Australian National University

Battery Storage and Grid Integration Program

An initiative of ***The Australian National University***

The role of dynamic operating envelopes in co-ordinating and optimising DER

evolve Project Knowledge Sharing Report #4

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1 Glossary

Term	Definition
Active Network Management	The operational systems and processes by which DER can be actively controlled to prevent breaching physical or operational limits.
Aggregation Zone	The region of a network within which operating envelopes can be aggregated.
Connection Point	The network location where a customer is electrically connected into the electricity system.
DER	Distributed Energy Resources, or 'DER', are smaller– scale devices that can either use, generate or store electricity, and form a part of the local distribution system, serving homes and businesses. DER can include renewable generation such as rooftop solar photovoltaic (PV) systems, energy storage, electric vehicles (EVs), and technology to manage demand at a premises.[1]
DNSP	Distribution Network Service Provider, the organisations responsible for managing and operating electricity distribution networks.
Hosting Capacity	The real and reactive power contributions from DER that can be imported or exported into the electricity grid without breaching the physical or operational limits of the electricity distribution network.
NMI	National Metering Identifier (NMI) is a unique 10 or 11 digit number used to identify every electricity network connection point in Australia.
(Dynamic) Operating Envelope	A dynamic operating envelope is a principled allocation of the available hosting capacity to individual or aggregate DER or connection points within a segment of an electricity distribution network in each time interval (usually 5 or 30 minutes). In this report, we will use dynamic operating envelope and operating envelope interchangeably.

[1] https://www.wa.gov.au/sites/default/files/2020-04/DER_Roadmap.pdf

2 Executive Summary

We are currently witnessing the increasing deployment of DER including distributed solar PV, residential and suburb scale battery storage, electric vehicles and controllable loads. Overwhelmingly, these DER resources are being installed in the low and medium voltage segments of electricity distribution networks. These DER assets can contribute to energy reliability and energy security through their participation in markets for energy and ancillary services. However, without appropriate co-ordination DER can in result in dynamic two-way flows of energy that threaten the physical or operational limits of electricity distribution networks.

In this context, there are open questions about what new technology capabilities, regulations and market mechanisms are necessary to support the integration of DER without breaching the physical and operational limits of distribution networks. In the evolve Project, we are exploring the use of dynamic operating envelopes to address this question.

In previous knowledge sharing reports, we have addressed and answered key questions including:

- What is an operating envelope?
- What are the benefits of operating envelopes?
- How are operating envelopes calculated and implemented?

In this report, we present a more detailed overview of how dynamic operating envelopes can be used to ensure that DER does not breach the physical or technical limits of the electricity distribution network as well as show how dynamic operating envelopes can also ensure that system security is maintained during periods of low operational demand. This report then presents a detailed case study demonstrating how dynamic operating envelopes can be used to support a high penetration of solar uptake by householders.

Dynamic Operating Envelope Use Cases

Chapter 4 of this report presents a detailed overview of how dynamic operating envelopes can be leveraged by both distribution network service providers as well as the system operator. The use cases explored in this section include:

- Managing Solar Generation (Export)
- Enabling DER Market Participation (Both Import and Export)
- Supporting EV Charging (Import)
- Using Dynamic Operating Envelopes to Maintain System Security

Detailed Case Study – Solar Export

Chapter 5 of this report presents a detailed case study of how dynamic operating envelopes can be used to enable a high penetration of solar PV on two low voltage feeders within the Essential Energy distribution network in Port Macquarie. The case study analyses the current hosting capacity of these feeders, showing how the current installations of solar are already breaching the physical and technical limits of the distribution network. The case study then demonstrates how these current breaches of physical and technical limits could be eliminated through the use of operating envelopes.

In the second phase of the case study, the report explores if even greater levels of solar PV can be accommodated through the use of operating envelopes. The case study show conclusively that operating envelopes are capable of effectively supporting customer uptake of significant amounts of solar generation whilst ensuring that physical and technical limits of the distribution network are not breached.

3 Introduction

3.1 Distributed Energy Resources (DER)

The uptake of Distributed Energy Resources (DER) represents a transformational change to the energy mix, structure and operation of power systems and markets. Overwhelmingly, these DER resources are being installed in the low and medium voltage segments of electricity distribution networks globally.

> *"Distributed Energy Resources, or 'DER', are smaller– scale devices that can either use, generate or store electricity, and form a part of the local distribution system, serving homes and businesses. DER can include renewable generation such as rooftop solar photovoltaic (PV) systems, energy storage, electric vehicles (EVs), and technology to manage demand at a premises".*[2]

As DER adoption increases, global electricity systems will demonstrate increasing levels of decentralisation, with this change currently occurring faster in Australia than any other nation (Figure 1).

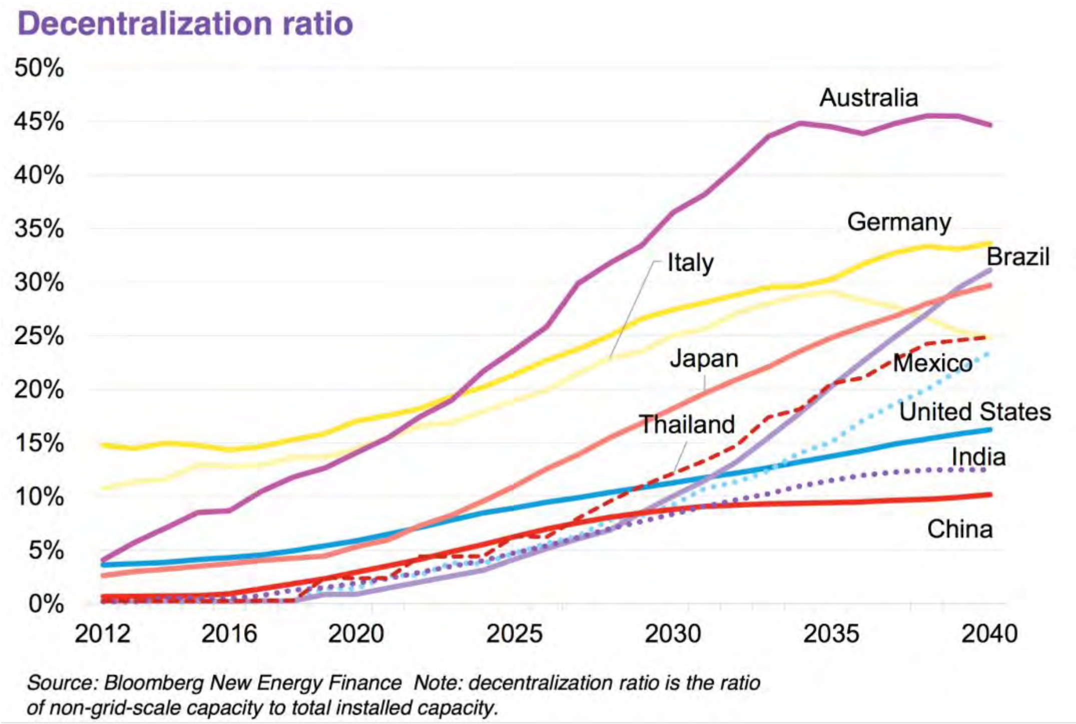

Figure 1. Many grids globally will demonstrate increasingly high levels of decentralisation over the decades ahead (Bloomberg New Energy Finance - New Energy Outlook 2017).

The AEMO 2020 Integrated System Plan (ISP)[3] notes that distributed energy resources are expected to double or even triple by 2040 and could provide up to 13% to 22% of total underlying annual NEM energy consumption by 2050. Driving the growth of DER in Australia will be the continued high uptake of distributed solar PV (Figure 2) through to 2050 and likely beyond.

The ISP also forecasts growth in behind the meter (BTM) residential battery storage. It is as yet unknown what percentage of BTM batteries will be orchestrated through participation in virtual power plants (VPPs) or if they will be predominantly installed by customers with solar PV to maximise solar self-consumption.

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[2] https://www.wa.gov.au/sites/default/files/2020-04/DER_Roadmap.pdf

[3] https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp

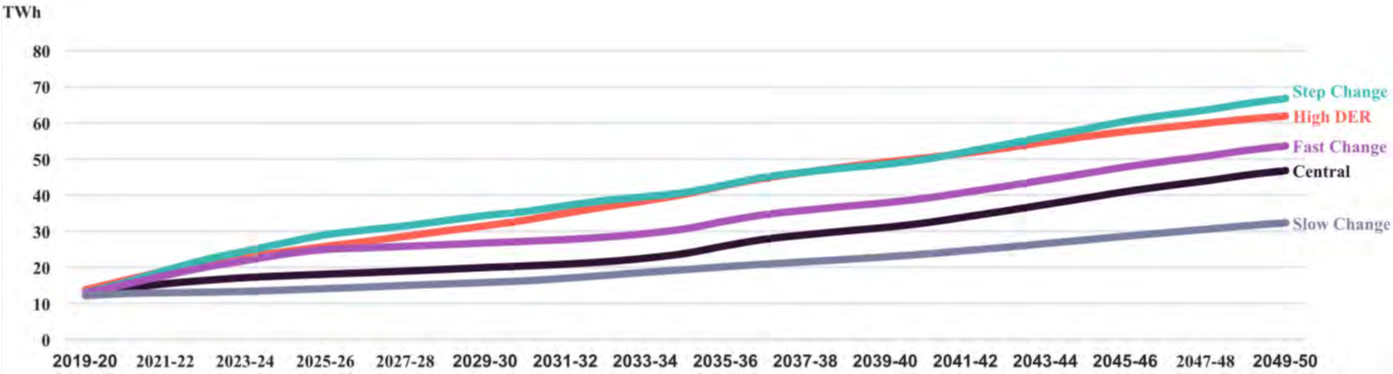

Figure 2. Distributed PV generation to 2050 (AEMO ISP 2020)

Battery storage connected within distribution networks is also likely to grow over the long term due to emerging opportunities for community and suburb scale batteries which offer benefits for customers who cannot access residential batteries. Community or suburb scale batteries will service customer desires for battery storage for those who cannot afford residential batteries, as well as those renting or who live in apartments, for whom it is often impossible to install batteries within their premises. While it is impossible to predict the uptake of community batteries, appropriate regulatory settings could result in a large fraction of the forecast utility battery uptake being community battery assets of less than 5MW[4].

From the mid-2020s onwards, there is also an expectation of greater electric vehicle (EV) adoption (Figure 3) which under the Step Change scenario modelled in the AEMO 2020 ISP would mean that:

"EVs account for 12% of underlying 'power point' NEM consumption by 2040"

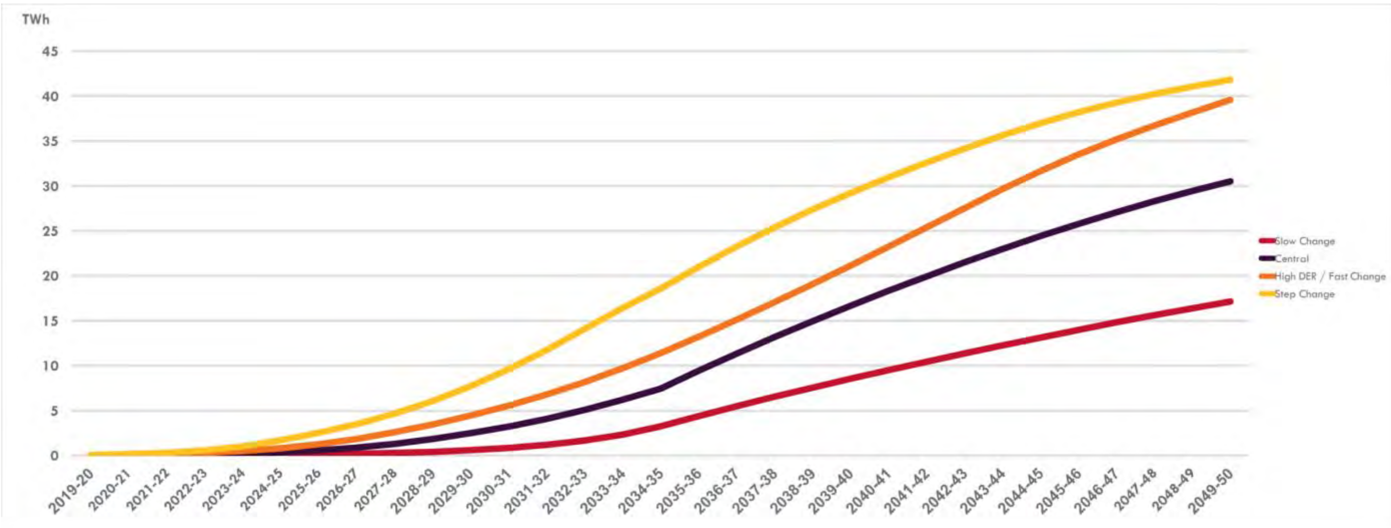

Figure 3. EV electricity consumption to 2050 (AEMO ESOO 2019[5])

While these DER assets will contribute to both increasing generation and demand, there is likely to be a significant time mismatch between the periods of peak DER import and export behaviour in the distribution network. While distributed solar generation tends to peak in the middle of the day, EV charging is likely to occur in the early to mid-evening. There is potential for battery storage to help balance this mismatch,

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[4] https://arena.gov.au/projects/community-models-for-deploying-and-operating-distributed-energy-resources/

[5] https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-reliability/nem-electricity-statement-of-opportunities-esoo

however, as a dispatchable resource, battery storage will also contribute to energy reliability and energy security through participation in markets for energy and ancillary services. Collectively, these considerations mean that the significant uptake of un-orchestrated DER will result in dynamic two-ways flows of energy within electricity distribution networks.

3.2 Electricity Distribution Networks

Electricity distribution networks provide the electrical connection from customers to the overall electricity grid (see Figure 4), allowing bi-directional flows of energy between the customer and the system. For this reason, electricity distribution networks are said to provide the "last mile" of connectivity. In Australia, electricity distribution networks span almost 900,000km[6].

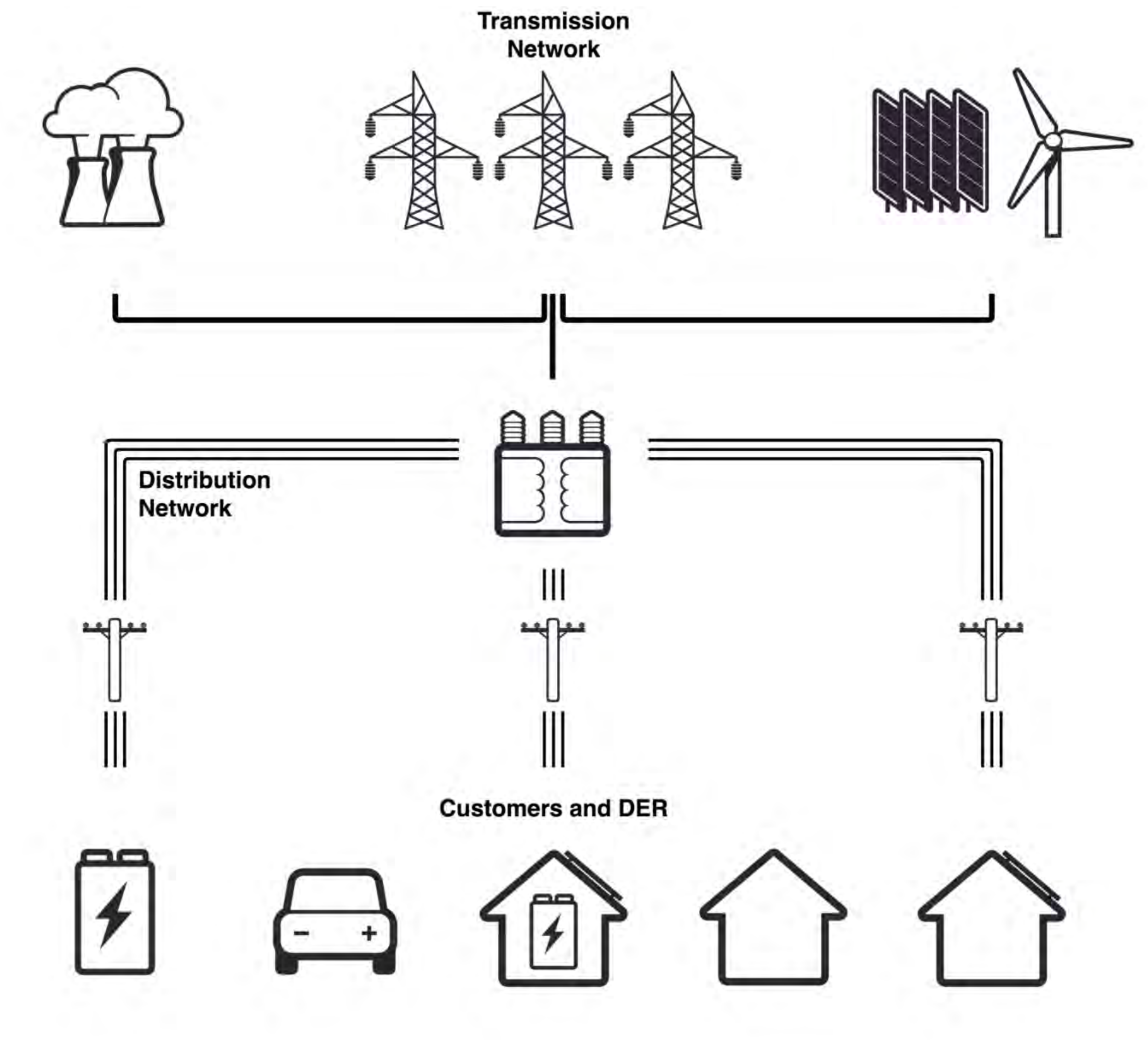


Figure 4. In Australia, DER assets are overwhelmingly installed in the low (415V) and medium (11kV) voltage regions of electricity distribution networks.

Prior to the uptake of DER, distribution networks typically experienced one-way aggregate energy flows that were predictable. The networks were designed such that they would remain within their physical and operational limits for these well characterised energy consumption patterns. In contrast, electricity distribution networks with a high uptake of DER will experience dynamic two-way flows of energy. As DER

[6] https://www.energynetworks.com.au/resources/fact-sheets/guide-to-australias-energy-networks/

assets also begin to routinely participate in markets for energy and ancillary services, their behaviour may threaten the physical or operational limits of distribution networks.

Under their operating licenses, the distribution network service providers (DNSPs) who operate electricity distribution networks must ensure their electricity distribution networks maintain certain “quality of supply” outcomes such as operating within certain voltage ranges at consumer connection points. The networks must also maintain high levels of reliability and availability, and are heavily penalised for breaches. In practice this means ensuring that distribution networks are operated within both voltage and thermal limits, something that is discussed in greater detail in the following section. It is worth noting that in some locations high uptake DER, particularly solar PV, are already breaching physical and operational limits (Figure 5).

Figure 5. Voltage measurements from customers participating in the ACT NextGen Battery Storage Program for the 30th August 2018. These measurements demonstrate over-voltage conditions during the day due to residential solar PV, with some under-voltage conditions occurring in the morning and evening peak periods due to high-demand. This image is a clear example of the increasing dynamic range of voltage conditions experienced on the electricity distribution network.

With the significant forecast uptake of DER, and an awareness of the challenges being faced by electricity distribution networks, there are open questions about what new technology capabilities, regulations and market mechanisms are necessary to support the integration of DER without breaching the physical and operational limits of distribution networks.

4 Use Cases for Operating Envelopes

Dynamic operating envelopes have the potential to achieve multiple operational goals for network and system operators. Indeed, the flexibility and broad applicability of dynamic operating envelopes is one of the key benefits of defining operating envelopes bi-directionally. The key use cases for dynamic operating envelopes are detailed below.

4.1 Managing Solar Generation (Export)

One of the key use cases for dynamic operating envelopes is to ensure that physical and operational distribution network limits are not breached during periods of peak solar generation. An operating envelope helps in this instance by signalling the need for reduced generation or for an overall reduction in export from a customer connection point.

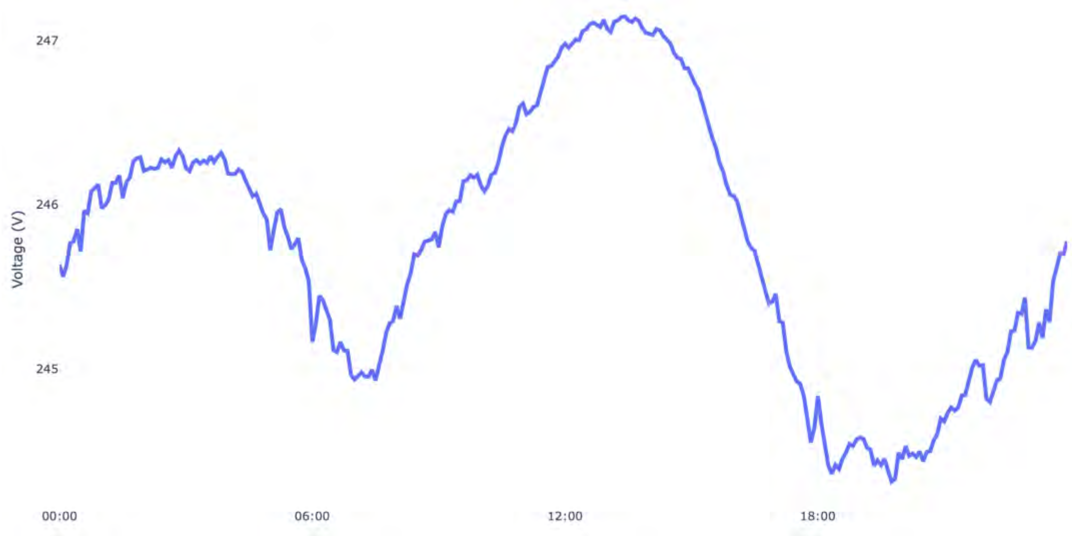
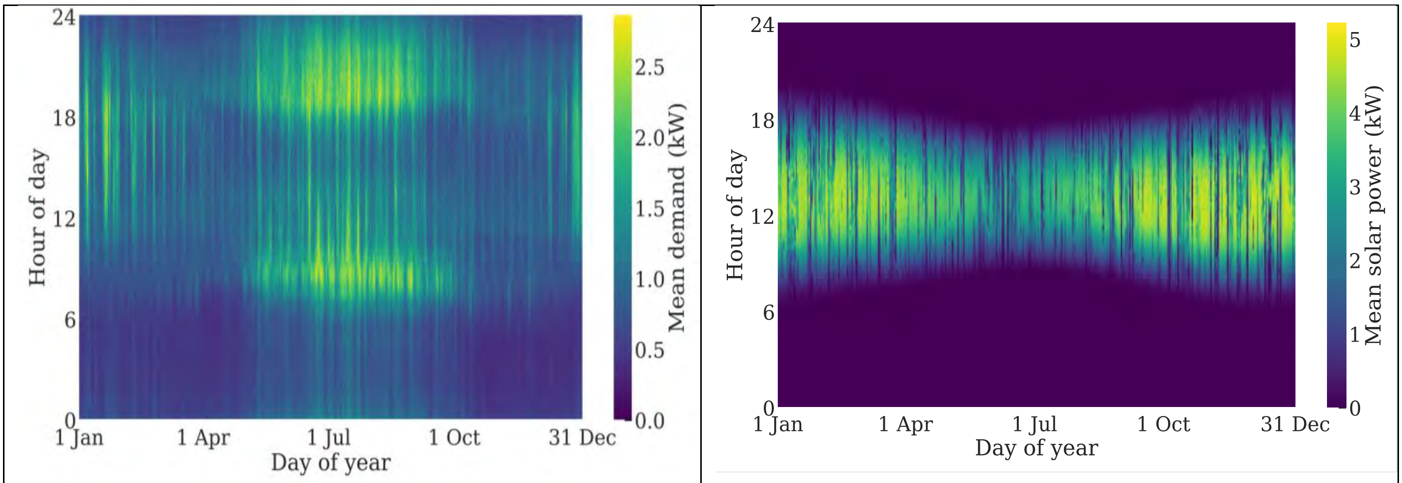


Figure 6. The average voltage on the network tends to be highest during the middle of the day when solar generation is at its peak. Data is the average daily voltage profile for 2018 from customers participating in the ACT NextGen Battery Program.

It is worth noting that peak solar generation is only likely to breach physical or operational limits when the underlying demand is low, and when solar generation is at its peak. In many areas this means that during the middle of the day (Figure 6) in mild spring and autumn days when demand is low (when heating and cooling are not necessary) (Figure 7), is likely to be when operating envelopes will be most operationally useful to address this particular use case.



(a) The mean demand for approximately 800 customers participating in the ACT NextGen Battery program in 2018.

(b) The mean solar generation for approximately 800 customers participating in the ACT NextGen Battery program in 2018.

Figure 7. The need for operating envelopes in spring and autumn is clearly demonstrated in these images where it can be seen that in spring and autumn there is low underlying demand (a) but almost full solar generation capacity in the middle of the da y (b). These conditions create a circumstance where highly correlated reverse flows of energy will occur, which has the potential to result in breaches of both voltage or thermal limits.

For customers with both solar PV and batteries, the operating envelope signals implicitly that it is better to defer charging of the battery until peak periods of energy generation (i.e. during the middle of the day). This example highlights one of the advantages of dynamic operating envelopes in that they provide clear signals to customers about how to modify DER asset behaviour, without being prescriptive about how this is achieved. Deferring battery charging in this way to soak up solar generation when it might cause network voltage or thermal breaches is unlikely to reduce net generation, nor impact the ROI of solar PV or battery storage.

4.2 DER Market Participation (Both Import and Export)

One of the key use cases identified for dynamic operating envelopes is that the additional network capacity can be used by DER assets to participate in markets for energy and ancillary services. By publishing an operating envelope, DER assets can participate in markets only up to the limit of the operating envelope. This ensures that market participation cannot infringe the safe and secure operating limits of the electricity distribution network. In circumstances where network limits will potentially result in constrained dispatch of DER in markets for energy and ancillary services, operating envelopes will provide valuable forecasts of available network capacity. This will ensure that forward DER bids in markets for energy and ancillary services are firm.

Ultimately, it is this use case that provides the reason for aligning the time interval of an operating envelope with the time interval of the market. A diagrammatic explanation of the relationship between operating envelopes and markets for energy and ancillary services can be seen in Figure 8.

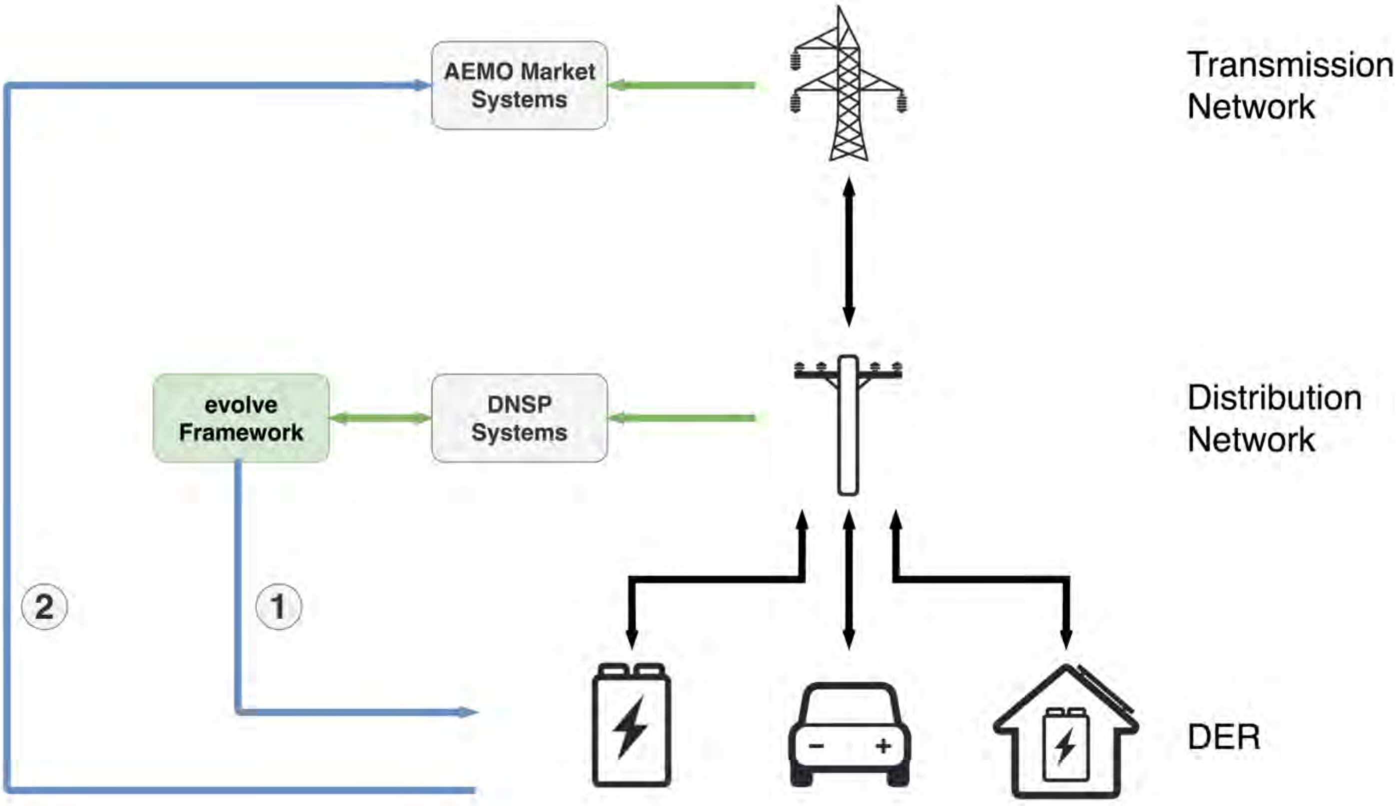


Figure 8. The use of dynamic operating envelopes allows DER to bid into markets for energy and ancillary services without breaching physical or operational limits of electricity distribution networks. In this diagram, green lines correspond to operational monitoring data and network visibility, whilst blue lines correspond to the sequence of actions being demonstrated through the evolve project.

In the evolve Project, this use case will be demonstrated in the following manner. DER will be sent operating envelopes (Step 1) before separately bidding into AEMO markets (Step 2).

4.3 EV Charging and V2G (Both Import and Export)

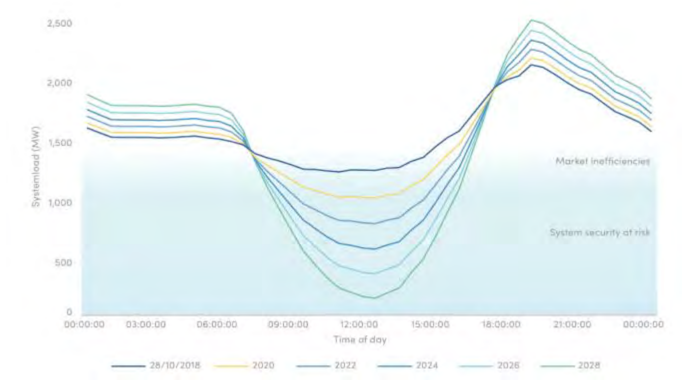
While electric vehicles uptake is only starting to occur, if all cars became electric there could be significant consequences to the correlated charging of electric vehicles in the evening. In a similar way to dealing with solar generation, an operating envelope would provide a clear signal to customers to defer, or reduce the power of EV charging to avoid breaching voltage or thermal constraints.

Furthermore, as vehicle-to-grid (V2G) capabilities become increasingly more widely available, there will also be a need to manage EV participation in markets for energy, ancillary and network services. This use case is also a subset of the DER market participation use case described in the previous section.

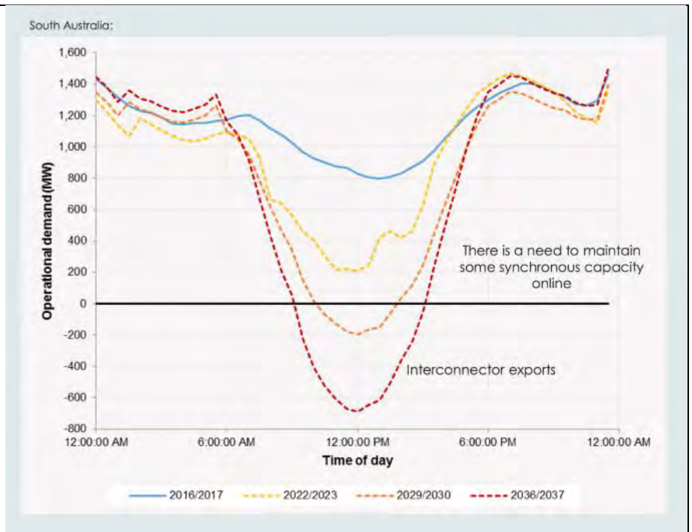
4.4 Using Operating Envelopes to Maintain System Security

While the evolve project is focussed on the development of operating envelopes to ensure that physical and operational network limits are not breached, there is emerging interest in the use of operating envelopes to help maintain system security limits during periods of high solar generation.

The reduction in minimum demand for both SA and WA can be seen in Figure 9 which will require solutions that may include solar curtailment, something that could be accomplished using operating envelopes. In this instance, the signal for operating envelopes could be published using the same mechanisms described in previous evolve knowledge sharing reports. However, in this circumstance, the source of information to define the operational security constraint would be sourced from AEMO systems. To accommodate this use case an additional data integration would therefore be needed with AEMO (Figure 10).



(a) *Forecast minimum demand in WA over the decade ahead.* [7]



(b) *Forecast minimum demand in SA over the decades ahead.* [8]

Figure 9. Understanding how to maintain energy security is an increasingly urgent challenge as several locations in Australia, in this case Western Australia and South Australia, are headed towards negative minimum demand over the coming decades.

[7] https://www.wa.gov.au/sites/default/files/2020-04/DER_Roadmap.pdf

[8] Riesz, Integration of DER: Operational Impacts, Future Electricity Markets Summit, Sydney, 2019.

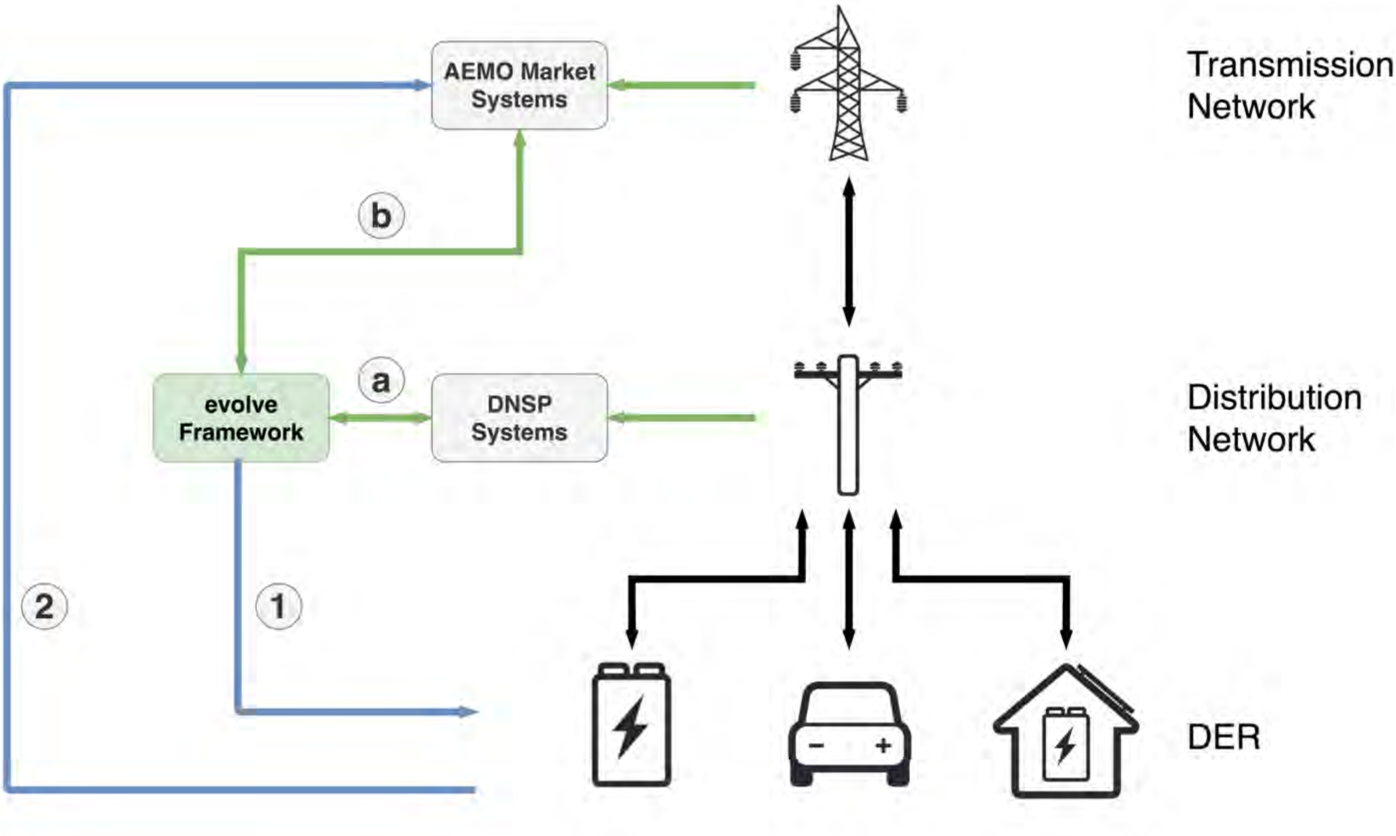


Figure 10. Operating envelopes could be used to manage system security constraints but this would require an additional integration with AEMO systems. If operating envelopes were also used to address system security concerns then the operating envelope algorithm would be updated to jointly solve for network voltage and thermal constraints and system security constraints.

We anticipate that there may emerge additional operational use cases for operating envelopes which emerge over the coming decade.

In the following Chapter we undertake a detailed case study that demonstrates the role of dynamic operating envelopes in co-ordinating and optimising DER. This case study show conclusively how we can use dynamic operating envelopes to manage the behaviour of solar PV through a detailed study of two low voltage feeders in the Essential Energy Network.

5 Detailed Case Study – Enabling Solar Generation

This case study will demonstrate how dynamic operating envelopes can benefit customers with residential PV solar systems without breaching physical or technical network limits. The case study is undertaken for the low voltage networks downstream of the 2-989150 and 2-985358 distribution transformers, on the CPM3B3 (Port Macquarie) feeder. High solar penetration on both LV segments with large PV systems has resulted in breaches of physical and operational limits of the network. These breaches have mostly been the breaching of thermal limits of fuses on the low voltage side of the distribution transformers. These breaches demonstrate that the current 5 kW inverter limit per customer is not adequate for these network sections. To avoid thermal overload issues the network operator has until now resorted to restricting the output of some solar PV customers.

This case study analyses the actions that could be taken to increase the total useful PV generation on the LV segments of interest while ensuring that network operates within its physical limits. The case study also demonstrates how the effective hosting capacity of the LV network segments can be maximised using operating envelopes.

5.1 Case Study Details

The LV network segments being analysed in this case study are the electrical network for a retirement village and comprise mostly residential premises. Figure 11 shows a map view of the entire CPM3B3 Feeder and Figure 12 presents satellite image and topology of the LV sections downstream of the 2-989150 and 2-985358 distribution transformers of interest.

Figure 11. Map view of CPM3B3 Feeder. MV and LV segments are shown in red and blue, respectively.

Figure 12. Satellite view of the LV sections under the distribution transformers being analysed in this case study.

The reasons for choosing this location to undertake this case study are outlined below:

- Both network segments have remarkably high PV penetration, with close to 100% of residents having PV solar systems installed.
- Anecdotally, many of these solar PV customers have large PV systems which were installed without approval from the DNSP.
- The total installed solar PV generation capacity is equivalent to or exceeds the thermal rating of both the distribution transformers.
- The DNSP (Essential Energy) has observed multiple occasions where the LV fuses have blown during hours of peak solar generation as the reverse power flow exceeds the LV thermal rating.
- The entire MV Feeder (CPM3B3) has PV penetration over 50% (523 out of total 994 connection points have solar PV installed) that might be affecting the MV voltage on the primary winding of the distribution transformers during hours of peak solar generation.

Table 1 provides details about the installed solar PV on these LV segments downstream of the transformers of interest. There is anecdotal evidence that the actual solar PV system sizes are likely to be larger than what has been declared to the DNSP and what is shown in Table 1. Figure 13 shows the estimated sizes of the installed PV systems downstream of both distribution transformers. These installed sizes have been estimated based on the maximum observed value in the meter data for each connection point in the network.

Transformer	Number of Households	Households with Solar PV	Total installed solar PV generation capacity - Based on inverter size (kW)	Transformer Thermal Rating (kVA)
2-985358	118	117	>=484.5 *	315
2-989150	86	79	>=292.1 *	315

Table 1. Details about the number of households with solar PV on the LV segments downstream of the two transformers of interest. The * denotes that anecdotal evidence suggest that the actual solar PV system sizes are likely to be larger than what has been declared to the DNSP. The actual size of the installed solar PV systems is estimated from the maximum observed export power value at the connection point and the results are shown in Figure 13.

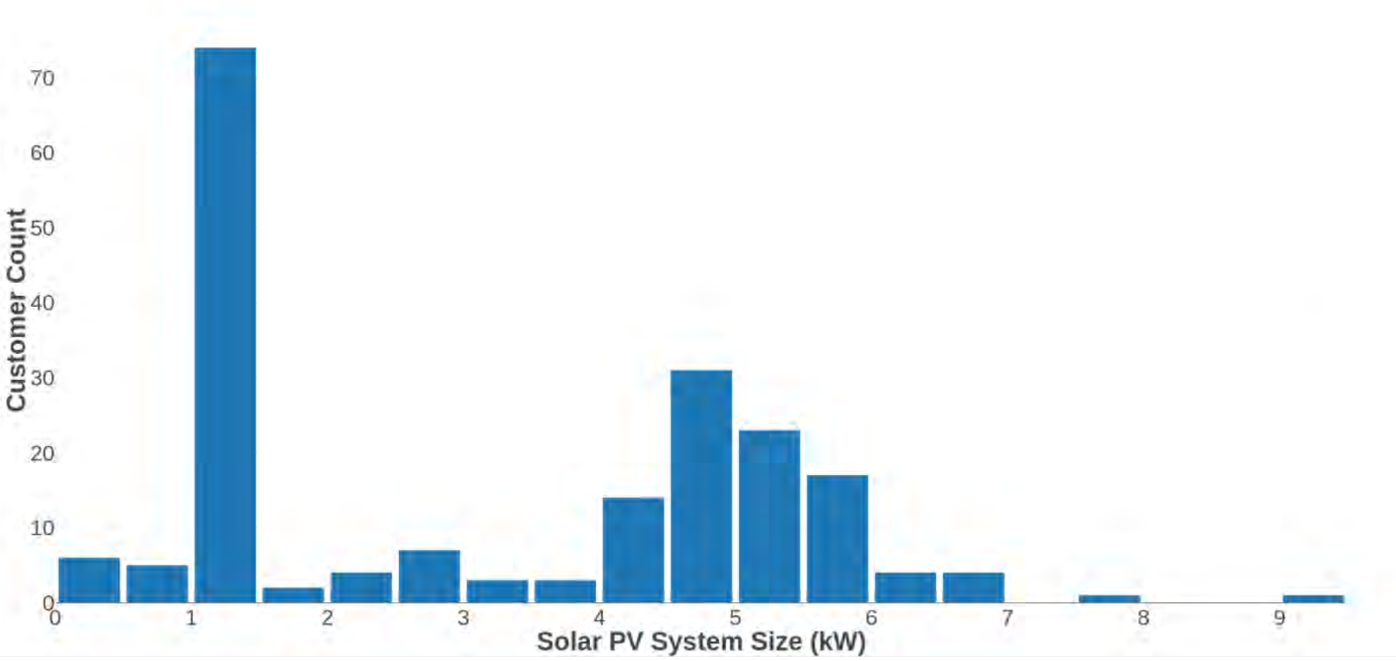


Figure 13. Estimated installed solar PV nameplate capacity for each household across both LV segments. The estimated PV capacity is based on the measured maximum export value of the household.

5.1.1 Physical and Operational Network Limits

Voltage Constraint Definition

Within the distribution network, there are prescribed voltage limits specified. These limits correspond to voltage limits for all connection points within the distribution network at a given voltage level. For this case study, we consider two low voltage segments of electricity distribution network with voltage limits shown in Table 2.

Australian Low Voltage Standards	**Voltage**
Nominal	230V
Upper Limit (+10%) (V_{max})	253V
Lower Limit (-6%) (V_{min})	216V

Table 2. The standard voltage levels for Australian electricity distribution networks

Thermal Constraint Definition

Another primary physical constraint in distribution networks are thermal limits. Thermal limits represent limits on the apparent power in a branch of the electricity distribution network. These limits vary widely depending on the asset type (conductor, transformer, etc) and the asset specifications such as conductor size or transformer type and size.

For this case study we use the distribution transformer rated power (kVA rating) to define the thermal constraints for the two LV network segments being analysed. Crucially, the net power flow through the transformer at any given time should not exceed its rated power. In this study we do not consider thermal losses, reactive power and disallow any loading above nameplate rating, simplifying the thermal constraint to be sum of net active power at all connections point to be less than or equal to the rated power of the corresponding distribution transformer. The rated power of the two distribution transformers in this case study are provided in Table 1.

5.1.2 Network Management Approaches

In this case study we will explore two approaches that DNSPs can take to ensure that the behaviour of the installed solar PV guarantees that the network remains within physical and operational limits. These are respectively; physical inverter curtailment and operating envelopes.

Physical Inverter Curtailment

The first network management approach that DNSPs can take is to physically limit the export of the solar PV inverter to some fixed limit. The chosen limit for our case study is the value determined through a traditional hosting capacity analysis. Household connection points where physical inverter curtailment is used are typically referred to as uncontrollable because once the curtailment is set it cannot be adjusted without visiting the inverter again.

Operating Envelopes

An operating envelope is the connection point behaviour that can be accommodated before physical or operational limits of a distribution network are breached. In this case study we will only be focussed on the export component of the operating envelope, where an export operating envelope is defined as the maximum power that can be exported from a customer connection point. For this case study, we will compare a monthly operating envelope which is a maximum export value for each month of the year with a dynamic operating envelope where the maximum export value is recalculated in each 30-minute interval. Household connection points where operating envelopes are used are typically referred to as controllable because the operating envelope can be adjusted via the communications channel to the inverter or home energy management system.

5.1.3 Case Study Stages

This case study is split into three key stages:

- **Stage 1.** In this stage of the case study we will calculate the hosting capacity of both LV network segments and compare the calculated hosting capacity to the currently installed solar PV generation.
- **Stage 2.** In the second stage of the analysis we will compare the two network management approaches (defined in the previous section) to assess which network management approach achieves the best outcomes for the currently installed solar PV on the LV network segments we are studying. To undertake this comparison we first assume all installed PV is physically curtailed at the inverter and then increase the percentage of households (20%, 50%, 80%) using monthly or dynamic operating envelopes.
- **Stage 3.** In the final stage of the case study we will assess how dynamic operating envelopes can be used to manage significantly greater installed solar PV on the LV network segments we are studying. To undertake this analysis we first assume all installed PV is physically curtailed at the inverter and then increase the percentage of households (20%, 50%, 80%) using a dynamic operating envelope. At the same time we increase the nameplate capacity of the installed solar systems (5kW, 10kW, 15kW and 20kW) where a dynamic operating envelope is enabled.

5.2 Case Study Data, Models and Calculation Methods

To better understand this case study it is necessary to describe the date sources, models and calculation methods that have been used.

5.2.1 Input Data

The following data is used as input into the calculations and analysis conducted in this case study.

Data Category	Details and Description
Topology and network model	• Complete LV topology for the network segments being analysed. • Electrical characteristics of the network segments including: ◦ Phasing, length and impedances of LV conductors. For a small number of the LV conductors used in this case study, the impedance data was incomplete. When this occurred, reasonable default values based on commercially available conductors were used instead. ◦ Power ratings for distribution transformers. ◦ Nominal voltage values for all LV network segments.
Solar PV system	• Solar size (inverter size) • Installation date
Tariffs	• The retail electricity tariff for each customer.
Metering	• Basic • Interval • Three phase meters at LV side of each distribution transformer which provided: ▪ Energy (Import and Export) ▪ Power (W, var, VA) ▪ RMS Voltage

Table 3. Description of the datasets used in the case study

The network topology, network electrical characteristics, and metering data were used as inputs to hosting capacity and operating envelope calculations which are detailed in the following sections. These algorithms are based on an underlying power flow calculation. Tariff data was used to support customer clustering in the load profiling exercise which is further detailed below. Solar PV system data was used to separate the connection point usage into consumption and generation profiles, as well as for load profiling and results analysis. Metering data, including voltage measurements, were used for both load profiling and for validation of the results.

5.2.2 Household Connection Point Model

For this case study, it will be helpful to have a model for each household connection point in the LV network segments being analysed. To this end, we will proceed with the connection point model shown in Figure 14. In this model each connection point includes some load, as well as a potential DER asset which for this case study will be exclusively used to refer to a potential solar PV installation.

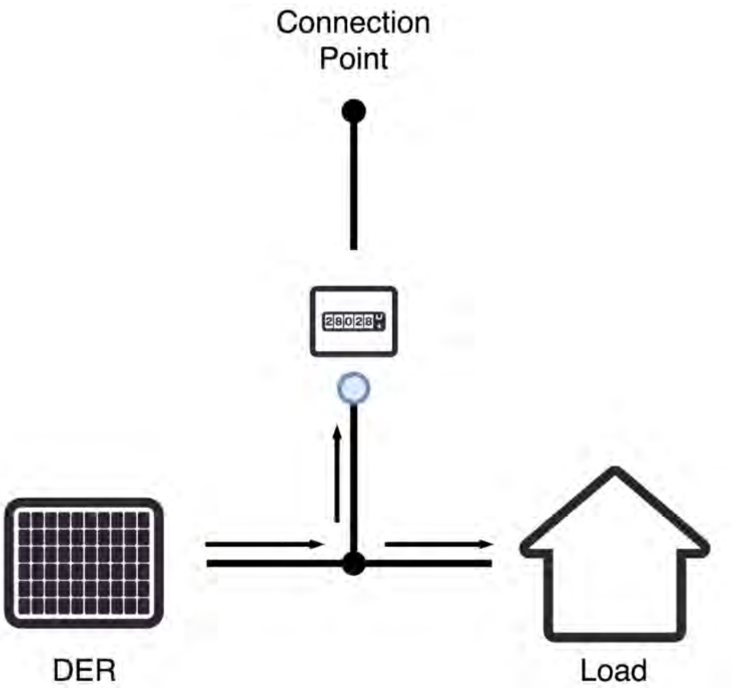


Figure 14 The model of a customer connection point that will be used to support the modelling in this case study. The blue dot in this diagram represents the point where the net power flow to or from the grid is metered.

The mathematical model that we will adopt for the behind the meter (BTM) model of a connection point shown in Figure 14 is given by:

$$G = L + S_c + S_u \quad (1)$$

where:

- G is the total (net) power at a connection point, *'Grid'* power.
- L is the power going to household consumption at a connection point, *'Load'*.
- S is the power generated by onsite solar generation behind a connection point, here *'Solar'*.
- Subscripts u, c denote 'uncontrollable' and 'controllable' portion of each solar component where a controllable solar component corresponds to sites where dynamic operating envelopes are enabled.

The model given in Eqn (1) can be simplified to represent the three possible connection point configurations observed in this case study. These configurations are detailed in Table 4.

Household Connection Point Configuration	Configuration Description
$\boldsymbol{G_u = \mathrm{L}}$ (2)	*'uncontrollable no solar'*, customers have household consumption and no solar.
$\boldsymbol{G_{us} = \mathrm{L} + S_u}$ (3)	*'uncontrollable solar'*, customers have household consumption and uncontrollable solar generation.
$\boldsymbol{G_c = \mathrm{L} + S_c}$ (4)	*'controllable'*, customers have household consumption and controllable solar generation (i.e. an operating envelope).

Table 4. The three household configurations used to undertake this case study.

5.2.3 Connection Point Metering Data

In order to complete the calculations described below (i.e. hosting capacity and operating envelopes), connection point interval metering data is needed for all households at reasonably high frequency (5-minute or 30-minute intervals). However, not all households have smart meters and so we require the synthesis of this interval metering data (i.e. load profiles) for premises that do not have smart meters. The process of generating this interval metering data is called *load profiling*.

For this case study, we have implemented three different methods for load profiling which require different data inputs and results in different accuracy of the synthesised interval metering data.

We assume we have a section of network with multiple premises for which we wish to determine connection point power for each 30-minute interval across some timespan. We have smart meter interval data for a subset of these premises. From this available data, we wish to construct estimates of the interval metering data for the remaining premises where interval metering data is not available. The three load profiling and synthesis methods are described below.

1. ***Only smart-meter data is known***. When we have no information about the unknown premises, we calculate the mean profile across all smart-meter premises and apply this mean load profile to the unknown premise. These are called *mean load profiles*.
2. ***Smart-meter and basic meter data is known***. The initial steps of this method are the same as 1.; we construct a mean profile from all smart-meter premises and apply it to all unknown premises. Since basic meter data is present, we can scale this mean profile based on the average daily export/import from each of the unknown sites. These are called *scaled mean load profiles*.
3. ***Smart-meter, basic meter, and tariff data is known***. The presence of tariff data (or any other grouping metric) allows us to group data with similar consumption profiles. For each of these groups, we apply the method as described in 2., resulting in a scaled mean profile for each group. These are called *group scaled mean load profiles*.

5.2.4 Assumption of independent network segment under each transformer

In the calculation methods described below, we will make use of power flow calculations. When undertaking these calculations, we will assume that the LV network segment connected downstream of each distribution transformer is independent of the upstream feeder. That is, we are solving power flow separately for the network downstream of transformers of interest ignoring the upstream distribution network. The LV connection of the corresponding distribution transformer is set as the slack bus for power flow calculations for each of the LV segments.

5.2.5 Hosting Capacity Calculation Method

Using the connection point models defined in the equations (2) - (4), we can describe our calculation method of Hosting Capacity in this section and Operating Envelopes in the following section.

To calculate the hosting capacity of all households in the LV network segment we assume that all connection points can be modelled using Eqn (3). At each connection point we then assign a relevant underlying demand profile for each 30 minutes interval. These load profiles are either determined by the interval smart data for that connection point, or are calculated using the load profiling method outlined previously in this report.

In this calculation of hosting capacity we are seeking to calculate the amount of solar that each connection point can host. We explicitly make the assumption that the hosting capacity at each connection point is identical. Explicitly, we are seeking an equal allocation of the hosting capacity for each LV network segment we are investigating in this case study. We note that we are note seeking the hosting capacity to be equal between the two network segments, only within each network segment separately.

For each time interval, the hosting capacity algorithm will progressively increase the magnitude of the solar installed at each connection point until either the thermal or voltage limits of the network are breached. The smallest such hosting capacity value calculated over all connection points and all time intervals is the hosting capacity for the one year duration of the case study which is based on data from 2020.

Figure 15 shows the solution flow diagram for the hosting capacity calculation.

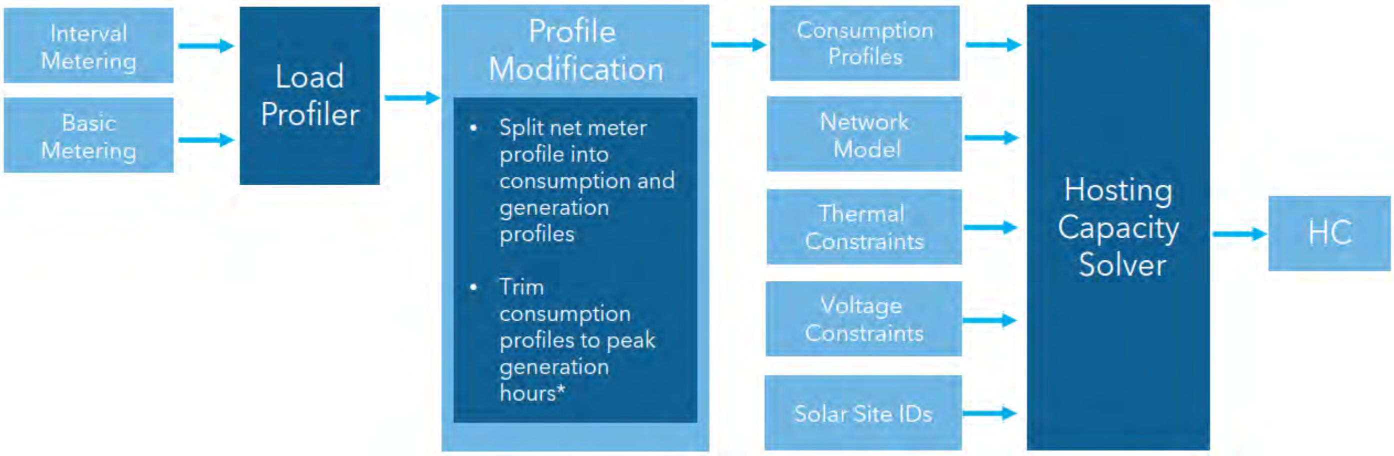


*Figure 15. Solution Flow Diagram for Hosting Capacity Calculation. * Under the assumption that the peak generation occurs between 10am-4pm daily, we calculate the hosting capacity value using the consumption profiles corresponding to this time interval each day. This is necessary to avoid an overly conservative hosting capacity value based on close to zero underlaying consumption during the night.*

5.2.6 Operating Envelopes calculations

To calculate the operating envelope we must first determine the number of connection points at which we assume operating envelopes are being applied. In this case study we calculate operating envelopes for various scenarios including when 20%, 50%, and 80% of sites are using operating envelopes.

For each scenario, we assume that for sites not enabled for operating envelopes, that the site can be modelled using either Eqn (2) or Eqn (3) which corresponds to sites with no solar, or sites with uncontrollable solar. For sites with uncontrollable solar, the maximum magnitude of the solar generation is assumed restricted to the hosting capacity value calculated for that LV voltage segment. That is where a value in a generation profile for uncontrollable site exceeds the hosting capacity value, it is set to the hosting capacity value. In practice, this restriction would be achieved using the physical inverter curtailment previously described. An example of how this assumption is applied can be seen in Figure 16.

Figure 16. Example of the connection point load profile for a randomly chosen site where generation was capped at the hosting capacity value. In this image, the original profile represents the net connection point power (consumption + generation) as per meter data. The modified profile represents the net connection point power after the generation profile is capped at the hosting capacity value while consumption profile is left unmodified (original consumption + capped generation)

Based on the percentage of sites using operating envelopes, the operating envelope algorithm progressively increases the operating envelope at each site until a voltage or thermal limit is breached. We explicitly make the assumption that the operating envelope at each connection point enabled for operating envelopes is identical. This represents an equal allocation of the network capacity being allocated to each connection point in the LV segment being analysed. We also note that we only calculate active power operating envelopes in this case study.

Figure 17 shows solution flow diagram for operating envelope calculation.

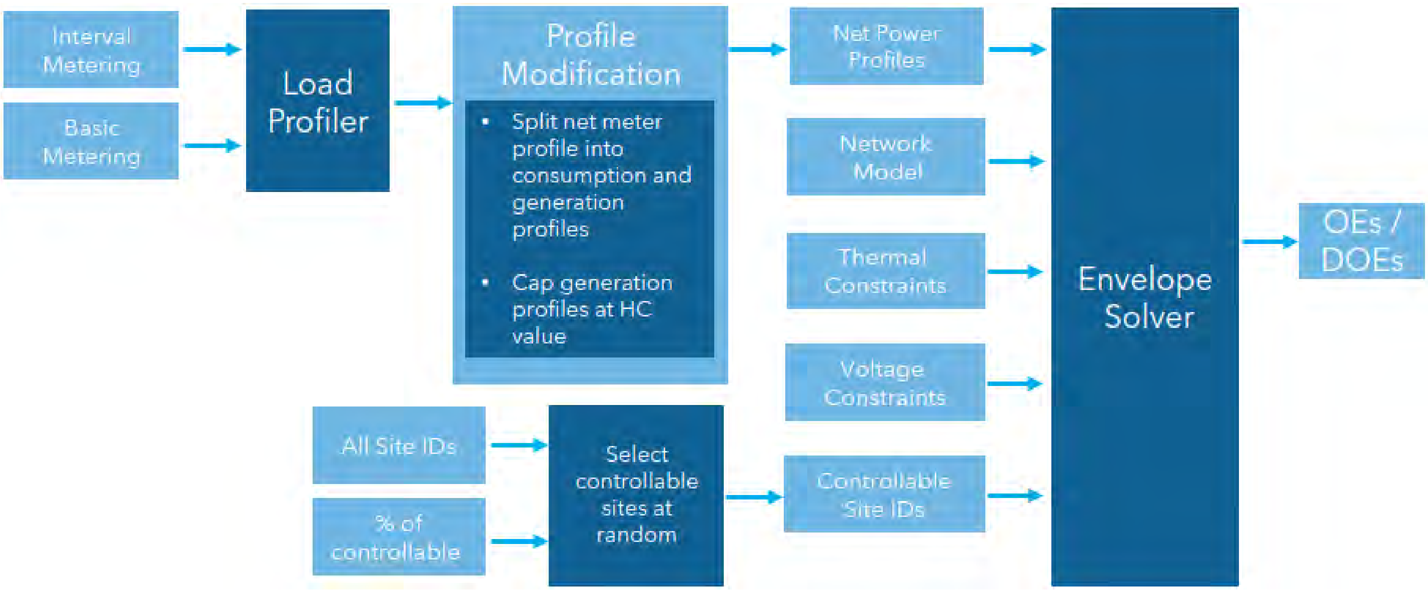


Figure 17. Solution Flow Diagram for Operating Envelopes calculation.

5.2.7 Varying solar size for controllable systems

To understand how operating envelopes can increase the amount of solar PV that can be accommodated in electricity distribution network, the final stage of this case study is to investigate increasing the nameplate capacity of installed solar PV at households where dynamic operating envelopes are used.

For each iteration we take a set of controllable sites, 20%, 50% and 80% controllable sites match those chosen for the operating envelope calculations. We then scale the corresponding generation profiles to a new nameplate capacity. Starting at 5kW, we also test increasing the nameplate capacity to 10kW, 15kW and 20kW. An example of these scaled generation profiles can be seen in Figure 18. Consistent with the operating envelopes calculations detailed previously, all uncontrollable solar generation is assumed to be capped at the per site hosting capacity value.

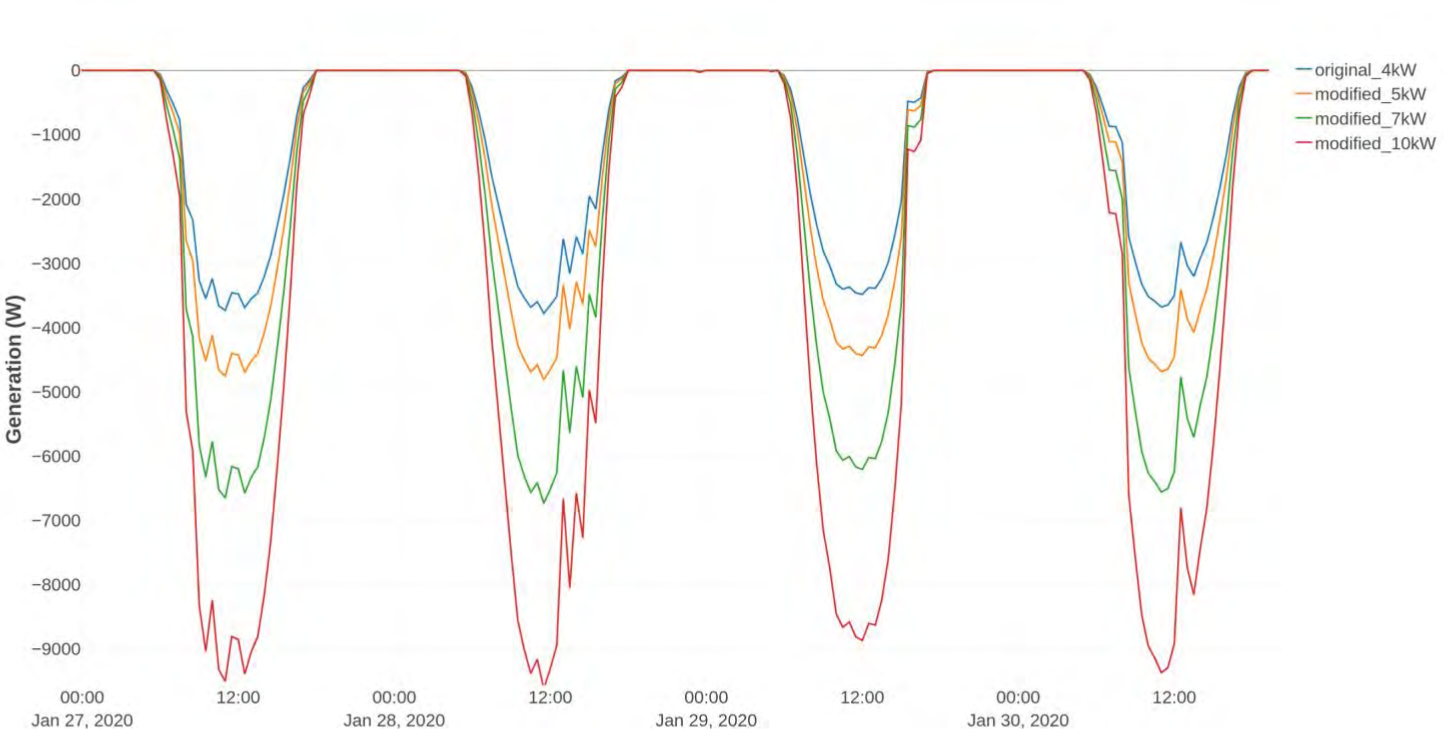


Figure 18. Example scaled generation profile for random controllable site

Figure 19 shows the solution flow diagram for calculation of the total energy export through each of the distribution transformer considering varying size of solar systems for controllable sites.

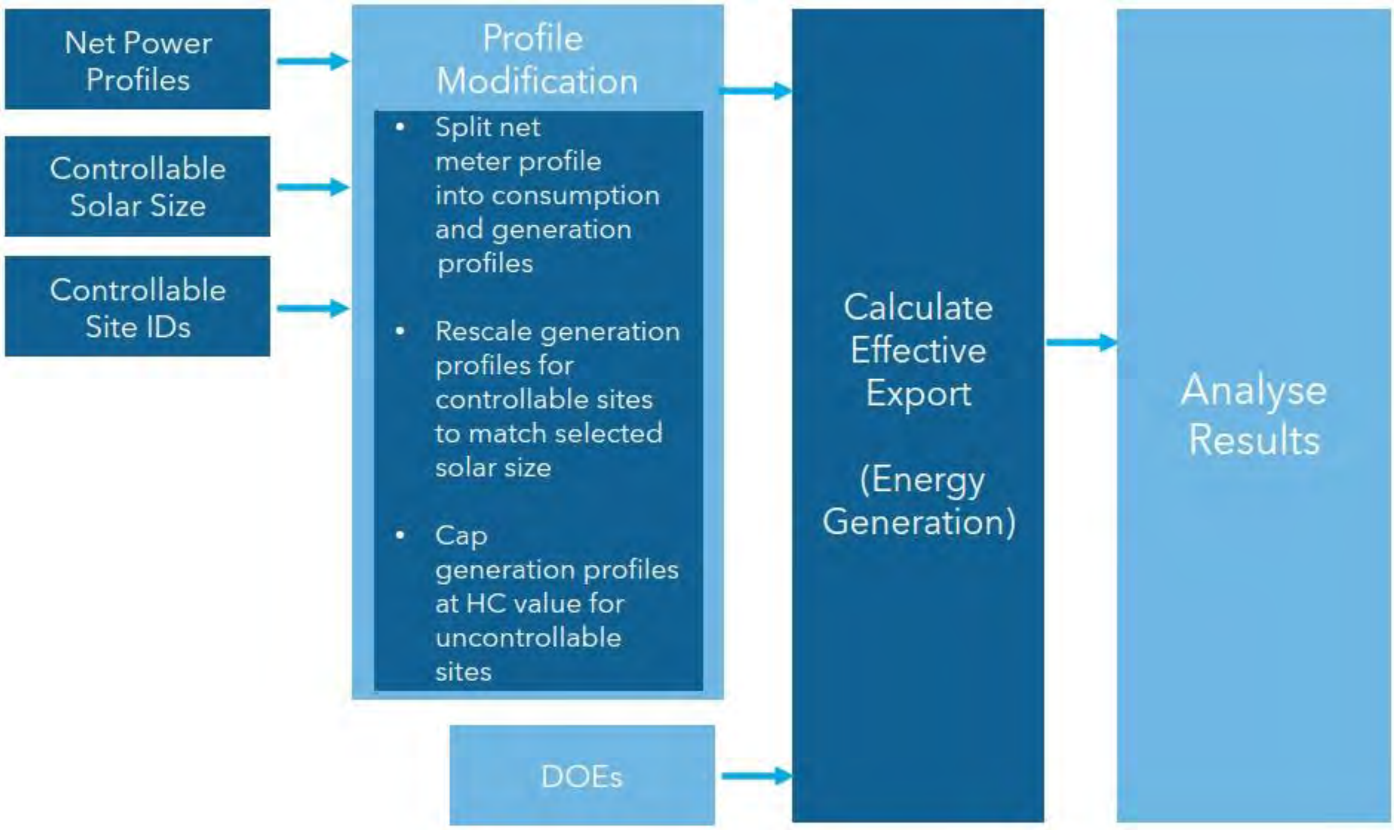


Figure 19. Solution Flow Diagram for varying solar PV size

5.3 Case Study Results

In the following sections, the results of the case study are presented. We compare the results of the different cases and scenarios on the basis of net annual energy export, as in all cases the network voltage and thermal limits are always adhered to.

5.3.1 Voltage Sensitivity Study

In Australia the nominal LV voltage in the distribution network is usually assumed to be between 230V – 240V. However, from the meter data available for this case study (see Table 5 below), we can observe that the mean LV voltage on both transformers is approximately 245V.

Transformer	Mean	Min	10th Percentile	50th Percentile	90th Percentile	Max
2-989150	244.85	241.15	243.40	244.85	246.33	249.11
2-985358	244.89	241.47	243.56	244.97	246.11	248.19

Table 5. Distribution of measured voltage values at the secondary connection of the distribution transformers

To understand the implications of this voltage setpoint in our calculation of hosting capacity and operating envelopes we undertake a voltage sensitivity analysis. To complete this sensitivity analysis we assume that the underlying consumption at all connection points is zero. We then calculate the hosting capacity to identify how the binding constraint changes depending on the slack bus voltage.

We calculate the hosting capacity for when the slack bus voltage is 230V, 240V and 245V. Table 6 shows how the slack bus voltage impacts the binding constraint for each LV segment downstream of the distribution transformers of interest. We can see that 2-985358 is always thermally constrained, thus the voltage on the LV side of the transformer will not fundamentally alter the calculated hosting capacity of this network segment. In contrast, we can see that for 2-989150, a distribution transformer voltage of 245V results in the network being voltage constrained. Should the DNSP be able to reduce the voltage on the LV side of the distribution transformer then there may be additional hosting capacity available, a result that can be inferred from the hosting capacity calculations reported in the following section.

Transformer ID	Slack Bus Voltage Setpoint	Binding Constraint (Import)	Binding Constraint (Export)
2-989150	230	Voltage Limits	Thermal Limits
	240	Thermal Limits	Thermal Limits
	245	Thermal Limits	Voltage Limits
2-985358	230	Thermal Limits	Thermal Limits
	240	Thermal Limits	Thermal Limits
	245	Thermal Limits	Thermal Limits

Table 6. Voltage sensitivity of the dominant constraint for each transformer

5.3.2 Hosting Capacity Study

Using the calculation methods outlined previously, the hosting capacity of both LV networks segments is calculated and the results can be found below in Table 7.

Transformer ID	Voltage Setpoint for Slack Bus	Calculated Hosting Capacity (Watts)
2-989150	245V	2930
2-985358	245V	3172

Table 7. Calculated Hosting Capacity value per site (in Watts) for the LV segment downstream of the indicated transformer.

As noted previously, the binding voltage constraint on the LV segment downstream of the 2-989150 distribution transformer is the likely explanation for the reduced hosting capacity when compared with the slightly increased hosting capacity for the LV network segment downstream of the 2-985358 transformer.

The histogram shown in Figure 20 demonstrates why the DNSP is already observing instances of physical and operational limits being breached in the LV network segments being investigated in this case study. Whilst the hosting capacity in both network segments is approximately 3kW (3000W), there are significant observed instances in the 2020 data set when individual sites are generating in excess of this hosting capacity value. Whilst an individual site being above the hosting capacity limit may not be problematic, the high correlation in solar generation from sites in close physical proximity means that it is likely that these occurrences of high generation are highly correlated and thus explain the observed voltage and thermal constraint violation described earlier in this case study.

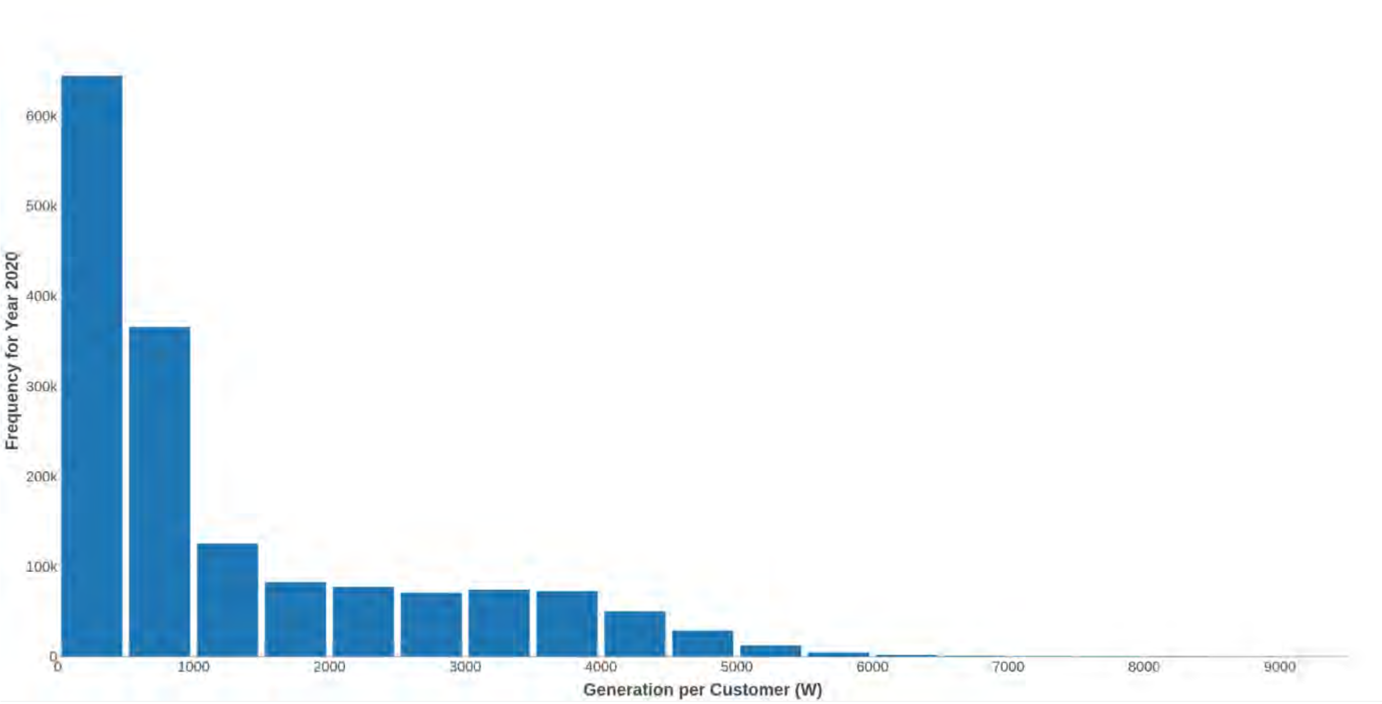


Figure 20. Instances of observed generation per site (in Watts) for both LV network segments based on 2020 generation profiles. From this histogram it is clear that there are many instances when the generation at indiviul sites exceeds the maximum hosting capacity value calculated in Table 7. This histogram explains why the DNSP is already observing instances of physical and operational limits being breached in these LV network segments.

We investigate the occurrences of solar generation breaching the hosting capacity value in further detail in Table 8 and Table 9. In Table 8, we calculate the percentile of the generation occurrences above the hosting capacity limit. In Table 9, we calculate the total number of customers with solar where observed generation exceeds hosting capacity value at least once during 2020.

Table 9 clearly demonstrates that about 50% of all customers with solar on both substations observed actual generation (throughout 2020) that exceeds the calculated hosting capacity value, and the majority for more than 200 days per year. This observation is consistent with breaches of the thermal constraints reported by the network operator and confirms the importance of a timely intervention by the DNSP to ensure that the network segment can operate within its physical and operational constraints.

Transformer ID	Mean	10th Percentile	50th Percentile	90th Percentile	Max
2-989150	863	146	707	1793	4583
2-985358	1073	187	937	2000	6343

Table 8. Distribution of generation instances greater than the calculated hosting capacity. All values in Watts.

Transformer ID	Total number of customers with solar	Total number of customers with solar where observed generation exceeds hosting capacity value (at least once over 2020)
2-989150	79	35 (~44%)
2-985358	117	65 (~56%)

Table 9. Number of solar sites on each LV network segment where observed generation exceeds the calculated hosting capacity.

As discussed previously in this report, we will compare various network management approaches. The first of these approaches is to implement a fixed physical curtailment by resizing the inverters (or updating inverter settings) so that it matches the calculated hosting capacity values for each network segment. Assuming the generation at all solar sites is capped at the calculated hosting capacity value, we can then calculate the total energy generation over one-year period prior to, and after, this intervention.

The results shown in Table 10 demonstrate that physical curtailment based on the hosting capacity value would reduce total generation export at the transformer by 15-20%. Such a radical reduction in generation output highlights the very conservative, and unnecessary, restrictions that fixed physical curtailment could result in. It is for this reason that we investigate how the physical and operational network constraints could be better managed using operating envelopes. We investigate monthly and dynamic operating envelopes in the following sections.

Transformer ID	Upstream energy export through transformer (MWh)	Upstream energy export through transformer under fixed inverter curtailment at the hosting capacity value (MWh)	Energy curtailed due to fixed inverter curtailment (MWh)
2-985358	415.426	352.099	62.039
2-989150	247.258	200.189	49.153

Table 10. A comparison of the total energy export through each distribution transformers prior to, and after, fixed inverter curtailment.

5.3.3 Monthly Operating Envelopes

We choose one-month resolution for the monthly dynamic operating envelopes. The export monthly operating envelopes are presented in Figure 21 for each network segment when 20%, 50%, and 80% of all solar sites are controllable (i.e. will have dynamic operating envelopes enabled).

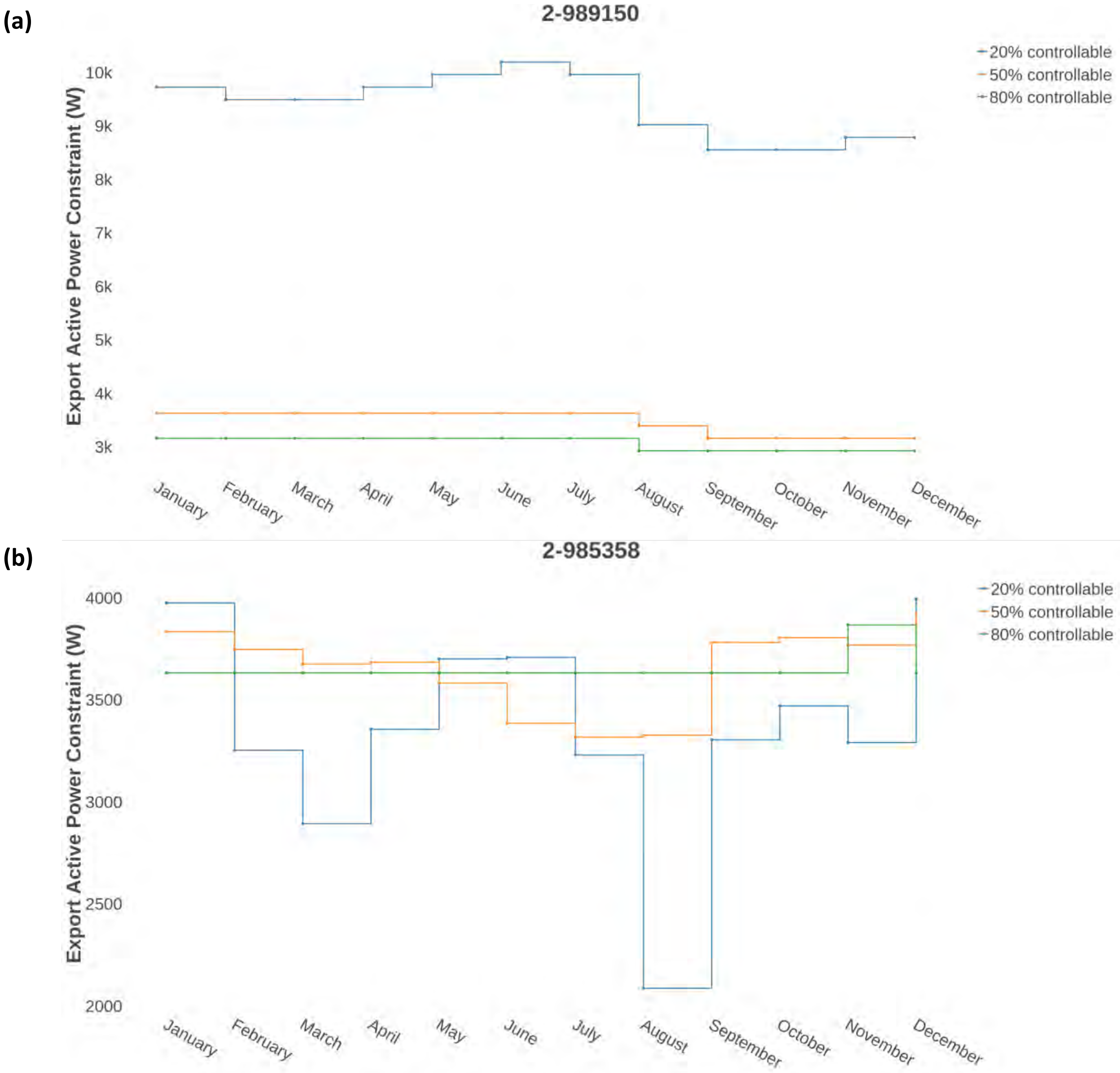


Figure 21. Monthly dynamic operating envelopes calculated with varying percentage of controllable solar system, for each of the network segments of interest.

Similar to the hosting capacity results discussion, we can calculate the effective upstream energy export through each transformer, assuming that at all controllable sites the export is curtailed at the monthly operating envelope value while at all uncontrollable solar generation is physically curtailed at the hosting capacity value. The net yearly energy export through each transformer under varying percentage of systems following monthly operating envelope is given in Table 11 and the energy lost due to curtailment is shown in Table 12. We can see that using monthly operating envelopes allows to achieve an increase in the net energy export through each transformer and reduce energy export loss due to curtailment.

An interesting point to note can be seen in Table 11, where we observe that the total upstream energy generation at 80% of sites using monthly dynamic operating envelopes is slightly less than the corresponding value when 50% of sites use dynamic operating envelopes. Our analysis indicates that this reduction is due to a reduction in available network capacity due to the congestion caused by highly correlated solar generation. Such an effect is not unexpected and highlights the importance of investigating the role that residential and neighbourhood battery storage will play in storing solar generation that might otherwise be curtailed.

Transformer	**Total upstream energy export through transformer when using monthly dynamic operating envelopes (MWh)**			
	% of controllable sites where monthly dynamic operating envelopes are enabled.			
	*0 **	*20*	*50*	*80*
2-985358	*352.099*	*356.753*	*371.466*	*388.777*
2-989150	*200.189*	*210.434*	*215.522*	*214.249*

*Table 11. Total upstream energy export at each transformer (in MWh) when monthly dynamic operating envelopes are enabled. *0% controllable column results refer to the case when generation at all solar sites used fixed inverter curtailment at the hosting capacity value and corresponds to the values in Table 10.*

Transformer	**Energy curtailed when using monthly dynamic operating envelopes (MWh)**			
	% of controllable sites where monthly dynamic operating envelopes are enabled.			
	*0**	*20*	*50*	*80*
2-985358	*62.039*	*57.384*	*42.671*	*25.360*
2-989150	*49.153*	*38.907*	*33.819*	*35.092*

*Table 12. Total energy curtailed (in MWh) when monthly dynamic operating envelopes are enabled.. *0% controllable column results refer to the case when generation at all solar sites uses fixed inverter curtailment at the hosting capaci*ty value *and corresponds to the values in Table 10.*

5.3.4 Dynamic Operating Envelopes

To allow even greater flexibility in active export management per interval, dynamic operating envelopes can be applied to controllable systems. We choose 30 minutes resolution for the Dynamic Operating Envelopes in this study. The export DOEs are presented in Figure 22 for each of the transformers with 20%, 50%, and 80% of all solar sites set to be controllable with dynamic operating envelopes enabled.

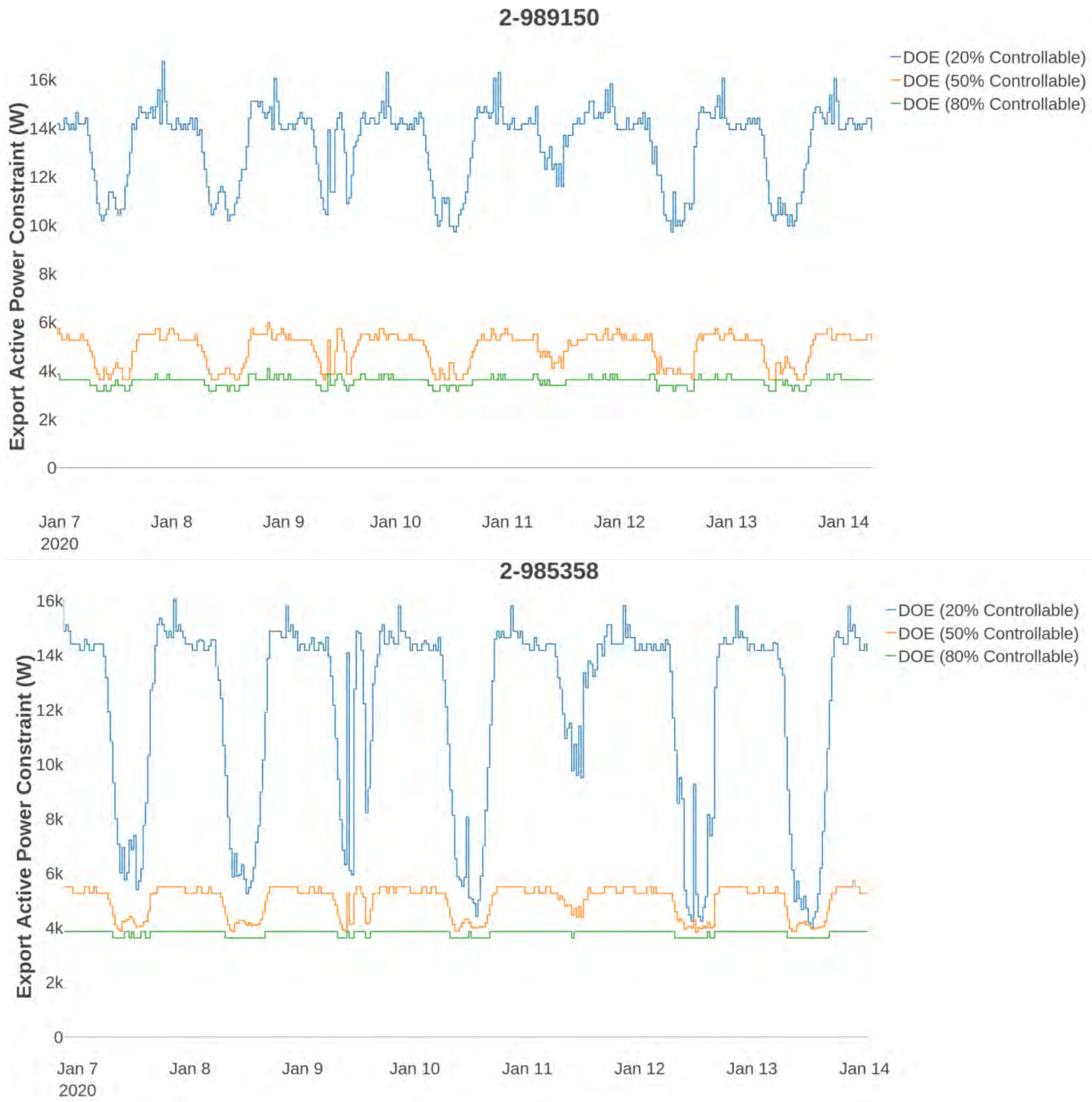


Figure 22. Illustration of DOEs (export active power constraint only) with varying percentage of controllable sites for one week in summer 2020.

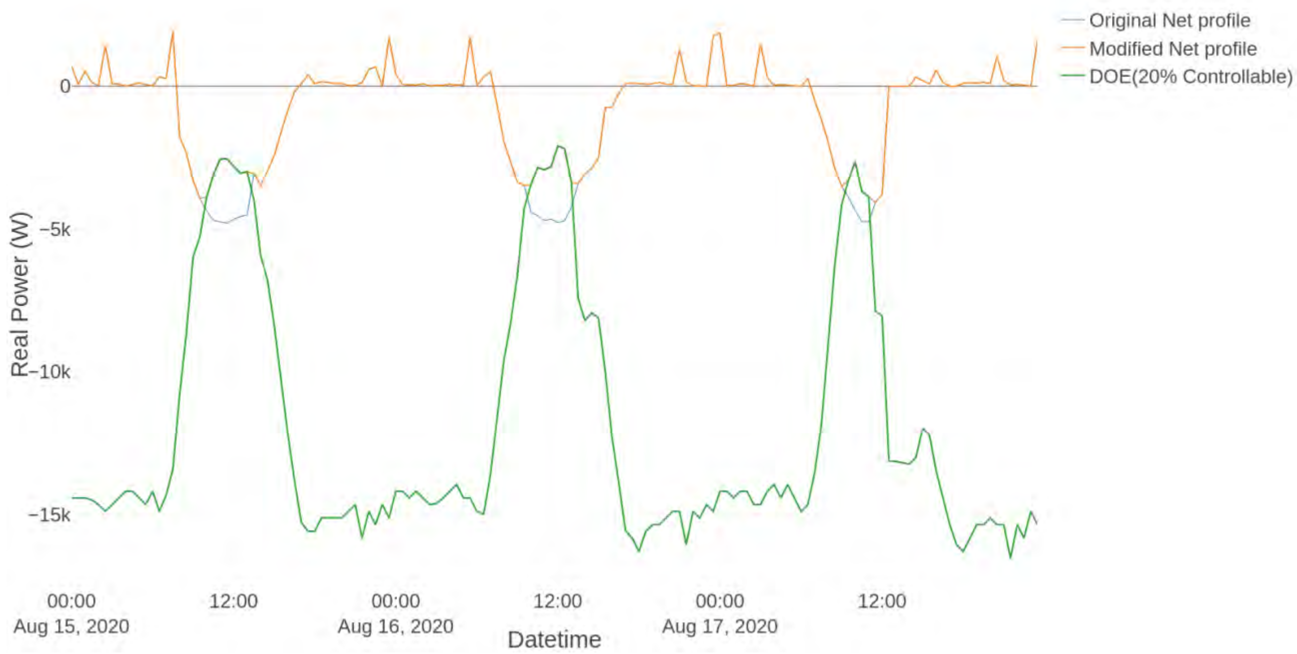


Figure 23. Illustration of a net power profile at a randomly chosen controllable site compared to DOE export constraint. In this image, the original profile represents the net connection point power (consumption + generation) as per meter data. The DOE constrained profile represents the net connection point power after net export at the connection poit is capped at DOE value while the net import value is left unmodified.

The net yearly upstream energy export through each transformer under varying percentage of systems with 30 minute dynamic operating envelopes enabled is shown in Table 13 and the energy lost due to curtailment with DOEs enabled in shown in Table 14. As observed previously in the monthly dynamic operating envelope results, we also see a slight reduction in total energy export as a high percentage of sites move to dynamic operating envelopes and there is considerable congestion in the network caused by the highly correlated energy export. It is worth noting that this is only observed in the 2-989150 network segment which we have previously noted is voltage constrained. Once again, these results motivate further investigations as to the role of both residential and neighbourhood batteries for soaking up this excess solar generation.

Transformer	**Total upstream energy export through transformer when using 30 minute dynamic operating envelopes (MWh)**			
	% of controllable sites where 30 minute dynamic operating envelopes are enabled.			
	*0 **	*20*	*50*	*80*
2-985358	*352.099*	*361.412*	*374.213*	*389.603*
2-989150	*200.189*	*210.434*	*219.504*	*218.133*

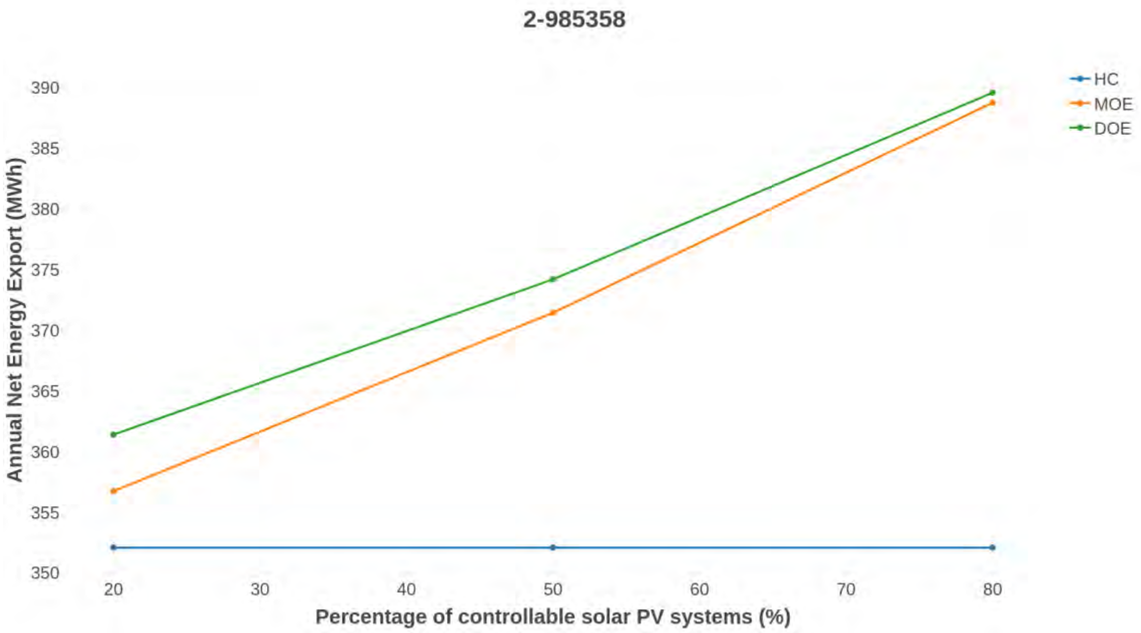
*Table 13. Total upstream energy export at each transformer (in MWh) when 30 minute dynamic operating envelopes are enabled. *0% controllable column results refer to the case when generation at all solar sites used fixed inverter curtailment at the hosting capacity value and corresponds to the values in Table 10.*

Transformer	**Energy curtailed when using 30 minute dynamic operating envelopes (MWh)**			
	% of controllable sites where 30 minute dynamic operating envelopes are enabled.			
	*0**	*20*	*50*	*80*
2-985358	*62.039*	*52.725*	*39.925*	*24.534*

2-989150	*49.153*	*38.907*	*29.837*	*31.209*

*Table 14. Total energy curtailed (in MWh) when 30 minute dynamic operating envelopes are enabled.. *0% controllable column results refer to the case when generation at all solar sites uses fixed inverter curtailment at the hosting capacity value and corresponds to the values in Table 10.*

Figure 24 shows comparative plots of total upstream energy export through each transformer when different network management approaches are used. What is clear is that both monthly and 30 minute dynamic operating envelopes result in far greater energy export, whilst still ensuring that physical and operational network limits are not breached. As might be expected, 30 minute dynamic operating envelopes unlock even greater energy export than monthly dynamic operating envelopes. The marginal difference between monthly and 30 minute dynamic operating envelopes suggest there is greater benefit to the seasonal changes in the underlying demand rather than intra-day changes to underlying demand, given the current installed DER capacity. As we will explore in the final section, 30 minute DOEs provide further benefits.



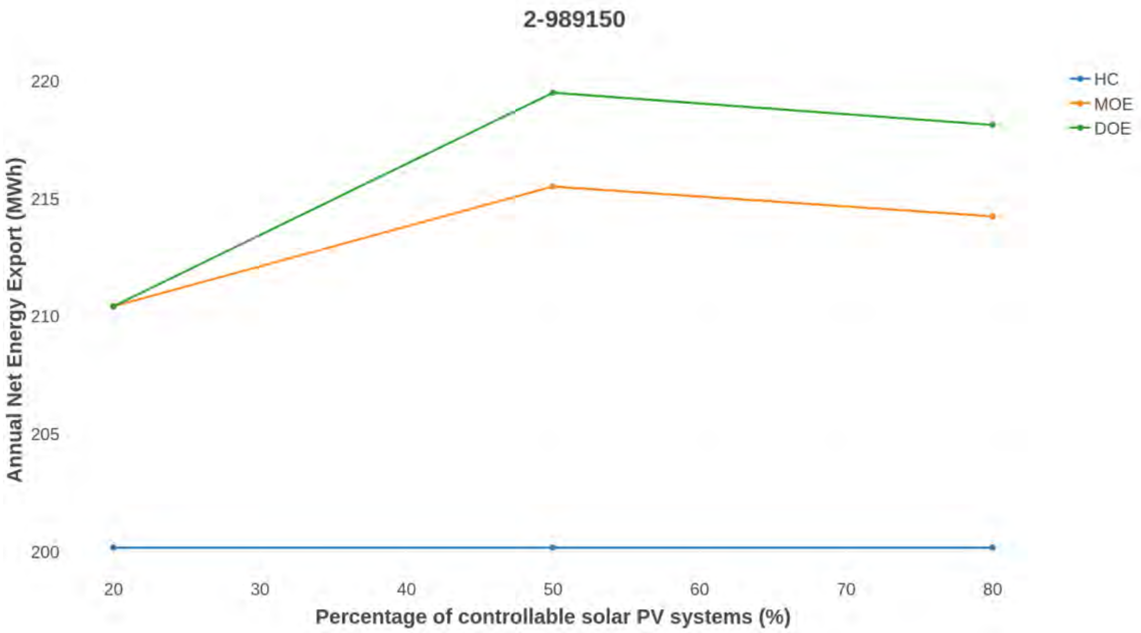


Figure 24. Total upstream energy export at each transformer (in MWh) based on the three network management approaches explored in this case study.

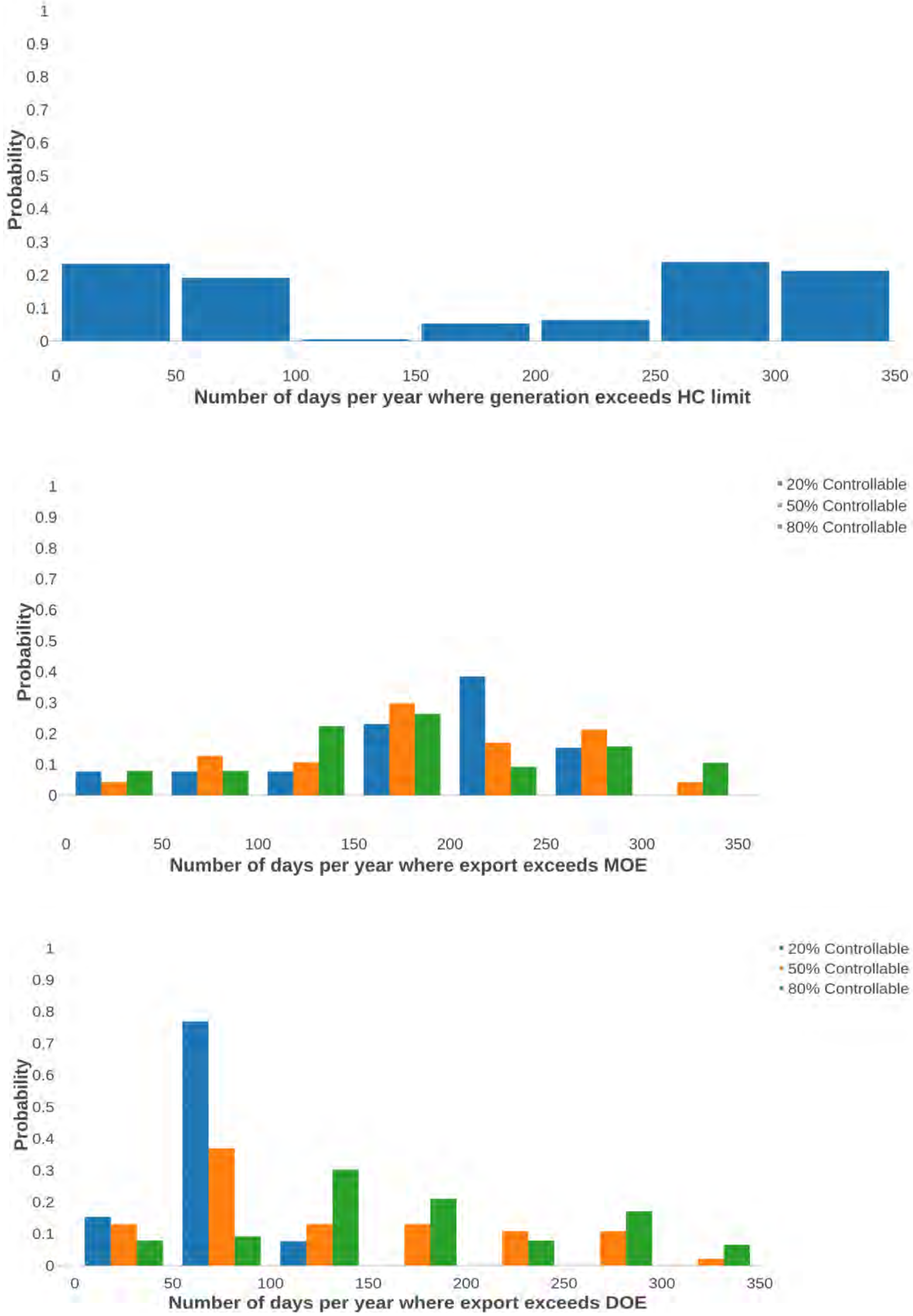


Figure 25 Comparison of the number of days where solar curtailment is necessary for different network management approaches. Crucially, we observe that for dynamic operating envelopes, both monthly and 30 minute, the instances of curtailment are far fewer, which corresponds to the significantly reduced curtailment necessary when dynamic operating envelopes are used to ensure that physical and operational network limits are not breached.

5.3.5 Varying solar size for controllable systems

One of the main advantages of dynamic operating envelopes is that they do not limit the allowed size of the installed solar on a controllable site, unlike physical inverter curtailment that requires a hard physical limit to solar generation. Using this feature of DOEs, a customer may install a large system, still following the DOEs but taking advantage of extra solar generation and export out of peak curtailment region by 'filling' the envelope. In the final section of this case study we investigate the role that DOEs can play in supporting the installation of larger solar nameplate capacities that are then managed using DOEs. Figure 26 shows multiple net load profiles for the same controllable site, where consumption remains the same but the solar generation curve is scaled to simulate increasing the installed nameplate capacity of solar PV.

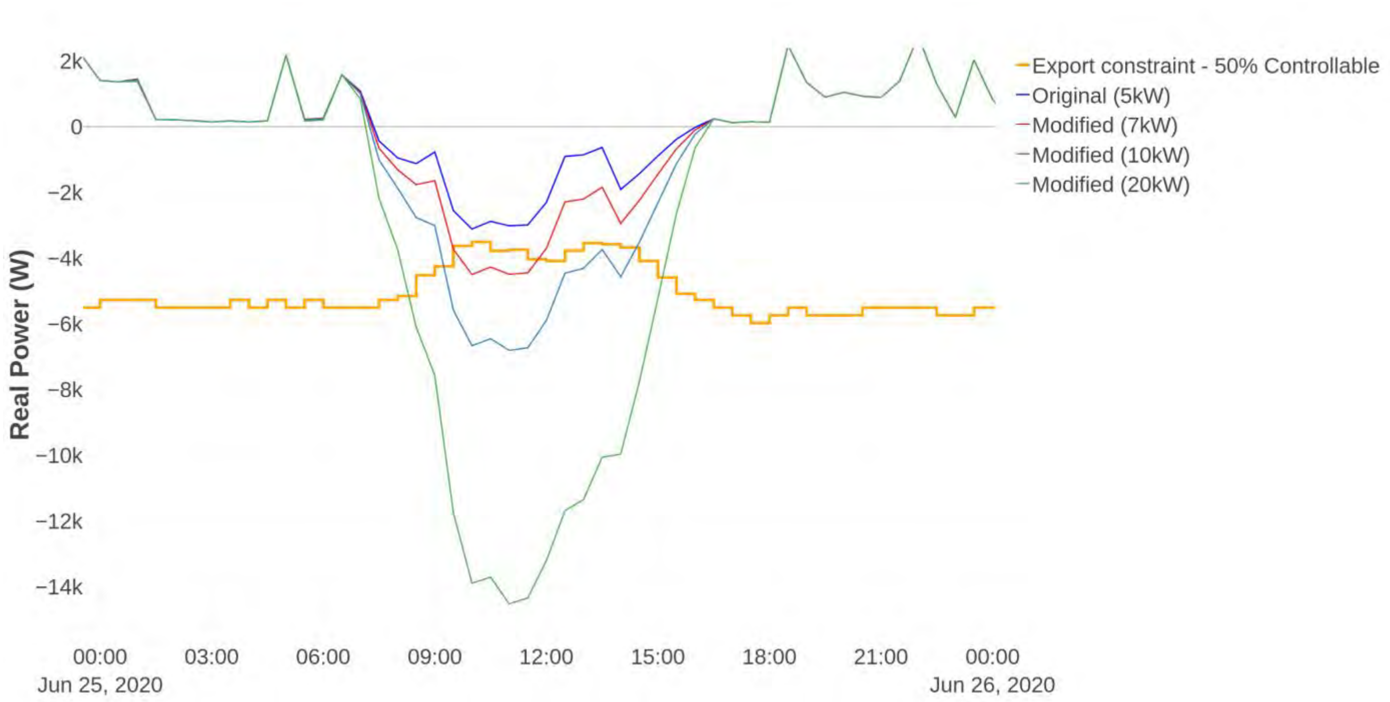


Figure 26. One-day export profile for varying installed solar size and the corresponding DOE. It is interesting to note that the extra solar generation starts to fill out the envelope, particularly in the shoulder period of generation. It is for this reason that dynamic operating envelopes can unlock additional generation, whilst still ensuring that physical and operational network constraints are not breached.

In this stage of the study, we aim to analyse the change in net energy export through a transformer for scaled up solar size on the controllable sites and increasing number of controllable solar systems.

For each combination of nameplate capacity of solar on each controllable site and percentage of controllable sites, the following steps are performed:

a. The solar generation on all non-controllable sites is assumed physically limited at the inverter to the calculated hosting capacity values given in Table 10 (assuming the generation is limited by the inverter sizing/settings).
b. The solar generation on all controllable sites generation are scaled to the increased nameplate capacity being simulated.
c. For each controllable site the connection point export value is restricted to corresponding DOEs for that site.
d. The effective connection point behaviour for each site, at each timestep, are used to calculate the total annual upstream energy export through the transformer.

Table 15 shows the calculated net energy export for each transformer for number of controllable solar systems 0%, 20%, 50%, 80% with nominal nameplate capacity of solar on controllable sites varying from 5kW to 20kW.

	Export (MWh) 2020 with varying % of controllable				
	% of controllable sites where 30 minute dynamic operating envelopes are enabled.	0	20	50	80
Transformer	**Controllable System Size (kW)**				
2-985358	Original System Size as analysed in Table 13.	352.099	361.412	374.213	389.603
	5		421.331	525.910	613.093
	7		481.793	636.737	782.033
	10		549.152	734.071	927.069
	15		625.612	823.720	1047.688
	20		677.487	878.696	1115.002
2-989150	Original System Size as analysed in Table 13.	200.189	210.434	219.504	218.133
	5		256.262	344.348	417.168
	7		305.980	419.627	507.199
	10		381.008	482.844	581.372
	15		487.383	540.617	646.886
	20		547.828	576.643	685.403

Table 15. Total export (MWh) over 2020 with varying controllable solar system size and % of controllable sites per transformer.

We can see that with increasing size of installed solar on controllable sites we can gain more energy export while adhering to the same dynamic operating envelopes. However, the growth in export gain reduces as we move towards the larger solar sizes and will eventually saturate when the entire operating envelope is *'filled in'*. Figure 27 and Figure 28 provide plots of energy export versus size of each controllable system for each network segment being analysed.

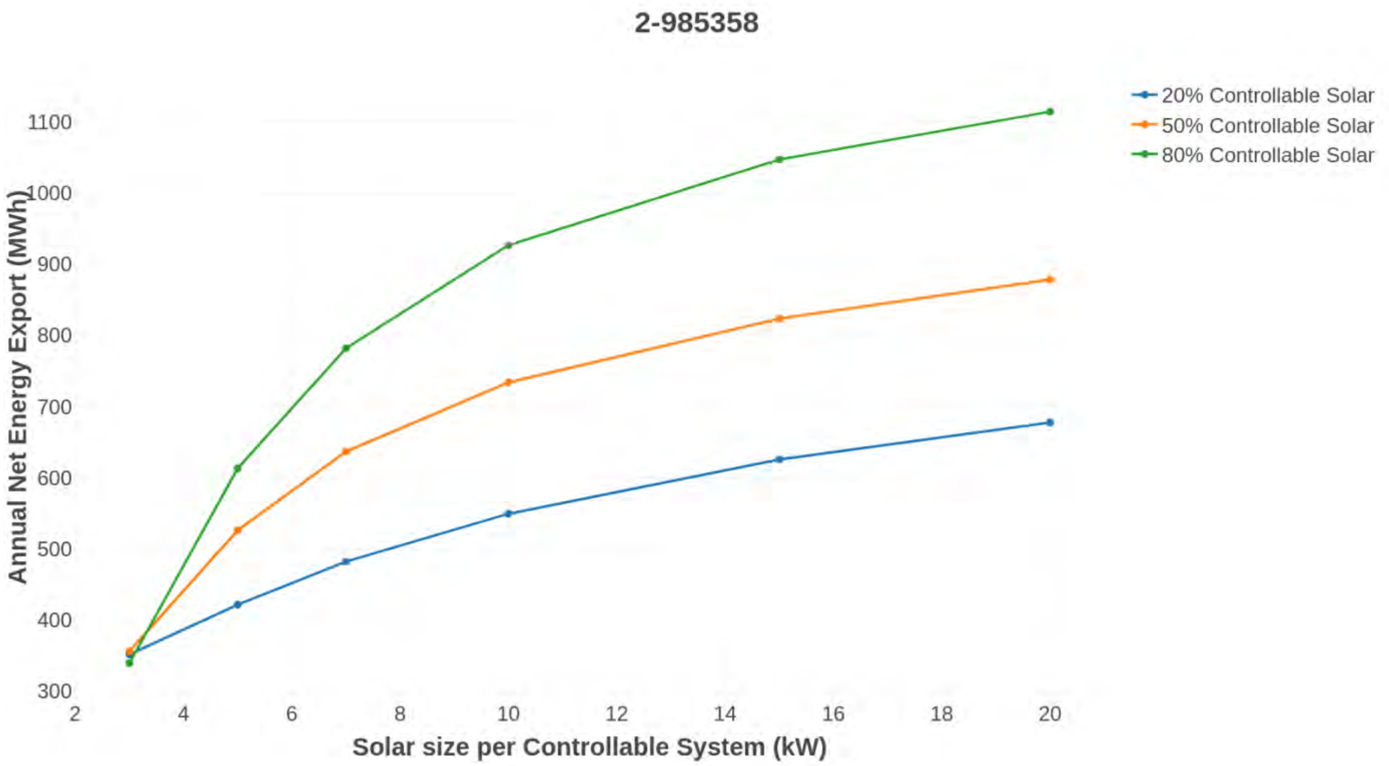


Figure 27. Trend of Annual Net Energy export through transformer 2-985358 over one-year period for increasing solar size on controllable sites

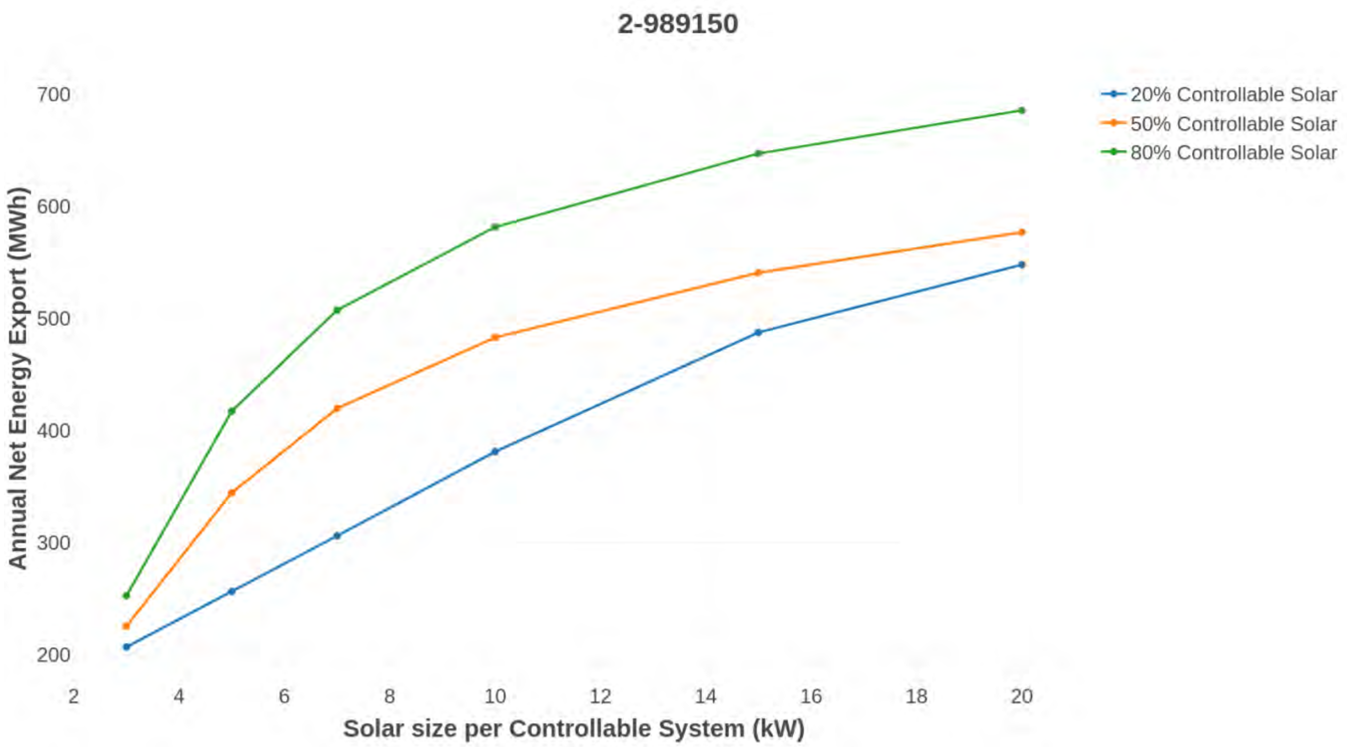


Figure 28. Trend of Annual Net Energy export through transformer 2-989150 over one-year period for increasing solar size on controllable sites

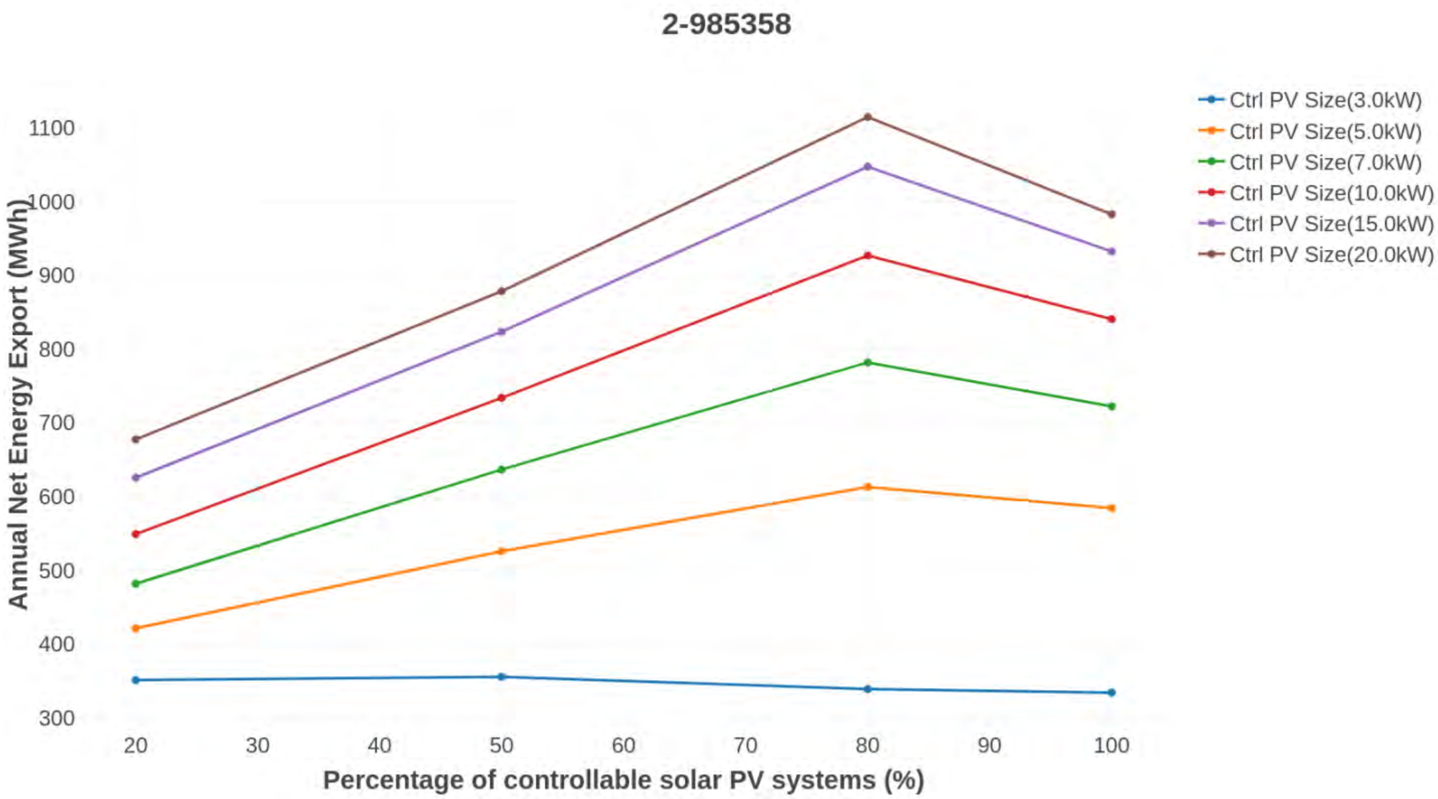


Figure 29. Trend of Annual Net Energy export through transformer 2-985358 over one-year period for increasing number of controllable sites

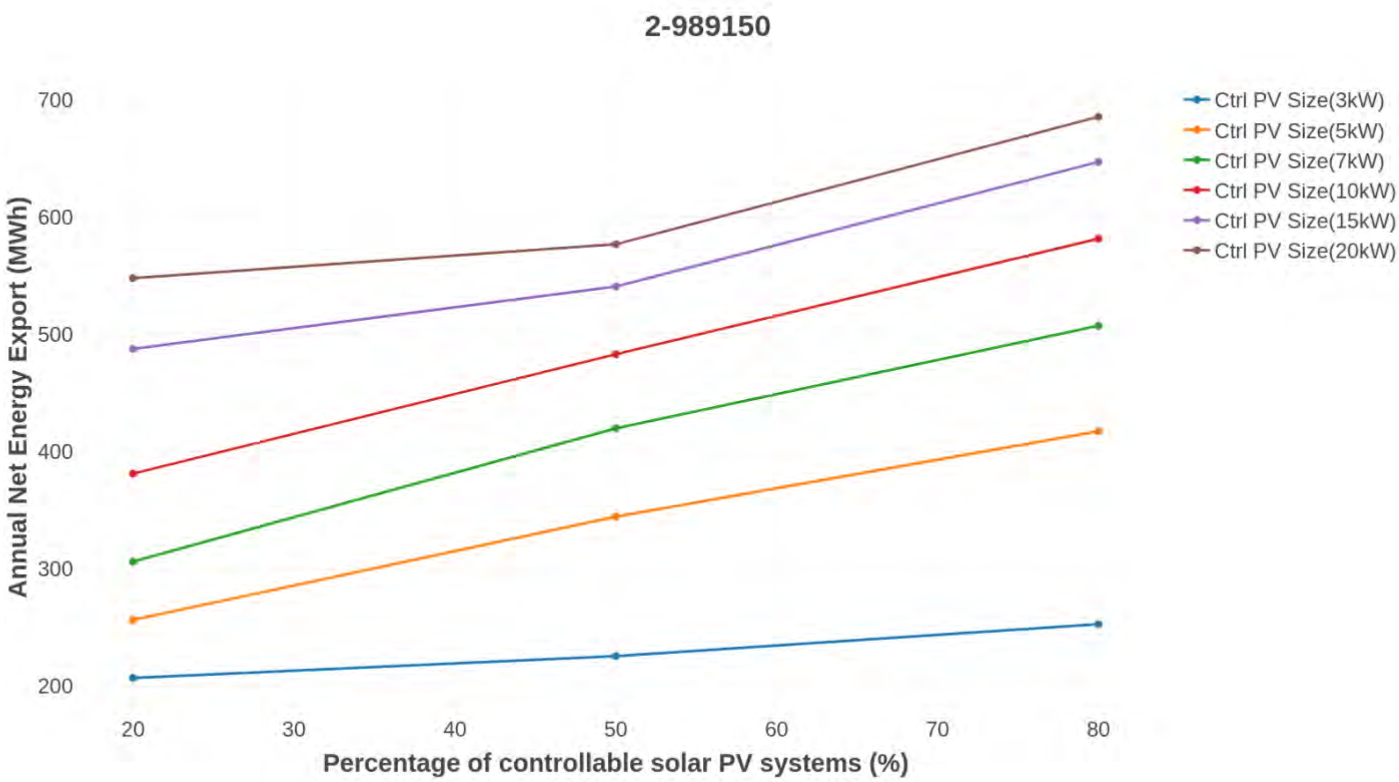


Figure 30. Trend of Annual Net Energy export through transformer 2-989150 over one-year period for increasing number of controllable sites

The case study shows conclusively that operating envelopes are capable of effectively supporting customer uptake of significant amounts of solar generation whilst ensuring that physical and technical limits of the distribution network are not breached.

5.4 Case Study Conclusions

The detailed case study presented in this section clearly describes the benefits of time varying connection point limits using monthly and dynamic operating envelopes.

The customer benefits are observed through increases net annual energy export through the grid. Based on the current levels of DER connected, the increase in energy throughput is approximately 15% to 20%, and increases to approximately 235% more energy if 80% of customers had 10kW and operated under 30 minute dynamic operating envelopes. This is a significant amount of additional energy that can be supplied into the energy system, without increasing the size of the network assets.