DS3 Losses Insight – Impact of domestic BESS on losses

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1. Executive Summary

This report analyses the impact of domestic photovoltaic (PV) generation and Battery Energy Storage Systems (BESS) on network losses for the low voltage (LV) network monitored as part of the Distributed Storage and Solar Study (DS3) project[1]. The analysis, which falls outside the scope of the DS3 project, calculates losses for the scenarios of (a) no PV-no BESS, (b) with PV-no BESS and (c) with PV and BESS. For scenario (c) two different BESS operating modes were examined, that of threshold charging (BESS charges/discharges based on excess generation/demand) and maximum impact (BESS charge/discharge at their maximum rate at set times). Average losses were calculated for single phase service as well as LV mains cables using half-hour data.

Analysis of various level of generation suggested that the relationship between network losses and PV generation resembles a parabola. Low levels of generation combined with high levels of consumption, at times experienced in the winter, have the potential to reduce losses. However as generation levels increase and/or consumption reduces, losses increase. On the mains cable, aggregated consumption exceeded generation in both winter and summer, hence PVs reduced losses. On the service cable this only happened during period of low generation levels hence it was observed that on average PV increased losses. The impact of BESS on the other hand varies depending on season, size and operating mode. When operating in threshold charging mode, BESS have a positive impact on losses (i.e. reduce losses) on both service and mains cables as they absorb excess generation and supply evening demand in both winter and summer. Although the impact of BESS is positive, overall losses in the summer are still high due to the low levels of consumption and high levels of PV generation. The impact of the maximum impact mode on the other hand is somewhat different. Although it also has a positive impact on losses, particularly on mains cables, its impact was less than that of the threshold charging mode as forcing the BESS to charge/discharge regardless of generation and demand caused additional power flows, particularly at periods of low generation or demand (charging the BESS in the winter and discharging it in the summer) or extended periods of generation (discharging the BESS in the summer).

Finally, regardless of the impact of PV generation and BESS on losses, which for the former at times may be negative, the wider environmental benefits of both as well as the network benefits of the latter need to be taken into account, particularly as these may outweigh them.

[1] DS3 is an NIA funded monitoring and impact assessment project which explored the potential for aggregator-controlled behind the meter BESS to reduce excess generation and evening peak demand. More information is available at: https://www.smarternetworks.org/project/nia_npg_011

Contents

2. Introduction

This report analyses the impact of domestic photovoltaic (PV) generation and Battery Energy Storage Systems (BESS) on network losses. Losses were calculated for the low voltage (LV) network monitored as part of the Distributed Storage and Solar Study (DS3) project. The analysis, which falls outside the scope of the DS3 project, calculates losses for the scenarios of a) no PV-no BESS, (b) with PV-no BESS and (c) with PV and BESS. For scenario (c) two different BESS operating modes were examined, that of threshold charging (BESS charges/discharges based on excess generation/demand) and maximum impact (BESS charge and discharge at their maximum rate at set times). Average losses were calculated for single phase service cables as well as LV mains using half-hour data.

3. Network configuration and BESS operating modes

3.1 Network configuration and data

For the purposes of this analysis, two sets of data were used; average half-hour data measured at households with BESS (via the BESS monitoring system which measures household consumption, PV generation and BESS activity separately), and average half-hour data measured on each feeder at the distribution substation. The following relevant parameters were used:

- **Households[2]:** consumption [W], generation [W], BESS consumption [W]; and
- **Substation:** load [kW] and voltage [V].

The distribution substation where the 40 BESS were installed is configured as per Figure 1 and supplies a total of 119 customers. The substation has five feeders of which one (Feeder 5) is spare and another is connected to the transformer (Feeder 3). BESS were installed across the remaining three feeders in 36 households, 27 of which had PV generation. The rating of BESS and PV are as follows:

- BESS power rating: 430W
- BESS capacity: 2 or 3 kWh
- PV generation rating: 26 systems of 2.7 kWp and 1 system of 3.78 kWp

The analysis presented in Section 5 was performed on Feeder 2 due to the concentration level of installed BESS and PV generation. For simplicity, the variation in BESS capacity and PV rating was ignored.

[2] Watt values were converted to Ampere using 230V

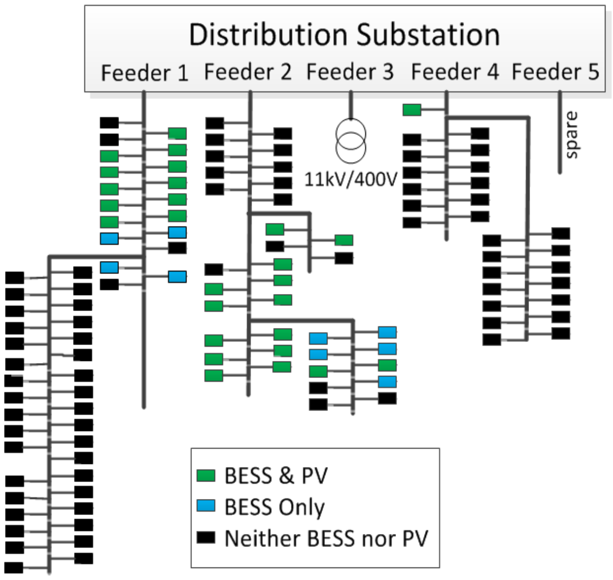

Figure 1: Network configuration indicating households with BESS and PV generation (PV)

3.2 BESS operating modes

A number of different BESS operating modes with various charging/discharging levels were trialled during the project to determine the impact of BESS on the network at peak evening demand and maximum generation in the winter and summer respectively. For the purpose of this analysis, data from two operating modes was used; that of threshold charging and that of maximum impact.

Threshold charging is designed to balance consumption and generation by storing excess generation and offsetting import. The inverter has a charging threshold of 100 W (the level of excess electricity demand or excess PV generation output at which the unit starts to (dis)charge) and tries to minimise the household import or export. This meant that during this scheme, only BESS in households with PVs were operating. The **maximum impact** mode on the other hand forces the BESS to charge during the day (10:00-16:00) and discharge during the evening (17:00-20:00) at full power in all households (with and without PV), regardless of generation and demand levels.

Table 1 shows the time periods each operating mode was trialled for. To align the analysis of network losses with that of the DS3 project, losses were calculated separately for the winter (01/10/2019 – 31/03/2018) and summer (01/04/2018 – 30/09/2018) periods, for each mode of operation and low carbon technology (LCT) combination (PV generation and BESS). Doing so allowed the calculation of network losses without any LCTs, with PV generation alone and with PV generation and BESS which in turn quantified the impact each of the two have on losses during each period separately, taking into account the varying levels of generation and demand. They were then combined to calculate the overall annual losses.

Operating mode	From	To
Threshold Charging (Winter)	01/10/2017 00:00	31/10/2017 23:30
Maximum Impact (Winter)	01/11/2017 00:00	26/01/2018 23:30
Maximum Impact (Summer)	17/05/2018 00:00	24/05/2018 23:30
Threshold Charging (Summer)	10/08/2018 00:00	30/09/2018 23:30

Table 1: BESS operating modes as trialled during the DS3 project

4. Methodology and assumptions

4.1 Data selection

Due to communication and other technical issues, data availability and quality was not consistent throughout the project, especially at household level. To take account of that, a subset of the whole dataset was used for the calculation of network losses.

For losses along single phase service cables, measurements from households with data availability greater than 95% during each BESS operating mode were selected and analysed, regardless of the LV feeder they were connected to. Table 2 below shows the number of the data points used for each operating mode. The measurements for each data point were used to calculate losses on each service cable (see Section 5), averaged to derive the average variable loss for a set of scenarios (see Section 5) and extrapolated over each period (winter and summer) to determine the equivalent average total variable loss per period.

Operating mode	Households	PV Generation
Threshold Charging (Winter)	26	11
Maximum Impact (Winter)	23	12
Maximum Impact (Summer)	17	8
Threshold Charging (Summer)	28	13

Table 2: Data points used for each operating mode

For losses on LV mains cable, measurements taken between 01/10/2017 and 30/09/2018 were selected and analysed. Although a BESS idle mode[3] was trialled to establish the base load, the load with PV but no BESS and with neither PV nor BESS was back-calculated using the data measured at the substation (net measurement) and that from each of the households. Given the number of available data points (households), the overall data availability and spread of customers along the LV mains cables and distribution substation, a single LV mains cable (Feeder 2 in Figure 1) was selected and analysed. Despite some partially available data, this approach was deemed to be more representative in determining the base load on the mains cable rather than taking a few days' worth of data captured during the idle mode and extrapolating it.

For both service and mains calculations, the average and peak losses were calculated for each time period using formulae (1) and (2) below during each operating mode. Finally, to take account of the inaccuracy of loss estimates as a result of varying time resolution (half-hourly values), an adjustment factor of 1.23[4] was applied.

$$P_{Lavg} = \frac{\sum_{n=1}^{T}(I_n^2 \text{ x } R)}{T} \tag{1}$$

$$P_{Lpeak} = I_{peak}^2 \text{ x } R \tag{2}$$

where:

$P_{Lavg} = Average\ power\ loss\ in\ kW, over\ a\ time\ period$

$P_{Lpeak} = Peak\ loss\ in\ kW\ during\ a\ time\ period$

$I_n = Loading\ in\ A, at\ HH\ number\ n$

$n = HH\ number$

$R = Resistance\ of\ the\ asset$

$T = Total\ HH\ in\ a\ period$

[3] During this period the BESS was switched off for a few days to determine the substation base load.
[4] G. Poursharif, A. Brint, M. Black and M. Marshall, "Analysing the ability of smart meter data to provide accurate information to the UK DNOs," in CIRED - Open Access Proceedings Journal, vol. 2017, no. 1, pp. 2078-2081, 10 2017

4.2 Network simplification

For single phase service calculations, the actual length and resistance value of each service cable was used (including neutral conductor). The service cable lengths varied between 5m and 34m with the average service length being 16m. The resistance value used is shown in Table 3.

Service type [in^2]	Resistance [Ω]	Neutral Resistance [Ω]
0.0225 Cu	1.575	1.26

Table 3: Service resistance values

For losses on LV mains cables, given the number of available data points (households), the overall data availability and spread of customers along the LV mains and distribution substation, a single LV mains cable (Feeder 2 in Figure 1) was selected and analysed to determine the impact of BESS on variable network losses. The selected feeder has 36 customers in total, 15 of which have PV generation and 20 BESS. To simplify the calculations, an equivalent feeder was used by splitting it into 3 sections as per Figure 2. As mentioned in section 3.1, any variation in BESS capacity and PV generation was ignored. The parameters of each section along with the allocation of customers and hence load are shown in Table 5. Load was allocated proportionally along each phase and section and average and peak losses were calculated by multiplying them with the relevant section resistance R indicated in Table 5.

Finally, to take into account that network feeders typically feed distributed loads along them rather than point loads at their end, a feeder load factor, FLF[5], was applied to each section. Table 4 shows the FLF used for each section.

Due to gaps in data and scattered monitoring points this analysis focuses on assessing the overall impact of BESS on losses rather than quantify the exact kWh lost hence this approach was deemed sufficient. The actual losses value may have been different had a more detailed approach been taken but it is anticipated that the overall impact trend would have been the same.

[5] According to the CoP for the Methodology of assessing losses (IMP/001/103) [Accessible at: https://www.northernpowergrid.com/document-library/], network feeders typically feed distributed loads along them rather than point loads at their end. A feeder loss factor, FLF, can be used to convert point load losses to losses as a result of distributed demand along a feeder.

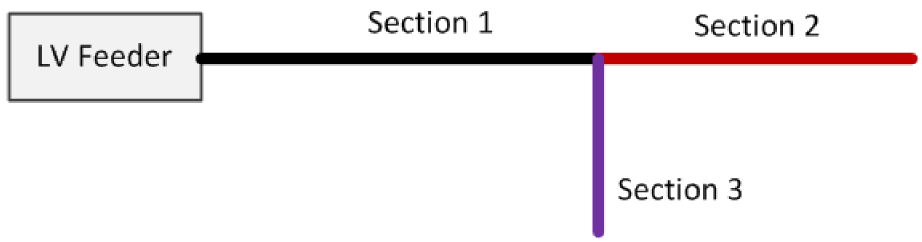

Figure 2: Equivalent LV feeder

Section	Section 1	Section 2	Section 3
FLF	0.36	0.38	0.46

Table 4: Feeder Loss Factor, FLF

Section	Feeder length [m]	Cable Type	Cable Resistance [Ω/km]	Section Resistance (Transformer + Cable section) [Ω]	Customer allocation [% of total customer number]	Load Allocation [% of total load]
1	140	0.3 Al	0.197	0.037	60%	100%
2	60	0.1 Al	0.394	0.060	30%	30%
3	40	0.3 Al	0.197	0.4445	10%	10%

Table 5: Equivalent LV feeder characteristics

Transformer size [kVA]	Resistance [Ω]
315	0.00901

Table 6: Transformer winding resistance

5. Losses calculation and discussion

The following formula (3) was used to calculate the total variable losses for each time period, N, (winter and summer) for the scenarios of:

(a) no PV-no BESS;
(b) with PV-no BESS; and
(c) with PV and BESS*

*For scenario (c) two different BESS operating modes were examined, those of threshold charging and maximum impact.

The average power loss for each scenario above was multiplied by *N* to calculate the total variable loss for each time period where N = 4383 (8766 hours in a year divided by two)[6].

$$Total\ variable\ loss\ in\ a\ period = Average\ power\ loss \text{ x } N \qquad (3)$$

where:

$P_{Lavg} = Average\ power\ loss\ in\ kW, over\ a\ time\ period$ (see Formula (1) in Section 4.1)

$N = time\ period\ (6\ months)$

5.1 Service cables

Variable network losses along service cables were calculated based on measurements taken from households as per Table 2. Losses in kWh were calculated separately for each household using the actual service length and their respective resistance value (including neutral conductor). The resistance value for the service cable is shown in Table 3 and the length of service cables varied between 5m and 34m with average service length being 16m.

As discussed earlier, losses were calculated separately for each period (winter and summer) and operating mode (threshold charging and maximum impact), using the measured and calculated data shown below:

- Household consumption (measured)
- Household generation (measured)
- BESS consumption (measured)
- Net household consumption – PV generation only (calculated)
- Net household consumption – PV generation and BESS (calculated)

[6] The sum of losses in each half-hour was divided by the number of half-hours to derive the average hourly value before multiplying it with the number of hours in that period.

The average power losses for each operating mode were calculated using formula (1) in Section 4.1 and extrapolated over 6 months (*N* = 4383) to derive the total variable losses for each operating mode in each of the winter and summer periods for each individual profile (consumption only, PV generation only, net consumption with PV and net consumption with PV and BESS). Figure 4 and Figure 6 below show the extrapolated variable losses per customer during the 6 month winter and summer periods respectively for consumption only, PV generation only, net consumption with PV generation only and net consumption with PV generation and BESS during both the threshold charging (blue) and maximum impact (red) operating modes.

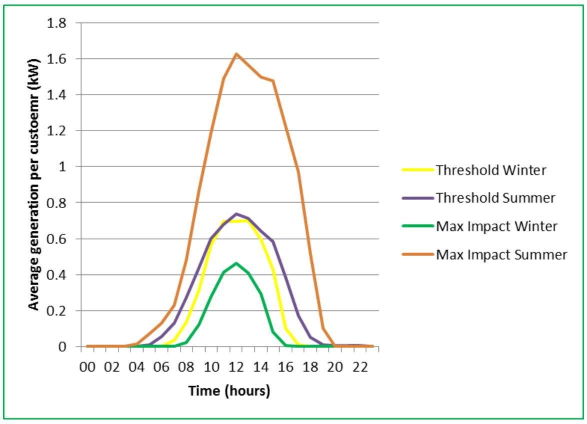

Figure 3: Generation levels in each time period

As per Figure 4, whilst in the winter consumption losses were similar across both operating mode trial periods, the different levels of generation experienced during each period, seen in Figure 3, led to different levels of PV generation losses. On average, when generation was high (experienced during the threshold charging mode), its average impact on losses was minimal, reduced by 3%, whereas when low (experienced during the maximum impact mode), losses reduced by an average of 12%. This suggests that the relationship between network losses and PV generation (and therefore penetration) on single phase service cables resembles a parabola. Finally, as per Figure 5, when operating in threshold charging mode, BESS had a positive impact on losses by reducing them by 19%. However, due to the low levels of generation experienced during the period the maximum impact mode was trialled, BESS had less impact (12% reduction) as the scheme was forcing the BESS to go through their charging/discharging cycle regardless of generation and demand. Had generation been higher during this period, its impact on losses and consequently that of the BESS would have been different as the BESS would have captured excess local generation and used it to supply the evening load. Regardless of the operating mode, BESS helped reduce losses by 12-19%.

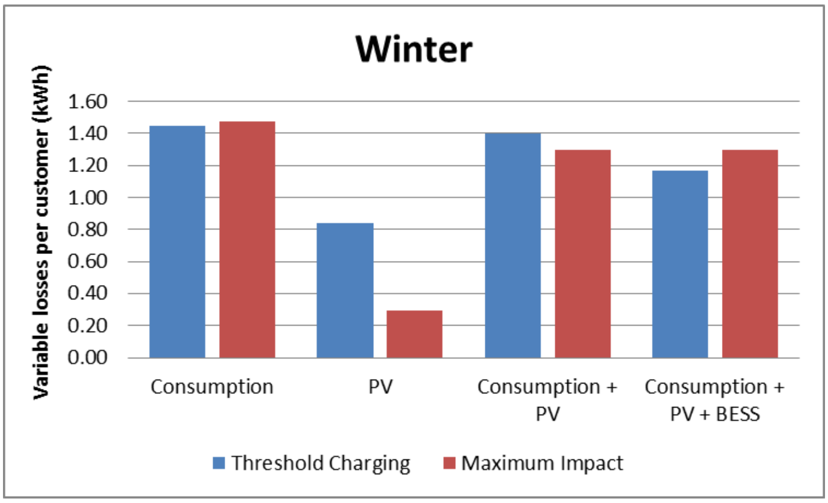

Figure 4: Service cable losses during the winter

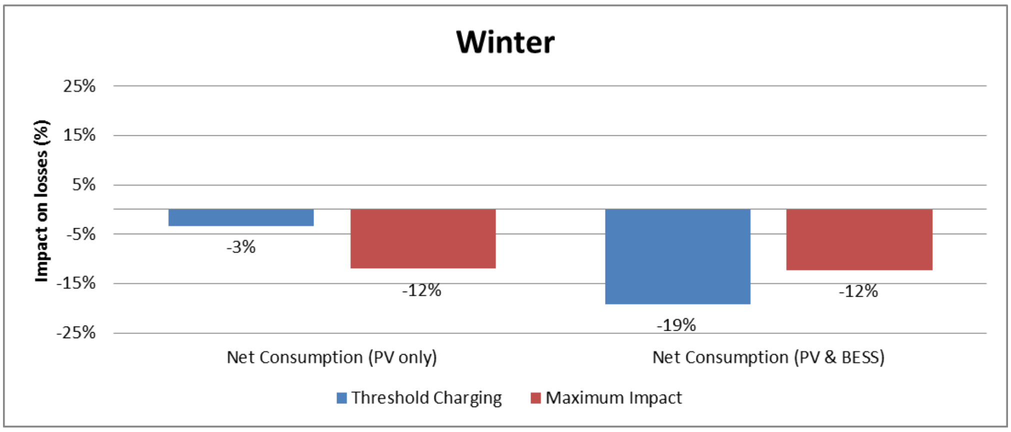

Figure 5: Percentage change of losses compared to consumption only (winter)

Unlike in the winter period, as per Figure 6, consumption losses in the summer were significantly less due to the lower levels of consumption hence the high levels of generation increased the combined consumption and generation losses on service cables significantly. However, analysis showed that regardless of its operating mode, BESS help reduce losses albeit these were still higher than those from pure consumption due to the high levels of PV generation. BESS operating in threshold charging mode reduced the increase in losses due to PV generation from 95% increase to 45% (compared to consumption alone) whereas operating in maximum impact mode reduced them from 154% increase due to PV generation to 95% (compared to consumption alone). Having said this, the levels of generation during each trial period (threshold charging and maximum impact) were different. It is anticipated that had the generation during the period the threshold charging mode was trialled been higher, the BESS impact would have been less as it would have charged earlier without necessarily discharging in the evening (due to the low consumption experienced in the summer).

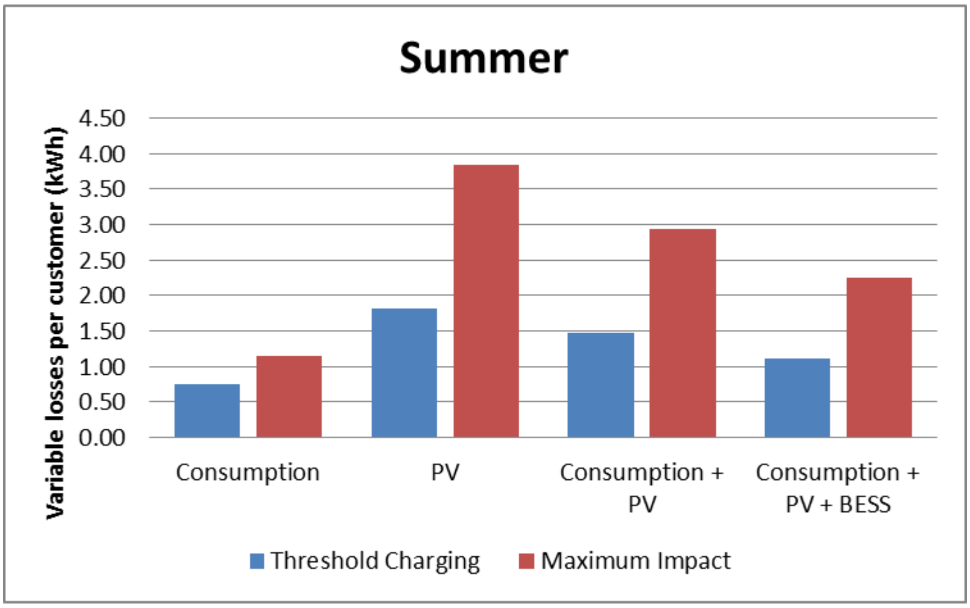

Figure 6: Service cable losses during the summer

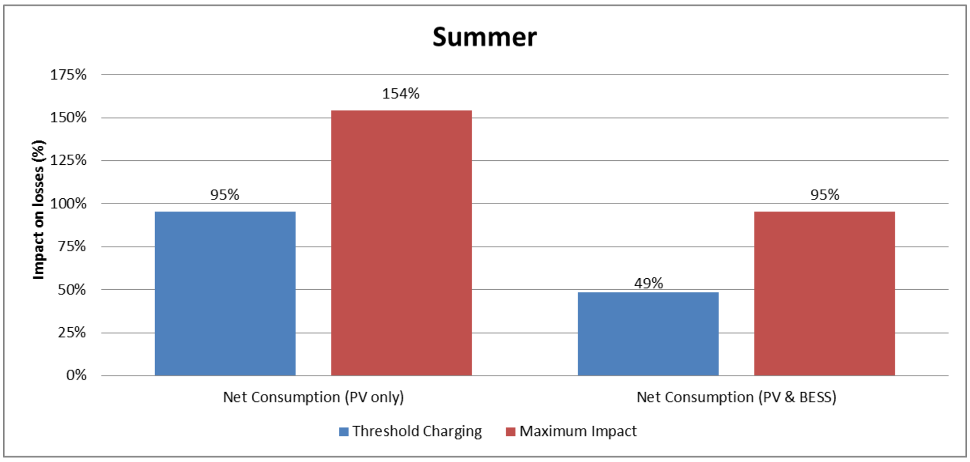

Figure 7: Percentage change of losses compared to consumption only (summer)

Analysing losses on service cables separately for the winter and summer periods gave an insight to the impact of various levels of PV generation and its relationship with losses, the impact of BESS in general as well as the impact of different BESS operating modes and their relationship with generation levels. Combining the losses over the two periods together paints a similar picture. As per Figure 8, since PV generation does not necessarily coincide with consumption, it increases losses. Operating in threshold charging mode, BESS have the potential to reduce the overall service cable losses whereas forcing them to charge/discharge during the maximum impact mode, regardless of generation and demand, increases losses as they increase the net power flows on the service cable by pulling power from and/or pushing power to the grid. Having said this, as discussed in the DS3 project reports[7], despite its potential impact on losses, the maximum impact scheme may reduce overall excess peak generation and demand which potentially may lead to increased network utilisation and the avoidance of network reinforcement.

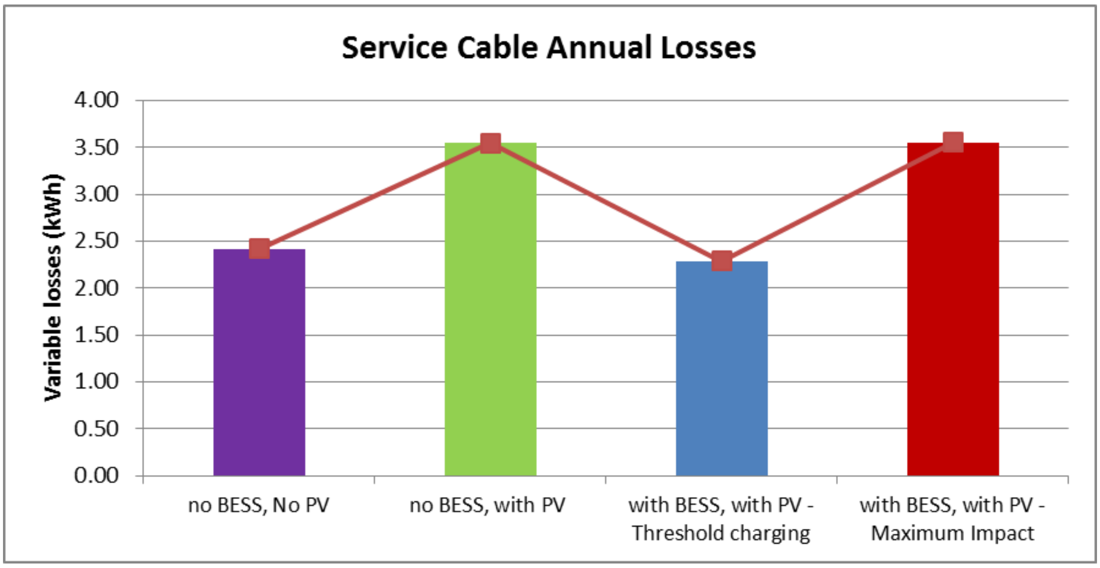

Figure 8: Average annual losses per single phase service cable (per customer)

5.2 LV feeder

As mentioned earlier, losses on the LV feeder were calculated based on half-hourly measured and derived values, using datasets from both the substation and households. This was achieved as follows:

(1) Load with PV and BESS: net measured load at substation*
(2) Load without PV or BESS: (1) – household generation – household BESS
(3) Load with PV but no BESS: (1) + household generation – household BESS

* The net measured load (1) is influenced by the BESS operating mode. Table 1 shows the time periods each operating mode was trialled for. Associating net measured data for each of the operating modes against calculated data allowed to derive losses and quantify the impact of BESS.

As it was mentioned in Section 4.2, the load on each section of the LV feeder was allocated proportionally and losses were calculated by multiplying the current going through each section with the relevant section resistance R indicated in Table 5. Although data availability was generally good (>90%) for more than 90% of the properties during the winter, data in the summer was partial

[7] DS3 Final Report [Accessible at: https://www.northernpowergrid.com/innovation/projects/distributed-storage-solar-study-nia-npg-011]

(sometimes down to 60%). However, the overall impact of BESS on losses was still quantified and observed.

The graphs in Figure 9 to Figure 12 show the measured net load on the feeder (blue) as well as the calculated load the feeder would have experienced if there was neither PV nor BESS (green line) or if there was PV but no BESS (red). All graphs show the clear impact of PV generation and BESS on the overall load profile of the feeder. Finally, Figure 13 shows the average levels of generation experienced on the same feeder during the period each BESS operating mode was trialled for.

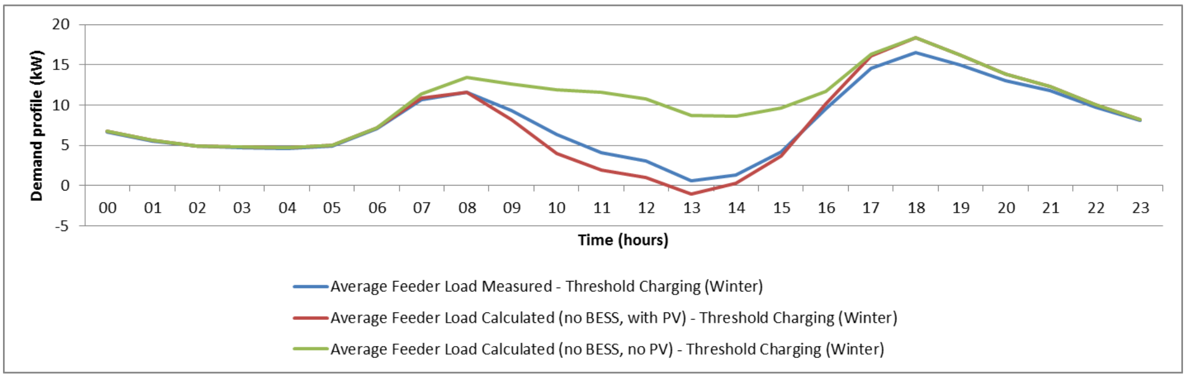

Figure 9: Threshold charging scheme (winter)

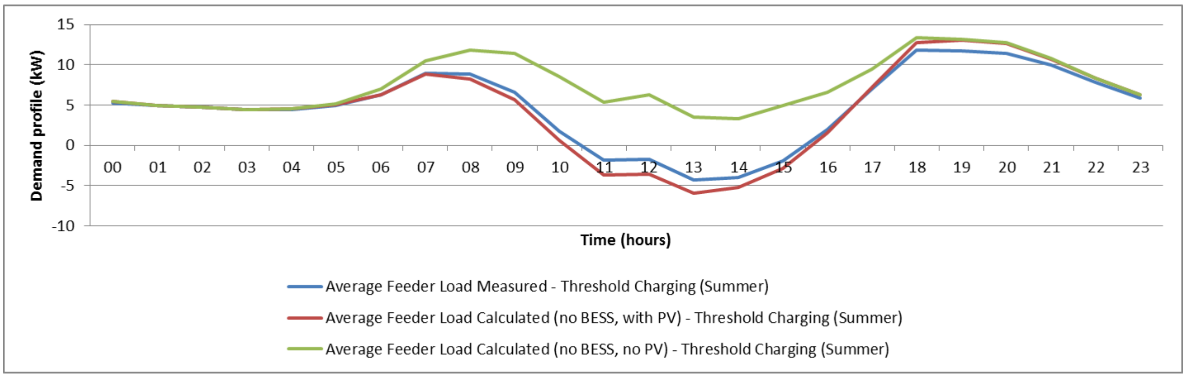

Figure 10: Threshold charging scheme (summer)

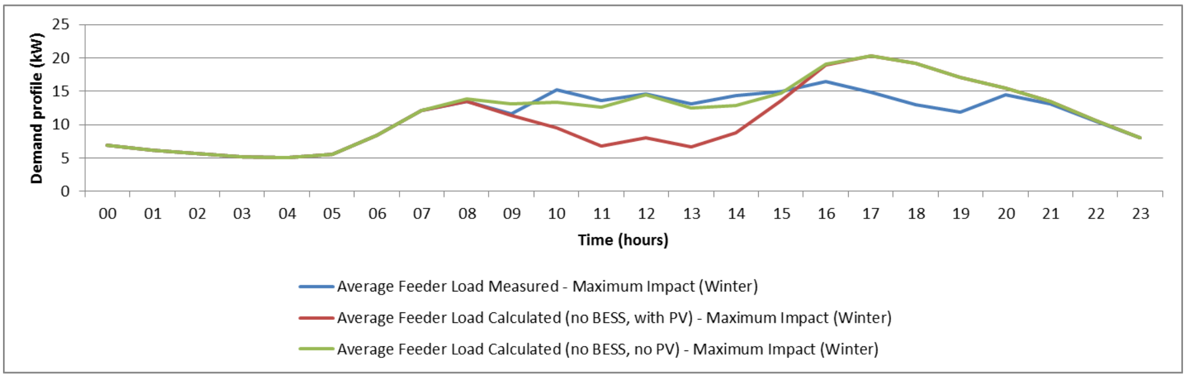

Figure 11: Maximum impact scheme (winter)

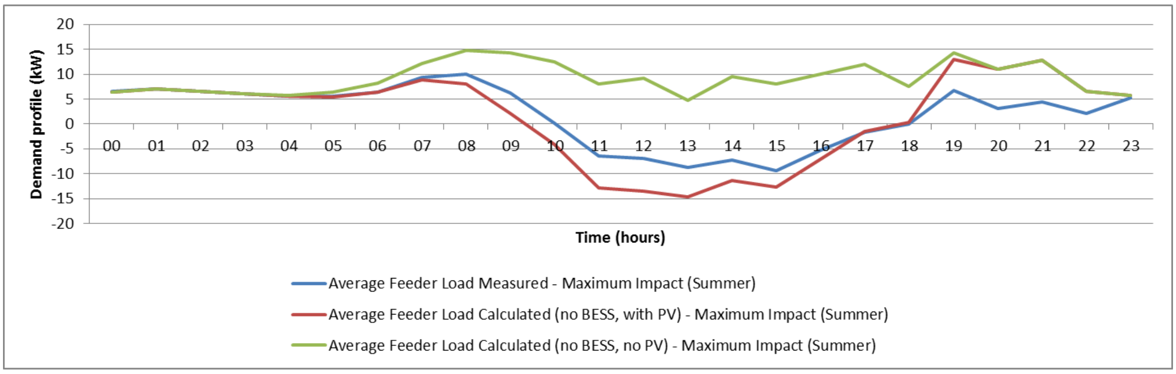

Figure 12: Maximum impact scheme (summer)

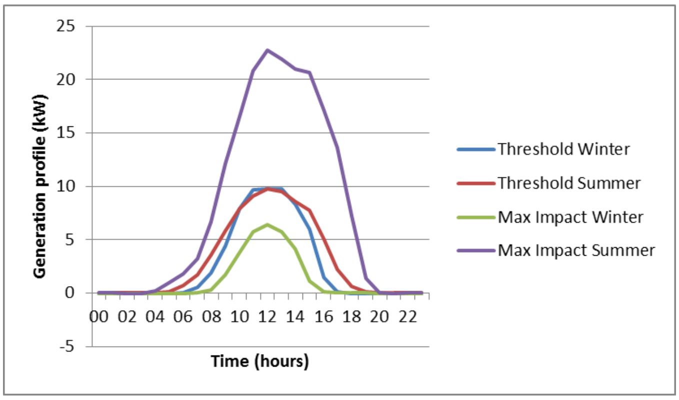

Figure 13: Average levels of generation during each BESS operating mode

Unlike its impact on the service cable, analysis shows that existing levels of PV penetration and hence PV generation on the LV feeder has a positive impact on losses as it reduced them by 37% in the winter (Figure 15) and 35% in the summer (Figure 17). However, as discussed in Section 5.1, the relationship between network losses and PV generation resembles a parabola as the latter does not necessarily coincide with demand. It is therefore anticipated that similar to the impact the increasing levels of PV generation between winter and summer had on losses, had PV penetration been higher, losses would increase.

According to Figure 14, although BESS helped reduce losses even further, the impact the two operating modes had varied. BESS operating in threshold charging mode during the winter helped reduce losses by 53% whereas the maximum impact mode reduced them by 30%. The difference is possibly due to the fact that the BESS were charging and discharging regardless of the levels of generation and demand, potentially causing additional power flows along the cable. Regardless, BESS managed to reduce network losses regardless of their operating mode.

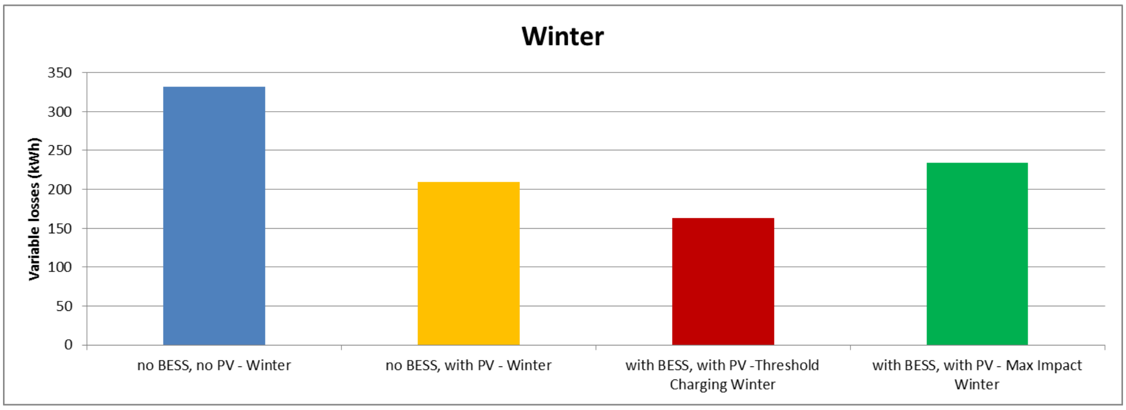

Figure 14: LV feeder cable losses during the winter

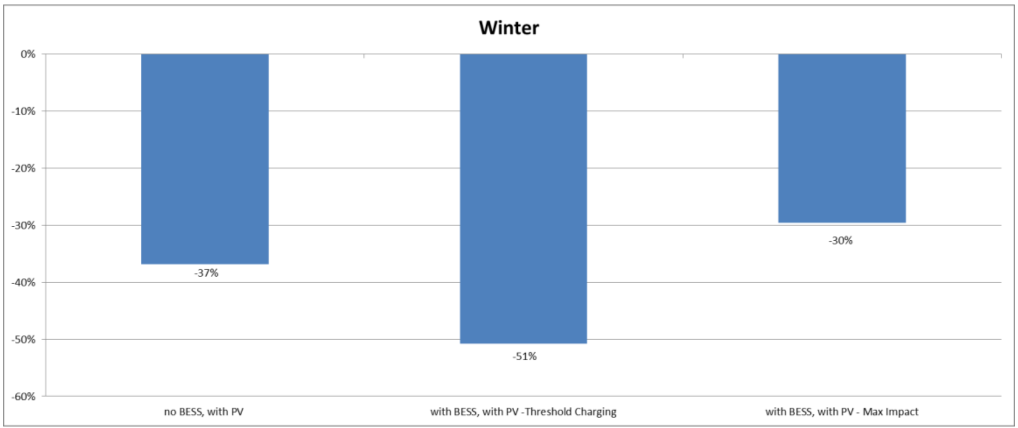

Figure 15: Percentage change of losses compared to consumption only

In the summer, the impact of BESS is somewhat different. Although current levels of PV generation helped reduce losses by an average of 35%, contrary to what it was anticipated, BESS did not have a great impact on losses. Low consumption levels combined with long generation days experienced in the summer suggest that when operating in threshold charging mode, BESS were not able to fully discharge in the evening, ending up being full on the following day. Similarly, when operating in maximum impact mode, BESS were being forced to discharge at the same time that PV generation might have been available, causing additional power flows on the network. Figure 17 shows a reduced impact which is anticipated to be due to the different levels of generation and consumption experienced during the periods the operating modes were trialled, as well as partial data availability at times. Better data availability in the summer may have given a better insight.

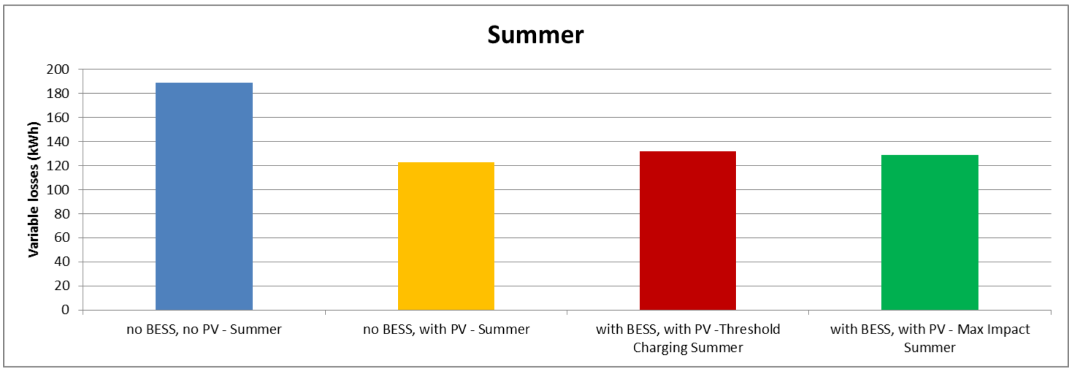

Figure 16: LV feeder cable losses during the summer

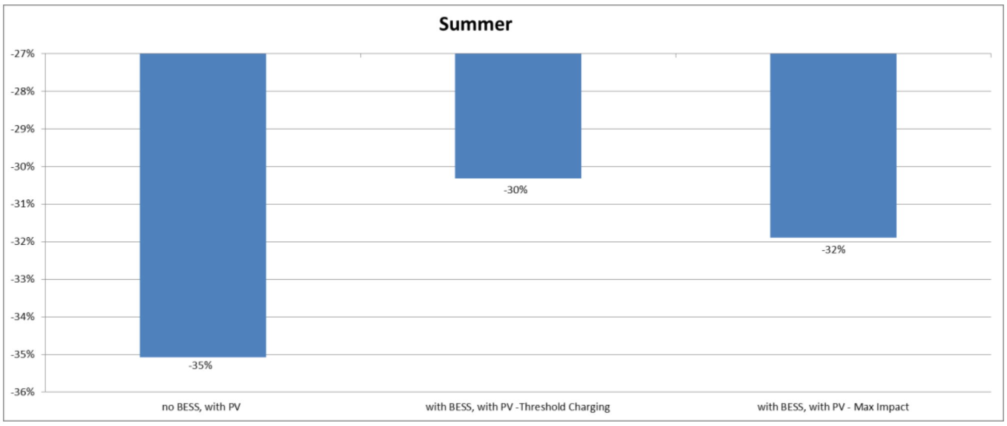

Figure 17: Percentage change of losses compared to consumption and consumption + PV – summer

Finally, Figure 18 shows the combined impact (winter and summer) of PV generation and BESS on the LV feeder. Unlike their impact on service cables, current levels of generation helped reduce overall losses on the LV feeder as they supplied some of the load locally. Operating in threshold charging mode, BESS reduced the overall losses even further whereas forcing them to charge/discharge regardless of generation and demand did not reduce them by the same amount as they caused additional power flows, particularly at periods of low generation or demand (charging the BESS in the winter and discharging it in the summer) or extended periods of generation (discharging the BESS in the summer). Having said this, as mentioned earlier, the maximum impact scheme may reduce overall excess peak generation and demand which potentially may lead to increased network utilisation and the avoidance of network reinforcement.

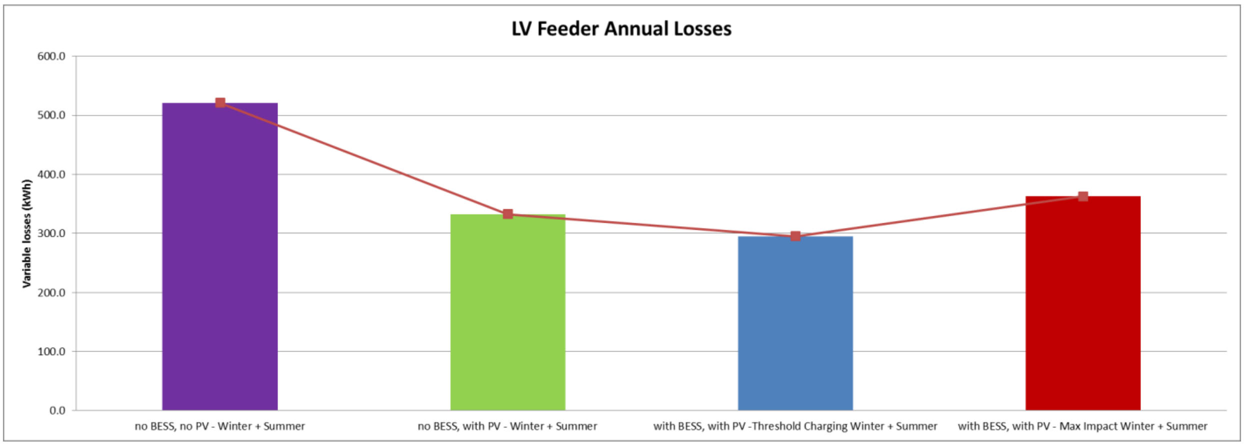

Figure 18: Total LV feeder cable losses per year

6. Conclusion

Analysis of various level of generation suggested that the relationship between network losses and PV generation resembles a parabola. Low levels of generation combined with high levels of consumption, at times experienced in the winter, have the potential to reduce losses. However as generation levels increase and/or consumption reduces, losses increase. On the mains cable, aggregated consumption exceeded generation in both winter and summer, hence PVs reduced losses. On the service cable this only happened during period of low generation levels hence it was observed that on average PV increased losses.

The impact of BESS on the other hand varies depending on season, size and operating mode. When operating in threshold charging mode, BESS have a positive impact on losses (i.e. reduce losses) on both service and mains cables as they absorb excess generation and supply evening demand in both winter and summer. Although the impact is positive, overall losses in the summer are still high due to the low levels of consumption and high levels of PV generation.

The impact of the maximum impact mode on the other hand is somewhat different. Although it also has a positive impact on losses, particularly on main cables, its impact was less than that of the threshold charging mode as forcing the BESS to charge/discharge regardless of generation and demand caused additional power flows, particularly at periods of low generation or demand (charging the BESS in the winter and discharging it in the summer) or extended periods of generation (discharging the BESS in the summer).

Finally, regardless of the impact of PV generation and BESS on losses, which for the former at times may be negative, the wider environmental benefits of both as well as the network benefits of the latter need to be taken into account, particularly as these may outweigh them.