowing zero carbon renewables to be connected (or avoid constraint). When the charging electricity has a CO_2 intensity of zero, the round-trip efficiency is irrelevant from a CO_2 savings perspective; instead, the BESS should be credited with the annual generation that it enables to be connected to the network, and the attendant displacement of marginal generation (usually at grid emission factors 2-3x higher than current grid average). It is worth noting that increased Round Trip Efficiency is still an important aspiration, as it reduces losses and hence costs associated with generation and network.

[5] LEM Residential Fleet Self-Consumption Summary Report

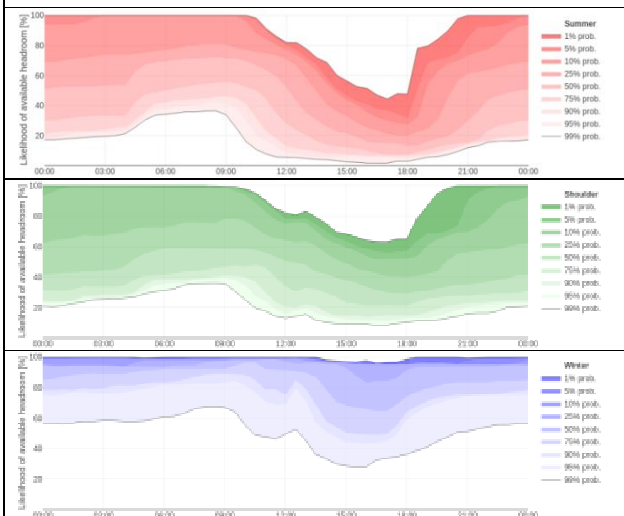
8. Appendices

8.1 Appendix A1: Headroom Analysis per Site

The complete series of site-specific Confidence Levels (CL) are detailed in this section. These correspond to the fleet-level (aggregate) figures provided in **Section 3** (Headroom Analysis).

8.1.1 Headroom Confidence Levels - 5kWh BESS

Site 1



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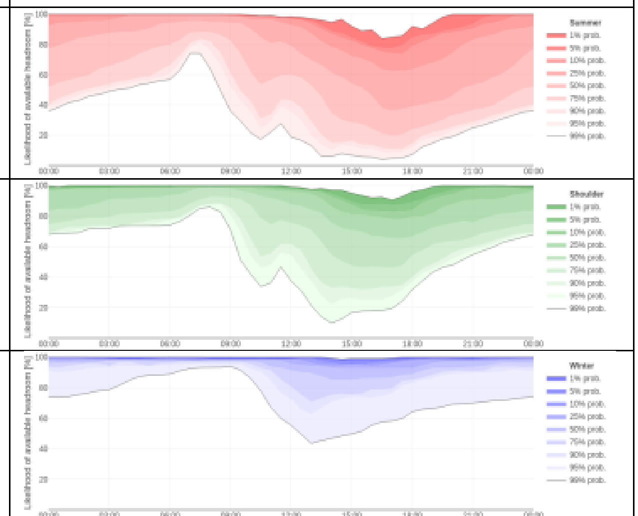

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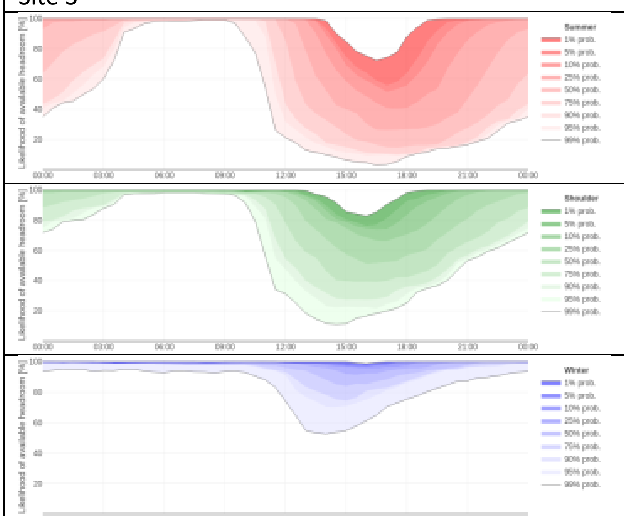

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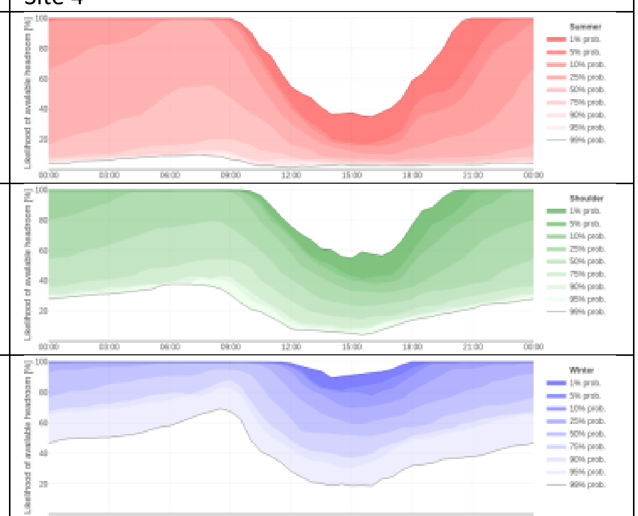

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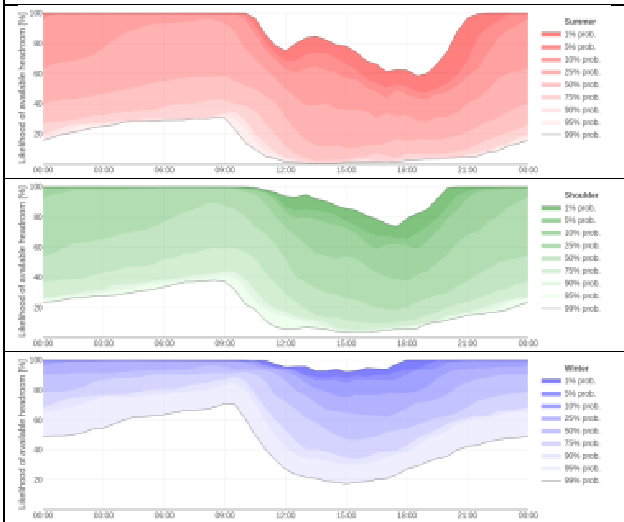

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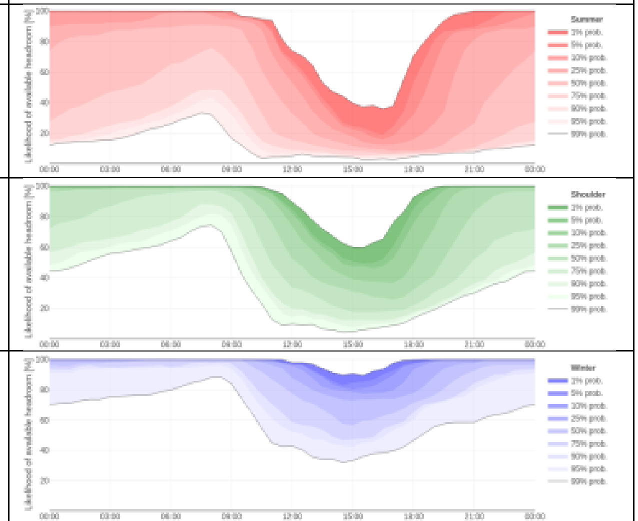

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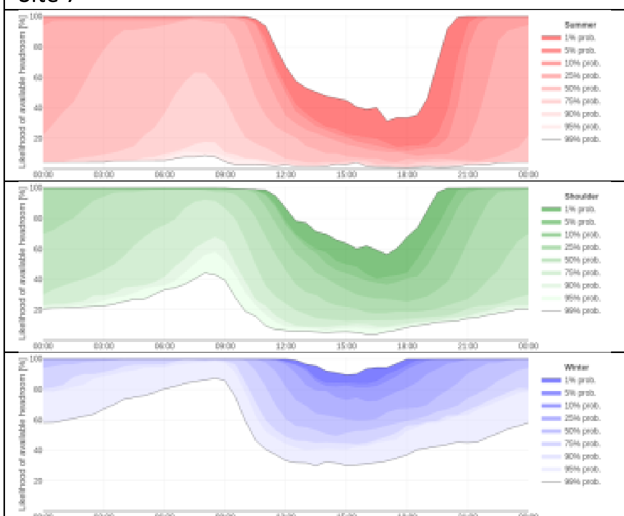

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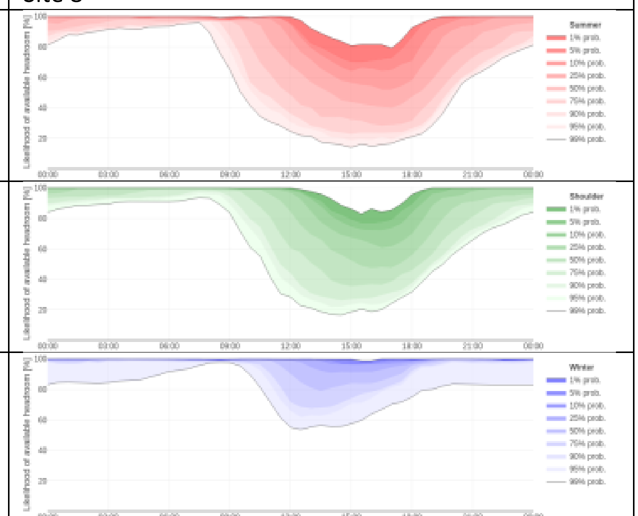

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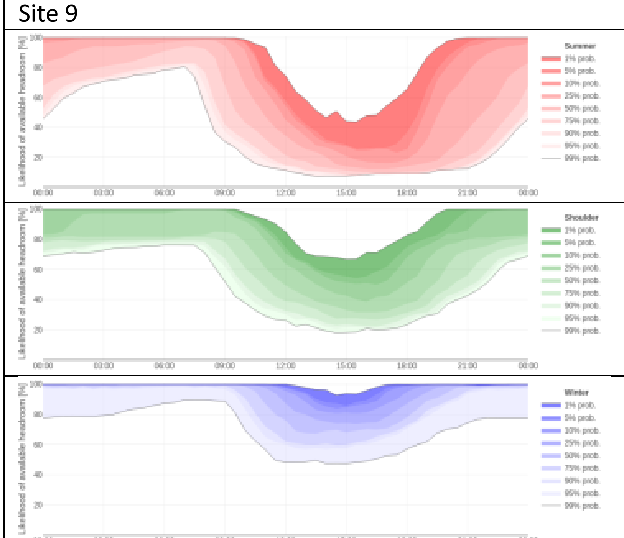

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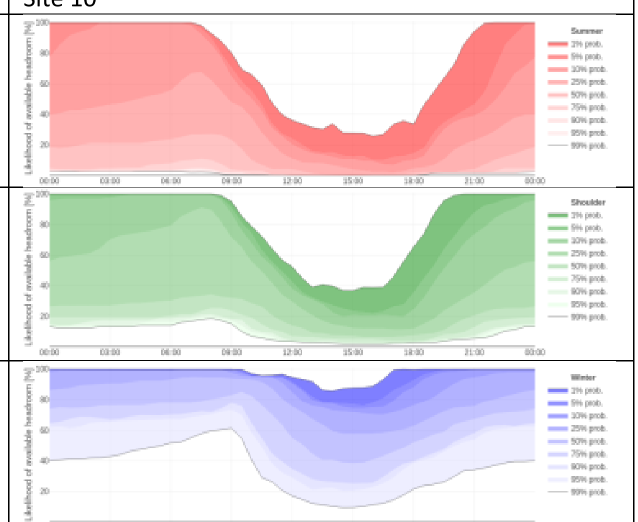

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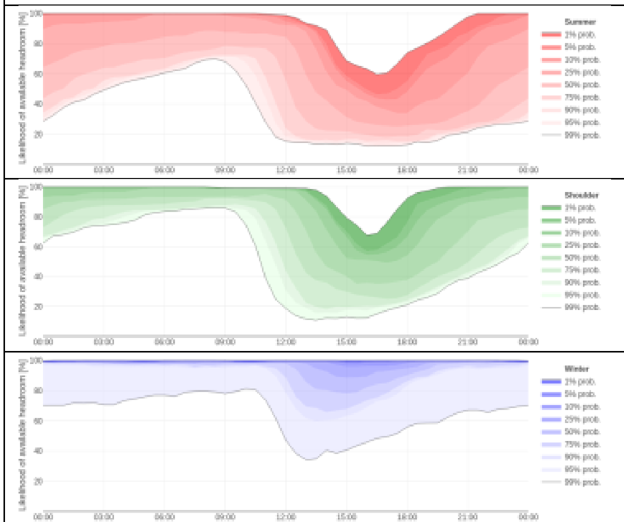

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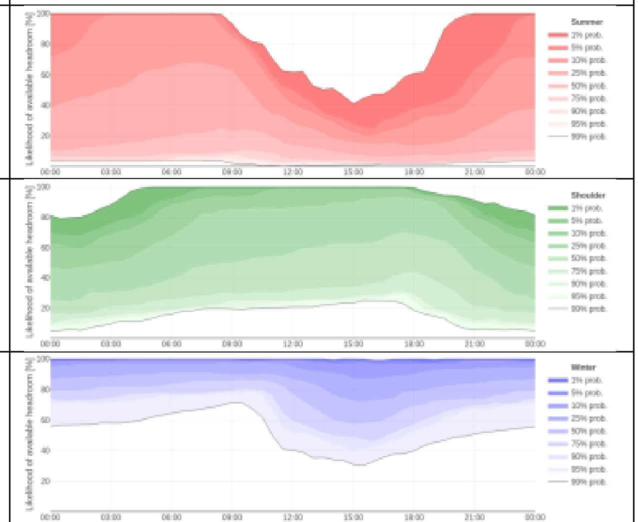

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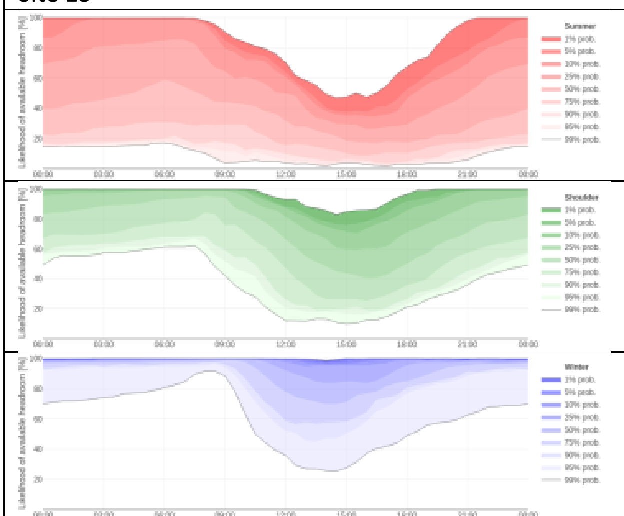

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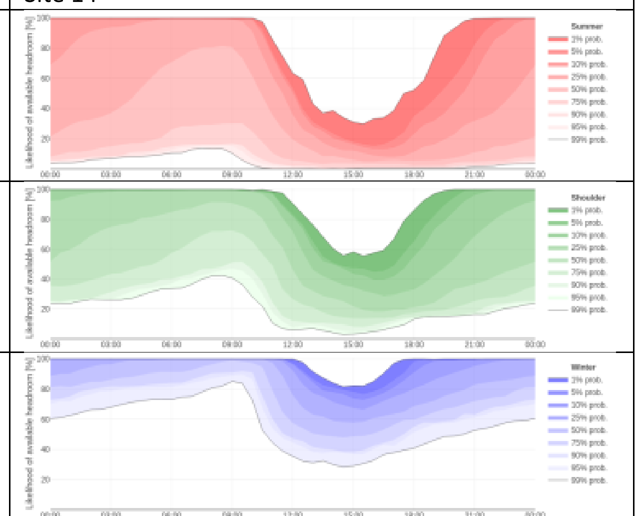

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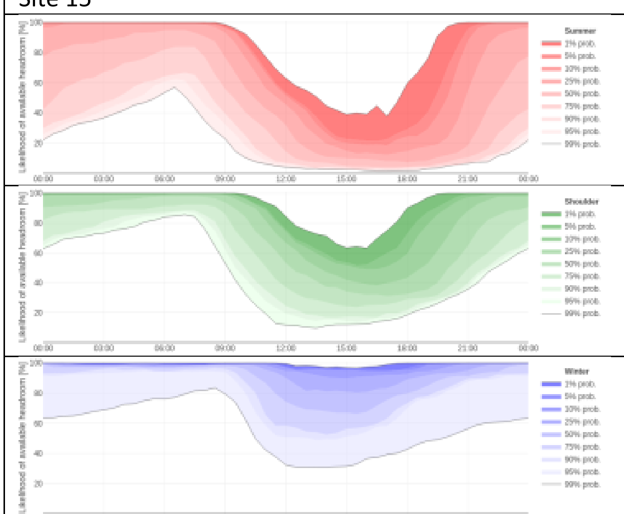

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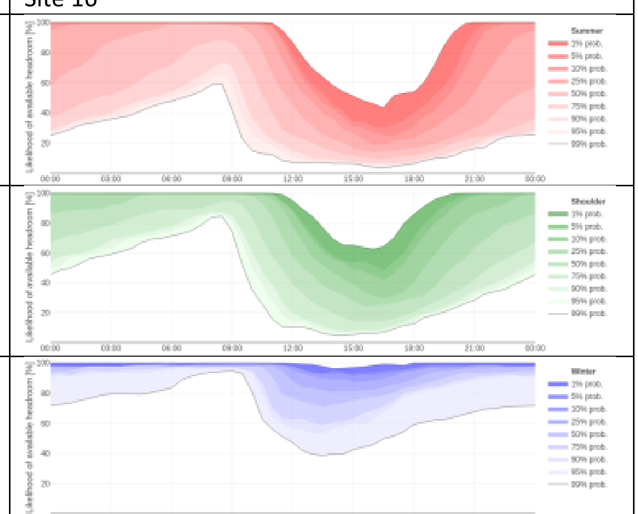

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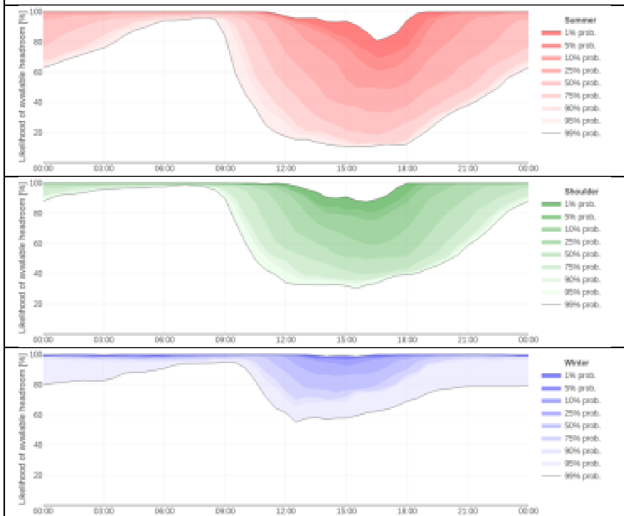

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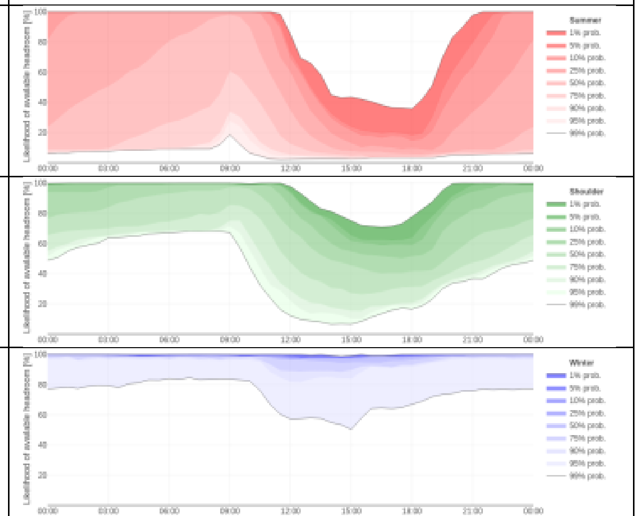

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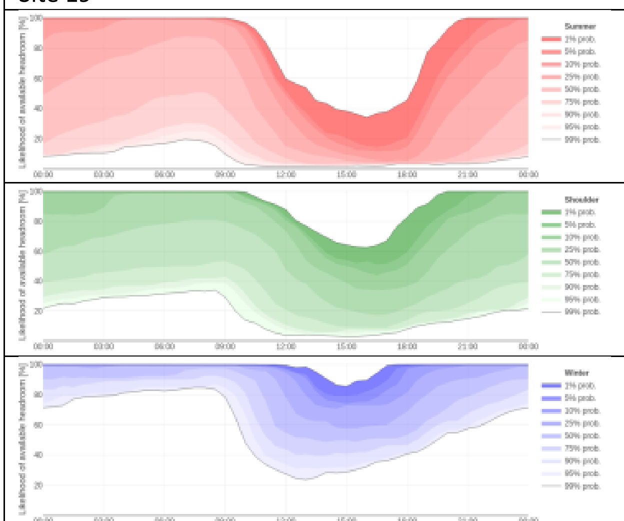

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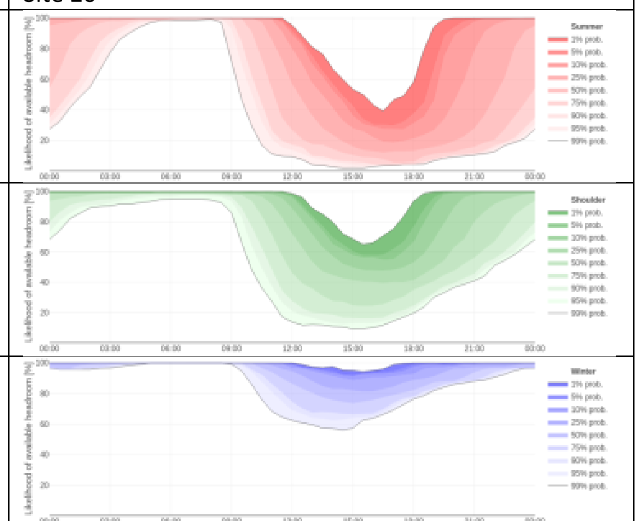

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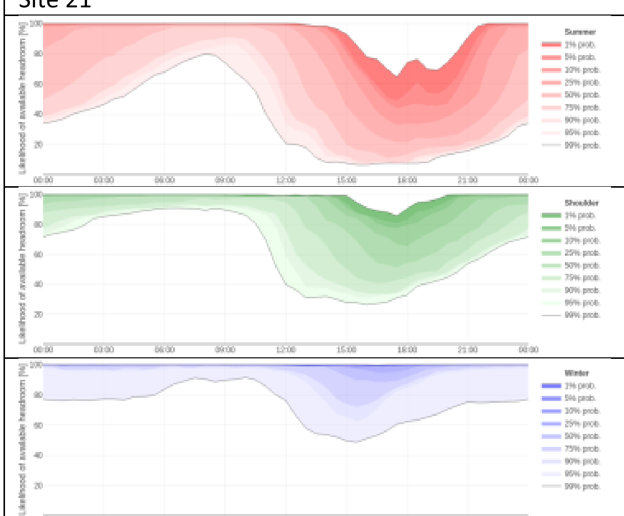

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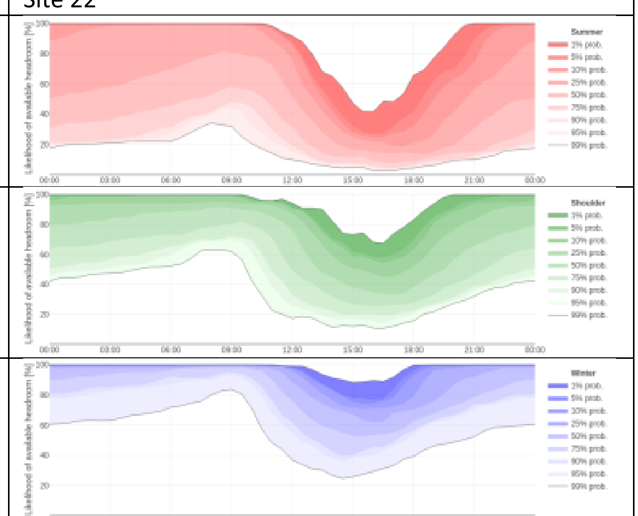

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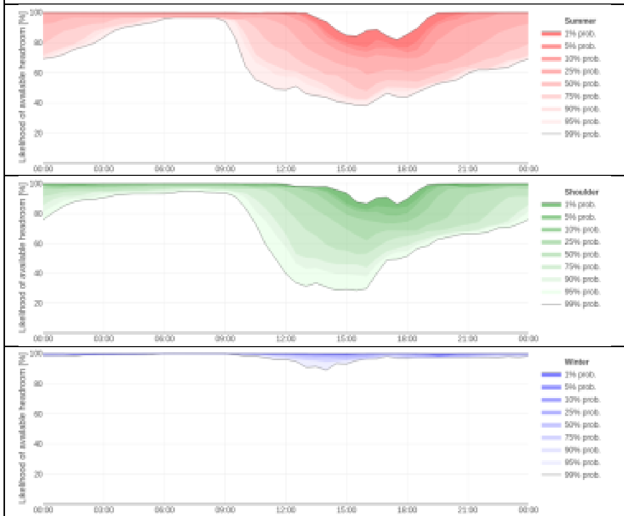

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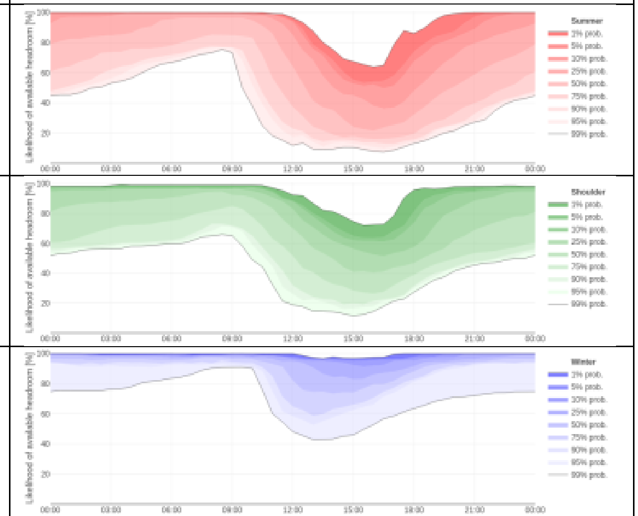

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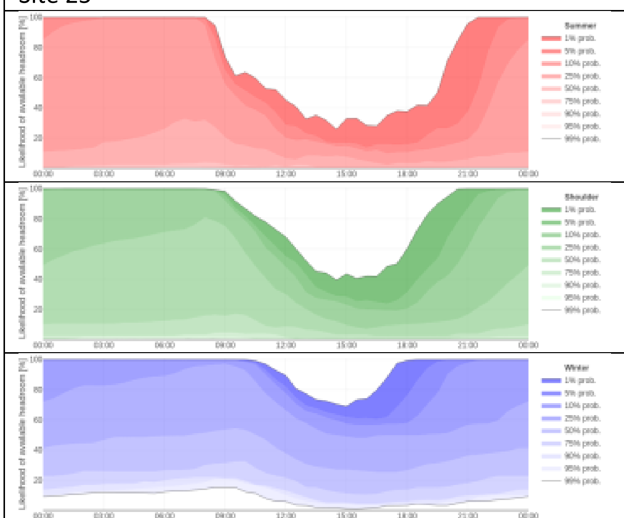
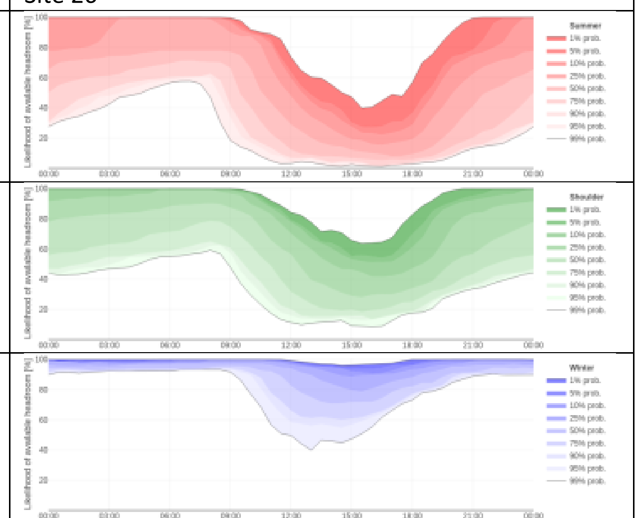


Site 26



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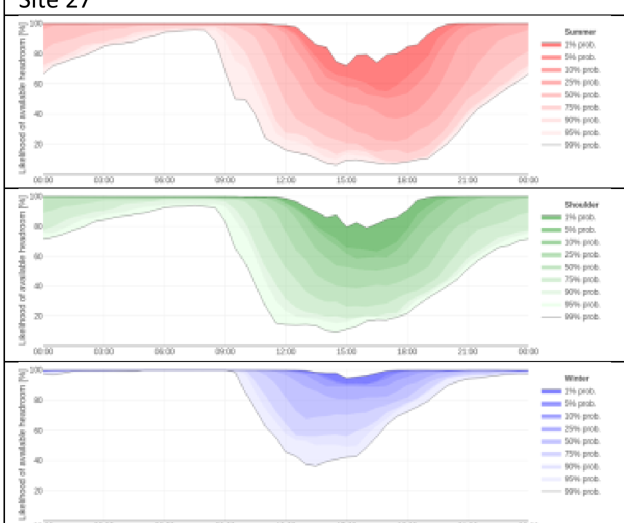

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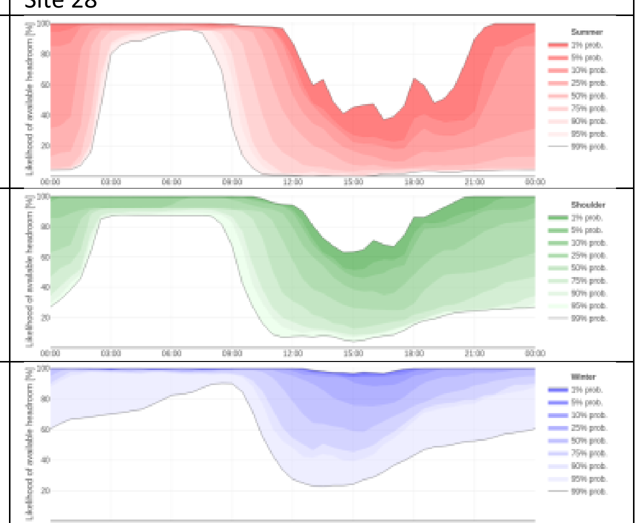

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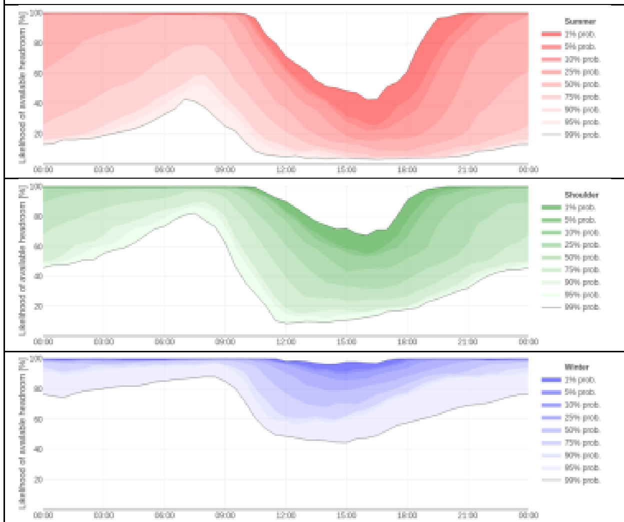	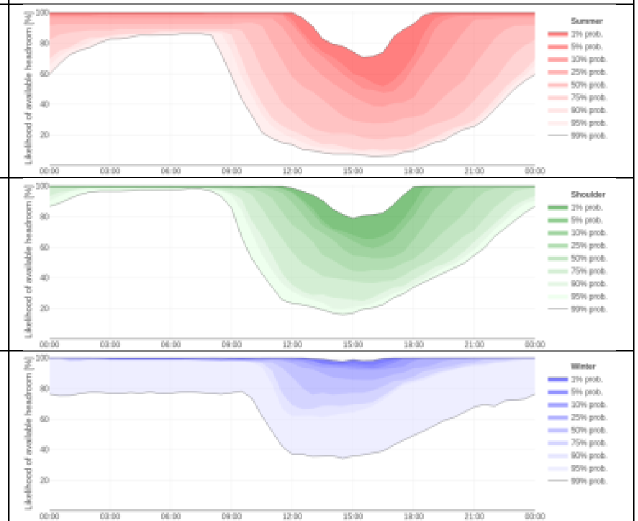
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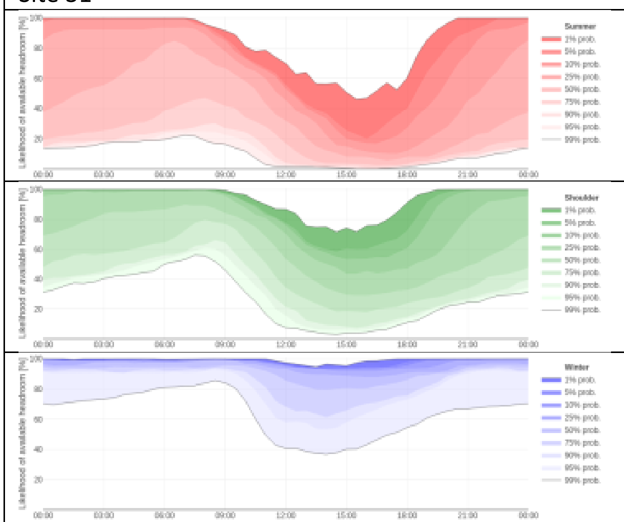	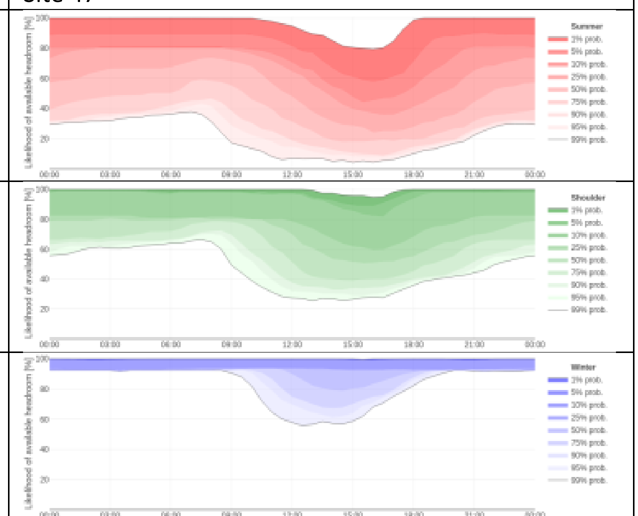
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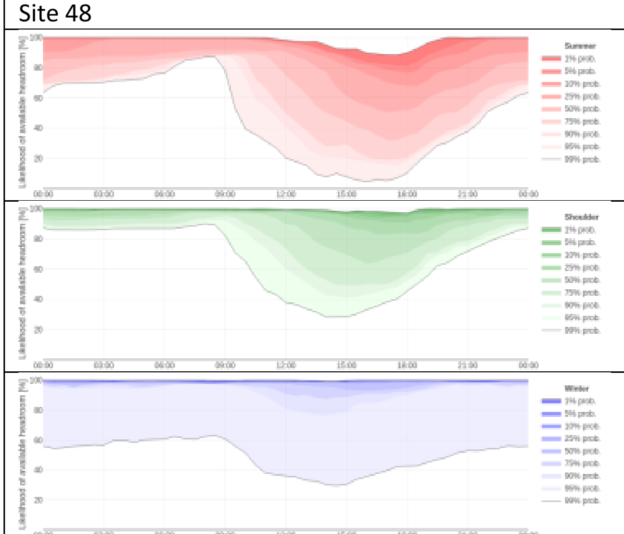	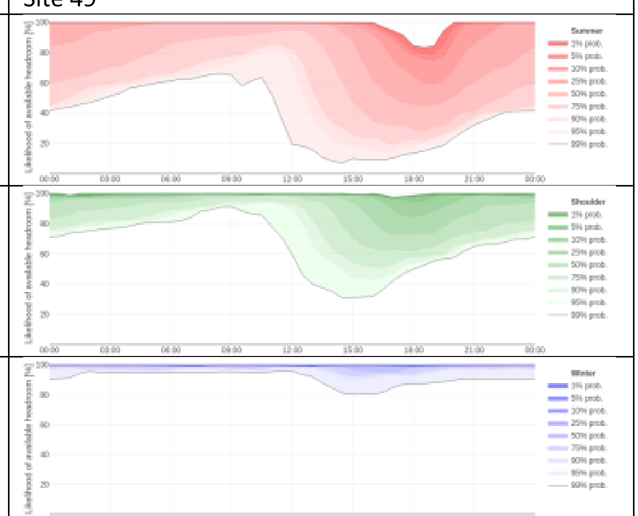

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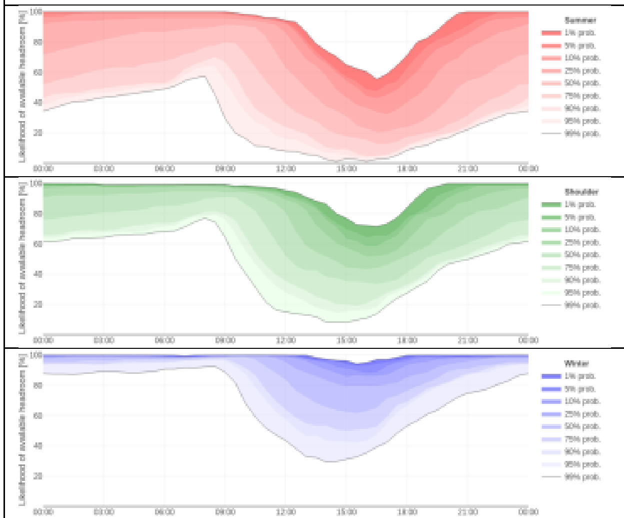

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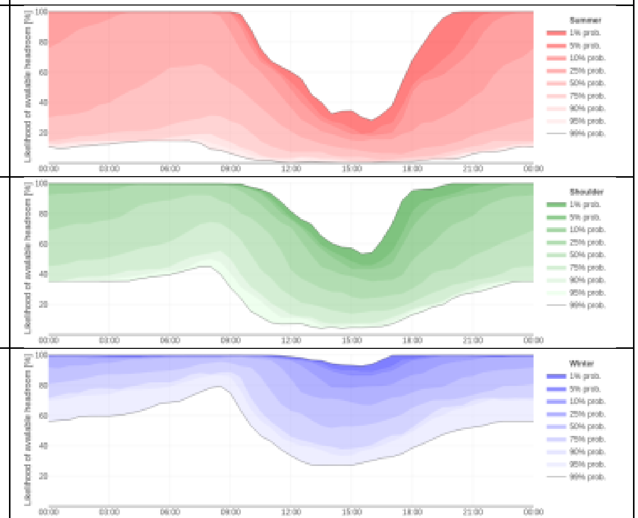

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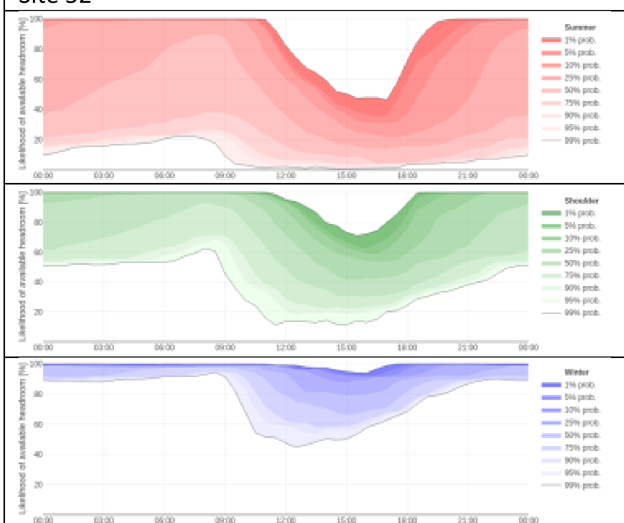

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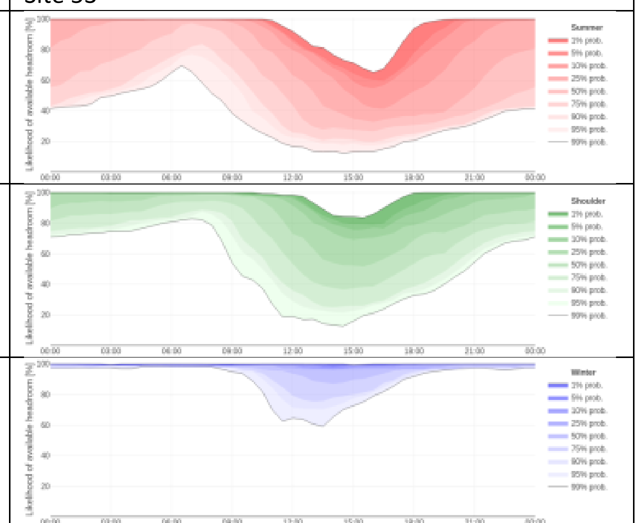

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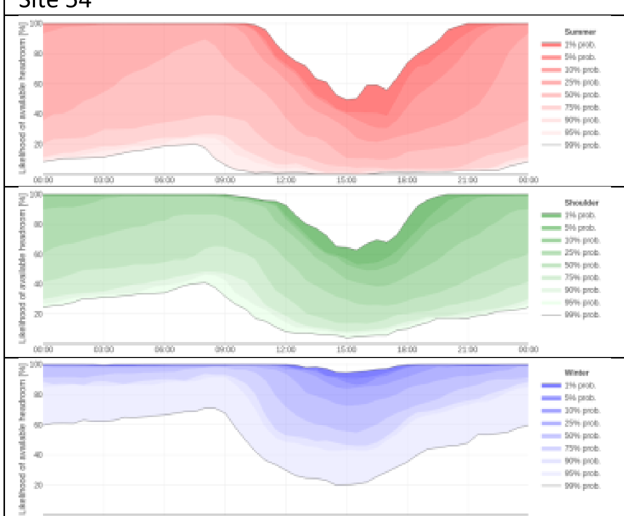

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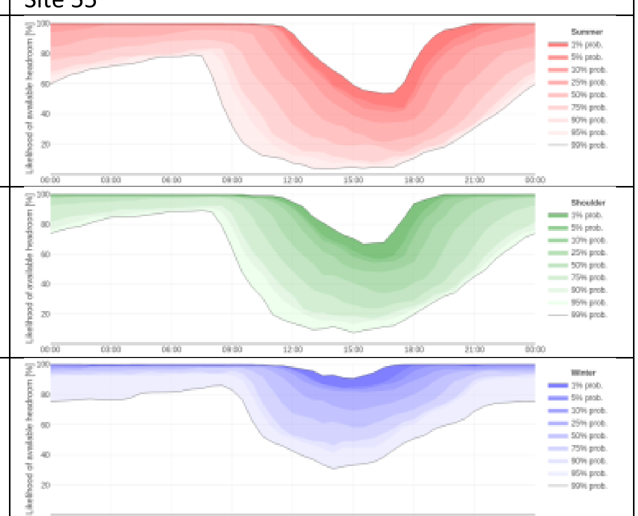

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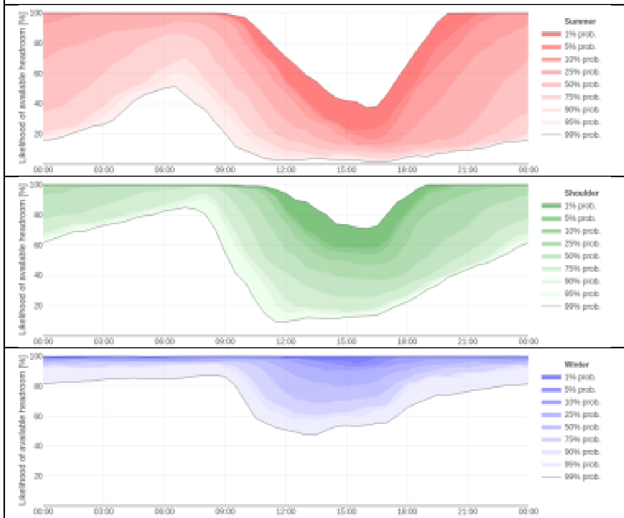

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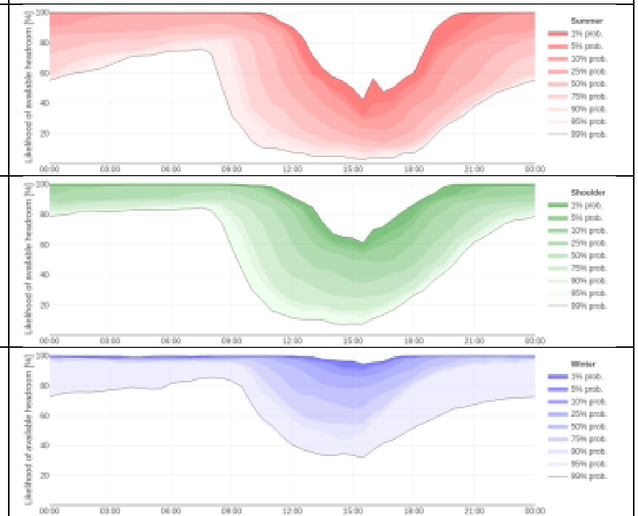

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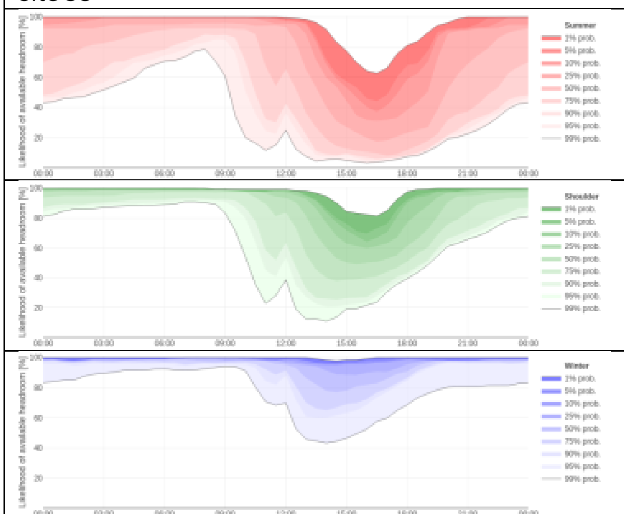

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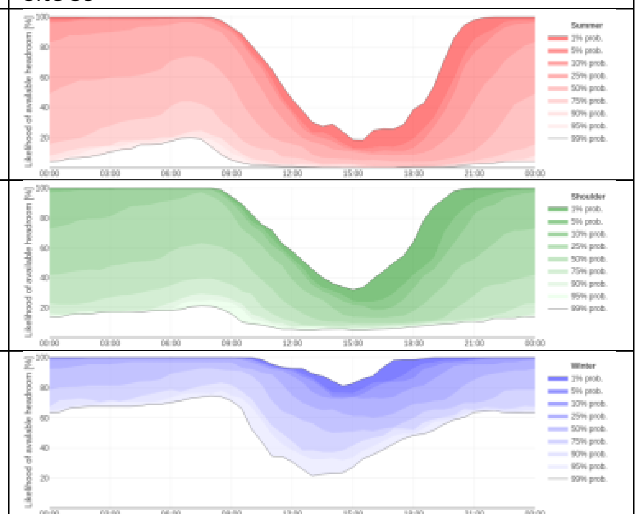

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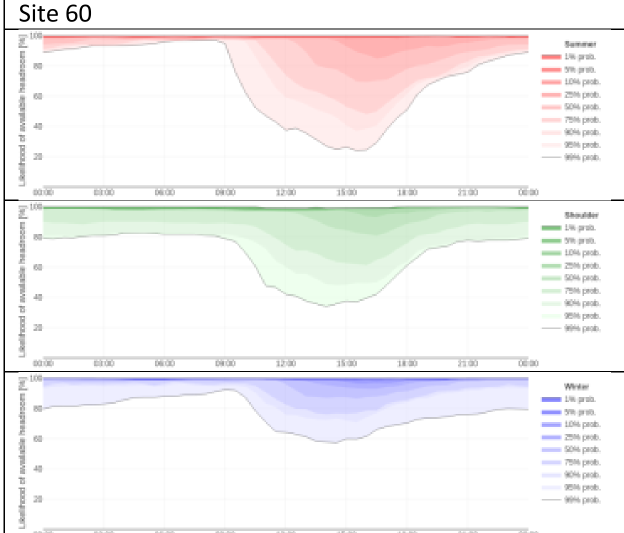

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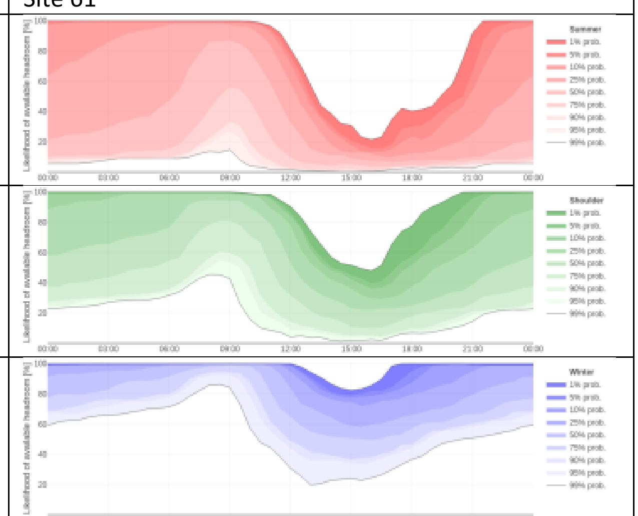

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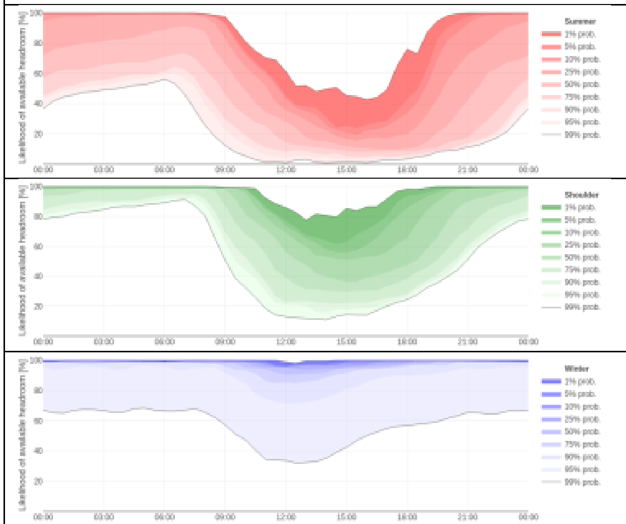

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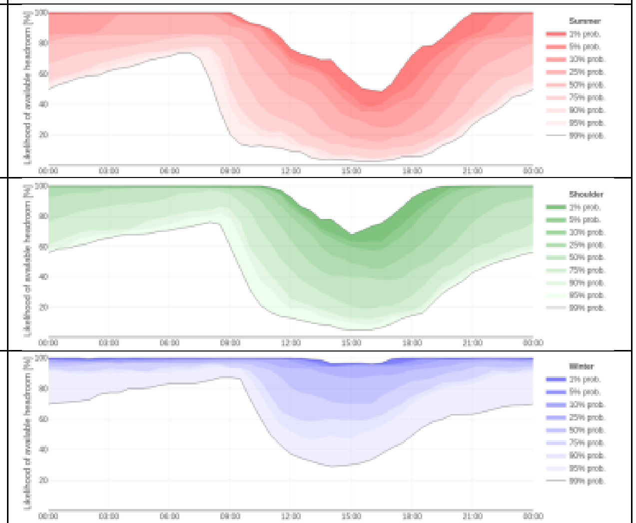

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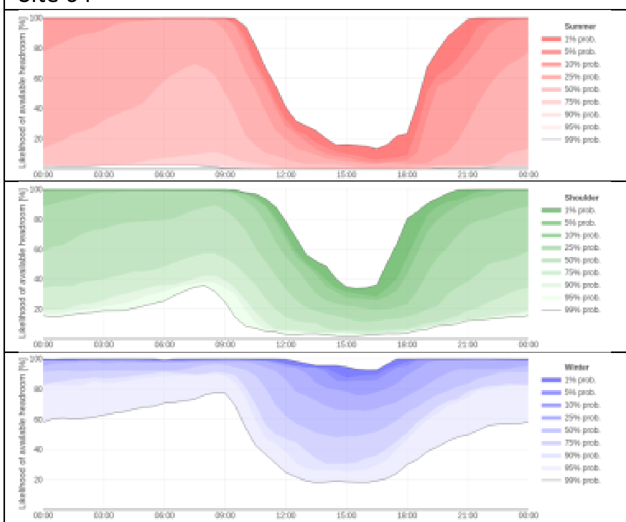

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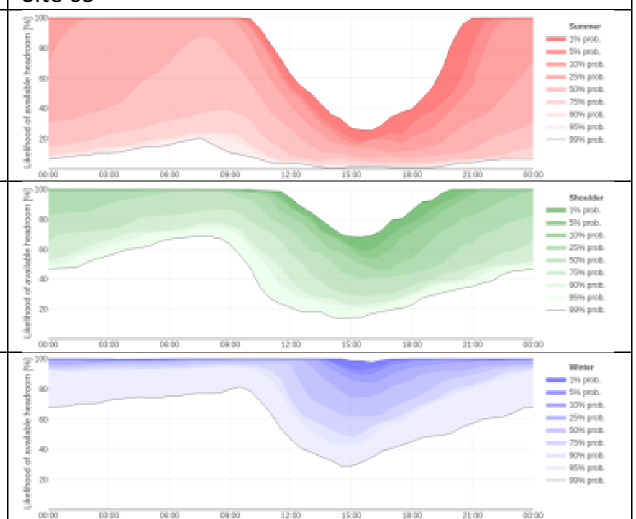

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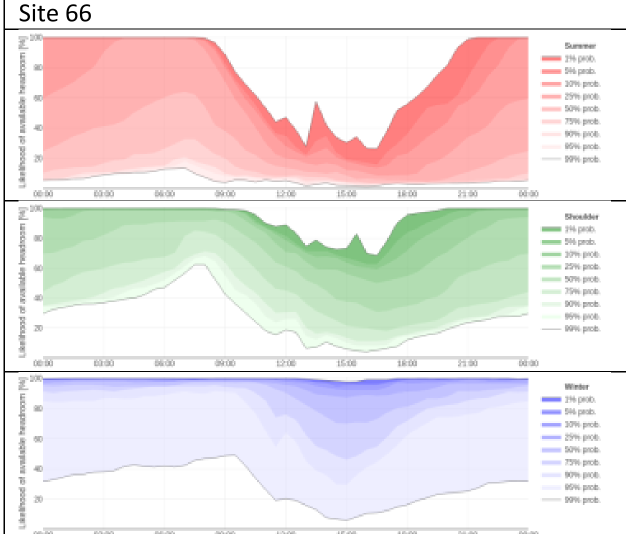

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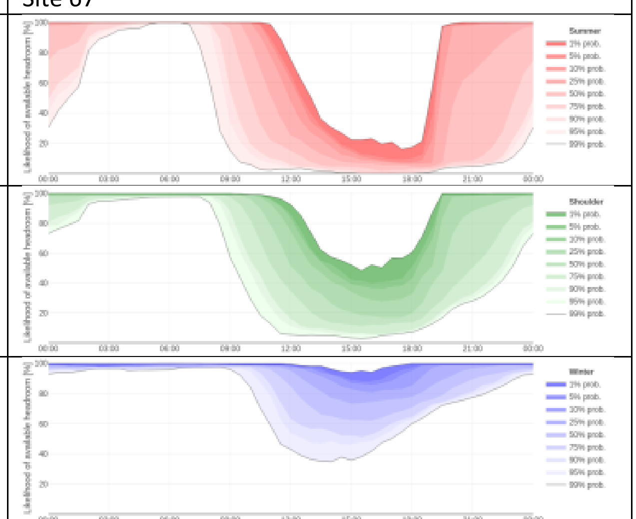

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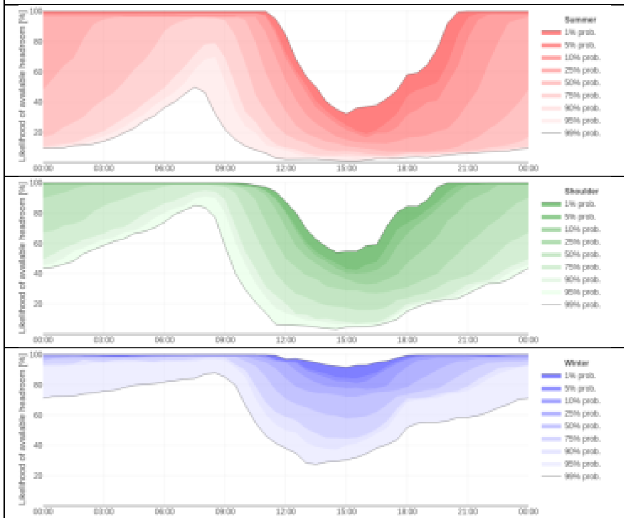

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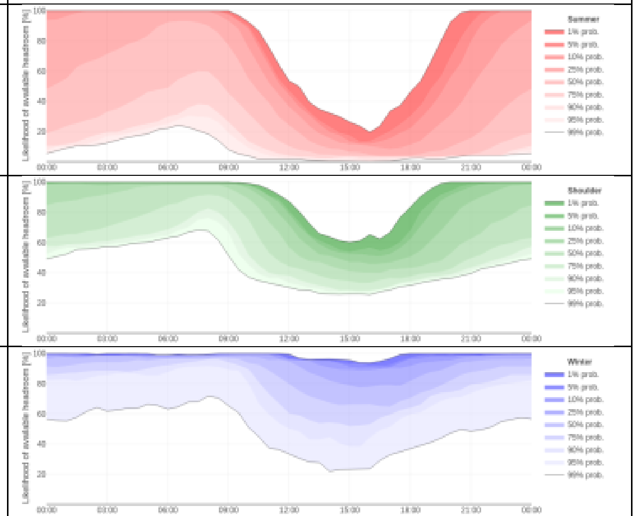

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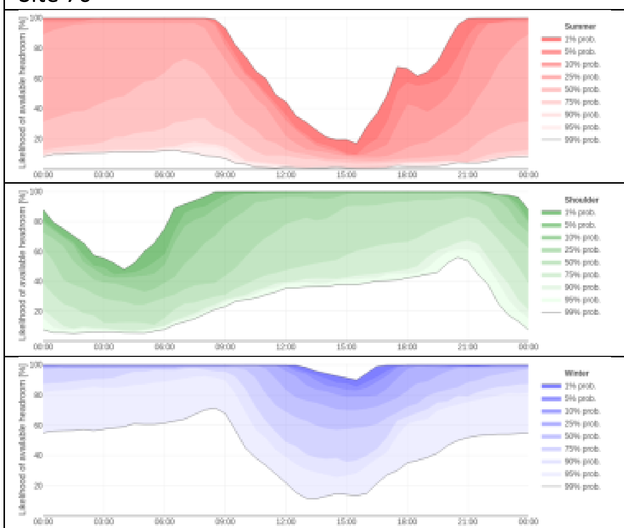

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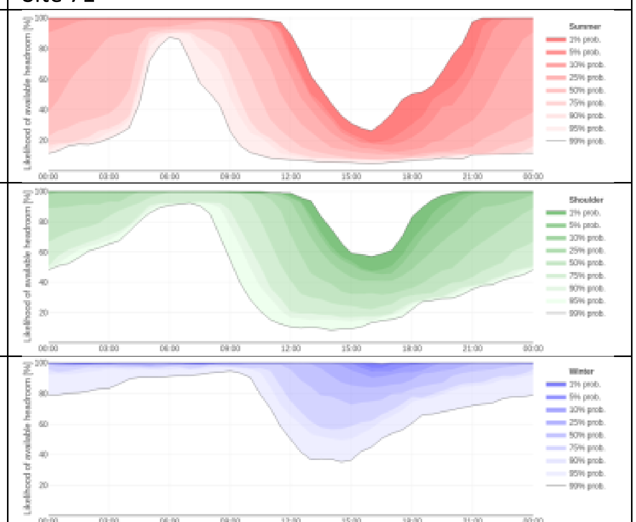

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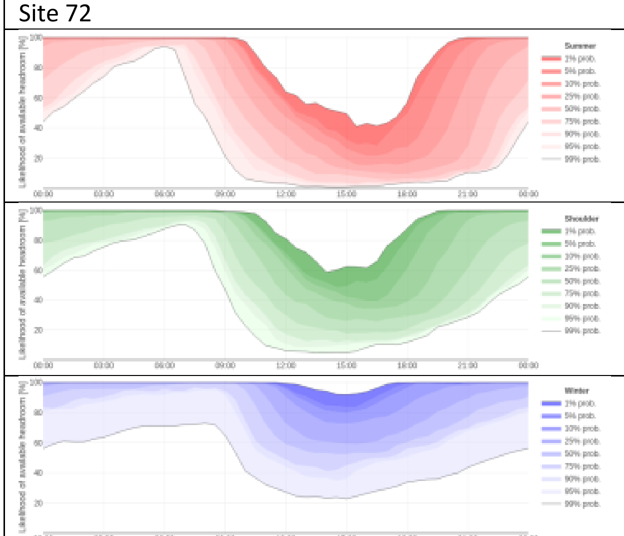

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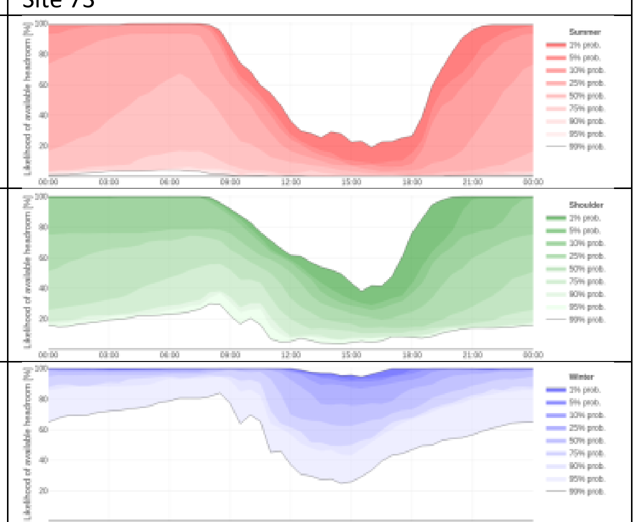

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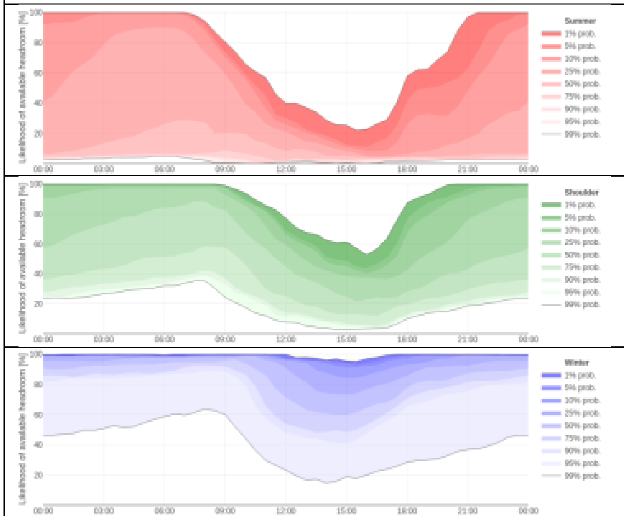	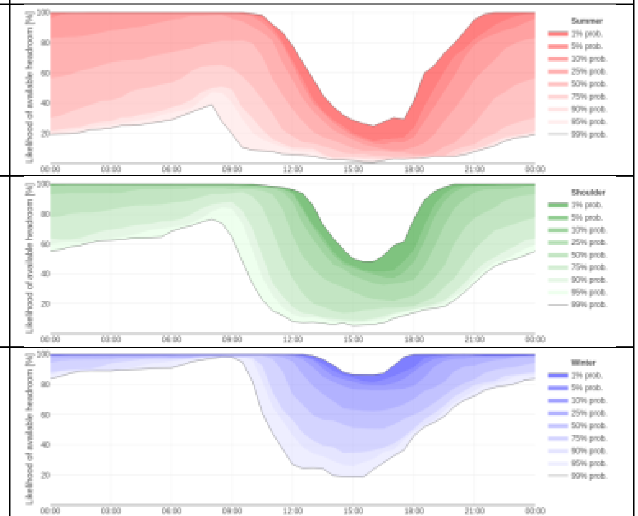
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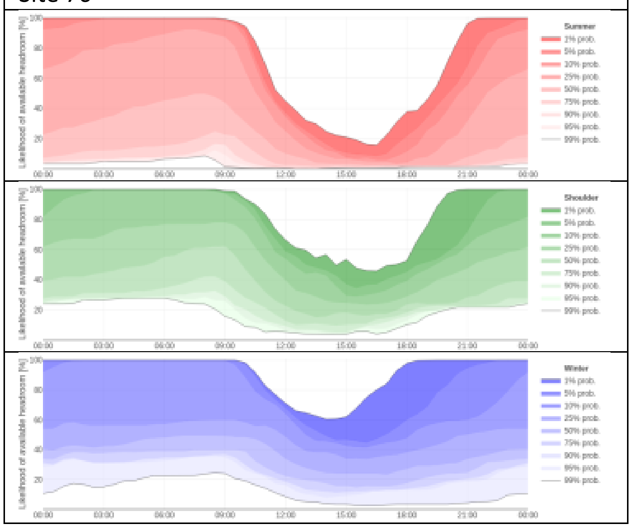	

8.1.2 Headroom Confidence Levels - 7.5kWh BESS

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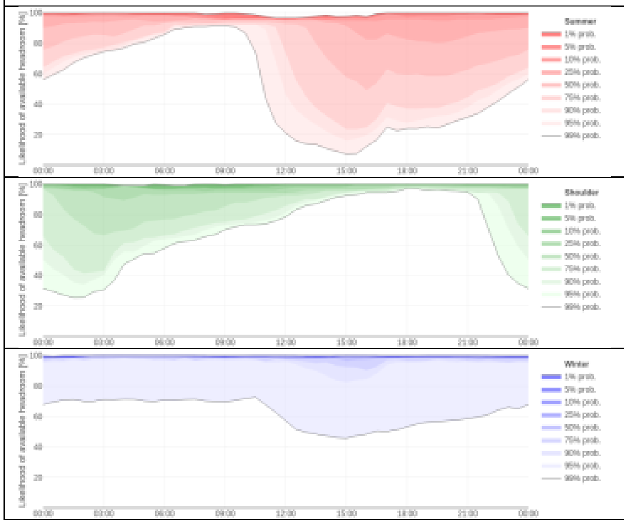

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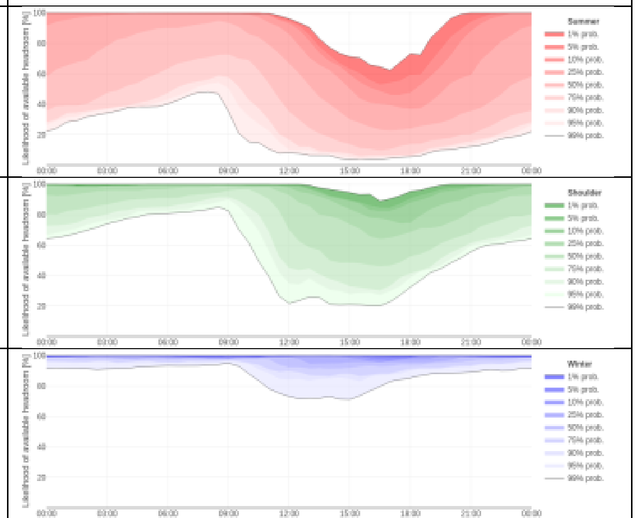

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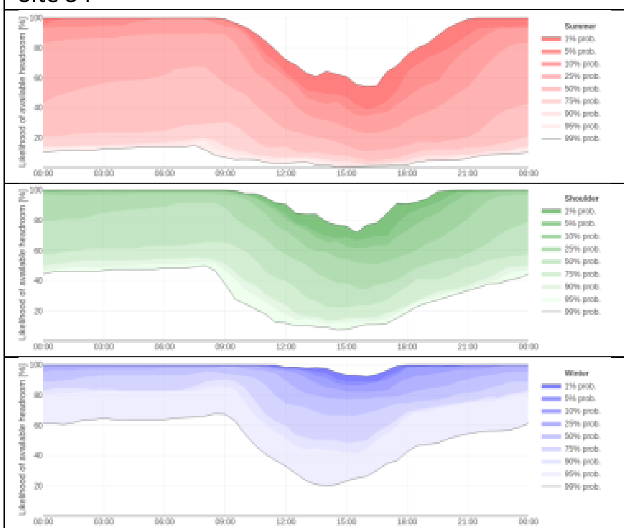

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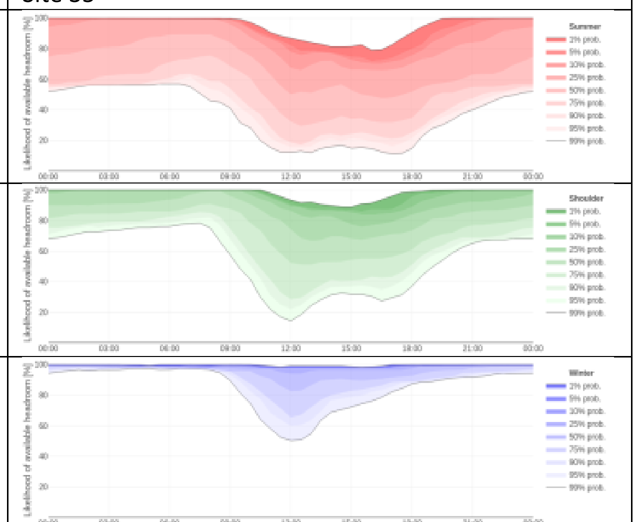

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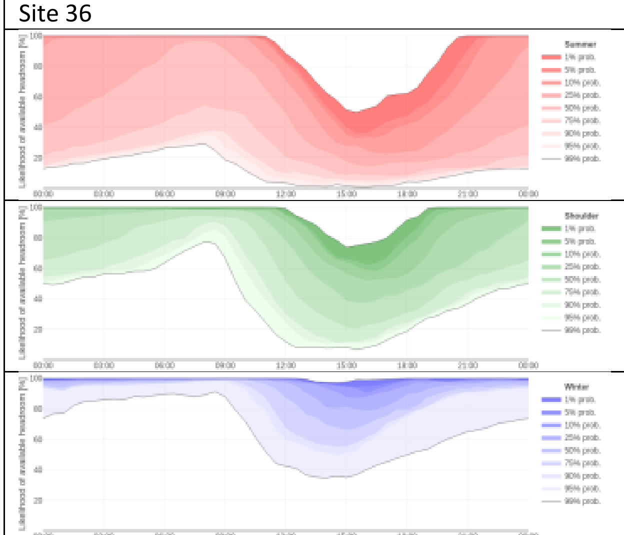

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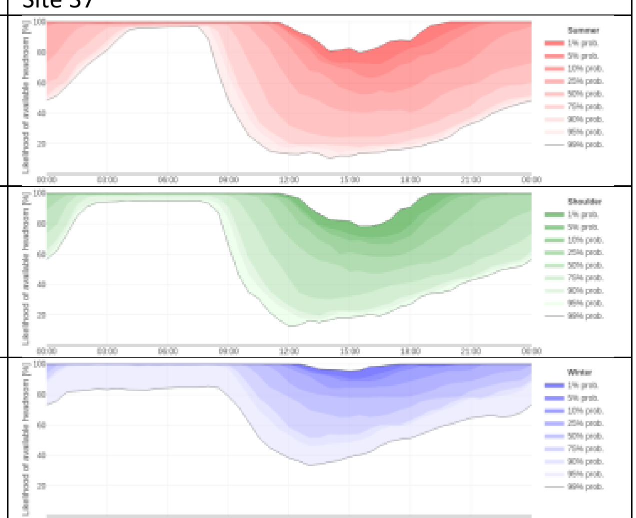

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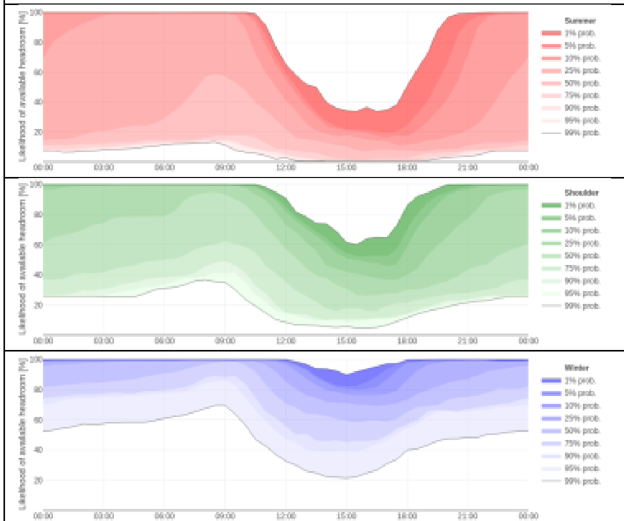

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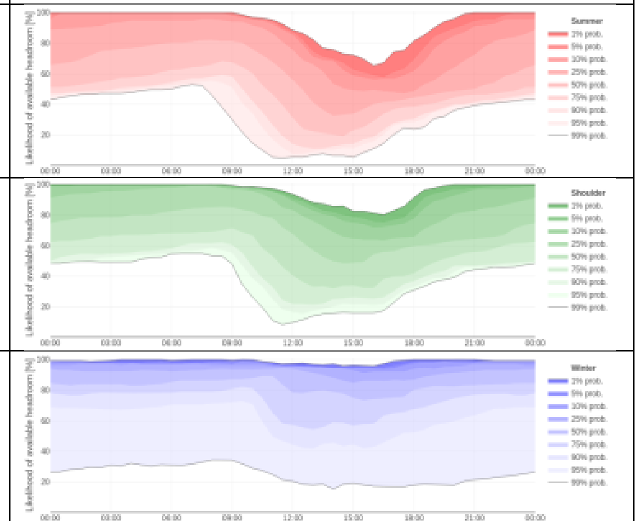

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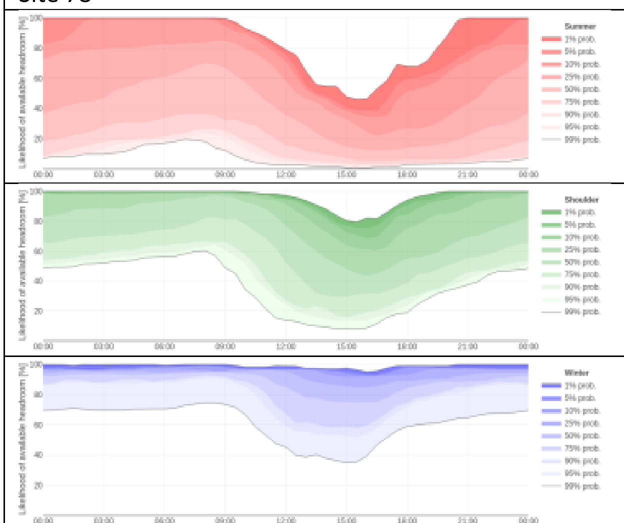

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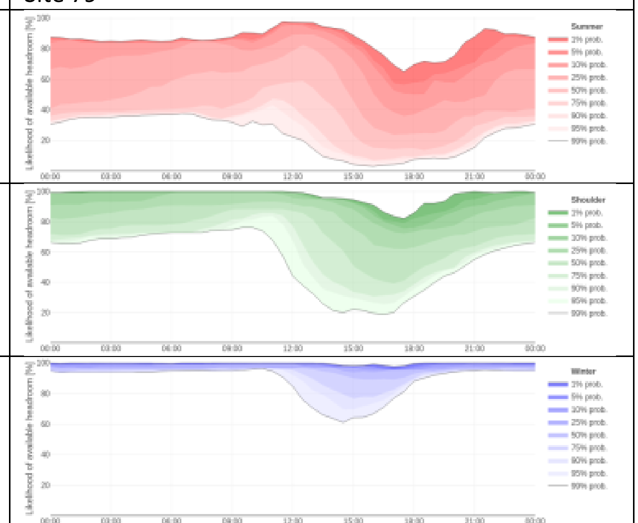

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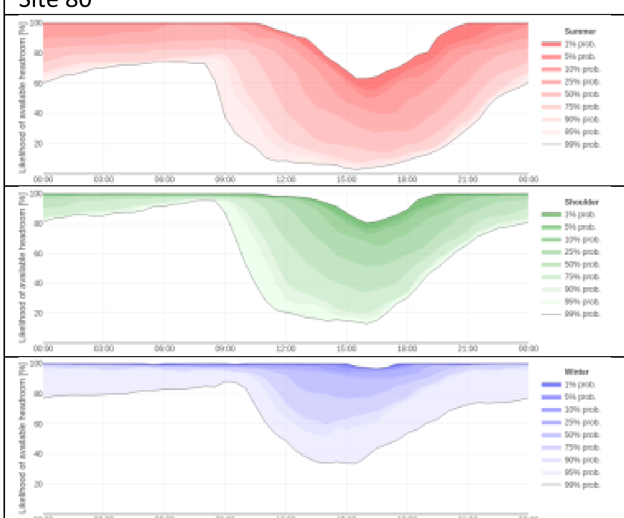

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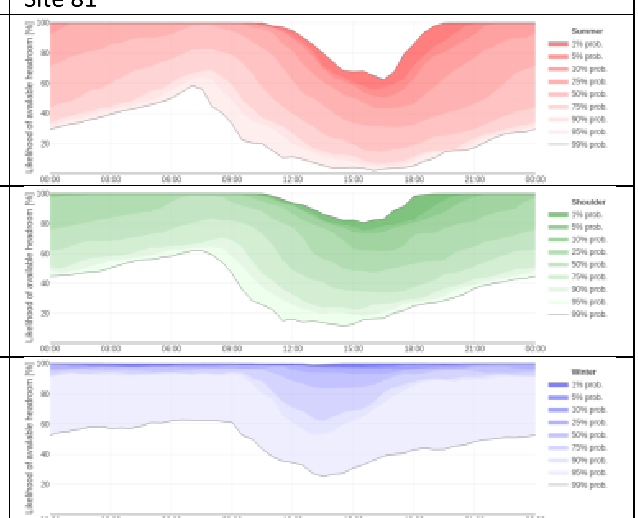

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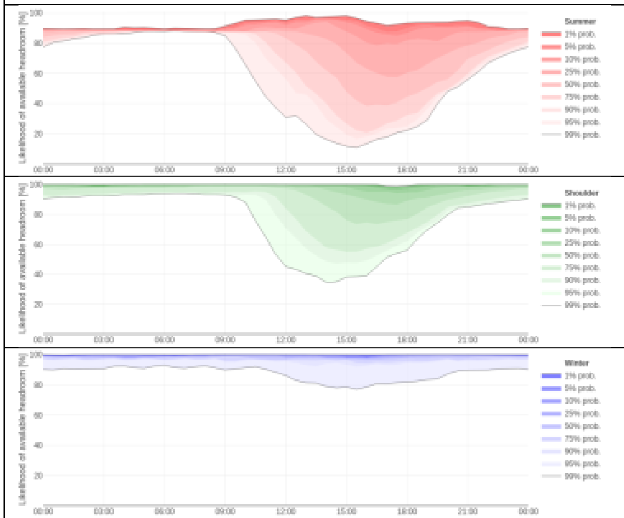

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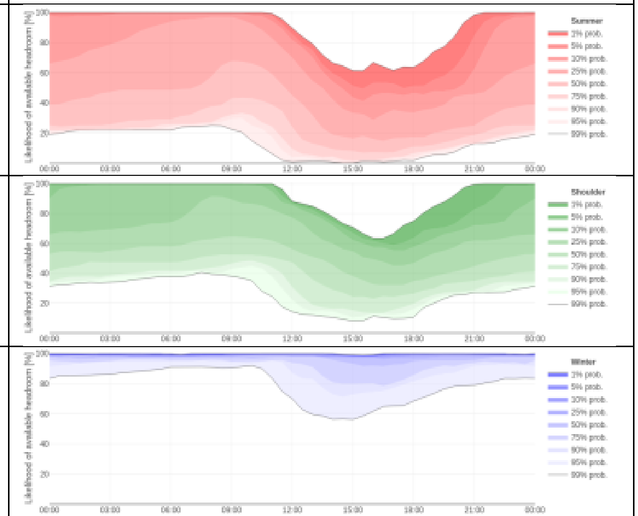

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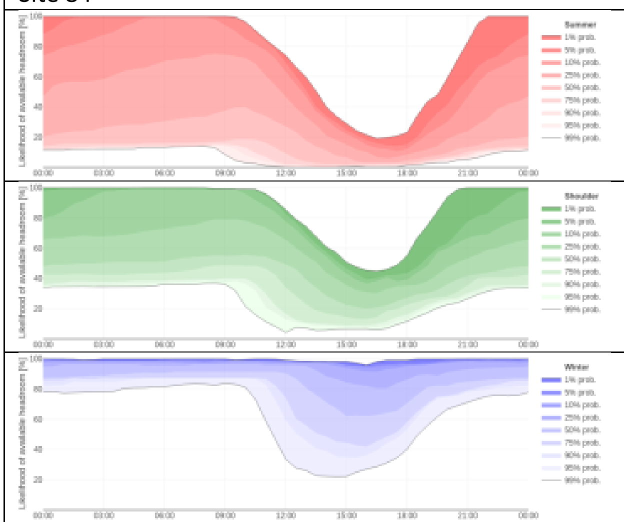

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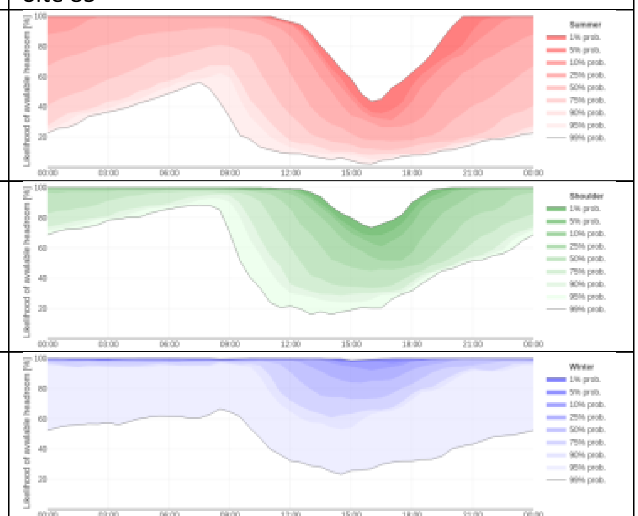

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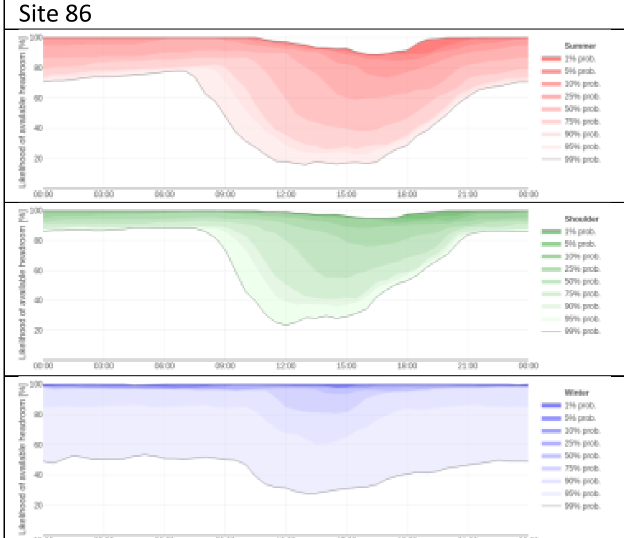

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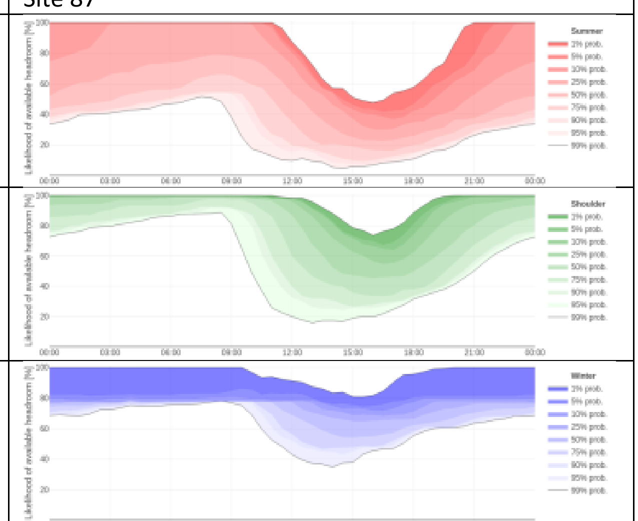

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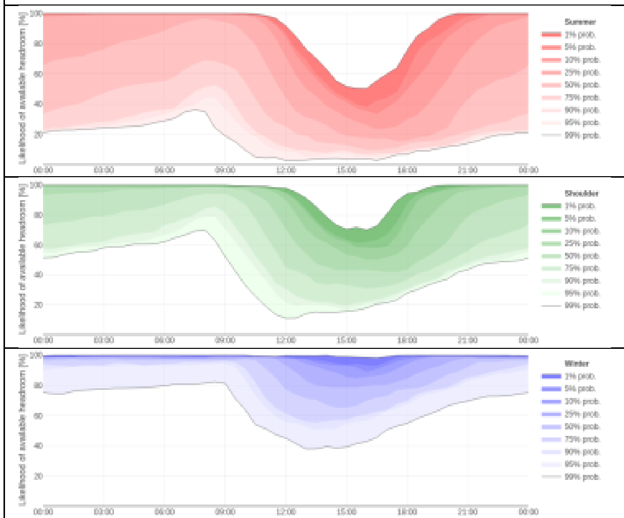

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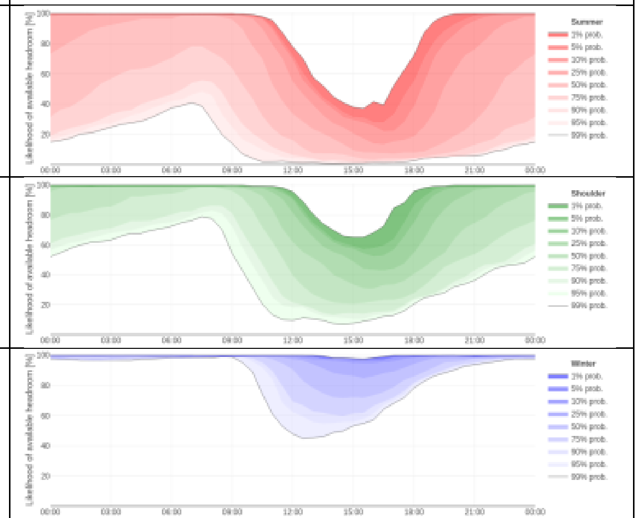

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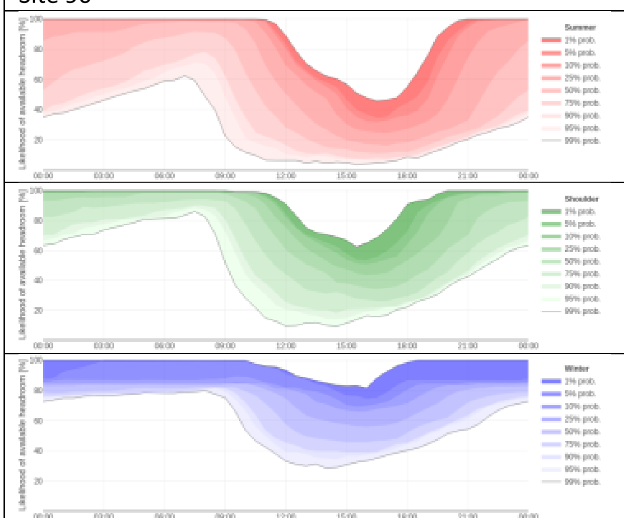

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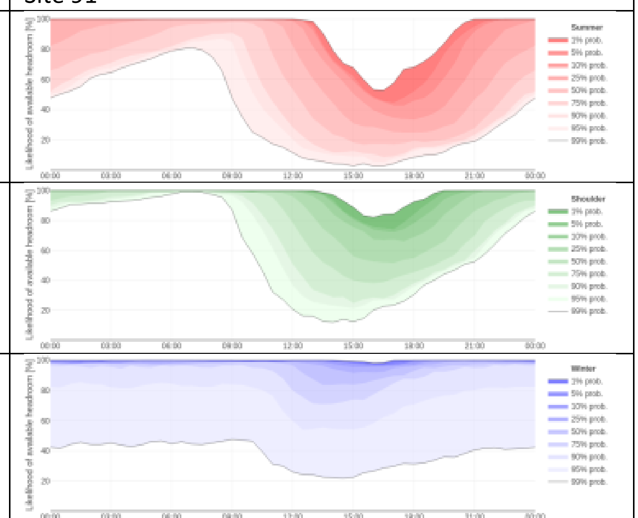

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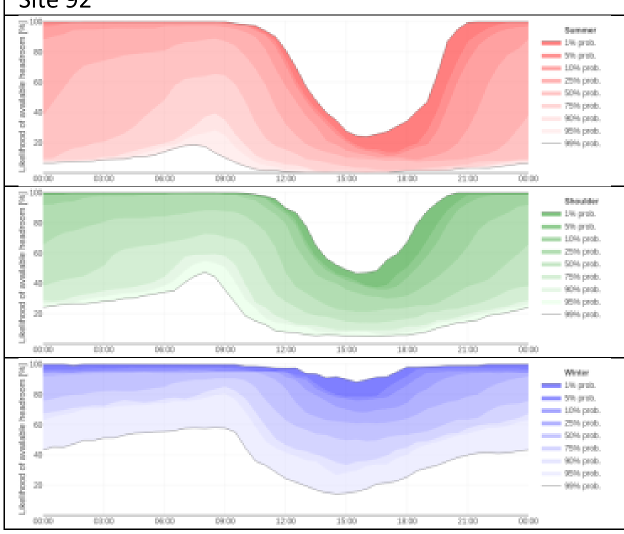

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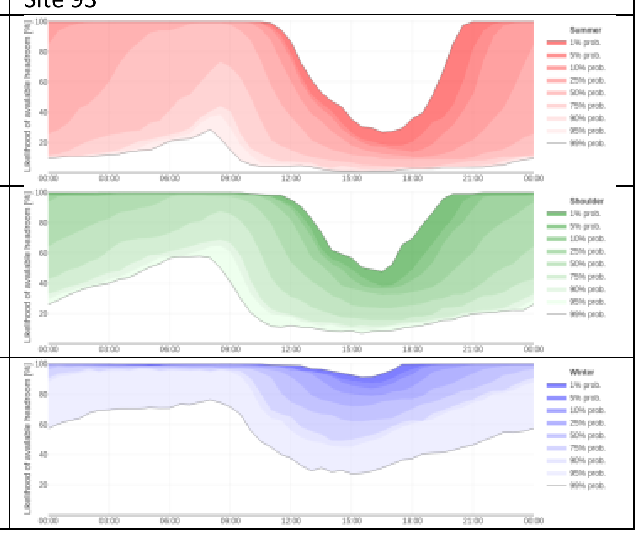

8.1.3 Headroom Confidence Levels - 10kWh BESS

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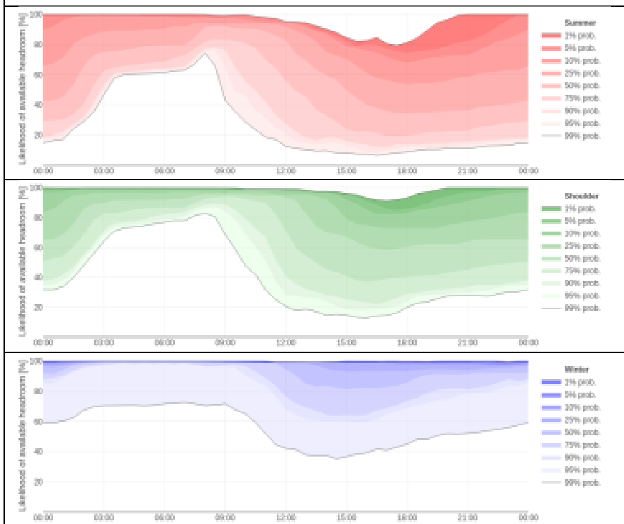	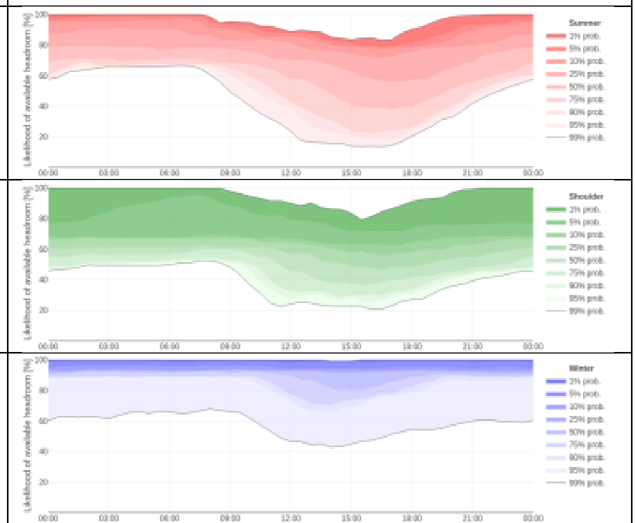
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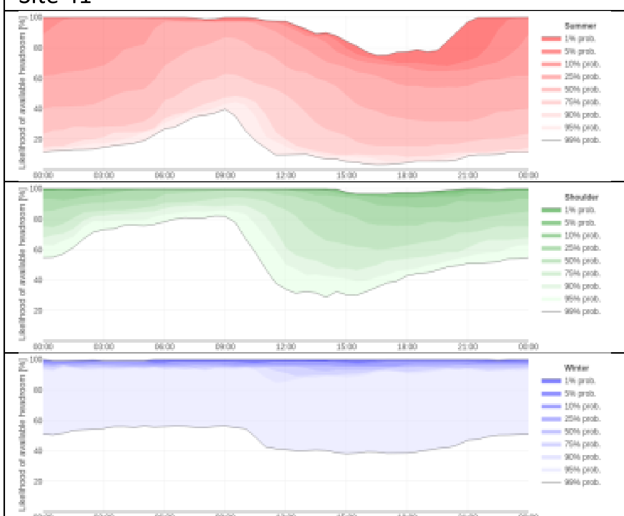	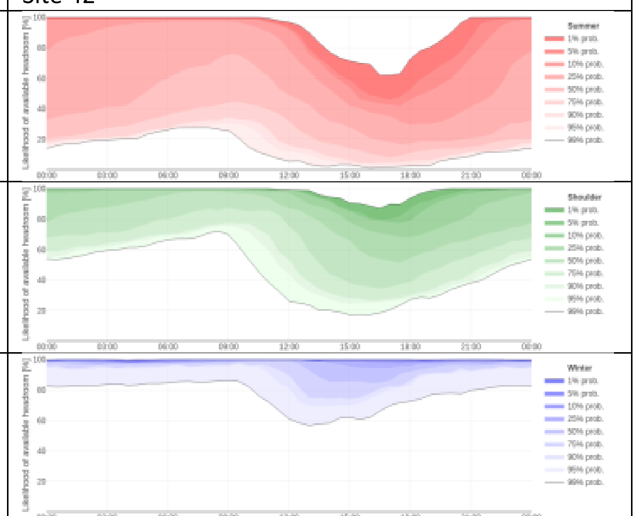
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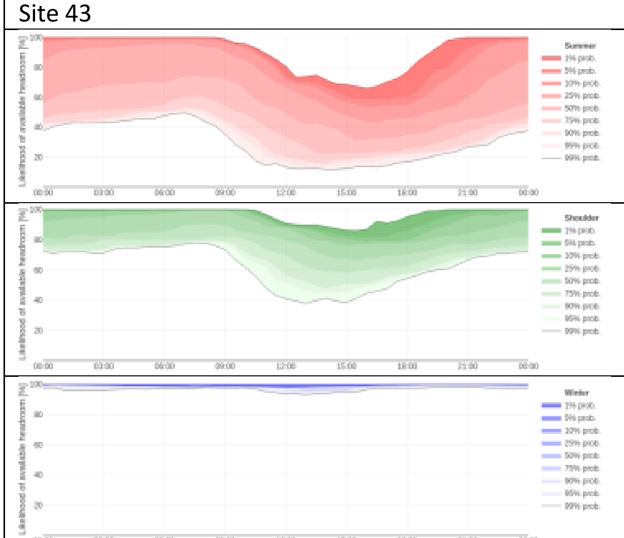	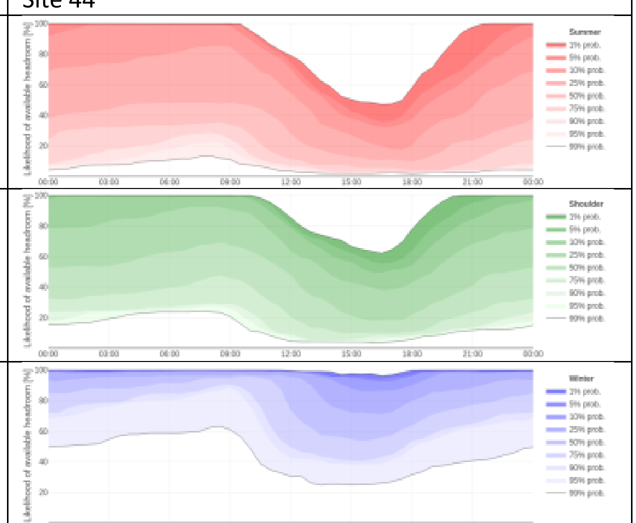

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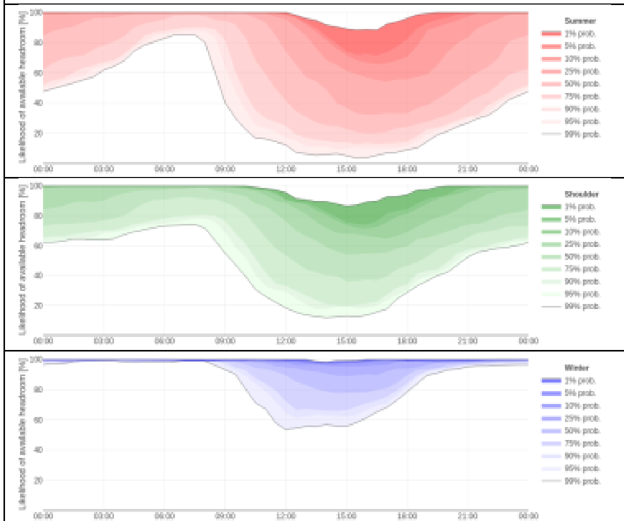

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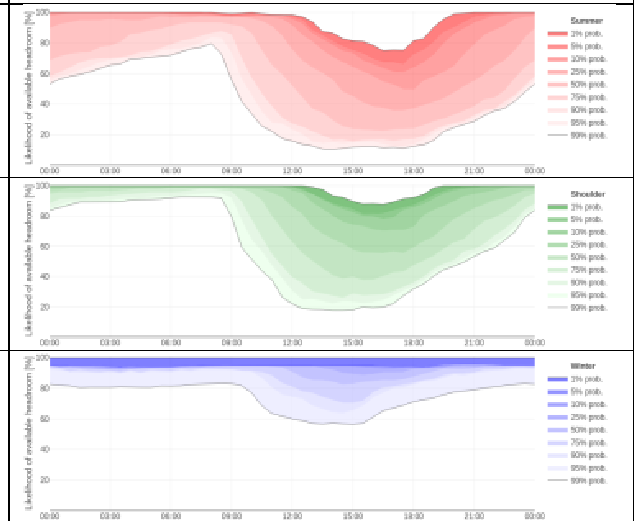

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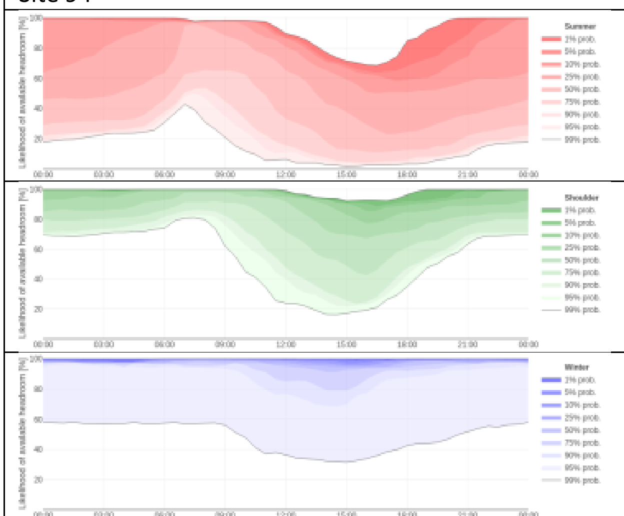

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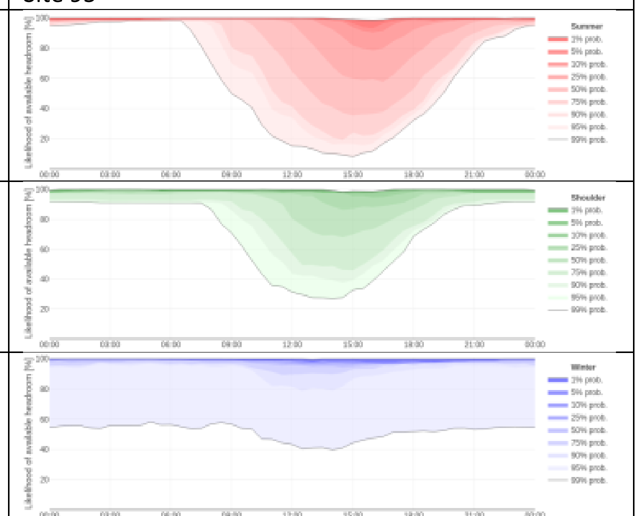

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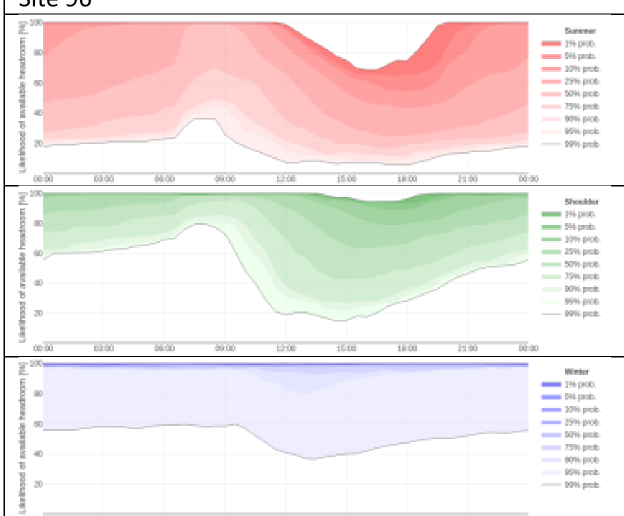

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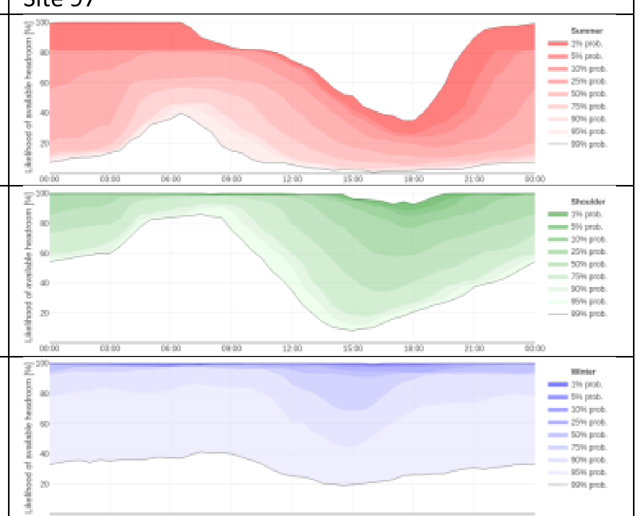

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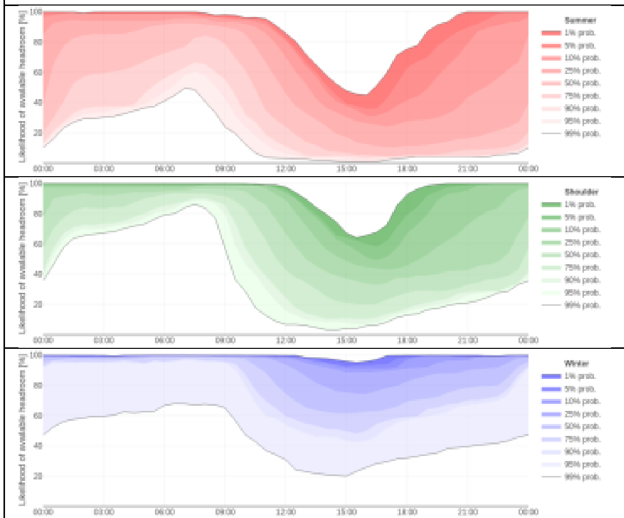

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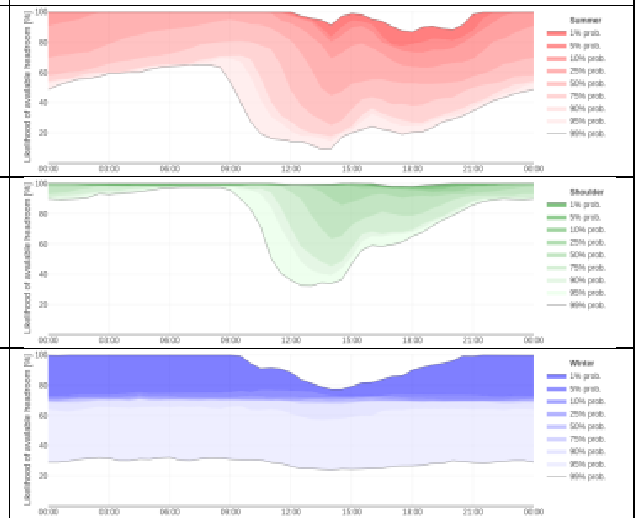
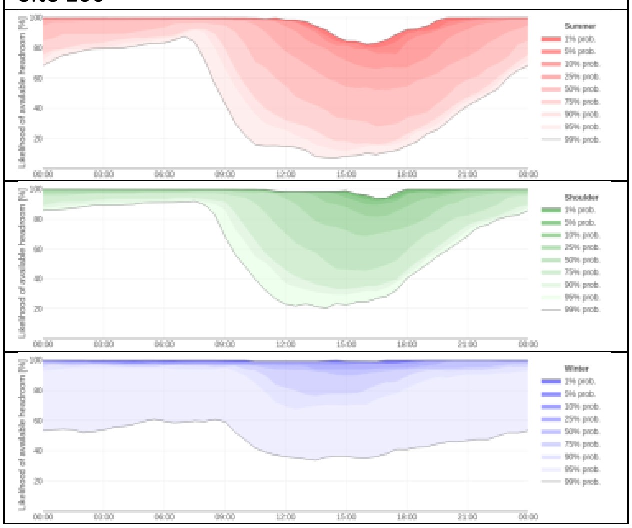


Site 100



8.2 Appendix A2: Headroom Analysis per Sub-Fleet

The complete series of site-specific Confidence Levels (CL) are detailed in this section. These correspond to the fleet-level (aggregate) figures provided in **Section 3** (Headroom Analysis).

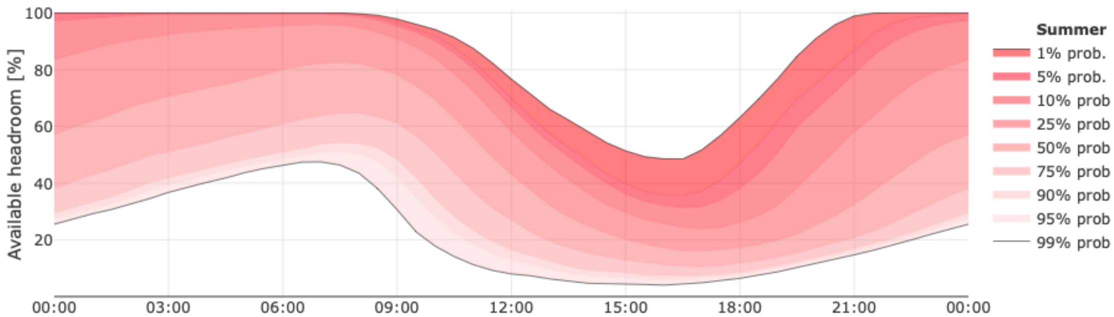


Figure A2-1: Summer headroom confidence levels (5kWh BESS sub-fleet)

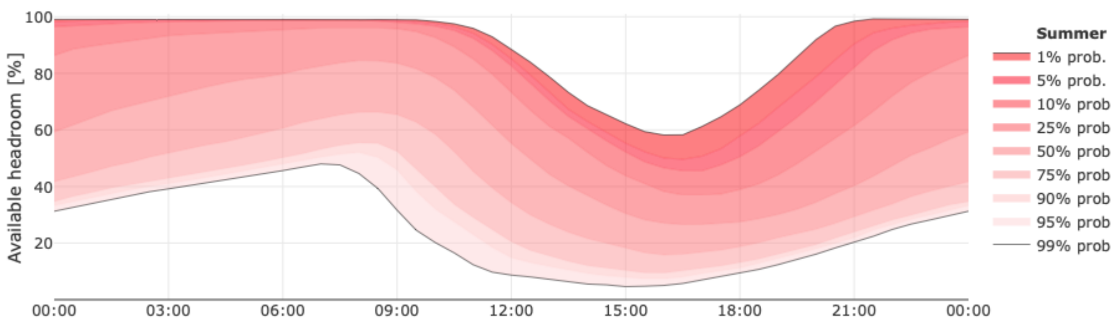


Figure A2-2: Summer headroom confidence levels (7.5kWh BESS sub-fleet)

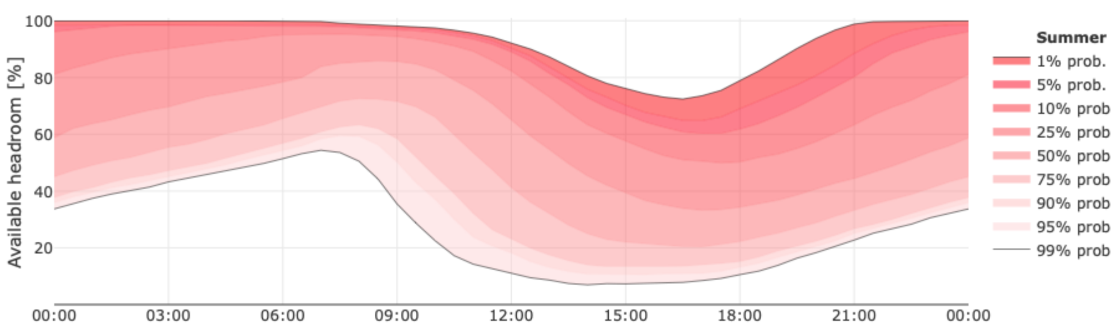


Figure A2-3: Summer headroom confidence levels (10kWh BESS sub-fleet)

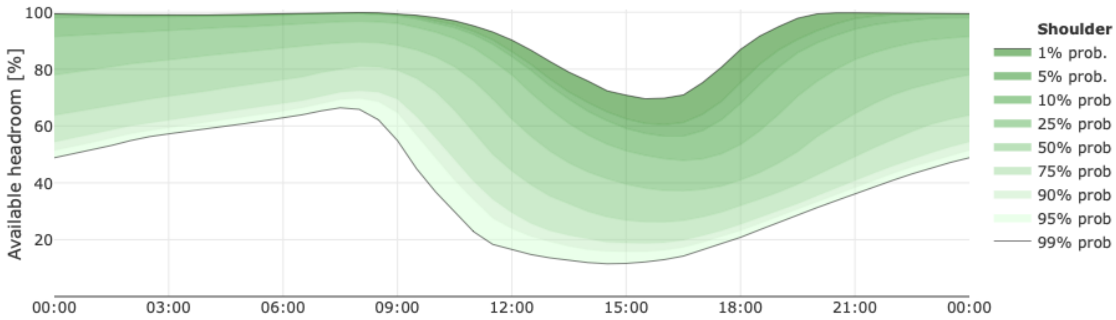


Figure A2-4: Shoulder headroom confidence levels (5kWh BESS sub-fleet)

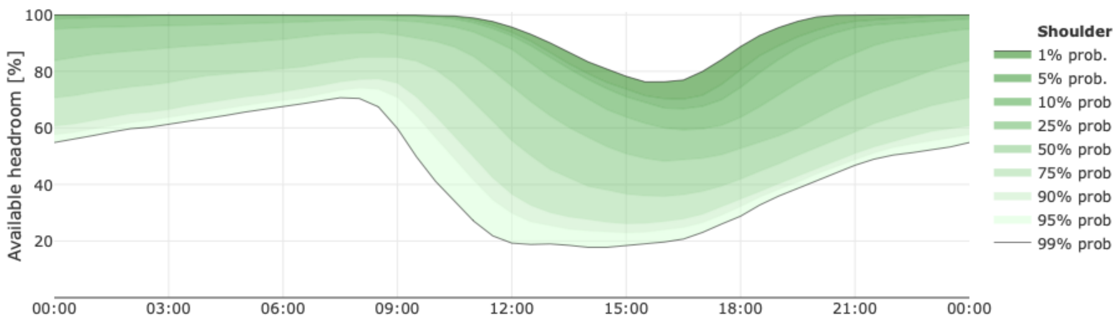


Figure A2-5: Shoulder headroom confidence levels (7.5kWh BESS sub-fleet)

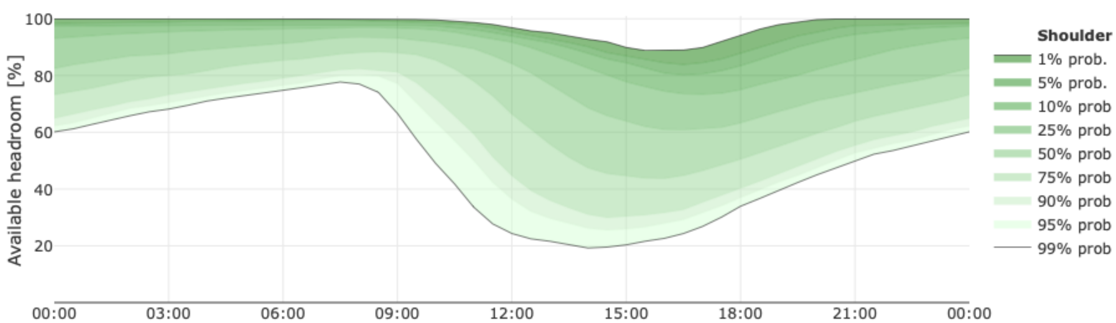


Figure A2-6: Shoulder headroom confidence levels (10kWh BESS sub-fleet)

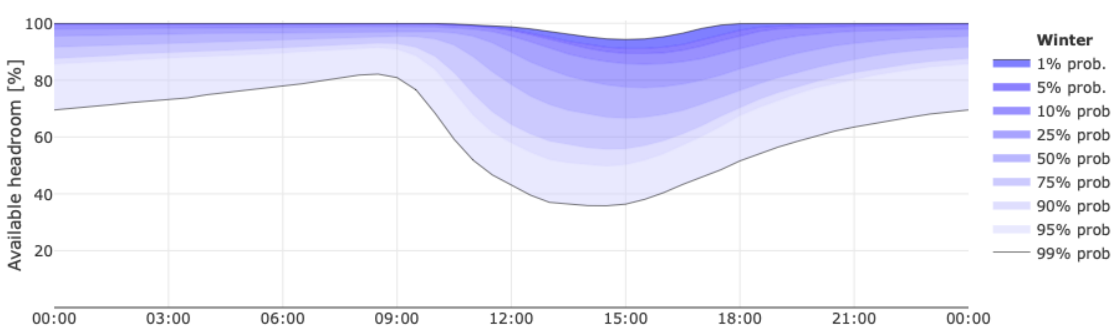


Figure A2-7: Winter headroom confidence levels (5kWh BESS sub-fleet)

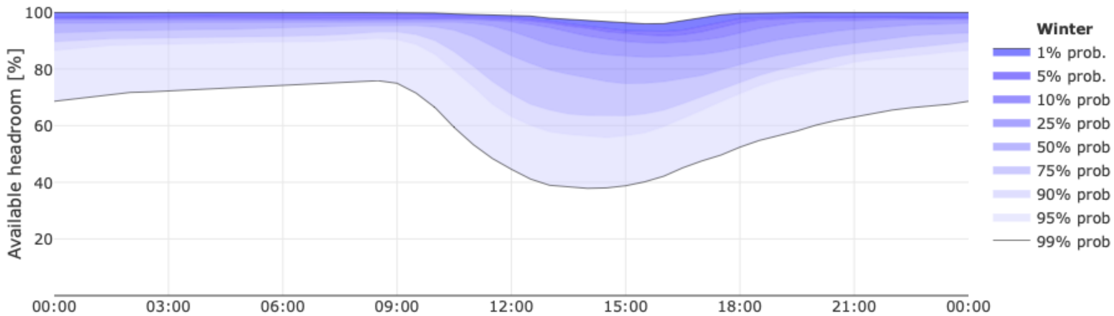


Figure A2-8: Winter headroom confidence levels (7.5kWh BESS sub-fleet)

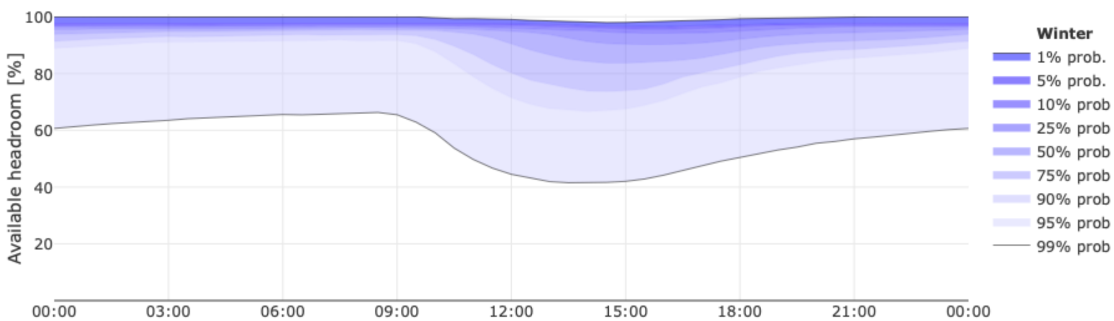


Figure A2-9: Winter headroom confidence levels (10kWh BESS sub-fleet)

8.3 Appendix B1: Time of Use Import Tariff

A summary of Time of Use (ToU) tariff data is provided in this Appendix (source: https://octopus.energy/agile/). Figure B-1 provides the entire dataset; this covers 1 year at 30min resolution. The seasons are divided into Summer (May-Aug), Shoulder (Mar, Apr, Sept, Oct) and Winter (Nov-Jan), as used elsewhere in this report. Daily minima and maxima are provided in Figure B-1, along with daily average.

Through figures B-2 to B-5, the half-hourly data is gathered for every day, for each of the three seasons. An average per season is provided, these are plotted together in Figure B-2, and by season in Figures B-3 to B-5.

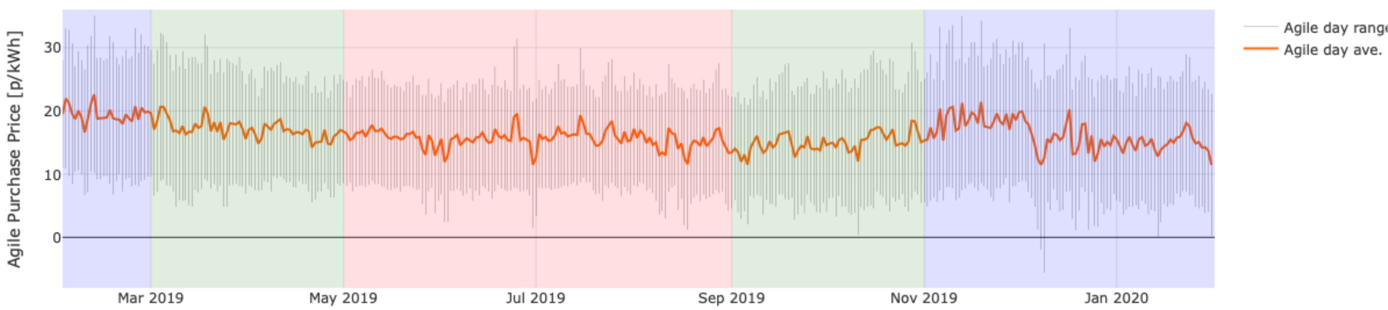


Figure B-1: *ToU tariff through 1 year (Feb 2019 to Jan 2020).*

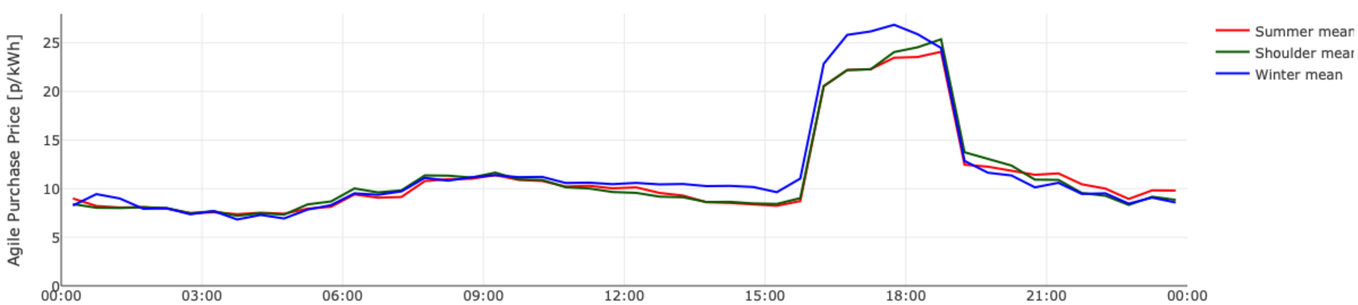


Figure B-2: *Average ToU tariffs for each season.*

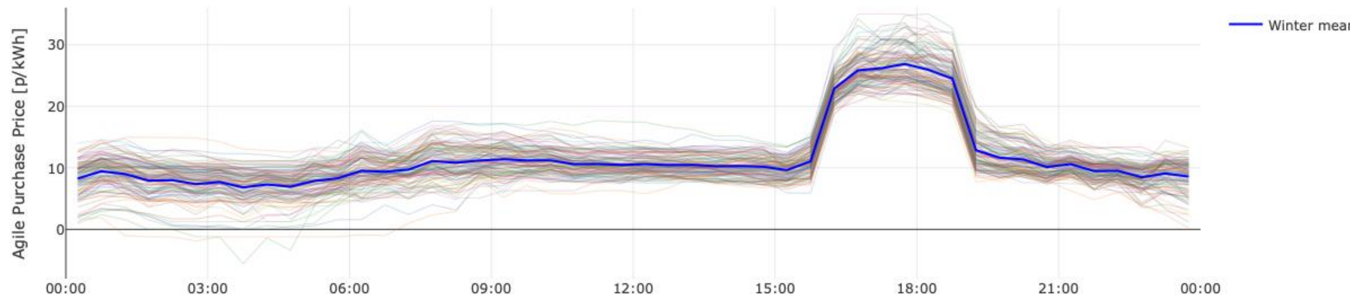


Figure B-3: *Winter ToU tariff, all data, including season mean*

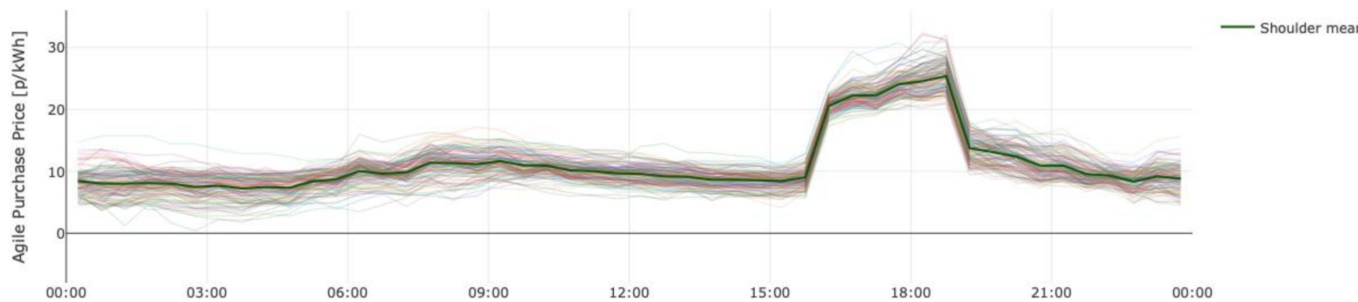


Figure B-4: *Shoulder ToU tariff, all data, including season mean.*

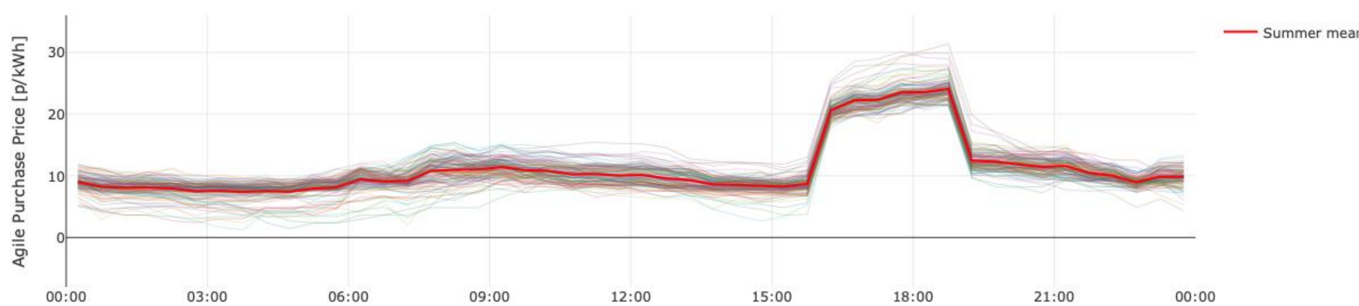


Figure B-5: *Summer ToU tariff, all data, including season mean*

8.4 Appendix B2: Flexibility Pricing

In this Appendix, we present analysis of successful flexibility bids published by Piclo[6] in September 2020. These bids were accepted by Distribution Network Operators [DNOs], and covered a range of assets including BESS, EV charging, industrial or commercial DSR, and generators. This information has been used to contextualise the Time of Use tariff-based arbitrage approach used as an example to demonstrate a means of monetising BESS headroom – see **Section 3** for details.

The bids typically comprise both an Availability price and Utilisation price, as below:

- Availability fee is paid to reserve dispatch of the contracted power level (MW) for the contracted period – it is paid irrelevant of dispatch behaviour
- Utilisation fee is paid if an asset is dispatched during the contracted period, to reflect the energy (MWh) delivered

The scatter in Figure B2-1 illustrates the wide range of both prices, and their relationship. It is not uncommon to have a contract with zero Availability fee, but most contract balance both fees.

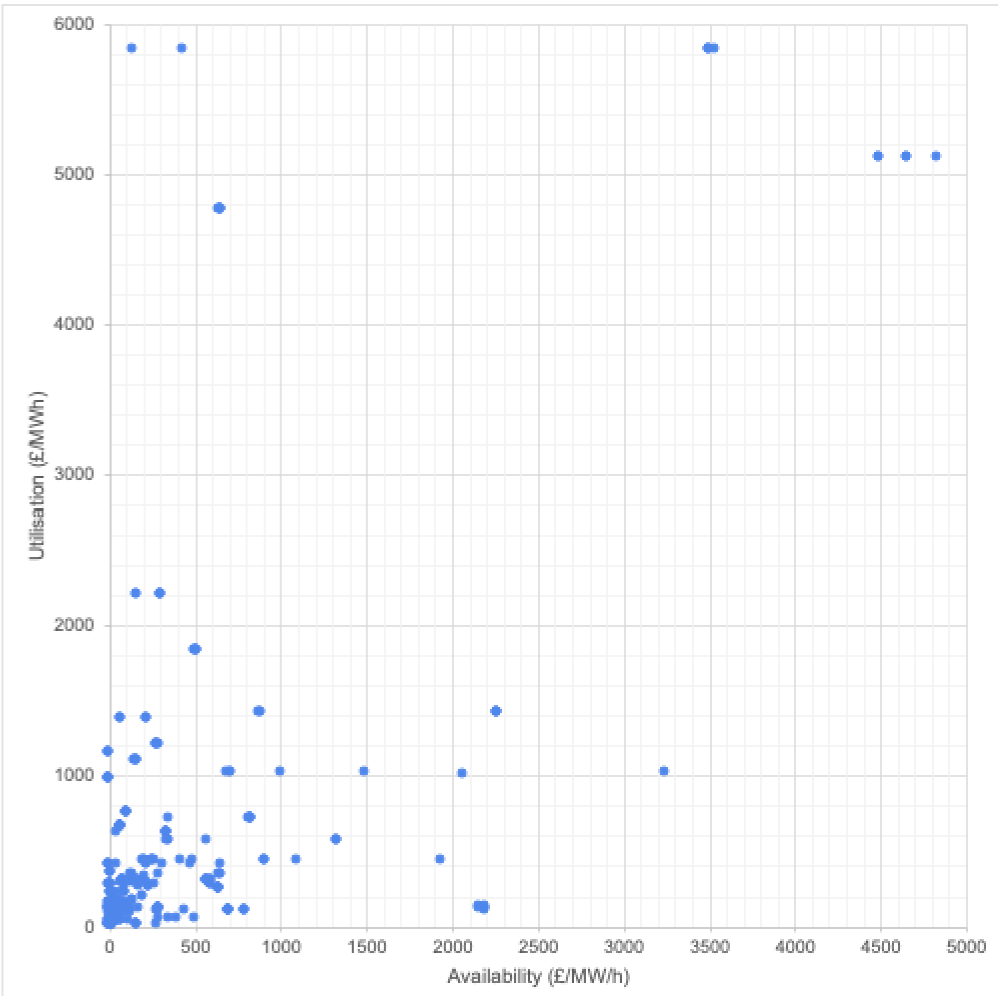


Figure B2-1: Utilisation vs Availability Fees, for successful flexibility service bids, Piclo, downloaded September 2020

In comparison with the Time of Use tariff arbitrage opportunity, which could provide opportunities to monetise at £3/MWh to £87/MWh, it is clear that most flexibility contracts could offer high value (i.e. £85/MWh) in either Availability or Utilisation.

Perhaps the most valid direct comparison with Time of Use tariff arbitrage is Utilisation fees. As illustrated by Figure B2-2, the vast majority of successful bids attract income great than £85/MWh. Coupled with any export revenue or Virtual Private Metering arrangement, and the earnings potential could be significant, assuming the BESS can be charged cost-effectivity.

[6] https://docs.google.com/forms/d/e/1FAIpQLSdAuzFWFInKAlXPmVHsSfD4v8V1-9mrp4vMQLzqFvFSdn523g/viewform

It is important to remember that if the BESS were to provide "negative demand" (i.e. charging) or symmetrical (charge/discharge) services, then charging costs would not be incurred, in contrast with price arbitrage techniques.

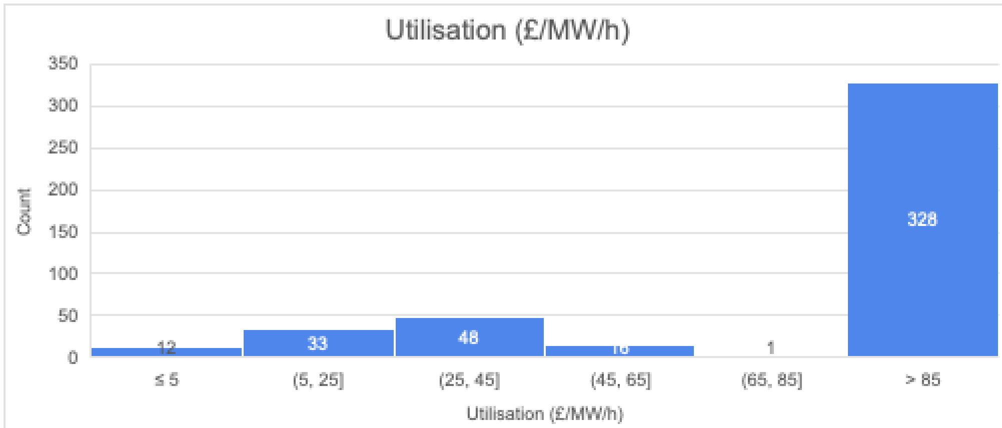


Figure B2-2: Distribution of Utilisation Fees, for successful flexibility service bids, Piclo, downloaded September 2020

The Availability fee can provide an alternative income stream, often in addition to Utilisation fees. As Figure B2-3 demonstrates, the value of availability fees alone can offer competitive alternatives to Time of Use arbitrage techniques; all the more so when providing "negative demand" or symmetrical services.

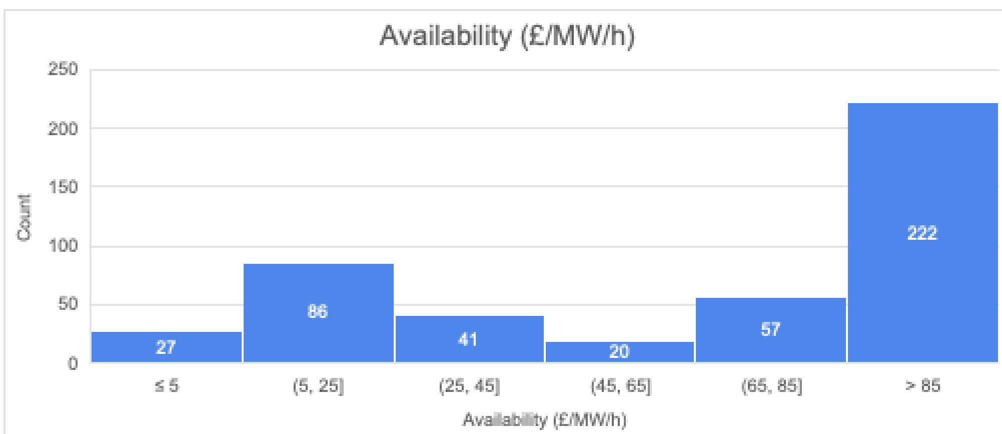


Figure B2-3: Distribution of Availability Fees, for successful flexibility service bids, Piclo, downloaded September 2020

8.5 Appendix B3: Wholesale Price Analysis

A summary of System Sell Price (SSP) is provided in this Appendix (source: Elexon - https://www.bmreports.com/). Figure C-1 provides the entire dataset; this covers 1 year at 30min resolution. The seasons are divided into Summer (May-Aug), Shoulder (Mar, Apr, Sept, Oct) and Winter (Nov-Jan), as used elsewhere in this report. Daily minima and maxima are provided in Figure C-1, along with daily average.

Through figures C-2 to C-5, the half-hourly data is gathered for every day, for each of the three seasons. An average per season is provided, these are plotted together in Figure C-2, and by season in Figures C-3 to C-5.

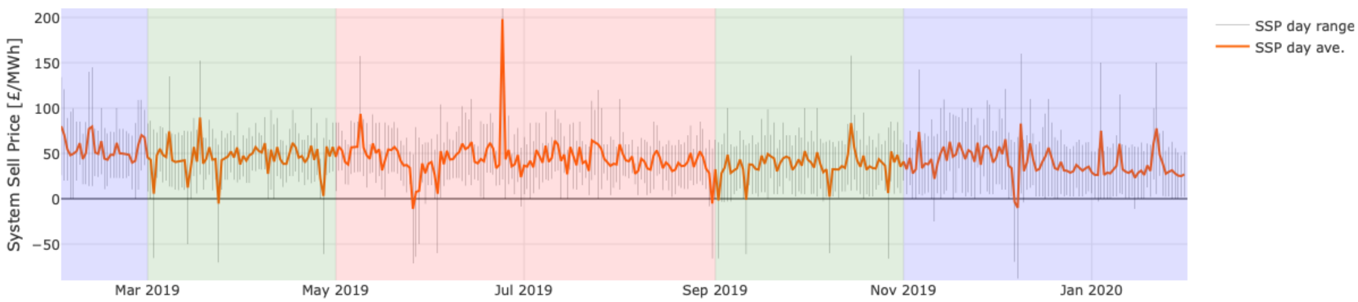


Figure C-1: *System price through 1 year (Feb 2019 to Jan 2020).*

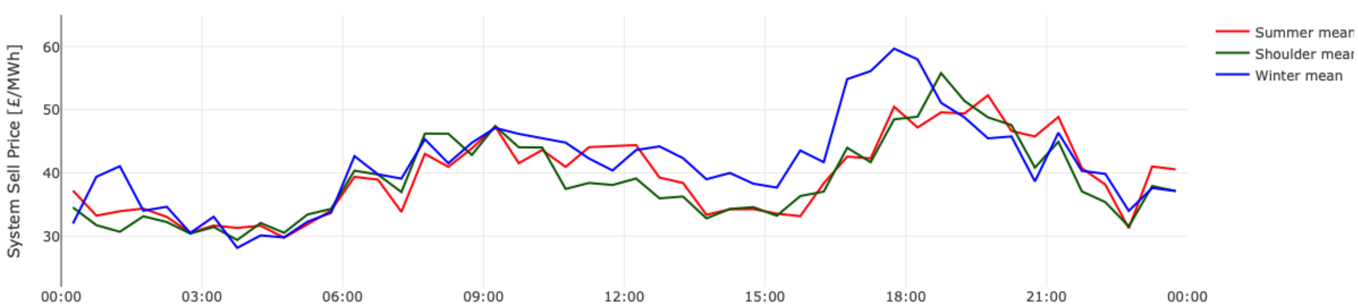


Figure C-2: *Average System price for each season.*

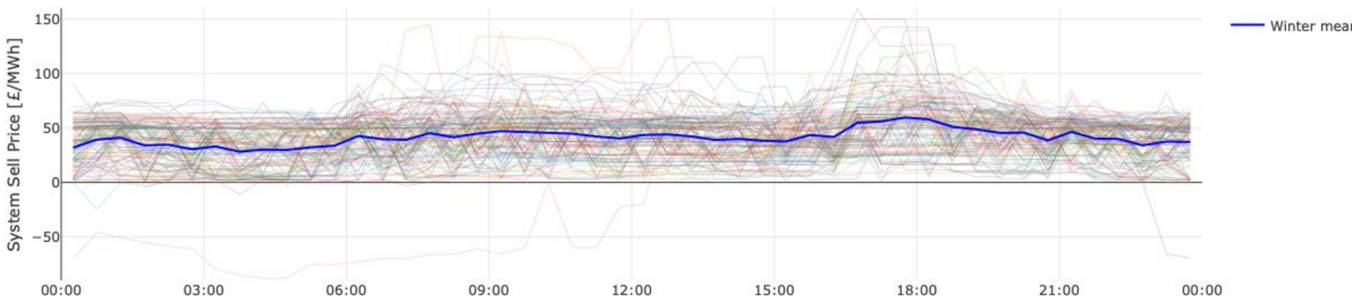


Figure C-3: *Winter System price, all data, including season mean*

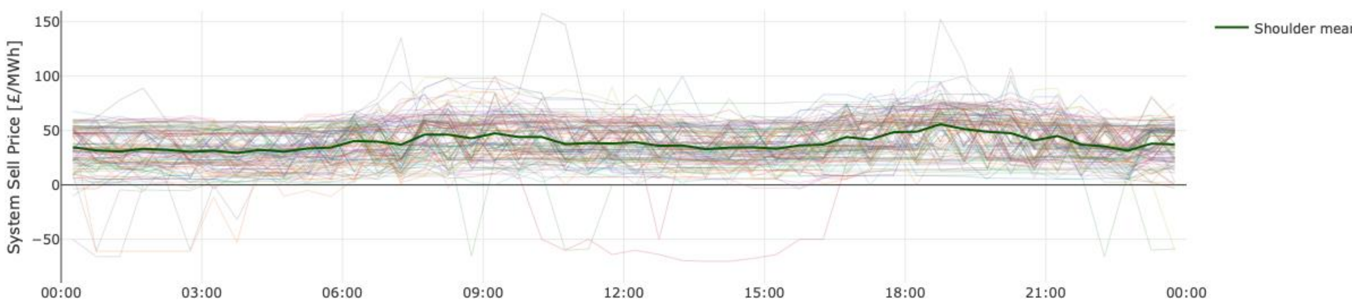


Figure C-4: *Shoulder System price, all data, including season mean*

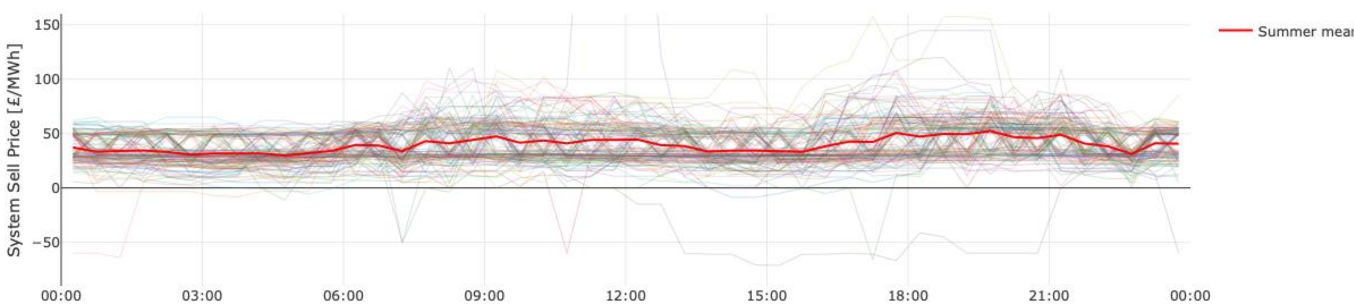


Figure C-5: *Summer System price, all data, including season mean*

8.6 Appendix C: Economic impact of BESS capacity upgrades

Relationship between additional value attributable to capacity upgrades under self-consumption mode only, and the value attributable to the combined PV & BESS solution as was available during the LEM trial. All capacity upgrades are shown in **Figures D-1 to D-6**, illustrating that those dwellings that accrued the highest value from the trail deployment would also do so from any subsequent BESS capacity upgrade.

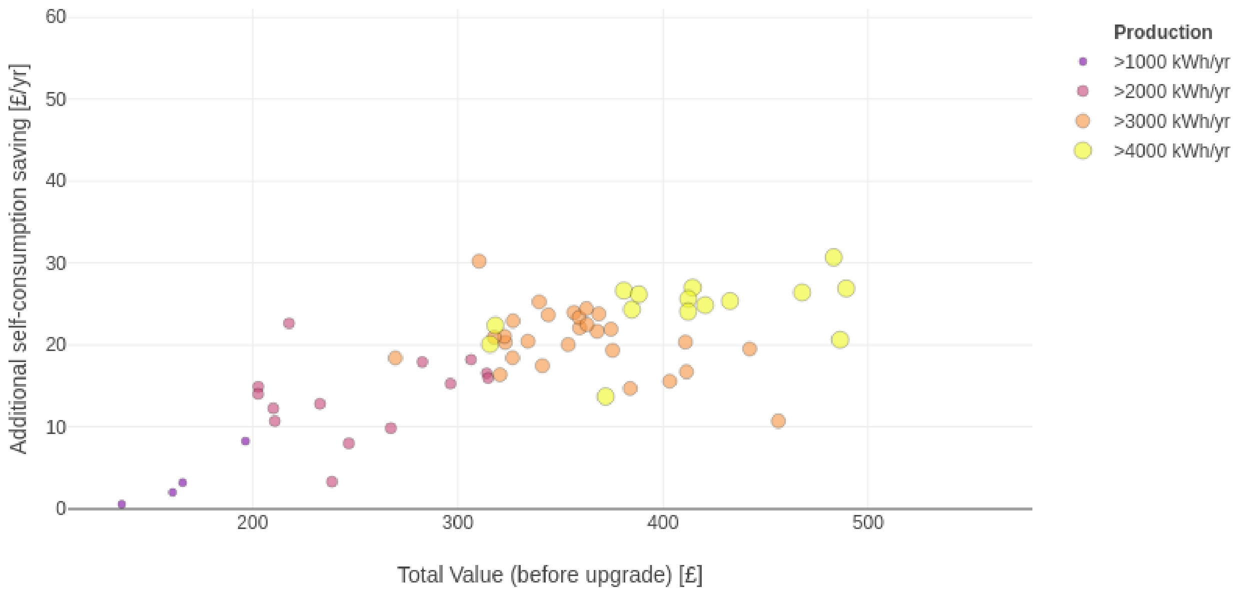


Figure D-1: Self-consumption savings due to BESS size increase: all 5kWh to 7.5kWh (counterfactual)

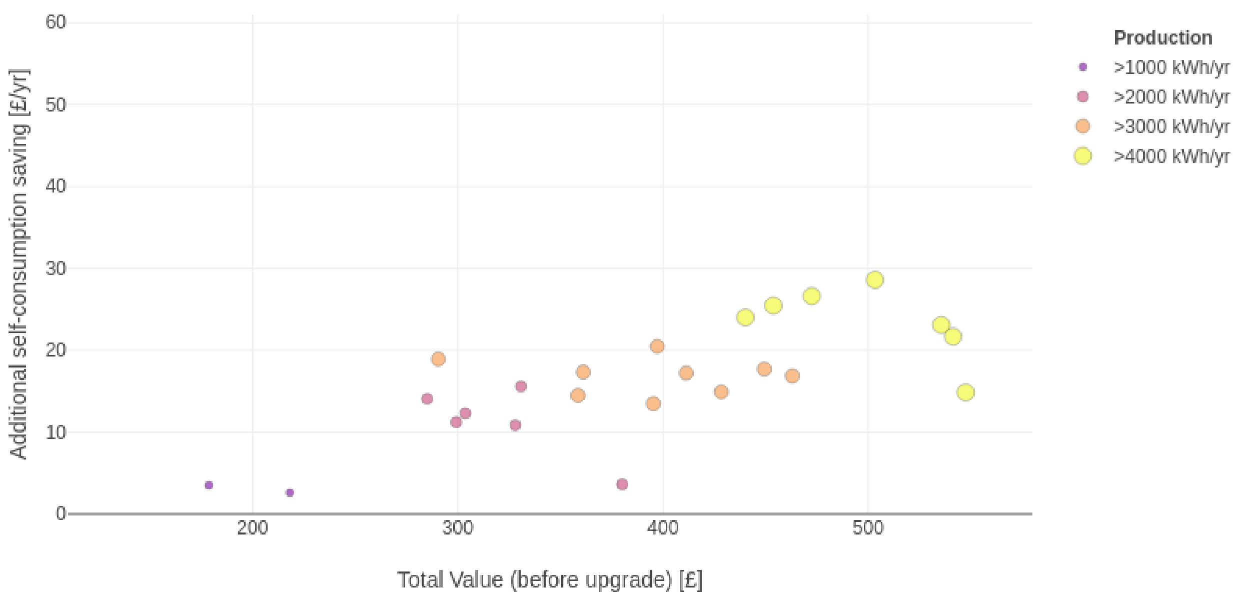


Figure D-2: Self-consumption savings due to BESS size increase: all 7.5kWh to 10kWh (counterfactual)

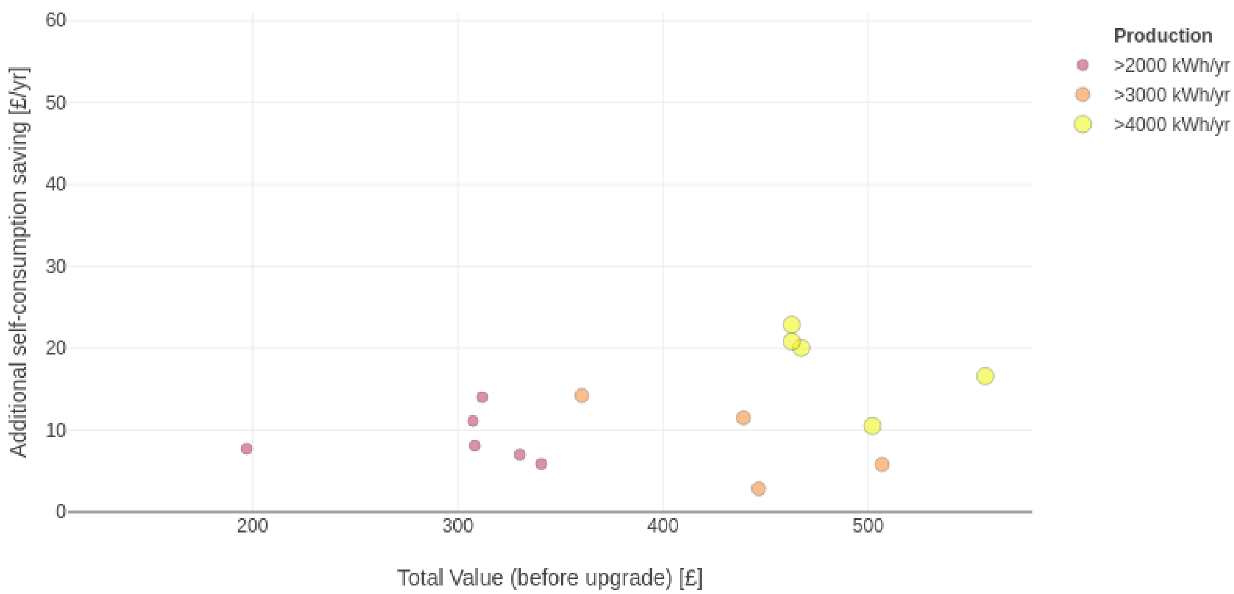


Figure D-3: Self-consumption savings due to BESS size increase: all 10kWh to 12.5kWh (counterfactual)

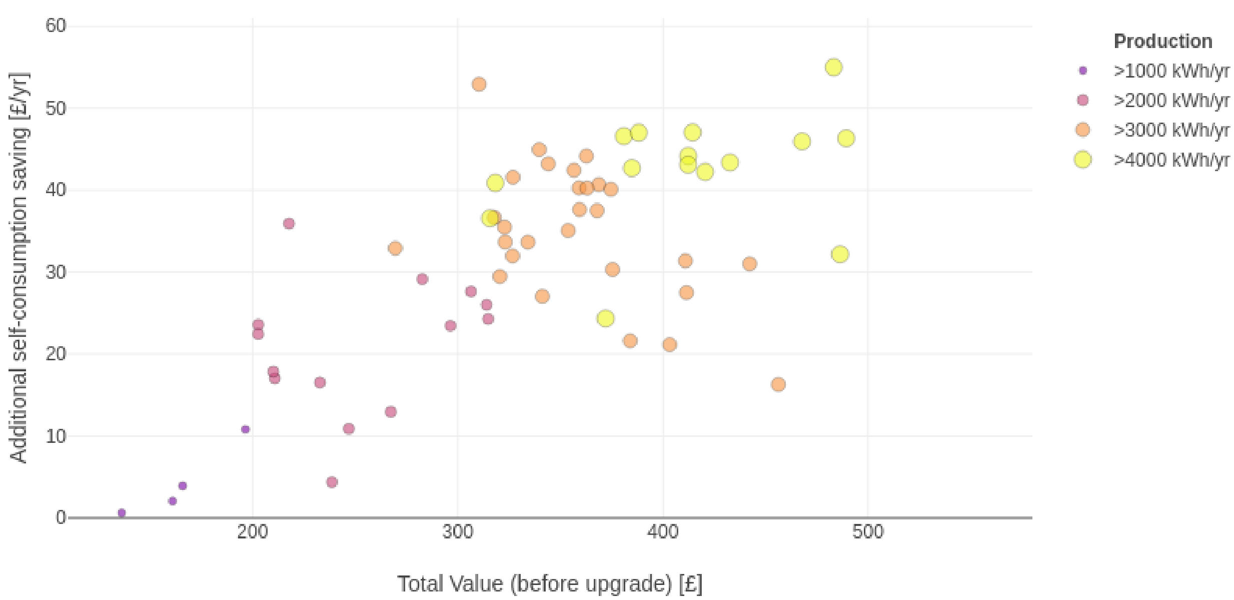


Figure D-4: Self-consumption savings due to BESS size increase: all 5kWh to 10kWh (counterfactual)

Figure D-5: Self-consumption savings due to BESS size increase: all 7.5kWh to 12.5kWh (counterfactual)

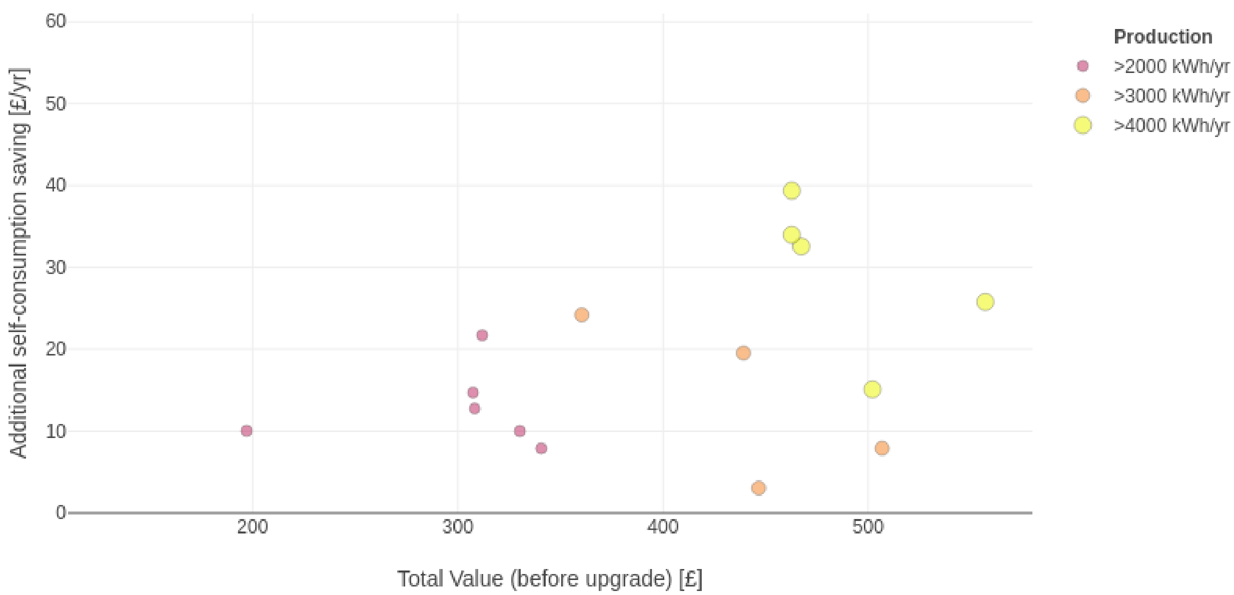


Figure D-6: Self-consumption savings due to BESS size increase: all 10kWh to 15kWh (counterfactual)