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Cornwall Local Energy Market

LEM Residential Fleet Self-Consumption Summary Report

Cornwall Local Energy Market, Centrica plc

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Executive Summary

The economic and environmental performance of BESS was compared to a baseline of the dwelling only and the estimated performance of the dwelling with installed PV only. Electricity consumption of the participating dwellings ranged from c2 to c20MWh and electricity billing costs were estimated to range from c£250 to £3,050pa. Three different capacities of BESS were installed in dwellings, and it was observed that those dwellings with higher electricity consumption generally had higher capacity BESS systems. This was not a universal truth as installation decisions were made on consumer estimated bills, which were found to be unreliable.

Electricity bill savings accrued from reduced grid import in dwellings with installed PV only ranged from £50 to £310 and export revenue using an assumed tariff of £0.055/kWh ranged from £50 to £220. The total value of the PV only deployment ranged from £100 to £430, generating dwelling emissions savings of 0.38 - 1.22 TCO_2e pa based on an annual system average grid emission factor.

The incremental value created by adding BESS caused by further reducing grid import to meet demand ranged from £75 to £300 and the combined PV&BESS deployment resulted in savings that ranged from £150-£550pa. However, BESS also reduced grid export resulting in an associated lost income to the dwelling of £50-£140pa. This lost export income reduced the incremental "Total Value" provided by BESS to £25-£160pa. Clearly, there will be dwellings where the deployment of BESS does not make economic sense.

To assist with performance assessment of the PV&BESS solutions, two KPI's were derived from the electricity import and export data; namely production deficit (BESS discharge + Grid import) and production surplus (BESS charge + grid export). The ratio of production surplus to production deficit was highly correlated with the residual grid import required by the dwelling. As this ratio increased, grid import fell following a power law relationship. The volume of grid export was also impacted by the BESS capacity, as might be expected. However, the trend was not absolute, it being disrupted by intra-day consumption behaviour. In this manner a dwelling with continuous daytime occupancy could reduce grid export of a dwelling of similar production and consumption, higher BESS capacity but no weekday, daytime occupancy.

BESS round trip efficiency (RTE) was influenced by annual consumption. As this figure fell below 4,000kWh pa, BESS RTE tended to fall below 70%. The average RTE of the fleet was found to be 70.3% (ranging from 50-81%), with this average figure being significantly lower than the manufacturer's estimates. RTE was heavily influenced by the charge/discharge power levels, with lower power levels on discharge prevalent in low consumption dwellings.

Dwelling could loosely be clustered by production and consumption levels, with respect to total savings from BESS & PV. Dwellings with PV production below 2400kWh pa typically returned the lowest total value (<£250). Dwelling with production greater than 3400kWh pa and consumption greater than 4000kWh typically retuned the highest value (>£400) with other dwellings placed in-between these two clusters. It was possible to predict with good accuracy the total value of the BESS & PV solution using the equation; $TV_{P\&BESS} = 0.052 * P^{0.0935} * C^{0.141}$. The subsequent linear relationship between forecasted and estimated $TV_{P\&BESS}$ had a coefficient of determination [R^2] value of 0.99 indicating a high degree of fit. Errors in the forecast tended to occur in the middle cluster of dwellings where the influence of inter-day behaviour was less swamped by either low/high production or high consumption.

Residential energy demand is influenced by seasonal, daily and stochastic variation. Seasonal and daily variations can be heavily influenced by external weather conditions, day of the week and habitual practices that might be inferred from household meta-data. However, the presence of a stochastic element makes prediction of inter-day consumption patterns that might influence BESS performance difficult and as a consequence only weak predictor variables were found. A larger dataset would be required to allow better characterisation of demand patterns and their subsequent influence on BESS performance in self-consumption operating mode.

1. Introduction

This document is a summary report of properties and system performance for the residential workstream of the Cornwall Local Energy Market [LEM] project. This report covers the 12-month period from Apr-2019 to Mar-2020, under predominantly Self-Consumption operation – with a limited period of dispatch testing in Q4-2019 and Q1-2020.

This document is supported by the following documents;

1. The description of system performance monitoring datapoints, and associated data coverage summary, as captured in the document titled *“LEM Residential Data Dictionary*”
2. The description of metadata datapoints, and associated metadata coverage summary, as captured in the document titled *“LEM Residential MetaData Summary Report*”
3. The residential participants selection methodology captured in the document titled *“Selecting participating properties – methodology and outcome*”
4. Library of documents titled “*Cornwall LEM Householder Participation Report*” as issued in February 2020
5. LEM Residential Participant Event presentation titled *“LEM Residential Dissemination Event Feb 2020_FINAL_v2.pptx”* as presented on 11th February 2020
6. The description of energy data available from the consumer focussed MySonnenBatterie portal in the document titled “App & Meter Guidance for Cornwall LEM Residential Project Participants”.

This document supports the analysis of BESS utilisation and optimisation/VPP dispatch headroom as presented in the document titled *“LEM Residential BESS Utilisation Summary Report”.*

This document is intended for those interested in detailed technical and commercial analysis of Battery Energy Storage System [BESS] performance under self-consumption operation.

2. Baseline: Production, Consumption & related Synthetic Variables/KPIs

2.1 Overview

The derivation of baseline data differed by battery type installed, and required the definition of synthetic variables (Production Surplus & Production Deficit), as discussed below:

- **Hybrid (dc-coupled);** since these sites did NOT have existing solar PV, all **consumption** would have been met by **grid import** (with attendant import costs and CO2 footprint), and there was zero **grid export** to monetise
- **Eco (ac-coupled);** since these sites had existing solar PV, we assume that the **production surplus** (i.e. the solar PV **production** not instantaneously required onsite to meet **consumption**) would result in **grid export**. The baseline **grid import** is due to **production deficit**, where the instantaneous **production** was insufficient to meet **consumption**

These baseline datasets are used in the calculation of economic value and CO2 savings, in order to estimate impacts and benefits of several scenarios for both ac and dc battery types, namely;

- Addition of Solar PV System to a grid import only home
- Retrofit of BESS to a Solar PV System only home
- Installation of a BESS plus Solar PV package to a grid import only home

The impacts and benefits can only be estimated, not only due to data coverage and quality, but also the limitation of reporting from the BESS controller, and lack of certainty on the proportions of BESS discharge that was exported to the grid, and BESS charge that was derived from grid import.

2.2 Consumption

As discussed in the previous section, annual consumption was estimated from MySonnenBatterie data in the period April 2019 to March 2020. The distribution of consumption presented in Figure 1 clearly illustrates that the Eco9.43 cluster (i.e. homes with existing PV provided with an ac-coupled battery) had higher consumption on average than the Hyrbid9.53 cluster. This should be considered when interpreting any subsequent comparisons of these 2 clusters.

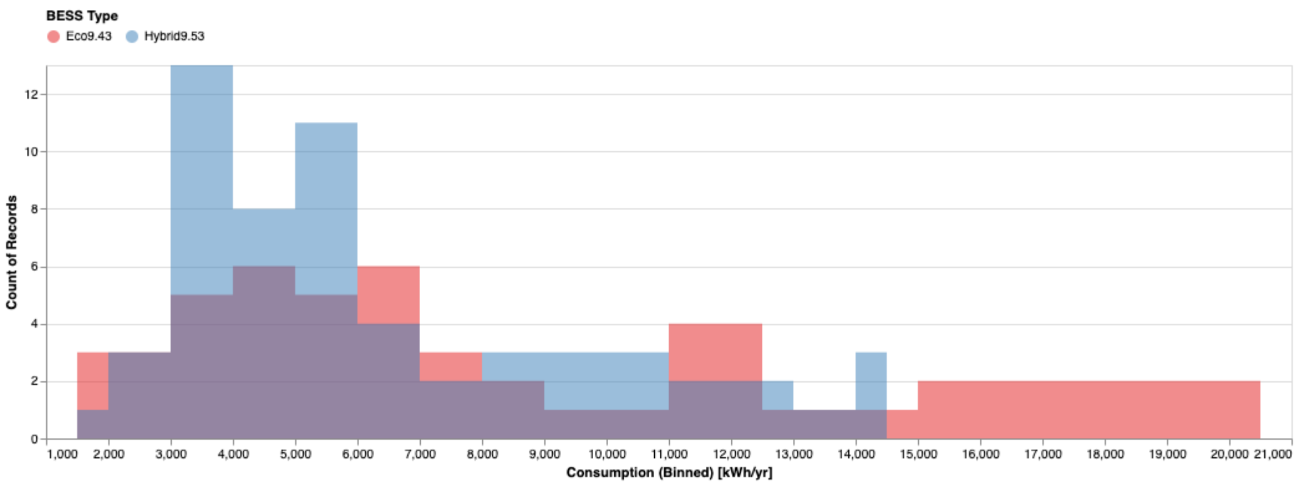

Figure 1: Distribution of Estimated Annual Consumption, based on Apr19-Mar20 data

To put the consumption figures in context, Ofgem issue Typical Domestic Consumption Values [TDCV], that are used by energy suppliers when providing context on energy bills. These are presented in Figure 2. Whilst most homes will fall into "Profile Class 1", whilst those with Economy 7 or Economy 10 meters (e.g. for overnight storage heating) will fall into "Profile Class 2".

The MetaData Summary Report provides more detail on the spread of heating system types (the predominate driver of Profile Class), however it is clear that the above distribution has significant representation by higher consumers, and limited contribution from lower consumers.

	kWh	TDCVs
Gas	Low	8,000
	Medium	12,000
	High	17,000
Electricity: Profile Class 1	Low	1,800
	Medium	2,900
	High	4,300
Electricity: Profile Class 2	Low	2,400
	Medium	4,200
	High	7,100

Figure 2: Typical Domestic Consumption Values [TDCV] for 01Apr2020 onwards, Ofgem[1]

The spread of consumption can further be considered by clusters of "Battery Type - Battery Energy Capacity [kWh]", as presented in Figure 3. There is a fair representation of medium and high consumers in each cluster, with the notable exceptions of "ac-kWh" and "dc-10kWh". This is to be expected, as the site selection and battery sizing methodology[2] used CUSTOMER ESTIMATED values of both consumption and Solar PV production as metrics to select battery capacity. The 15 "large" 10kWh batteries was assigned to high-consumption homes, assuring an almost even (8-7) distribution across ac-coupled and dc-coupled systems, respectively.

[1] https://www.ofgem.gov.uk/gas/retail-market/monitoring-data-and-statistics/typical-domestic-consumption-values

[2] Selecting participating properties – methodology and outcome v0.3 161017.docx

There are many homes whose consumption values suggest they should have been assigned a larger battery, especially in the ac-coupled cluster. This can be explained in several ways:

- Production was also used as a decision metric; those with low production would have been assigned a "medium" (7.5kWh) or "small" (5kWh) battery
- The customer's estimate of consumption may have bene inaccurate, or their consumption patterns materially changed since answering the survey
- The customer's declaration of electric heating or electric vehicles was used to prioritise "large" batteries within a cost-constrained battery fleet; some high consumers were deliberately demoted to manage cost
- It was desirable to have some marginal cases to be slightly over or under-sized, in order to identify the impact[3]

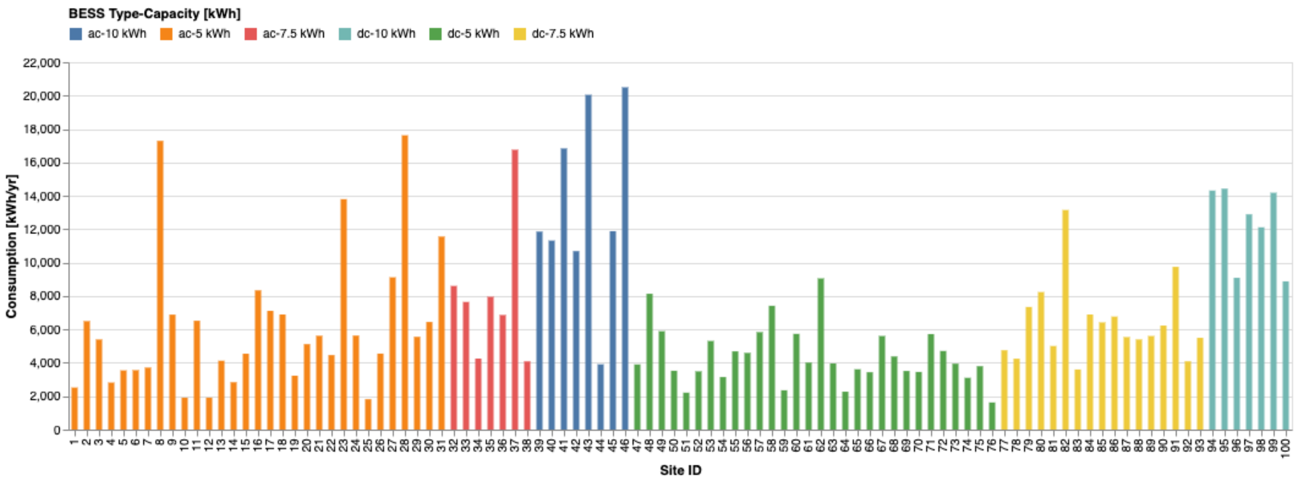

Figure 3: Annual Consumption Estimate by Site, based on Apr19-Mar20

The approximate fleet level daily consumption, from January 2019 to March 2020 is presented in Figure 4, split by the BESS Type-Capacity clusters. As it omits missing or corrupted data, a small amount of day-to day variation (usually <2% of total value) is explained by data quality issues. The remainder is true reflection of real-life variation within and between seasons. The impact of this variation on BESS value, BESS sizing strategies and utilisation opportunities will be explored in the follow-up report on BESS utilisation[4].

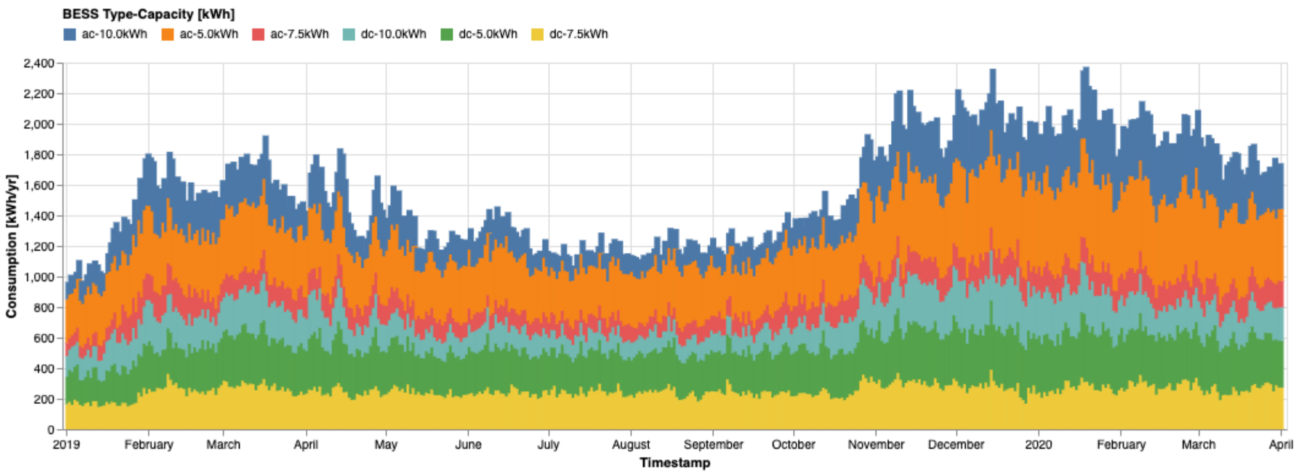

Figure 4: Approximate fleet level daily Consumption, split by BESS Type-Energy Capacity cluster, before scaling for missing data

[3] However, with the inaccuracy in customer consumption estimates, and estimating PV production from panel quantity alone (as PV system design characteristics were commonly unavailable for the ac-coupled cluster), such a comparison was later deemed unconstructive

[4] LEM Residential BESS Utilisation Summary Report

2.3 Production

The distribution of production presented in Figure 5 clearly illustrates that the Eco9.43 cluster (i.e. homes with existing PV provided with an ac-coupled battery) had higher production on average than the Hyrbid9.53 cluster. This should be considered when interpreting any subsequent comparisons of these 2 clusters.

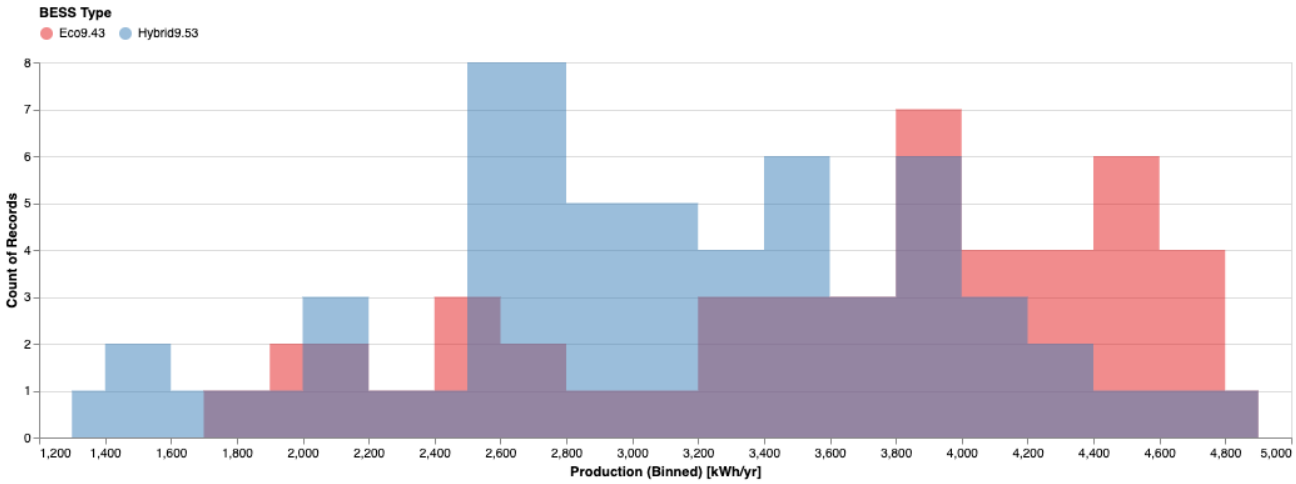

Figure 5: Distribution of Estimated Annual Production, based on Apr19-Mar20 data

There is a clear spread of production across the BESS Type-Capacity clusters, as illustrated by Figure 6. Some of the outliers (e.g. Sites 60 & 86) can be explained by long-term issues with PV system, such as blown fuse to one array but not another.

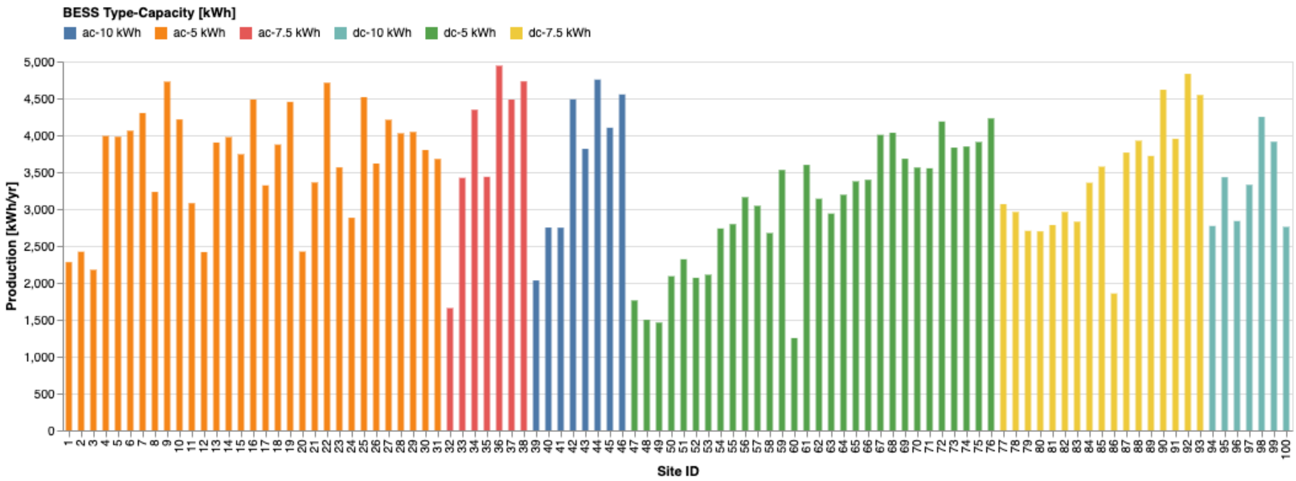

Figure 6: Annual Production Estimate by Site, based on Apr19-Mar20

The seasonal variation in fleet-level production, as presented in Figure 7, is as expected, especially after accounting for the addition of new sites during Jan-Apr 2019. The day-to-day volatility of production, within seasons, is important to consider when assessing daily or half-hourly results on a daily basis.

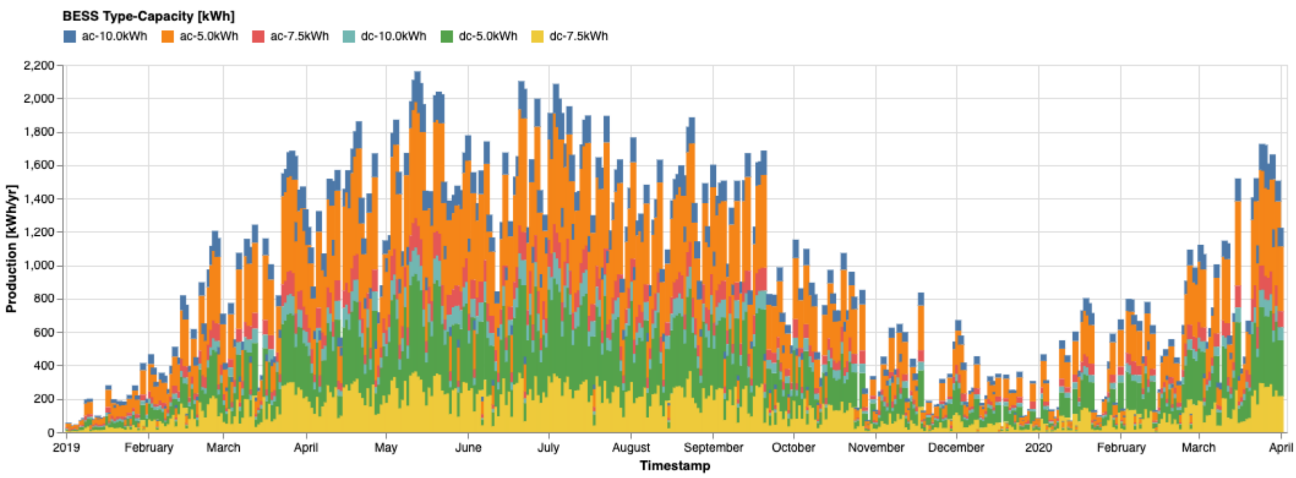

Figure 7: Approximate fleet level daily Production, split by BESS Type-Energy Capacity cluster, before scaling for missing data

2.4 Production/Consumption Ratio

The utilisation of Solar PV and BESS – and hence financial and CO_2 savings – are driven by the combination of production & consumption. Figure 8 illustrates the distribution of the annual Production/Consumption Ratio, which is simple to calculate using annual data. There are several major observations from this chart:

- The majority of sites consume much more than they produce by Solar PV; the interaction of this with BESS utilisation will be explored in a subsequent report[5]
- Generally, there is a similar spread of Production/Consumption ratios across both BESS Type clusters

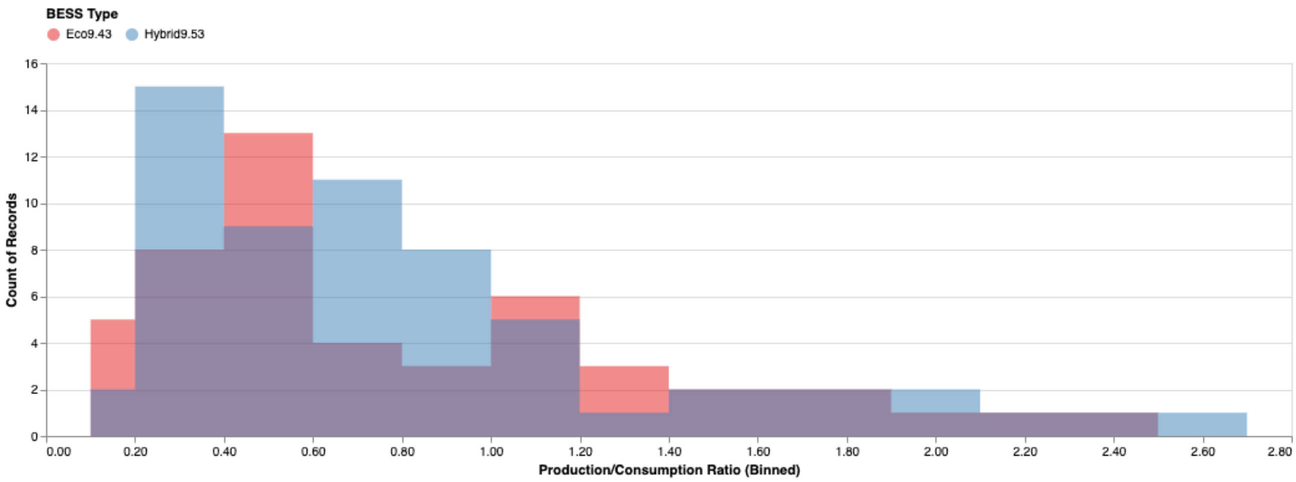

Figure 8: Distribution of Estimated Annual Production/Consumption Ratio, based on Apr19-Mar20 data

Within the BESS Type-Capacity clusters, the representation of Production/Consumption Ratios is varied, as is illustrated in Figure 9. The major observations are:

- “Small” (5kWh) BESS have a wider range of Production/Consumption Rati, from <<1 to >>1
- “Medium” (7.5kWh) BESS have Production/Consumption ratio mostly < 1, with a few > 1
- “Large” (10kWh) BESS have Production/Consumption ratio predominately < 0.5, with a lone example >0.5

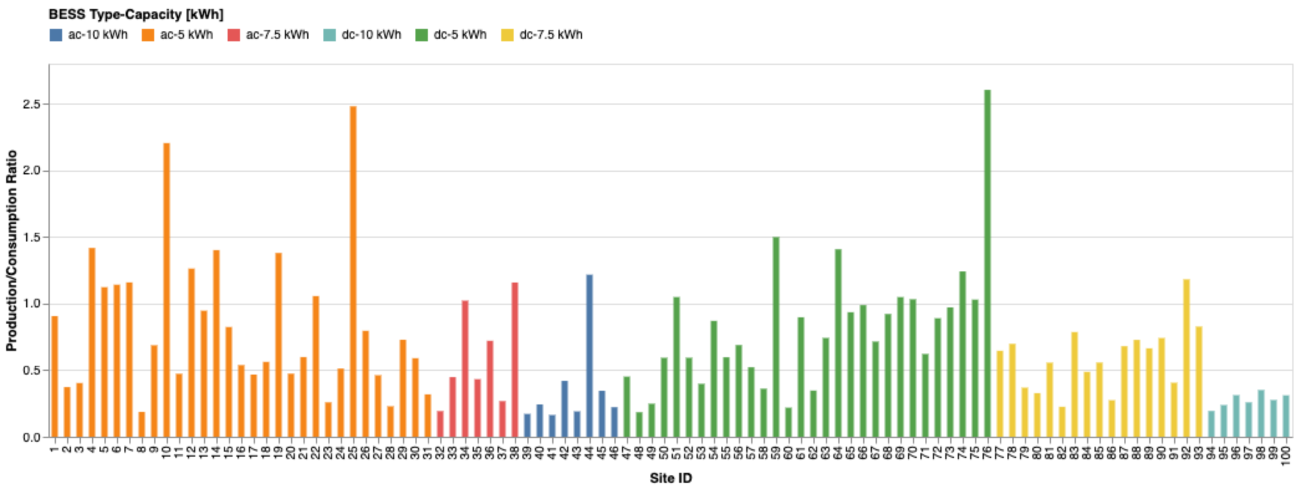

Figure 9: Annual Production/Consumption Ratio Estimate by Site, based on Apr19-Mar20

[5] LEM Residential BESS Utilisation Summary Report

2.5 Production Surplus

In order to understand the opportunity to charge the BESS during self-consumption operation, the Production Surplus can be calculated using sub-daily data (e.g. 1-mintue or 30-minute) via Equation 1. This Production Surplus is the energy (or power) not immediately utilised to meet on-site consumption; i.e. either charged to BESS of exported to Grid.

$$Production\ Surplus, Ps = BESS\ Charge + Grid\ Export$$

Equation 1: Production Surplus

As can be seen later in this report, and as will be explored in the subsequent report on BESS utilisation[6], Production Surplus is an important metric to predict BESS Utilisation, BESS Round Trip Efficiency, and hence financial and CO_2 savings. As Figure 10 illustrates, the distribution of Production Surplus between both BESS Type clusters is similar.

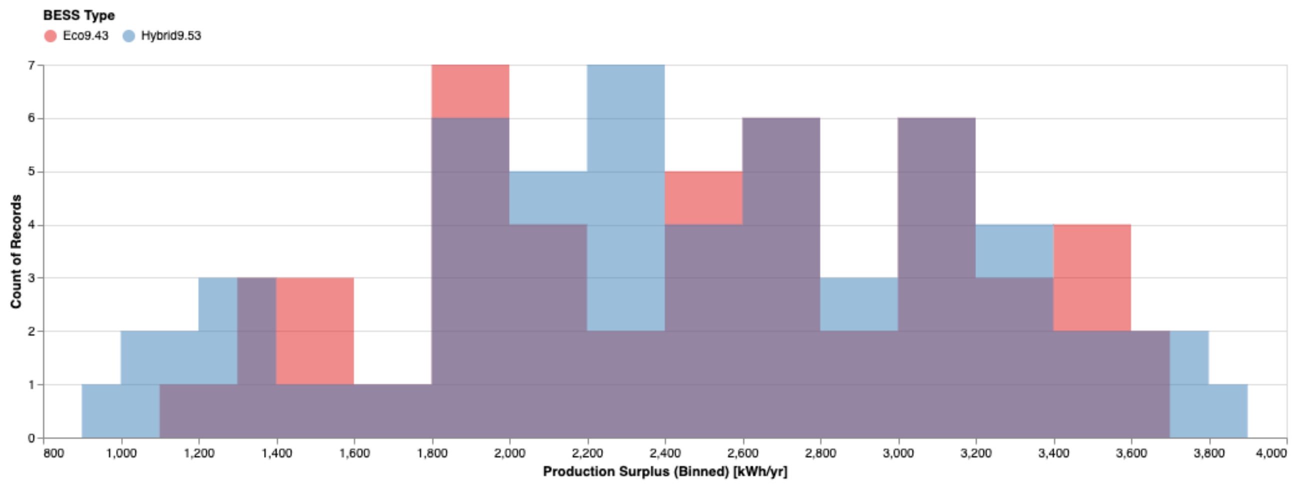

Figure 10: Distribution of Estimated Annual Production Surplus, based on Apr19-Mar20 data

As can be expected, there is significant variation in Production Surplus by Site, and within each BESS Type – BESS Capacity cluster, as shown in Figure 11, with the notable exception of the dc-coupled-10kWh cluster. The general variability is not only due to the variation in annual Production & annual Consumption, but also the relative shapes of Production & Consumption, as explored in Section 4.

The importance of intra-day variation in production & consumption - as calculated from data with sub-daily temporal precision - cannot be understated. It undermines the use of annual production & consumption data as a sole determinant to predict self-consumption performance and savings.

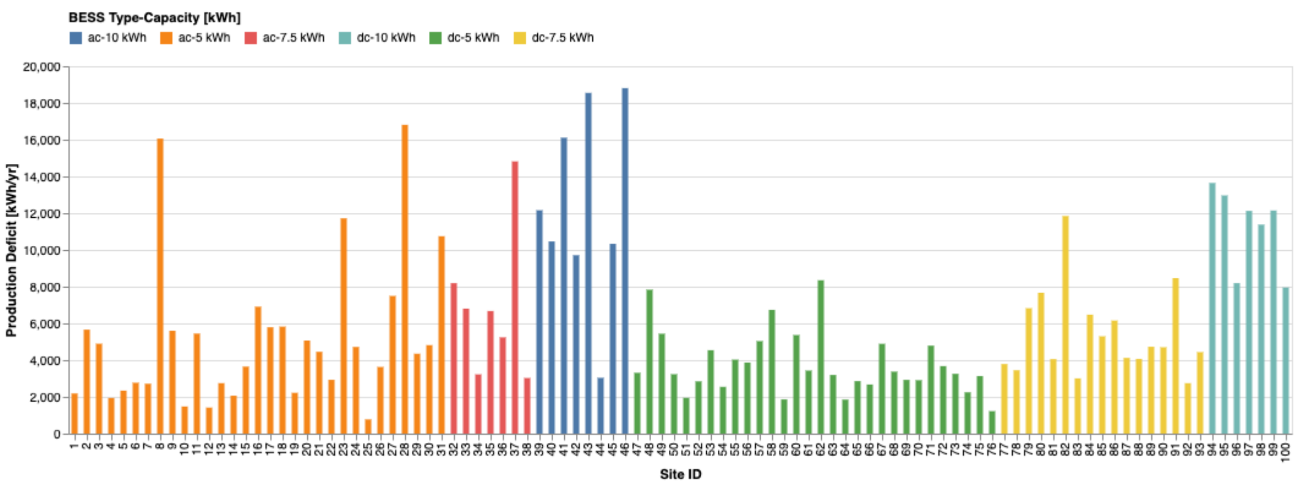

Figure 11: Annual Production Surplus Estimate by Site, based on Apr19-Mar20

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As expected, the Production Surplus is generally higher in the summer than in winter, but Figure 12 highlights the impact of intra-season (i.e. day-to-day) variation of both consumption and production (as presented in Figure 4 and Figure 7, respectively) on Production Surplus from self-consumption operation. As explored in the subsequent report on BESS utilisation[7], this will have a similar impact on alternative BESS utilisation and/or sizing.

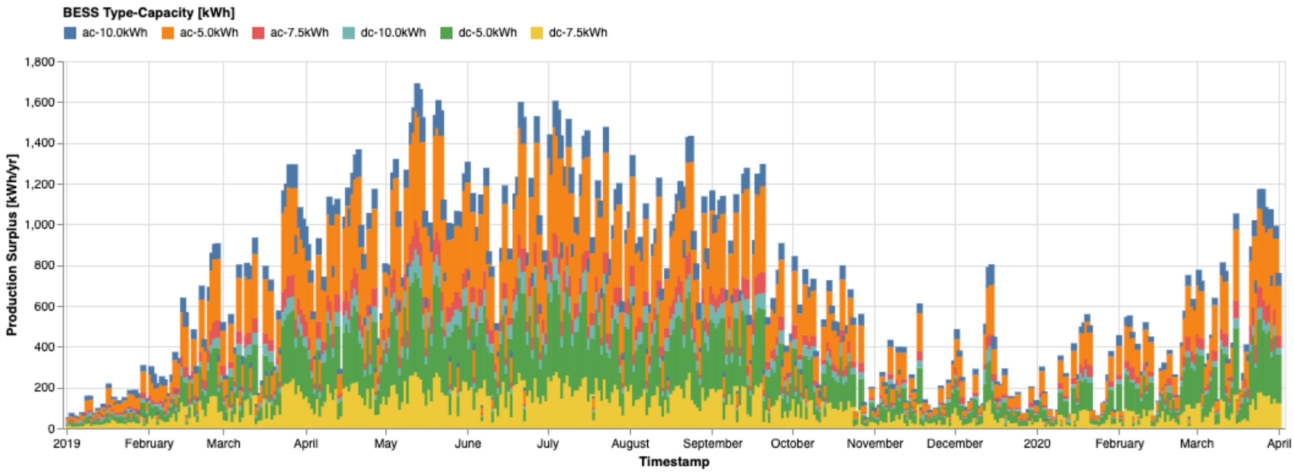

Figure 12: Approximate fleet level daily Production Surplus, split by BESS Type-Energy Capacity cluster, before scaling for missing data

[7] LEM Residential BESS Utilisation Summary Report

2.6 Production Deficit

In order to understand the opportunity to discharge the BESS during self-consumption operation, the Production Deficit can be calculated using sub-daily data (e.g. 1-mintue or 30-minute) via Equation 2. This Production Deficit is the energy (or power) required to meet consumption that is not immediately self-consumed from on-site production; i.e. it is sourced from discharge from BESS and/or import from Gird.

$$Production\ Deficit, Pd = BESS\ Discharge + Grid\ Import$$

Equation 2: Production Deficit

As can be seen later in this report, Production Deficit is an import metric to predict BESS Round Trip Efficiency, due to the impact of low average discharge rates on BESS discharge efficiency. Production Deficit will also be an important metric in BESS Utilisation & BESS sizing, as will be explored in the subsequent report on BESS utilisation[8]. As Figure 13 illustrates, the distribution of Production Surplus between both BESS Type clusters is similar.

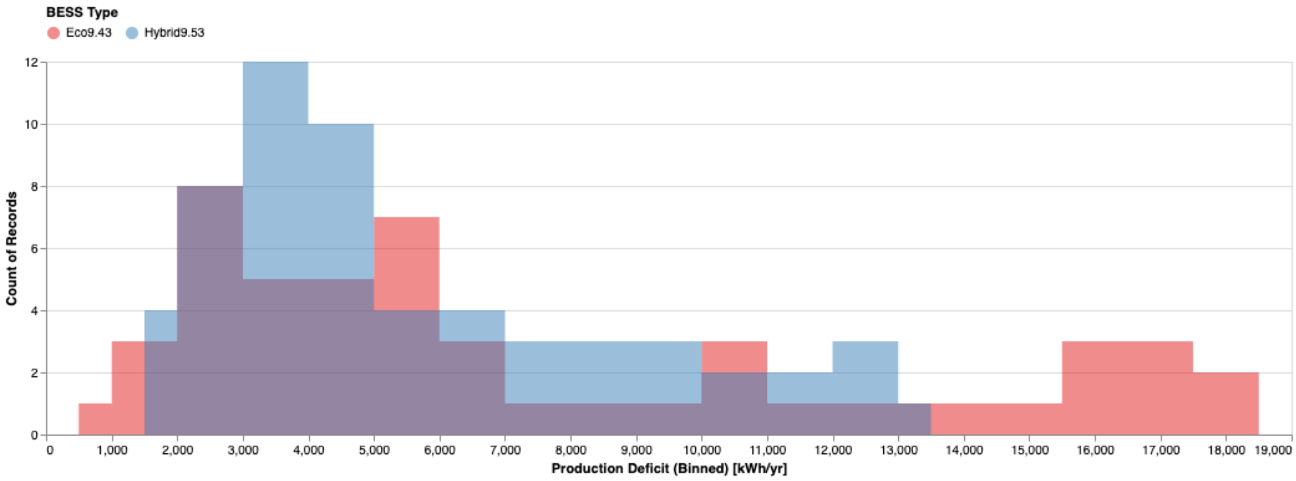

Figure 13: Distribution of Estimated Annual Production Deficit, based on Apr19-Mar20 data

As can be expected, there is significant variation in Production Deficit by Site, and within each BESS Type – BESS Capacity cluster, as shown in Figure 14, with the notable exception of the dc-coupled-10kWh cluster.

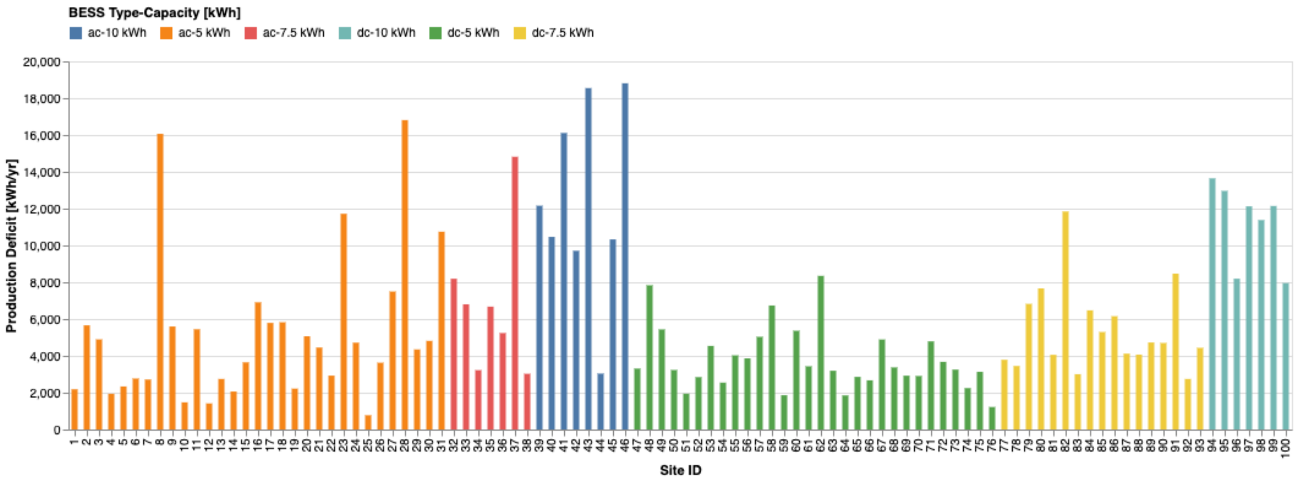

Figure 14: Annual Production Deficit Estimate by Site, based on Apr19-Mar20

[8] LEM Residential BESS Utilisation Summary Report

As expected, the Production Deficit is generally higher in the winter than in summer, but Figure 15 again highlights the impact of intra-season variation of both consumption and production on Production Deficit from self-consumption operation. As explored in the subsequent report on BESS utilisation[9], this will have a similar impact on alternative BESS utilisation and/or sizing.

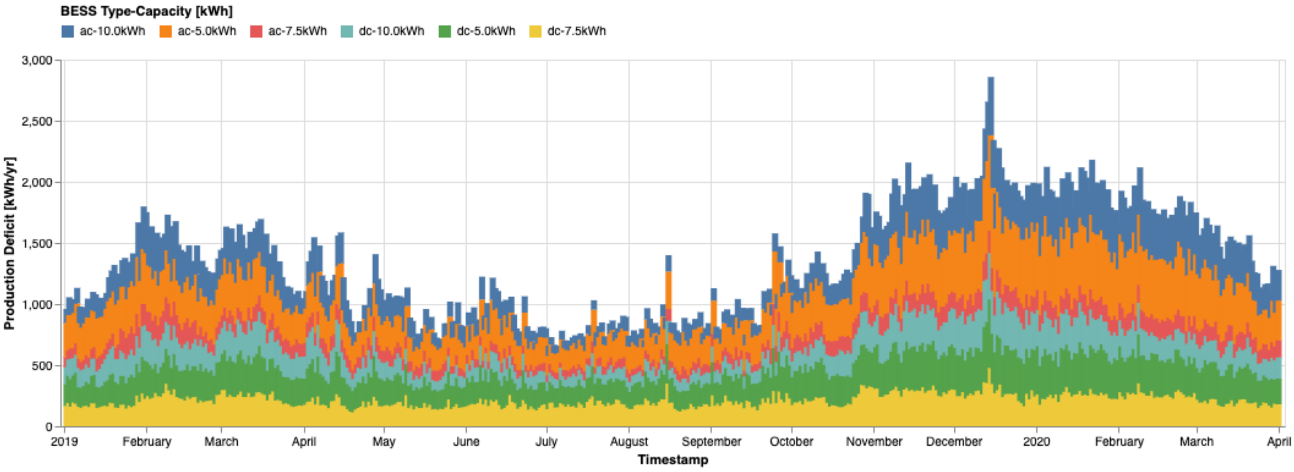

Figure 15: Approximate fleet level daily Production Deficit, split by BESS Type-Energy Capacity cluster, before scaling for missing data

[9] LEM Residential BESS Utilisation Summary Report

2.7 Production Surplus/Deficit Ratio

Since both Production Surplus and Production deficit can vary significantly between sites, due to the relative shapes of Production & Consumption profiles presented in Section 4, an additional metric can be used to classify sites. The Production Surplus/Deficit Ratio can be calculated using Equation 3.

$$Production\ Surplus/Deficit\ Ratio, Psdr = \frac{Production\ Surplus}{Production\ Deficit}$$

Equation 3: Production Surplus/Deficit Ratio

As can be seen later in this report, Production Surplus is an important metric to predict Grid Import, Grid Export and BESS Round Trip Efficiency. Figure 16 illustrates that whilst the ac-coupled BESS type cluster has several more examples of high Production Surplus/Deficit Ratios than the dc-coupled cluster, both clusters have most examples between 0.25 – 1.5.

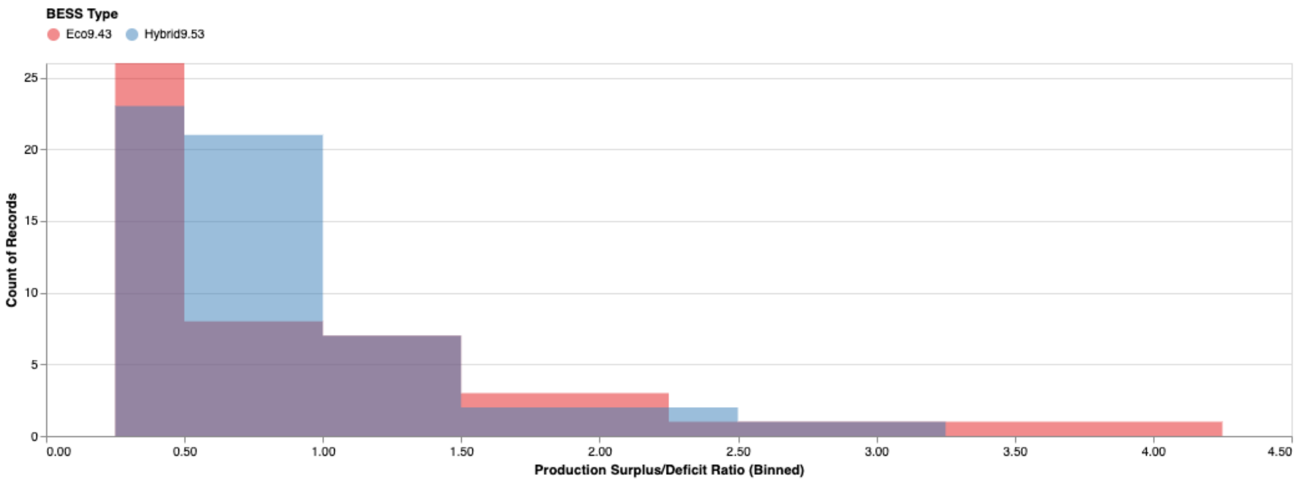

Figure 16: Distribution of Estimated Annual Production Surplus/Deficit Ratio, based on Apr19-Mar20 data

As before, there is significant variation in Production Surplus/Deficit Ratio by Site, and within each BESS Type – BESS Capacity cluster, as shown in Figure 17, with the notable exception of the dc-coupled-10kWh cluster.

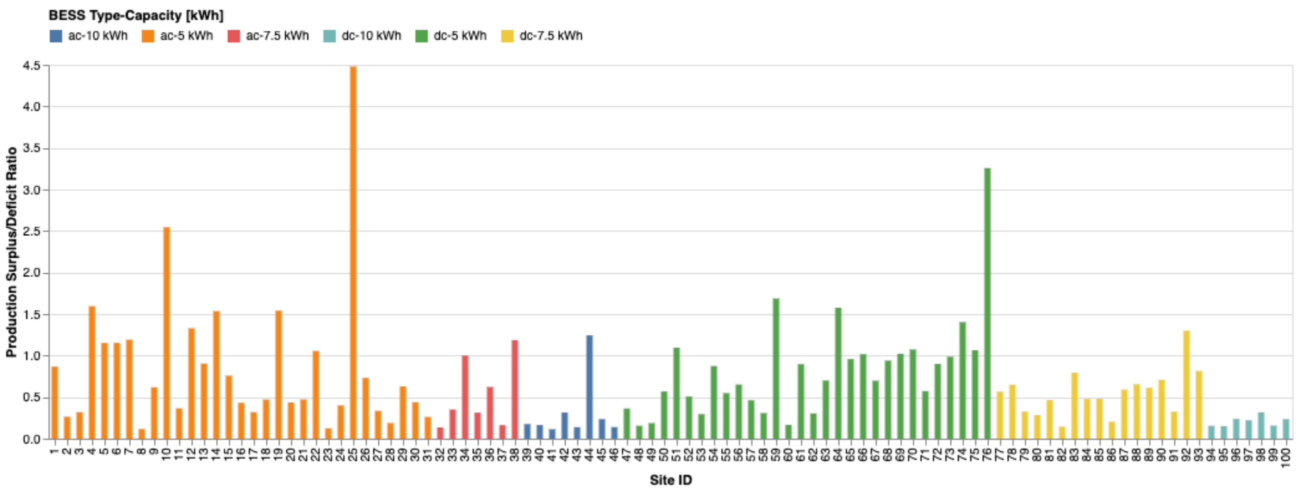

Figure 17: Annual Production Surplus/Deficit Ratio Estimate by Site, based on Apr19-Mar20

2.8 Baseline Grid Import Costs with Import Only

The baseline electrical costs were calculated from Consumption, assuming that all energy was purchased from the grid, which are presented for each site in Figure 18. Standing charges, dual fuel discounts, and payment method discounts are excluded; instead, all consumption is charged at a flat £0.15/kWh tariff. For clarity, the impacts of Solar PV system and/or BESS are excluded on all sites for this baseline calculation.

There are several general trends to consider when comparing any subsequent cost saving results across the BESS Type-Capacity clusters, as discussed in Section 2.2:

- The consumption, and hence baseline energy cost, increases on average with BESS capacity
- This difference is most notable with the large 10kW BESS
- There is more variability in Baseline cost within each BESS Type-Capacity cluster with ac-coupled batteries

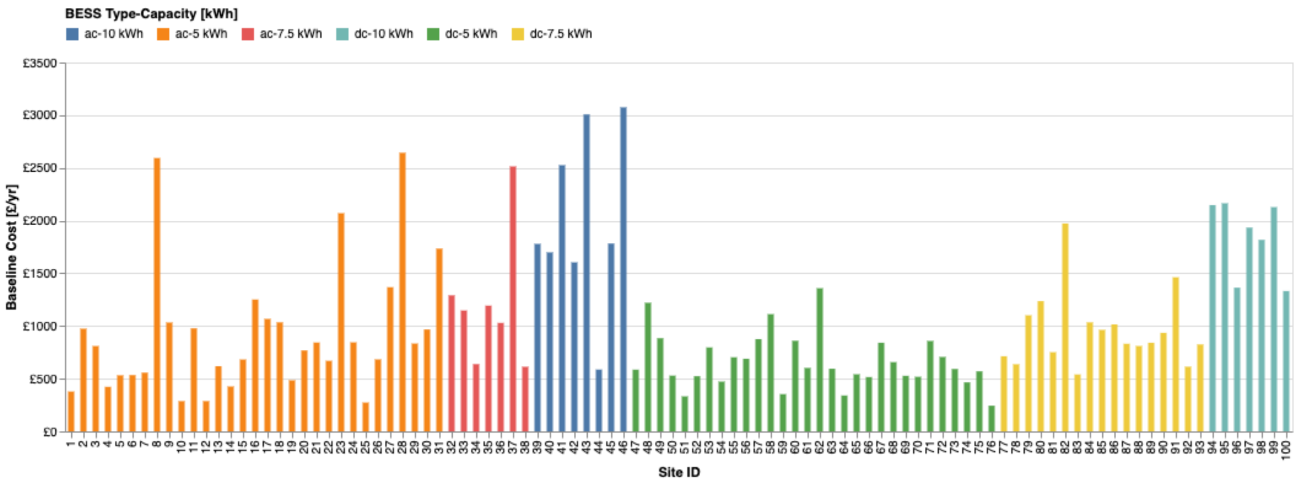

Figure 18: Annual Baseline Grid Energy Cost Estimate by Site, based on Apr19-Mar20

2.9 CO_2 Footprint for All Sites with Import Only

Similar to the baseline electrical costs discussed in Section 2.8, the baseline CO_2 Footprint was calculated from Consumption, assuming that all energy was purchased from the grid. The results are presented for each site in Figure 19, calculated using the latest Average Carbon Intensity of the UK's National Grid [kgCO_2-equivalent/kWh]. This CO_2-equivalent intensity is quoted by BEIS at the time of writing as 0.233kgCO2/kWh[10], which is understood to be based on fiscal year 2019/20 generation figures.

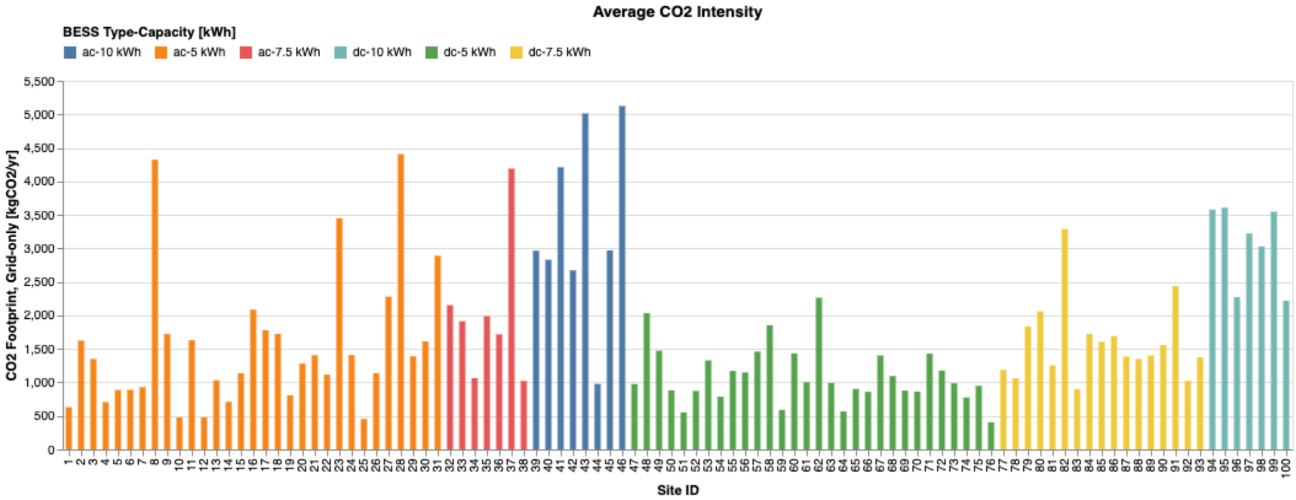

Figure 19: Annual Baseline CO_2 Footprint Estimate by Site, based on Apr19-Mar20, using Average CO_2 Intensity

[10] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/891106/Conversion_Factors_2020_-_Full_set__for_advanced_users_.xlsx

3. BESS Performance: Charge, Discharge, RTE, Grid Import & Grid Export

3.1 Overview

The metrics discussed in this section augment the underlying consumption, production and corresponding derived parameters to introduce value to the customer through grid import reduction savings, and mitigated grid export income. In contrast to PV-only dwellings (which capitalise from grid export and constrained export income, discounting legacy FiT schemes), the BESS introduces opportunities to mitigate low-yield export income in order to increase self-consumption (and lower grid imports). This does, however, come with Round Trip Efficiency (RTE) overheads; it is therefore critical to maintain a good understanding of charge and discharge cycles, as discussed in this section.

As discussed previously, a number of more complex issues are discussed in the subsequent BESS utilisation report[11].

[11] LEM Residential BESS Utilisation Summary Report

3.2 Grid Import

Of the notable features in Figure 20, grid import is generally higher in at sites with the larger 10kWh BESS; a limited number of other sites, particularly in the ac-5kWh cluster, exceed 8,000kWh/yr. To understand the effectiveness of the battery installation it is important, however, that this is considered in relation to consumption and grid export. The bias of larger import levels at the 10kWh BESS sites was driven by higher underlying consumption levels. As is discussed below, grid export was low at these sites, which implied that the BESS was effective.

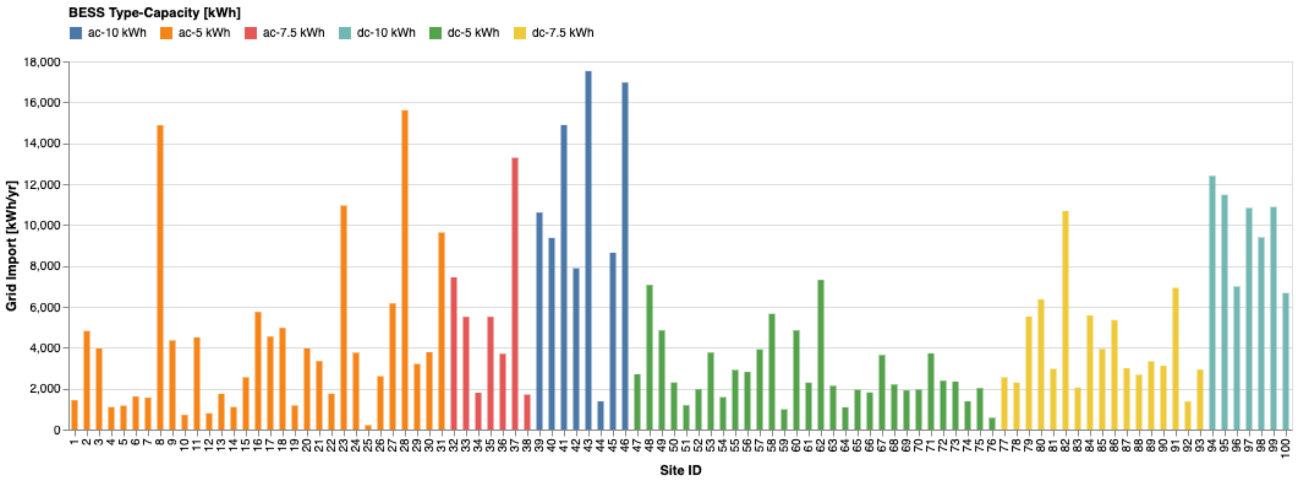

Figure 20: Annual Grid Import Estimate by Site, based on Apr19-Mar20

When compared directly to the distribution of consumption in Figure 1, a marked lowering baseline grid imports is clearly demonstrated in Figure 21 (notwithstanding the existing contributions of the existing PV installations). Grid imports are below 7,000kWh for the majority of sites as a result of the PV and BESS, in many cases, imports are well below this value.

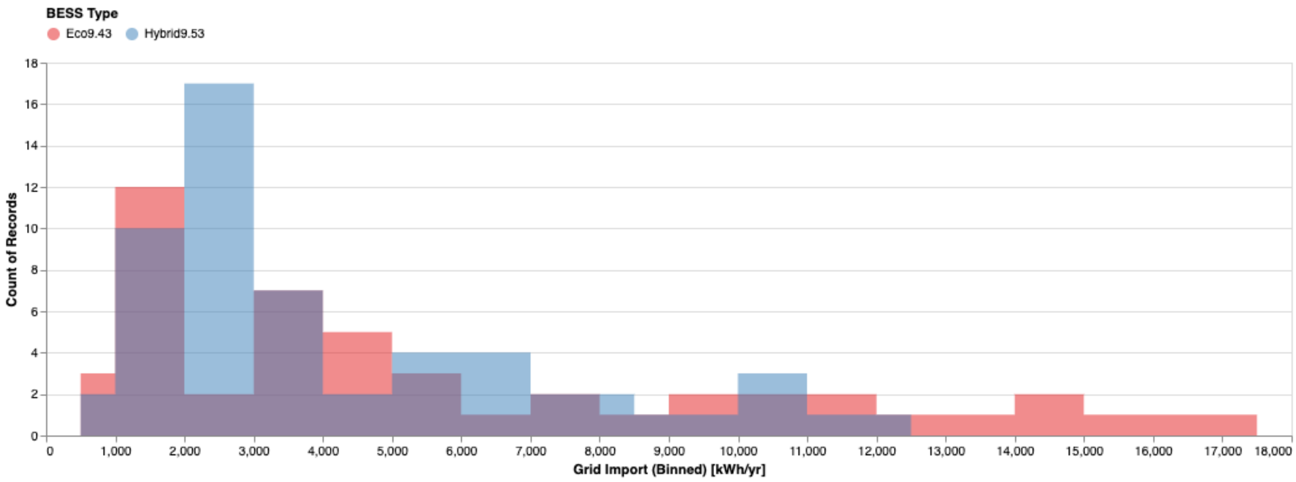

Figure 21: Distribution of Estimated Annual Grid Import, based on Apr19-Mar20 data

There is, however, a severe seasonal discrepancy in the contributions that the PV and BESS make towards lowering grid imports, as seen in Figure 22. The combined effects of higher consumption and lower production result in marginal benefits in winter grid import levels. Aggregate consumption levels above 2,000kWh/day were common between mid-November and the end of March; in Figure 22, it is noted that grid imports are not markedly different.

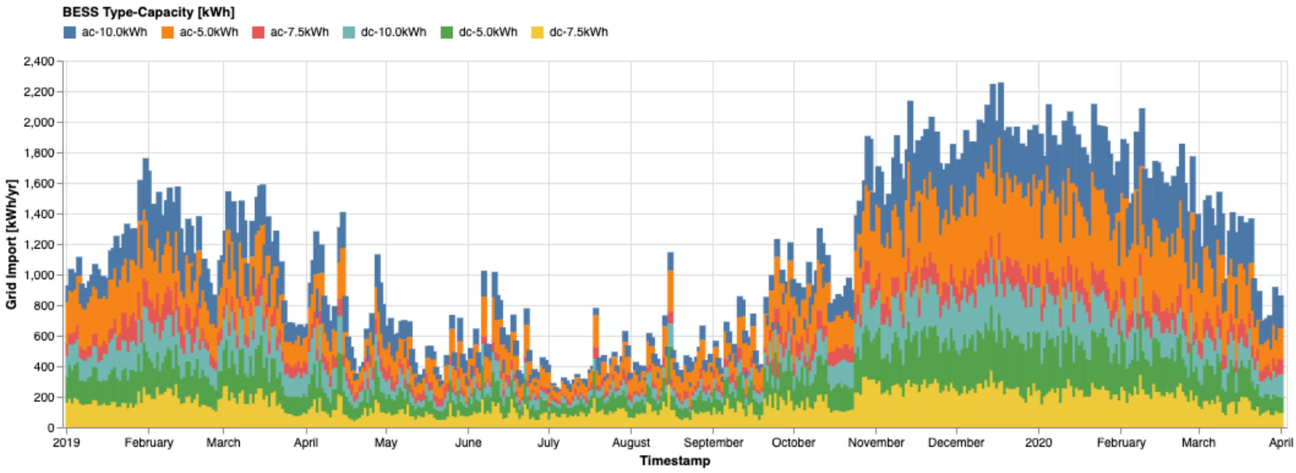

Figure 22: Approximate fleet level daily Grid Import, split by BESS Type-Energy Capacity cluster, before scaling for missing data

As a primary objective of lowering grid imports, it is also relevant to consider the Production Surplus/Deficit Ratio. It is clear that any dwelling which experiences larger surplus than deficit, achieving a ratio larger than 1.0, will benefit from low grid import costs, as seen in Figure 23. As noted previously, there is no specific trend with relation to battery size. Sites with a 10kWh BESS can still experience significant grid import levels; this is due to underlying high consumption at these sites.

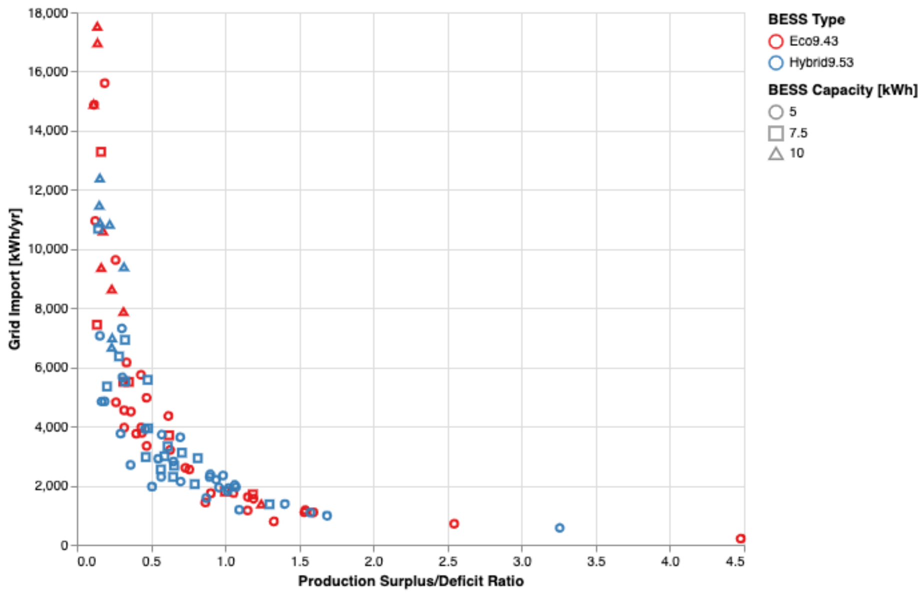

Figure 23: Grid Import vs Production Surplus/Deficit Ratio, using Annual Estimates, based on Apr19-Mar20 data

3.3 Grid Export

As mentioned previously, grid export is a key determinant of overall BESS performance; aside from the potential for grid services income, value to the customer must be driven by increasing self-consumption, at the expense of grid exports. A major factor in the ability of the batteries to perform this task is clearly the capacity. Between the 5, 7.5 and 10kWh batteries, there is a significant reduction in grid export levels, shown in Figure 24. Furthermore, it is interesting to note the low levels of export achieved by the 10kWh batteries, indicating that these were generally capable of making a significant impact on self-consumption. It must be stressed, however, that site-by-site variation is heavily dependent on intra-day consumption patterns, both within the discrete BESS size/type clusters and between different clusters. Further details in intra-day behaviour is provided later in this report.

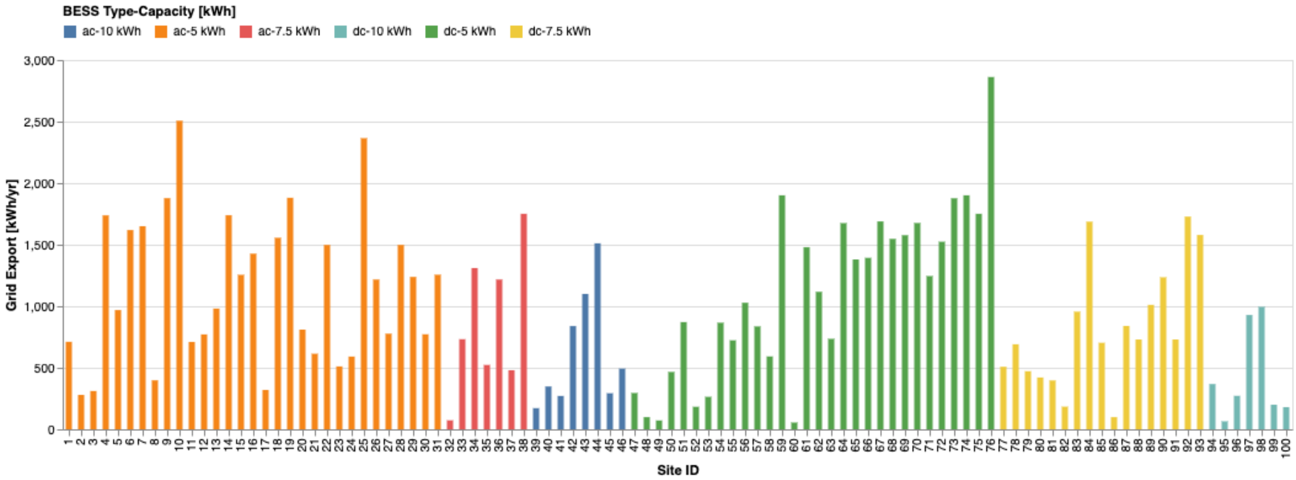

Figure 24: Annual Grid Export Estimate by Site, based on Apr19-Mar20

The distribution of grid export levels across the sites, as provided in Figure 25, is considered in conjunction with the consumption/production ratio in Figure 9. A number of sites towards the right-hand side fail to achieve adequate grid import reduction. From Figure 24, for example, the extreme cases of sites 10, 25 and 76, all export more electricity than consumed on-site (between 4,000-4,500kWh were produced at these sites, all three had 5kWh batteries). With reference to Figure 9, these same three sites correspond to large spikes in consumption/production ratio (as consumption was below 2,000 at all three sites). Further detail can be seen in the later intra-day behaviour section, that these sites also had low demand during the day.

On the basis of the above observations, in any sites that have high production/consumption ratio, including those in the slightly lower band between 1.0 and 2.0, the battery will struggle to fully discharge during the course of any given day. It is interesting to note that this occurs at a number of the Eco sites; prior to the installation of the battery, these sites were not particularly well suited to PV. A battery system alone, however, does not fully address this issue, due to very low consumption levels. These sites would need to engage with the LEM Market Platform or other grid services to provide adequate utilisation of their batteries.

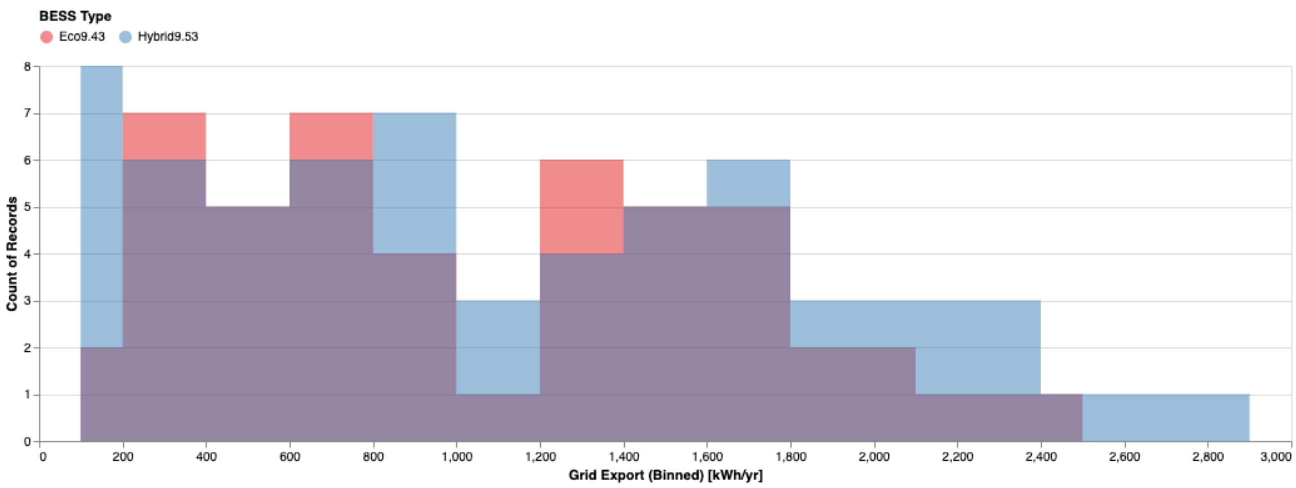

Figure 25: Distribution of Estimated Annual Grid Export, based on Apr19-Mar20 data

Seasonal variation of grid exports, as presented in Figure 28, agrees with expectations, as driven by underlying production behaviour. Severe drops in grid export levels typically correspond to periods of poor solar conditions, rather than changes to consumption behaviour.

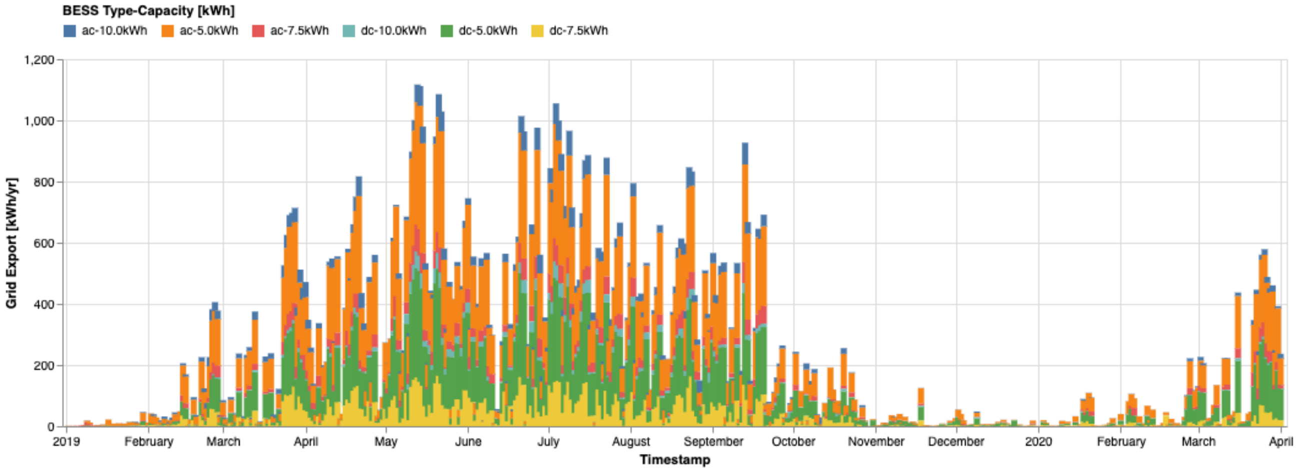

Figure 26: Approximate fleet level daily Grid Export, split by BESS Type-Energy Capacity cluster, before scaling for missing data

Unfortunately, there is not a strong relationship between Grid Export and either Production/Consumption Ratio (Figure 27) or Production Surplus/Deficit Ratio (Figure 28). Therefore, predicting Grid Export in isolation is difficult, as may be useful when assessing impact on grid constraints or a wider Virtual Power Plant.

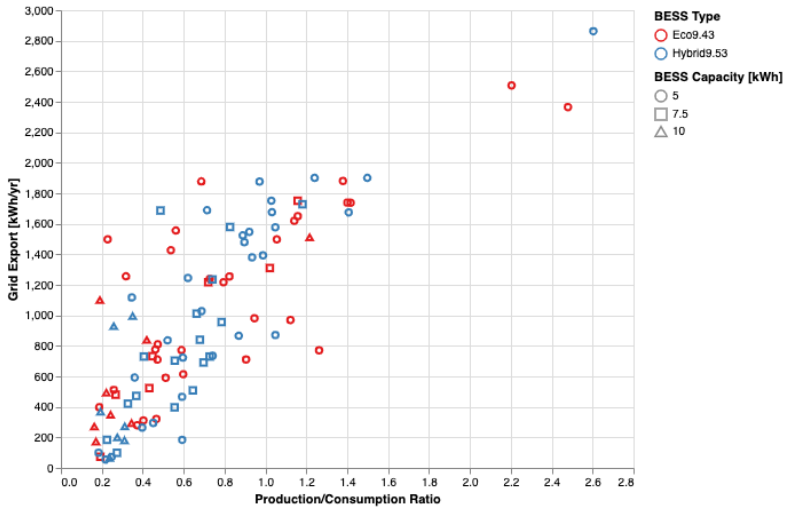

Figure 27: Grid Export vs Production/Consumption Ratio, using Annual Estimates, based on Apr19-Mar20 data

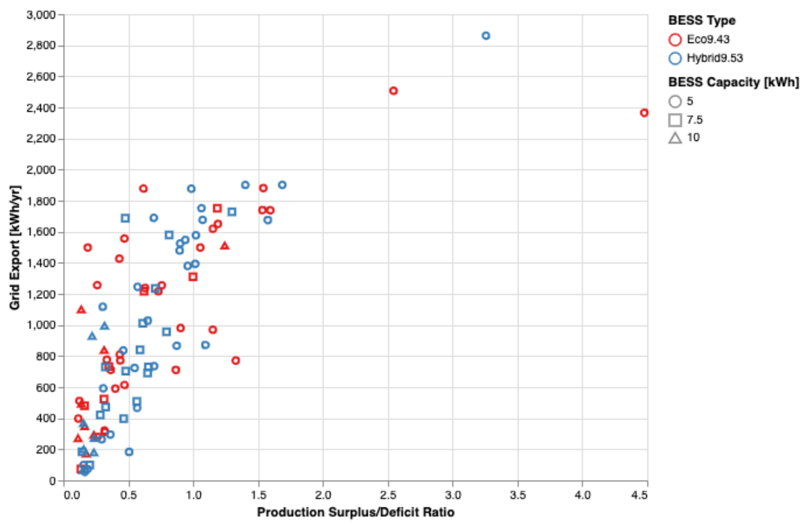

Figure 28: Grid Export vs Production Surplus/Deficit Ratio, using Annual Estimates, based on Apr19-Mar20 data

3.4 Grid Import vs Grid Export

By comparing Grid Import and Grid Export – as presented in Figure 29 – it is clear that the time varying nature of both Production & Consumption can lead to significant Grid Import & grid Export from the same site, when considered on an annual basis. This again highlights the value of sub-daily daily in the assessment of BESS + Solar PV performance.

Figure 29: Grid Export vs Grid Import, using Annual Estimates, based on Apr19-Mar20 data, with histograms per axis

3.5 BESS Charge

The distribution of production presented in Figure 30 suggests that the dc-coupled (Hybrid9.54) cluster charged the BESS marginally more on average than the ac-coupled (Eco9.43) cluster. It Is assumed that this is due to variation in the annual values and daily patterns of Production and Consumption, rather than system difference in battery operation.

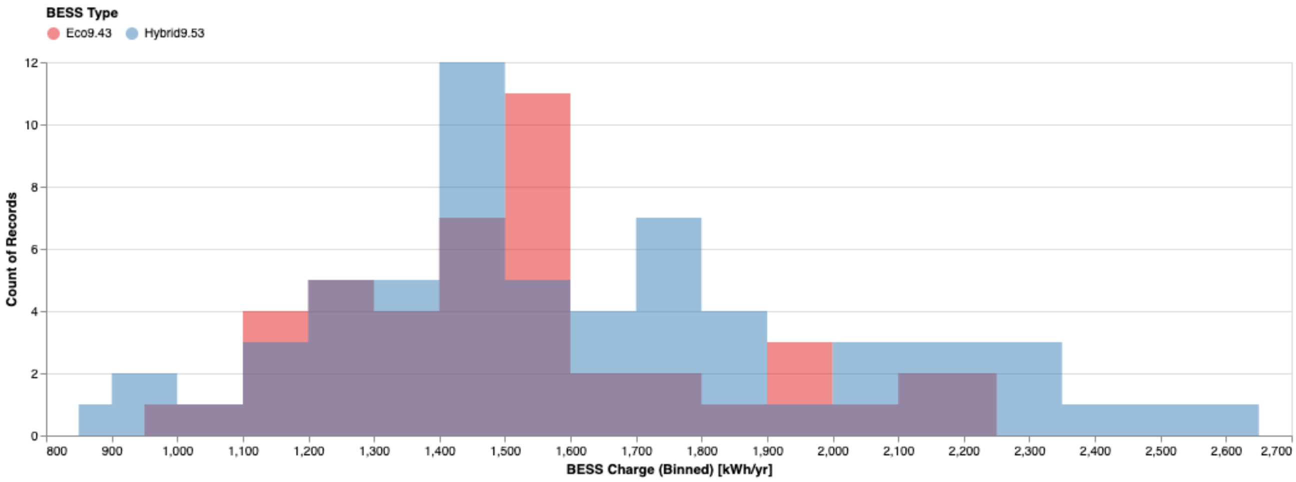

Figure 30: Distribution of Estimated Annual BESS Charge, based on Apr19-Mar20 data

As shown in Figure 31, there is significant variation in BESS Charge between BESS Type-Capacity clusters, as expected as larger BESS can support more throughput per day, and within each cluster, due to Production/Consumption variations.

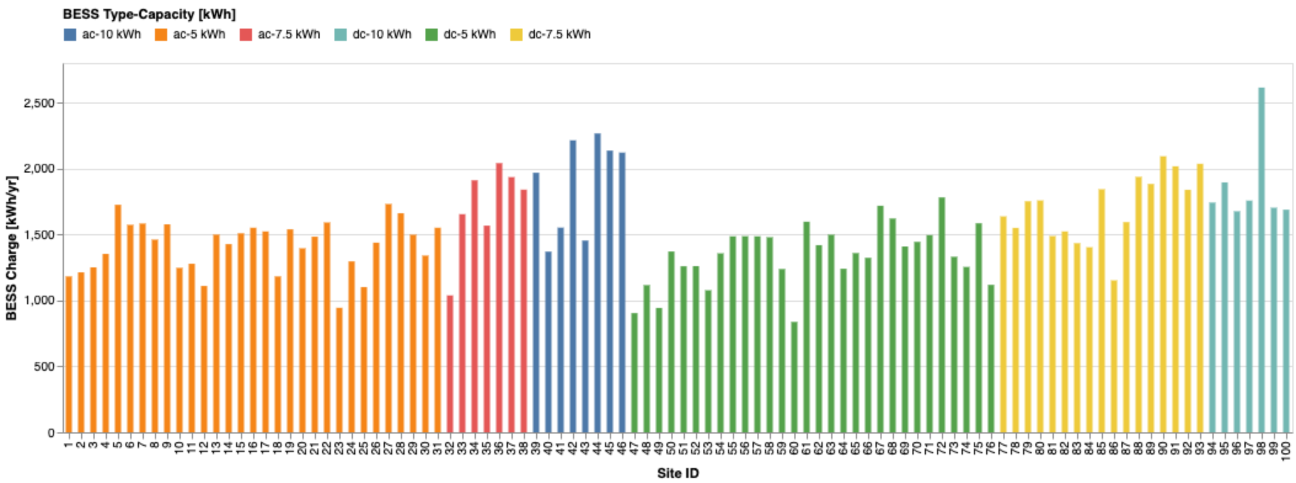

Figure 31: Annual BESS Charge Estimate by Site, based on Apr19-Mar20

The daily variation in BESS Charge is presented in Figure 30. The concept of inter-day energy transfer will be discussed in the subsequent report on BESS Utilisation.

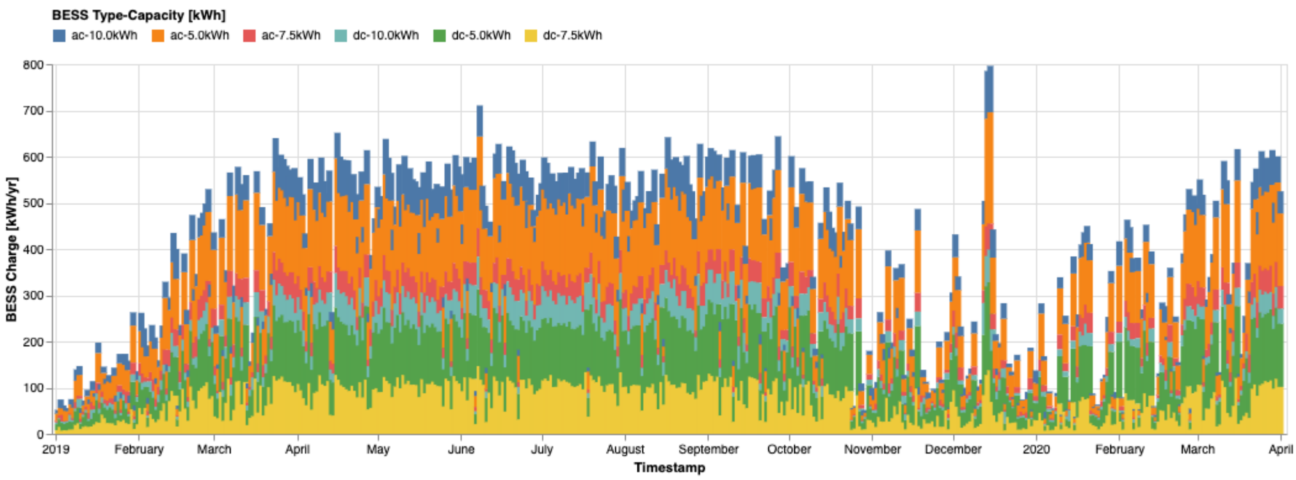

Figure 32: Approximate fleet level daily BESS Charge, split by BESS Type-Energy Capacity cluster, before scaling for missing data

3.6 BESS Discharge

Despite the potential change in BESS Charge distribution discussed in Section 3.5, the distribution of BESS Discharge presented in Figure 33 suggests that the dc-coupled and ac-coupled clusters have similar discharge energy throughput.

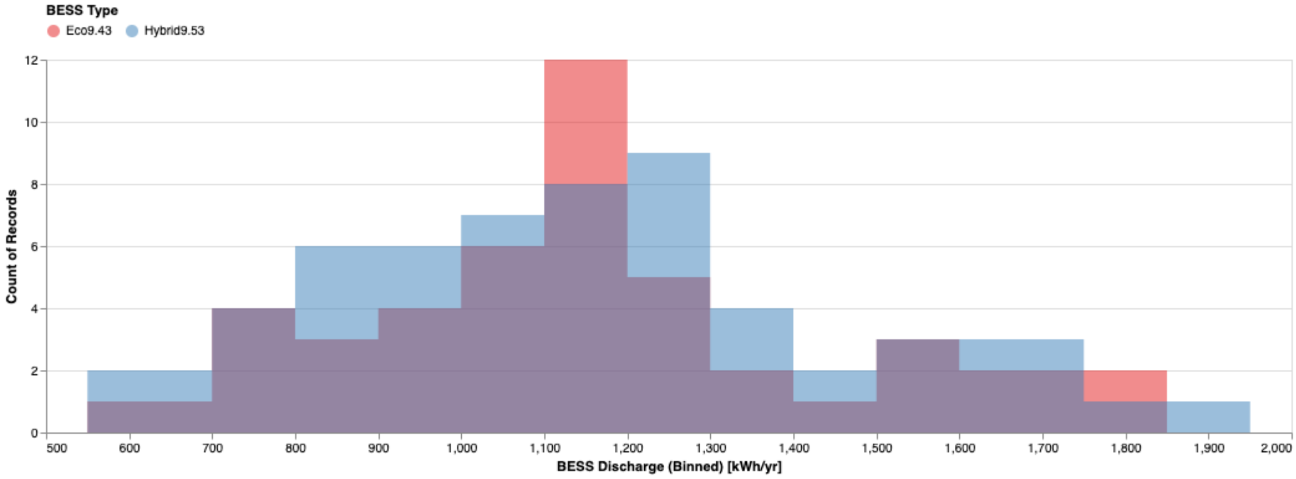

Figure 33: Distribution of Estimated Annual BESS Discharge, based on Apr19-Mar20 data

As with BESS Charge, there is significant variation in BESS Discharge between BESS Type-Capacity clusters (as would be expected), and within each cluster, as shown in Figure 34.

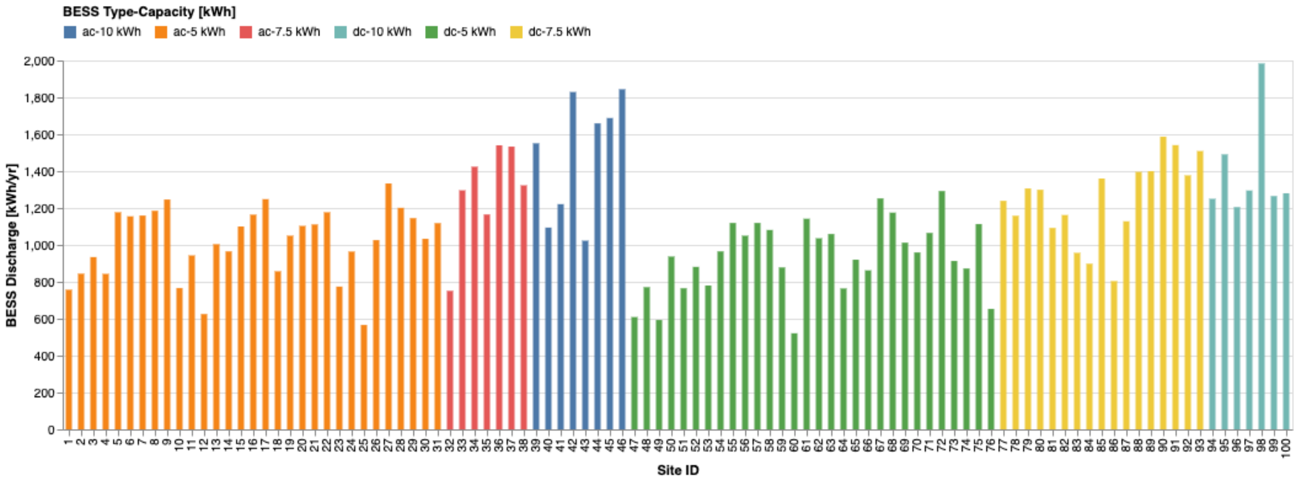

Figure 34: Annual BESS Discharge Estimate by Site, based on Apr19-Mar20

The daily variation in BESS Discharge is presented in Figure 35. The concept of inter-day energy transfer will be discussed in the subsequent report on BESS Utilisation.

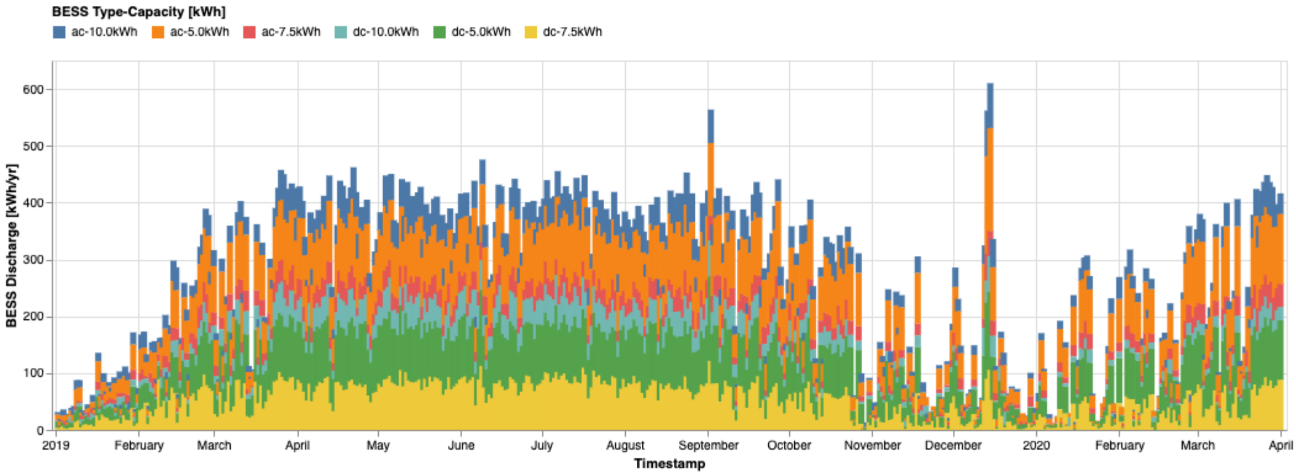

Figure 35: Approximate fleet level daily BESS Discharge, split by BESS Type-Energy Capacity cluster, before scaling for missing data

3.7 BESS Charge vs BESS Discharge

By considering the variation against a notional line of best fit between BESS Charge and BESS Discharge – as presented in Figure 36 – the variation in Round Trip Efficiency vs BESS energy throughput (as either Charge or Discharge) can be shown to be significant, yet relatively minor. Since the notional best fit line is straight, there is no clear change in RTE with throughput, within the domains of BESS Charge & Discharge experienced in the LEM Residential trial.

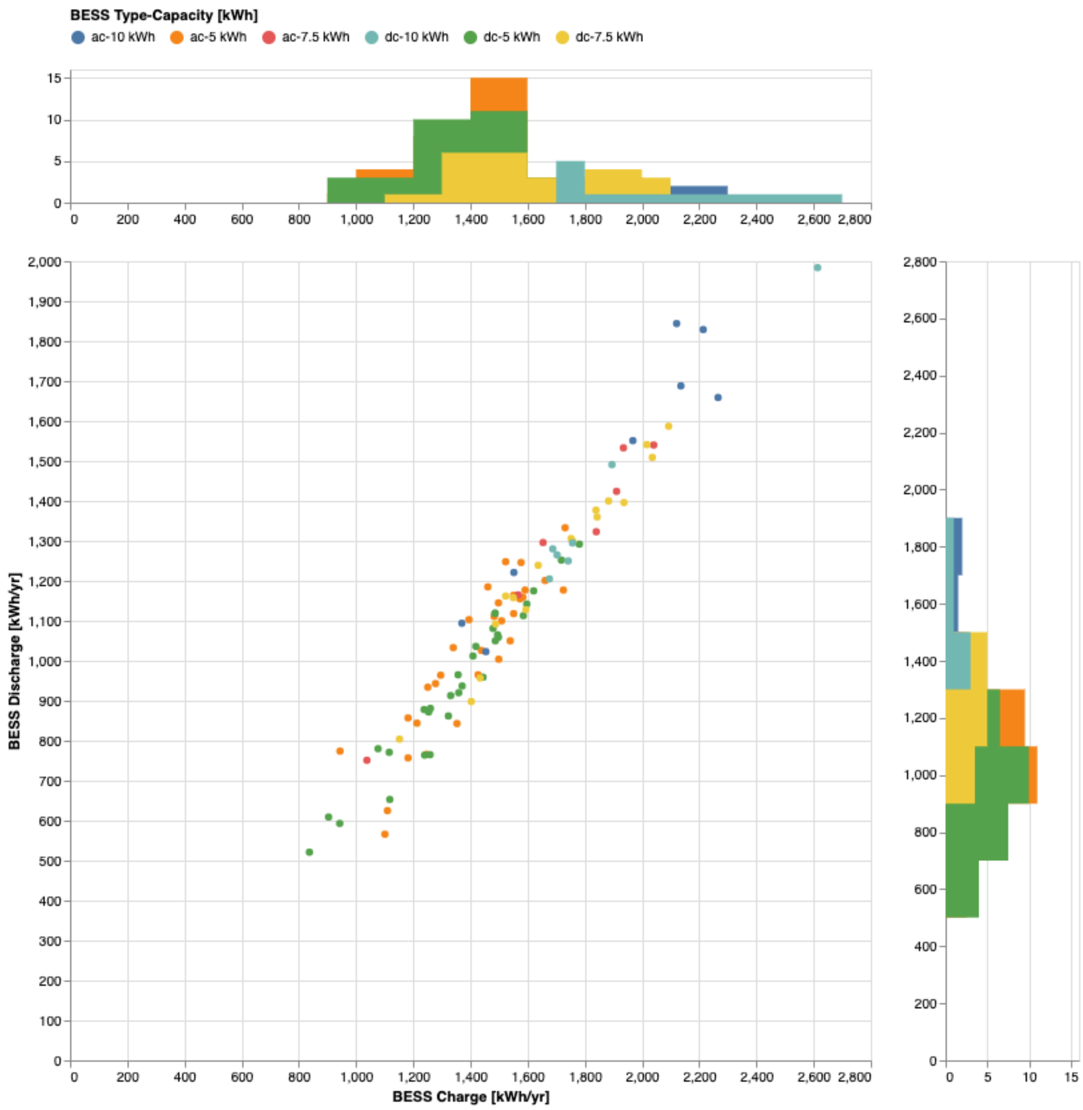

Figure 36: BESS Discharge vs BESS Charge, using Annual Estimates, based on Apr19-Mar20 data, with histograms per axis

3.8 BESS Round Trip Efficiency

3.8.1 Definition

Round Trip Efficiency [RTE] is defined using Equation 4, where BESS Charge is inclusive of all energy for parasitic loads (i.e. controller, meters, user interfaces) during both active operation (charge/discharge) and standby.

$$Round\ Trip\ Efficiency, RTE = \frac{BESS\ Discharge}{BESS\ Charge}$$

Equation 4: Round Trip Efficiency [RTE] calculation

3.8.2 RTE Fleet Performance

The distribution of Round Trip Efficiency between the ac-coupled and dc-coupled clusters is shown in Figure 37. We would caution the reader against concluding that the dc-coupled BESS Type is intrinsically less efficient than the dc-coupled Type, as the clusters have different sites in terms of annual Production, annual Consumption, and the various KPIs that demonstrate co-incidence (or otherwise) of Production and Consumption.

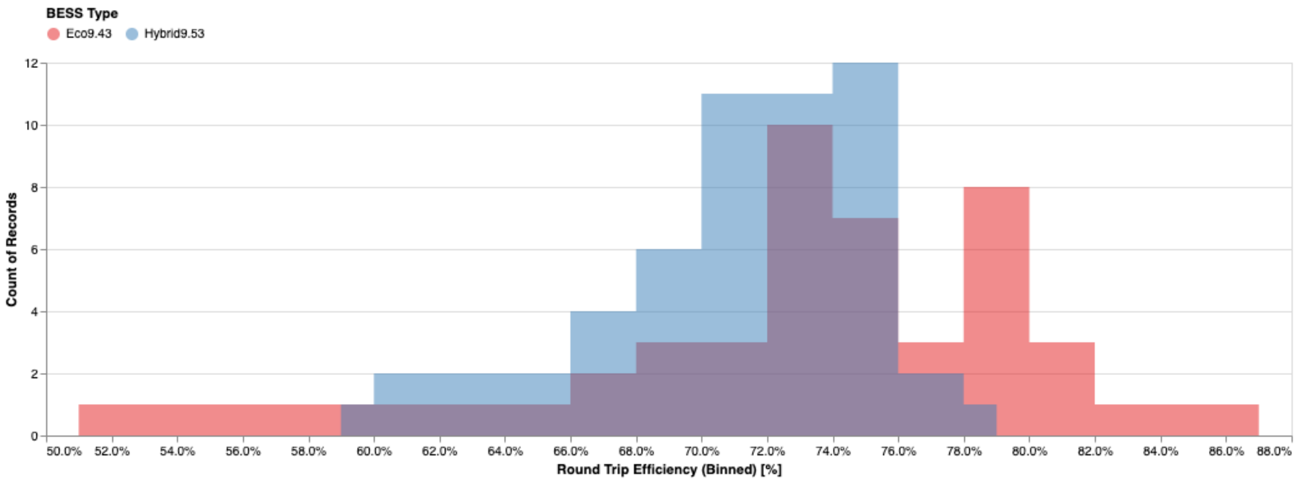

Figure 37: Distribution of Estimated Annual BESS Round Trip Efficiency, based on Apr19-Mar20 data

The spread of Round Trip Efficiency across the fleet is presented in Figure 38, where again it is cautioned against concluding that larger Capacity BESS have intrinsically higher efficiency. These effects are likely due to higher Production and Consumption values for sites that were assigned larger BESS.

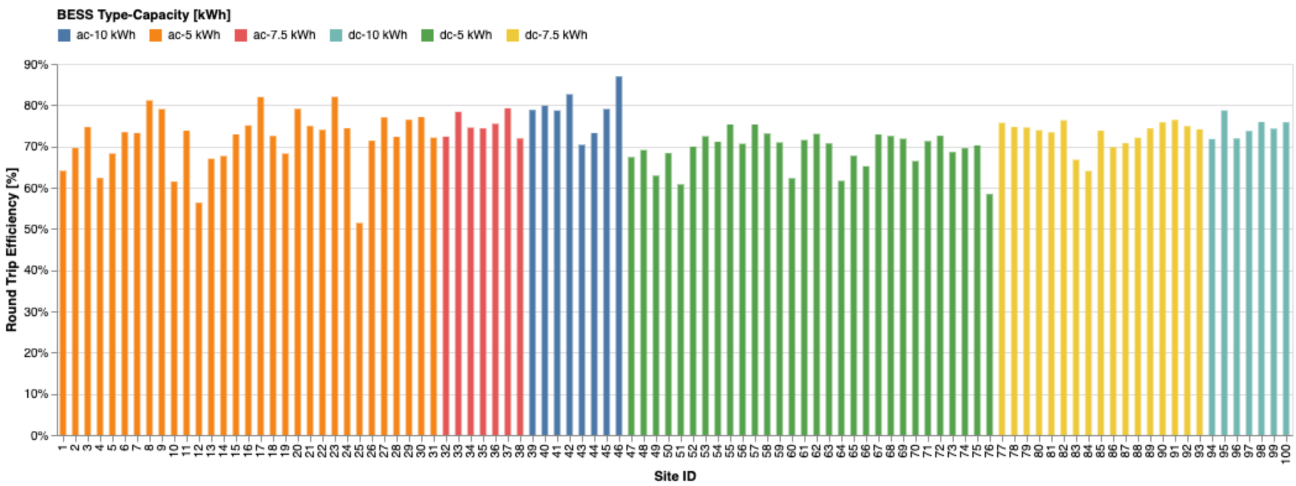

Figure 38: Annual BESS Round Trip Efficiency Estimate by Site, based on Apr19-Mar20

3.8.3 *Predicting RTE*

To support the discussions on Round Trip Efficiency variation against BESS Type or BESS Capacity, Figure 39 illustrates that the primary driver of Round Trip Efficiency is Consumption.

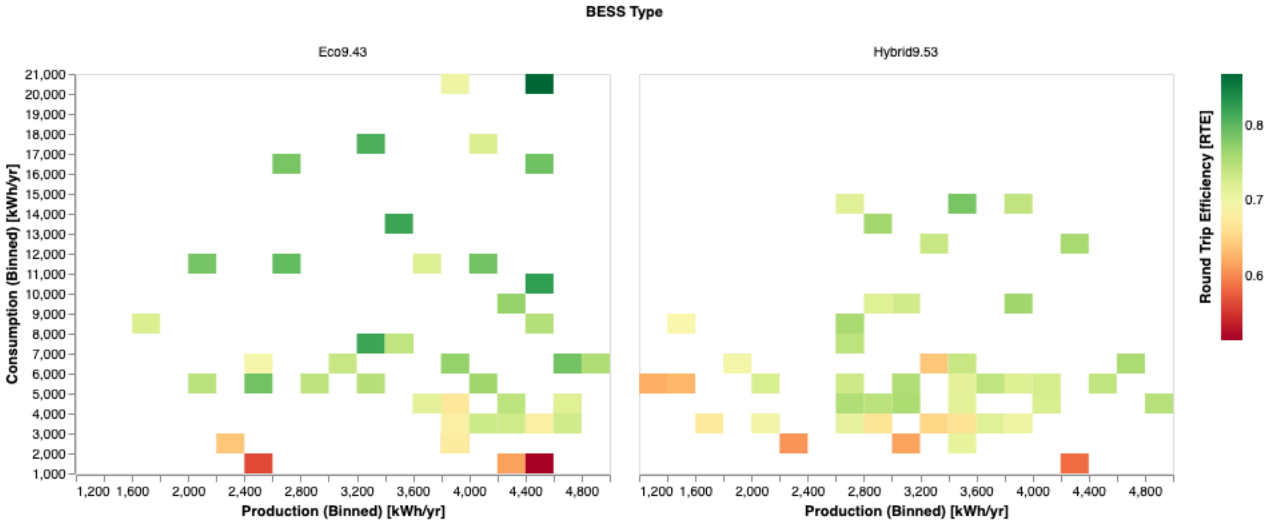

Figure 39: BESS Round Trip Efficiency by Consumption vs Production bins, using Annual Estimates, based on Apr19-Mar20 data, clustered by BESS Type

Exploring this relationship between Round Trip Efficiency and Consumption further, Figure 40 demonstrates that there is a tipping point, below which the energy throughput of BESS is so low as for the RTE to be dominated by parasitic losses during standby. There is little apparent difference between the performance of BESS Types with similar annual consumption values.

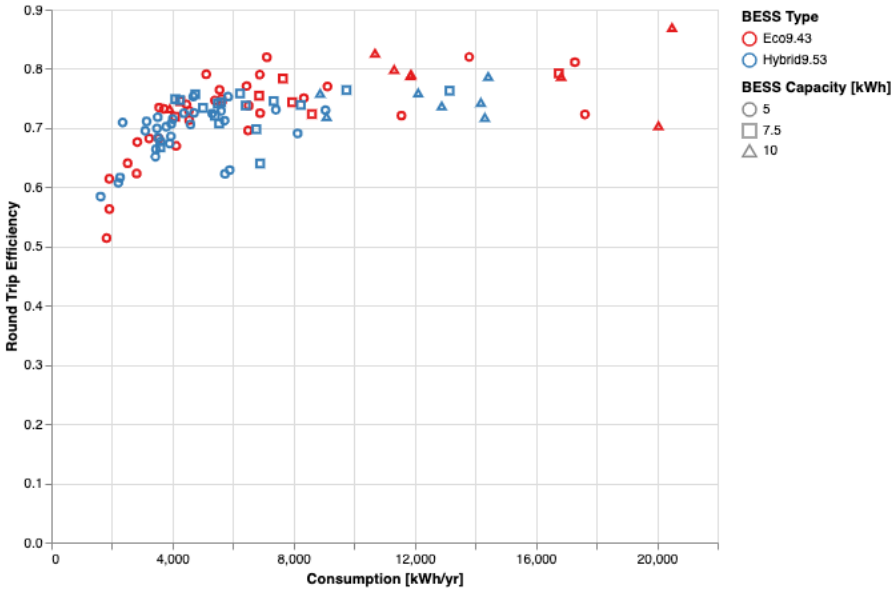

Figure 40: BESS Round Trip Efficiency vs Consumption, using Annual Estimates, based on Apr19-Mar20 data

The weak relationship between Round Trip Efficiency and Production is visible in Figure 41. It does not demonstrate a clear tipping point (as in the case of Consumption in Figure 40), but on average higher annual Production and higher RTE are corelated. Whether this is due to a weak underlying relationship between Production & Consumption is unclear.

The RTE results against the Production/Consumption Ratio – as presented in Figure 42 – are insufficiently distributed to identify any relationship against the ratio.

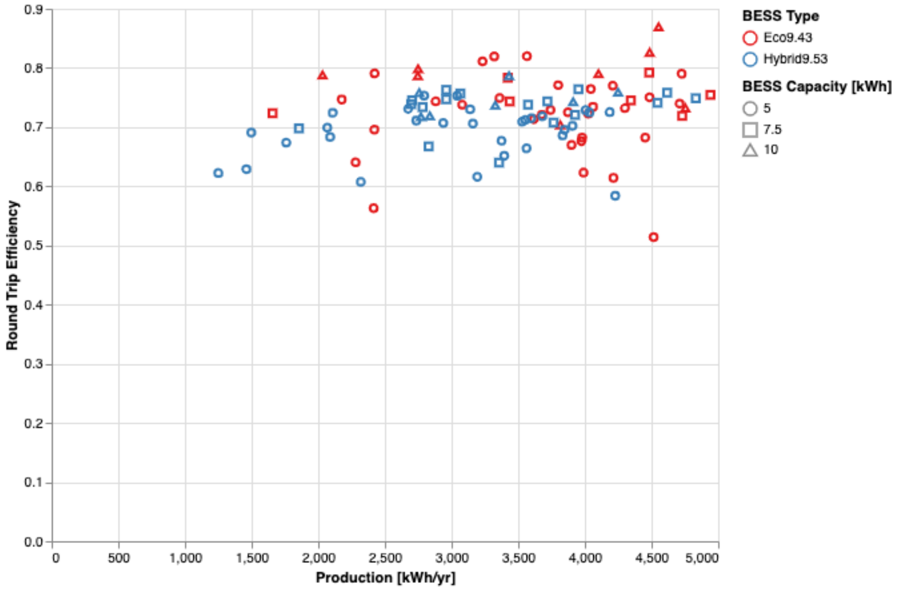

Figure 41: BESS Round Trip Efficiency vs Production, using Annual Estimates, based on Apr19-Mar20 data

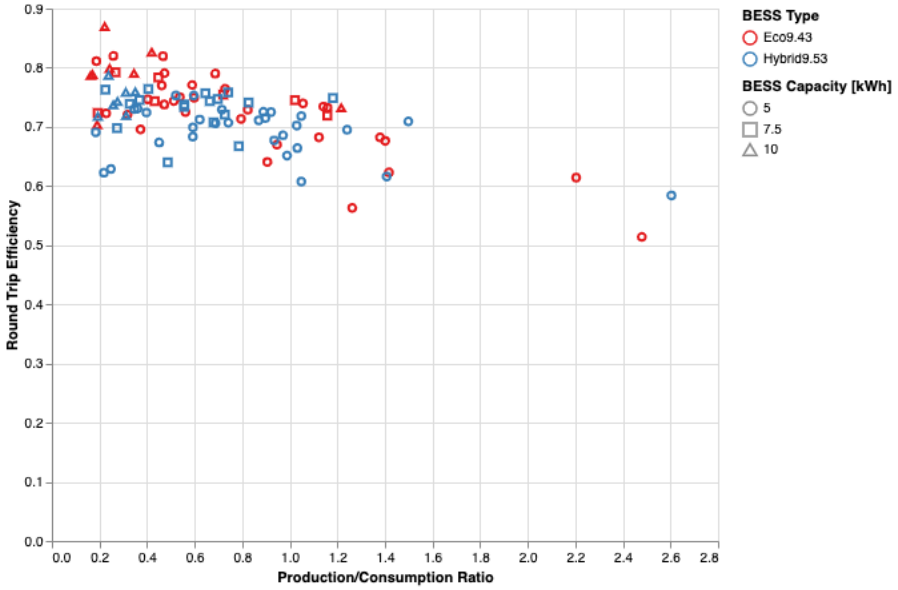

Figure 42: BESS Round Trip Efficiency vs Production/Consumption Ratio, using Annual Estimates, based on Apr19-Mar20 data

The heatmaps in Figure 43 show a clear relationship between Production Deficit and RTE, for each BESS Type.

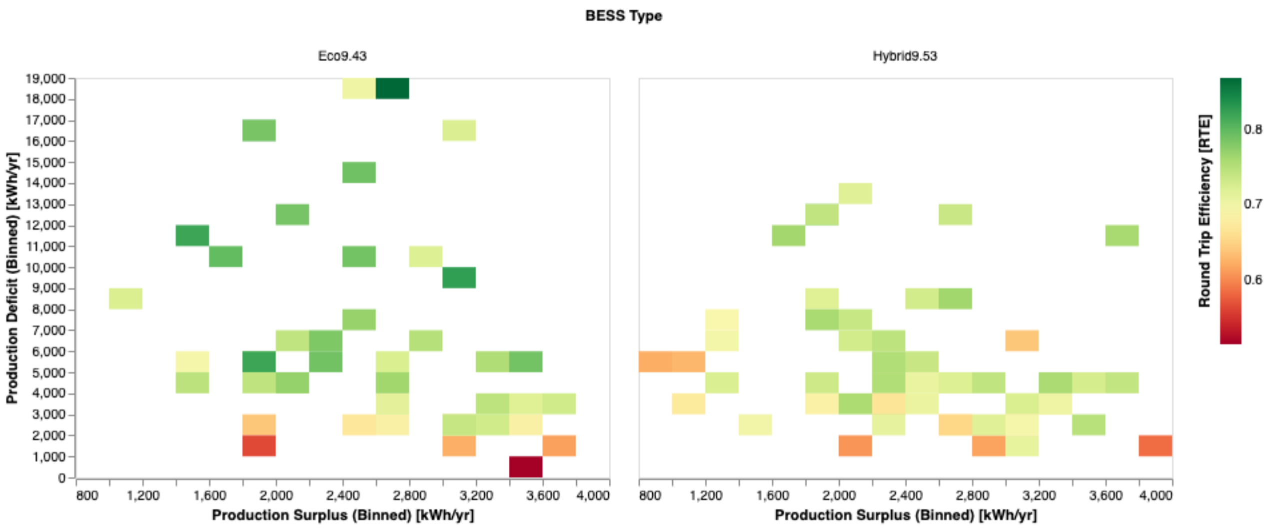

Figure 43: BESS Round Trip Efficiency by Production Deficit vs Surplus bins, using Annual Estimates based on Apr19-Mar20 data, clustered by BESS Type

Focussing on the relationship of Round Trip Efficiency with Production deficit – as presented in Figure 44 – it is clear that low Production Deficit – which translates to low requirement for BESS Discharge, results in significant reduction in RTE.

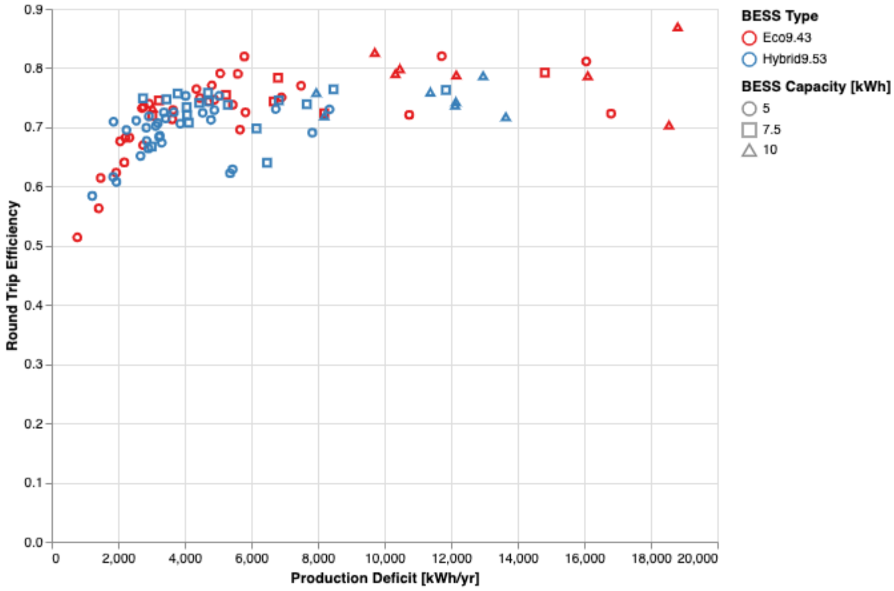

Figure 44: BESS Round Trip Efficiency vs Production Deficit, using Annual Estimates, based on Apr19-Mar20 data

In order to explore this further, the relationship between Round Trip Efficiency and the BESS/Consumption Power Ratio is presented in Figure 45. It suggests that as BESS Power Capacity increases versus the average consumption power level, then RTE reduces. This is in agreement with the part-load efficiency curve of the BESS (where Discharge Efficiency reduces as Discharge Power reduces). It is interesting that RTE is dominated by Discharge part-load effects, and not charge part-load effects, and is a factor to consider when sizing batteries as energy efficiency measures continue to reduce average consumption power levels.

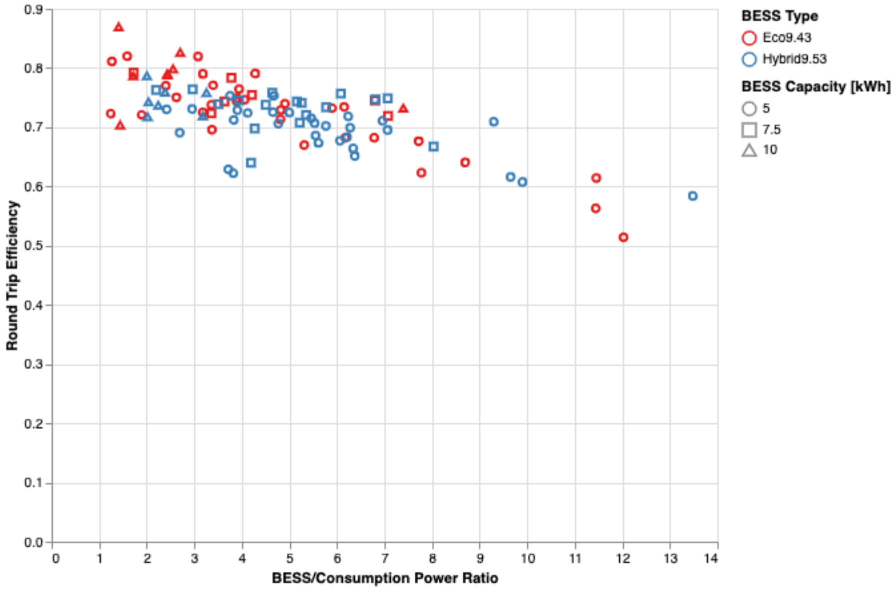

Figure 45: BESS Round Trip Efficiency vs Bess Rated Power / Consumption Average Power Ratio, using Annual Estimates, based on Apr19-Mar20 data

4. Understanding & Predicting Benefits with BESS

4.1 Overview

In this section, we explore the Financial and CO_2 Benefits of Solar PV Systems, the impact of BESS on the savings of homes with Solar PV, and the combined benefit of Solar PV Systems & BESS.

This report focuses on fixed energy tariffs and CO_2-equivalent intensity, ignoring the half-hourly variation of tariffs and CO_2-equivalent intensity throughout the year. In a subsequent report[12], the impact of such variation on financial and CO_2-equivalent savings will be explored, in the context of Self-Consumption, alternative BESS sizing, and trading of BESS flexibility to unlock additional income streams.

In a similar vein, both Average and margin CO_2-equivaelnt intensity figures are used, to draw attention to the potential for zero-carbon generation - or zero-carbon generation buffered via a BESS – to displace grid-connected generation with above average CO_2-equivalent intensity. This concept is explored farther in the subsequent BESS utilisation report.

Financial savings are disaggregated between technologies (BESS vs Solar PV), and the Total Financial Value is disaggregated by the constituent value stream (Grid Import Cost Avoidance and Export Income via Export Tariff).

The focus of this report is to understand how the benefits vary with when operating in Self-Consumption mode with the current BESS sizing for each site, which was based on upfront estimates of annual Solar PV Production and electrical Consumption. The distribution and interrelation of Production & Consumption was discussed in Section 2. An accompanying report[13] on MetaData collected during this trial, we explored the accuracy of such Consumption and Production predictions, and the major challenges using customer or 3rd party-derived MetaData to make assumptions on Consumption.

The ability to predict Total Financial Value using annual data is compared with approaches that rely upon greater temporal precision (such as provided half-hourly smart meter data or 1-minute smart home monitoring systems). As we explore in the subsequent report on BESS Utilisation, this additional granularity of production & consumption data can drive the effective prediction of value (from Self-Consumption and Trading) from different BESS sizes, in order to optimise BESS utilisation and hence improve returns from both financial and embodied CO_2 perspectives.

12 LEM Residential BESS Utilisation Summary Report

13 LEM Residential MetaData Summary Report

4.2 Financial Benefit of Solar PV Systems

4.2.1 Summary

Before considering the incremental value of BESS systems, it is important to understand the value offered by Solar PV systems in isolation. This draws attention to the tension between import avoidance and reduced export tariff income, and hence the complexity of considering alternative BESS utilisation options, as discussed in a subsequent report[14].

4.2.2 Import Avoidance Savings from Solar PV

The Import Avoidance Savings from Solar PV are calculated using Equation 5 and Equation 6, using the data collected during Self-Consumption operation with Solar PV and BESS.

$$Import\ Avoidance\ Savings\ from\ Solar\ PV, ISpv = Self\ Consumed\ Solar\ PV x\ Import\ Tariff$$

Equation 5: Import Avoidance Savings from Solar PV, ISpv

$$Self\ Consumed\ Solar\ PV, ESpv = \text{Consumption} - \text{Grid Import} - \text{BESS Discharge}$$

Equation 6: Self Consumed Solar PV, ESpv

As illustrated by the results for Sites 20 & 39 in Figure 46, this calculation relies upon a key simplification; that all BESS Discharge is consumed on-site. In reality, however, a proportion of BESS Discharge will be exported due to a combination of factors, including:

1. The rate of change of production and/or consumption is faster than the response time of the BESS controller, and hence some grid spill will result when production increases or consumption decreases
2. The delivery of grid services will intentionally discharge the BESS to result in Grid Export; this was tested across the fleet in varying degrees during the trial period
3. Faults in BESS control systems, mis-configuration or mis-placement of BESS meters will result in unintentional Grid Export during BESS discharge, and in some cases due to massive increases in BESS Charge/Discharge cycles

The first 2 factors above have impacted all sites, whilst a large minority of sites suffered from issues described in factor 3. Clearly Sites 20 & 39 have suffered most, hence their poor performance. The duration and/or re-occurrence of these issues was such that it was difficult to interpolate to replace data with that likely to accurately reflect operation with a fully functioning system.

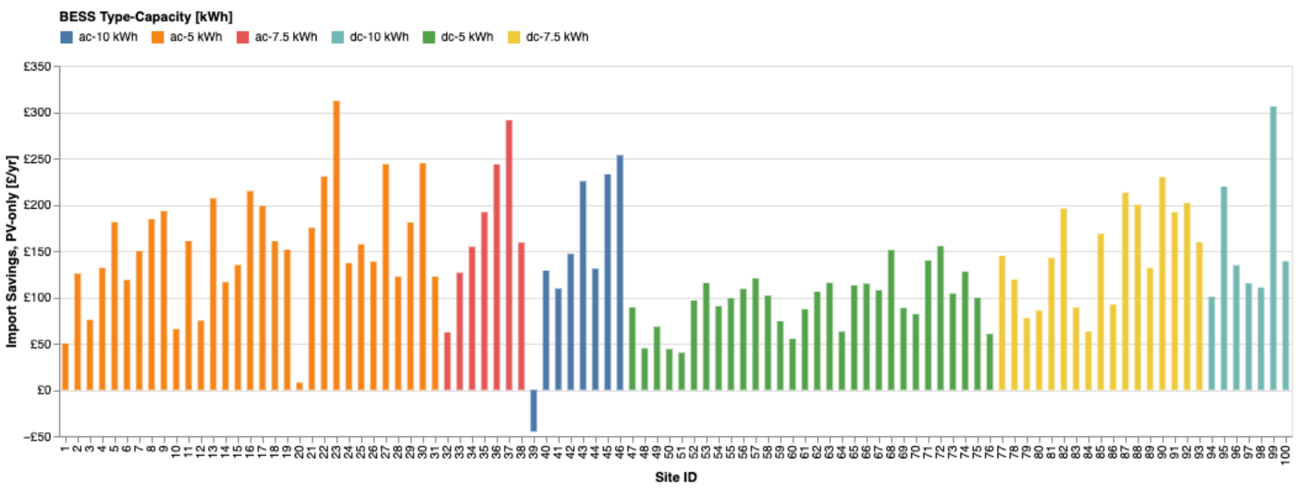

Figure 46: Annual Import Avoidance Cost Savings Estimate by Site, based on Apr19-Mar20

[14] LEM Residential BESS Utilisation Summary Report

4.2.3 *Export Income from Solar PV*

In addition to Grid Import Cost Avoidance, the Production Surplus from Solar PV systems can earn an Export Tariff. The results presented in Figure 47 were calculated using Equation 7 & Equation 8, using an Export Tariff of £0.055/kWh.

$$Export\ Income\ from\ Solar\ PV, EIpv = Grid\ Export\ without\ BESS\ x\ Export\ Tariff$$

Equation 7: Export Income from Solar PV, EIpv

$$Grid\ Export\ without\ BESS, GEpv = \text{Grid Export + BESS Charge}$$

Equation 8: Self Consumed Solar PV, GEpv

As discussed in the previous sub-section, the calculations rely upon a key simplification; that all BESS Charge is sourced from Production that would otherwise been exported to grid. In reality, however, a proportion of BESS Charge will be imported due to a combination of factors, including:

1. The rate of change of production and/or consumption is faster than the response time of the BESS controller, and hence some grid import for charging will result when production decreases or consumption increases
2. The delivery of grid services will intentionally charge the BESS using Grid Import; this was tested across the fleet in varying degrees during the trial period
3. Faults in BESS control systems, mis-configuration or mis-placement of BESS meters will result in unintentional Grid Import during BESS Charge, and in some cases due to massive increases in BESS Charge/Discharge cycles

Whilst the results in Figure 47 do not obviously highlight any sites that suffer from the above factors, the first 2 had a minor impact on all sites, and the 3rd factor had an impact on a few sites; including Sites 20 & 39.

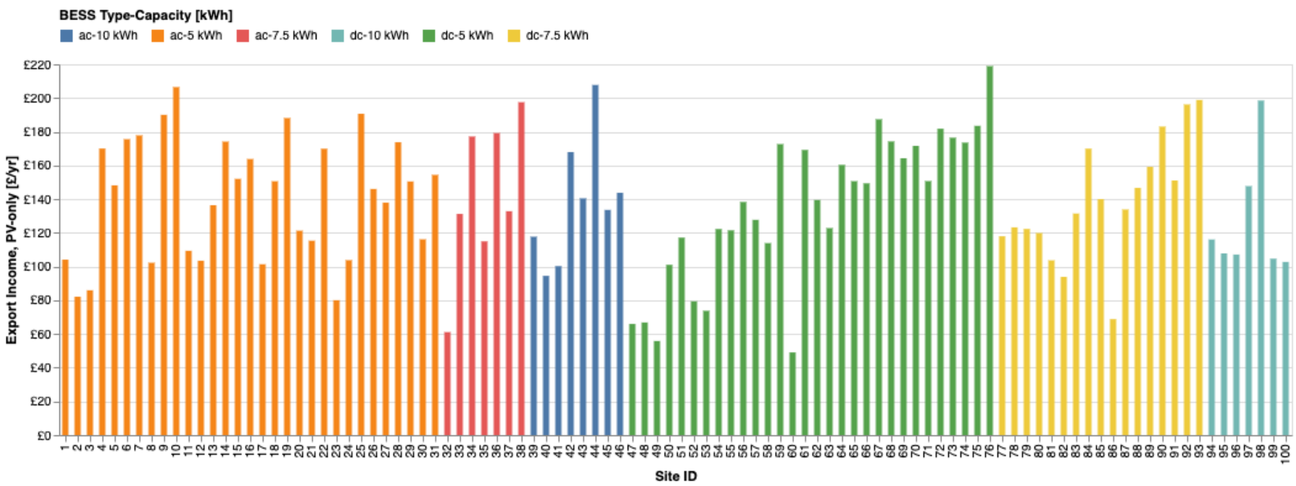

Figure 47: Annual Export Income from Solar PV Estimate by Site, based on Apr19-Mar20

4.2.4 *Total Financial Value of Solar PV*

By considering both Grid Import Avoidance Savings and Export Tariff Income, the Total Financial Value of Solar PV systems can be assessed, as presented in Figure 48. The caveats discussed in the previous sub-sections must be borne in mind when interpreting these results. The restricted value of Solar PV to Sites 20 & 39 is obvious, but additional sites will have suffered in by varying amounts.

This is an unfortunate restriction of back-calculating savings from a single trial period where a bundle of technologies operated in tandem. The inclusion of the Independent Monitoring System [IMS] was designed to reduce dependence on the BESS system control system data, which has allowed some faults (as summarised in factor 3 in the previous sub-sections) to be corrected.

However, in order to accurately infer the performance of individual energy system elements, additional parameters would need to be logged by the BESS control system, preferably as energy [Wh] values.

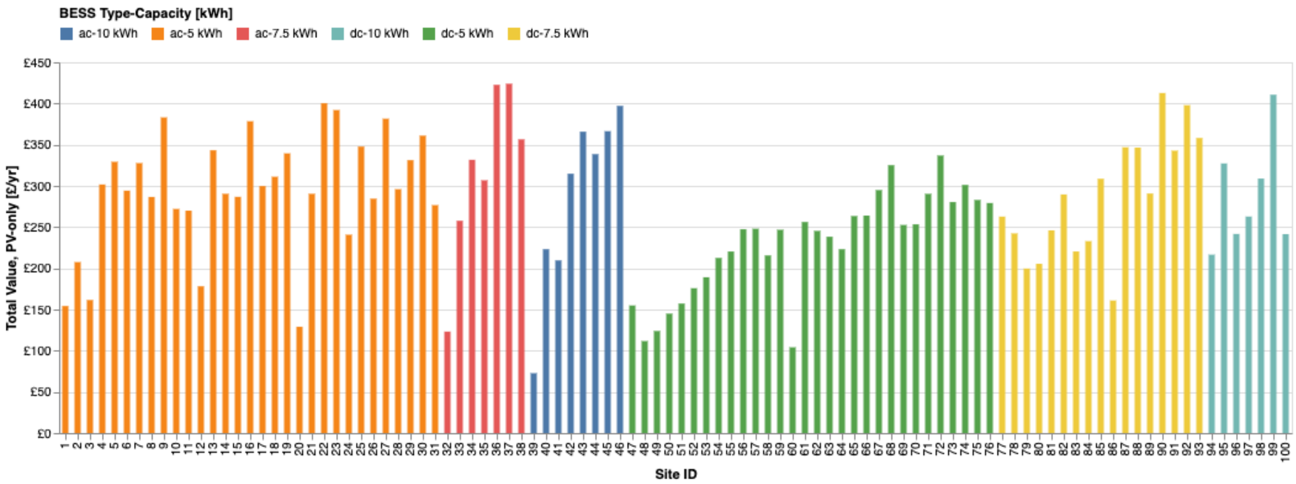

Figure 48: Annual Total Financial Value Estimate of Solar PV by Site, based on Apr19-Mar20

4.3 CO_2 Savings from Solar PV Systems

4.3.1 Average CO_2 Intensity

The CO_2 savings attributed with each site's Solar PV System were calculated using the Average CO_2-equivalent intensity discussed in the previous sub-section, and are presented in Figure 49.

They do not suffer from the same uncertainties in inference as cost impacts, as it is assumed that all electricity has the same CO2 savings impact, regardless of whether it is self-consumed on-site or exported. This is in-line with the historical assumptions used by the Standard Assessment Procedure [SAP] and other UK government methodologies, where grid losses were ignored.

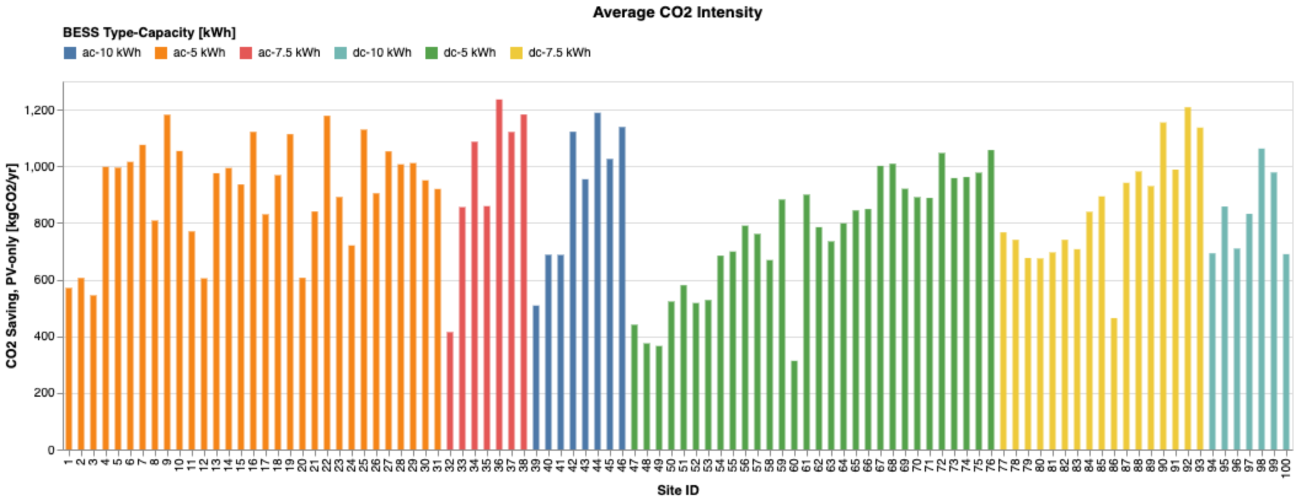

Figure 49: Annual CO_2 Savings Estimate by Site, based on Apr19-Mar20, using Average CO_2 Intensity

4.3.2 Marginal CO_2 Intensity

The CO_2-equivalent savings attributed with each site's Solar PV System were re-calculated using a nominal value of Marginal CO_2-equivalent intensity (0.54kgCO_2-equivalent/kWh), and are presented in Figure 50.

A marginal CO_2 intensity considers that type of generation likely to be displaced by the solar PV system. In this case, we have considered a Gas Engine Peaking Power Station, with a nominal electrical efficiency [%HHV] of 37%, after losses.

This marginal CO2-equivalent intensity is perhaps more suitable for discussion of incremental savings from a BESS which primarily discharges in peak periods where gas peaking plants are mostly likely to be active (ie. Early morning through mid-evening). The assessment of Solar PV savings with Margin CO2-equivalent intensity are provided for contextual comparison.

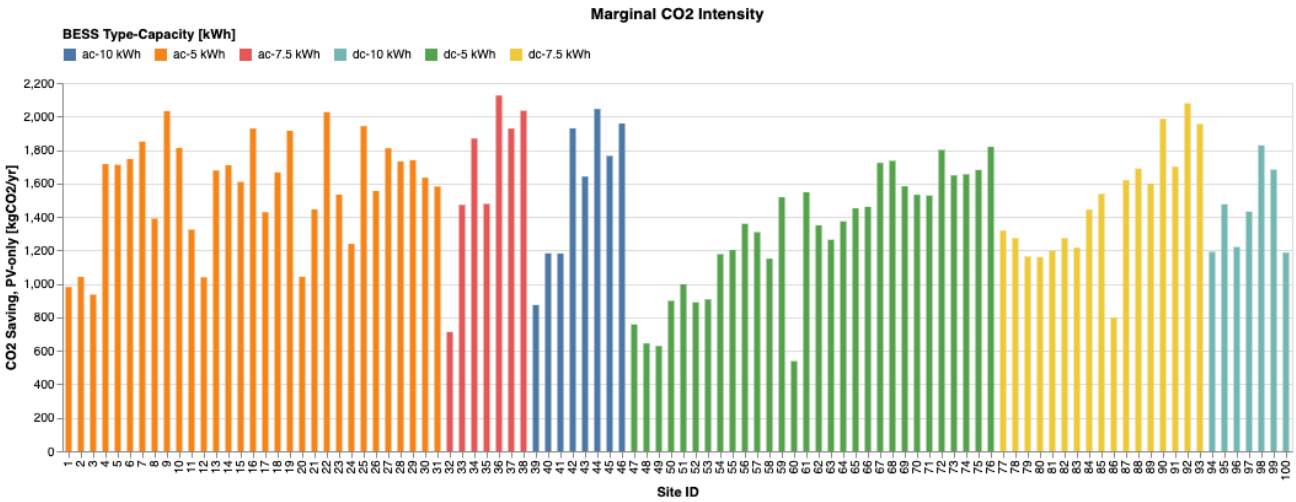

Figure 50: Annual CO_2 Savings Estimate by Site, based on Apr19-Mar20, using Marginal CO_2 Intensity

4.4 Financial Benefit of BESS and BESS + Solar PV Systems

4.4.1 Import Savings

The additional Grid Import Avoidance Cost Savings due to the addition of a BESS to a Solar PV system was estimated for all sites, regardless of whether a Solar PV System was installed pre-trial (i.e. it was not for all dc-coupled systems). The results, as presented in Figure 51, show that a broadly comparable range of savings were achieved across both BESS Types (ac- coupled and dc-coupled).

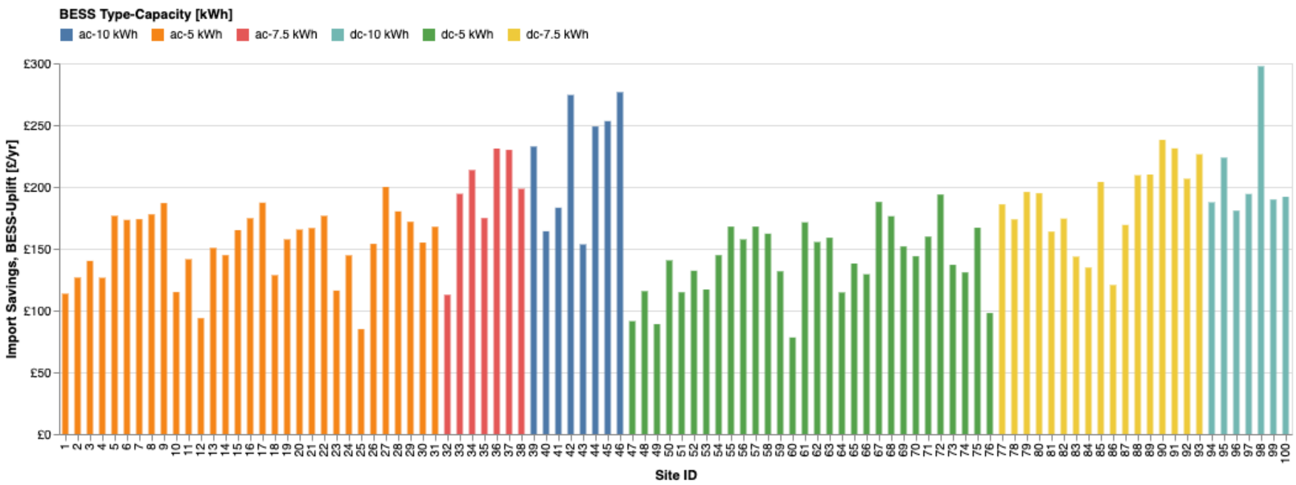

Figure 51: Annual Grid Import Cost Savings Estimate due to BESS by Site, based on Apr19-Mar20

In a similar vein, the overall Grid Import Avoidance Cost Savings due to the addition of a BESS and Solar PV system combination was estimated for all sites, regardless of whether a Solar PV System was installed pre-trial. Again, the results, as presented in Figure 52, show that a broadly comparable range of savings were achieved across both BESS Types (ac-coupled and dc-coupled).

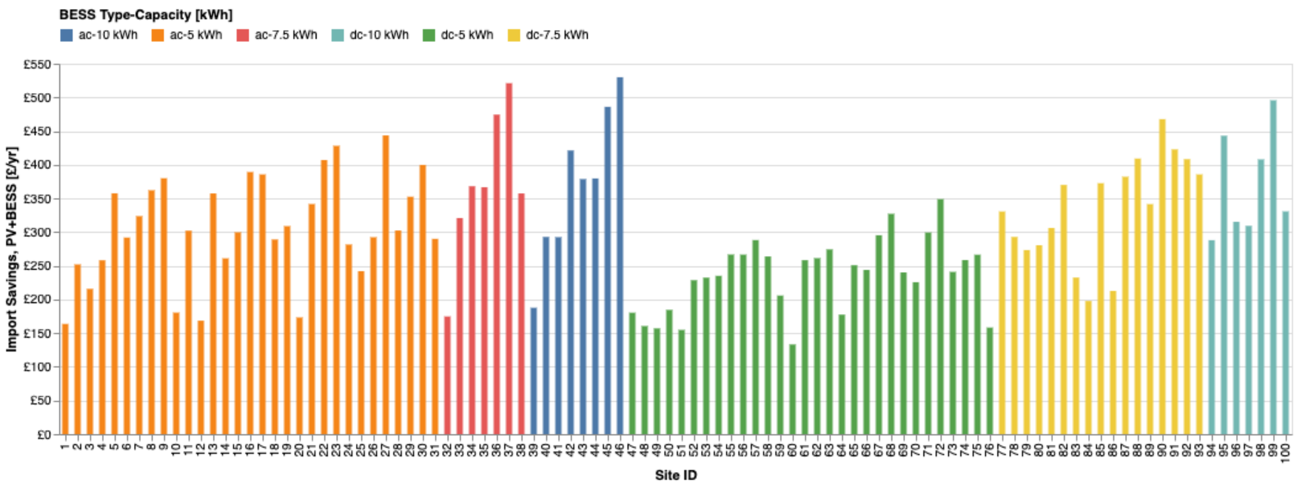

Figure 52: Annual Grid Import Cost Estimate after PV and BESS installation by Site, based on Apr19-Mar20

4.4.2 Export Income

As can be expected, the addition of a Self-Consumption operated BESS to a Solar PV System will limit the Export Income available, as Export is charged in the BESS for later use. By comparing Figure 53 and Figure 54, it is clear that BESS which can effectively capture the majority of grid export can diminish Export Income to almost zero.

It should be noted that the ability of a Self-Consumption operated BESS to reduce Grid Export is constrained by both the available Production Surplus (Production not used immediately on-site, and hence available to charge) and Production Deficit (Consumption that is not met directly by Solar PV). Since the majority of Production Surplus and Production Deficit will be decoupled in time, the available BESS energy capacity will restrict the impact on Grid Export reduction. Furthermore, the electrical power capacity of the BESS, compared to the electrical power of the available Production Surplus and Deficit, will further restrict Grid Export reduction.

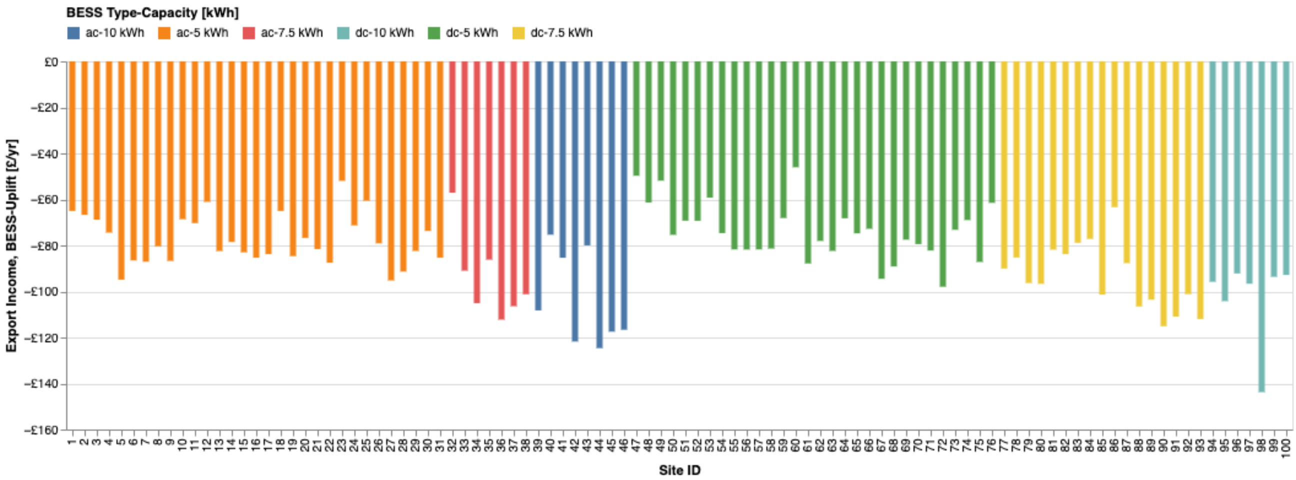

Figure 53: Annual Estimate of Impact on Export Income due to BESS by Site, based on Apr19-Mar20

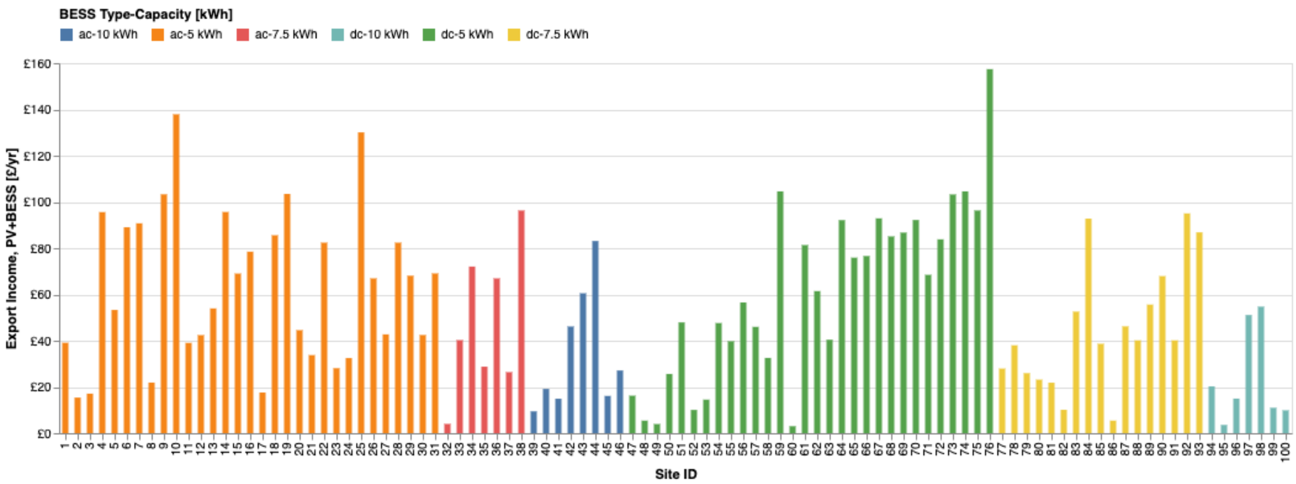

Figure 54: Annual Estimate of Export Income after installation of BESS by Site, based on Apr19-Mar20

4.4.3 *Total Financial Value*

The Total Financial Value (i.e. Grid Import Cost Avoidance and Export Income) from the addition of a BESS to a Solar PV system is presented in Figure 55. Similar to the discussion on Export Income in the previous sub-section, there are many factors constraining the ability of the BESS to affect a significant saving.

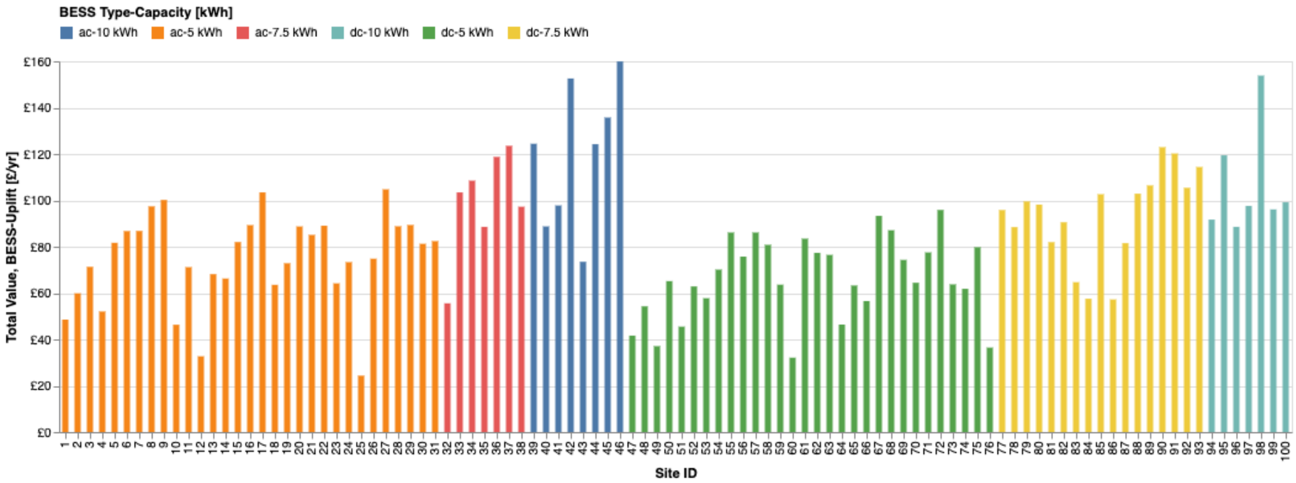

Figure 55: Annual Estimate of Total Financial Value due to BESS by Site, based on Apr19-Mar20

The Total Financial Value (i.e. Grid Import Cost Avoidance and Export Income) for the addition of both BESS and Solar PV system to a home without any such technologies is presented in Figure 56. Whilst there is certainly variation between clusters of BESS Type-BESS Energy capacity, this is typically outweighed by variations within each cluster. It is thought unlikely that those sites with relatively-limited Total financial Value in the "medium" (7.5kWh) or "large" (10kWh) BESS clusters are suffering from restrictions imposed by BESS size, but by Production Surplus or Production Deficit. This topic will be addressed further in the subsequent report on BESS utilisation[15].

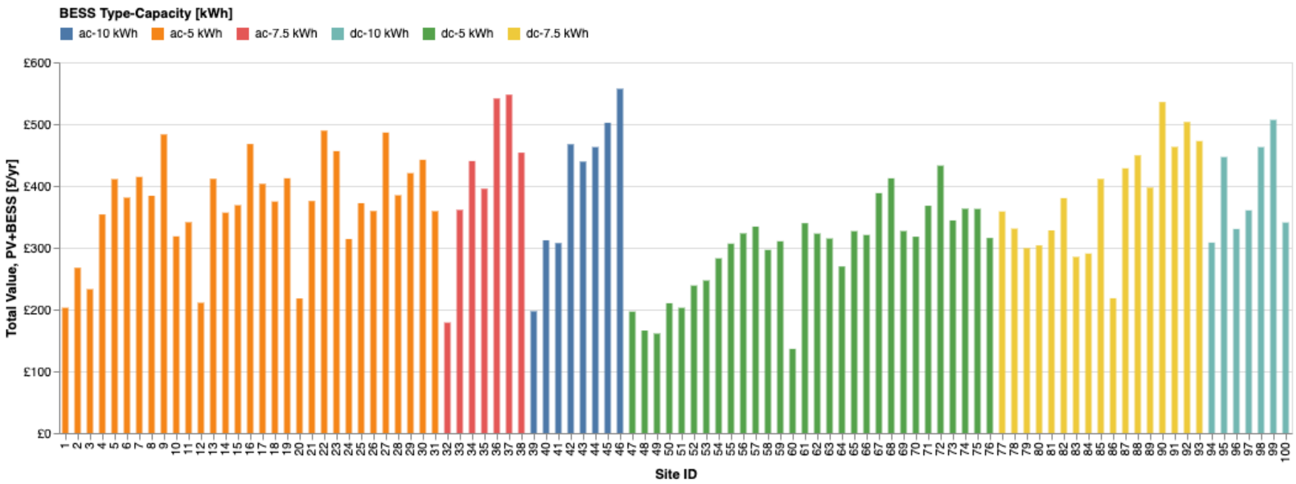

Figure 56: Annual Estimate of Total Financial Value due to BESS + Solar PV by Site, based on Apr19-Mar20

[15] LEM Residential BESS Utilisation Summary Report

4.5 CO_2 Savings Impact with BESS

4.5.1 CO_2 Impact: Average CO_2 Intensity

The CO_2-equivalent Impact the addition of a BESS to a Solar PV system is presented in Figure 57, using average CO_2e intensity, to reflect the displacement of average grid emissions. The negative impacts are driven by the operational Round Trip Efficiency [RTE], inclusive of charging losses, discharging losses, and parasitic loads during both active operation and in standby.

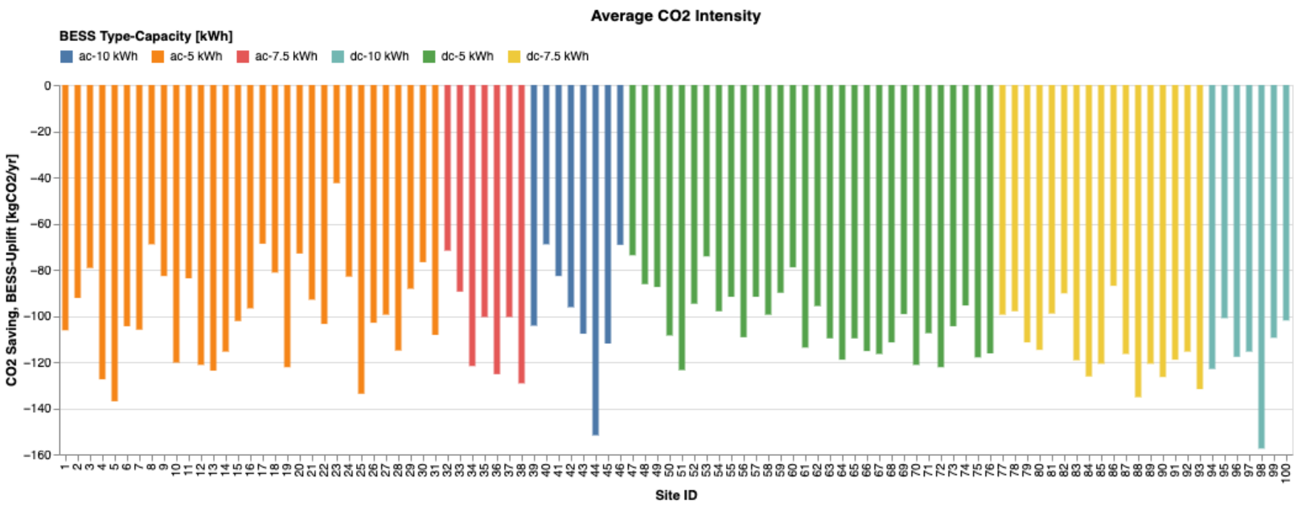

Figure 57: Annual Estimate of Impact on CO_2 Footprint due to BESS by Site, based on Apr19-Mar20, using Average CO_2 Intensity

The total CO2-equivalent saving for a combined BESS + Solar PV system, using average CO_2e intensity, is presented for each site in Figure 58. Since the comparison of BESS RTE between ac-coupled and dc-coupled – as discussed in Section 3.8 – was inconclusive, it is thought likely that the majority of difference in CO_2e savings between ac- and dc-coupled BESS is due to differences in Production Surplus & Production Deficit, and in co-incidental to BESS Type.

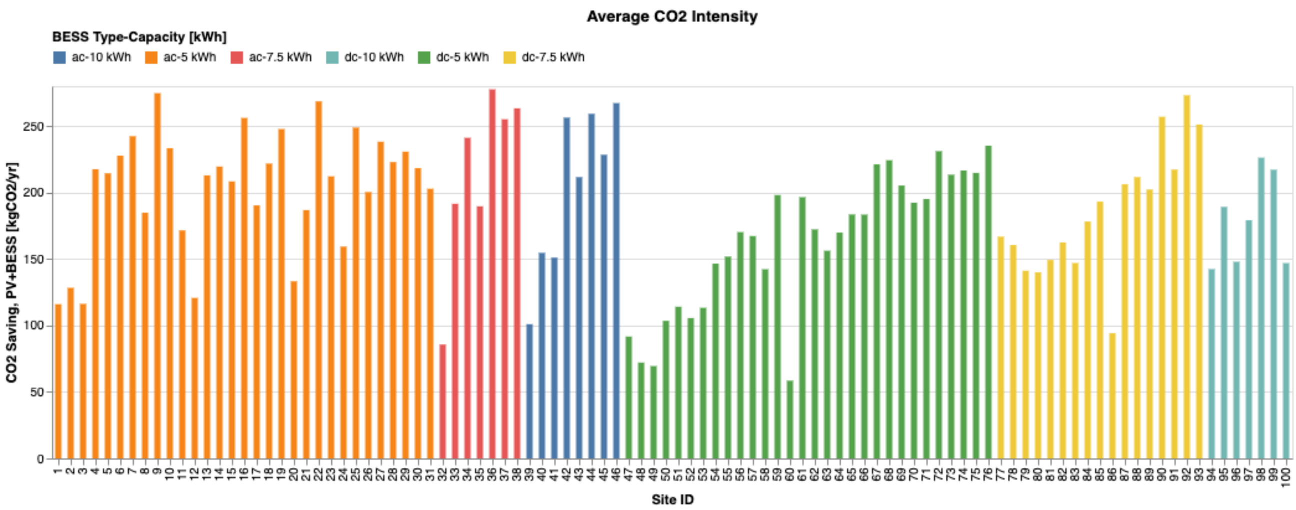

Figure 58: Annual Estimate of Total CO_2 Saving due to BESS + Solar PV by Site, based on Apr19-Mar20, using Average CO_2 Intensity

4.5.2 CO_2 Impact: Marginal CO_2 Intensity

The CO_2-equivalent Impact the addition of a BESS to a Solar PV system is presented in Figure 59, using marginal CO_2e intensity, to reflect the displacement of generation likely to be displaced at peak times, with a higher emission intensity. It is argued that, if the emissions reduction potential of a combined BESS + Solar PV system were to be considered using marginal intensity, then the impact of BESS inefficiency should be considered on the same basis.

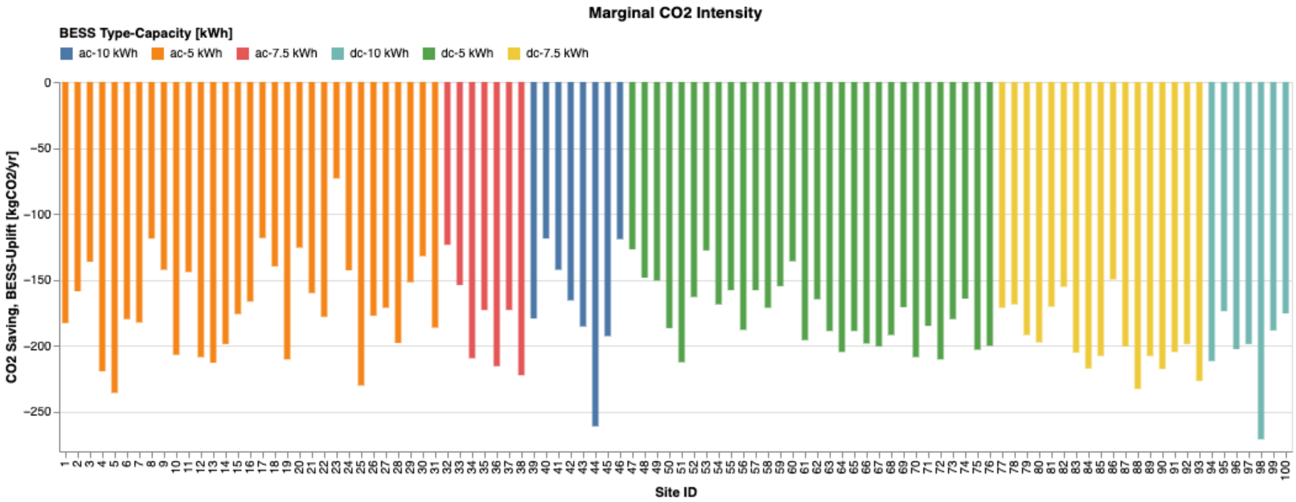

Figure 59: Annual Estimate of Impact on CO_2 Footprint due to BESS by Site, based on Apr19-Mar20, using Marginal CO_2 Intensity

The total CO2-equivalent saving for a combined BESS + Solar PV system, using marginal CO_2e intensity, is presented for each site in Figure 60. In the subsequent report on BESS Utilisation, the impact of half-hourly CO_2e intensity is likely to give a firer view on overall CO_2e savings than either Marginal or Average intensity.

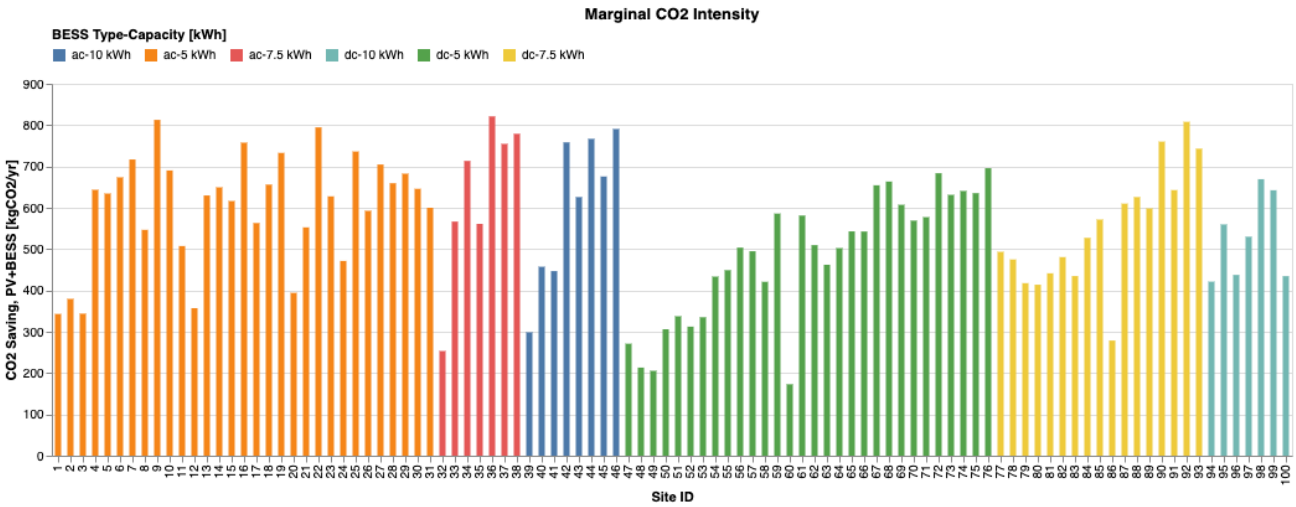

Figure 60: Annual Estimate of CO_2 Savings due to BESS + Solar PV by Site, based on Apr19-Mar20, using Marginal CO_2 Intensity

4.6 Predicting Financial Savings with BESS + Solar PV

4.6.1 Production vs Consumption

In the Participant Reports, a simplified matrix of Production vs Consumption was used to cluster Total Financial Value results, as presented in Figure 61, and discussed in the LEM Residential Participant Event presentation[16]. Please note that these Financial Value figures were calculated from annual projection created in January 2020, and hence differ from figures presented in this end-of-trial report.

Figure 61: Production - Consumption Matrix to visualise ESTIMATED Total Financial Value as projected in January 2020

To further develop approaches beyond course ranges of Production & Consumption, a heatmap was created with higher resolution bins, as presented in Figure 62 for the entire LEM Residential fleet.

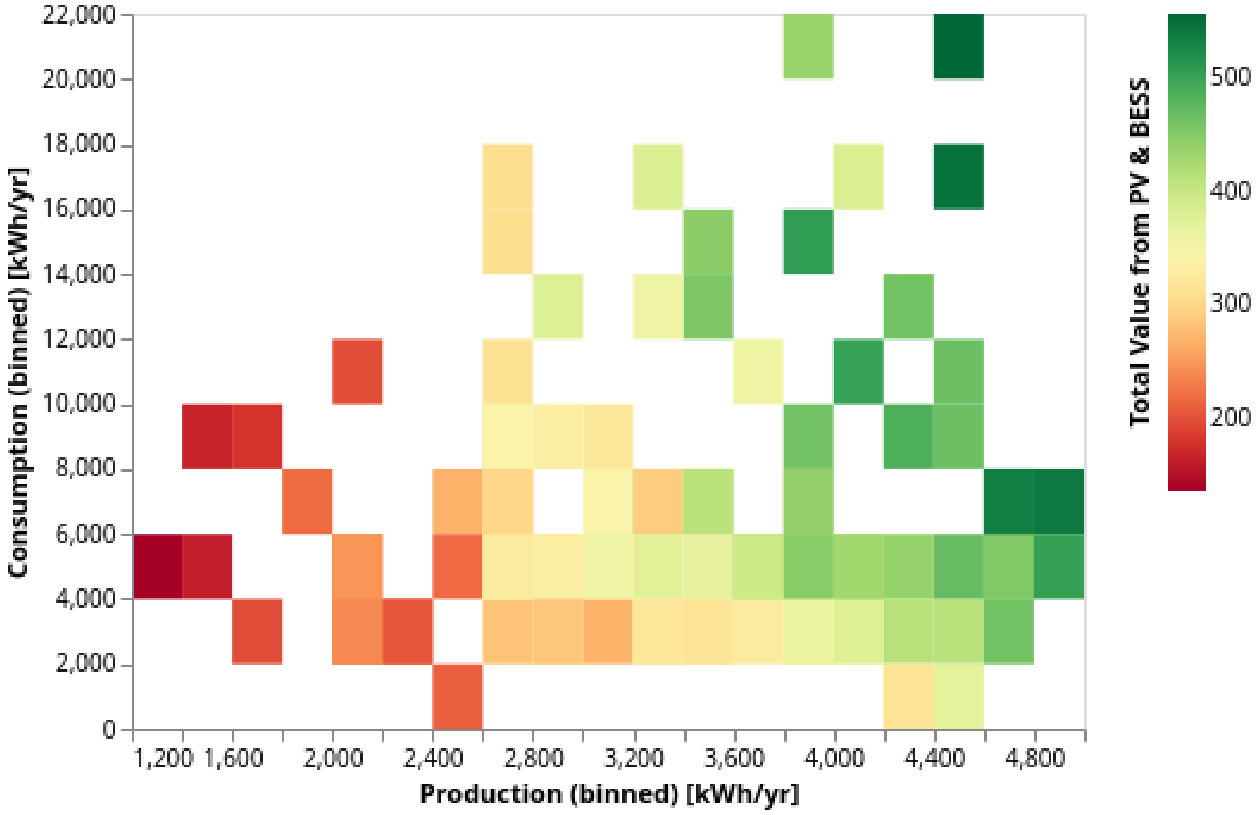

Figure 62: Total financial Value (for BESS + Solar PV) by Consumption vs Production bins, using Annual Estimates, based on Apr19-Mar20 data

[16] LEM Residential Dissemination Event Feb 2020_FINAL_v2.pptx

The heatmap was also disaggregated by BESS Type, to ascertain any significant variation in relationship of Total Financial Value with Production & Consumption – as presented in Figure 63 – but significant variation was not readily apparent. Further analysis focussed on the entire fleet, in order to maximise the datapoints available for statistical analysis.

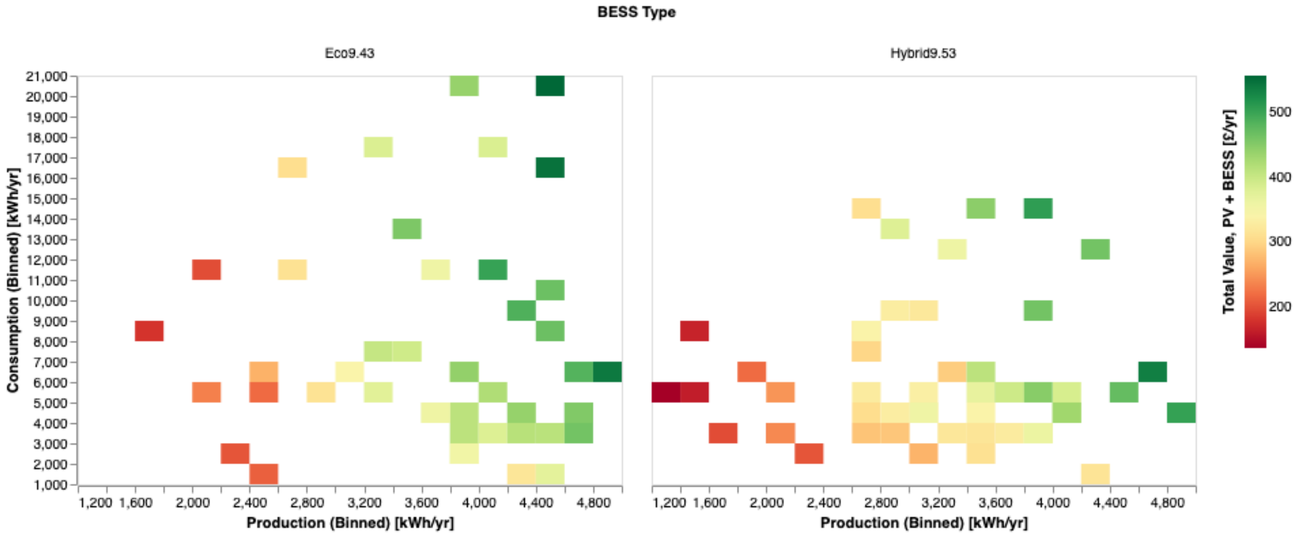

Figure 63: Total Financial Value (for BESS + Solar PV) by Consumption vs Production bins, using Annual Estimates, based on Apr19-Mar20 data, grouped by BESS Type

A statistical modelling approach was examined for Total Value estimation using annual production and consumption metrics, along with their derived quantities. It was observed that distinct bi-variate trends occurred in distribution heatmaps between the following metric relations:

- Production (P) and Consumption (C);
- Production Surplus (Ps) and Production Deficit (Pd).

In an attempt to explore prediction using only annual data – which is more readily available at time of marketing, sales or design – the initial focus was the Production & Consumption relationships. It was not possible to establish clear independent correlation of these individual variables with Total Value; however, in the above combinations these demonstrated suitable trends for bi-variate curve fitting, as in Figure 62. An optimisation library was therefore used to obtain best fit parameters to the model described by Equation 9.

$$TV_{model} = aX^bY^c$$

Equation 9: Model of Total Financial Value vs Production & Consumption

The resulting formula to predict Total Financial Value from annual Production & Consumption is shown in Equation 10.

$$TV_{PC} = 0.052 \times P^{0.935}C^{0.141}$$

Equation 10: Formula to calculate predicted Total Financial Value, TV from annual Production, P & Consumption, C

It must be emphasised that any Total Financial Value's calculated by Equation 10 are based on assumptions, including:

- Grid Import Tariff of £0.15/kWh
- Grid Export Tariff of £0.055/kWh
- The production & consumption profiles of each site in the LEM Residential Fleet, as they vary by season, day, and time
- The performance characteristics of the specific BESS installed in each site
- The match of that BESS with the production & consumption profiles of that site

The model was compared with results from the 100 site LEM Residential Trial, producing a linear relation with R^2=0.9943, but which still demonstrates significant variation with Total Financial Value data points that are neither at the upper or lower ends of the dataset. This suggests that additional effects are at play than can be described by changes in annual Production or annual Consumption alone. True statistical robustness for a prediction algorithm is difficult to quantify without both a training an testing dataset, but the available 100 site dataset, with limited sites in each "corner" of a production vs consumption plot makes such discrete datasets unviable.

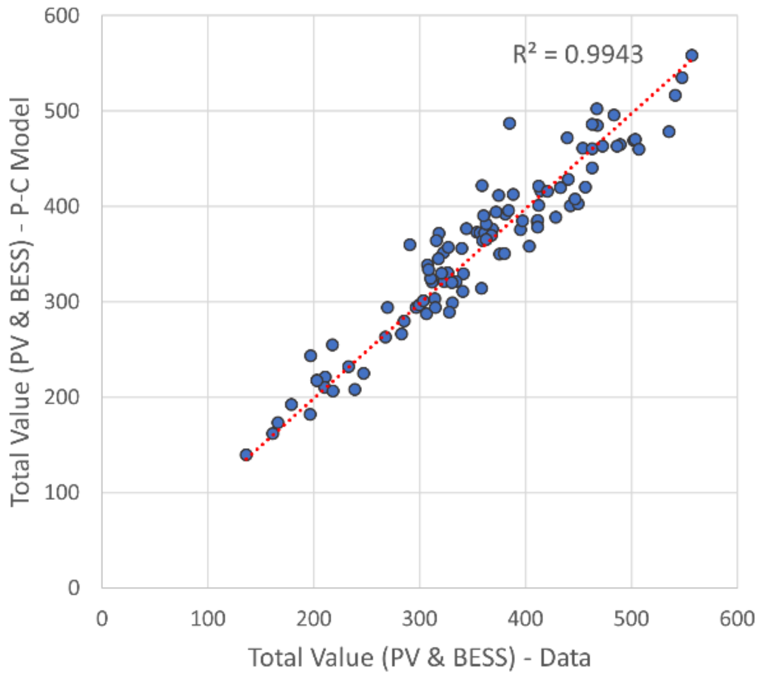

Figure 64: Scatter comparing modelling Total Financial Value (BESS + Solar PV) vs "actual" data, using model with Production & Consumption

Despite the limitations of the model in Equation 10, the heatmap created from it – as presented in Figure 65 – has the advantage of complete coverage across the Production & Consumption domains as used by Figure 62. This is expected to act as a "rule of thumb" to understand potential Financial Value from self-consumption operation of BESS & Solar PV.

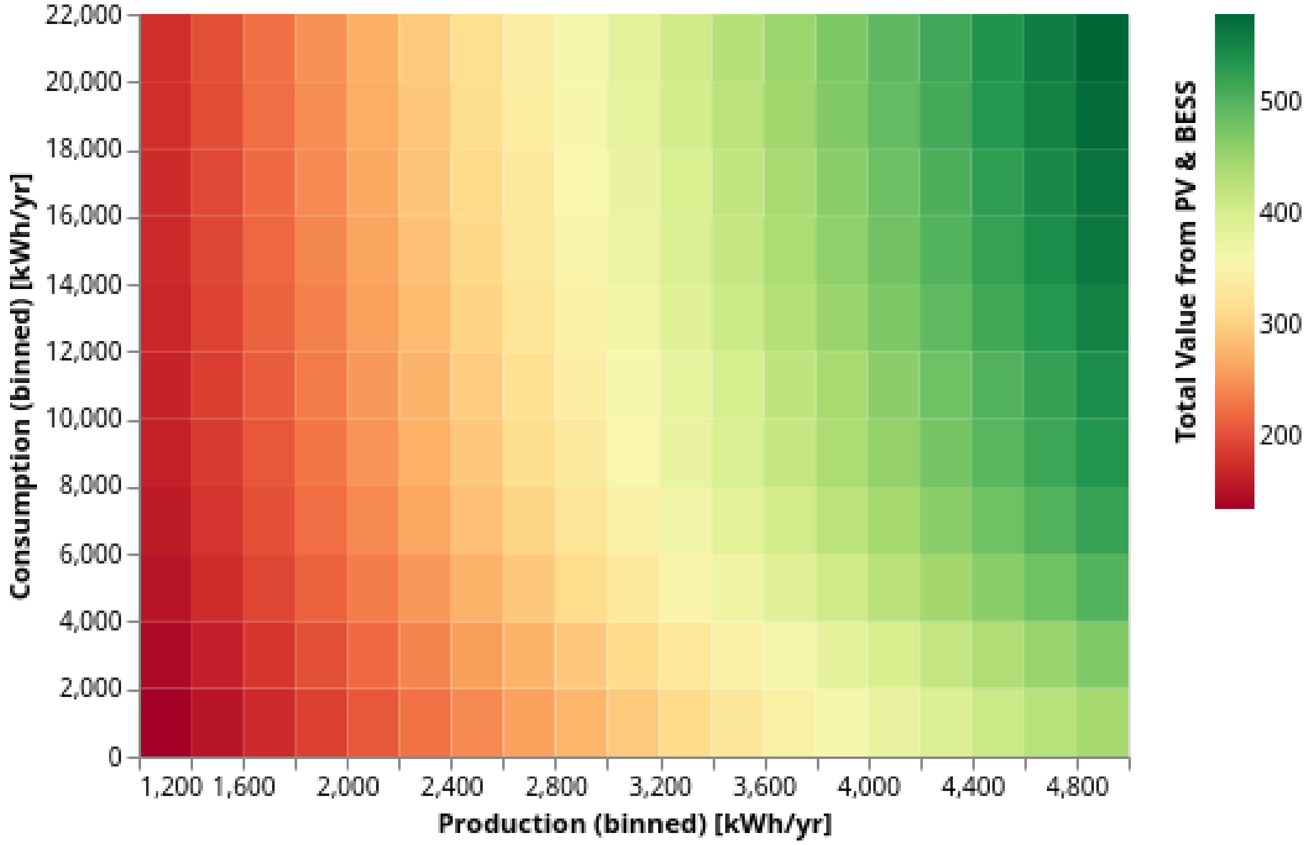

Figure 65: Total Financial Value (for BESS + Solar PV) by Consumption vs Production bins, using Predication Model

4.6.2 Production Surplus vs Production Deficit

As discussed in the previous sub-section, Equation 10, which describes the relationship between Total financial Value and Production and Consumption is limited in its prediction accuracy. With the availability of time varying data (with a temporal precision similar to or better than smart metering), the same approach was attempting using production Surplus and Production Deficit. These terms, as defined in Sections 2.5 and 2.6, respectively, are calculate each minute, in order to consider the impact of time-varying production and consumption patterns.

The heatmap of Total Financial Value (for BESS + Solar PV system) against Production Surplus versus Production Deficit is presented in Figure 66. It is generally similar to Figure 62, but with perhaps a less-defined variation in the diagonal.

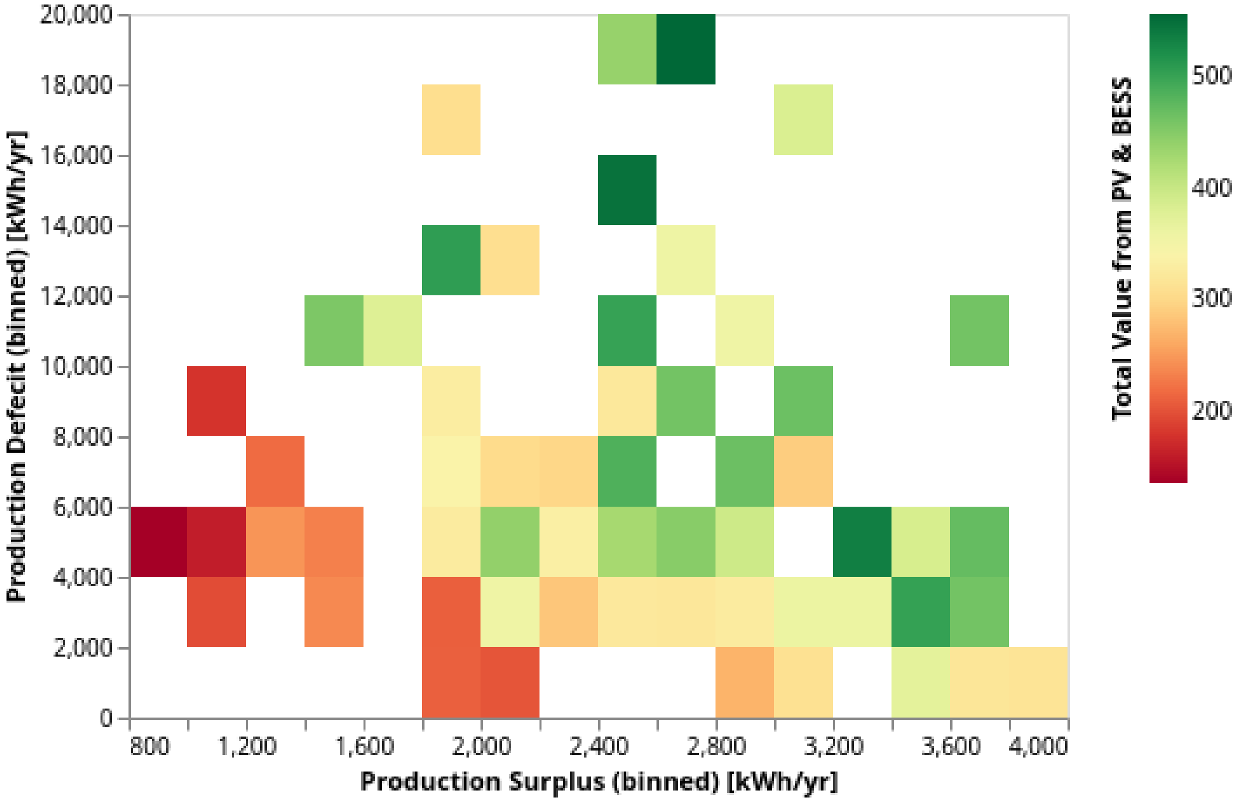

Figure 66: Total financial Value (for BESS + Solar PV) by Production Deficit vs Production Surplus bins, using Annual Estimates, based on Apr19-Mar20 data

Similar to the last sub-section, a model in the form of Equation 9 was used to derive Equation 11, which is sued to estimate Total Financial Value (of BESS + Solar PV system) from Production Surplus and Production Deficit.

$$TV_{PsPd} = 0.571 \times P_s^{0.640} P_d^{0.170}$$

Equation 11: Formula to calculate predicted Total Financial Value, TV from annual Production Surplus, Pd & Production Deficit, Pd

The performance of the Production Surplus-Production Deficit model against actual values was slightly lower than that for the Production-Consumption relationship, with R^2=0.9696, and significant deviation at low, medium and high Financial Value, which is highly suggestive of other factors at play.

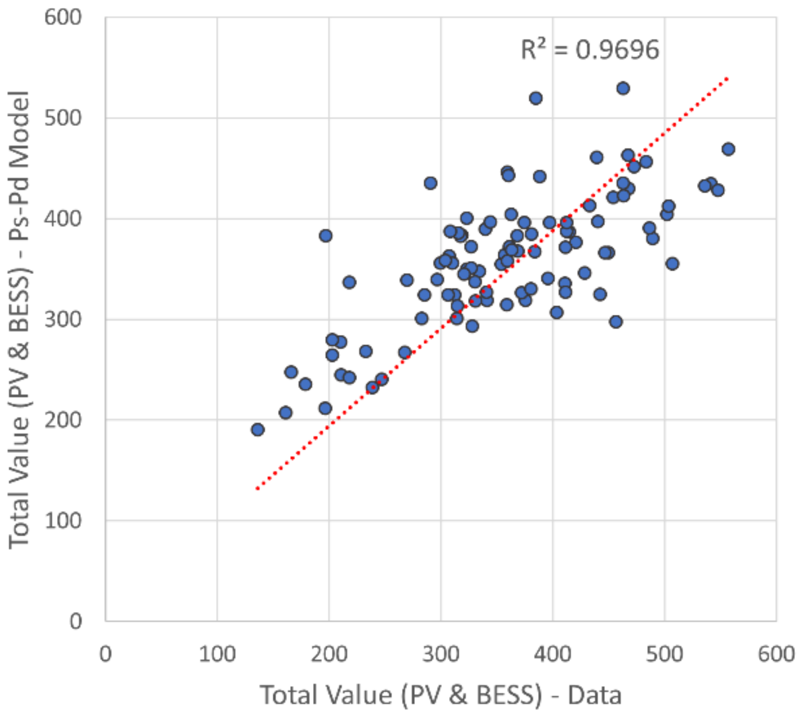

Figure 67: Scatter comparing modelling Total Financial Value (BESS + Solar PV) vs "actual" data, using model with Production Deficit & Surplus

However, the resulting heatmap of Predicted Total Financial Value (for BESS + Solar PV system) against Production Surplus versus Production Deficit – as presented in Figure 68 – is a useful "Rule of Thumb", especially where Smart Meter data for an existing Solar PV system is available, as Production Surplus = Grid Export and Production Deficit = Grid Import on that scenario. In practice, however, the utilisation will likely be limited, but it does suggest that further work with savings prediction when considering time-varying performance is merited. This topic will be discussed in the subsequent report on BESS Utilisation[17].

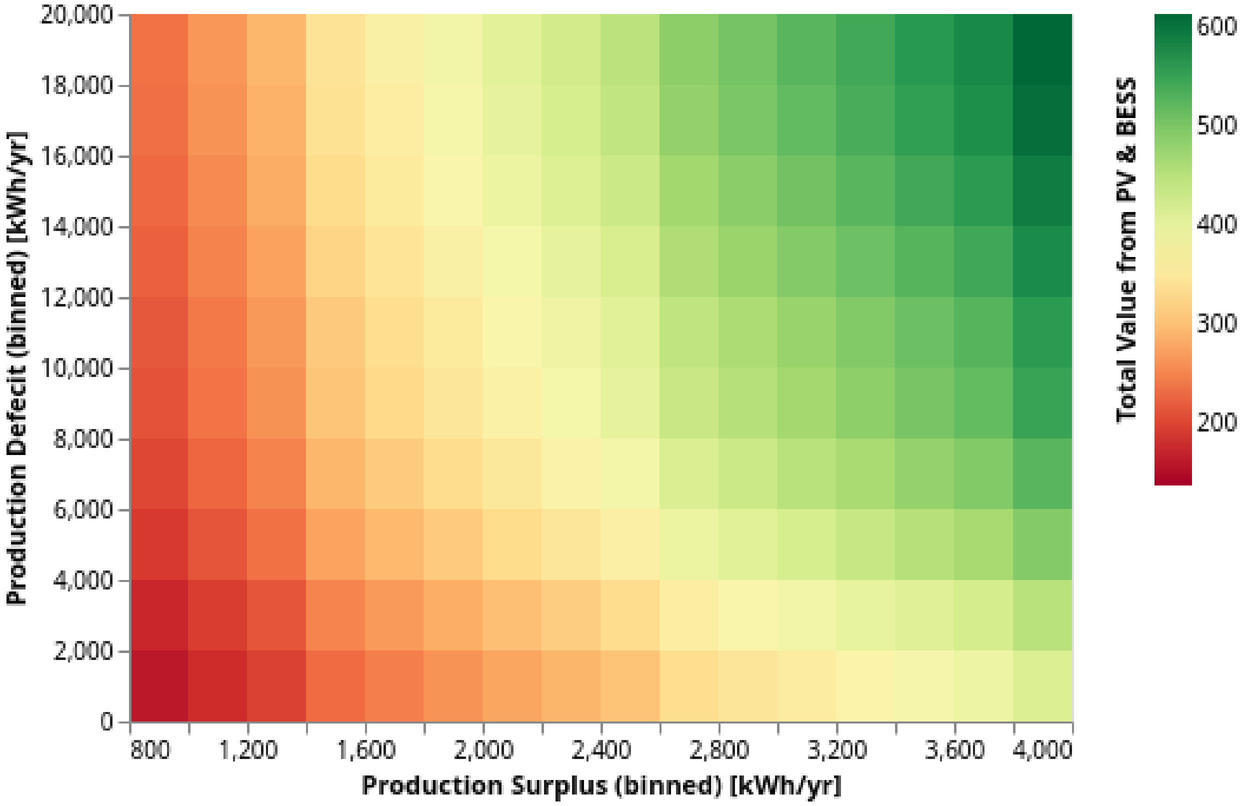

Figure 68: Total Financial Value (for BESS + Solar PV) by Production Deficit vs Production Surplus bins, using Predication Model

[17] LEM Residential BESS Utilisation Summary Report

4.7 Predicting CO_2 Savings with BESS + Solar PV

4.7.1 Average CO_2 Intensity

A similar approach to that described in Section 4.6 was taken to visualise the CO_2-equivalent savings against Production versus Consumption, using Average CO_2-equivalent intensity, as presented in Figure 69, grouped by BESS Type.

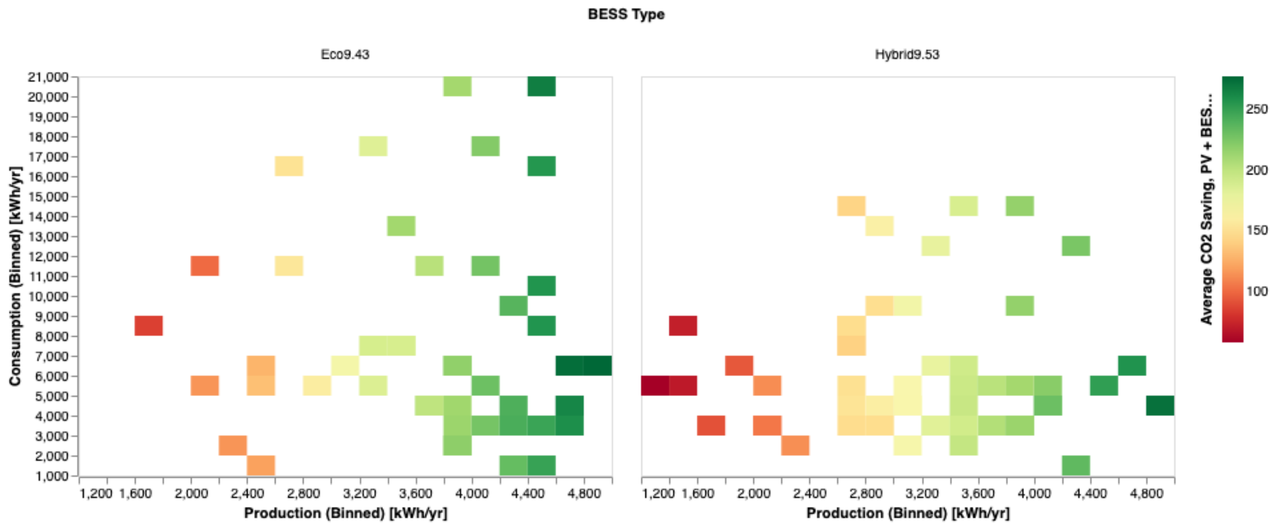

Figure 69: CO_2 Savings of BESS + Solar PV by Consumption vs Production bins, using Annual Estimates based on Apr19-Mar20 data, clustered by BESS Type, using Average CO_2 Intensity

4.7.2 Marginal CO_2 Intensity

The visualisation of the CO_2-equivalent savings against Production versus Consumption was repeated using Marginal CO_2-equivalent intensity, as presented in Figure 70, again grouped by BESS Type.

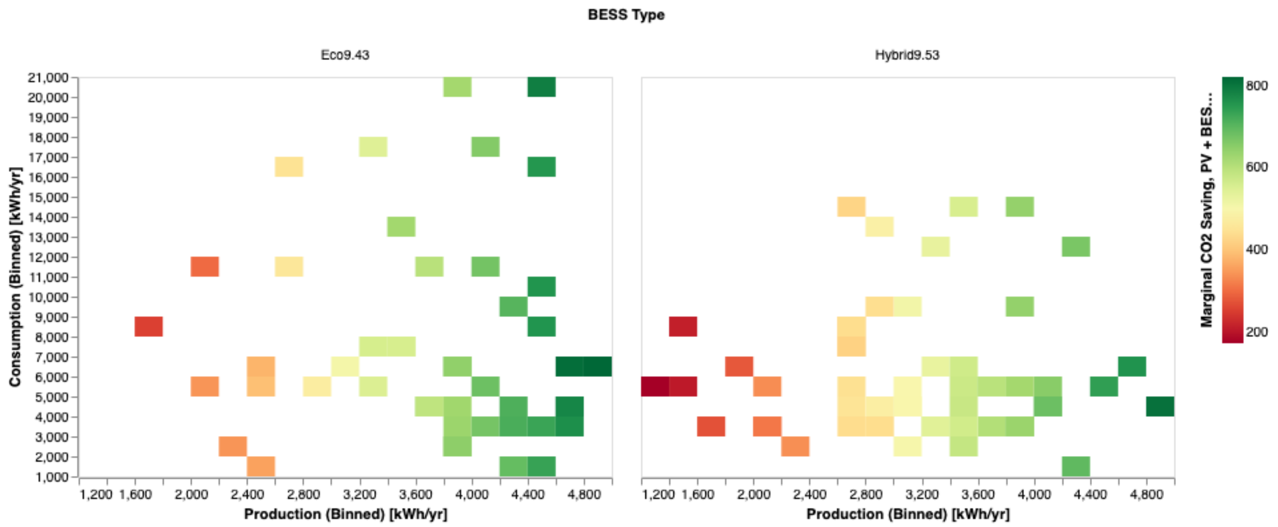

Figure 70: CO_2 Savings of BESS + Solar PV by Consumption vs Production bins, using Annual Estimates based on Apr19-Mar20 data, clustered by BESS Type, using Marginal CO_2 Intensity

5. Intra-day Effects

5.1 Summary

The patterns that occur within the day can show elements of underlying causes of battery under-utilisation and other performance issues; charts with at a resolution of 30 minutes have been provided in this section to highlight aggregate and diversified effects. Whilst there are a number of relevant performance related aspects that can be discussed, the variation and inherent randomness of household behaviour do not lend themselves to absolute determination of future processes for characterising potential asset performance.

The charts discussed in this section show seasonal averages by half-hourly timestamp, of site measurements and derived metrics across four months (May-Aug for summer, Nov-Feb for winter). Furthermore, Section 7.1 shows aggregate patterns across all sites.

For assessment of self-consumption performance, particular attention has been paid to the summer-time performance. Additional considerations are required for assessment of increased winter BESS utilisation; this is explored in the corresponding follow-up report[18]. Part of the follow-up BESS utilisation analysis will explore application of various synthetic parameter, derived from the measurement data. These parameters include the parameters outlined in Table 1 in the Data Dictionary[19].

[18] LEM Residential BESS Utilisation Summary Report

[19] LEM Residential Data Dictionary

5.2 Aggregate Patterns by Season

5.2.1 Consumption patterns by season

Aggregate consumption measurements in Figure 71 and Figure 72 reflect expected diversified seasonal patterns. A 50% rise in peak evening diversified consumption occurs in winter as a result of increased household consumption from heating and hot water (where this is electricity-based), ovens, tumble dryers and other lighting and appliance use. These same factors also results in a clear morning peak more than 20% higher than through early morning and mid-day.

A further notable distinction between summer and winter consumption patterns is a substantial rise in night-time demand. In summer, night-time demand is consistently below 0.2kWh/30m per site; in winter this is close to 0.4kWh/30m, which matches winter day-time demand levels. This is caused by storage heater and DHW immersion heater use, and is directly affected by Economy 7 tariff contract use.

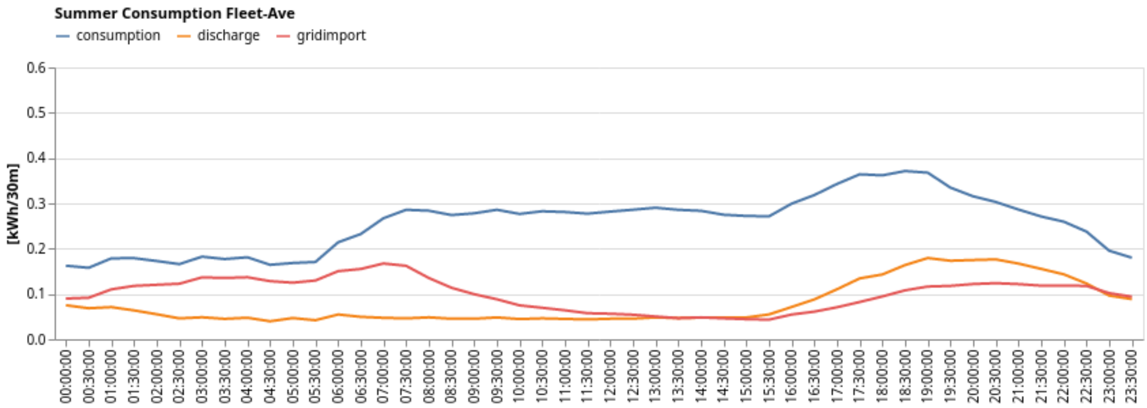

Figure 71: Summer consumption patterns, average across all sites

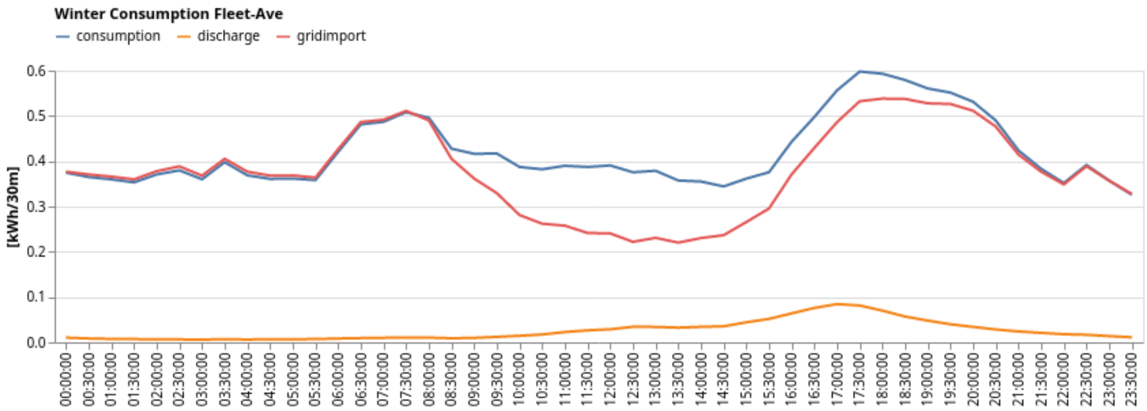

Figure 72: Winter consumption patterns, average across all sites

5.2.2 PV and battery contributions: summer

Consumption is met using grid imports, PV production and battery discharge (after RTE losses), which all vary considerably during the day, and change drastically between the seasons. Across the diversified summer results in Figure 71, battery discharge provides a sustained (24 hour) baseline contribution to meet demand of around 0.05kWh/30m per site. This rises close to 0.2kWh/30m in the summer evening, as the batteries gradually take over from diminishing PV production levels. The combined impact of PV and battery contributions result in drastically suppressed grid imports throughout the middle part of the day and evening. The diversified evening peak in grid imports is shifted from around 18:30 to a long plateau between 19:00 and 22:30. The corresponding import magnitude drops by over 300%, from around 3.8kWh/30m per site, to 1.2kWh/30m. The highest levels of grid import now occurs between 03:00 and 08:00 as a result of the PV and BESS, with a reduced peak at around 07:00.

5.2.3 PV and battery contributions: winter

Winter grid import levels are 300% higher during the morning peak and 450% higher during the evening peak, as shown in Figure 72. Outside of these peaks, grid import levels are also substantially higher. This is caused by a combination of increased consumption and drastically diminished contributions from the PV and battery systems. Day-time grid imports still drop by between 150-200% during the middle part of the day as a result of PV; however, the overall performance of the system in winter is undermined by very poor production levels.

5.2.4 Production, charge and export by season

The aggregate variation on production, battery charging and grid exports are shown in Figure 73 and Figure 74. Aside from substantial differences in both peak and net energy production levels between summer and winter, the reaction of export activity is also relevant. In winter, a combination of restricted production and increased consumption results in very low levels of grid export. The main winter concerns are clearly ***'battery under-utilisation due to low production'***, which is assessed separately as part of the headroom analysis. In summer, however, around 50% of all PV production is exported to the grid, with direct implications for customer revenue potential. For a given site, this is related to both the intra-day consumption patterns (favouring households that are at home during the day) and battery capacity.

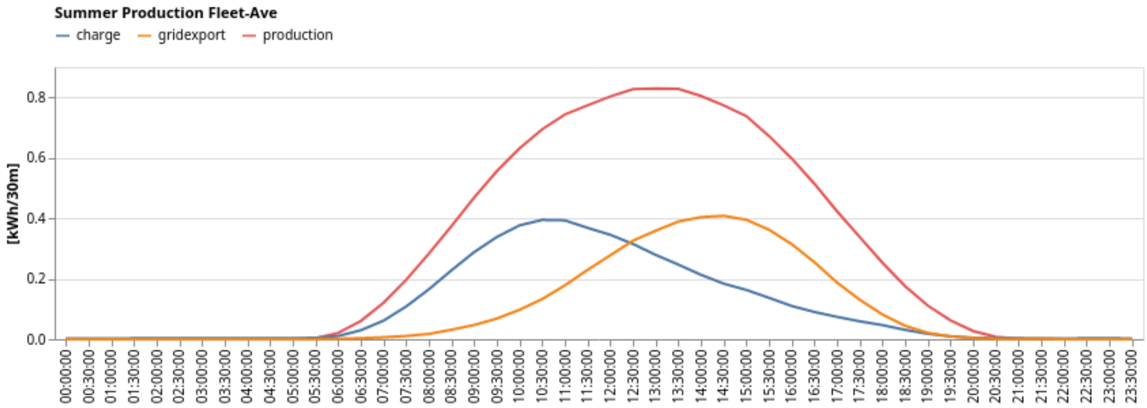

Figure 73: Summer production patterns, average across all sites

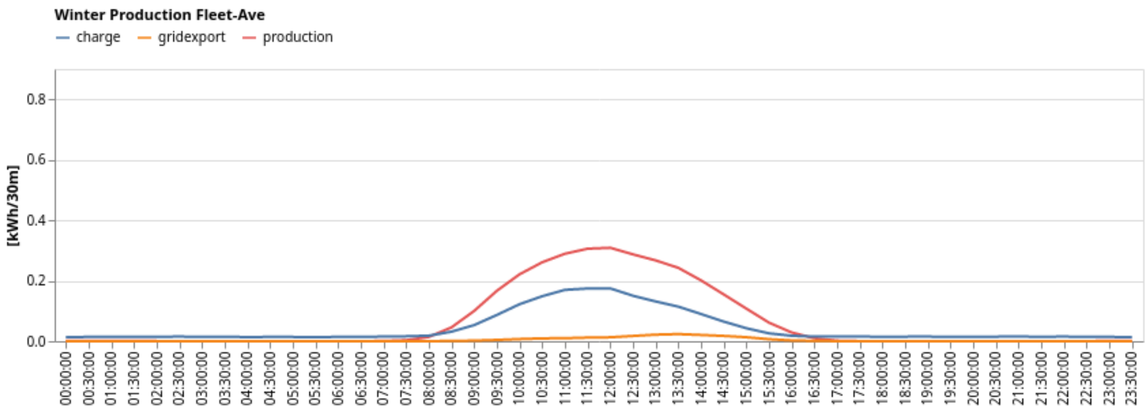

Figure 74: Winter production patterns, average across all sites

Whilst increasing battery capacity may help lower exports at some sites, the random nature of demand and distribution of energy behaviour prohibits any deterministic approach for identifying such sites. Occurrence of ***'battery under-utilisation due to over-sizing'*** can be seen in Figure 73 and Figure 74, which show aggregate and disaggregate summer-time patterns for state of charge. Furthermore, this hides day-to-day variation, including situations where certain batteries remain almost fully-charge for sustained periods.

5.3 Summertime-average 30m Daily Distribution Heatmaps

Further examination of self-consumption was assessed by considering the half-hourly summer-time patterns at each test site. A series of Daily Distribution Heatmaps are provided below:

- Figure 75, Production [kWh/30m]
- Figure 76, Consumption [kWh/30m]
- Figure 77, Grid Import [kWh/30m]
- Figure 78, Grid Export [kWh/30m]
- Figure 79, Battery Charge [kWh/30m]
- Figure 80, Battery Discharge [kWh/30m]
- Figure 81, State of Charge (%)
- Figure 82, Production Surplus (Ps) [kWh/30m]
- Figure 83, Production Deficit (Pd) [kWh/30m]
- Figure 84, Production Surplus/Deficit Ratio (Psdr)
- Figure 85, Production/Consumption Ratio (PCr)

The charts are sorted by Total Value for the combined PV and BESS system. Distinct behaviours are visible in terms of the times of day that the various measurements and parameters are high, medium or low (i.e. with colour variation from left to right). With exception of production, the charts demonstrate that there is a lack of definitive pattern emergence between the sites (i.e. no clear trends in colour variation from top to bottom).

The combined effect of a wide range of site and household specific characteristics mean that basic inspection of daily demand patterns is not sufficient for performance estimation. Figure 75 shows a very diverse mix of behavioural patterns which do not conform to groups of performance bands, on the basis of shape alone.

It is clear that for production, increased savings are strongly correlated to PV output, as shown in Figure 76. PV production curves that deviate significantly from the optimised sun path are generally further down the performance results. The installed capacity is naturally a significant factor (visible as the column of yellow markers) although there are larger PV installations that also perform poorly.

Regarding grid export activity (Figure 78), it was found that export was uncommon for 10kWh BESS. The poorest performing sites are also more likely to suffer from low production levels, rather than lost revenue potential due to export. This is clear from the low occurrence of export for the worst performing sites.

The patterns of state of charge vary significantly across the sites in Figure 81. Instances where batteries remain with a low state of charge occur when there is sufficient consumption during production times - this is more common for the 10kWh BESS. The other sub-optimal case is where batteries remain close to fully charged - these sites have very low demand, and could be utilised further for Grid Services tasks both in summer and winter.

5.3.1 Consumption

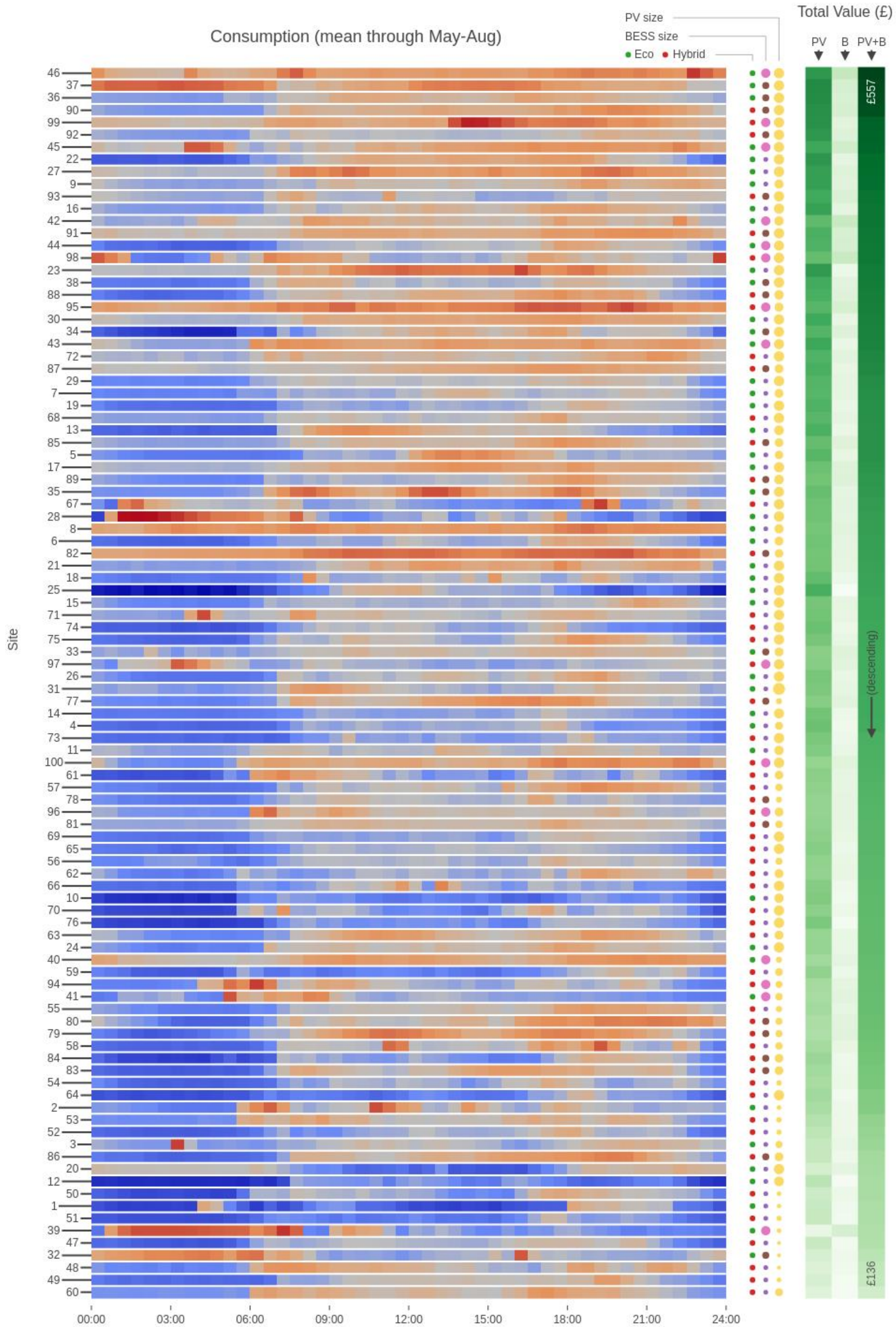

Figure 75: Average Consumption by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.2 Production

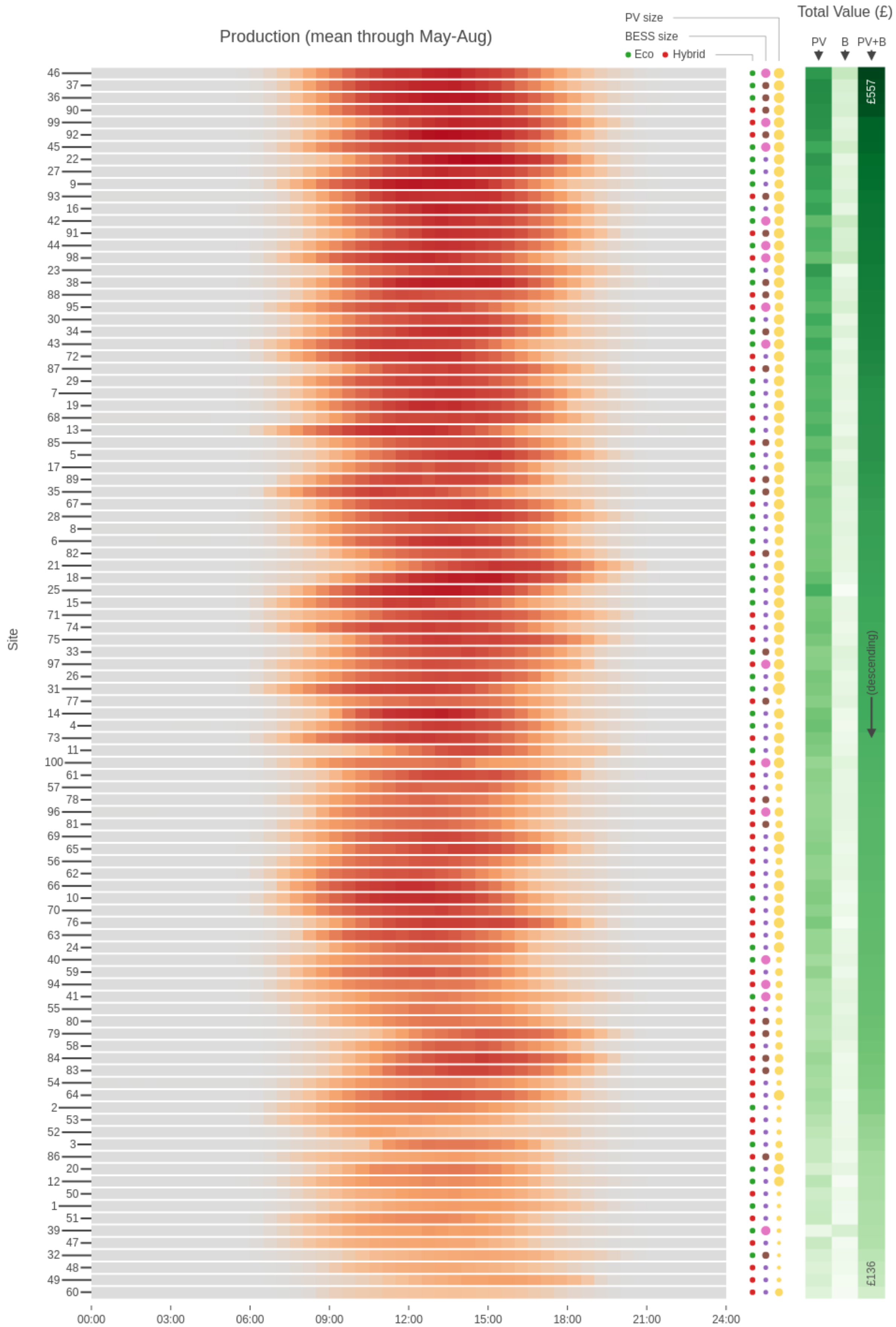

Figure 76: Average Production by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.3 Grid Import

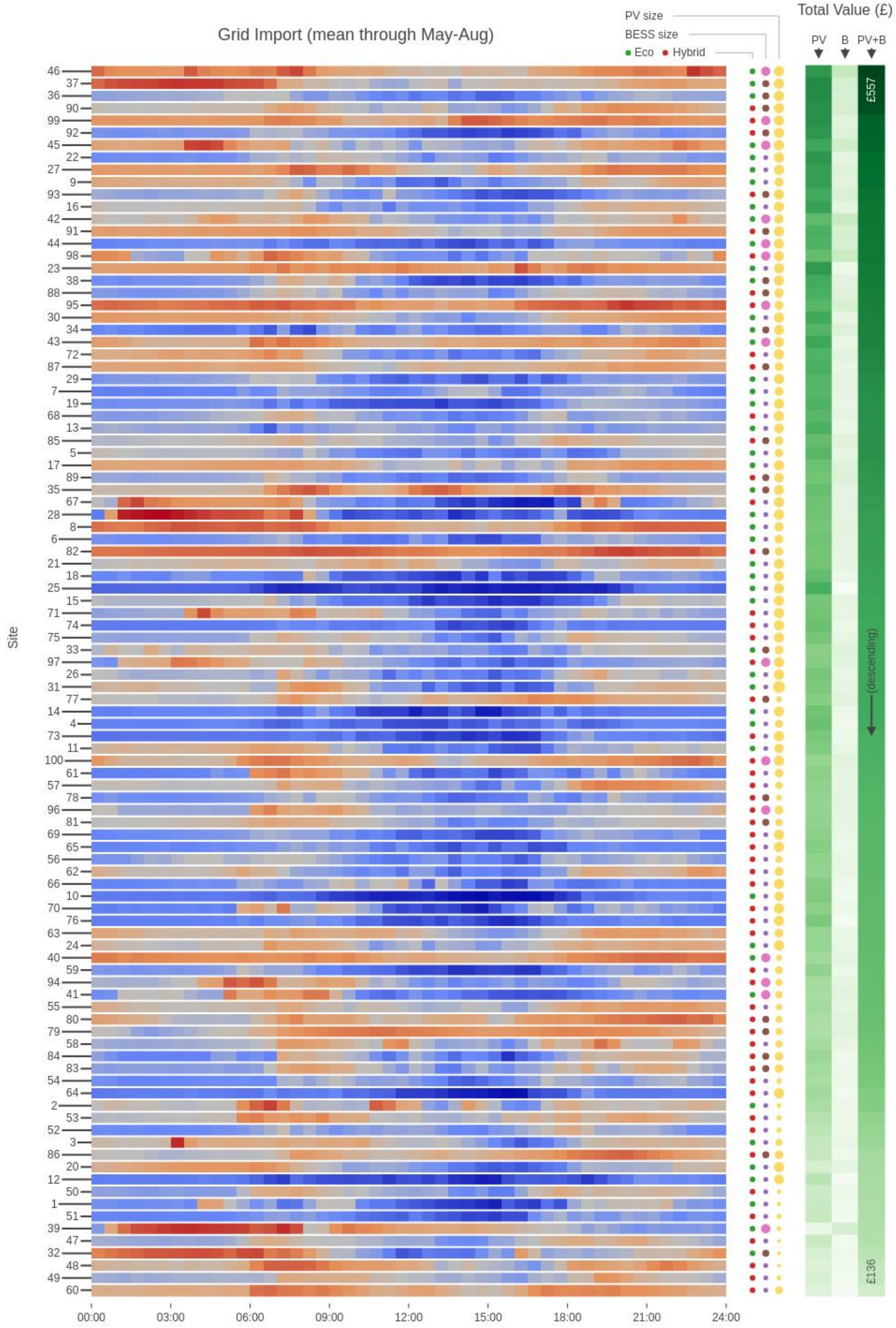

Figure 77: Average Grid Import by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.4 Grid Export

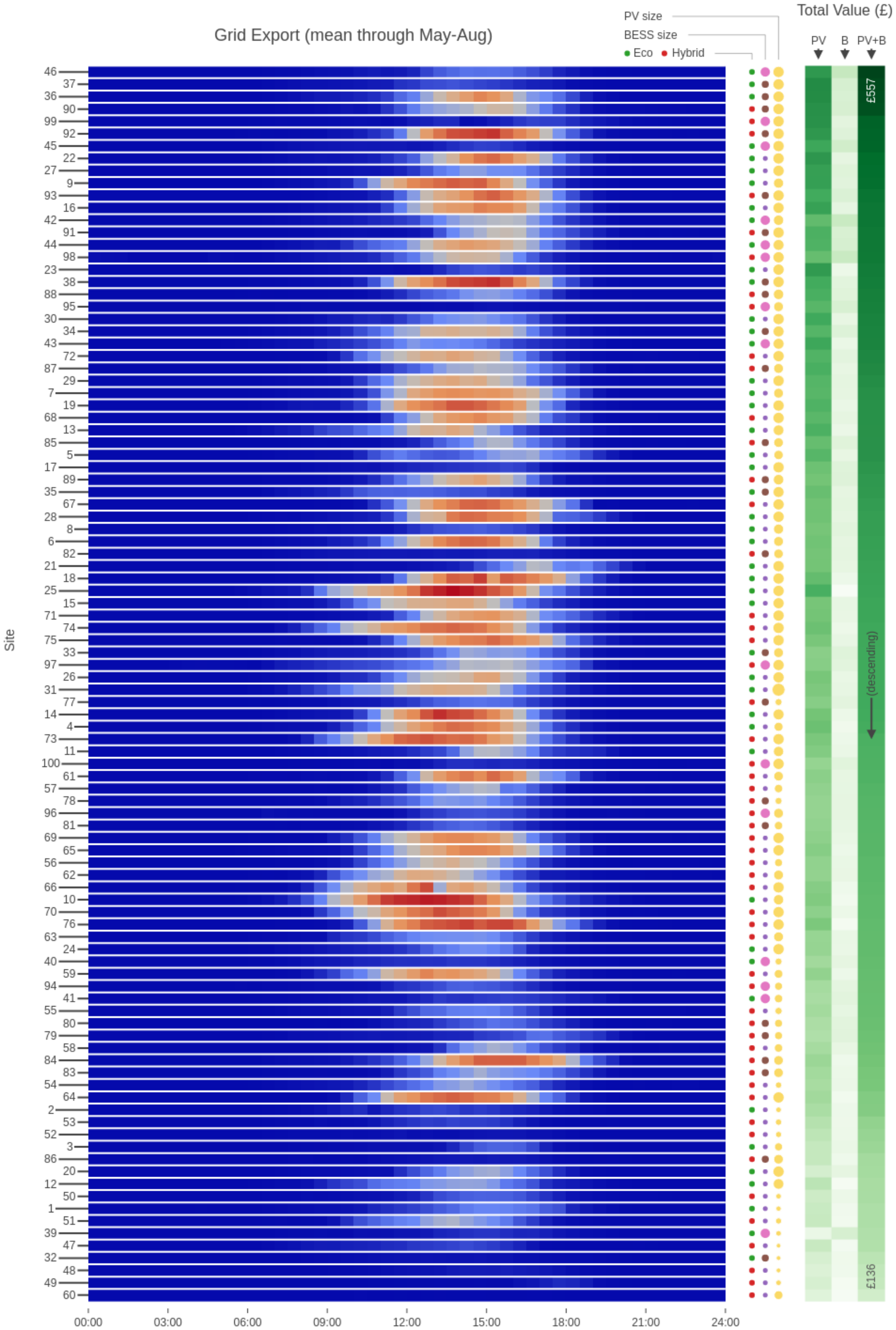

Figure 78: Average Grid Export by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.5 BESS Charge

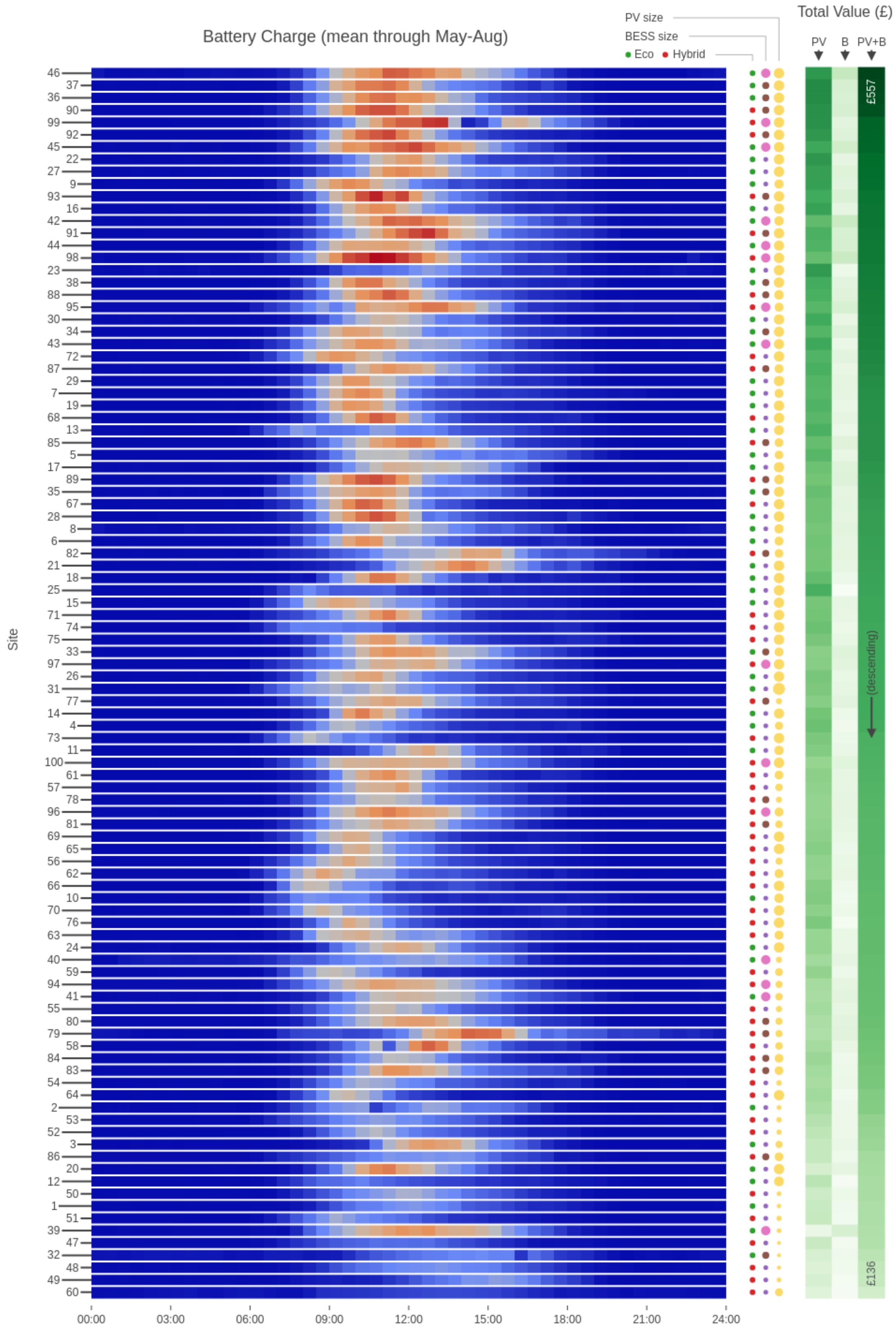

Figure 79: Average BESS Charge by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.6 BESS Discharge

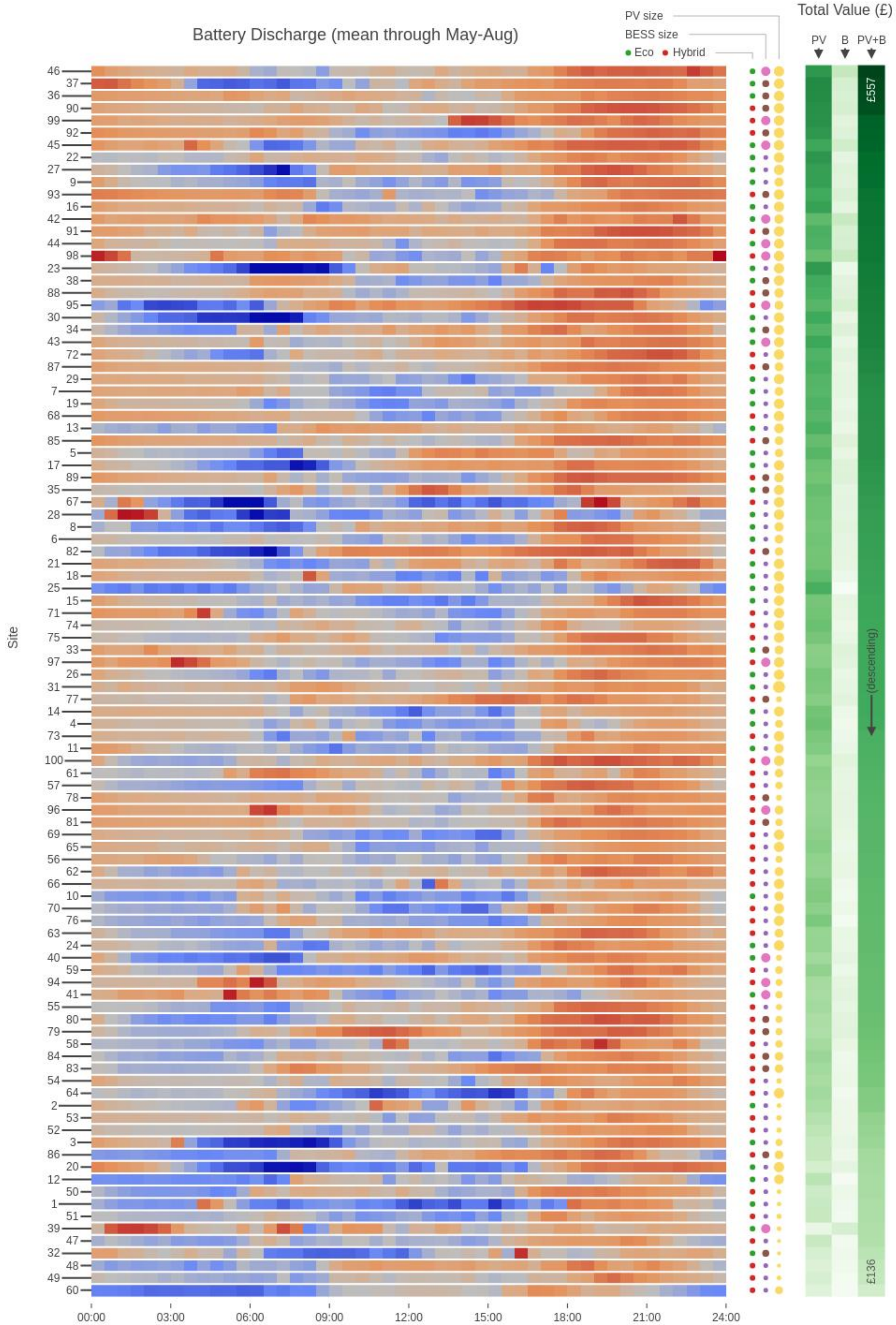

Figure 80: Average BESS Discharge by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.7 State of Charge

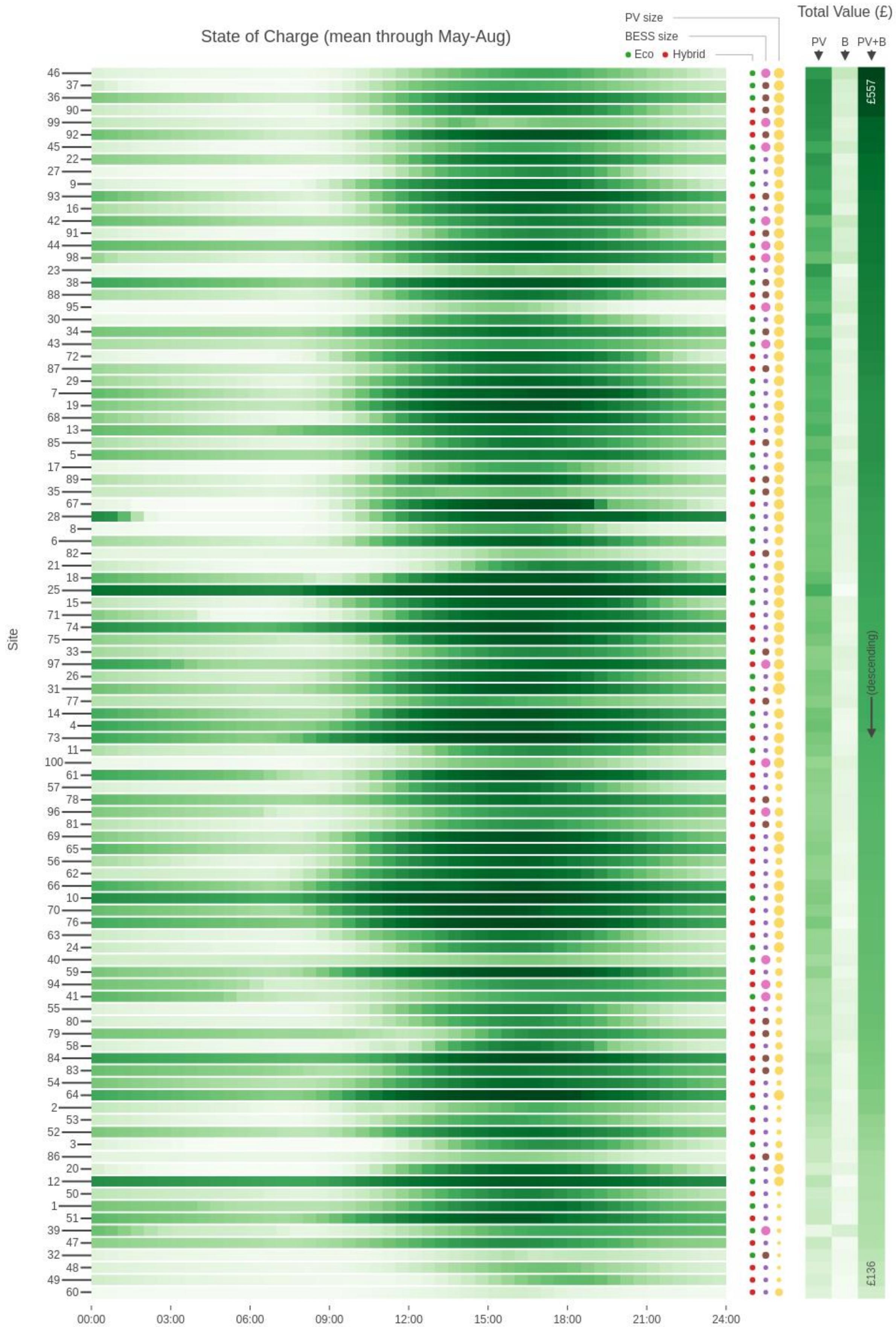

Figure 81: Average BESS State of Charge by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.8 Production Surplus

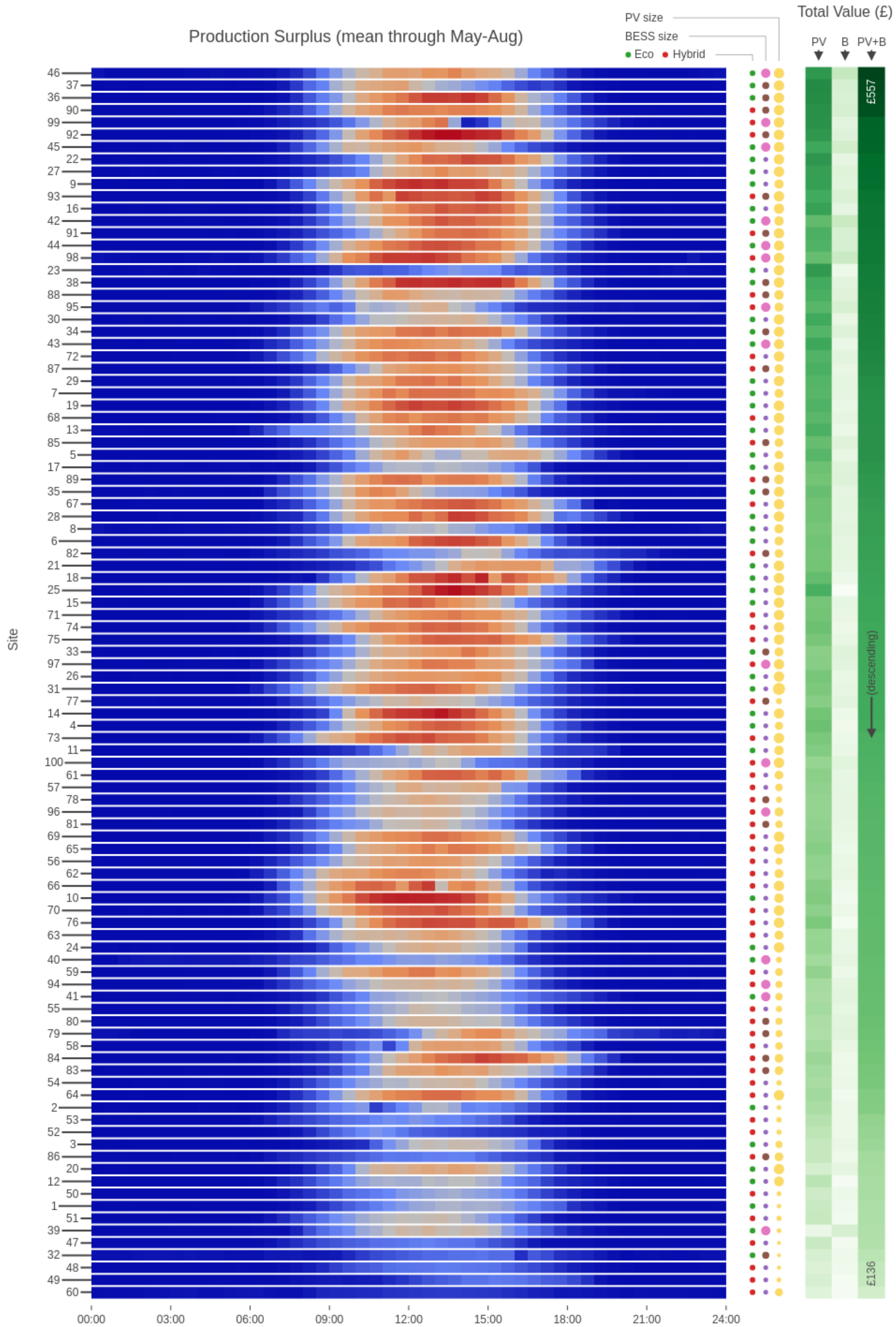

Figure 82: Average Production Surplus by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.9 Production deficit

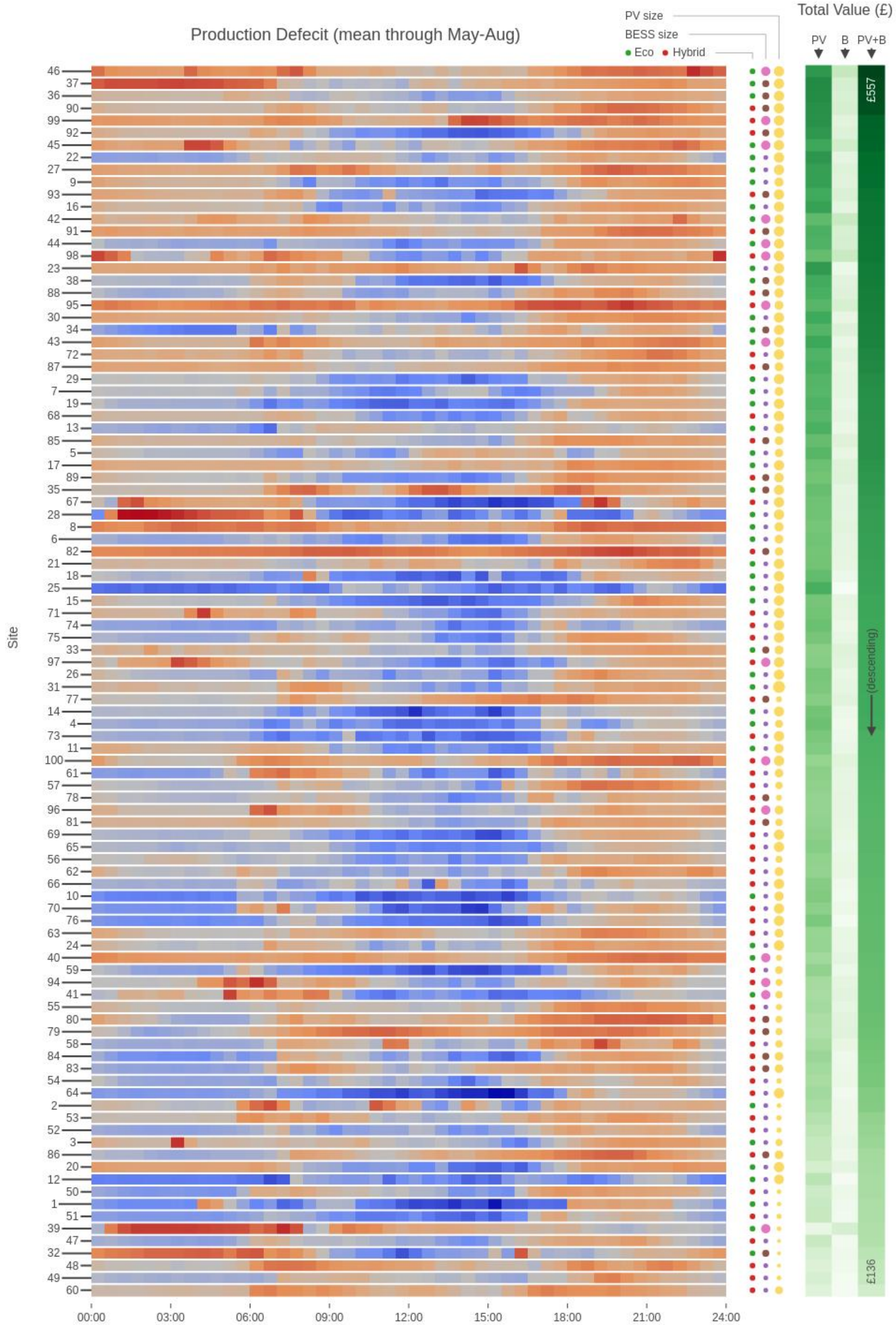

Figure 83: Average Production Deficit by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.10 Production Surplus/Deficit Ratio

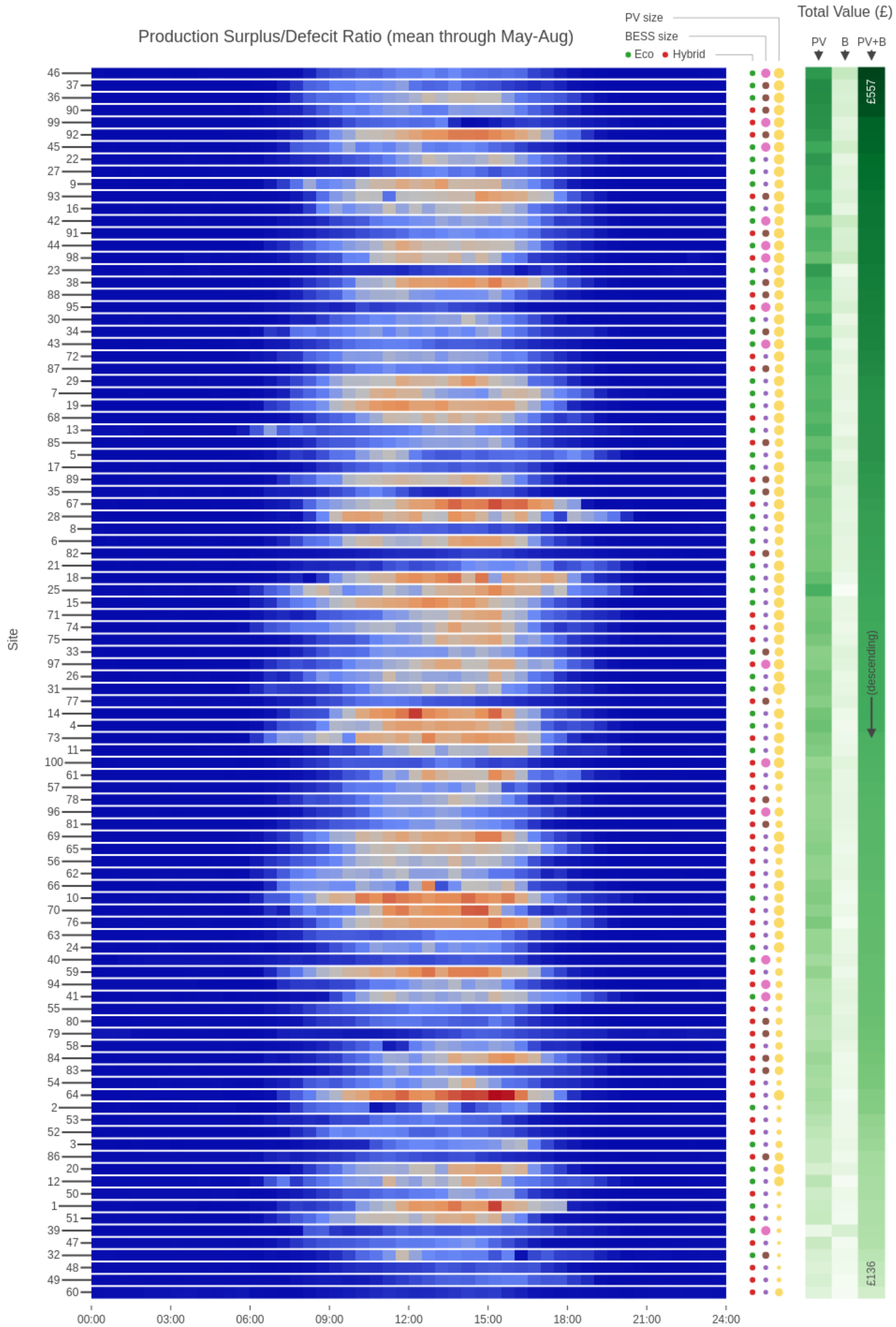

Figure 84: Average Production Surplus/Deficit Ratio by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

5.3.11 Production/Consumption Ratio

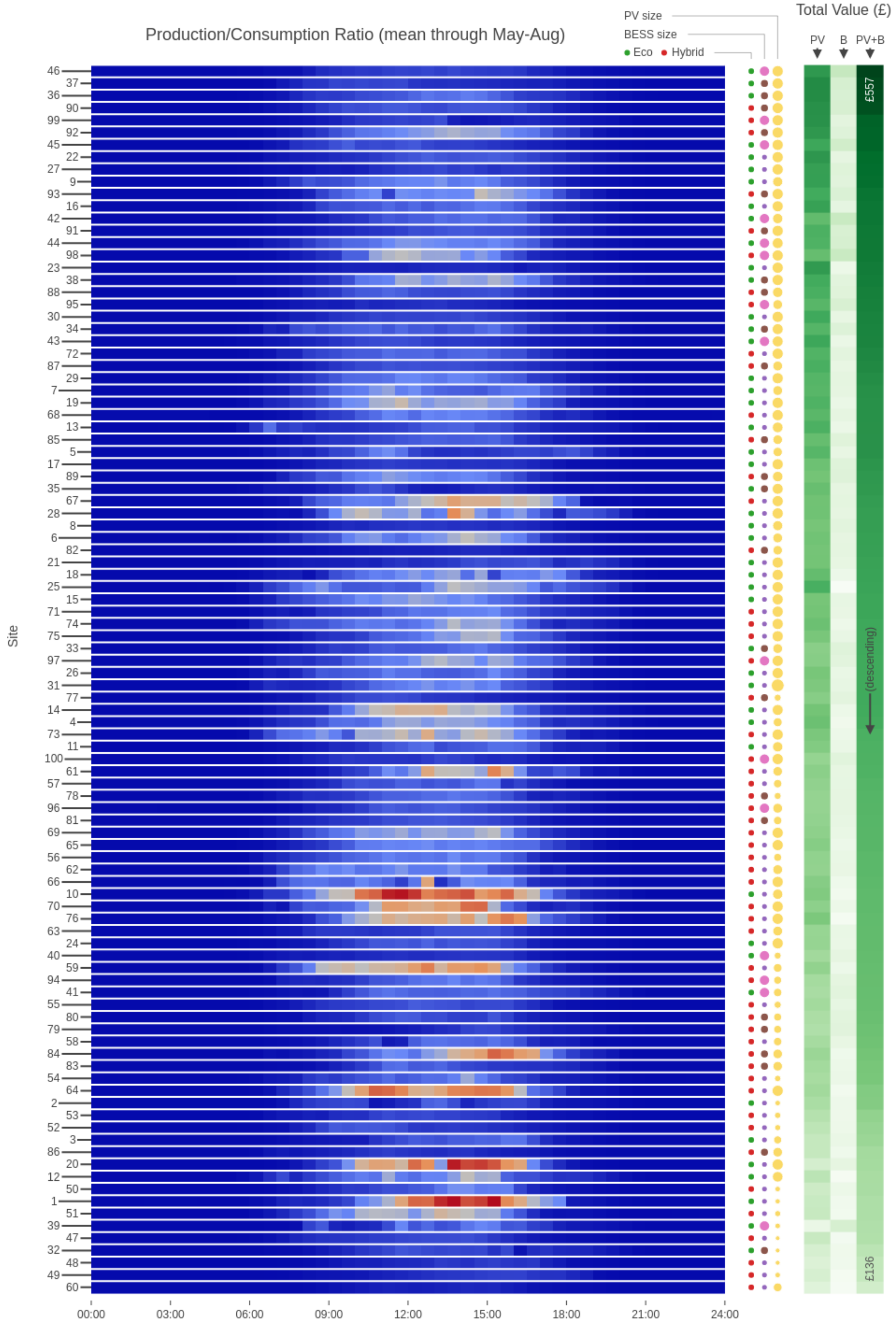

Figure 85: Average Production/Consumption Ratio by 30m Period, using data between May19-Aug19, per Site, ranked by Total Financial Savings

APPENDICES

6. Appendix A: Seasonal Change by Site

6.1 Summary

To support the analysis of both annualised results and intra-day patterns, further work was carried out to automate a process for parameterisation of daily consumption patterns throughout the year. The aim of this process was to attempt to better describe performance variation through the seasons, by creating a small set of parameters to describe each dwelling or household. The specific objectives were two-fold:

1. to describe the seasonal variation for all sites;
2. to describe day-to-day variation for all sites, to interpret the potential effect of weekdays versus weekends and underlying randomness of behaviour within households (particularly with regard to major loads).

The premise of this method is to approximate the daily consumption patterns (kWh/day) as a cosine function, using a least-squares fit. With respect to Objective 1, this implies determining the amplitude, phase shift, and offset from zero of an idealised curve. Of these three harmonic parameters, only the amplitude was considered as a descriptor for seasonal variation. For Objective 2, the average magnitude of daily change was taken as a description of 'jaggedness' of daily consumption patterns. The amplitude and 'jaggedness' were therefore both considered as synthesised meta-descriptions of dwellings/households. These were considered for potential use as clustering parameters, for specific use where smart meter data can be obtained for potential customers.

Summarised results for this process are provided in Figure 86 through to Figure 98. It was possible to generate reasonable approximations of daily consumption throughout the year at 92 out of the 100 sites. Sites that did not respond effectively to this process experienced significant behavioural change between the two winters of the trial, which may have occurred for various reasons, such as major changes to the household.

Based on the harmonic trends throughout the year, sites generally fitted one of five categories with respect to Objective 1: significant, moderate, slight, flat or inverted seasonal change (where inverted, summer consumption was larger than in winter). For Objective 2, the sites could be categorised as low, moderate or high day-to-day variation. A summary of the parametric groups is provided in Table 1, along with corresponding result examples from Figure 86 through to Figure 98.

		Day-to-day variation		
		Low (# occurrences)	**Mod. (# occurrences)**	**High (# occurrences)**
Seasonal change	**Significant**	*n/a*	Figure 89 (6 sites)	Figure 94 (10 sites)
	Moderate	Figure 86 (2 sites)	Figure 90 (5 sites)	Figure 95 (5 sites)
	Slight	Figure 87 (11 sites)	Figure 91 (19 sites)	Figure 96 (6 sites)
	Flat	Figure 88 (17 sites)	Figure 92 (12 sites)	Figure 97 (2 sites)
	Inverted	*n/a*	Figure 93 (3 sites)	Figure 98 (2 sites)

Table 1: Summary results from parametric analysis annual trends and day-to-day variation.

6.2 Low day-to-day variation

Example sites with low day-to-day variation are provided in Figure 86 to Figure 88. As the amplitudes were absolute values, these sites were all characterised by low annualised consumption. The lack of day-to-day variation also implies weak influence on demand from large loads like electric showers and electric heating. In contrast, very flat consumption patterns, as Site 54 (Figure 88) is dominated by small loads.

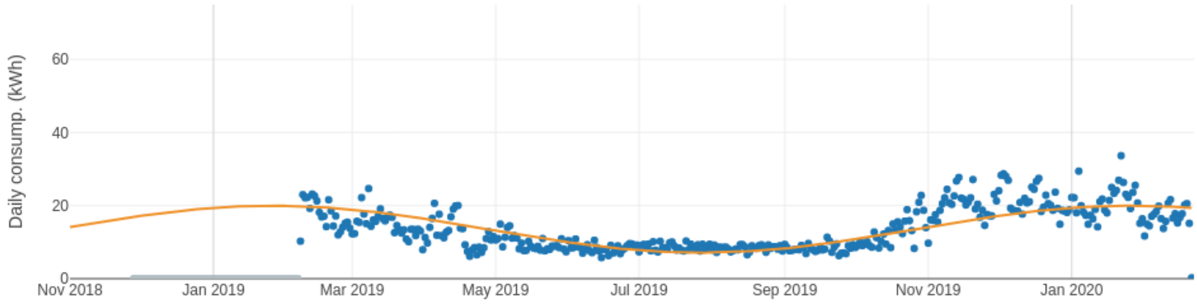

Figure 86: Site 49: Moderate seasonal change, low day-to-day variation

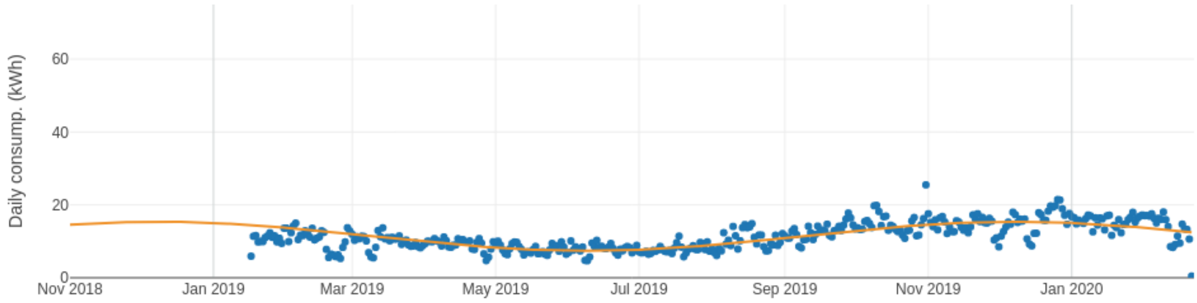

Figure 87: Site 20: Slight seasonal change, low day-to-day variation

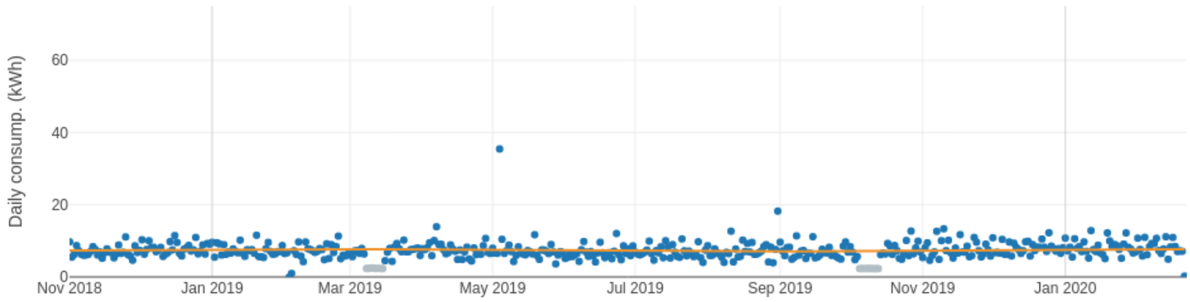

Figure 88: Site 54: No seasonal change (flat), low day-to-day variation

6.3 Moderate day-to-day variation

Figure 89 to Figure 93 show moderate day-to-day variation. This can occur as undulations over weeks/fortnights (as Figure 89) or as more stochastic patterns over winter periods, due to electric heating use.

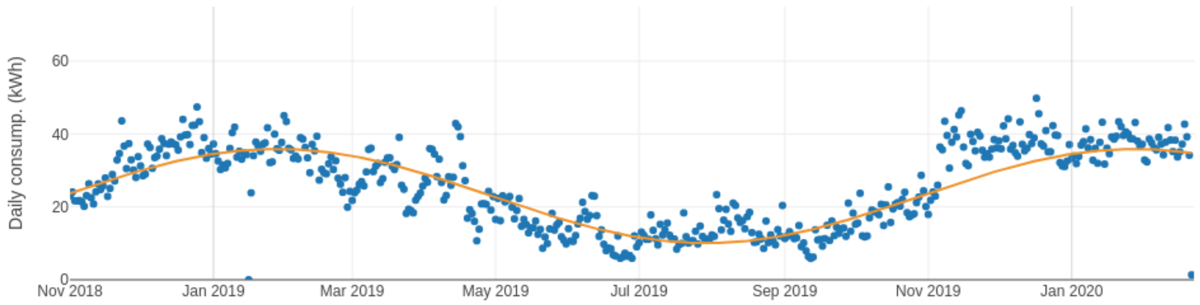

Figure 89: Site 42: Significant seasonal change, moderate day-to-day variation

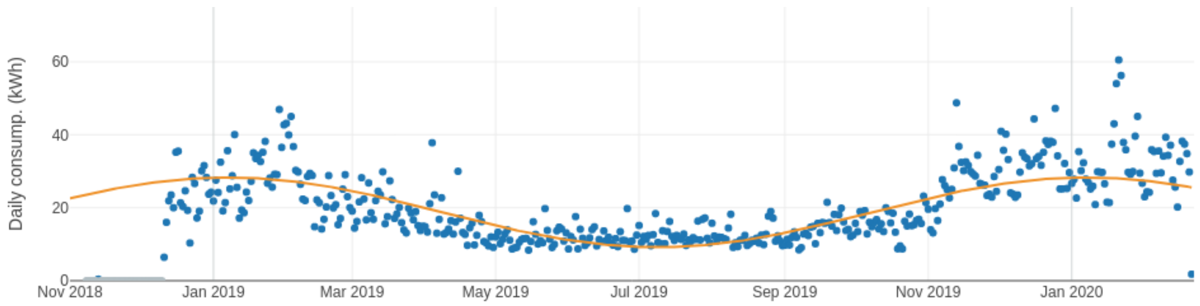

Figure 90: Site 96: Moderate seasonal change, moderate day-to-day variation

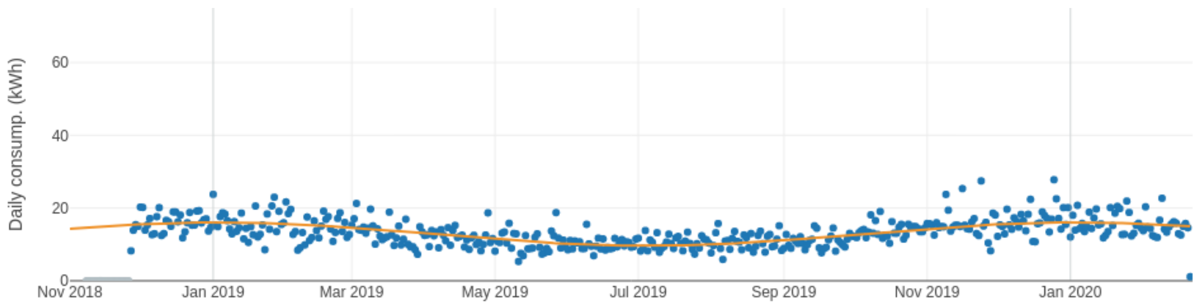

Figure 91: Site 89: Slight seasonal change, moderate day-to-day variation

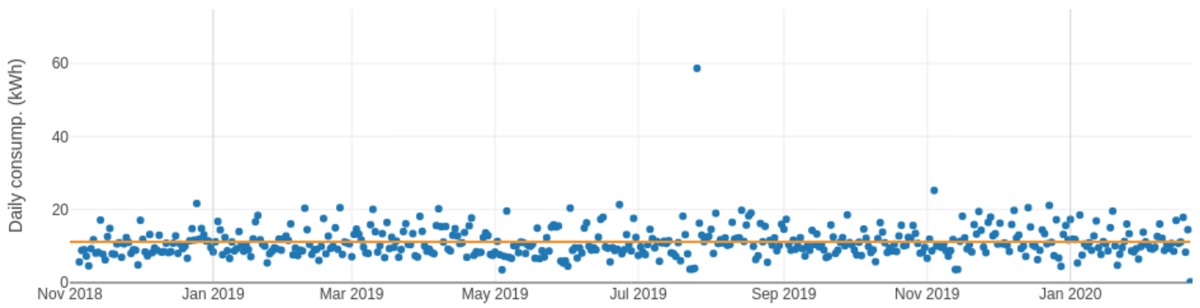

Figure 92: Site 55: No seasonal change (flat), moderate day-to-day variation

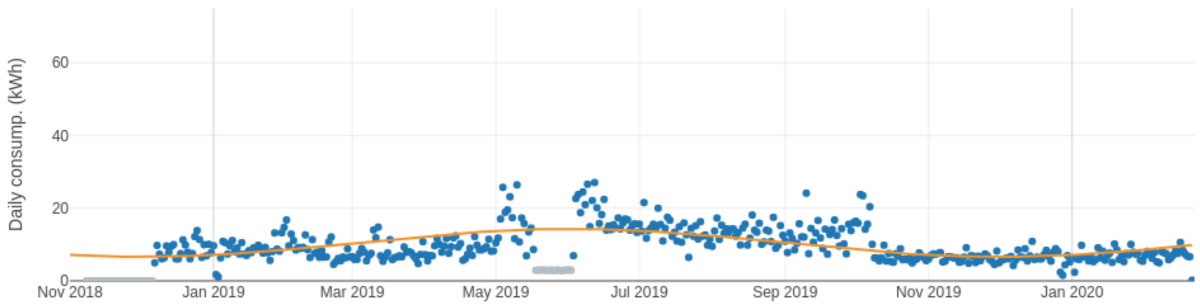

Figure 93: Site 63: Inverted seasonal change, moderate day-to-day variation

6.4 High day-to-day variation

Figure 94 to Figure 98 show significant day-to-day variation dominated by stochastic behaviour in homes with major loads. As indicated in Table 1, significant seasonal change often corresponds to very jagged profiles, such as Figure 94.

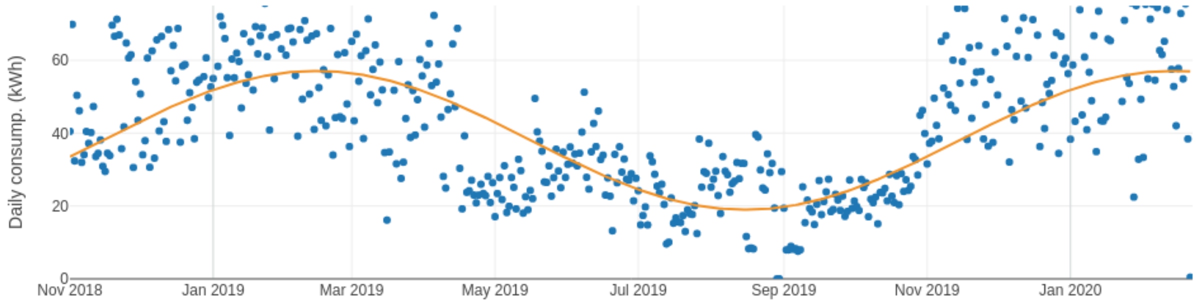

Figure 94: Site 8: Significant seasonal change, high day-to-day variation

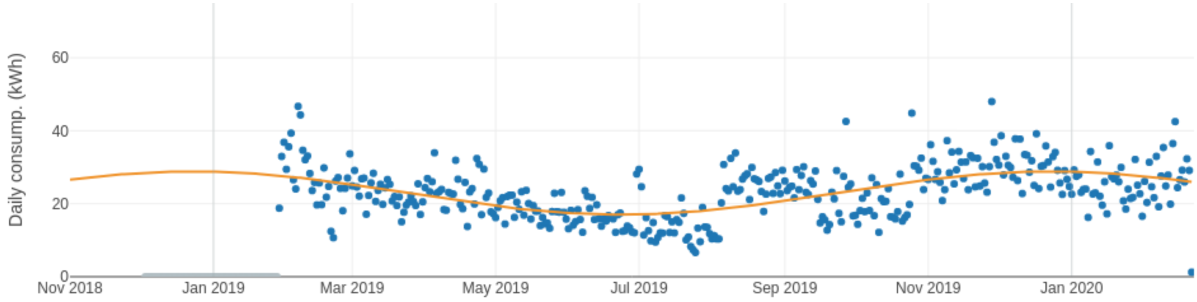

Figure 95: Site 91: Moderate seasonal change, high day-to-day variation

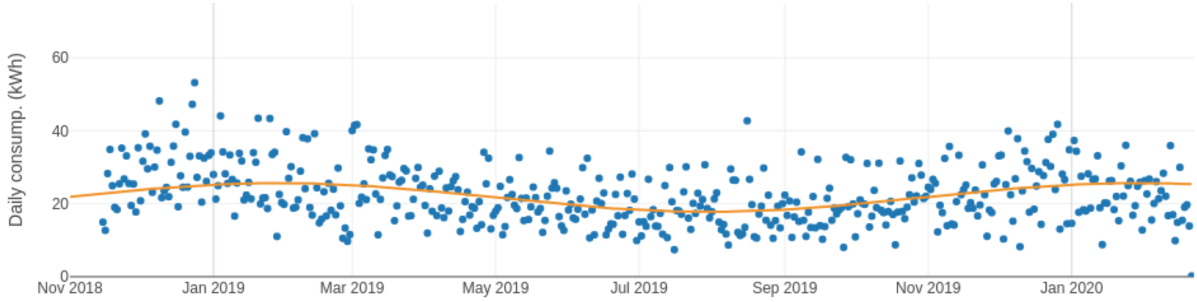

Figure 96: Site 100: Slight seasonal change, high day-to-day variation

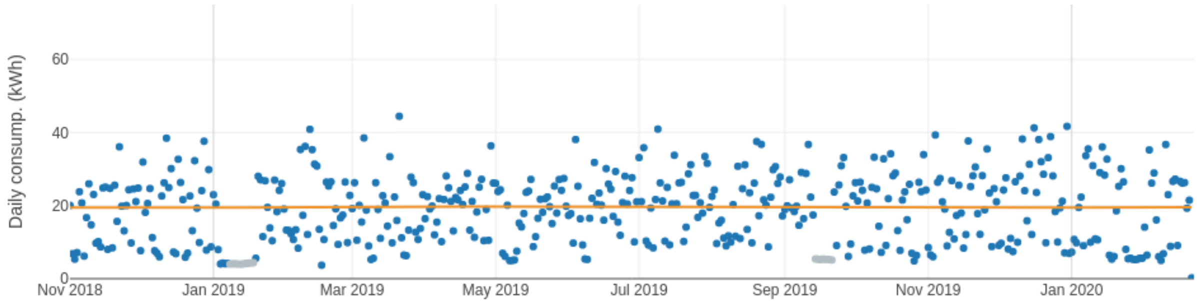

Figure 97: Site 35: No seasonal change (flat), high day-to-day variation

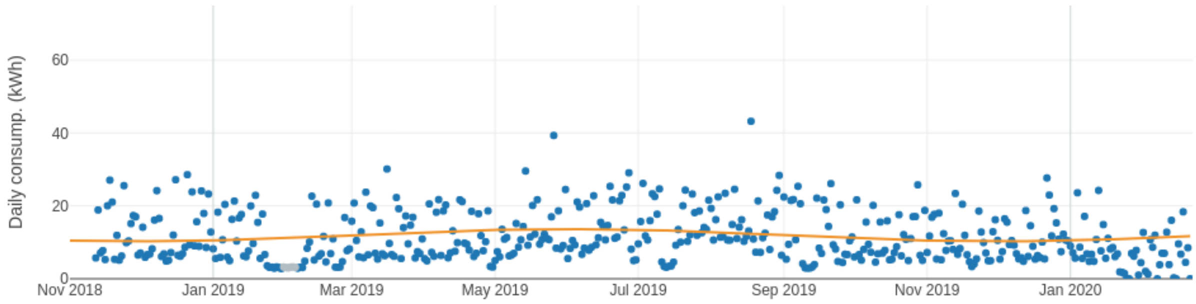

Figure 98: Site 77: Inverted seasonal change, high day-to-day variation