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Solo Energy Ltd.

FlexiGrid

The impact of a storage network on existing and future grid infrastructure using Power Systems analysis software

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Executive Summary

Solo Energy has collaborated with ESB Networks and DNV GL to study the impact of connecting a cluster of behind-the-meter battery units, coupled with rooftop Solar PV generation, at a representative housing development in a representative location on the Irish distribution system. The impact of the installations on the local distribution system in the immediate vicinity of the housing development was assessed.

The network model is based on a real 10 kV and low voltage network supplying a growing town and surrounding rural area. We modelled a new housing development of sixty-eight homes, equipped with air-source heat pumps, of which thirty are fitted with an Energy Storage System incorporating Solar PV and battery storage.

The results of the FlexiGrid analysis indicate the following in relation to the local distribution network given a high penetration of behind the-meter-battery storage installations in a clustered environment:

Peak Demand	**The winter peak demand on the local distribution network is reduced.** **There is a smoothing of the load profile on the distribution substation, MV feeder, distribution transformer and low voltage network.** **The most significant benefits are felt on the distribution transformer and the LV network, with a reduction in the order of 20% on the distribution transformer at the time of peak demand.** **There is increase in capacity for transfer of demand from other feeders on the medium voltage feeder.** **The contribution from the battery storage should be coordinated to avoid the introduction of new peaks at either end of the discharge period.** **Larger scale deployment, together with aggregated and controlled operation, has the potential to significantly reduce the peak demand and smooth the load profile**
Voltage Profile	**The voltage at all points on the MV and LV feeders is increased under the peak demand scenario.** **Larger scale deployment, together with aggregated and controlled operation, has the potential to assist in voltage regulation on the distribution network.**
Network Losses	**The losses on the MV and LV feeders are reduced, enabling more economic operation of existing distribution assets.** **Larger scale deployment, together with aggregated and controlled operation, has the potential to significantly reduce network losses, resulting in reduced network operating costs, and defer the roll out of new distribution infrastructure.**

The FlexiGrid analysis considers a limited number of battery storage units coupled with Solar PV. The analysis indicates that, even with a limited number of installations, there are clear benefits on the local distribution network.

The wider application of distributed battery storage, coupled with Solar PV, on the distribution system, together with the aggregated and controlled operation of these installations, has the potential to

significantly reduce peak loadings, assist in voltage regulation and provide immediate savings in the reduction of network losses, therefore delivering cost savings to the distribution system operator and, ultimately, the consumer.

The project has established a methodology for modelling the impact of renewable technologies on the distribution network and this approach can be used for the evaluation of larger scale deployment. Information gathered after construction of the development considered in the FlexiGrid study is completed can be used to refine the model, study the actual operating regime of the installed renewable technology and validate the findings of this report.

In addition, Solo Energy intends to roll out its first physical pilot project, 'eStore', in Ireland in 2017. The eStore project will demonstrate the operation of Solo's proposed distributed battery storage network at domestic and small commercial level. The operation of such a network will be the first of its kind for Ireland. eStore will incorporate the installation of behind-the-meter battery storage devices, in some instances together with solar PV, at several locations with different customer types. With FlexiGrid as a basis, this presents a unique opportunity to compare the results of power flow analysis of the eStore pilot project to real world monitoring data.

1 Introduction

1.1 Project description

Solo Energy has collaborated with ESB Networks (ESBN) and DNV GL to carry out a system study of the impact of connecting a cluster of behind-the-meter battery units coupled with rooftop Solar PV generation on a representative housing development in a representative location on the Irish distribution system. Synergi Electric, a DNV GL product, was used as the network analysis tool.

Solo's 100% renewable energy supply business model centres on the deployment of distributed behind-the-meter energy storage on the distribution network. This distributed energy storage network will be aggregated, controlled and operated as a Virtual Power Plant(s) (VPP), shifting energy supply from periods of peak demand and peak wholesale energy price, to periods of peak renewable generation and low wholesale energy price. Furthermore, the VPP operation will facilitate the provision of ancillary services to system operators. The FlexiGrid study is more limited in focus, assessing the impact of a limited number of such installations on the local distribution system in the immediate vicinity of the housing development; the aggregated VPP operation is not considered.

It was expected that there would be important lessons on the operation of the distributed generation systems and the benefits and restrictions that will apply. The project also provides a modelling method that can be extended to obtain indications of the maximum capacity of individual renewable technologies and combinations of renewable technologies that could be absorbed on Low Voltage (LV) and Medium Voltage (MV) networks.

This study concentrated on the following components of the ESBN network: -

- The LV network and the MV/LV distribution transformers supplying the new housing estate and any existing customers
- The MV (10 kV) network and any distribution transformer connection points on the feeders
- The MV (38 kV/10 kV) transformers at the primary substation

1.2 Funding

The project has achieved grant funding from the Sustainable Energy Authority of Ireland (SEAI) as part of the Sustainable Energy Research, Development and Demonstration Programme (RD&D) 2016.

1.3 Objectives

The objective of the impact study is to provide an improved understanding of the effects, on the local ESBN distribution system, of domestic properties being equipped with an Energy Storage System (ESS) incorporating Solar PV microgeneration and a coupled battery storage system. The project studies: -

- the impact of the demand of a new build housing estate equipped with air source heat pumps (sixty-eight houses)
- the further impact of equipping thirty houses with ESS on a representative semi-rural ESBN network

1.4 Deliverables

The deliverables of the project are detailed in *SEAI Energy Research, Development and Demonstration Programme 2016, RDD00101 2nd Amendment to Grant Agreement, 14th October 2016* and summarised below:

- Produce a desensitised report of the FlexiGrid research project, demonstrating how each and every consumer can play a critical role in the advancement of the Irish grid system, leading the transition from a nation of passive consumers to active prosumers
- Make the report available to industry and "disseminate at selected energy sector conferences"
- Assist in the development of a "roadmap for active citizen participation, the advancement of smart metering technologies and an altogether greener system".

1.5 Scope

The scope of the analysis is divided into the following parts:

1. Develop a network model, based on real network data, of a representative semi-rural distribution system in Synergi software
    - Review MV model supplied by ESBN
    - Augment model with MV/LV transformers and LV network
    - Apply load and generation profiles to model
2. Perform time stamped batch power flow analysis: MV and LV network power flows for the following cases:
    - Existing network
    - Network incorporating new housing load with no ESS
    - Network incorporating new housing load with ESS

FIGURE 1 RENEWABLE TECHNOLOGIES CONSIDERED IN FLEXIGRID STUDY

2 New Housing

We modelled a new housing development of sixty-eight homes, equipped with air-source heat pumps, of which thirty are fitted with an Energy Storage System incorporating Solar PV and battery storage. The household demand is based on available industry data. The Solar PV and battery storage equipment is modelled as per supplier datasheets.

The study modelled the new demand expected from a new housing development of sixty-eight houses all being fitted with air-source heat pumps for space and water heating. In a pilot project thirty of these houses will be equipped with the ESS incorporating Solar PV microgeneration and a coupled battery storage system.

FIGURE 2 – SITE LAYOUT USED FOR THE FLEXIGRID DEVELOPMENT

2.1 Electricity Demand

To model the demand of the houses we have used the household electricity profile from the UK Department of Energy & Climate Change (DECC) study, '*Further Analysis of Data from the Household Electricity Usage Study: Correlation of Consumption with Low Carbon Technologies* [1] *(CCLCT Study)'*. In Section 6.1 of this paper the study provides average daily load curves for a household with a heat pump for February and for August.

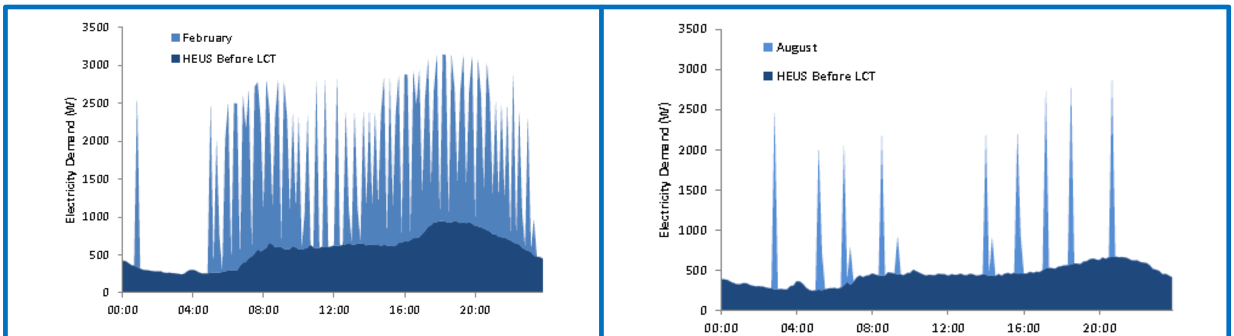


Figure 23: Average diurnal electricity demand of a representative heat pump profile for February, overlaid on the average HEUS household profile (with any displaced primary electric heating removed) for an average day in February.

Figure 24: Average diurnal electricity demand of a representative heat pump profile for August, overlaid on the average HEUS household profile (with any displaced primary electric heating removed) for an average day in August.

FIGURE 3 – AVERAGE DEMAND PROFILES FOR PROPERTIES WITH HEAT PUMPS FROM THE LOW CARBON TECHNOLOGIES CCLCT HOUSEHOLD ELECTRICITY USAGE STUDY

The profiles are based on a population of two-hundred and fifty properties which is greater than the sixty-eight properties in the FlexiGrid development. We have allowed a correction factor to the load profiles to reflect the expected higher average peak which is a result of a lower diversity or increased coincidence of the electricity demand. Further discussion on the actual profiles used in the FlexiGrid study is provided in Section 8.

2.2 Heat Pump

All sixty-eight properties are to be equipped with an air-to-water heat pump to provide an under-floor heating system and a hot water storage system. We have been provided with details of the Samsung air-source heat pumps that will be deployed at the housing development. The units are available with heat outputs of 5, 9 and 12 kW. For the FlexiGrid study we are using the 9 kW unit which requires a power input of 2.14 kW per property.

2.3 Solar PV

The Solar PV equipment is to be installed in the thirty properties along with the battery storage systems. This study has used the technical data for the Solarworld Sunmodule Plus SW290 as the reference model for the network analysis. A single panel has a maximum power output of 290 W at an irradiation level of 1000 W/m^2. We have modelled eight panels for each installation and the key technical data for the renewable generation model for each property is shown in Table 1.

TABLE 1 – SOLAR PV TECHNICAL DATA

	Value	Unit
Max power (single unit)[1]	290	W
No. of units per installation	8	-
Total power	2.32	kW

1. Performance values based on Standard Test Conditions (STC): 1000 W/m2, 25oC, A.M 1.5

The Solar PV panels generate electricity as a direct current (dc) and to interface with the 50 Hz alternating current (ac) system the panels are connected to an inverter to convert the dc current to ac current. We have used the SMA Solar Technology Sunnyboy 2.5 as the technical model for the network analysis. The key technical data for the inverter is shown in Table 2.

TABLE 2 – SOLAR PV INVERTER TECHNICAL DATA

	Value	Unit
Rated power	2.65	kW
Nominal AC voltage	230	V
Frequency	50	Hz
Rated power factor	100%	-
Power factor range	+80% (lagging) -80% (leading)	-
Power factor setting for studies[1]	+95% (lagging)	-
Max efficiency	97.2%	-
European weighted efficiency[2]	96.7	%

1. Power factor selected matches feeder load power factor used in ESB planning studies
2. Value to be applied to FlexiGrid study is the European weighted efficiency

2.4 Battery Storage System

The battery storage equipment is to be installed in the thirty properties along with the Solar PV systems. This study has used the technical data for the Tesla Powerwall 2 AC as the reference model for the network analysis. The key technical data for the battery inverter is shown in Table 3.

TABLE 3 – TESLA POWERWALL 2 TECHNICAL DATA

	Value	Unit
AC Energy	13.2	kWh
Max continuous output[1]	5	kW
Max peak output	7	kW
Nominal AC voltage	230	V
Frequency	50	Hz
Rated power factor	100%	-
Power factor range	+85% (lagging) -85% (leading)	-
Power factor setting for studies[2]	+95%	-
Round trip efficiency	89%	-
Charging efficiency (assumed)[3]	94.3%	-
Discharging efficiency (assumed)[3]	94.3%	-
Maximum discharge level	0%	

1. Battery continuous rating set to 5 kW. Output restrictions to be applied as charge/discharge rates (73.6%)
2. Power factor selected matches feeder load power factor used in ESB planning studies
3. Assumed charging and discharging efficiencies are equal in value

3 Renewable Energy and Non-Dispatchable Generation

Aggregated behind-the-meter energy storage can turn sources of non-dispatchable renewable generation into controllable assets.

Energy storage is currently classified as microgeneration in Ireland and a new asset class is required to facilitate the development of appropriate policies.

Solo's VPP platform can turn non-dispatchable renewable generation into a source of fully controllable, dispatchable asset. However, significant regulatory and policy change will be required to facilitate this. In particular, the following will need to be addressed: -

- rules and regulation will need revision
- rules for contingency (e.g. percentage of output, capacity or number of available units used for the evaluation of firm capacity)
- availability of output power would need to be part of a commercial agreement
- availability targets, power outputs and time of operation would need guarantees

The comments made in this report are limited to technical matters only, and are made to facilitate a discussion on current policy and decisions related to distribution assets and renewable technology.

4 Impact on the System Peak and Minimum Load Conditions

The Energy Storage Systems reduce the peak demand and assist in smoothing the load profile on the distribution substation, MV feeder, distribution transformer and LV network.

-

The most significant benefits are felt at the distribution transformer and the LV network, with a 31.6% reduction in peak demand on the distribution transformer in the FlexiGrid case.

-

Wider scale ESS deployment, together with aggregated and controlled operation as a VPP, has the potential to significantly reduce the peak demand, smooth the load profile and thereby facilitate the utilisation of distribution feeders and transformers of lower rating

4.1 Basis for System Peak and Minimum Load Studies

To assess the impact of the new demand and the ESS systems we looked at network operation for conditions that are consistent with the days used for the system loading values published by ESB. For the following system loading conditions: -

1. Peak demand on the ESB winter maximum load reading day in December 2015 (17:00 pm)
2. Midday demand on the minimum load reading day to coincide with maximum contribution from the Solar PV (12:00pm)

The impact of the demand and ESS systems was analysed at three levels: -

- At the primary substation
- On the existing MV feeder that will host the FlexiGrid development
- On the proposed local distribution substation that will supply the FlexiGrid development

4.2 Impact on the primary substation

4.2.1 Substation Capacity

The primary substation is equipped with two 38 kV/10 kV transformers which have a continuous rating of 5 MVA giving a total continuous capacity of 10 MVA at the substation. This limitation is designed to keep the temperature hot spot within the winding of the transformer within the design limits.

The system security standards for a demand of this size requires that the utility maintain customer supplies in the event of an equipment failure. In this case the failure of one of the primary substation transformers would be one of the most severe outages considered when considering the maximum demand that can be supplied by the substation.

Primary transformers very rarely have a demand applied that continues at the same level. In emergency conditions, like a failure of one of the transformers, it is normal practice to allow the transformers to operate above the continuous rating where the cyclical nature of demand allows the winding to cool between the peaks of demand. In this instance ESB, for network planning purposes, use an emergency rating of 150% of the continuous rating or 7.5 MVA (Source: ESB Synergi Electric network model equipment warehouse). The maximum demand that can be supplied by the primary substation is normally calculated using the following algorithm: -

$$Maximum\ substation\ demand = Emergency\ rating\ of\ transformer + Transfer\ Capacity\ to\ other\ Substations$$

In the FlexiGrid study we have not included the capacity of any interconnection to any other adjacent substations in our considerations.

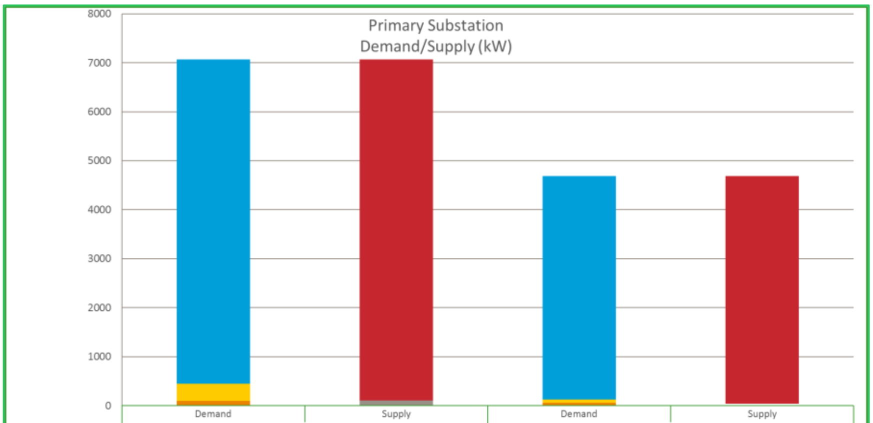
4.2.2 Demand and Supply Capacity

Using the network model, we carried out a power flow analysis using the feeder circuit demands for the winter peak load reading day in December 2015 at 18:00pm. The total demand from all the feeder circuits was 7.19 MVA.

We added the new low voltage network to the model and the associated demand for the sixty-eight new houses. This increased the demand on the substation to 7.58 MVA, which exceeds the 7.5 MVA emergency rating. This equates to a 391 kVA (5.4%) increase in demand. This is based on an average peak demand from a new house of 5 kW at 93% power factor using the profiles in the CCLCT study corrected for a lower population of properties. General load is assumed to have a power factor of 95% and the heat pump a power factor of 90%; this results in the overall power factor of 93%.

We then included the ESS systems in the low voltage network and this reduced the demand at the primary substation to 7.46 MVA which is a reduction of 124 kVA (1.6%) of the peak demand with the new development. This contribution to the demand from the ESS systems at the time of the peak is limited to the battery storage systems as the peak occurs outside daylight hours which eliminates any support from the solar PV units. The impact of the ESS systems on the substation is relatively small at this level of the network however the contribution does maintain the demand within the emergency rating for the substation by 0.4 MVA (8%).

The winter peak kW demand for the substation including the kW demand from the FlexiGrid development and network losses is shown in the left column in Figure 4 alongside the supply including the contribution from the 38 kV network via the primary substation and the ESS systems.



	Winter Max Demand	Winter Max Supply	Summer Min Demand	Summer Min Supply
Existing MV Network	6622.0		4567.4	
New Housing	351.3		62.1	
Network Losses	98.1		62.3	
From Primary SS		6962.2		4656.1
Battery		109.3		
Solar				36.1

FIGURE 4 – WINTER MAXIMUM AND SUMMER MINIMUM POWER DEMAND (KW) AT THE PRIMARY SUBSTATION

The process used for the winter study was repeated for the summer minimum conditions. In this instance, before application of the demand for the FlexiGrid housing, the primary substation is supplying 4.93 MVA.

Adding the new low voltage network to the model and the associated demand for the sixty-eight new houses increased the demand on the substation to 5 MVA which equates to a 68 kVA (1.4%) increase in demand. This is based on an average peak demand for one of the new houses of 0.9 kW at 95% power factor using the profiles in the CCLCT study corrected for a lower population of properties.

We then included the ESS systems in the low voltage network and this reduced the demand at the primary substation to 4.96 MVA which is a reduction of 39 kVA (0.8%) of the peak demand with the new development. This contribution to the demand from the ESS systems at the time of the summer minimum is limited to the solar PV units as the peak occurs during the peak irradiation period and we have assumed that there is not any support from the battery storage systems.

The impact of the ESS systems on the substation is relatively small at this level of the network however the contribution does maintain the demand marginally within the continuous rating for a single primary transformer by 0.04 MVA (0.08%).

The summer minimum kW demand for the substation including the kW demand from the FlexiGrid development and network losses is shown in the right column in Figure 4 alongside the supply including the contribution from the 38 kV network via the primary substation and the ESS systems.

4.2.3 Diurnal demand profile

For the winter maximum conditions, the impact on the primary substation of the electricity demand from the FlexiGrid development and the effect of the ESS systems is illustrated in Figure 5. The charging/discharging of the ESS battery systems fills the night time valley and reduces the early evening peak. The extent of the smoothing of the profile is modest in line with the scale of the contribution in relation to the total demand on the primary substation. This smoothed profile with a reduced peak demand provides a reduction in copper losses in the primary transformers.

Wider application of ESS systems throughout the MV feeders supplied by the primary substation could provide a greater impact on the peak and fill the trough however as this increases there is a greater need to consider demand response services to avoid over compensation and replacing the existing peaks and troughs with new peaks and troughs at other times in the daily cycle. In addition, the introduction of other technologies such as wind generation, commercial Solar PV and Electric Vehicles would provide additional potential conflicts that would need to be influenced to avoid creating bottlenecks.

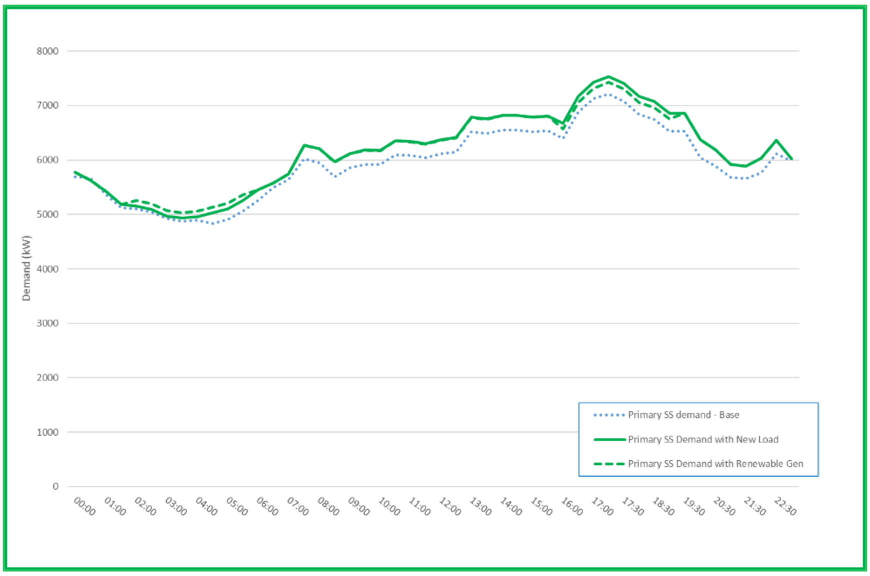


FIGURE 5 – WINTER DIURNAL DEMAND PROFILE AT THE PRIMARY SUBSTATION

The summer diurnal curve in Figure 6 illustrates the impact of the ESS Solar PV generation on the midday demand which during this period is similar in value to the evening peak. For this study the operating regime for the ESS battery storage (night time charge and early evening discharge) is consistent with the regime used in the winter.

In the summer period, there is increased opportunity to consider coordinating the outputs of the Solar PV, the charge/discharge regime for the battery system and the operation of the heat pumps to provide better smoothing of the diurnal demand curve.

This has the potential to increase the period that planned maintenance of the primary substation can be carried out without exceeding the continuous rating. On a wider scale, ESS systems working with other renewable technologies could help to smooth the demand profile on the transmission systems and provide economic benefits for generation dispatch and maintenance.

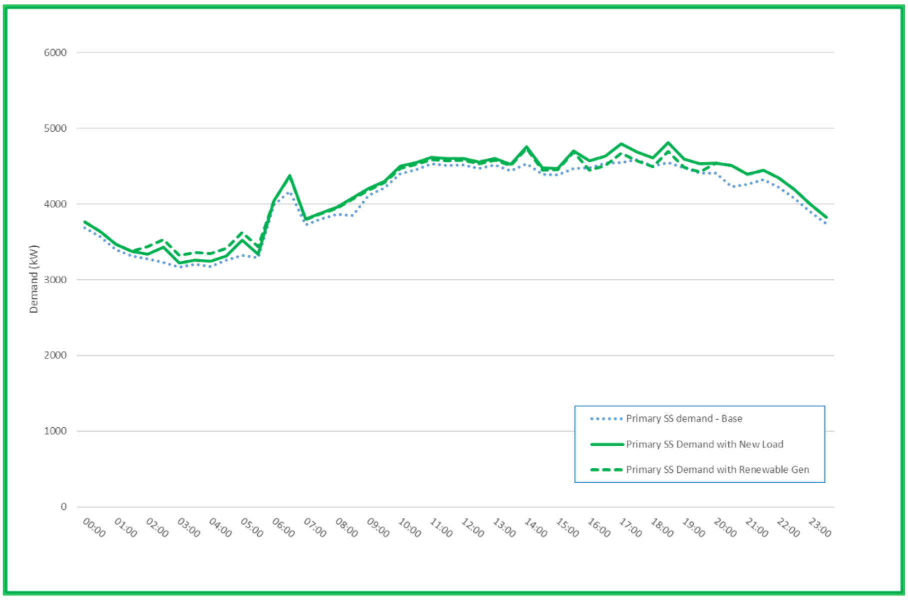


FIGURE 6 – SUMMER DIURNAL DEMAND PROFILE AT THE PRIMARY SUBSTATION

4.3 Impact on the Medium Voltage (MV) Feeder Circuit

4.3.1 Feeder Capacity

The MV Feeder Circuit is controlled by a 630-amp (11.4 MVA) circuit breaker. The feeder circuit supplies underground cables and overhead lines and leaves the substation as an underground cable with a rated winter current of 532 amps (9.65 MVA). The circuit gradually tapers to smaller conductor size underground cables and overhead lines as the demand supplies reduces. This is a conventional approach to MV networks designed to feed electricity from the main source the primary substation.

4.3.2 Demand and Supply Capacity

The power flow analysis using the feeder circuit demands for the winter peak load reading day in December 2015 at 18:00pm calculated that the total demand for the feeder circuits was 2.34 MVA.

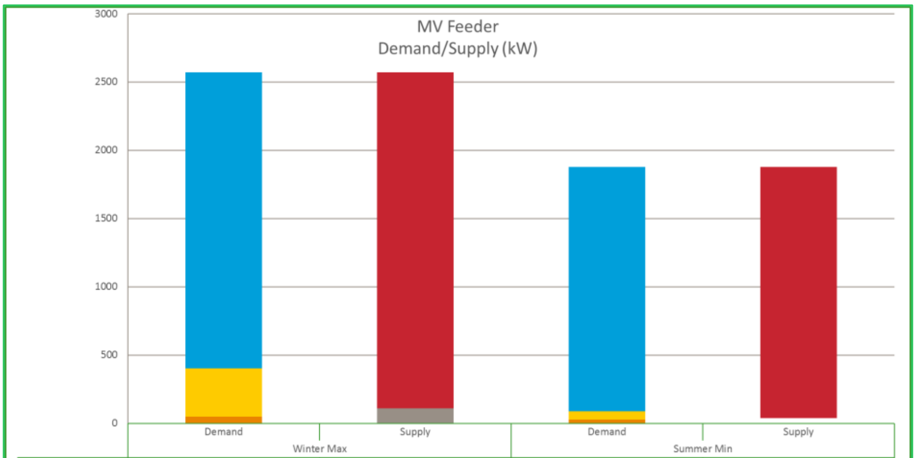
Adding the new low voltage network to the model and the associated demand for the sixty-eight new houses increased the demand on the substation to 2.71 MVA which equates to a 379 kVA (16.2%) increase in demand.

Note: The increase in the feeder demand is slightly lower than the increase on the primary substation demand. This is expected because the network losses associated with the substation and the primary transformers are not incurred on the MV feeder.

We then included the ESS systems in the low voltage network and this reduced the demand at the primary substation to 2.59 MVA which is a reduction of 120 kVA (4.4%) of the peak demand with the new development.

The impact of the ESS systems on the substation is more significant at this level of the network, however the winter peak loads are well within the capacity of the feeder circuit breaker and the underground cables and overhead lines in the circuit. All underground cables and overhead lines operate at a peak demand which is less than 50% of their continuous rating.

The winter peak kW demand for the MV feeder including the kW demand from the FlexiGrid development and network losses is shown in the left column in Figure 7 alongside the supply including the contribution from the 38 kV network via the primary substation and the ESS systems.



	Winter Max Demand	Winter Max Supply	Summer Min Demand	Summer Min Supply
Existing MV Network	2171.7		1788.9	
New Housing	351.3		62.1	
Network Losses	49.0		27.0	
From Primary SS		2462.0		1843.0
Battery		109.0		
Solar				36.0

FIGURE 7 – WINTER MAXIMUM AND SUMMER MINIMUM POWER DEMAND (KW) ON THE MV FEEDER

The study for summer minimum conditions, before application of the demand for the FlexiGrid housing, calculated the demand on the MV feeder as 1.91 MVA.

Adding the new low voltage network to the model and the associated demand for the sixty-eight new houses increased the demand on the substation to 1.98 MVA which equates to a 67 kVA (3.5%) increase in demand. This is based on an average peak demand from a new house of 0.9 kW at 95% power factor.

Including the ESS systems in the low voltage network reduced the demand at the primary substation to 1.94 MVA which is a reduction of 39 kVA (2.0%) of the peak demand with the new development. As previously stated the contribution to the demand from the ESS systems is limited to the solar PV units.

The impact of the ESS systems on the feeder circuit in summer conditions is relatively small and there is no significant relief to the MV underground cables and overhead lines in the feeder.

The summer minimum kW demand for the MV feeder including the kW demand from the FlexiGrid development and network losses is shown in the right column in Figure 7 alongside the supply including the contribution from the 38 kV network via the primary substation and the ESS systems.

4.3.3 Diurnal Demand Profile

For the winter maximum conditions, the impact on the MV Feeder Circuit of the electricity demand from the FlexiGrid development and the effect of the ESS systems is similar to the impact on the primary substation and this is illustrated in Figure 8. The charging/discharging of the ESS battery systems fills the night time valley and reduces the early evening peak. The extent of the smoothing of the profile is higher as the scale of the contribution in relation to the total demand on the MV feeder is greater than that for the primary substation.

The main benefits of the ESS on the feeder is a modest increased capacity for transfer of demand from other feeders if additional transfer capacity is required (110 kW at peak) and reduction in network losses.

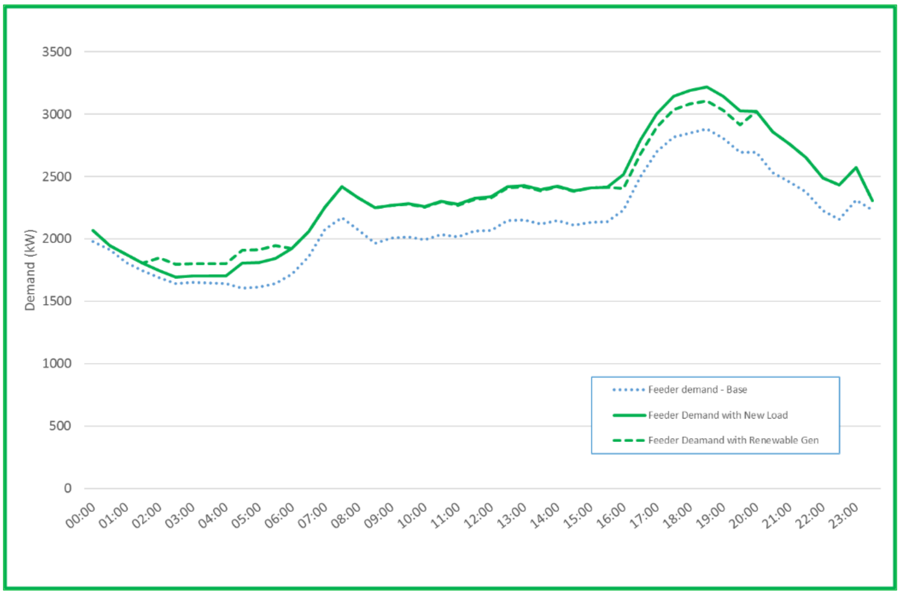


FIGURE 8 – WINTER DIURNAL DEMAND PROFILE AT THE MV FEEDER CIRCUIT

The summer diurnal curve in Figure 9 again illustrates the impact of the ESS Solar PV generation on the midday demand which during this period is slightly lower in value to the evening peak. In the summer period, the opportunity to consider coordinating the outputs of the Solar PV, the charge/discharge regime for the battery system and the operation of the heat pumps to provide better smoothing of the diurnal demand curve also applies. This has the potential to increase the capacity for transfer further and further reduce network losses.

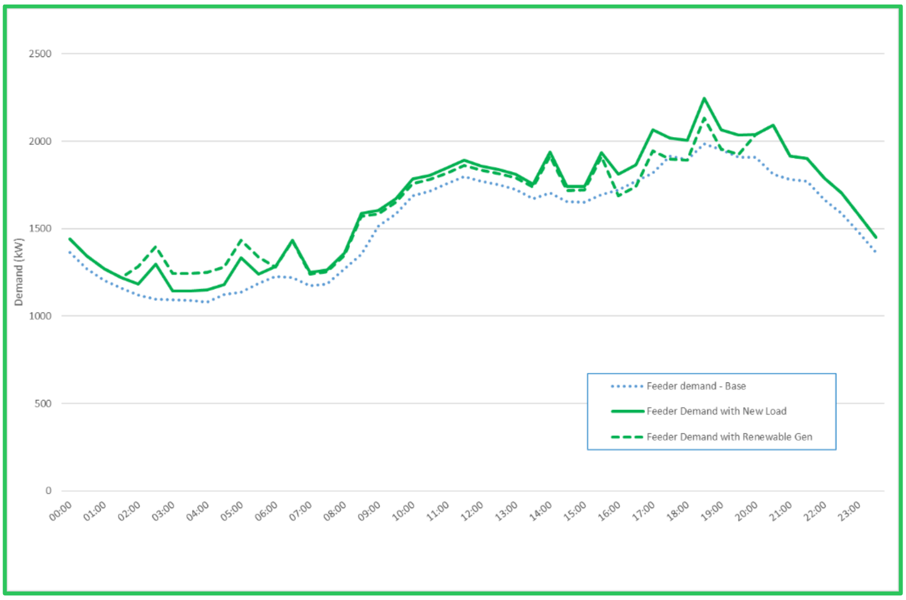


FIGURE 9 – SUMMER DIURNAL DEMAND PROFILE AT THE MV FEEDER CIRCUIT

4.4 Impact on the distribution transformer and Low Voltage (LV) Network

4.4.1 Transformer Capacity

The distribution transformer selected to supply the LV network has a continuous rating of 630 kVA. Like the primary transformers this limitation is designed to keep the temperature hot spot within the winding of the transformer within the design limits. A 10% overload capacity is allowed for a cyclical demand if this occurs only on a small number of days. This increases the capacity to 693 kVA if these conditions are met. In this instance ESB for network planning purposes use an emergency rating of 110% of the continuous rating or 693 kVA (Source: ESB Synergi Electric network model equipment warehouse).

4.4.2 Demand and Supply Capacity - distribution transformer

The power flow analysis using the demand profiles from the CCLCT study corrected for the smaller group of customers calculated the total demand for the transformer as 373.8 kVA.

Including the ESS systems in the low voltage network reduced the demand for the transformer to 255.8 kVA which is a reduction of 118 kVA (31.6%) of the peak demand for the new development. There are some potential implications for the selection of the distribution transformer size. We originally chose a 630 kVA rated transformer as the demand for the FlexiGrid development is close to the rated value of the next size down (400 kVA) and there would be no room for additional load (e.g. electric vehicles or additional housing). To examine if the impact of the ESS systems would support selection of a lower rating for the transformer we need to examine how the demand and ESS systems work together over a normal day. This is explored further in Section 4.4.4.

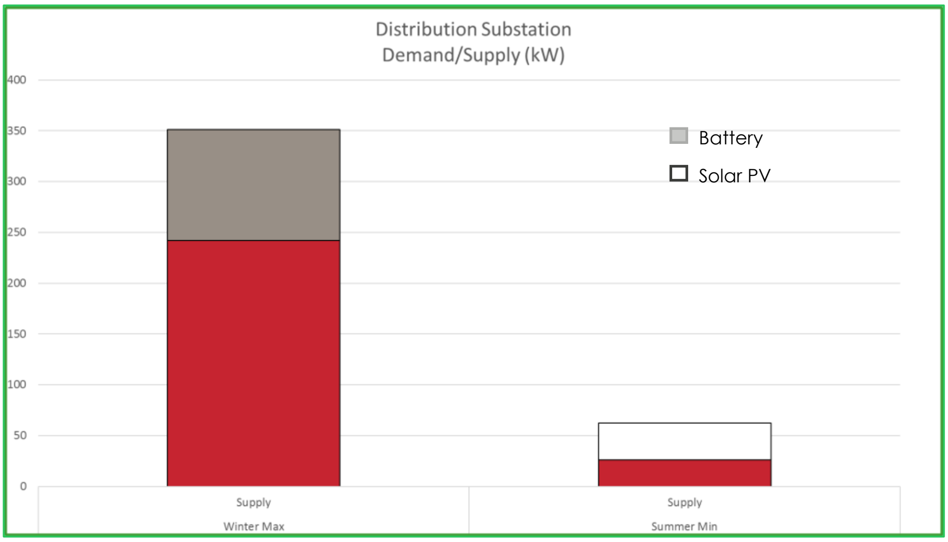


FIGURE 10 – WINTER MAXIMUM AND SUMMER MINIMUM POWER DEMAND (KW) ON THE DISTRIBUTION SUBSTATION

4.4.3 Demand and Supply Capacity – LV Cables

ESB have a single standard cable size for LV networks using a 185 mm^2 cross sectional area conductor. The number of LV feeders selected to supply all sixty-eight properties was six.

Table 4 shows the winter maximum demand on the LV underground cable feeders. ESBN advised that the economic loading of LV cables is in the order of 30%, i.e. 70 to 80 kVA.

TABLE 4 – WINTER MAXIMUM DEMANDS ON THE LV UNDERGROUND CABLE FEEDERS

LV Feeder	Rating (KVA)	Demand (kVA)	Net Demand with ESS (kVA)	% Contribution from ESS
01	246.64	52.81	29.41	44.3%
02	246.64	87.60	64.20	26.7%
03	246.64	60.08	37.00	38.4%
04	246.64	59.14	46.49	21.4%
05	246.64	47.43	24.35	48.7%
06	246.64	63.25	51.55	18.5%

4.4.4 Diurnal Demand Profile

For the winter maximum conditions, the impact on the distribution substation of the electricity demand from the FlexiGrid development and the effect of the ESS systems is greater than their impact on the primary substation and the MV feeder. This is illustrated in Figure 11.

The charging of the ESS battery systems fills the night time valley but creates a new peak when the heat pumps commence the early morning heat cycle. In the study the battery charge start time is set to 01:00am and the charging rate is set to 3.65 kW which is 73% of the rated charging capacity. We have also assumed that the batteries fully discharge during the evening peak period. Ideally the charging regime should not coincide with the early morning heat pump pick up load. This can be achieved if the customers are encouraged to schedule the heat pump and battery charging periods to avoid any coincidence or alternatively if the control of the heat pump and battery system are integrated and programmed to avoid coincident operation.

The discharging of the ESS battery systems creates a valley in the traditional peak period and includes a steep decrease in demand when the discharge period starts and a steep increase when the discharge period ends.

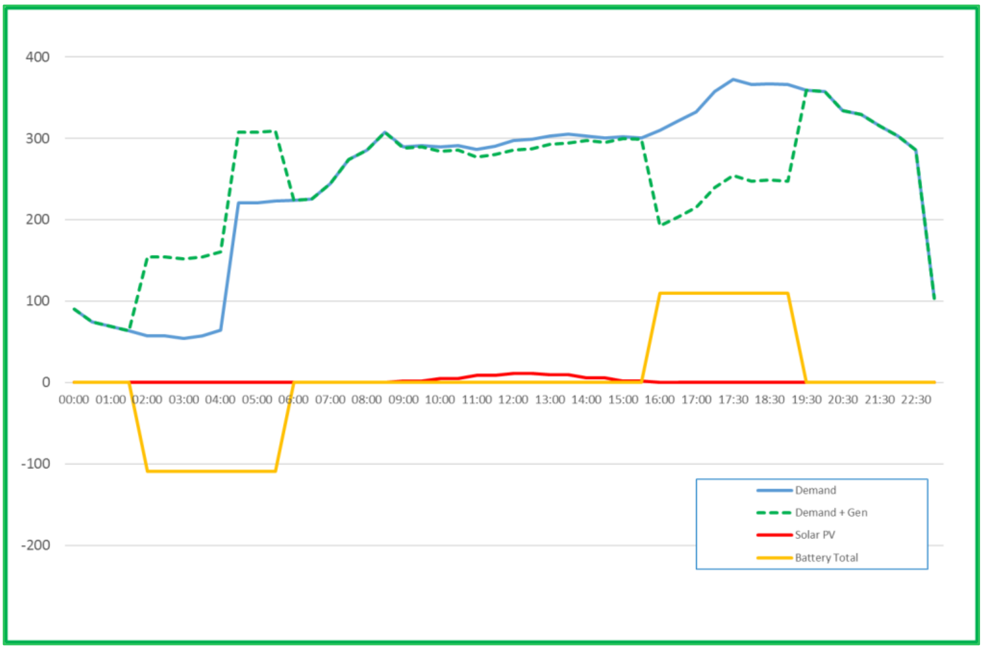


FIGURE 11 – WINTER DIURNAL DEMAND PROFILE AT THE DISTRIBUTION SUBSTATION

The summer diurnal curve in Figure 12 again illustrates the impact of the ESS Solar PV generation on the midday demand is slightly lower in value to the evening peak. Also, the evening peak occurs later between 20:00 and 22:00. The case for extending the period of discharge for the ESS battery systems is stronger and there is also potential to extend the discharge period into the daytime shoulder (08:00am to 16:00pm).

In the summer period, the opportunity to consider coordinating the outputs of the Solar PV, the charge/discharge regime for the battery system and the operation of the heat pumps to provide better smoothing of the diurnal demand curve also applies. Coordination of the heat pump water heating cycle with a discharge from the ESS battery system would smooth out the spikes in the profile. This would avoid: -

- short bursts of higher network losses in the LV and MV circuits and resistive losses in the distribution transformer
- voltage fluctuations (only in the case where such voltage fluctuations are outside limits as any attempt to exceed standard requirements is uneconomic)

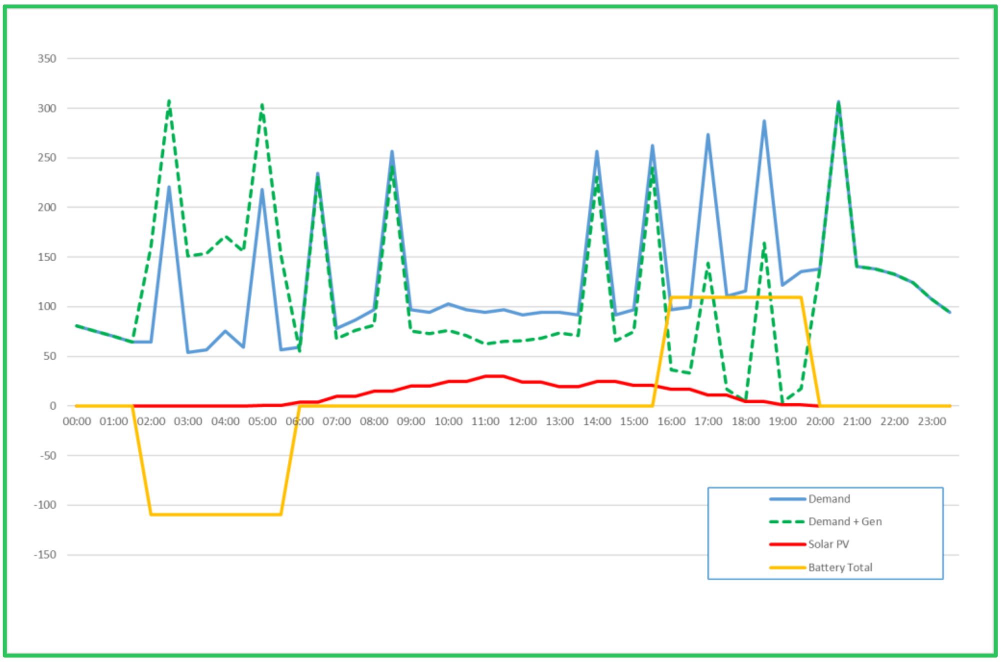


FIGURE 12 – SUMMER DIURNAL DEMAND PROFILE AT THE DISTRIBUTION SUBSTATION

4.4.5 Options for improved impact on the distribution transformer and LV Network

A better profile could be achieved if the total discharge from the group of properties is controlled and takes place over a longer period (say 16:00 – 21:00) and at a lower total output value. This can be achieved by

- reducing the discharge rate of each individual ESS battery storage system
- staggering the output periods for the installations
- aggregated management and operation of the ESS battery systems as a VPP

Adopting this approach should be carefully considered to make sure that the benefits gained at the distribution substation do not countermand any benefits that accrue at the primary substation and the MV feeder level. If the emphasis is on reducing the system and substation peaks and smoothing the demand profile at the system level, this may override the opportunity to reduce the transformer capacity and network losses at the distribution substation level of the system.

5 Impact on the Voltage Profile

The Energy Storage Systems increase the voltage levels at all points on the MV and LV feeders under the peak demand scenario.

Larger scale deployment, together with aggregated and controlled operation as a VPP, has the potential to assist in voltage regulation of the distribution network.

5.1 Medium Voltage Feeder

Figure 13 shows the voltage profile for the MV feeder circuit from the winter maximum power flow studies. With the additional demand for the FlexiGrid development, the minimum voltage value reduces to 98.1%. This increases the voltage drop to 3.4% below the source target and is within typical design limits.

The impact of the ESS system increases the voltage levels at all points on the feeder. The minimum voltage rises to 98.3%.

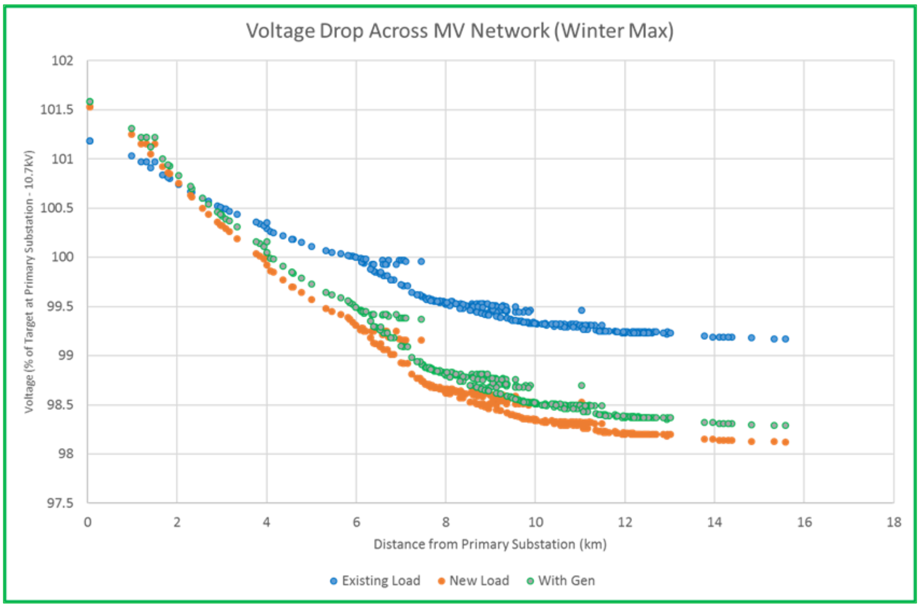


FIGURE 13 – WINTER MAXIMUM VOLTAGE PROFILE ON THE MV FEEDER

The impact of the ESS system on the diurnal voltage profile for the MV feeder circuit is shown in Figure 14. The curves show the voltage on the 10 kV busbar at the primary substation, the tee connection point that supplies the housing estate where the FlexiGrid development is located and the remote point on the feeder with the lowest voltage level.

The charging of the ESS battery storage depresses the voltage level in the early hours of the morning and the discharge of the ESS battery system increases the voltage during the system peak period 16:00pm – 18:00pm.

If the demand levels transition from low levels to higher values in the morning (6:00am – 8:00am and 22:00pm - 00:00am) there is some turbulence in the results as the tap changer moves between tap position 11 and 12. This phenomenon is not created by the operation of the ESS system and is seen in the studies without the ESS system.

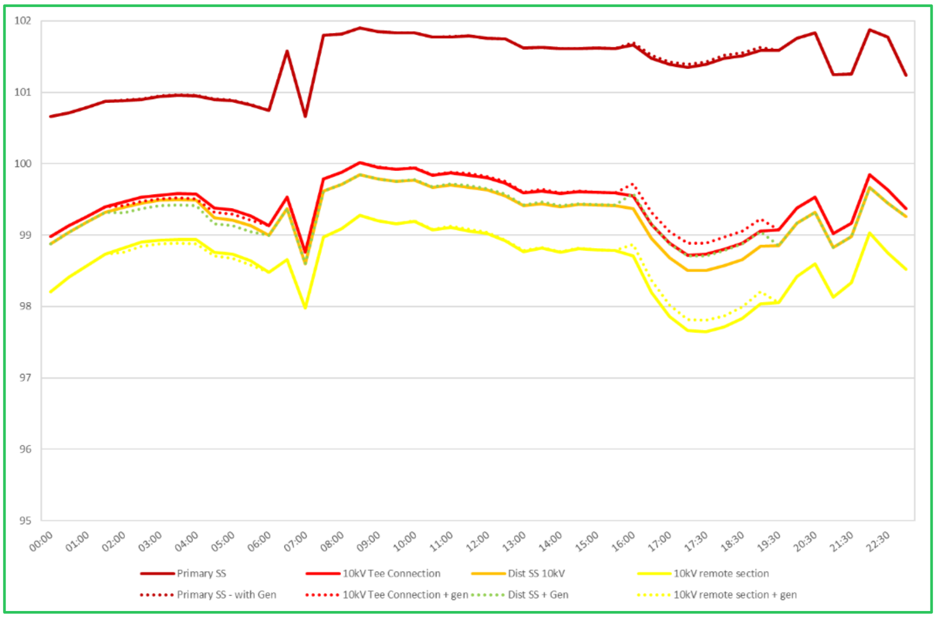


Figure 14 – Winter maximum voltage diurnal profile on the MV feeder

5.2 Low Voltage Network

Figure 15 shows the voltage profile for the LV feeder circuits from the winter maximum power flow studies. With the additional demand for the FlexiGrid development the voltage at the LV terminals of the distribution substation is 97.8% and the minimum voltage value reduces to 96.2%. This voltage drop of 1.6% is within typical design limits.

The impact of the ESS system increases the voltage levels at all points on the LV feeders. The voltage at the LV terminals of the distribution transformer increases to 98.5% and the minimum voltage rises to 97.3%.

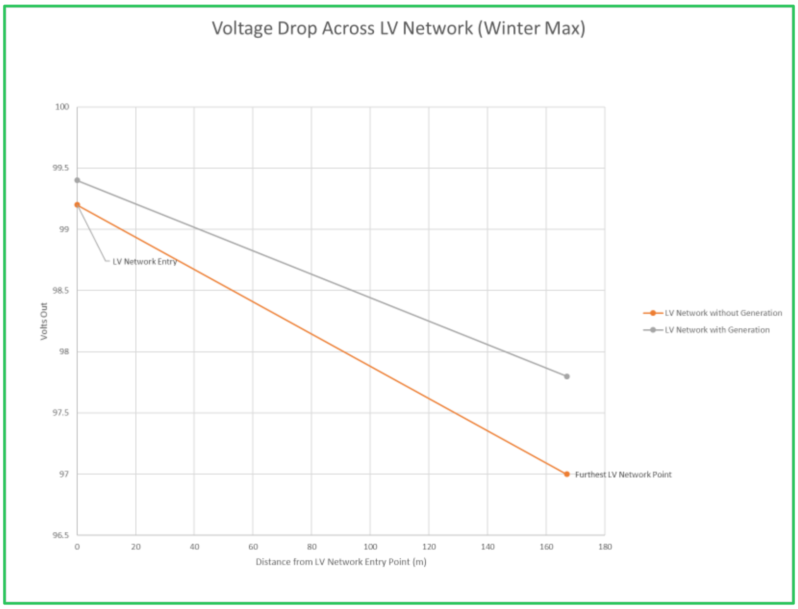


Figure 15 – Winter maximum voltage profile on the LV network

The impact of the ESS system on the diurnal voltage profile for the LV Network is shown in Figure 16. The curves show the voltage on the LV busbar of the distribution substation and the remote point on the feeder with the lowest voltage level.

The voltage variation caused by the charging and discharging of the ESS battery storage is more pronounced at this voltage level.

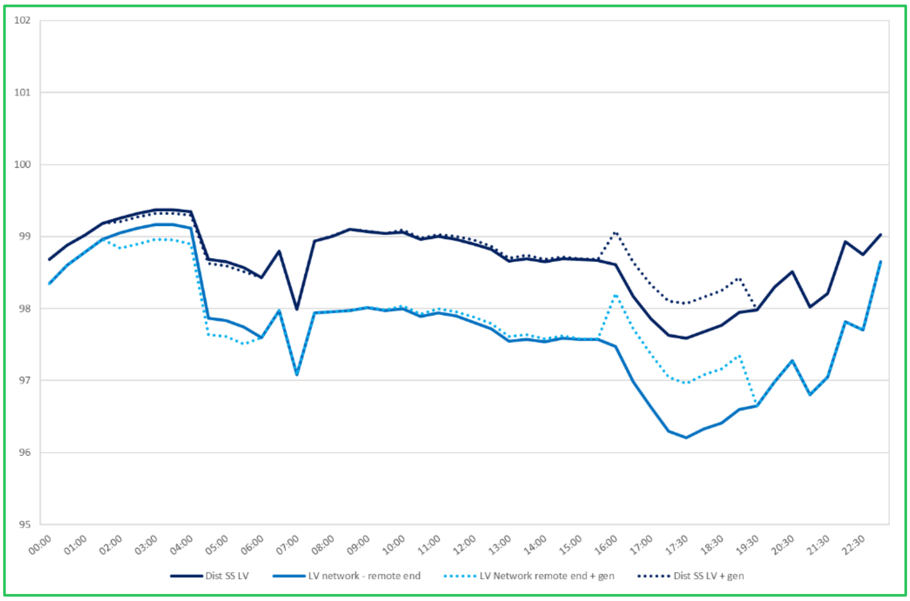


FIGURE 16 – WINTER MAXIMUM DIURNAL VOLTAGE PROFILE ON THE LV NETWORK

5.3 Summer Minimum Voltage Profile

The impact of the ESS system on the diurnal voltage profile during summer minimum conditions is shown in Figure 17. In this period the heat pump is providing hot water only and has a more intermittent demand pattern. This causes the spikier nature of the voltage profile. The study assumes that the cycling of the heat pumps in the individual properties are coincident however it is expected that the variable hot water usage patterns and thermal performance of the hot water storage will not be consistent. This would reduce the size of the voltage spikes but increase their frequency.

The combined impact of the ESS Solar PV output and the charging/discharging of the battery storage system flattens the base line profile but does not reduce the extent of the spikes caused by the heat pump demand on the base line profile.

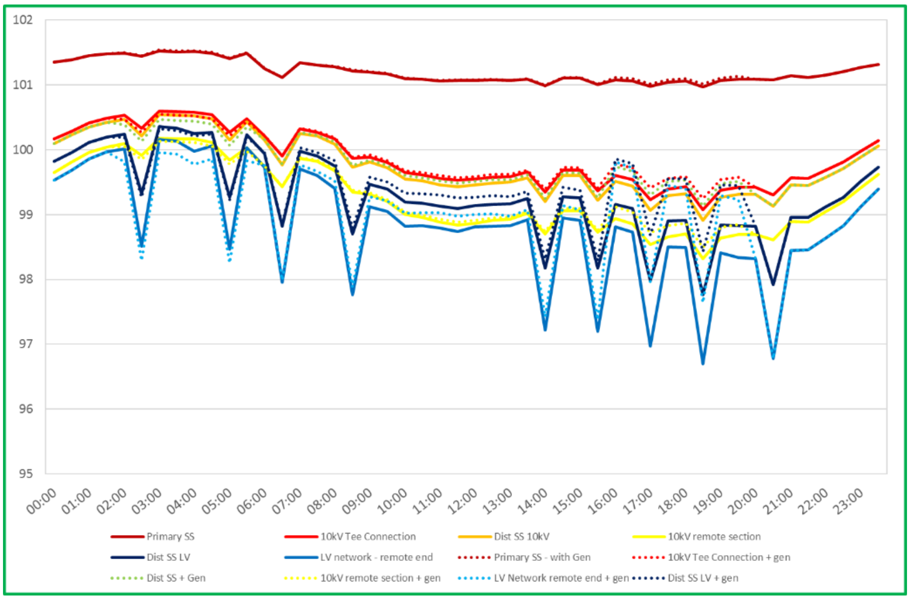


FIGURE 17 – SUMMER MINIMUM DIURNAL VOLTAGE PROFILE ON THE LV NETWORK

6 Impact on Network Losses

The Energy Storage Systems reduce losses on the MV and LV feeders in the FlexiGrid analysis, enabling more economic operation of distribution assets.

Larger scale deployment, together with aggregated and controlled operation as a VPP, has the potential to significantly reduce network losses, resulting in reduced network operating costs, and defer the upgrading of existing distribution infrastructure.

Losses, both technical and commercial, are inherent to the operation of the power system. Technical losses result from energy dissipated in feeders and transformers and magnetic losses in transformers. Such losses can prove to be a significant overhead; an overhead which is ultimately borne by the customer.

DSOs must manage losses on an ongoing basis to reduce the associated costs. However, there is a balance to be struck between the ongoing loss costs associated with the operation of existing distribution infrastructure and the investment in new infrastructure. There is an optimal level of losses where the costs of reducing the losses balance the cost of supply. This optimal level results at a relatively low loss rate, i.e. losses as a percentage of throughput. Losses increase as the level of loading on the distribution infrastructure is increased. For existing overhead lines, for example, the economic loading is typically in the order of 50% of the conductor rating. Distributed energy storage can be used to reduce peak loading on the distribution system, thereby reducing loss costs and delaying the deployment of infrastructure upgrades. FlexiGrid examines the potential reduction in technical losses resulting from the representative housing development with ESS incorporating Solar PV and a coupled battery storage system.

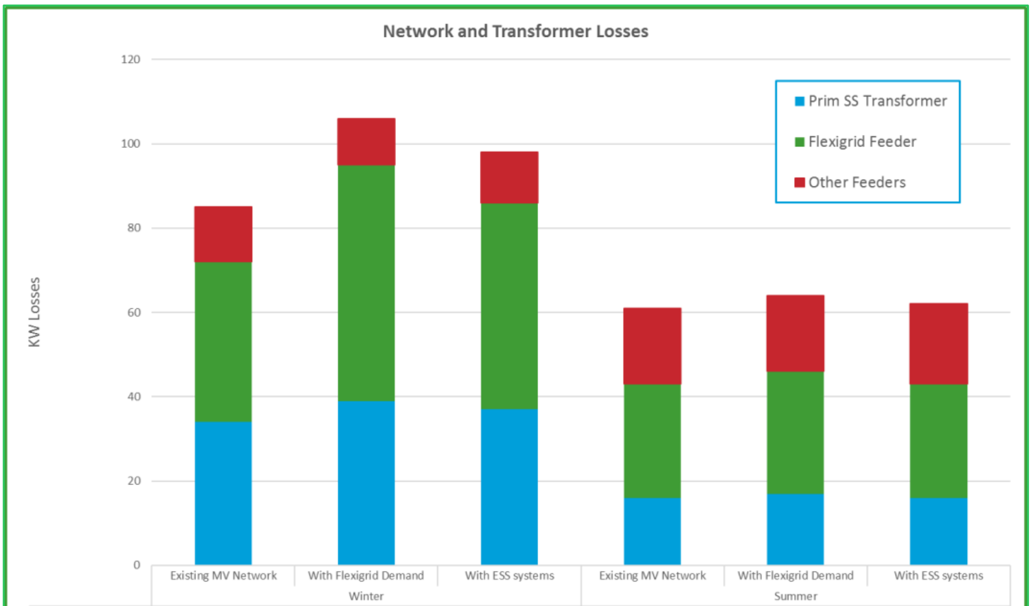
At the time of the winter maximum load reading the power flow study calculates the total technical losses on the primary substation and the MV Network supplied from the substation. The value calculated is 85 kW which is 1.26% of the total demand on the substation.

The losses related to the primary transformers account for 40.0% of the losses and the FlexiGrid MV feeder circuit (C15) a further 44.7%.

The introduction of the additional demand from the FlexiGrid development increases the losses to 106 kW with an increased proportion of the losses occurring in the FlexiGrid MV Feeder circuit (52.8%).

The impact of the ESS systems reduces the losses to 98 kW and the proportion of the losses occurring in the FlexiGrid MV Feeder circuit is reduced to 50.0%.

The calculated loss values for the winter maximum and summer minimum conditions are shown in Figure 18.



	Winter: Existing MV Network	Winter: With Flexigrid Demand	Winter: With ESS systems	Summer: Existing MV Network	Summer: With Flexigrid Demand	Summer: With ESS systems
Other Feeders	13	11	12	18	18	19
Flexigrid Feeder	38	56	49	27	29	27
Prim SS Transformer	34	39	37	16	17	16

FIGURE 18 – WINTER MAXIMUM DIURNAL VOLTAGE PROFILE ON THE LV NETWORK

It is clear from the analysis that wider deployment of a distributed behind-the-meter energy storage can have a significant impact on loss performance at distribution level, with potentially significant cost savings for both the DSO and the consumer.

It is generally more appropriate to express loss figures in kWh. This can be carried out using three possible methods: -

1. Carry out a full year study using a full 365 x 24 diurnal demand model which calculates the accumulated kWh losses for the period
2. Carry out a full year study using a simplified demand model with daily diurnal demand profiles for weekdays and weekend days for each month of the year
3. Apply a loss load factor to the peak kW losses. The loss load factor is normally derived from load research.

The cost of completing a full year diurnal study or preparing a simplified demand model was beyond the funding available within this project. Similarly, option (3) was considered outside the scope of this analysis. Whilst the battery round trip efficiency is discussed in Section 2.4 and Table 3 the efficiency does not impact on the studies as the energy (kWh) performance over time was not evaluated.

7 The Network Model

The network model is based on a real 10 kV and LV network supplying a growing town and surrounding rural area. The relevant data has been provided by ESBN.

7.1 Primary Substation

The network model is based on a real and typical 10 kV network supplying a growing town and the surrounding rural area. The town is expanding rapidly with a mixture of industrial, logistics and domestic developments along with a growth in tourism.

The primary substation supplies the local town and the surrounding rural area. The substation reduces the voltage from 38 kV to 10.47 kV and is equipped with two 5 MVA transformers. The voltage at the 10.47 kV busbar is controlled by an on-load tap changers set to a target voltage of 10.7 kV.

Figure 19 – A typical two transformer primary substation

Eight 10.47 kV feeder circuits distribute the electricity from the substation to the local distribution transformers (10.47 kV/400 V) and large customers taking supply at 10.47 kV.

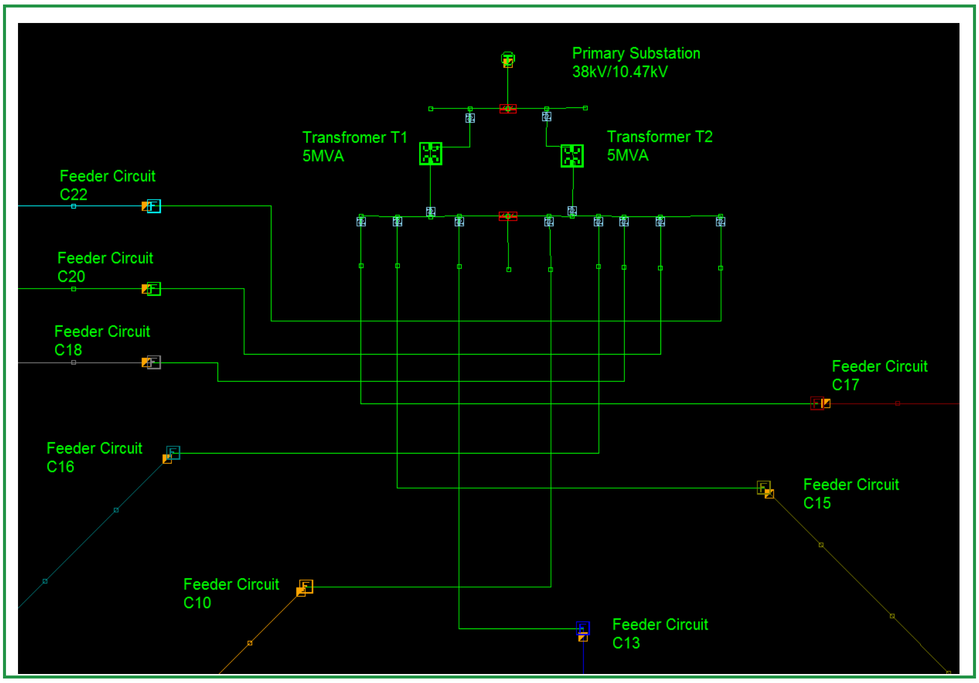


FIGURE 20 – PRIMARY SUBSTATION SINGLE LINE DIAGRAM

7.2 Medium Voltage (10 kV) feeder

The housing development is located to the south of the primary substation and the main town centre. The closest feeder circuit is C15 which initially supplies part of the town centre and then continues further south to supply a mainly rural area.

FIGURE 21 – PRIMARY SUBSTATION SINGLE LINE DIAGRAM

The C15 feeder has a total circuit route length of 40 km with overhead lines making up 72% of the feeder length and the remaining 28% is underground cable. The new housing is a real proposed development that is located on the edge of a recently built housing estate to the south of the main town centre. The housing estate is supplied from an existing overhead spur connection. The spur connection is located at a route distance of 5.9 km from the primary substation. The overhead spur transitions to underground cable as it enters the estate.

FIGURE 22 – TRANSITION FROM OVERHEAD LINE TO UNDERGROUND CABLE AT THE EDGE OF THE EXISTING HOUSING ESTATE

To supply the new housing estate, it is necessary to install a new distribution substation with a 630 kVA 10.47 kV/400 V transformer which will be connected into the underground section of the spur connection.

7.3 Low Voltage Network

To study the impact of the electricity demand on the low voltage network we have modelled the low voltage mains from the distribution substation to the street pillars where groups of customers will be connected to.

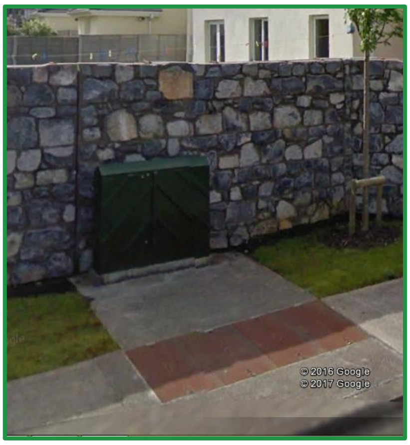


FIGURE 23 – EXISTING STREET PILLAR ON THE ADJACENT HOUSING ESTATE

The design of the LV network includes six low voltage underground cable feeders and a total of eleven load points with an average of six customers connected at each load point. Synergi Electric supports unbalanced network models with a full three phase representation of the network. Over the whole network the number of customers connected to each phase were balanced with twenty-two connected to one of the three phases and twenty-three to the other two.

At 10 of the 11 load points three of the ESS solar PV and battery systems were modelled with one connected to each of the three phases.

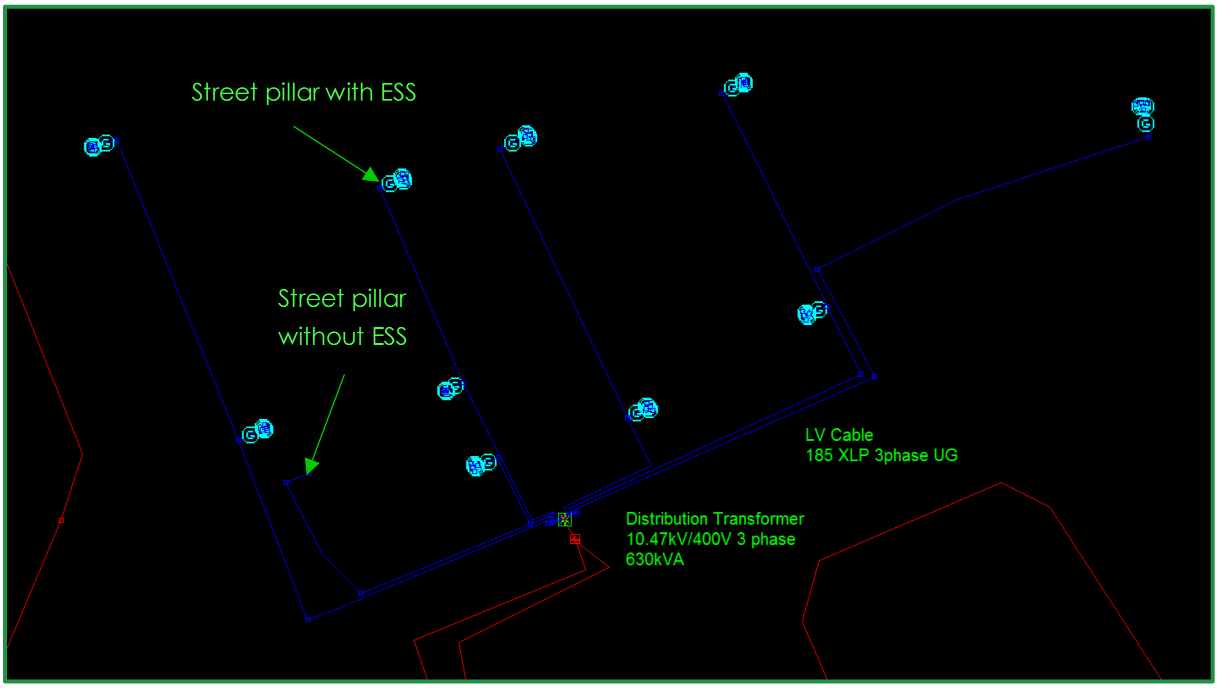


FIGURE 24 – LV NETWORK MODEL

8 Demand Profile

The demand model is comprised of existing demand, additional demand in new houses, output from Solar PV and charging and discharging of the battery storage systems.

8.1 Demand Components

To analyse the operation of the network downstream of the primary substation it was necessary to model the demand at each of the load points on the MV circuit. The demand model is built up with the following four components:

- Existing demand on the MV circuits
- Additional demand in the new houses on the development (general demand and heat pump)
- Output from the Solar PV microgenerators
- Charging demand to and discharge output from the battery storage systems

8.2 Existing Demand on the MV Circuit

Load points on the MV feeders include: -

- distribution transformers which supply LV networks that have several customers connected to them
- connections that supply larger single customers

Ideally, we would have actual values of demand at each of these load points but this is not normally the case with existing MV networks.

It has not been normal practice to install distribution transformers with metering although modern substations do offer the facilities to install metering and remote communication equipment.

As part of their tariff requirements large customers generally have maximum demand measured for each month and these may have time series values available. This data is specific to individual customers and confidential. It was not possible to include time series data for these customers in the FlexiGrid studies – this would require agreement with the individual customers involved.

The network model in this study uses known load information to build a representative demand profile on the MV network. There are three sources of historical data that are used to estimate the existing demand on the distribution transformers and at the large customer's substations connected to the existing MV network: -

- Current (amps) readings from the meters installed on each of the 10.47kV circuits connected to the primary substation – these were available as a time series at half hourly intervals. The studies included half hourly values for the winter load reading day in December 2015 and the August Bank Holiday week in 2016.
- Aggregated annual electricity usage (kWh) values for all the customers connected to each of the distribution transformers on each 10.47 kV circuit
- Maximum demand readings for each of the large customers connected to the 10.47 kV circuits

The load allocation tool in Synergi Electric was used to create a load profile for MV network and this model was used to simulate and analyse the various power flows, as well as evaluate the benefits to the distribution and transmission networks from a variety of operational programs.

8.3 Demand on the FlexiGrid Development

Between 2010 and 2011, the Department of Energy and Climate Change (DECC), the Department for the Environment Food and Rural Affairs (Defra) and the Energy Saving Trust conducted the Household Electricity Usage Study2 (HEUS) to examine the electricity usage patterns of two hundred and fifty owner-occupier households in England. This study produced comprehensive household electricity usage profiles resolved to the level of individual appliances.

The CCLCT study draws on the diurnal load curves for domestic houses developed from the HEUS study and explores the impact of low carbon technologies (LCTs) on the demand curves.

The CCLCT study provides the annual average diurnal electricity demand curves for a domestic property with heat pumps.

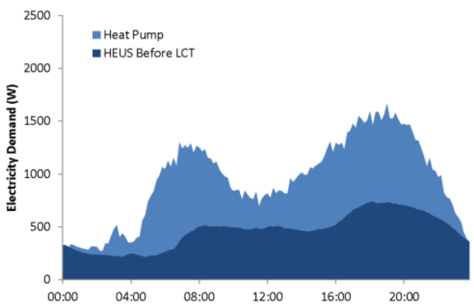


Figure 22: Annual average diurnal electricity demand for a single household using an aggregated average heat pump profile (reflecting the forecast UK composition of air-source and ground-source heat pumps). Any displaced primary electric heating has been removed and no DSR is assumed.

This average profile hides the spikey nature of the electricity demand for a single domestic property during a typical winter and summer's day.

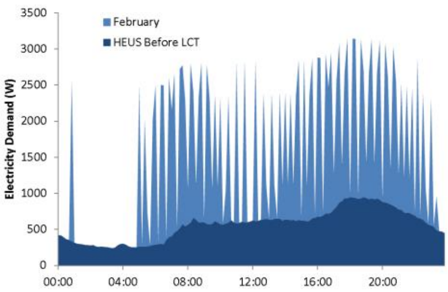


Figure 23: Average diurnal electricity demand of a representative heat pump profile for February, overlaid on the average HEUS household profile (with any displaced primary electric heating removed) for an average day in February.

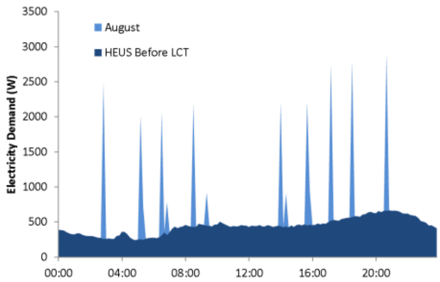


Figure 24: Average diurnal electricity demand of a representative heat pump profile for August, overlaid on the average HEUS household profile (with any displaced primary electric heating removed) for an average day in August.

The FlexiGrid model includes the LV sections up to a street pillar which supplies between six and twelve properties. The heat pump cycling in individual properties will not be coincident and we can expect some smoothing of the demand profile at the street pillars compared to the profile for individual properties provided in the CCLCT study.

We have assumed that the LV service connections will be evenly spread across the three phases available at each street pillar, which results in a range of two to four properties per phase.

For the FlexiGrid study we are using the 9kW heat pump which, as outlined in Section 2.2, requires a power input of 2.14 kW.

Based on the heating power input the additional demand capacity per phase will be between 4.28 kW and 16.56 kW on each street pillar. The electricity demand for an air source heat pump is provided in the CCLCT study which shows the cycling thirty-nine times in the period between 04:00am and midnight. If the time clocks on the sixty-eight properties are set to the same time and the systems are set to start at the same time, then we could expect all heat pumps in the properties to start their heating programme at the same time seeing a total uplift of 68 x 2.14 kW (154.52 kW). The cycling patterns will be broadly similar at the beginning as the heat pumps warm the properties up to temperature and then will gradually be less coincident as the thermostat settings and thermal performance of each property will be different due to the personal preferences and behaviours of individual occupants.

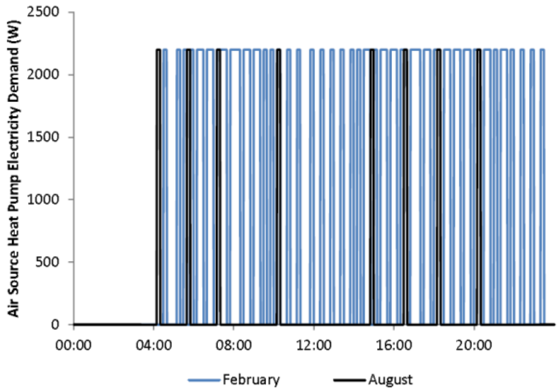


Figure 18: Electricity demand from an air source heat pump during representative days in February and August.

The FlexiGrid study is examining the impact of Solar PV generation and battery storage on the distribution system and for these purposes we consider that we can assume that on a typical winter's day the start times of the heating systems will be staggered and cycling patterns will not coincide providing a relatively smooth profile at each load point.

We cannot make the same assumptions for a typical summer day in August as the CCLCT study shows the heat pump cycling to the 'ON' status for eight short duration periods between 04:00 and 20:30. Allowing for non-coincidence this is likely to result in a spiked demand profile. We have two options for the load profile on the new properties: -

1. Assume that there is no heating in the selected period (August bank holiday)
2. Create an aggregate profile that includes non-coincident cycling of heating at the properties on connected to each street pillar

We consider that the impact of cycling does not have significant relevance to the impact of Solar PV and battery systems on the distribution system and recommend that option 1 is used for the summer demands in the FlexiGrid study. The impact of heating cycling should be a subject for other studies.

In summary, it is proposed to adopt the average diurnal energy consumption profile from the CCLCT study without heat pumps for the August bank holiday week. For the winter period time-series analysis, we propose to use the base average diurnal energy consumption profile from the CCLCT study plus an aggregated heat pump energy consumption based on a 2.14 kW per property for the period 04:00 to 21:00 reducing to a lower value for the period 21:00-midnight. In the period 21:00-midnight the following values will be applied based on the number of properties per phase: -

TABLE 5 – HEAT PUMP INPUT ENERGY RATING/PHASE

Number of properties/phase	Total heat pump input energy rating/phase (kW)	Energy per property (kW)
2	4.28	2.14
3	6.42	2.14
4	8.56	2.14

An average peak demand of 5 kW was assumed for each of the FlexiGrid development properties which included the heat pump demand at 2.1 kW between the hours of 04:00am and 23:00pm.

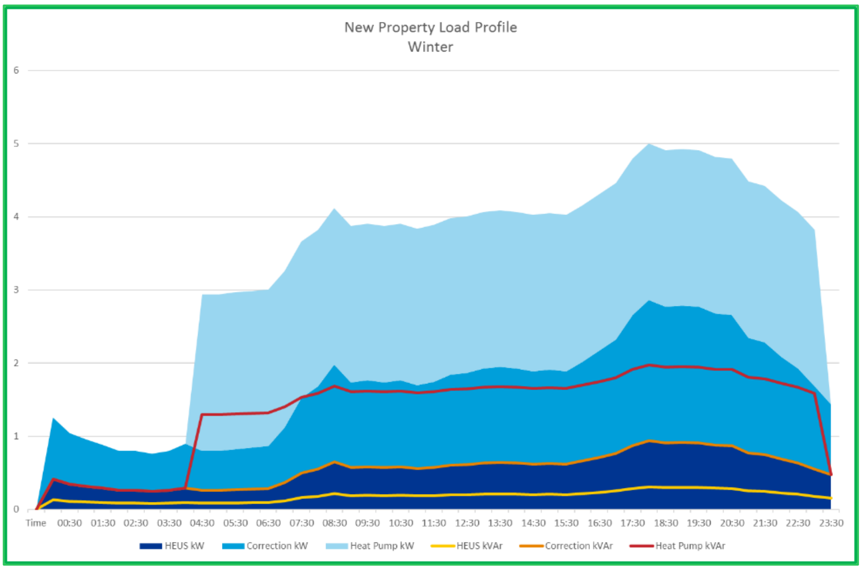


FIGURE 25 – FLEXIGRID PROPERTY WINTER LOAD PROFILE

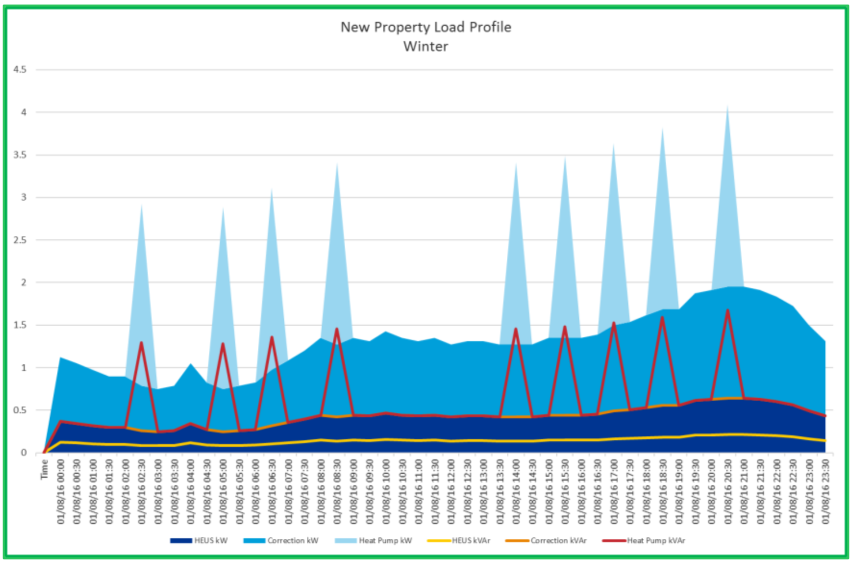


FIGURE 26 – FLEXIGRID PROPERTY SUMMER LOAD PROFILE

8.4 Output from the ESS Systems

8.4.1 Solar PV systems

The modelling of solar PV generation in Synergi Electric allows the output to be determined using two methods: -

- A power output profile based on measured or forecast output
- Calculated output using a weather profile with irradiance values (W/m^2)

Half hourly weather data is available from internet sites and we sampled historical data and calculated data based on the location in Ireland where the FlexiGrid development is situated. The output of the ESS Solar PV systems is calculated from these weather profiles.

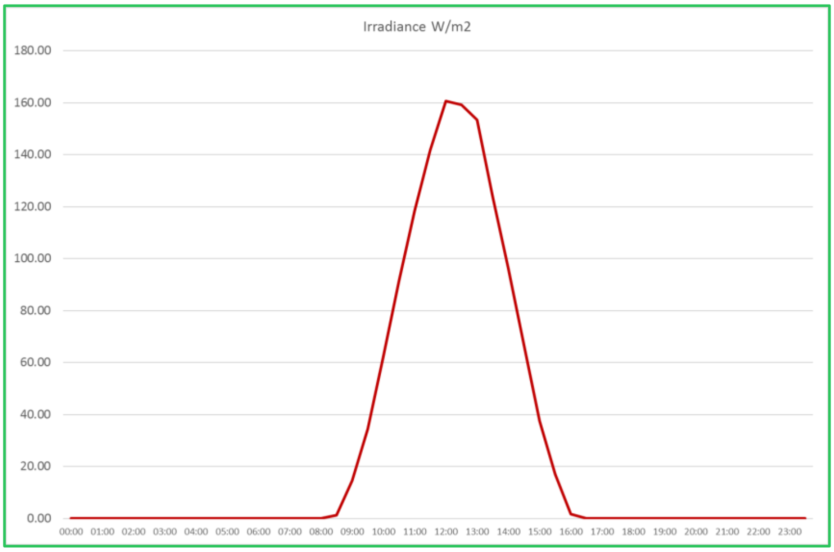


FIGURE 27 – DECEMBER IRRADIANCE PROFILE

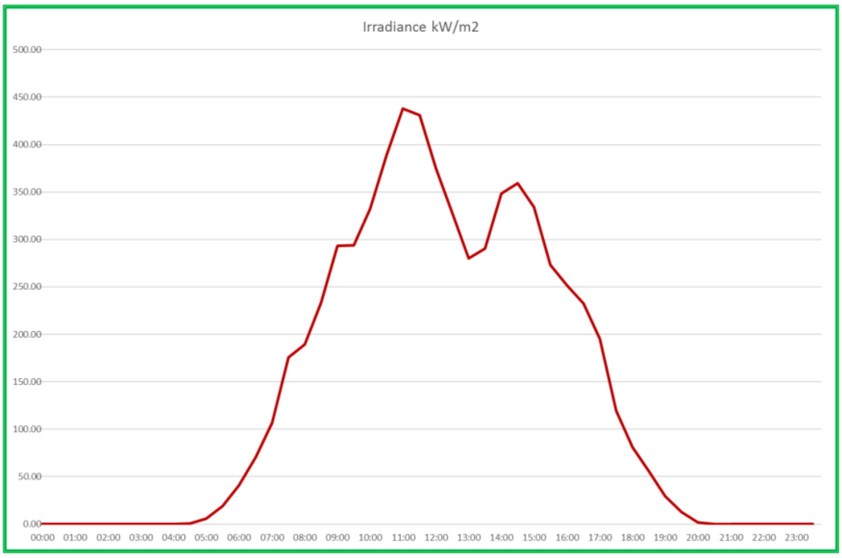


FIGURE 28 – AUGUST IRRADIANCE PROFILE

8.4.2 Battery System Operation – Winter Period

The operating regime for the battery systems are another variable. There needs to be a regime of charging and discharging that fits with the load profile and the availability of PV solar output and low cost electricity.

The main ESS battery discharge period was targeted at the evening peak load period. It was envisaged that this will provide maximum benefit to the ESB network and in the future, may incentivise customers if a powershift type tariff is introduced. If the discharge period is between 4:00pm and 8:00pm this would provide a full discharge of the battery if discharged at a discharge power of 3.68 kW (4 x 3.68 kW > 13.2 kWh).

With solar irradiation at low levels we cannot expect solar PV generation to be greater than the load profile during the period 11:00am to 3:00pm with no surplus output. There is no strong basis to charge the battery system over this period and the current tariff regime does not provide any incentives to increase power input from the LV network for discharge later. The FlexiGrid study assumed that the ESS batteries would be fully charged in the night-time period when there is access to low cost electricity.

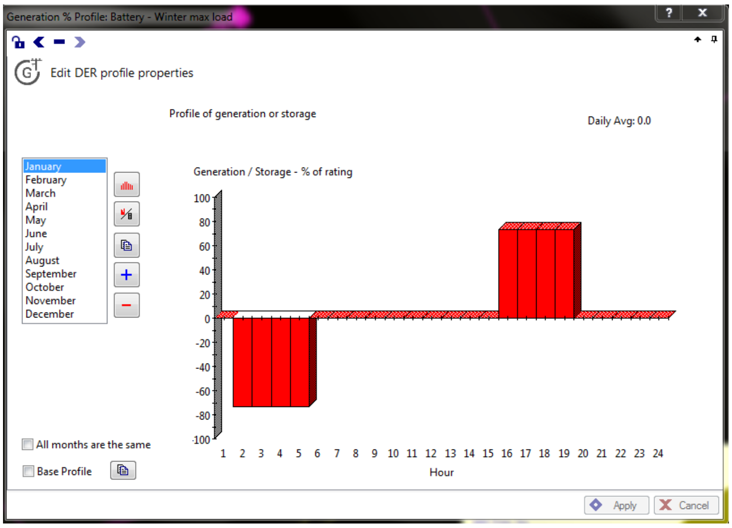


Figure 29 – Profile of generation and/or storage

9 Further Work

The work undertaken as part of the FlexiGrid project demonstrates the prospective benefits of distributed behind-the-meter energy storage on the distribution system.

A logical next step in any future work is to extend the model to include the VPP functionality to examine the effects of aggregated and controlled operation of the cluster network of battery storage devices and/or Solar PV on the local distribution system represented in the FlexiGrid model.

The modelling methodology can be readily extended to examine a larger section of the distribution network with a view to assessing the effects of the integration of distributed battery storage at a macro level, again including the aggregated operation of the battery storage.

Finally, Solo Energy intends to roll out its first physical pilot projects in 2017. With FlexiGrid as a basis, this presents a unique opportunity to compare the results of power flow analysis of the pilot project(s) to real world monitoring data.

10 References

1. Further Analysis of Data from the Household Electricity Usage Study: Correlation of Consumption with Low Carbon Technologies - Element Energy 2014

2. Household Electricity Usage Study – UK Department of Energy & Climate Change (DECC) 2011