Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia

CSIRO GPST Stage 2

Topic 8 – Distributed Energy Resources

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Executive Summary

This document presents the final report (Milestone 4) of the project "Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia" funded by CSIRO as part of the stage 2 of the "Australian Research for Global Power Systems Transformation (G-PST)".

Australia is leading the world on rooftop solar photovoltaic (PV) with more than one in three houses having the technology. This and other Distributed Energy Resources (DER) such as batteries and electric vehicles are creating opportunities to homes and businesses as they can reduce energy bills but also, through aggregators, can participate in the electricity market managed by the Australian Energy Market Operator (AEMO). The challenge, however, is to ensure we make the most of the existing electricity distribution infrastructure (e.g., distribution lines, transformers) connecting homes and businesses whilst ensuring its integrity.

One way for distribution companies – who own and operate the electricity distribution infrastructure and are known in Australia as Distribution Network Service Providers (DNSPs) – to ensure the integrity of the electricity distribution infrastructure is by orchestrating DERs, in other words, by actively defining export and/or import limits at the connection point of customers or for the DER technology itself. This concept is known in Australia as *Operating Envelopes* (OEs, aka Dynamic Operating Envelopes) and is being demonstrated by different DNSPs through multi-million trials funded by the Australian Renewable Energy Agency (ARENA). While these trials are extremely valuable in understanding the different aspects associated with the implementation of OEs, in practice, each DNSP is adopting different approaches. This is because different DNSPs, due to regional and/or historical reasons, have different data availability when it comes to residential Low Voltage (LV) electrical network models (topology, impedances, phase grouping) and customer monitoring (smart meters).

This project has carried out an assessment of the benefits and drawbacks of different OE implementations likely to be seen across Australia. It provides metrics and recommendations for DNSPs and AEMO to assist them in their decision-making process by investigating in detail, quantitatively and qualitatively, different potential OE implementations (specifically, different approaches to calculate OEs at the customer connection point). This project draws recommendations by:

- Characterising the spectrum of available infrastructure/data across Australian DNSPs.
- Defining the potential OE implementations (including calculation and allocation) according to the spectrum identified.
- Defining key metrics that capture the interests and concerns of key stakeholders (i.e., customers, DNSPs, AEMO).
- Carrying out detailed power flow simulations using realistic unbalanced three-phase HV-LV distribution network models considering the different OE implementations and different DER mixes and uptake.

- Using the results of the simulations to assess the performance of each OE implementation, and to provide recommendations for stakeholders.

After surveying all DNSPs in Australia, it was possible to observe a large diversity on the available infrastructure/data they have (from electrical network models to network and customer monitoring to forecasting) which confirms the need to assess different OE implementations. In addition, the survey allowed to observe that all DNSPs are moving towards the modernisation of their infrastructure/data availability (e.g., more monitoring, better electrical models, etc.) but, as it can be expected, each one of them has their own pace, which is subject to their regional requirements and characteristics.

Four spectra were created to show the current available infrastructure/data of Australian DNSPs. These spectra are: *Available Electrical Models, Available Network Monitoring, Available Customer Monitoring, Available Forecast*.

From these four spectra an overall spectrum was created to cluster DNSPs according to their general level of available infrastructure/data. Four clusters were identified: *Moderate Transition, Fast Transition, Very Fast Transition, and Step Transition*.

Once the available infrastructure/data was identified, four different approaches to calculate OEs (or OE implementations) were produced, each one of them vary in terms of complexity and accuracy, they are:

1. Ideal OE (used as benchmark)
2. Asset Capacity OE
3. Asset Capacity & Critical Voltage (AC_CrV) OE
4. Asset Capacity & Delta Voltage (AC_ΔV) OE

The **Ideal OE is the most advanced** and, hence, **most accurate** operating envelope approach as it uses power flows to carry out calculations. However, it needs a full electrical LV network model and full monitoring of customers plus transformer monitoring, which makes its implementation very complex. If the model and monitoring data are correct, it can guarantee the operation of the network within technical limits (i.e., voltage and thermal) as well as the maximum possible export and/or import limits. Although this OE implementation approach is only used as benchmark in this report, it is interesting to highlight the DNSPs that are closer to be able use this option in the future.

The **Asset Capacity OE is the least advanced** and, hence, the **least accurate** operating envelope approach as it only considers the thermal aspect of the distribution transformer to calculate the spare capacity and split it among active customers. To do so, it only needs the monitoring and capacity of one element of the network (the distribution transformer), which makes its implementation very simple. Although the Asset Capacity OE implementation does not cater for voltage aspects, the latest PV inverter standard that combines Volt-Watt and Volt-var functions may help in areas with low numbers of active customers (those being given OEs). However, this OE implementation is not recommended in areas with medium or high numbers of active customers.

The **AC_CrV OE is more advanced than the Asset Capacity OE as both voltage and thermal issues are considered** instead of only thermal issues. Thermal issues are solved by calculating the spare capacity of the distribution transformer, while voltages issues are solved by estimating the voltage at the critical customer via a sensitivity curve (using historical active power and voltage of the critical customer). Although it needs more monitoring than the Asset Capacity OE, this extra requirement is minimal – only two points of the LV network, specifically the distribution transformer and the critical customer – which makes its implementation relatively simple. Given that the AC_CrV OE does not need the electrical models of the LV networks, this OE implementation has great potential to be used by DNSPs that have limited or no availability of such electrical models.

The **AC_ΔV OE is more advanced than the AC_CrV OE**, given that **it can capture better the daily voltage variations due to the interactions with the upstream HV network**. Thermal issues are solved by calculating the spare capacity of the distribution transformer, while voltages issues are solved by estimating the voltage at the critical customer via sensitivity curves (using historical aggregated active power on the LV network and voltage at the head of the LV feeder and at the critical customer). The monitoring requirements are the same as for the AC_CrV OE, which makes its implementation also relatively simple and has great potential to be used by DNSPs that has limited or no availability of such electrical models.

To assess the performance of these OE implementations nine metrics were defined: OE accuracy, voltage compliance, maximum voltage, minimum voltage, asset utilisation, total OE gain, aggregated exports/imports, equity/fairness, and complexity and cost of implementation. These metrics cover (to different extents) four interests and/or concerns from the stakeholders (i.e., DNSPs, AEMO, customers): network performance, impact on customers, service provision, and feasibility.

The following recommendations consider the OE implementations investigated in this project, their ability to keep the network within the required technical limits (i.e., voltages and thermal) and which DNSPs could be in a position to use them.

Asset Capacity OE

1. **Can be used by DNSPs that monitor distribution transformers**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy and South Australia Power Networks), Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy) and Step Transition cluster (Evoenergy), may already have the required capabilities to implement the Asset Capacity OE.
2. **Can be used in the short-term or in areas with low numbers of active customers**. Although the Asset Capacity OE implementation does not cater for voltage aspects, the latest PV inverter standard that combines Volt-Watt and Volt-var functions may help in

areas with low numbers of active customers. However, it is not recommended in areas with medium or high numbers of active customers.

3. **Can be used in areas with thermal problems but not voltage problems**. The Asset Capacity OE implementation only consider thermal aspects on its calculation.

Asset Capacity & Critical Voltage OE

1. **Can be used by DNSPs that monitor distribution transformers and have historical non-market data from some LV customers (or critical points of the LV networks)**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy) and Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_CrV OE.
2. **Can be used by DNSPs with full monitoring of LV customers**. The full monitoring of LV customers could be used to estimate the power flow on the distribution transformer. The DNSPs that fall in this category are Ausnet Services, CitiPower, Horizon Power, Jemena, Powercor, and United Energy.
3. **Can be used in the medium-term or in areas with medium numbers of active customers**. The performance of the AC_CrV OE implementation may be enough for areas with medium numbers of active customers, but it is not recommended in areas with high numbers.

Asset Capacity & Delta Voltage OE

1. **Can be used by DNSPs that monitor distribution transformers and have historical non-market data from some LV customers (or critical points of the LV networks)**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy) and Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_ΔV OE.
2. **Can be used in the medium-term or in areas with medium numbers of active customers**. The performance of the AC_ΔV OE implementation may be enough for areas with medium numbers of active customers, but it is not recommended in areas with high numbers.

Ideal OE

1. **To be used in the long-term or in areas with high numbers of active customers**. The Ideal OE implementation is the most accurate OE approach, however, it is recommended to be used for high numbers of active customers. Since it requires full electrical LV network models and full monitoring of customers plus transformer monitoring, it is likely that DNSPs might require a few years to fully adopt this OE implementation.

2. Although none of the DNSPs have all the required capabilities to implement the Ideal OE today, the DNSPs of the Step Transition cluster (Evoenergy and Horizon Power) and some of the Very Fast Transition (Ausgrid, Citipower, Powercor, and United Energy) cluster are the ones with the highest potential to use it first in the near future in some parts of their networks.

In conclusion, this project has demonstrated that full electrical LV network models and full monitoring of network/customers are not necessarily needed to calculate adequate OEs for low/medium numbers of active customers. Simpler OE implementations that require very limited knowledge of the electrical network and very limited monitoring may be good enough (not perfect though) to solve excessive voltage rise/drop and asset congestion on areas with low to medium numbers of active customers. This suggests that for the near future, complex OE implementations are not needed in most of the distribution network areas. Nevertheless, for the long-term, more advanced OE implementations will be required.

Acknowledgements

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We also would like to thank all the Australian Distribution Network Service Providers (DNSPs) that kindly participated in our engagement sessions and the workshop. Their valuable information and feedback have been used, to the extent that is possible, to bring an adequate overview of the available infrastructure/data across Australian DNSPs.

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Abbreviations

ACT	Australian Capital Territory
AC_CrV	Asset Capacity & Critical Voltage
AC_ΔV	Asset Capacity & Delta Voltage
AEMO	Australian Energy Market Operator
Alloc.	Allocation
ARENA	Australian Renewable Energy Agency
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Cust.	Customer
DER	Distributed Energy Resource
Develop.	Development
Distr.	Distribution
DNSP	Distribution Network Service Provider
DTx	Distribution Transformer
Ener.	Energy
Exp.	Export(s)
G-PST	Global Power Systems Transformation
HoF	Head of Feeder
HV	High Voltage (e.g., 22kV or 11kV line-to-line)
Imp.	Import(s)
LV	Low Voltage (below 1kV, e.g., 400V line-to-line)
MV	Medium Voltage
Net.	Network
NMI	National Meter Identifier
NSW	New South Wales
NT	Northern Territory
OE	Operating Envelope
PV	Photovoltaic
QLD	Queensland
SA	South Australia
TAS	Tasmania
Transf.	Transformer
VIC	Victoria
WA	Western Australia
ZS	Zone Substation

1 Introduction

This document presents the final report (Milestone 4) of the project "Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia" funded by CSIRO as part of the stage 2 of the "Australian Research for Global Power Systems Transformation (G-PST)".

Australia is leading the world on rooftop solar photovoltaic (PV) with more than one in three houses having the technology [2]. This and other Distributed Energy Resources (DER) such as batteries and electric vehicles are creating opportunities to homes and businesses as they can reduce energy bills but also, through aggregators, can participate in the electricity market managed by the Australian Energy Market Operator (AEMO). The challenge, however, is to ensure we make the most of the existing electricity distribution infrastructure (e.g., distribution lines, transformers) connecting homes and businesses whilst ensuring its integrity.

One way for distribution companies – who own and operate the electricity distribution infrastructure and are known in Australia as Distribution Network Service Providers (DNSPs) – to ensure the integrity of the electricity distribution infrastructure is by orchestrating DERs, in other words, by actively defining export and/or import limits at the connection point of customers or for the DER technology itself. This concept is known in Australia as *Operating Envelopes* (OEs, aka Dynamic Operating Envelopes [3]) and is being demonstrated by different DNSPs through multi-million trials funded by the Australian Renewable Energy Agency (ARENA), such as Project Symphony [4], Project EDGE [5, 6], and Project Flexible Exports [7]. While these trials are extremely valuable in understanding the different aspects associated with the implementation of OEs, in practice, each DNSP is adopting different approaches. This is because different DNSPs, due to regional and/or historical reasons, have different data availability when it comes to residential Low Voltage (LV) electrical network models (topology, impedances, phase grouping) and customer monitoring (smart meters).

This project has carried out an assessment of the benefits and drawbacks of different OE implementations likely to be seen across Australia. It provides metrics and recommendations for DNSPs and AEMO to assist them in their decision-making process by investigating in detail, quantitatively and qualitatively, different potential OE implementations (specifically, different approaches to calculate OEs at the customer connection point). This project draws recommendations by:

- Characterising the spectrum of available infrastructure/data across Australian DNSPs.
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- Defining key metrics that capture the interests and concerns of key stakeholders (i.e., customers, DNSPs, AEMO).
- Carrying out detailed power flow simulations using realistic unbalanced three-phase HV-LV distribution network models considering the different OE implementations and different DER mixes and uptake.

- Quantifying the resulting DER hosting capacity from each OE implementation.
- Quantifying the facilitation of services provided by DER from each OE implementation.

The next subsection shows the parts of the Australian Research Plan for Topic 8 – DER [1] that are addressed by this project. The rest of this report is structured as follows. In Chapter 2, the available infrastructure/data across Australian DNSPs is presented. In Chapter 3, the general concept of operating envelopes as well as the ideal/benchmark approach to calculate operating envelopes are presented. In Chapter 4, the concept of simpler approaches to calculate operating envelopes as well as the assessment metrics are presented. In Chapter 5, all operating envelopes are implemented and assessed considering detailed power flow simulations by using a realistic unbalanced three-phase HV-LV distribution network model. In addition, the feedback from DNSPs on the implemented OEs is presented. Finally, recommendations are presented in Chapter 6 and the conclusions in Chapter 7.

1.1 Progress Related to the Australia's GPST Research Roadmap

The findings from this project directly and indirectly answer many of the research questions prioritised by the Australian Research Plan for Topic 8 – DER [1], specifically:

- *RQ0.1 What data flows (DER specs, measurements, forecasts, etc.) are needed to ensure AEMO has enough DER/net demand visibility to adequately operate a DER-rich system in different time scales (mins to hours)?*

  This project partially addresses this question as it demonstrates that the net demand (which includes DERs) of active customers together with distribution transformer monitoring is very important to have a reasonable visibility of DER-rich LV networks. Since this question relates to AEMO, they are interested in the transmission/distribution interface and not on the LV networks per se. However, the estimations for the LV networks could be aggregated and combined with zone substation measurements to have an improved estimate at the Transmission-Distribution interface. In addition, this project partially assesses the effects of DER orchestration strategies via different implementations of operating envelopes on the net demand of LV networks. Nonetheless, other aspects mentioned in the research plan should still be investigated. This project addresses around 22% of this question.

- *RQ1.1 For each of the potential technical frameworks for orchestrating DERs in Australia (e.g., based on the OpEN Project), what is the most cost-effective DER control approach to deal with the expected technological diversity and ubiquity of DERs?*

  This project demonstrates that the use of operating envelopes, when applied at the connection point of customers, is agnostic of the DER technology since it considers the net exports or imports. Thus, the technology diversity of DERs or the type of services to be provided should not be a problem when using operating envelopes to orchestrate DERs. However, operating envelopes can be implemented in different ways, some more complex and costly, others less complex and less expensive. To this end, this project provides recommendations on the pros and cons of four different OE implementation. These recommendations are based on defined metrics that capture the interest and concerns of different stakeholders. Nonetheless, other aspects mentioned in the research plan should still be investigated, such as the types of control approaches (e.g., centralised, distributed, local, hierarchical, etc.). This project addresses around 40% of this question.

- *RQ1.2 For each DER control approach, what is the most adequate decision-making algorithm (solution method)?*

  This project demonstrates that the use of operating envelopes, when applied at the connection point of customers, is agnostic of the DER technology since it considers the net exports or imports. Thus, the technology diversity of DERs or the type of services to be provided should not be a problem when using operating envelopes to orchestrate DERs. However, operating envelopes can be implemented in different ways, some more complex and costly, others less complex and less expensive. To this end, this project is providing recommendations on the pros and cons of four different OE implementation. These recommendations are based on defined metrics that capture the interest and concerns of different stakeholders. Nonetheless, other aspects mentioned in the research plan should still be investigated, such as the use of optimisation-based algorithms and advanced data-driven algorithms. This project addresses around 50% of this question.

- *RQ1.3 What is the role of DER standards in concert with the future orchestration of DER?*

  This project considers the most updated Australian standard regarding the use of Volt-Watt and Volt-var for grid connection of energy systems via inverters. Therefore, the effect of DER standards on the OE calculations is being partially investigated and recommendations are provided. Nonetheless, other aspects mentioned in the research plan should still be investigated. This project addresses around 25% of this question.

- *RQ2.1 For each of the potential technical frameworks for orchestrating DERs and the corresponding decision-making algorithms, what is the most cost-effective communication and control infrastructure?*

  This project produces a qualitative (and high-level) assessment of the infrastructure needed for the different operating envelopes and, hence, the potential associated cost. However, this is not a thorough comparison of all the different potential frameworks. Nonetheless, other aspects mentioned in the research plan should still be investigated. This project addresses around 40% of this question.

- *RQ4.2 What is the minimum availability of ancillary services from DERs at strategic points in the system throughout the year and across multiple years?*

  This project quantifies, to some extent, the volume of services that could be safely (considering voltages and thermal limits at the distribution network) provided to AEMO when using different operating envelopes implementations. These estimations are not being made across the year though, or across multiple years, but they provide valuable insights. Nonetheless, other aspects mentioned in the research plan should still be investigated. This project addresses around 30% of this question.

- *RQ5.1 What are the necessary organisational and regulatory changes to enable the provisioning of ancillary services from DERs?*

  This project provides recommendations that can be used to make organisational and regulatory changes for DNSPs in the context of operating envelopes which, in turn, relates to the provisions of ancillary services from DERs. Nonetheless, other aspects mentioned in the research plan should still be investigated. This project addresses around 25% of this question.

- *RQ5.2 What are the necessary considerations of establishing a distribution-level market (for energy and services)?*

  From a technical perspective, for distribution-level markets to work, DNSPs should be able to assess how the poles and wires are affected by different power flows to determine what can and cannot be done by third parties (e.g., aggregators). This project demonstrates that the principles behind the operating envelopes not only can help DNSPs to carry out those assessments but also that the calculated operating envelopes give the export/import limit that third parties must respect in order to keep the poles and wires within the required technical limits (i.e., voltages and thermal). Nonetheless, many other aspects mentioned in the research plan should still be investigated. This project addresses around 20% of this question.

2 Available Infrastructure/Data Across Australian DNSPs

In order to define some of the different OE implementations that are likely to be seen in Australia, this project surveyed all DNSPs across the country to better understand their available infrastructure/data (i.e., electrical models, network monitoring, customer monitoring, and forecast). Since OEs are expected to be implemented on lower voltage levels, the focus of the survey was on the Medium Voltage (MV) – also known as high voltage (HV) by some DNSPs – and LV networks. In most cases, MV (or HV) networks have nominal line-to-line voltages below 50kV (e.g., 22kV, 11kV) and LV networks below 1kV (e.g., 400V).

From the survey, four spectra were created to show where each DNSP stands in terms of available infrastructure/data. Results show that, in general, there is a large diversity on the available infrastructure/data across Australian DNSPs, which confirms the need to assess different OE implementations. It is worth noting that all DNSPs are moving towards the modernisation of their infrastructure/data availability (e.g., more monitoring, better electrical models). However, each one of them has their own pace, which is subject to their regional requirements and characteristics.

The rest of this section presents the methodology to define the available infrastructure/data across Australian DNSPs as well as four spectra that define this available infrastructure/data and an overall spectrum to show the pace of each DNSP in the energy transition.

2.1 Methodology

The methodology used to define the available infrastructure/data across Australian DNSPs is made of three main parts:

a) a survey of the Australian DNSPs
b) the creation of four spectra that represent the availability of infrastructure/data
c) the creation of an overall spectrum that cluster DNSPs according to their general level of available infrastructure/data

These are explained in more detail below.

a) The **survey of the Australian DNSPs** was carried out considering the following main steps.

   i) Selection of data to be collected: The focus of the survey was to understand DNSPs available electrical models, monitoring, and forecast, which can be used to propose the different OE implementations. To have a good understanding on how detailed DNSPs' knowledge of their distribution network is, questions (presented below) were directed to various elements of the distribution network, ranging from the zone substation to LV customers. More specifically, these elements were zone substation transformers, HV feeders, HV customers, distribution transformers (DTx), LV feeders, LV customers. The questions directed to each of the previously listed elements were:

- Does the DNSP have electrical models for the given elements (including topology)?
- Are these electrical models operational (i.e., can be used to run simulations with real-time data, such as power flows) or are they only existing somewhere in the database?
- Which monitoring/measurement data the DNSP has available (e.g., voltages, currents, power factor)?
- Are these data operational (e.g., data retrieved every minute) or just historical data (e.g., data retrieved once a day)?
- Does the DNSP make any type of forecast at these locations (i.e., elements location)?

ii) Review of DNSPs most recent annual planning reports: To answer these questions, the most recent annual planning report (or equivalent) of all 16 DNSPs in Australia were reviewed. This review helped to answer partially/fully some of the questions presented before, but there was still some valuable information missing.

iii) Interview with DNSPs: To fill the gap of missing information and confirm the collected data from the reviews, interviews were scheduled with all Australian DNSPs. In these interviews the project was introduced, and all the questions (previously stated) were asked, even though some of them were already answered by the review. In addition, the participants were asked to comment on possible key metrics to assess the OE implementations.

b) Once the survey was finished and the collected data was processed, **four spectra** were created to show the available infrastructure/data across Australian DNSPs, they are:

i) Availability of electrical models: this spectrum shows up to which point of the distribution network each DNSP has electrical models for. It also shows the state of development of the electrical model, in other words, whether the model is used for planning, or it is semi-operational (i.e., it has functions that works in real-time, or it is at final stages of the implementation of operational capabilities), or it is operational (i.e., it is ready to be used to run simulations with real-time data collected from the network, such as power flows).

ii) Availability of network monitoring: this spectrum shows to which point of the distribution network each DNSP has network monitoring for. It also shows the monitoring capabilities, in other words, whether the monitoring is only available as a historical data (i.e., the monitored data is retrieved with delays of hours), or it is semi-operational (i.e., the monitored data can be retrieved in real-time, but it is not used as default), or it is operational (i.e., the monitored data is currently being retrieved in real-time or near real-time, e.g., within minutes).

iii) Availability of customers monitoring: this spectrum shows the type of monitoring of HV and LV customers that each DNSP has available. There are two types of monitored data, market data and non-market data. The former corresponds to measurements related to energy usage, such as half-hourly energy consumption (kWh), while the latter corresponds to more technical measurements, such as active/reactive power and voltage every few minutes. It also shows the monitoring capabilities, in other words, whether the monitoring is only available as a historical data (i.e., the monitored data is retrieved with delays of hours), or it is retrieved in near real-time (i.e., every few minutes). In addition, it shows whether the data is freely available to the DNSP or the DNSP must buy the data from a third party.

iv) Availability of forecast: this spectrum shows to which point of the distribution network each DNSP has forecast for. It also shows the forecast capabilities, in other words, whether the forecast is used for planning (e.g., it is done once or twice a year) or it is operational (e.g., it is updated more constantly).

c) Based on the diversity of available infrastructure/data presented in the four spectra, DNSPs were clustered (using a kind of average from the four spectra), and an **overall spectrum** was created. The overall spectrum is made of four clusters: *Moderate Transition, Fast Transition, Very Fast Transition, and Step Transition*.

2.2 Australian DNSPs

As mentioned before, this project surveyed all DNSPs across Australia, and Table 1 presents a list of these DNSPs together with respective states.

Table 1. List of Australian DNSPs with respective states.

DISTRIBUTION NETWORK SERVICE PROVIDER	STATE
Ausgrid	New South Wales (NSW)
AusNet Services	Victoria (VIC)
CitiPower	Victoria (VIC)
Endeavour Energy	New South Wales (NSW)
Energex	Queensland (QLD)
Ergon Energy	Queensland (QLD)
Essential Energy	New South Wales (NSW)
Evoenergy	Australian Capital Territory (ACT)
Horizon Power	Western Australia (WA)
Jemena	Victoria (VIC)
Powercor	Victoria (VIC)
Power and Water Corporation	Northern Territory (NT)
South Australia Power Networks	South Australia (SA)
TasNetworks	Tasmania (TAS)
United Energy	Victoria (VIC)
Western Power	Western Australia (WA)

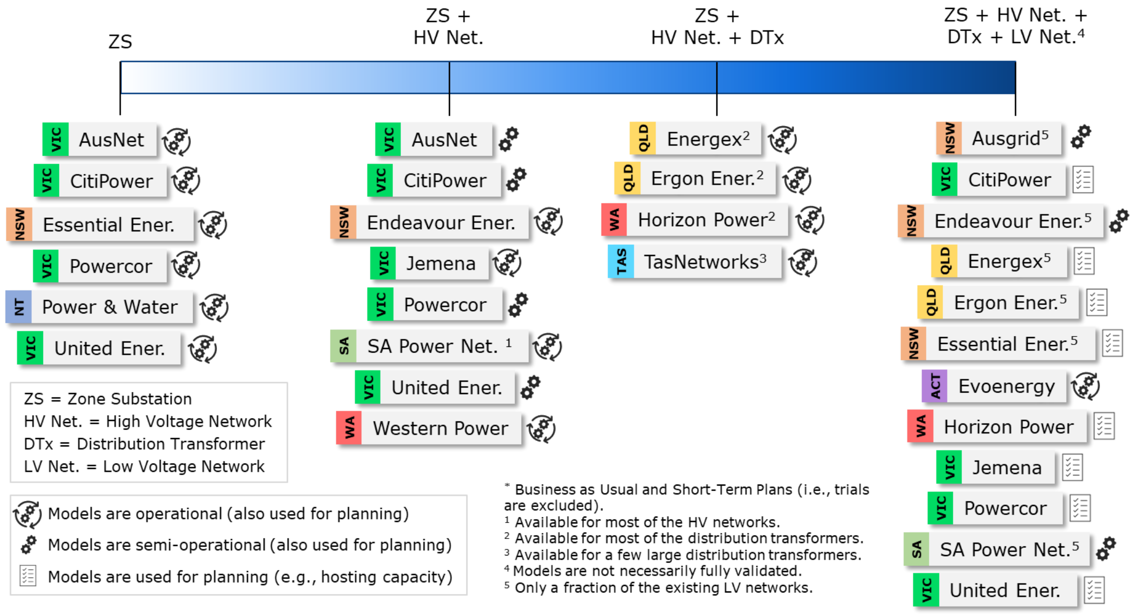

Figure 1. Availability of electrical models.

2.3 Spectra

2.3.1 Availability of Electrical Models

The spectrum of availability of electrical models is presented in Figure 1. The position of a given DNSP on the spectrum shows up to which point of the distribution network it has electrical models for. The icons next to a given DNSP shows whether the model is used for planning, or it is semi-operational (i.e., it has functions that work in real-time, or it is at final stages of the implementation of operational capabilities), or it is operational (i.e., it is ready to be used to run simulations with real-time data collected from the network, such as power flows).

To facilitate the correct analysis of the spectrum, consider the next two examples. Take Ausgrid as the first example, it is placed at the end of the spectrum (ZS + HV Net. + DTx + LV Net.) with a semi-operational icon next to it. This means that Ausgrid has semi-operational electrical models for the entire distribution network, down to the LV networks. Sometimes a DNSP appears twice (or three times) in a spectrum, this is to show the diversity on their electrical models. Take AusNet Services as the second example, it is placed at the start of the spectrum (ZS) with an operational icon next to it, and it is also placed in the second level of the spectrum (ZS + HV Net.) with the semi-operational icon next to it. This means that AusNet has electrical models for the zone substation that are fully operational, and that its electrical models for the HV network is only semi-operational. This way of analysing the spectrum should be used for all DNSPs. Note that, when necessary, superscripts are used to give more information about the available infrastructure/data.

In general, the spectrum shows a large diversity of available electrical models among the DNSPs. Nonetheless, around 75% of the DNSPs have some type (e.g., planning, semi-operational,

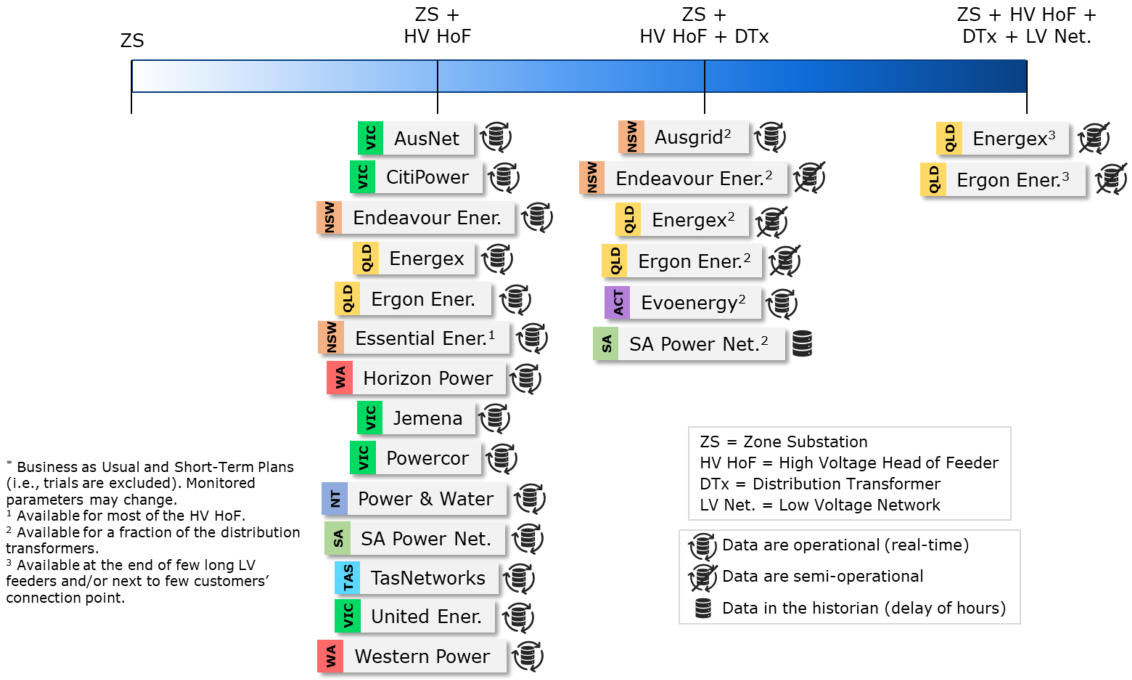

Figure 2. Availability of network monitoring.

operational) of electrical models down to the LV network, meaning that they have some capability on creating electrical models that could run power flows and eventually be used to calculate OEs. Although the survey did not collect specific details on how these electrical models of the LV network are created, the survey revealed that most of the LV network models are not necessarily fully validated, meaning that using these models to calculate OEs could lead to ineffective values (i.e., they might not avoid network problems or might over constrained customers).

Looking for the future, there is an indication that all DNSPs are moving towards the creation/improvement of electrical models for the lower voltage levels of their distribution networks. However, as it is to be expected, each one of them has their own pace, which is subject to their regional requirements and characteristics. Therefore, if two DNSPs are compared and one of them is more advanced on the available electrical network models than the other, it does not mean that one is behind the other (in terms of the energy transition), but that they are likely to have different regional realities, and, consequently, different requirements.

2.3.2 Availability of Network Monitoring

The spectrum of availability of network monitoring is presented in Figure 2. The position of a given DNSP on the spectrum shows up to which point of the distribution network it has network monitoring for. The icons next to a given DNSP shows whether the monitoring is only available as a historical data (i.e., the monitored data is retrieved with delays of hours), or it is semi-operational (i.e., the monitored data can be retrieved in real-time, but it is not used as default), or it is operational (i.e., the monitored data is retrieved in real-time or near real-time, e.g., within minutes). Note that the way to analyse this spectrum is similar to the one described in Section

2.3.1. Also note that, when necessary, superscripts are used to give more information about the available infrastructure/data. Finally, note that very specific information such as exact monitored points (e.g., primary/secondary side of transformer) or monitored parameters (e.g., voltage, current, active power, reactive power, apparent power) was not the focus of the survey, so no information of this sort is given in this report.

In general, the spectrum shows that all DNSPs have operational monitoring at the head of the HV feeder, which does not help on the calculation of OEs for customers connected to the LV network (unless an integrated HV-LV electrical model is available and with full monitoring of customers). Nonetheless, around 37% of the DNSPs have been investing on increasing the monitoring at the LV network, manly on distribution transformers, but also at the end of long LV feeders. These investments are usually targeted to LV networks that have been facing technical challenges (e.g., high overvoltages) due to high penetration of DERs. The adoption of such LV monitoring is important, since it is possible to capture more parameters (e.g., net demand, voltages) that are usually required to calculate more accurate the OEs.

An important aspect to be mentioned is that 60% of the DNSPs that are not currently investing on LV network monitoring have full smart meter deployment (i.e., all customers have smart meters, including customers connected to the LV network). Since these DNSPs own these smart meters, they have full access to the monitored data. Having access to such high amount of smart meter data has the potential to give them a lot of information that can be useful for the network operation and creation/improvement of electrical models. Thus, it is likely that they are first trying to leverage the existing data before making any investment on such network monitoring. Nevertheless, at least one of the DNSPs in this category already see the benefit of investing on LV network monitoring, which make sense when considering the calculation of OEs for customers connected to the LV network.

2.3.3 Availability of Customer Monitoring

The spectrum of availability of customer monitoring is presented in Figure 3. It shows the type of HV and LV customers monitoring that each DNSP has available. There are two types of monitored data, market data and non-market data. The former corresponds to measurements related to energy usage, such as half-hourly energy consumption (kWh), while the latter corresponds to more technical measurements, such as active/reactive power and voltage every few minutes. The icons next to a given DNSP shows whether the monitoring is only available as historical data (i.e., the monitored data is retrieved with delays of hours), or it is retrieved in near real-time (i.e., every few minutes). In addition, icons show whether the data is freely available to the DNSP or the DNSP must buy the data from a third party. Note that the way to analyse this spectrum is similar to the one described in Section 2.3.1. Also note that, when necessary, superscripts are used to give more information about the available infrastructure/data.

In general, all DNSPs can have access to market data, but non-market data – which is required for calculating OEs – is not always available to them. Only DNSPs from the states of Victoria and Western Australia have full access to this data (as they own and operate the smart meters), while

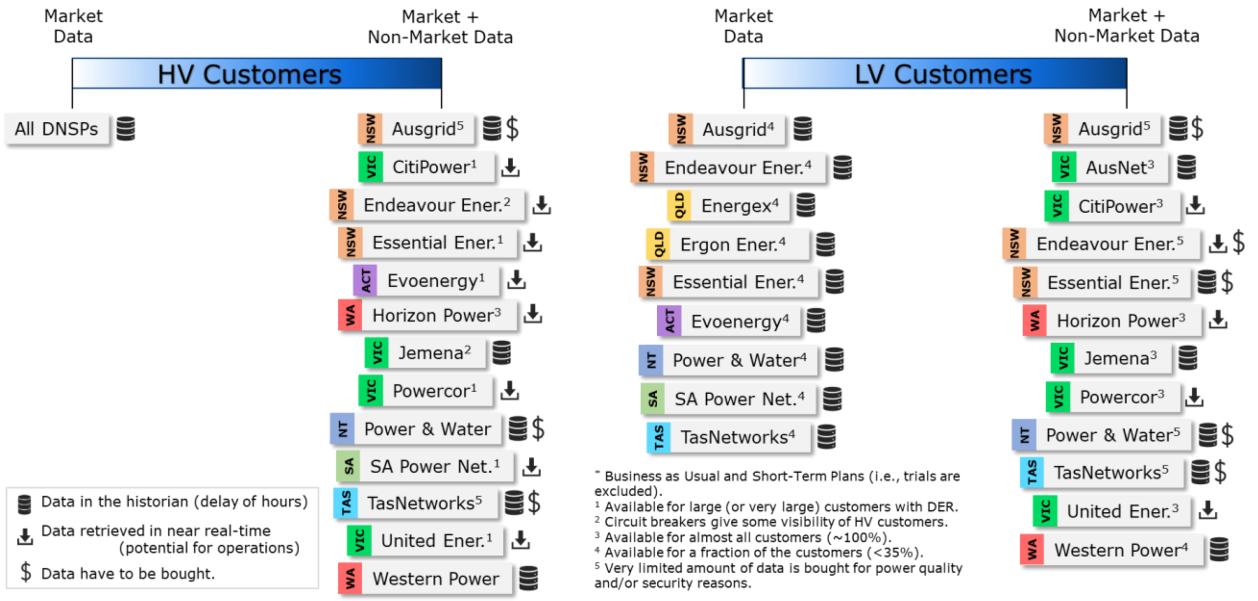

Figure 3. Availability of customer monitoring.

DNSPs from other states usually must buy this data from a third party. In fact, the necessity of buying smart meters data is one of the motivations for some DNSPs to invest on their own LV network monitoring. In this way they can avoid buying smart meters data, which can get expensive when bought in scale. In addition, it is important to note that in some parts of Australia, although some customers have smart meters, it is not possible to buy their non-market data simply because the smart meters owner does not have this option available. So, an alternative that has been explored by at least one DNSP is to get access to the DERs inverter data, instead of smart meters data. Of course, in this case, the DNSP will only get access to the generated power and the voltage, but not to the consumed power. Nevertheless, having this data is better than having nothing.

An important aspect to be mentioned is that although some DNSPs have access to non-market data (required for calculating OEs) of LV customers, 58% of them still cannot access that data in real-time (or near real-time), making a real-time OE calculation difficult to be implemented. Therefore, OE implementations that does not rely on real-time smart meter data are an alternative (at least until they get real-time or near real-time access to that data), such as the three simple OE implementations presented in this project.

2.3.4 Availability of Forecast

The spectrum of availability of forecast is presented in Figure 4. The position of a given DNSP on the spectrum shows up to which point of the distribution network it has forecast for. The icons next to the DNSP shows whether the forecast is used for planning (e.g., it is done once or twice a year) or it is operational (e.g., it is constantly updated). Note that, when necessary, superscripts are used to give more information about the available infrastructure/data.

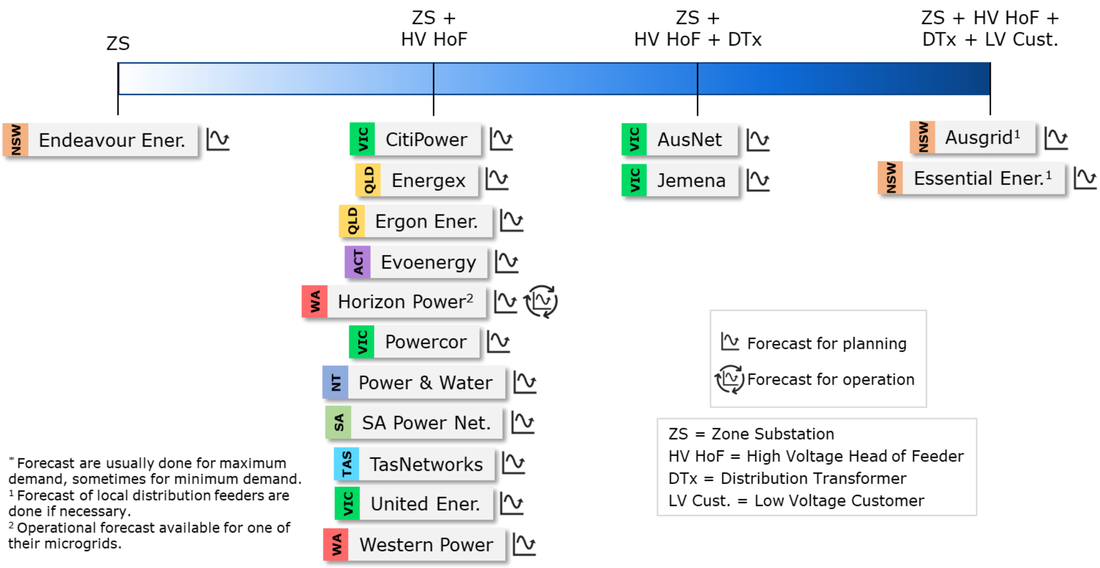

Figure 4. Availability of forecast.

Almost all DNSPs make forecast to the HV head of feeder only. This forecast is intended for planning, so it is usually done for a few periods of the year and for maximum demand. However, in recent years, planning forecast is also being done for minimum demand due to the increased penetration of PV systems. However, the forecast techniques used for the aggregated demand of thousands of customers and for specific times of the year are unlikely to be adequate for the more granular (a distribution transformer or even individual customers) and operational (e.g., every 5 minutes a few hours ahead) purposes of OEs.

Therefore, having the future implementation of OEs in mind as well as the development of better overall forecast, around 25% of the DNSPs are trying to develop forecasts that are closer to the end customer. However, they have been facing considerable challenges on creating accurate and granular forecast for such situations, when the diversity factor is considerably reduced, making it extremely difficult to make accurate forecast.

2.3.5 Overall

Finally, to provide a more holistic description of the infrastructure/data availability of Australian DNSPs, an overall spectrum was also created from the four spectra, as presented in Figure 5. The DNSPs were clustered based on the diversity of available infrastructure/data. Four clusters were identified: *Moderate Transition*, *Fast Transition*, *Very Fast Transition*, and *Step Transition*.

In general, as already mentioned before, all DNSPs are moving towards the modernisation of their infrastructure/data availability (e.g., more monitoring, better electrical models). However, each one of them has their own pace, which is subject to their regional requirements and characteristics. This overall spectrum helps to illustrate the stage of each DNSP on the energy transition.

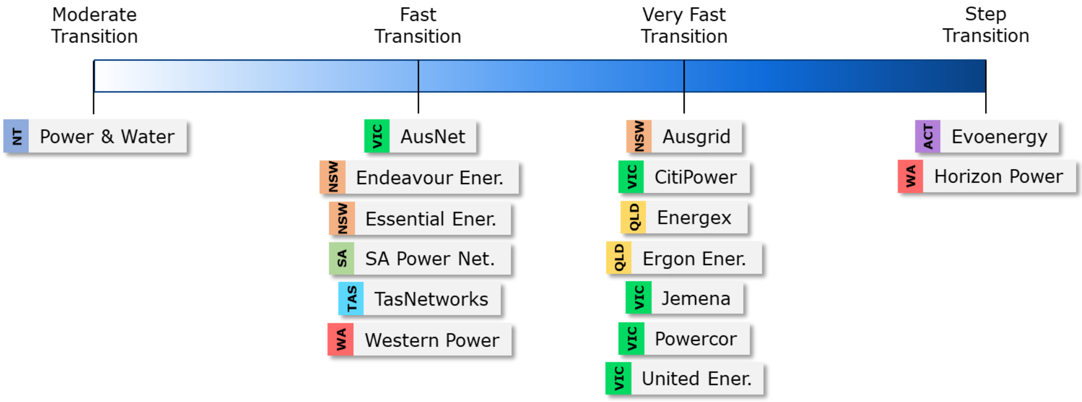

Figure 5. Overall spectrum.

3 Operating Envelopes

To properly understand operating envelopes, it is important to first define two types of distribution network customers:

- *Active* customers, the ones that engage with aggregators; and
- *Passive* customers, the ones that do not engage with aggregators.

A passive customer has a fixed maximum allowed power exports/imports at the connection point, which is usually defined by the connection agreement with the DNSP and/or by the circuit breaker rating at the site. These customers may have DER installed in their sites or not. In contrast, the active customer has a maximum allowed exports and/or imports defined by operating envelopes [8-12] – time-varying (e.g., in 5-minute intervals) export and/or import limits – calculated by the DNSP. These customers should have DERs installed in their sites, usually a PV system and a battery, but other DERs can also be present.

Operating envelopes are calculated to maintain the network operation within technical limits (e.g., voltage and thermal limits). So, once calculated, these operating envelopes are sent to DER aggregators, which, in turn, must use operating envelope values as maximum limits when managing their DER portfolio. This should allow the network to operate within acceptable technical limits, thus also guaranteeing the delivery of bottom-up services.

Operating envelopes can be implemented in different ways, and they will vary in terms of complexity and accuracy. The complexity relates to the required infrastructure/data (e.g., electrical models of the electricity network and monitoring data such as smart meter data) and how elaborated is the calculation of the operating envelope, while the accuracy relates to how precise the operating envelope calculation is. In fact, although operating envelopes implementation can vary, a general architecture can be defined, as presented in the following section.

3.1 General Architecture of Operating Envelopes

The generic architecture to implement operating envelopes is shown in Figure 6. In general, any operating envelope implementation will have three main parts:

- *input data;*
- *operating envelope algorithm; and,*
- *output.*

The *input data* part will have all the necessary data for the calculation of a given operating envelope implementation. In turn, this necessary data will vary according to the operating envelope implementation, but they are usually of two types, time-varying data (e.g., voltage magnitude, net demand), and static database (e.g., network model, asset capacity, regulatory limits). The *operating envelope algorithm* part is the engine that processes the input data to

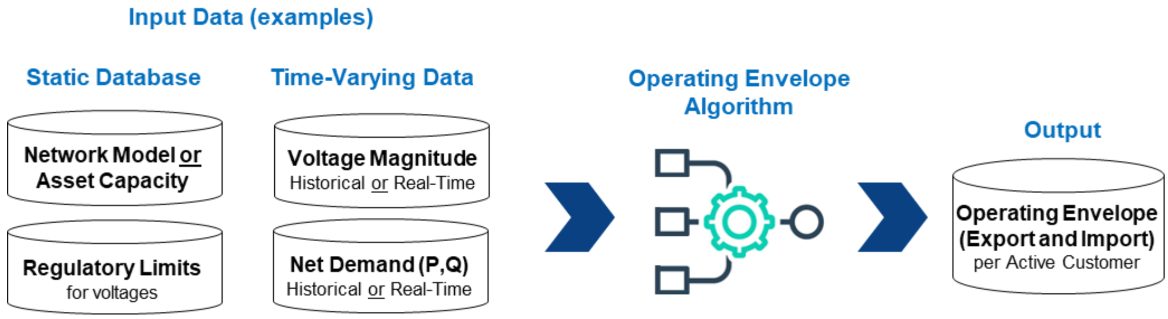

Figure 6. General architecture of OEs with examples of input data.

calculate the operating envelope values. This algorithm will also be different for each operating envelope implementation. The *output* part is the operating envelope that was calculated by the engine, and it consists of time-varying values (i.e., maximum active power for exports and imports) for each active customer of the considered network.

Given that operating envelopes have a time-varying nature, its calculation can be done in two ways:

- Near real-time calculation: It only calculates operating envelopes for the next time interval (i.e., next 5-minute interval). Its time-varying input consists of the latest measurements from the network and/or customers (e.g., voltage magnitude, net demand), and its output consists of a single value for export and a single value for import, both to be used only in the next time interval. Being near real-time, this calculation must be repeated every time interval (e.g., every 5 minutes) using the most updated measurements.
- In-advance calculation: It calculates operating envelopes for multiple time intervals (e.g., next 24h in 5-minute interval). Its time-varying input consists of forecast of the network measurements and/or customers (e.g., voltage magnitude, net demand), and its output consists of multiple values for export and multiple values for import. Each one of these multiple values is related to a specific time interval, thus it must be used to the correct time interval to be effective. Given that forecasts, in general, becomes less accurate over longer periods, this calculation should be repeated every few time intervals (e.g., every few hours) using the most updated forecasts.

Taking in consideration that operating envelopes are meant to be used by aggregators to participate on electricity markets, the ideal scenario is to use the in-advance calculation. However, if the intention is to only avoid distribution network issues, the near real-time calculation could work well. In this project the forecast component is not being considered, instead a persistent forecast based on historical data is being used to demonstrate the concept of the operating envelope implementation and related assessment.

3.2 Ideal Operating Envelope

The Ideal OE is the most advanced and, hence, the most accurate operating envelope approach as it uses power flows to carry out calculations. However, it needs a full electrical network model and

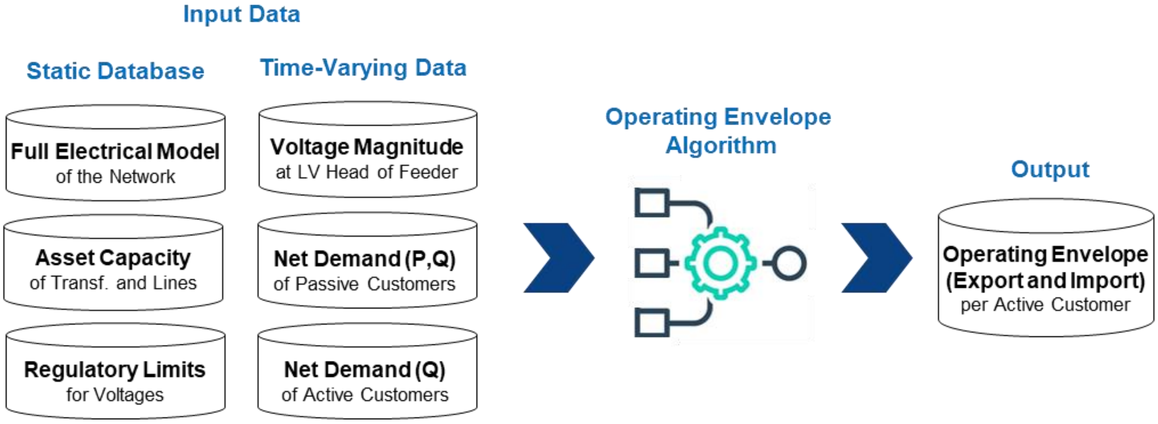

Figure 7. Architecture for the Ideal OE.

full monitoring of customers, which makes its implementation complex. If the model and monitoring data are correct, it can guarantee the operation of the network within technical limits (i.e., voltage and thermal) as well as the maximum possible export and/or import limits. Therefore, this operating envelope is used as a benchmark for the simpler ones to be presented and studied in this project.

Although this OE implementation approach is only used as benchmark in this report, it is interesting to highlight the DNSPs that are closer to be able use this option in the future, given that none of them have all the required capabilities to implement it (excluding trials). Therefore, considering the survey on the available infrastructure/data across Australian DNSPs, the DNSPs of the *Step Transition* cluster (Evoenergy and Horizon Power) and some of the *Very Fast Transition* (Ausgrid, Citipower, Powercor, and United Energy) cluster are the ones with the highest potential to use it first in the near future in some parts of their networks.

The architecture for the Ideal OE is shown in Figure 7, and each part of the architecture is explained in the next sections.

3.2.1 Input Data

As previously discussed, the input data brings all the necessary data for the calculation of a given operating envelope implementation. In the case of the ideal operating envelope used in this project (which is calculated for a single LV network and considering single-phase residential customers) the following time-varying data and static database inputs are necessary.

Time-Varying Data

- Voltage Magnitude at LV Head of Feeder: It gives the necessary voltage reference to perform accurate power flow analyses of a given LV network. Since LV feeders usually have three phases, this measurement is required to be per phase.
- Net Demand (P, Q) of Passive Customers: The net active and reactive power demand (i.e., P and Q, respectively) of passive customers, which is necessary to perform accurate power flow

analyses of the LV network. To account for any DER that might be installed in the customer's site, this measurement is required to be taken at the point of connection and per phase.

- Net Demand (Q) of Active Customers: The net reactive power demand (i.e., Q) of active customers, which is necessary to perform accurate power flow analyses of the LV network. To account for any DER that might be installed in the customer's site, this measurement is required to be taken at the point of connection and per phase.

Static Database

- Full Electrical Model of the Network: The electrical model of a given LV network, which is necessary to perform accurate power flow analyses of the network. It consists of the topology, phase connection of assets and customers, and impedances of conductors and transformers.
- Asset Capacity of Transformers and Lines: The rated capacity of network assets, which is necessary to ensure that the calculated operating envelopes will not exceed the maximum physical (i.e., thermal) capability of network assets.
- Regulatory Limits for Voltages: The maximum and minimum voltage magnitude allowed by regulation, which is necessary to ensure that the calculated operating envelopes will not exceed regulatory limits. In Australia, the limits for LV customers are 253V and 216V [13].

3.2.2 Operating Envelope Algorithms

As previously discussed, the operating envelope algorithm is the engine that process the input data to calculate the operating envelopes. In the case of the ideal operating envelope used in this project, an electrical network model of a given LV network together with the corresponding time-varying input data is used to carry out heuristic algorithms. These algorithms consist of a series of power flows calculations exploring exports/imports up to the point that a network limit (voltages or thermal) in any part of the LV network is breached. Note that the calculation of operating envelopes for exports and imports are very similar, but they must be done separately. For simplicity, only the export algorithms are described here. The following heuristic algorithms to calculate the ideal operating envelope are considered in this project.

Proportional Allocation

i) For a given point in time (e.g., at 12:00PM), set the corresponding time-varying data – voltages at the head of the LV feeder, and net demand from passive customers (P, Q) and active customers (Q) – into their correct place in the LV electrical network model. Note that these values are fixed until the algorithm moves to the next time step (e.g., 5 min).

ii) Set the net active power of all active customers to the maximum possible value for the corresponding connection point (e.g., 10kW).

iii) Run the power flow calculation and check if any network limit (voltage or thermal) is breached.

iv) If any network limit is breached, reduce the net active power of all active customers by a pre-defined value (e.g., 1kW). Run the power flow calculation again for the new values.

v) Repeat steps iii) and iv) up to the point that no network limit is breached. At this point the operating envelope value for each customer and current time step (e.g., 12:00PM) is defined by the net active power being used for each active customer.

vi) Move to the next time step (e.g., 12:05PM) and restart the process from i).

Maximum Allocation

i) For a given point in time (e.g., at 12:00PM), set the corresponding time-varying data – voltages at the head of the LV feeder, and net demand from passive customers (P, Q) and active customers (Q) – into their correct place in the LV electrical network model. Note that these values are fixed until the algorithm moves to the next time step (e.g., 5 min).

ii) Set the net active power of all active customers to the maximum possible value for the corresponding connection point (e.g., 10kW).

iii) Run the power flow calculation and check if any network limit (voltage or thermal) is breached.

iv) If any thermal limit is breached, reduce the net active power of all active customers by a pre-defined value (e.g., 1kW). Run the power flow calculation again for the new values.

v) If any voltage limit is breached, find the most affected (with the higher voltage) active customer, and reduce its net active power by a pre-defined value (e.g., 1kW). Run the power flow calculation again for the new value.

vi) Repeat steps iii), iv) and v) up to the point that no network limit is breached. At this point the operating envelope value for each customer and current time step (e.g., 12:00PM) is defined by the net active power being used for each active customer.

vii) Move to the next time step (e.g., 12:05PM) and restart the process from i).

Further comments:

- Note that the maximum allocation algorithm can only be used for the Ideal OE, because it depends on having full electrical models and full monitoring. This allocation algorithm is presented for completeness.
- The pre-defined value to reduce the OE should be decided case by case, given that it will interfere on how precise the OE will be and how long the OE calculation will take. A too small value will get a more precise OE, but it will take longer to converge. While a too large value will lose precision, but the OE calculation will be faster.

3.2.3 Output

As previously discussed, the output is the operating envelope that is calculated by the engine.

- Operating Envelope (Export/Import) for Active Customers: It consists of time-varying values (i.e., maximum active power for exports/imports) for each active customer of the LV network.

3.3 Operating Envelopes Review

Some projects that are related to the use of operating envelopes or export limits were reviewed with a focus on the implementation and calculation of the operating envelopes. In general, the focus of these projects is not on the algorithms to calculate the operating envelopes, so this project complements the existing knowledge on operating envelopes by proposing and implementing different operating envelopes, assessing, and comparing them. An overview of each project is given below, and a summary of findings is presented in Table 2. Note that this review was carried out on mid-2022, since then some of these projects have probably produced more outputs that are not considered here.

The Evolve DER Project [3, 14-19] focused on the creation of a communications platform (Evolve Platform) for exchange of electrical network models and measurement data between DNSPs and aggregators. It also demonstrates the operational mechanisms by which these operating envelopes can be calculated, published and utilised. Although the project explores some allocation techniques, it does not provide details about how they calculate operating envelopes.

Project Edith [3, 20, 21] builds on the work developed in the Evolve DER Project to test how different tools (i.e., Dynamic Operating Envelopes and Dynamic Network Prices) can work together in practice in a way that achieves positive outcomes by using a simple offer for customer involved in the trial. However, it is not specific on how to calculate operating envelopes. Nevertheless, this project has just started, so they might explore the subject in the future.

The Flexible Exports for Solar PV Trial project [3, 7, 22-25] focus to build standards-based flexible exports capability on Australia's leading inverter manufacturers. This project calculates the export limit based on the available capacity of distribution transformers. Note that in this project the export limit is calculated for the DER and not for the connection point of the customer.

Project EDGE [3, 5, 26-28] seeks to understand, test, and demonstrate a proof-of-concept DER Marketplace that enables efficient and secure coordination of aggregated DERs to provide wholesale and local network services within the constraints of the distribution network. It considers the use of full electrical models and full monitoring for the trial, so the operating envelope is as in the Ideal OE.

Project Symphony [3, 4, 29-34] aims to facilitate DER integration, and to do so it is developing a platform that is capable of registering, aggregating, and orchestrating customer DER to provide both on-market and off-market services. This project considers the use of full electrical models and full monitoring for the trial, so it is likely that the operating envelope is calculated as in the ideal OE, but it is not clear which method is used.

Table 2. Review of Projects Related to Operating Envelopes or Export Limits.

		PROJECT NAME (START YEAR – END YEAR)				
		EVOLVE DER PROJECT [3, 14-19] (2019 - 2022)	**PROJECT EDGE [3, 5, 26-28] (2020 - 2023)**	**PROJECT EDITH [3, 20, 21] (2022 - TBD)**	**FLEXIBLE EXPORTS FOR SOLAR PV TRIAL [3, 7, 22-25] (2020 - 2023)**	**PROJECT SYMPHONY [3, 4, 29-34] (2021 - 2023)**
OPERATING ENVELOPE	**TIME-VARYING INPUT DATA**	Power and energy from DTx; Voltage, power factor, and current at HV feeders. Energy data from customers. Weather data and solar irradiance.	Voltage magnitude at LV HoF. Net demand (P, Q) of passive cust. Net demand (Q) of active customers.	Not specified	Not specified	Power and energy from DTx. Voltage, power factor, and current at HV feeders. Energy data from customers. Weather data and solar irradiance.
	STATIC INPUT DATA	Electrical network model (HV+LV)	Electrical network model (LV). DER inverter capacity.	Not specified	Not specified, but it seems to use substation (DTx) data.	Electrical network model (HV+LV)
	OE IMPLEMENTATION. AND/OR CALCULATION METHOD	Not specified, but it mentions the combination of techniques drawn from mathematical optimisation, OPF analysis, and power systems analysis.	Ideal OE. Calculation uses an iterative process (guided by the allocation method) where a simplified power flow is run until network limits (voltage and/or thermal) are achieved.	Not specified, but it leverages Evolve DER Project OE implementation.	Asset Capacity OE. Calculate available capacity of the substation and divide it among DERs.	Not specified, but it leverages Evolve DER Project OE implementation.
	CONSIDERED CONTRAINTS	Thermal limit of assets. Voltage limits. Possible contingencies.	Thermal limit of assets. Voltage limits.	Not specified	Not specified, but it seems to consider asset capacity.	Thermal limits. Voltage limits under develop. NMI export/import limitations.
	ALLOCATION METHOD	Equal alloc. at LV feeder level. Equal allocation at DTx level. Maximal allocation at NMI level.	Equal allocation. Maximise service. Weighted allocation.	Not specified, but it will test interaction between OE allocation and dynamic pricing.	Not specified	Proportional alloc. (Inverter rating). Proportional alloc. (forecast energy). Weighted allocation (Inverter rating & forecast energy). Multistage criteria allocation.
	OE LOCATION	Customer connection point (NMI)	Customer connection point (NMI)	Not specified	DER device	Customer connection point (NMI)
	OUTPUT	Exp. and imp. power limits (P or P, Q_{fix})	Exp. and imp. power limits (P or P, Q_{fix})	Not specified	DER export power limits (P)	Export and import power limits (P)
	ASEESSMENT METRICS	Curtailed energy. Total energy exports.	Customer voltages. Asset utilisation. Total power exports	Not specified	Total energy exports. Customer energy exports	Allocation efficiency. Forecast energy supported. Scalability. Reliability. Allocation fairness. Minimum export service level. Energy buyback rebates. Environment impact.
	COMPARISONS	Not applicable	Comparisons are made for the different allocation methods.	Not Applicable	Not Applicable	Comparisons are made for the different allocation methods.

4 OE Implementations and Assessment Metrics

This chapter presents three simpler alternatives (if compared to the complex Ideal OE) to implement operating envelopes. The general idea is to present operating envelopes that can be implemented in the absence of full electrical LV network models and full monitoring of network/customers.

4.1 Asset Capacity Operating Envelope

The Asset Capacity OE is the least advanced and, hence, the least accurate operating envelope approach as it only considers the thermal aspect of the distribution transformer to calculate the spare capacity and split it among active customers. To do so, it only needs the monitoring and capacity of one element of the network (the distribution transformer), which makes its implementation very simple. Although it is a very simple OE approach to implement, it does not cater for voltage aspects, which is the most common technical problem currently faced by DNSPs (due to high penetration of DERs). In addition, given that this project calculates this OE considering only the capacity of the distribution transformer, it is possible to have thermal problems on the LV head of feeder. Nonetheless, the calculation algorithm can be easily modified to consider this extra constraint, but more data would need to be available.

By itself, this OE implementation could be a cost-effective solution to DNSPs that has some LV networks achieving the thermal limits of the distribution transformer but not facing voltage problems. Considering the survey on the available infrastructure/data across Australian DNSPs, the DNSPs with monitoring at distribution transformers, which are considered to be in the *Fast Transition* cluster (Endeavour Energy and South Australia Power Networks), *Very Fast Transition* cluster (Ausgrid, Energex, and Ergon Energy) and *Step Transition* cluster (Evoenergy), may already have the required capabilities to implement the Asset Capacity OE. However, other DNSPs would need to make investments before using the Asset Capacity OE, particularly on the monitoring of distribution transformers.

The architecture for the Asset Capacity OE is shown in Figure 8, and each part of the architecture is explained in the next sections.

4.1.1 Input Data

As discussed in Section 3.1, the input data brings all the necessary data for the calculation of a given operating envelope implementation. In the case of the Asset Capacity OE used in this project, the following time-varying data and static database inputs are necessary.

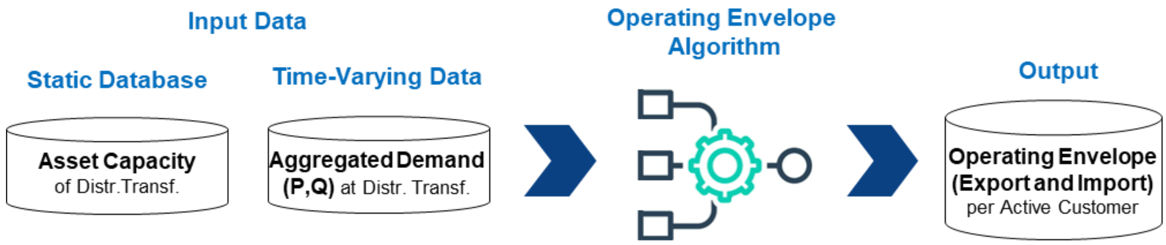

Figure 8. Architecture for the Asset Capacity OE.

Time-Varying Data

- Aggregated Demand (P, Q) at Distribution Transformer: It is the active and reactive power passing through the secondary (LV) side of the distribution transformer, which is necessary to calculate the distribution transformer spare capacity. Since the LV feeders/network usually have three phases, this measurement is required to be per phase.

Static Database

- Capacity of the Distribution Transformer: It is the rated capacity of the distribution transformer, which is necessary to ensure that the calculated operating envelopes will not exceed the maximum physical (i.e., thermal) capability of the asset.

4.1.2 Operating Envelope Algorithm

As discussed in Section 3.1, the operating envelope algorithm is the engine that process the input data to calculate the operating envelopes. In the case of the Asset Capacity OE, it uses the capacity of the distribution transformer together with time-varying input data to carry out a simple algorithm that calculate the spare capacity and split it among active customers. Note that the calculation of operating envelopes for exports and imports are very similar, but they must be done separately. For simplicity, only the export algorithm is described here. Details of the proportional allocation algorithm are shown below.

Proportional Allocation

i) For a given point in time (e.g., at 12:00PM), use the corresponding time-varying data – aggregated demand (P, Q) at the distribution transformer – to calculate the spare capacity of the distribution transformer. For this, take the measured/forecast active power at the distribution transformer and discount the estimated aggregated net active power of active customers. Then, subtract the result obtained previously from the rated capacity of the distribution transformer to find the spare capacity.

ii) If there is a spare capacity available, proportionally (based on DER size) divide the available spare capacity to all active customers. At this point the operating envelope value for each customer and current time step (e.g., 12:00PM) is defined by the proportionally divided spare capacity. If there is no spare capacity available, the operating envelope value to all active customers is zero.

iii) Move to the next time step (e.g., 12:05PM) and restart the process from i).

Further comments:

- In i), for the estimation of the aggregated active power of active customers, it is expected that DNSPs will have access to historical/operational net demand data from active customers, or any other data that would allow them to estimate this value. However, in this project, a perfect estimation is considered. Note that this project recognises that making the estimation of the aggregated active power of active customers may be challenging, but it is necessary for the correct calculation of the spare capacity. Disregarding this estimation or having a very inaccurate estimation will directly affect the operating envelope values.
- Note that network losses are not being included in this project, which will inevitably lead to some inaccuracies on the OE calculation of both exports and imports, but this will be prominent on the imports. The inclusion of network losses into this algorithm is easy though.

4.1.3 Output

As discussed in Section 3.1, the output is the operating envelope that is calculated by the engine.

- Operating Envelope (Export/Import) for Active Customers: It consists of time-varying values (i.e., maximum active power for exports/imports) for each active customer of the LV network.

4.2 Asset Capacity & Critical Voltage Operating Envelope

The Asset Capacity & Critical Voltage (AC_CrV) OE is more advanced than the Asset Capacity OE as both voltage and thermal issues are considered instead of only thermal issues. Thermal issues are solved by calculating the spare capacity of the distribution transformer, while voltages issues are solved by estimating the voltage at the critical customer via a sensitivity curve (using historical active power and voltage of the critical customer). Although it needs more monitoring than the Asset Capacity OE, this extra requirement is minimal – only at two points of the LV network, specifically the distribution transformer and the critical customer – which makes its implementation to be relatively simple. However, since the voltage estimation is only based on the monitoring of the critical customer, this OE does not capture well the daily voltage variations due to interactions with the upstream HV network and its values are usually a bit on the conservative side (considering that the correct critical customer is selected). It is important to note that the selection of the critical customer can make a considerable difference on the effectiveness of the OE to solve voltage problems. In case the selected critical customer is not the actual critical customer, it will generate inaccurate/ineffective OEs.

Given that the AC_CrV OE does not need the electrical models of the LV networks, this OE implementation has great potential to be used by DNSPs that have limited or no availability of such electrical models. Considering the survey on the available infrastructure/data across Australian DNSPs, the DNSPs with availability of distribution transformers monitoring and historical non-market data for some LV customers (or critical points of the LV networks), which are

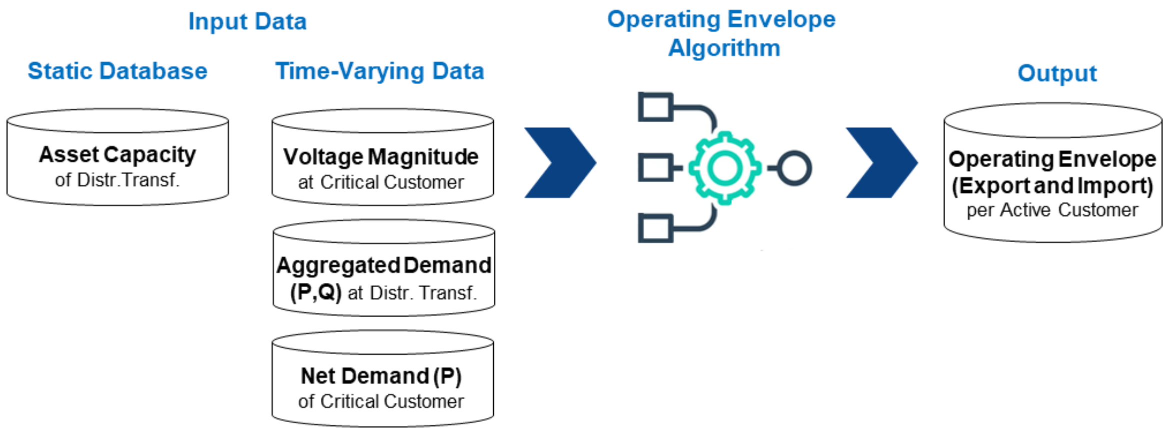

Figure 9. Architecture for the AC_CrV OE.

considered to be in the *Fast Transition* cluster (Endeavour Energy) and *Very Fast Transition* cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_CrV OE. Another set of DNSPs that may already have the required capabilities to implement the AC_CrV OE are the ones with full monitoring of LV customers, specifically Ausnet Services, CitiPower, Horizon Power, Jemena, Powercor, and United Energy. These DNSPs could use the full monitoring of LV customers to estimate the power flow on the distribution transformer. However, other DNSPs would need to make investments before using the AC_CrV OE, most of them on the operational monitoring of distribution transformers (unless they have other ways to estimate the power flow in the distribution transformers) and few others in non-market data monitoring of LV customers (particularly the critical ones).

The architecture for the AC_CrV OE is shown in Figure 9, and each part of the architecture is explained in the next sections.

4.2.1 Input Data

As discussed in Section 3.1, the input data brings all the necessary data for the calculation of a given operating envelope implementation. In the case of the AC_CrV OE the following time-varying data and static database inputs are necessary.

Time-Varying Data

- Voltage Magnitude at Critical Customer: It is the historical voltage magnitude of the critical active customer in the LV network, which is used (together with the net active power demand of the same customer) to create a sensitivity curve that gives an estimation of the voltage at that critical customer.
- Net Demand (P) of Critical Customer: It is the historical net active power demand of the critical active customer in the LV network, which is used (together with the voltage magnitude of the same customer) to create a sensitivity curve that gives an estimation of the voltage at that critical customer.

- Aggregated Demand (P, Q) at the Distribution Transformer: It is the active and reactive power passing through the secondary (LV) side of the distribution transformer, which is necessary to calculate the distribution transformer spare capacity. Since the LV feeders/network usually have three phases, this measurement is required to be per phase.

Static Database

- Capacity of the Distribution Transformer: It is the rated capacity of the distribution transformer, which is necessary to ensure that the calculated operating envelopes will not exceed the maximum physical (i.e., thermal) capability of the asset.

Further comments:

- In this project it is considered minimum knowledge of the LV network, thus the critical customer is only selected based on its distance from the distribution transformer (the furthest active customer from the distribution transformer). Also, only one critical customer is considered for the LV network, even if it has more than one LV feeder. However, it may not be the best way to choose the critical customer since the actual critical customer could be another one, which would generate inaccurate/ineffective OEs (as discussed previously).

4.2.2 Operating Envelope Algorithm

As discussed in Section 3.1, the operating envelope algorithm is the engine that process the input data to calculate the operating envelopes. In the case of the AC_CrV OE, a requirement to calculate the OE is a P-V sensitivity curve that is used to estimate the voltage at the critical customer from its net active power demand. This P-V sensitivity curve can be obtained beforehand with historical data, and it does not need to be obtained for every time step since the sensitivity curve may not change much within short time periods. Note that the creation of this P-V sensitivity curve for exports and imports are very similar, but they must be done separately. For simplicity, only the export is described here. Details on how to obtain this P-V sensitivity curve are given below.

P-V Sensitivity Curve

i) Take the historical net active power demand of the critical customer for a given period (e.g., two days) and use them as input to a polynomial fit function from a standard library (e.g., Python NumPy) to create the P-V sensitivity curve.

Once the required sensitivity curve is available, the AC_CrV OE algorithm has two main steps. First, the capacity of the distribution transformer together with its time-varying input data is used to calculate its spare capacity. Second, the P-V sensitivity curve for the critical customer is used to estimate its voltage. These two are used in combination to calculate the operating envelopes. Note that the calculation of operating envelopes for exports and imports are very similar, but they must be done separately. For simplicity, only the export algorithm is described here. Details of the proportional allocation algorithm are given below.

Proportional Allocation

i) For a given point in time (e.g., at 12:00PM), use the corresponding time-varying data – aggregated demand (P, Q) at the distribution transformer – to calculate the spare capacity of the distribution transformer. For this, take the measured/forecast active power at the distribution transformer and discount the estimated aggregated net active power of active customers. Then, subtract the result obtained previously from the rated capacity of the distribution transformer to find the spare capacity.

ii) If there is a spare capacity available, proportionally (based on DER size) divide the available spare capacity to all active customers and continue the algorithm from step iii). If there is no spare capacity available, the operating envelope value to all active customers is zero and jump to step vii).

iii) Take the spare capacity allocated to the critical customer (P*) and use the P-V sensitivity curve to estimate the voltage magnitude (V*) at this customer.

iv) Check if the critical customer voltage breaches the network limit.

v) If network limit is breached, reduce the net active power (P*) of all active customers by a pre-defined value (e.g., 1kW). Use the P-V sensitivity curve again for the new values to estimate the new voltage (V*) at the critical customer.

vi) Repeat step iv) and v) up to the point that no network limit is breached. At this point the operating envelope value for each customer and current time step (e.g., 12:00PM) is defined by the net active power (P*) being used for each active customer.

vii) Move to the next time step (e.g., 12:05PM) and restart the process from i).

Further comments:

- In i), for the estimation of the aggregated active power of active customers, it is expected that DNSPs will have access to historical/operational net demand data from active customers, or any other data that would allow them to estimate this value. However, in this project, a perfect estimation is considered. Note that this project recognises that making the estimation of the aggregated active power of active customers may be challenging, but it is necessary for the correct calculation of the spare capacity. Disregarding this estimation or having a very inaccurate estimation will directly affect the operating envelope values.
- Note that network losses are not being included in this project, which will inevitably lead to some inaccuracies on the OE calculation of both exports and imports, but this will be prominent on the imports. The inclusion of network losses into this algorithm is easy though.

4.2.3 Output

As discussed in Section 3.1, the output is the operating envelope that is calculated by the engine.

- Operating Envelope (Export/Import) for Active Customers: It consists of time-varying values (i.e., maximum active power for exports/imports) for each active customer of the LV network.

4.3 Asset Capacity & Delta Voltage Operating Envelope

The Asset Capacity & Delta Voltage (AC_ΔV) OE is more advanced than the AC_CrV OE, given that it can capture better the daily voltage variations due to interactions with the upstream HV network. Thermal issues are solved by calculating the spare capacity of the distribution transformer, while voltages issues are solved by estimating the voltage at the critical customer via sensitivity curves (using historical aggregated active power on the LV network and voltage at the head of the LV feeder and at the critical customer). The monitoring requirements are the same as for the AC_CrV OE, which makes its implementation also relatively simple. It is important to note that the selection of the critical customer can make a considerable difference on the effectiveness of the OE to solve voltage problems. In case the selected critical customer is not the actual critical customer, it will generate inaccurate/ineffective OEs.

Similar to the AC_CrV OE, the AC_ΔV OE implementation does not need the electrical models of the LV networks, so it has great potential to be used by DNSPs that has limited or no availability of such electrical models. Considering the survey on the available infrastructure/data across Australian DNSPs, the DNSPs with availability of distribution transformers monitoring and historical non-market data for some LV customers (or critical points of the LV networks), which are considered to be in the *Fast Transition* cluster (Endeavour Energy) and *Very Fast Transition* cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_ΔV OE. Note that since this OE requires a voltage monitoring at the distribution transformer, having a full monitoring of the LV customers does not help (as in the AC_CrV OE). Therefore, other DNSPs would need to make investments before using the AC_ΔV OE, most of them on the operational monitoring of distribution transformers (unless they have other ways to estimate the power flow and voltages in the distribution transformers) and few others in non-market data monitoring of LV customers (particularly the critical ones).

The architecture for the Asset Capacity OE is shown in Figure 10, and each part of the architecture is explained in the next sections.

4.3.1 Input Data

As discussed in Section 3.1, the input data brings all the necessary data for the calculation of a given operating envelope implementation. In the case of the AC_ΔV OE the following time-varying data and static database inputs are necessary.

Time-Varying Data

- Voltage Magnitude at the Distribution Transformer and Critical Customer: It is the historical voltage magnitude at the secondary side of the distribution transformer as well as at the critical active customer. These historical data are used (together with the aggregated active power demand at the distribution transformer) to create sensitivity curves that give estimations of the voltage at the distribution transformer and the delta voltage between the distribution

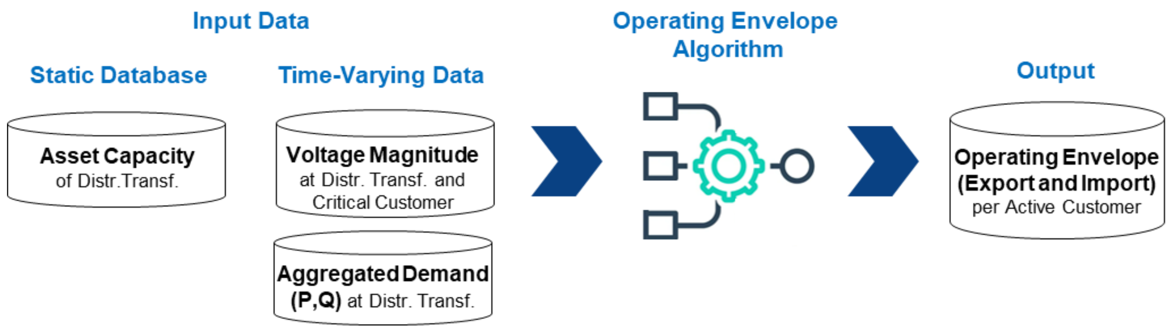

Figure 10. Architecture for the AC_ΔV OE.

transformer and the critical customer, which, in turn, also allows to estimate the voltage at the critical customer.

- Aggregated Demand (P, Q) at the Distribution Transformer: It is the active and reactive power passing through the secondary (LV) side of the distribution transformer, which is necessary to calculate the distribution transformer spare capacity. The active power is also used to create the sensitivity curves for voltages (as mentioned above). Since the LV feeders/network usually have three phases, this measurement is required to be per phase.

Static Database

- Asset Capacity of Distribution Transformer: It is the rated capacity of the distribution transformer, which is necessary to ensure that the calculated operating envelopes will not exceed the maximum physical (i.e., thermal) capability of the asset.

Further comments:

- In this project it is considered minimum knowledge of the LV network, thus the critical customer is only selected based on its distance from the distribution transformer (the furthest active customer from the distribution transformer). Also, only one critical customer is considered for the LV network, even if it has more than one LV feeder. However, it may not be the best way to choose the critical customer since the actual critical customer could be another one, which would generate inaccurate/ineffective OEs (as discussed previously).

4.3.2 Operating Envelope Algorithm

As discussed in Section 3.1, the operating envelope algorithm is the engine that process the input data to calculate the operating envelopes. In the case of the AC_ΔV OE, there are two requirements to calculate the OE. First, a P_{DTx}-V_{DTx} sensitivity curve that is used to estimate the voltage magnitude at the DTx for a given aggregated active power passing through the DTx. Second, a P_{DTx}-ΔV sensitivity curve that is used to estimate the delta voltage between the DTx and the critical customer for a given aggregated active power passing through the DTx. These sensitivity curves can be obtained beforehand with historical data, and they do not need to be obtained for every time step since the sensitivity curves may not change much within short time periods. Note that the creation of these sensitivity curves for exports and imports are very similar, but they must be done separately. For simplicity, only the export is described here. Details on how to obtain both P_{DTx}-V_{DTx} and P_{DTx}-ΔV sensitivity curves are given below.

P_{DTx}-V_{DTx} Sensitivity Curve

i) Take the historical aggregated active power of the DTx for a given period (e.g., two days) and separate the time steps in which the LV network is exporting power.

ii) Separate the historical voltage magnitude of the DTx for when the LV network is exporting power.

iii) Take the separated data for voltage magnitude and aggregated active power of the DTx and use them as input to a polynomial fit function from a standard library (e.g., Python NumPy) to create the P_{DTx}-V_{DTx} sensitivity curve.

P_{DTx}-ΔV Sensitivity Curve

i) Take the historical aggregated active power of the DTx for a given period (e.g., two days) and separate the time steps in which the LV network is exporting power.

ii) Separate the historical voltage magnitude of the critical customer for when the LV network is exporting power.

iii) Take the separated data for voltage magnitude of the critical customer and aggregated active power of the DTx and use them as input to a polynomial fit function from a standard library (e.g., Python NumPy) to create the P_{DTx}-ΔV sensitivity curve.

Once the required sensitivity curves are available, the AC_ΔV OE algorithm has two main steps. First, the capacity of the DTx together with its time-varying input data is used to calculate its spare capacity. Second, both P_{DTx}-V_{DTx} and P_{DTx}-ΔV sensitivity curves are used to estimate the voltage at the critical customer for a given aggregated active power passing through the DTx. The spare capacity and estimated voltage at the critical customer are used in combination to calculate the operating envelopes. Note that the calculation of operating envelopes for exports and imports are very similar, but they must be done separately. For simplicity, only the export algorithm is described here. Details of the proportional allocation algorithm are given below.

Proportional Allocation

i) For a given point in time (e.g., at 12:00PM), use the corresponding time-varying data – aggregated demand (P, Q) at the distribution transformer – to calculate the spare capacity of the distribution transformer. For this, take the measured/forecast active power at the distribution transformer and discount the estimated aggregated net active power of active customers. Then, subtract the result obtained previously from the rated capacity of the distribution transformer to find the spare capacity.

ii) If there is a spare capacity available, proportionally (based on DER size) divide the available spare capacity to all active customers and continue the algorithm from step iii). If there is no spare capacity available, the operating envelope value to all active customers is zero and jump to step x).

iii) Calculate the expected aggregated active power of the distribution transformer (P_{DTx}*) after the allocation of the spare capacity. For this, use the total allocated spare capacity and the current power flow at the DTx (after discounting the estimated aggregated net active power of active customers) to calculate the P_{DTx}*.

iv) Calculate the expected voltage at the distribution transformer (V_{DTx}*) after the allocation of the spare capacity. For this, take the expected aggregated active power of the distribution transformer (P_{DTx}*) calculated in iii), and use the P_{DTx}-V_{DTx} sensitivity curve to estimate the voltage magnitude (V_{DTx}*) at the distribution transformer.

v) Calculate the expected delta voltage (ΔV*) between the distribution transformer and the critical customer after the allocation of the spare capacity. For this, take the expected aggregated active power of the distribution transformer (P_{DTx}*) calculated in iii), and use the P_{DTx}-ΔV sensitivity curve to estimate the delta voltage (ΔV*).

vi) Calculate the expected voltage at the critical customer (V*) by summing the expected voltage at the distribution transformer (V_{DTx}*) and the expected delta voltage (ΔV*).

vii) Check if the critical customer voltage breaches the network limit.

viii) If the network limit is breached, reduce the net active power of all active customers by a pre-defined value (e.g., 1kW). Repeat iii), iv), v) and vi) for the new values to estimate the new voltage at the critical customer (V*).

ix) Repeat step vii) and viii) up to the point that no network limit is breached. At this point the operating envelope value for each customer and current time step (e.g., 12:00PM) is defined by the net active power being used for each active customer.

x) Move to the next time step (e.g., 12:05PM) and restart the process from i).

Further comments:

- In i), for the estimation of the aggregated active power of active customers, it is expected that DNSPs will have access to historical/operational net demand data from active customers, or any other data that would allow them to estimate this value. However, in this project, a perfect estimation is considered. Note that this project recognises that making the estimation of the aggregated active power of active customers may be challenging, but it is necessary for the correct calculation of the spare capacity. Disregarding this estimation or having a very inaccurate estimation will directly affect the operating envelope values.
- Note that network losses are not being included in this project, which will inevitably lead to some inaccuracies on the OE calculation of both exports and imports, but this will be prominent on the imports. The inclusion of network losses into this algorithm is easy though.

4.3.3 Output

As discussed in Section 3.1, the output is the operating envelope that is calculated by the engine.

- Operating Envelope (Export/Import) for Active Customers: It consists of time-varying values (i.e., maximum active power for exports/imports) for each active customer of the LV network.

4.4 Assessment Metrics

This section presents the assessment metrics that are used to assess and compare the performance of each operating envelope implementation. It is important to notice that this project assess the effectiveness of the OEs to solve technical problems when all active customers are fully utilising their OEs (for exports or imports), which is when the network is used on its limits and thermal or voltage issues are expected to happen in case the OE is not accurate. However, this may not be the worst-case scenario for assessing voltages, because depending on how much each active customer decides to use from their available OE, voltages can go a bit higher due to unbalance effects [35, 36]. Although, theoretically, voltages could get a bit worse with high unbalance (exceeding the limits), it is unlikely for that to happen often enough to be an issue. Therefore, the assessment carried out here is appropriate for assessing the different OEs.

4.4.1 OE Accuracy

Type: Quantitative.

Focus: Accuracy of the OE calculation method.

Definition: The absolute mismatch between the operating envelope calculated via a simpler OE and the operating envelope calculated via the Ideal OE, which is calculated for each time step of the day (e.g., every 5 minutes).

Assessment: The absolute mismatch is presented as minimum, average, and maximum values instead of showing every time step of the day. The larger the mismatch, the worse is the accuracy. This assessment is done for each operating envelope implementation presented in Section 4.

4.4.2 Voltage Compliance

Type: Quantitative.

Focus: Network Performance.

Definition: Network-wide compliance is met if up to 1% of measurements below 216V and up to 1% of measurements above 253V are maintained across at least 95% of the customers on a given period (usually a week). In the case of this report this assessment is done for one day. The calculations follow the current Australian standard AS 61000.3.100–2011 [37].

Assessment: The assessment is made for when all active customers use the maximum value of the calculated operating envelope, which is when the network is used on its limits and voltage issues are expected to happen in case the OE is not accurate. This assessment is done for each proposed operating envelope implementation, and a comparison is made among them. The following colour classification applies to this assessment in the case study:

- Green: Perfect. Voltage compliance is 100% across the considered network.
- Yellow: Acceptable. Voltage compliance is at least 95% across the considered network.
- Red: Not acceptable. Voltage compliance is below 95% across the considered network.

4.4.3 Maximum Voltage

Type: Quantitative.

Focus: Network Performance.

Definition: The maximum voltage that any customer achieves in a given day.

Assessment: This assessment is made for exports only, because during exports voltages tend to rise. Also, the assessment is made for when all active customers use the maximum value (for exports) of the calculated operating envelope, which is when the network is used on its limits and voltage issues are expected to happen in case the OE is not accurate. In addition, this assessment is done for each proposed operating envelope implementation, and a comparison is made among them. The following colour classification applies to this assessment in the case study:

- Green: Perfect. Maximum voltage is well within the steady state limit (≤253V).
- Yellow: Acceptable (if very few isolated cases). Maximum voltage is above the steady state limit (>253V), but below the DER inverter tripping limit (<258V).
- Red: Not acceptable. Maximum voltage is above the DER inverter tripping limit (≥258V).

4.4.4 Minimum Voltage

Type: Quantitative.

Focus: Network Performance.

Definition: The minimum voltage that any customer achieves in a given day.

Assessment: This assessment is made for imports only, because during imports voltages tend to drop. Also, the assessment is made for when all active customers use the maximum value (for imports) of the calculated operating envelope, which is when the network is used on its limits and voltage issues are expected to happen in case the OE is not accurate. In addition, this assessment is done for each proposed operating envelope implementation, and a comparison is made among them. The following colour classification applies to this assessment in the case study:

- Green: Perfect. Minimum voltage is well within the steady state limit (≥216V).

- Yellow: Acceptable (if very few isolated cases). Minimum voltage is below the steady state limit (<216V), but above the voltage dip limit (>207V).
- Red: Not acceptable. Minimum voltage is below the voltage dip limit (≤207V).

4.4.5 Asset Utilisation

Type: Quantitative.

Focus: Network Performance.

Definition: The maximum current of the three phases on the distribution transformer, and the maximum current of the three phases of a line divided by its corresponding rated capacity, which is calculated for each time step of the day (e.g., every 5 minutes). The utilisation level of the transformer, TU_t, for each time step $t \in T$ is calculated by Eq. 1; where I_t^{Tx} is the maximum current of the three phases passing through the transformer at time step $t \in T$, and I^{Tx_rated} is the rated current per phase (calculated from the rated kVA) of the transformer. The utilisation level of lines, $LU_{l,t}$, for each line $l \in L$ and time step $t \in T$ is calculated by Eq. 2; where $I_{l,t}$ is the maximum current of the three phases passing through line $l \in L$ at time step $t \in T$, and I_l^{rated} is the rated current per phase of line $l \in L$.

$$TU_t[\%] = \frac{I_t^{Tx}}{I^{Tx\_rated}} * 100 \quad \forall\, t \in T \qquad \text{Eq. 1}$$

$$LU_{l,t}[\%] = \frac{I_{l,t}}{I_l^{rated}} * 100 \quad \forall\, l \in L, t \in T \qquad \text{Eq. 2}$$

Assessment: The assessment is made for when all active customers use the maximum value of the calculated operating envelope, which is when the network is used on its limits and thermal issues are expected to happen in case the OE is not accurate. This assessment is done for each proposed operating envelope implementation, and a comparison is made among them. The following colour classification applies to this assessment in the case study:

- Green: Perfect. Asset utilisation is well within the limit (≤100%).
- Yellow: Acceptable (if isolated assessed). Asset utilisation is above the thermal limit (>100%), but below the acceptable overload (≤110%).
- Red: Not acceptable. Asset utilisation is above the acceptable overload (>110%).

4.4.6 Total OE Gain

Type: Quantitative.

Focus: Impact on Customers.

Definition: The total energy that is possible to be generated in a day by fully utilising the calculated operating envelope (export component), subtracted by the total energy that is possible to be generated in a day by fully utilising a fixed export limit (usually used as a simpler alternative to OEs). The total avoided curtailment, TAC, is calculated by Eq. 3; where $P_{t,c_a}^{OE\_exp}$ is the active power from the operating envelope (exports) for an active customer $c_a \in C$ at time step $t \in T$, and $P_{t,c_a}^{Fix\_exp}$ is the active power from the fixed exports for an active customer $c_a \in C$ at time step $t \in T$.

$$TAC[MWh] = \frac{\sum_{t\in T}\sum_{c_a\in C}\left(P_{t,c_a}^{OE\_exp} - P_{t,c_a}^{Fix\_exp}\right)}{\#\ time\ steps\ in\ an\ hour} \qquad \textbf{Eq. 3}$$

Assessment: The total avoided curtailment is calculated for a conservative fixed export of 1.5kW at the customer connection point, which is being used by at least one DNSP in Australia [38]. This assessment is done for each proposed operating envelope implementation, and a comparison is made among them.

4.4.7 Aggregated Exports/Imports

Type: Quantitative.

Focus: Services Provision.

Definition: The aggregated exports of active power from active customers for each time step of the day (e.g., every 5 minutes) if fully utilising the calculated operating envelope, or by utilising fixed export limits. The aggregated exports when using operating envelopes, AE_t^{OE}, for each time step $t \in T$ is calculated by Eq. 4; where $P_{t,c_a}^{OE\_exp}$ is the maximum active power export allowed by the operating envelope of an active customer $c_a \in C$ at time step $t \in T$. The aggregated exports when using fixed export limits, AE_t^{Fix}, for each time step $t \in T$ is calculated by Eq. 5; where $P_{t,c_a}^{Fix\_exp}$ is the maximum active power export allowed by the fixed export limit of an active customer $c_a \in C$ at time step $t \in T$. Note that similar metrics can be calculated for imports. The aggregated export/imports as energy for the whole day is calculated by summing all time steps $t \in T$ of the results obtained in Eq. 4. The same can be done for Eq. 5.

$$AE_t^{OE}[kW] = \sum_{c_a\in C} P_{t,c_a}^{OE\_exp} \quad \forall\, t \in T \qquad \textbf{Eq. 4}$$

$$AE_t^{Fix}[kW] = \sum_{c_a\in C} P_{t,c_a}^{Fix\_exp} \quad \forall\, t \in T \qquad \textbf{Eq. 5}$$

Assessment: The assessment is made by comparing the aggregated exports/imports at few time steps for when fully utilising the available operating envelopes and for when utilising conservative fixed export limits (1.5kW at the customer connection point, which is being used by at least one DNSP in Australia [38]). The aggregated export/imports as energy for the whole day is also assessed. These assessments are done for each proposed operating envelope implementation, and a comparison is made among them.

4.4.8 Equity/Fairness

Type: Quantitative.

Focus: Impact on Customers.

Definition: The equity/fairness of each allocation method is given by the Jain's Fairness Index (JFI), which quantify the spread of the OE value that each customer receives. The JFI ranges from 0 to 1, where a higher JFI indicates a higher level of fairness among customers. For instance, when the JFI is equal to 1, all customers received the same OE value (i.e., as fair as it can be). The Jain's Fairness Index, JFI_t, for each time step of the day is calculated by Eq. 6; where $P_{t,c_a}^{OE\_exp}$ is the maximum active power export allowed by the operating envelope of an active customer $c_a \in C$ at time step $t \in T$, and $c_a^{\#}$ is the number of active customers.

$$JFI_t = \frac{\left(\sum_{c_a \in C} P_{t,c_a}^{OE\_exp}\right)^2}{c_a^{\#} * \sum_{c_a \in C} \left(P_{t,c_a}^{OE\_exp}\right)^2} \quad \forall\, t \in T \qquad \textbf{Eq. 6}$$

Assessment: The equity/fairness assessment is made by comparing the Jain's Fairness Index of each allocation method. This assessment is done for each proposed operating envelope implementation, and a comparison is made among them.

4.4.9 Cost and Complexity of Implementation

Type: Qualitative.

Focus: Feasibility.

Definitions:

- Complexity of Implementation: A qualitative assessment is done based on the required infrastructure (including the penetration of smart meters) and data (including the amount of data transmission and details of electrical models) that are necessary to implement the proposed operating envelope.
- Cost of Implementation: A qualitative assessment (e.g., using symbols such as $, $$, $$$) is done based on the required infrastructure and data for each proposed operating envelope implementation.

Assessment: The assessment is made by comparing the cost and complexity of each operating envelope implementation.

5 Assessment of the Operating Envelope Implementations

The main objective of this section is to assess the performance of the operating envelope implementations presented in Section 4 via a study case. Results from each OE implementation is presented and compared to the Ideal OE (the benchmark). In addition, a very conservative fixed export of 1.5kW that is being used by at least one DNSP in Australia [38] is also assessed and compared to the Ideal OE. This fixed export is also used as reference to calculate the metric named total OE gain. For completeness, the results of the Ideal OE with maximum allocation are presented and discussed. Finally, a complete comparison is presented with all simulated cases.

5.1 Case Study

5.1.1 HV-LV Distribution Network

This study uses a real 22kV HV feeder in Victoria, Australia, as shown in Figure 11. The HV feeder starts at the 66kV/22kV primary substation transformer, where the 66kV (1.0 p.u.) is considered constant. There are 79 distribution transformers connected to this HV feeder, and their transformation ratio is 22kV/0.433kV with off-load tap changer (off-LTC) at the middle position (not affecting the ratio) – overall providing a natural boost of around 8% from the nominal voltage of 0.4kV which is common in Australia. Each one of these distribution transformers has an off-LTC that allows to adjust its transformation ratio in 5 different positions, which are -5%, -2.5%, 0%, +2.5%, +5% on the secondary of the distribution transformer.

Given that the electrical models of LV feeders were not available for this HV feeder, pseudo-LV feeders are created based on few available information (e.g., number of customers per transformer) and the distribution company design principles [39]. In total there are approximately 3,374 customers across all the pseudo-LV feeders, mostly residential single-phase connections.

It is important to notice that the modelling of the HV part is crucial to capture voltage variations that occur at the primary side of the distribution transformer throughout the day, which is caused by all other customers connected to the HV feeder. The consideration of these variations allows the calculation of more accurate operating envelopes for the selected LV network.

5.1.2 Considerations and Studied Scenarios

This case study considers a total penetration of approximately 30% of PV systems in the HV-LV distribution network, which is close to the current average penetration of residential PV systems in Australia [2]. The location of these PV systems is randomly chosen considering all the 3,374 customers on the entire distribution network. These PV systems are considered to have an installed capacity of 5kW. Given that there is a reasonable penetration of PV systems in this

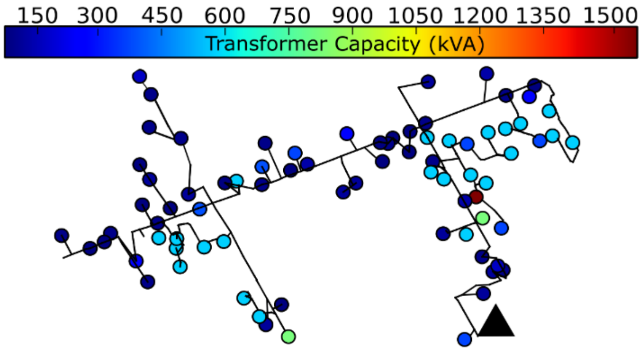

Figure 11. Real Australian HV feeder (22kV).

network, the off-LTC of each distribution transformer is individually adjusted to improve the voltage headroom on the corresponding LV network. This is done in a way that no voltage would get outside the limits during an entire year. Note that since each LV network has a different location on the HV feeder and different combination of demand/generation, they are differently impacted by voltage rise/drop, hence, each LV network gets a different off-LTC setting. These are realistic considerations that intend to bring the case study closer to the industry practice.

Another aspect considered to make the case study more realistic is the implementation of simultaneous Volt-var and Volt-Watt functions on the PV inverters, as required by the Australian standard AS 61000.3.100–2011 [37]. These are implemented to all PV systems of passive customers according to the settings given by the Australian standard. Note that this case study does not implement these inverter settings to active customers, given that they must respect the calculated OEs that is meant to avoid network problems.

The above considerations are related to the general modelling of the whole HV-LV distribution network, now it is needed to state the considerations for the selected LV network for which the OEs are calculated for. The representation of the selected LV network is shown in Figure 12. It has three LV feeders with a total of 114 customers, and it has a penetration of approximately 30% of PV systems (i.e., 35 of the 114 customers have PV systems), which belongs to passive customers. As already mentioned before, these PV systems have an installed capacity of 5kW. Since the operating envelopes are calculated and applied only to active customers (customers that engage with aggregators), they are added to this network on top of the already existing PV penetration. To do so, some passive customers without PV systems are randomly selected to become active customers. These active customers are considered to have PV systems and batteries, which have a combined installed capacity of 10kW, in turn, this value becomes the maximum possible export of the OEs. In addition, houses are considered to have a fuse of 14kW, which becomes the maximum possible import of the OEs. Four scenarios of active customers are considered:

- Scenario 1: approximately 5% of active customers, leading to an approximated 35% of total DER penetration in the selected LV network.
- Scenario 2: approximately 15% of active customers, leading to approximated 45% of total DER penetration in the selected LV network.

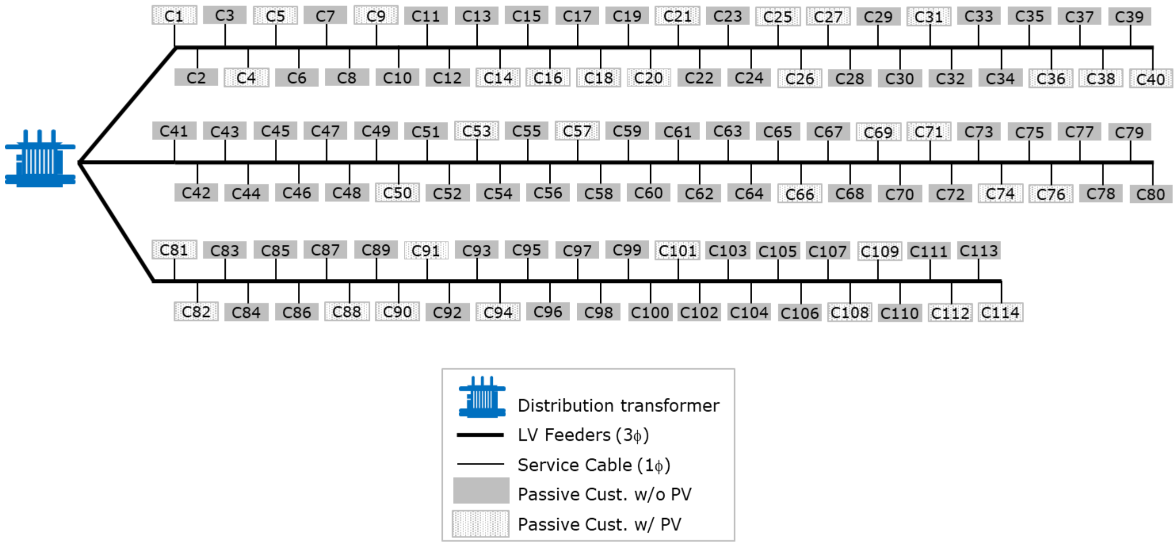

Figure 12. Representation of the LV network selected for testing OE implementations.

- Scenario 3: approximately 25% of active customers, leading to approximated 55% of total DER penetration in the selected LV network.
- Scenario 4: approximately 40% of active customers, leading to approximated 70% of total DER penetration in the selected LV network.

Finally, the demand for each customer and the PV resource availability are based on real data from 2014, Victoria, Australia, and correspond to 24h in a summer weekday. The demand is from a pool of 5-minutes resolution (realistic interpolation from 30-minutes resolution), day-long (i.e., 288 points), anonymized smart meter. The active power demand profile for customers is randomly selected from this pool, and random inductive power factor between 0.90 p.u. and 0.99 p.u. is assumed for the reactive power demand. The PV resource availability (same resolution as the demand) is based on a 1-minute resolution, normalized historical solar irradiance data [40].

5.1.3 Results and Discussions

Fixed Export

The resulting operating envelopes from the Fixed Export and the Ideal OE for all scenarios are shown in Figure 13. As the name already suggests, the operating envelope generated by the Fixed Export has the same value (1.5kW) for the net demand export limit to all active customers for the entire day and for any of the considered scenarios. On the opposite side is the Ideal OE, in which its generated operating envelope tends to decrease as the numbers of active customers gets higher. This can be clearly seen when comparing different scenarios of the Ideal OE, compare scenario 1 with scenario 4 for instance. This happens because more active customers mean more power being exported/imported, which increases the voltage rise/drop, hence, the operating envelope gets lower to keep the LV network within the voltage limits. Another possibility is that the increased exported/imported power achieves a thermal limit in the LV network, which will also

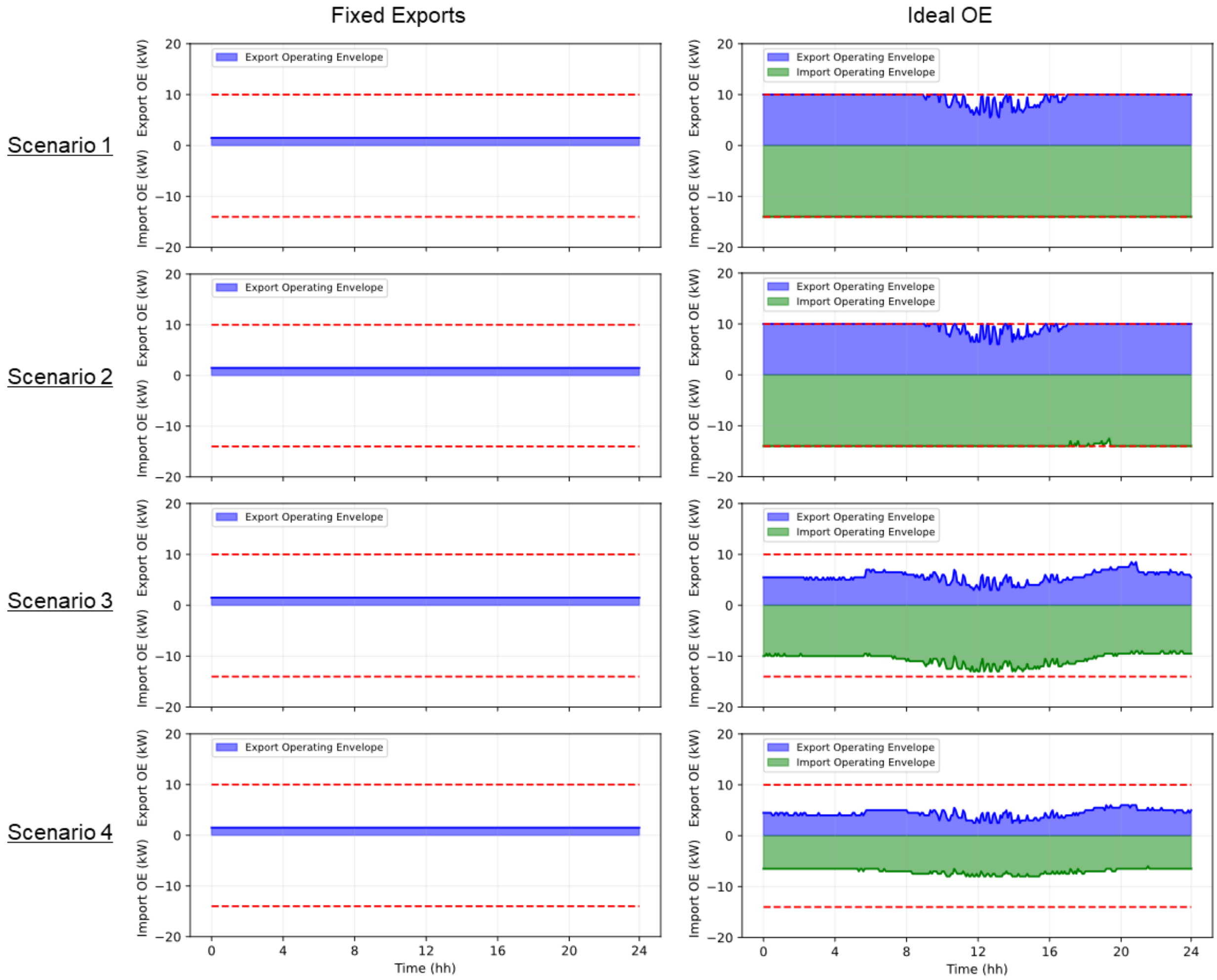

Figure 13. Resulting operating envelopes from the Fixed Export and the Ideal OE (proportional allocation) for all scenarios.

result in a reduction of the operating envelope to avoid thermal problems. In this case study, the OE export is constrained by voltage issues, while the OE imports is constrained by thermal issues. Note that since this Ideal OE calculation considers a proportional allocation and all DERs have the same size, the presented operating envelope for a given scenario is applied to all active customers.

In regard to the performance of the Fixed Export, it is able to avoid technical problems (i.e., voltages and thermal problems) in the LV network for all the tested scenarios, as shown in Table 3. However, when compared to the Ideal OE implementation – which is also able to avoid technical problems in the LV network for all the tested scenarios, as expected – there is a clear mismatch between them, which is quantified in Table 4. In average, the mismatch ranges from very high in scenarios 1 and 2 (≥8kW) to high in scenarios 2 and 4 (≥2.9kW), highlighting that the Fixed Export of 1.5kW is too conservative for this LV network. This has a high impact on the volume of services (aggregated exports) that active customers could provide to the system, as shown in Table 3. In the worst presented case (active customer penetration of 5% at 8PM) the Fixed Export allows only a small fraction, around 15%, of the services that would be possible if the Ideal OE was used instead. In the best presented case (active customer penetration of 40% at 12PM), the Fixed

Table 3. Performance Assessment of the Fixed Export.

EXPORTS			FIXED EXPORT				IDEAL OPERATING ENVELOPE (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MAXIMUM VOLTAGE AT CUSTOMERS (V)			249	249	250	251	253	253	253	253
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	100	100	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		24	27	32	38	28	45	44	55
	LV HoF (%)		34	34	40	45	44	57	67	77
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	0.2	0.6	1	1.6	1.1	3.7	3.8	4.7
	POWER (kW)	8AM	7.5	24	42	67.5	50	160	168	225
		12PM	7.5	24	42	67.5	33	104	98	135
		8PM	7.5	24	42	67.5	50	160	210	270
TOTAL OE GAIN	ENERGY (MWh)	WHOLE DAY	0	0	0	0	1	3.1	2.8	3.1
	POWER (kW)	8AM	0	0	0	0	43	136	126	158
		12PM	0	0	0	0	25	80	56	68
		8PM	0	0	0	0	43	136	168	203

Table 4. Mismatch Between the Fixed Exports and the Ideal OE.

	MISMATCH	SCENARIO			
		1	2	3	4
EXPORTS (kW)	MAXIMUM	8.5	8.5	7	4.5
	AVERAGE	8	8.1	4.1	2.9
	MINIMUM	4	4.5	1.5	1

Export still allow only around 50% of the services that would be possible if the Ideal OE was used instead. In other words, using the Ideal OE instead of the Fixed Export can enable (among the cases presented in the table) a gain on the volume of services that ranges from 25kW to 203kW depending on the time of the day.

In summary, the use of a conservative Fixed Export significantly restricts active customers throughout the day and for different scenarios.

Asset Capacity OE

The resulting operating envelopes from the Asset Capacity OE and the Ideal OE for all scenarios are shown in Figure 15. The operating envelope generated by the Asset Capacity OE tends to decrease as the numbers of active customers get higher. However, it only starts reducing for the OE import from scenario 3, where the penetration of active customers achieves 25%. In scenario 4,

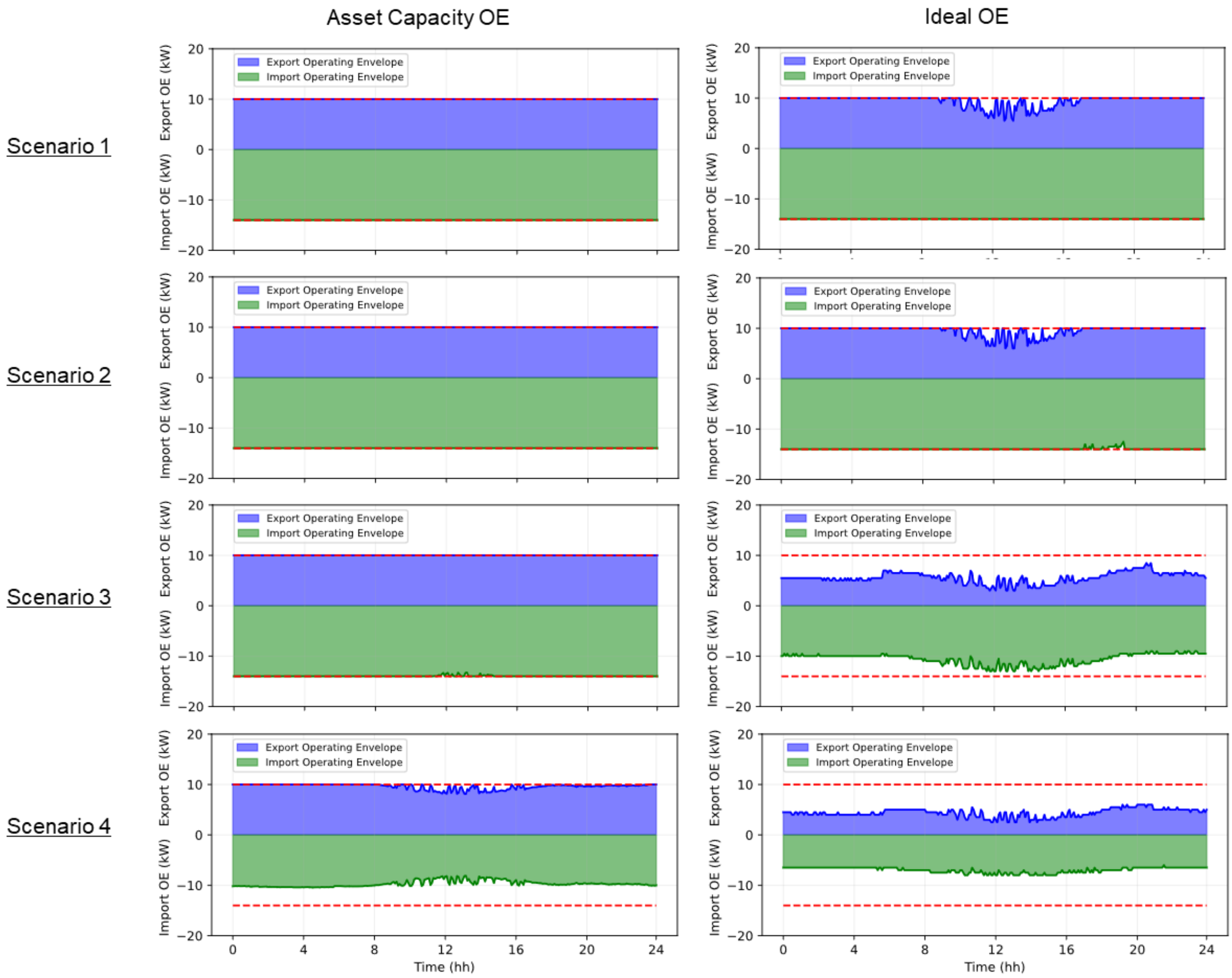

Figure 14. Resulting operating envelopes from the Asset Capacity OE and the Ideal OE (proportional allocation) for all scenarios.

where the penetration of active customers achieves 40%, both OE export and OE import decreases on times of higher export/import in the LV network. Although the operating envelope generated by the Ideal OE also tends to decrease as the numbers of active customers get higher, it contrasts with the Asset Capacity OE by starting to limit exports already from scenario 1, where the penetration of active customers in only 5%, and starts limiting imports from scenario 2, where the penetration of active customers increases to 15%. However, this delay on the reduction of operating envelope values of the Asset Capacity OE implementation is expected, given that this OE implementation only cater for thermal constraints on the distribution transformer and the first problems to occur in this case study is related to the voltages. Therefore, the Ideal OE implementation starts limiting its operating envelope value early because of voltage problems, while the Asset Capacity OE implementation starts limiting its operating envelope value later because it is only designed to cater for thermal problems. Finally, note that since both Asset Capacity OE and Ideal OE consider a proportional allocation and all DERs have the same size, the presented operating envelope for a given scenario is applied to all active customers.

Table 5. Performance assessment of the Asset Capacity OE (exports).

EXPORTS			OPERATING ENVELOPE: ASSET CAPACITY				OPERATING ENVELOPE: IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MAXIMUM VOLTAGE AT CUSTOMERS (V)			256	256	261	265	253	253	253	253
LV NETWORK VOLTAGE COMPLIANCE (%)			96	96	75	57	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		32	54	77	94	28	45	44	55
MAXIMUM UTILISATION	LV HoF (%)		52	59	103	131	44	57	67	77
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.2	3.8	6.7	10.4	1.1	3.7	3.8	4.7
AGGREGATED EXPORTS	POWER (kW)	8AM	50	160	280	450	50	160	168	225
AGGREGATED EXPORTS	POWER (kW)	12PM	50	160	280	374	33	104	98	135
AGGREGATED EXPORTS	POWER (kW)	8PM	50	160	280	437	50	160	210	270
TOTAL OE GAIN	ENERGY (MWh)	WHOLE DAY	1	3.3	5.7	8.8	1	3.1	2.8	3.1
TOTAL OE GAIN	POWER (kW)	8AM	43	136	238	383	43	136	126	158
TOTAL OE GAIN	POWER (kW)	12PM	43	136	238	305	25	80	56	68
TOTAL OE GAIN	POWER (kW)	8PM	43	136	238	370	43	136	168	203
EQUITY / FAINERSS (JFI)			1				1			
IMPLEMENTATION	COMPLEXITY		Single-Point Monitoring				Full Monitoring + Full Electrical Models			
IMPLEMENTATION	COST		$				$$$$$			

In regard to the performance of the Asset Capacity OE implementation for the exports, results from Table 5 shows that it guarantees functional compliance in terms of voltages for scenarios 1 and 2. In these two scenarios, few customers achieve up to 256V (below the inverter tripping point of 258V), but the network-wide voltage compliance is still within the Australian standard requirement of 95%. However, it is not able to guarantee voltage compliance on scenarios 3 and 4, where the maximum voltage achieves up to 265V (way above the inverter tripping point) and network-wide voltage compliance achieves down to 57% only on the worst case (scenario 4). This result is no surprise though, given that the Asset Capacity OE implementation does not consider voltage problems by design. In fact, the only reason for scenarios 1 and 2 to present a functional compliance on voltages is the existence of Volt-var function on PV inverters of the passive customers. In this case, the passive customers with PV systems are reducing the voltage rise by absorbing reactive power. Nevertheless, this reactive power compensation saturates for higher numbers of active customers, as observed on scenarios 3 and 4. Therefore, although the Asset Capacity OE implementation does not avoid voltage problems, it can still work well for low numbers of active customers (i.e., scenarios 1 and 2) due to the support from the PV systems' inverters of passive customers. However, it is not recommended to be used for high numbers of active customers.

Table 6. Mismatch between the Asset Capacity OE and the Ideal OE.

	MISMATCH	SCENARIOS			
		1	2	3	4
EXPORTS (kW)	MAXIMUM	4.5	4	7	6
	AVERAGE	0.5	0.4	4.4	5.2
	MINIMUM	0	0	1.5	3.5
IMPORTS (kW)	MAXIMUM	0	1.5	5	4
	AVERAGE	0	< 0.1	3.4	2.7
	MINIMUM	0	0	0.3	0.1

Furthermore, the Asset Capacity OE implementation for the exports performs well in all scenarios in terms of distribution transformer utilisation, which presents a maximum utilisation of 94% for scenario 4. However, the maximum utilisation of the LV head of feeder achieves up to 131% for scenario 4, which is not acceptable. This happens because the capacity of the LV head of feeder is not considered on this OE implementation by design. Nevertheless, the addition of this extra constraint can be easily added to this OE implementation by the expense of having more information of the active customers connected to each LV feeder and a per feeder monitoring at the head of LV feeder.

In regard to the accuracy of the Asset Capacity OE implementation for the exports, the results from Table 6 shows that the mismatch is lower for smaller number of active customers (scenarios 1 and 2) and higher for larger number of active customers (scenarios 3 and 4). For scenarios 1 and 2, the average mismatches are respectively around 0.5kW and 0.4kW for the entire day, but the variation between maximum and minimum can be considerable. As shown in Figure 15, outside PV generation periods (before 9AM and after 6PM) the mismatch is zero, while during the PV generation period (between 9AM and 6PM) the mismatch can achieve up to 4.5kW. This happens because during the PV generation period the voltage passes the statutory upper limit, which makes the Ideal OE to limit its operating envelope value, while the Asset Capacity OE does not react to voltage problems due to its design considerations, as previously discussed. A direct consequence is that the Asset Capacity OE allows slightly higher volume of services in some periods of the day than the Ideal OE, as shown in Table 5, but under the cost of having some customers outside the statutory voltage limit, which should not be alarming since the LV network is still within the functional voltage compliance, as previously discussed. These mismatches get much worse for scenarios 3 and 4, when the high numbers of active customers make the voltages to increase considerably (when exporting power), hence, requiring a considerable limitation of the operating envelope values, which cannot be sensed by the Asset Capacity OE implementation. Besides, in scenario 4, the thermal limit of the LV head of feeder gets congested, which is also not sensed by the Asset Capacity OE implementation due to design considerations, as already explained before. A direct consequence is that the Asset Capacity OE (incorrectly) allows much higher volume of services than the Ideal OE, as shown in Table 5 in red. However, this volume of service is not feasible because the LV network will be way beyond its limits. This highlights that the Asset Capacity OE implementation is not recommended for large number of active customers.

Table 7. Performance assessment of the Asset Capacity OE (imports).

IMPORTS			OPERATING ENVELOPE							
			ASSET CAPACITY				IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MINIMUM VOLTAGE AT CUSTOMERS (V)			220	220	203	210	220	220	217	220
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	95	87	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		31	62	98	107	31	62	70	76
	LV HoF (%)		64	107	154	155	64	100	100	100
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.7	5.4	9.4	10.5	1.7	5.4	7.1	7.5
	POWER (kW)	8AM	70	224	392	450	70	224	308	315
		12PM	70	224	378	374	70	224	364	360
		8PM	70	224	392	437	70	224	266	293
EQUITY / FAIRNESS (JFI)			1				1			
IMPLEMENTATION	COMPLEXITY		Single-Point Monitoring				Full Monitoring + Full Electrical Models			
	COST		$				$$$$$			

In regard to the OE gain presented in Table 5, the Asset Capacity OE implementation allows more than 5x the volume of services offered by the Fixed Exports for scenarios 1 (extra services of 43kW) and scenario 2 (extra services of 136kW). This highlights the over conservative value of the Fixed Export for this LV network and shows that this OE implementation is a good alternative to the Fixed Exports for lower numbers of active customers. Note that the OE gain of scenarios 3 and 4 are not feasible.

Regarding the equity/fairness presented in Table 5, the Asset Capacity OE implementation and Ideal OE Proportional Allocation are equal to 1, meaning that the fairness is the maximum possible. This happens because all active customers receive the same OE value due to the proportional allocation algorithm and same size of DERs.

Similar analyses can be made for the results of the Asset Capacity OE implementation for the imports, shown in Table 7. In general, the conclusions are similar to the OE exports, that this OE implementation works better for lower numbers of active customers (scenarios 1 and 2), while the use for higher numbers of active customers is not recommended. It is important to highlight that on the OE imports it is possible to see the impact of not considering the losses when calculating the spare capacity of the distribution transformer (this was a design decision already explained in Section 4). This impact is clearly shown on the distribution utilisation for scenario 4, where the utilisation achieves 107%. Although this value is still within the acceptable range, it highlights the importance of considering the losses on the algorithm design. Note that the inclusion of network losses into this algorithm is easy, as already mentioned in Section 4. In addition, the consideration of the LV head of feeder thermal constraints is more relevant for the imports, given that it starts showing overutilisation even for scenario 2 that has a considerably low numbers of active customers, and getting very bad on scenarios 3 and 4.

Finally, the complexity of implementation of the Asset Capacity OE and the Ideal OE are shown in Table 5 or Table 7 (repeated in both tables). The Ideal OE is clearly a very complex operating envelope to be implemented since it needs full monitoring of the LV network as well as highly accurate full electrical models of the LV networks. In contrast, the Asset Capacity OE is a very simple operating envelope to be implemented since it only needs monitoring at a single point of the network (at the distribution transformer), and no electrical model. Consequently, the cost of implementation of the Asset Capacity OE is expected to be much lower than the Ideal OE, because not only less equipment is needed but also no electrical models is required, which can postpone the investment of huge sums of money to quickly create accurate electrical models. Instead, these electrical models can be developed during longer periods, which also spreads the investment cost along the time.

In summary, although the Asset Capacity OE implementation does not cater for voltage aspects, the latest PV inverter standard that combines Volt-Watt and Volt-var functions may help in areas with low numbers of active customers (those being given OEs). However, this OE implementation is not recommended in areas with medium or high numbers of active customers.

Asset Capacity & Critical Voltage OE

The resulting operating envelopes from the Asset Capacity & Critical Voltage OE and the Ideal OE for all scenarios are shown in Figure 15. Results show that the AC_CrV OE export has an almost constant operating envelope throughout the day for a given scenario. This happens because the P-V sensitivity curve of the critical customer (used to estimate the voltage) does not capture well the daily voltage variations of the LV head of the feeder. From the figure it can be observed that the operating envelopes generated by the AC_CrV OE are usually more conservative than the Ideal OE, particularly for lower numbers of active customers. Note that since both AC_CrV OE and Ideal OE consider a proportional allocation and all DERs have the same size, the presented operating envelope for a given scenario is applied to all active customers.

In regard to the performance of the AC_CrV OE implementation for the exports, results from Table 8 shows that it guarantees perfect compliance in terms of voltages for scenarios 1 and 2. In these two scenarios, all customers are equal or below 253V (the steady state voltage limit), hence, the network-wide voltage compliance is 100%. However, it is not able to guarantee voltage compliance on scenarios 3 and 4, where the maximum voltage achieves up to 257V and 254V (both still below the inverter tripping point) and network-wide voltage compliance achieves down to 94% in both scenarios (just below the network-wide voltage compliance limit). In this case, the AC_CrV OE – which is also helped by the default Volt-VAr function on PV inverters of passive customers – almost achieve a network-wide functional compliance of voltages for the medium (scenario 3) and high (scenario 4) active customer penetration. It is important to mention that the

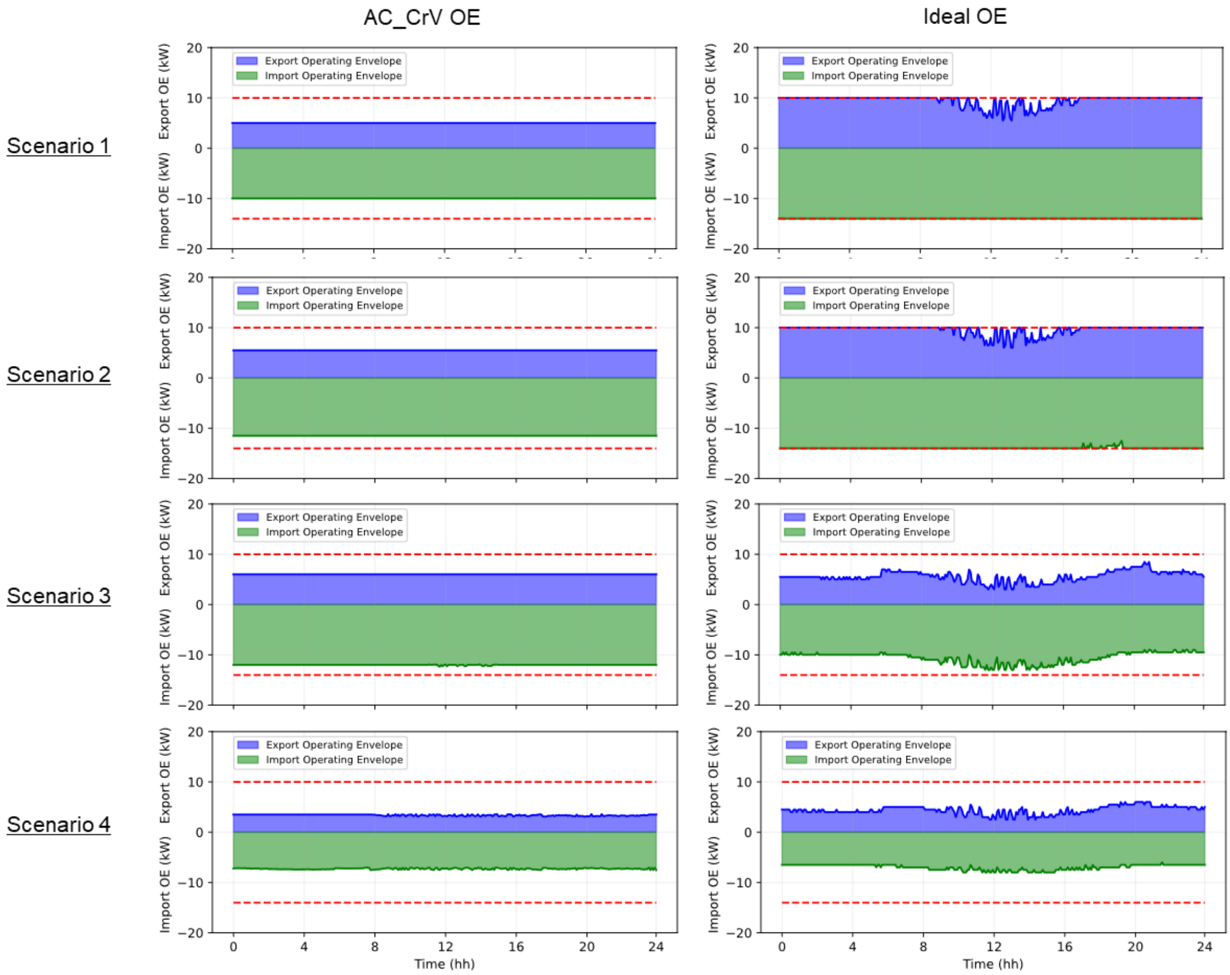

Figure 15. Resulting operating envelopes from the Asset Capacity & Critical Voltage OE and the Ideal OE (proportional allocation) for all scenarios.

selected critical customer (the furthest from the LV head of feeder) is not the actual critical customer for scenario 3. Thus, it is inevitable to think that if the correct critical customer were selected, the scenario 3 could fall within the functional compliance for voltages. Therefore, the AC_CrV OE implementation works well for lower numbers of active customers (i.e., scenarios 1 and 2), while for the medium numbers of active customers (i.e., scenario 3) it might still work if the correct critical customer is selected, but it does not work perfectly for high numbers of active customers.

Furthermore, the AC_CrV OE implementation for the exports performs well in all scenarios in terms of distribution transformer utilisation, which presents a maximum utilisation of only 56% for scenario 3. The utilisation of the LV head of feeder also stays within the limits for all scenarios, which presents a maximum utilisation of 76% for scenario 3.

In regard to the accuracy of the AC_CrV OE implementation for the exports, the results from Table 9 shows that the mismatch is higher for smaller number of active customers (scenarios 1 and 2) and lower for larger number of active customers (scenarios 3 and 4). On the one hand, for scenarios 1 and 2, the average mismatches are respectively around 4.5kW and 4.1kW for the entire day. This high mismatch happens because the AC_CrV OE values are very conservative (due

Table 8. Performance assessment of the Asset Capacity & Critical Voltage OE (exports).

EXPORTS			OPERATING ENVELOPE							
			AC_CrV				IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MAXIMUM VOLTAGE AT CUSTOMERS (V)			252	253	257	254	253	253	253	253
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	94	94	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		27	40	56	52	28	45	44	55
	LV HoF (%)		39	41	76	65	44	57	67	77
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	0.6	2.1	4	3.7	1.1	3.7	3.8	4.7
	POWER (kW)	8AM	25	88	168	156	50	160	168	225
		12PM	25	88	168	146	33	104	98	135
		8PM	25	88	168	144	50	160	210	270
TOTAL OE GAIN	ENERGY (MWh)	WHOLE DAY	0.4	1.5	3	2	1	3.1	2.8	3.1
	POWER (kW)	8AM	18	64	126	89	43	136	126	158
		12PM	18	64	126	79	25	80	56	68
		8PM	18	64	126	77	43	136	168	203
EQUITY / FAIRNESS (JFI)			1				1			
IMPLEMENTATION	COMPLEXITY		Two-Points Monitoring				Full Monitoring + Full Electrical Models			
	COST		$$				$$$$$			

to overestimation of voltages by the AC_CrV OE) if compared to the Ideal OE values, as shown in Figure 15. A direct consequence is that the AC_CrV OE allows less volume of services in some periods of the day than the Ideal OE, as shown in Table 8. In some cases, such as in scenario 1 at 8AM, it can limit the volume of services to half of the actual possible value. On the other hand, for scenarios 3 and 4, the average mismatch drops to around 1kW for both scenarios. Consequently, in these scenarios the volume of services allowed by the AC_CrV OE fluctuates as higher and lower values than the ones allowed by the Ideal OE (depending on the time of the day), but overall allowing less volume of services than the Ideal OE, as shown in red in Table 8. Nevertheless, as the colour indicates, these volumes of service are not feasible because the LV network will be slightly beyond its limits.

In regard to the OE gain presented in Table 8, although the AC_CrV OE values are conservative for scenarios 1 and 2, it still allows more than 2x the volume of services offered by the Fixed Exports. For scenarios 1 there is an extra volume of services of around 18kW and for scenario 2 there is an extra volume of services of around 64kW. This highlights the overly conservative value of the Fixed Export for this LV network and shows that this OE implementation is a good alternative to the Fixed Exports for lower numbers of active customers. Note that the OE gain of scenarios 3 and 4, although close to the feasible point (as already explained before), they are not feasible.

Table 9. Mismatch between the Asset Capacity & Critical Voltage OE and the Ideal OE.

	MISMATCH	SCENARIOS 1	2	3	4
EXPORTS (kW)	MAXIMUM	5	4.5	3	2.9
	AVERAGE	4.5	4.1	0.9	1.1
	MINIMUM	0.5	0.5	0	< 0.1
IMPORTS (kW)	MAXIMUM	4	2.5	3	1.3
	AVERAGE	4	2.5	1.6	0.6
	MINIMUM	4	1	0	< 0.1

Table 10. Performance assessment of the Asset Capacity & Critical Voltage OE (imports).

IMPORTS			OPERATING ENVELOPE: AC_CrV				IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MINIMUM VOLTAGE AT CUSTOMERS (V)			225	223	209	216	220	220	217	220
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	96	100	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		26	53	85	83	31	62	70	76
	LV HoF (%)		50	90	131	115	64	100	100	100
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.2	4.4	8.1	7.9	1.7	5.4	7.1	7.5
	POWER (kW)	8AM	50	184	336	336	70	224	308	315
		12PM	50	184	334	326	70	224	364	360
		8PM	50	184	336	324	70	224	266	293
EQUITY / FAIRNESS (JFI)			1				1			
IMPLEMENTATION	COMPLEXITY		Two-Points Monitoring				Full Monitoring + Full Electrical Models			
	COST		$$				$$$$$			

Regarding the equity/fairness presented in Table 8, the AC_CrV OE implementation and Ideal OE Proportional Allocation are equal to 1, meaning that the fairness is the maximum possible. This happens because all active customers receive the same OE value due to the proportional allocation algorithm and same size of DERs.

Similar analyses can be made for the results of the AC_CrV OE implementation for the imports, shown in Table 10. In general, the conclusions are similar to the OE exports, that this OE implementation works well for lower numbers of active customers (i.e., scenarios 1 and 2), while for medium numbers of active customers (i.e., scenario 3) it might still work if the correct critical customer is selected. In contrast with the OE export, for higher numbers of active customers it may also work. Note that the very high utilisation of the head of feeder is not a surprise, because the AC_CrV OE algorithm used in this project was designed without considering the thermal limits

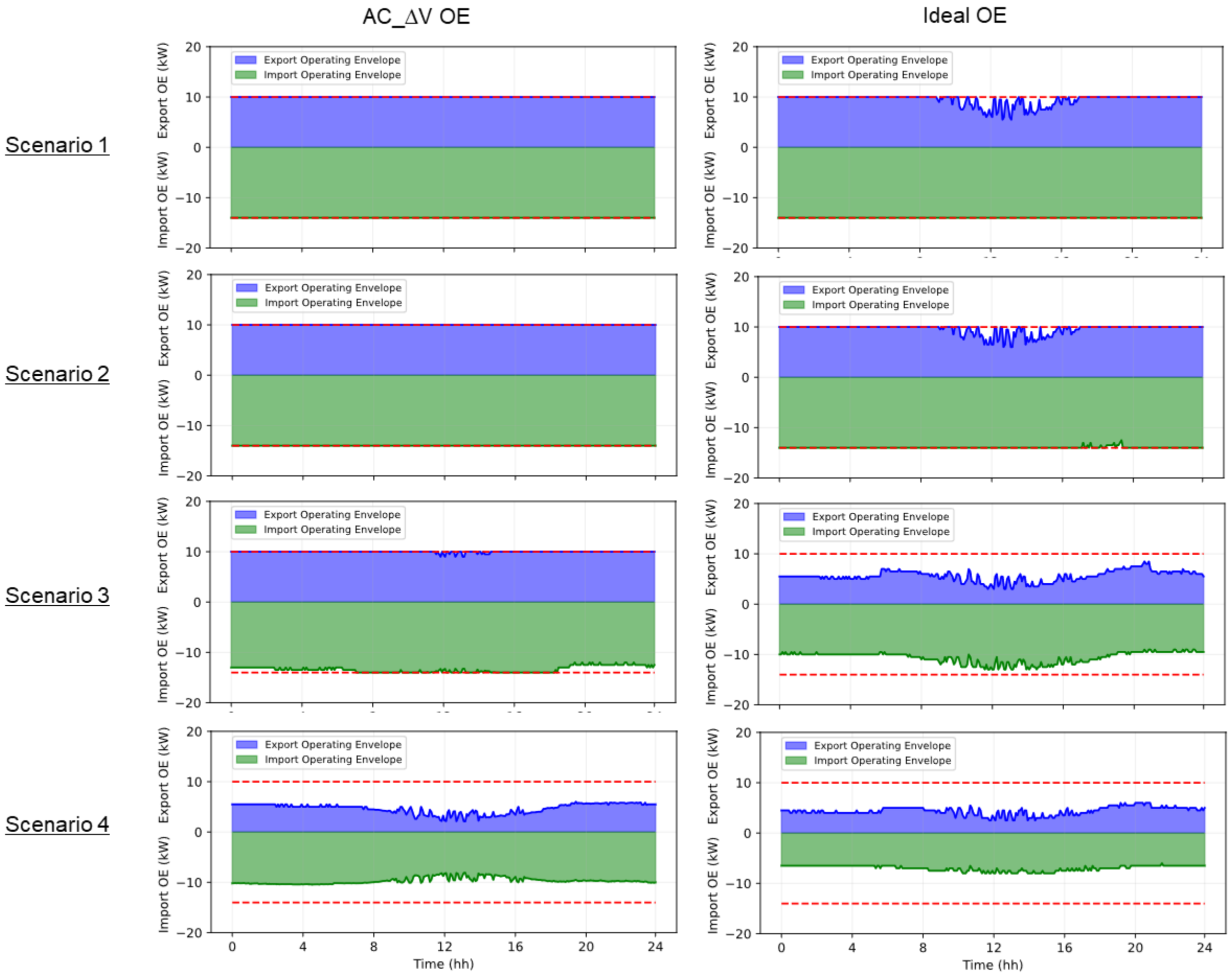

Figure 16. Resulting operating envelopes from the Asset Capacity & Delta Voltage OE and the Ideal OE (proportional allocation) for all scenarios.

of the LV head of feeder. As already mentioned before, adding this constraint to the algorithm is not difficult, but would require some extra information from the LV network, such extra information was considered not available in this project.

Finally, the complexity of implementation of the AC_CrV OE and the Ideal OE are shown in Table 8 or Table 10 (repeated in both tables). As already mentioned before, the Ideal OE is clearly a very complex operating envelope to be implemented since it needs full monitoring of the LV network as well as highly accurate full electrical models of the LV networks. In contrast, the AC_CrV OE is a simple operating envelope to be implemented since it only needs two monitoring points in the network, one at the distribution transformer and another at a critical customer, and no electrical model. Consequently, the cost of implementation of the AC_CrV OE, although slightly higher than the Asset Capacity OE, is expected to be much lower than the Ideal OE, because not only less equipment is needed but also no electrical models is required, which can postpone the investment of huge sums of money to quickly create accurate electrical models. Instead, these electrical models can be developed during longer periods, which also spreads the investment cost along the time.

In summary, although the Asset Capacity & Critical Voltage OE implementation does not capture well the voltage fluctuations on the LV head of feeder, it works well for areas with low numbers of active customers (i.e., scenarios 1 and 2). It also may be enough for areas with a medium number of active customers (i.e., scenario 3). However, it is not recommended in areas with high numbers of active customers (i.e., scenario 4).

Asset Capacity & Delta Voltage OE

The resulting operating envelopes from the AC_ΔV OE and the Ideal OE for all scenarios are shown in Figure 16. Results show that the operating envelopes generated by the AC_ΔV OE tends to decrease as the number of active customers gets higher, as expected. However, it only starts reducing the OE export on scenario 3, where the penetration of active customers achieves 25%. This happens because the AC_ΔV OE export underestimate the voltages on scenarios 1 and 2. In scenario 3, although the OE export value starts to reduce, it is too small if compared to the Ideal OE. It is likely to be due to the incorrect selection of the critical customer – since the methodology uses the furthest active customer from the LV head of feeder as the critical customer – as previously mentioned. In scenario 4, it is possible to see that the AC_ΔV OE indeed reflects the

Table 11. Performance assessment of the Asset Capacity & Delta Voltage OE (exports).

EXPORTS			OPERATING ENVELOPE							
			AC_ΔV				IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MAXIMUM VOLTAGE AT CUSTOMERS (V)			256	256	261	256	253	253	253	253
LV NETWORK VOLTAGE COMPLIANCE (%)			96	96	75	87	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		32	54	74	48	28	45	44	55
	LV HoF (%)		52	59	101	75	44	57	67	77
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.2	3.8	6.7	5	1.1	3.7	3.8	4.7
	POWER (kW)	8AM	50	160	280	203	50	160	168	225
		12PM	50	160	266	104	33	104	98	135
		8PM	50	160	280	257	50	160	210	270
TOTAL OE GAIN	ENERGY (MWh)	WHOLE DAY	1	3.3	5.7	3.4	1	3.1	2.8	3.1
	POWER (kW)	8AM	43	136	238	135	43	136	126	158
		12PM	43	136	224	35	25	80	56	68
		8PM	43	136	238	190	43	136	168	203
EQUITY / FAIRNESS (JFI)			1				1			
IMPLEMENTATION	COMPLEXITY		Two-Points Monitoring				Full Monitoring + Full Electrical Models			
	COST		$$				$$$$$			

Table 12. Mismatch between the Asset Capacity & Delta Voltage OE and the Ideal OE.

	MISMATCH	SCENARIOS			
		1	2	3	4
EXPORTS (kW)	MAXIMUM	4.5	4	6.5	1.5
	AVERAGE	0.5	0.4	4.4	0.5
	MINIMUM	0	0	1.5	0
IMPORTS (kW)	MAXIMUM	0	1.5	4	4
	AVERAGE	0	< 0.1	2.8	2.7
	MINIMUM	0	0	0.2	0.1

variation of voltages at the head of the LV feeder. In terms of the AC_ΔV OE import, it seems to work well for scenarios 1 and 2, while the operating envelope value is relaxed (not limiting enough) for scenarios 3 and 4. Finally, note that since both AC_ΔV OE and Ideal OE consider a proportional allocation and all DERs have the same size, the presented operating envelope for a given scenario is applied to all active customers.

In regard to the performance of the AC_ΔV OE implementation for the exports, results from Table 11 shows that it guarantees functional compliance in terms of voltages for scenarios 1 and 2. In these two scenarios, few customers achieve up to 256V (below the inverter tripping point of 258V), but the network-wide voltage compliance is still within the Australian standard requirement of 95%. However, it is not able to guarantee voltage compliance on scenarios 3 and 4, where the maximum voltage achieves up to 261V (above the inverter tripping point) and 256V (below the inverter tripping point) and network-wide voltage compliance achieves down to 75% and 87% (well below the network-wide voltage compliance limit). The reason for the voltages in scenario 3 being way outside the limits, and even worse than the voltages on scenario 4 (which has higher numbers of active customers), is the incorrect selected critical customer, as already mentioned before. Thus, it is inevitable to think that if the correct critical customer were selected, the scenario 3 could fall within the functional compliance for voltages. Therefore, the AC_ΔV OE implementation has an acceptable performance for lower numbers of active customers (i.e., scenarios 1 and 2), while for the medium numbers of active customers (i.e., scenario 3) it might still work if the correct critical customer is selected, but it does not work very well for high numbers of active customers.

Furthermore, the AC_ΔV OE implementation for the exports performs well in all scenarios in terms of distribution transformer utilisation, which presents a maximum utilisation of only 74% for scenario 3. The utilisation of the LV head of feeder also stays within acceptable limits for all scenarios, which presents a maximum utilisation of 101% for scenario 3. Again, note that the incorrect selection of the critical customer is likely to be negatively affecting this performance.

In regard to the accuracy of the AC_ΔV OE implementation for the exports, the results from Table 12 shows that the average mismatch is small for all scenarios but scenario 3, which has the incorrect critical customer. For scenarios 1 and 2, the average mismatches are respectively around 0.5kW and 0.4kW for the entire day, but the variation between maximum and minimum can be

Table 13. Performance assessment of the Asset Capacity & Delta Voltage OE (imports).

IMPORTS			OPERATING ENVELOPE							
			AC_ΔV				IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MINIMUM VOLTAGE AT CUSTOMERS (V)			220	220	208	210	220	220	217	220
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	95	87	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		31	62	88	107	31	62	70	76
	LV HoF (%)		64	107	139	155	64	100	100	100
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.7	5.4	9.0	10.5	1.7	5.4	7.1	7.5
	POWER (kW)	8AM	70	224	392	450	70	224	308	315
		12PM	70	224	375	374	70	224	364	360
		8PM	70	224	350	437	70	224	266	293
EQUITY / FAIRNESS (JFI)			1				1			
IMPLEMENTATION	COMPLEXITY		Two-Points Monitoring				Full Monitoring + Full Electrical Models			
	COST		$$				$$$$$			

considerable. As shown in Figure 16, outside PV generation periods (before 9AM and after 6PM) the mismatch is zero, while during the PV generation period (between 9AM and 6PM) the mismatch can achieve up to 4.5kW. This happens because during the PV generation period the voltage passes the statutory upper limit, which makes the Ideal OE to limit its operating envelope value, while the AC_ΔV OE underestimate the voltages on scenarios 1 and 2, as previously discussed. A direct consequence is that the AC_ΔV OE allows slightly higher volume of services in some periods of the day than the Ideal OE, as shown in Table 11, but under the cost of having some customers outside the statutory voltage limit, which should not be alarming since the LV network is still within the functional voltage compliance, as previously discussed. For scenario 4, although the average and maximum mismatches are only 0.5kW and 1.5kW, respectively, the voltage compliance is not satisfied, making the delivery of potential services impossible. For scenario 3, both average and maximum mismatch are too high, making it impossible to deliver the services.

In regard to the OE gain presented in Table 11, the AC_ΔV OE allows more than 5x the volume of services allowed by the Fixed Exports for scenarios 1 (extra services of 43kW) and scenario 2 (extra services of 136kW). This highlights the over conservative value of the Fixed Export for this LV network and shows that this OE implementation is a good alternative to the Fixed Exports for lower penetration of active customers. Note that the OE gain of scenarios 3 and 4 are not feasible.

Regarding the equity/fairness presented in Table 11Table 8, the AC_ΔV OE implementation and Ideal OE Proportional Allocation are equal to 1, meaning that the fairness is the maximum possible. This happens because all active customers receive the same OE value due to the proportional allocation algorithm and same size of DERs.

Similar analyses can be made for the results of the AC_ΔV OE implementation for the imports, shown in Table 13. In general, the conclusions are similar to the OE exports, that this OE implementation has an acceptable performance for lower numbers of active customers (i.e., scenarios 1 and 2), while for the medium numbers of active customers (i.e., scenario 3) it might still work if the correct critical customer is selected, but it does not work very well for high numbers of active customers. Note that the same observations regarding the consideration of losses and the LV head of feeder thermal constraints made for the Asset Capacity OE implementation can be made for the AC_ΔV OE implementation.

Finally, the complexity of implementation of the AC_ΔV OE and the Ideal OE are shown in Table 11 or Table 13 (repeated in both tables). As already mentioned before, the Ideal OE is clearly a very complex operating envelope to be implemented since it needs full monitoring of the LV network as well as highly accurate full electrical models of the LV networks. In contrast, the AC_ΔV OE is a simple operating envelope to be implemented since it only needs two monitoring points in the network, one at the distribution transformer and another at a critical customer, and no electrical model. Consequently, the cost of implementation of the AC_ΔV OE is expected to be the same as the AC_CrV OE, so it is expected to be much lower than the Ideal OE, because not only less equipment is needed but also no electrical models is required, which can postpone the investment of huge sums of money to quickly create accurate electrical models. Instead, these electrical models can be developed during longer periods, which also spreads the investment cost along the time.

In summary, the Asset Capacity & Delta Voltage OE implementation is able to capture the voltage fluctuations due to interactions with the upstream HV network, but its recommended use is still similar to the AC_CrV OE. It can have an acceptable performance for areas with low numbers of active customers (i.e., scenarios 1 and 2), and it may also be enough for areas with a medium number of active customers (i.e., scenario 3). However, it is not recommended in areas with high numbers of active customers (i.e., scenario 4).

Ideal OE Maximum Allocation

For completeness, the results of the Ideal OE with maximum allocation are presented and discussed. The resulting operating envelope from the Ideal OE Maximum Allocation and the Ideal OE Proportional Allocation for two active customers of scenario 1 is shown in Figure 17. Results show that the Ideal OE Maximum Allocation gives different operating envelope values for each of the customers, while the Ideal OE Proportional Allocation gives the same to both customers. This happens because the Ideal OE Maximum Allocation reduces the operating envelope values only for active customers which are having problems, such as for customer C32 that is closer to the end of the feeder and faces voltage issues. While the Ideal OE Proportional Allocation constrains all active customers according to the most affected one, so the operating envelope calculated for customer C32 is used to all other active customers. Note that in this case all DERs have the same size, which makes the proportional allocation to be the same to all active customers. To better visualise the operating envelope values for all active customers, Figure 18 shows a stack plot for all

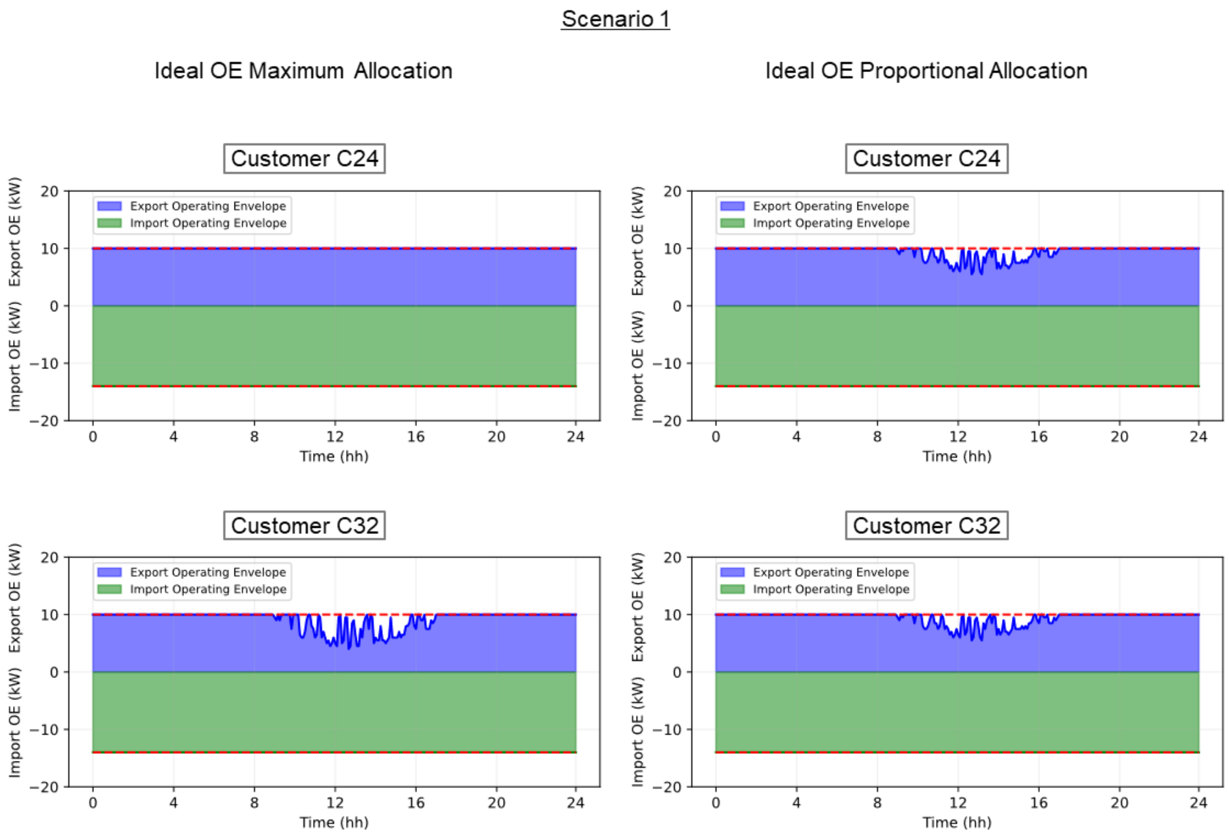

Figure 17. Resulting operating envelopes from the Ideal OE Maximum Allocation and the Ideal OE Proportional Allocation for two active customers of scenario 1.

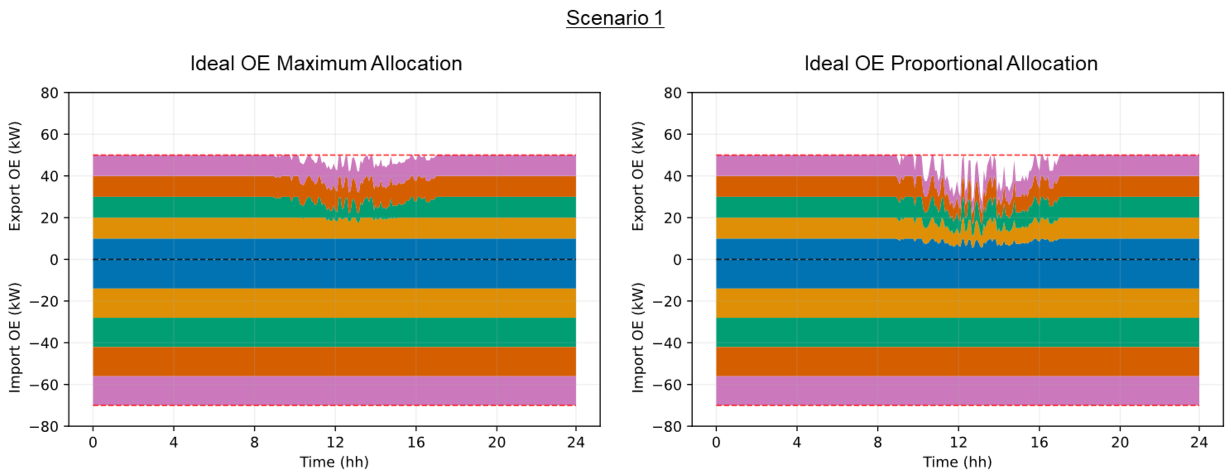

Figure 18. Stack plot for all operating envelope values calculated by the Ideal OE Maximum Allocation and the Ideal OE Proportional Allocation for scenario 1.

operating envelope values calculated by the Ideal OE Maximum Allocation and Ideal OE Proportional Allocation for scenario 1. Note that similar behaviour happens for the other scenarios, but they are not presented as pictures in this report.

Table 14. Performance assessment of the Ideal OE Maximum Allocation (exports).

EXPORTS			OPERATING ENVELOPE							
			IDEAL (MAXIMUM ALLOCATION)				IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MAXIMUM VOLTAGE AT CUSTOMERS (V)			253	253	253	253	253	253	253	253
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	100	100	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		30	53	69	71	28	45	44	55
	LV HoF (%)		44	59	78	91	44	57	67	77
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.2	3.8	6.3	7.1	1.1	3.7	3.8	4.7
	POWER (kW)	8AM	50	160	268	292	50	160	168	225
		12PM	44	155	232	239	33	104	98	135
		8PM	50	232	273	322	50	160	210	270
TOTAL OE GAIN	ENERGY (MWh)	WHOLE DAY	1	3.2	5.3	5.5	1	3.1	2.8	3.1
	POWER (kW)	8AM	43	136	226	224	43	136	126	158
		12PM	36	131	190	172	25	80	56	68
		8PM	43	136	231	255	43	136	168	203
EQUITY / FAIRNESS (JFI)			0.93-1	0.98-1	0.88-1	0.83-0.99	1			
IMPLEMENTATION	COMPLEXITY		Full Monitoring + Full Electrical Models							
	COST		$$$$$							

Regarding the performance of the Ideal OE Maximum Allocation for the exports, results from Table 14 shows that it always guarantees that the network operates within the required limits from both voltage and thermal aspects. This was already expected because the Ideal OE considers full monitoring and full (and perfect) electrical models of the network, allowing to calculate the most accurate operating envelope.

The “maximum allocation” becomes evident when comparing the volume of aggregated exports of the Ideal OE Maximum Allocation and Ideal OE Proportional Allocation. The Ideal OE Maximum Allocation can guarantee an aggregated export up to 322kW in scenario 4 at 8PM, while the Ideal OE Proportional Allocation can only guarantee 270kW, which corresponds to an extra 19% on the aggregated exports for that time of the day. Note that this extra volume of services becomes more prominent for medium (scenario 3) or higher (scenario 4) numbers of active customers, when voltage issues become more severe. Therefore, the Ideal OE Proportional Allocation ends up issuing a very restrict operating envelope to all active customers (since it uses as reference the worst affected active customer), while the Ideal OE Maximum Allocation restrict more the active customers with worse problems. Inevitably, the higher volume of aggregated exports allowed by the Ideal OE Maximum Allocation will also have a higher total OE gain (based on the Fixed Export approach) when compared to the Ideal OE Proportional Allocation.

Table 15. Performance assessment of the Ideal OE Maximum Allocation (imports).

IMPORTS			OPERATING ENVELOPE							
			IDEAL (MAXIMUM ALLOCATION)				IDEAL (PROPORTIONAL ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40
MINIMUM VOLTAGE AT CUSTOMERS (V)			220	220	217	220	220	220	217	220
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	100	100	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		31	62	70	76	31	62	70	76
	LV HoF (%)		64	100	100	100	64	100	100	100
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.7	5.4	7.1	7.5	1.7	5.4	7.1	7.5
	POWER (kW)	8AM	70	224	308	315	70	224	308	315
		12PM	70	224	364	360	70	224	364	360
		8PM	70	224	266	293	70	224	266	293
EQUITY / FAIRNESS (JFI)			1				1			
IMPLEMENTATION	COMPLEXITY		Full Monitoring + Full Electrical Models							
	COST		$$$$$							

In regard to the equity/fairness, the Ideal OE Maximum Allocation is the only OE implementation presented in this project that has different JFI (all the others OE implementations were equal to 1, so maximum fairness). The JFI for the Ideal OE Maximum Allocation varies from 0.93 to 1 in scenario 1, achieving its highest fairness index, and it achieves its lower fairness index in scenario 4, with a variation from 0.83 to 0.99. This is a direct effect of the "maximum allocation", which individually calculate operating envelopes for each active customer to avoid technical problems.

Similar analyses can be made for the imports of the Ideal OE Maximum Allocation, shown in Table 15. In terms of technical compliance of the network, the conclusions are as in the OE exports that this OE implementation always guarantees that the network operates within the required limits from both voltage and thermal aspects. The difference is that the volume of aggregated exports is the same for both Ideal OE Maximum Allocation and Ideal OE Proportional Allocation. This happen because the operating envelopes are limited by the thermal capacity of the LV head of feeder and not by voltages, thus, according to the maximum allocation algorithm, the OE values are equally reduced to all active customers.

Finally, the complexity of implementation of the Ideal OE Maximum Allocation and Proportional Allocation are shown in Table 14 or Table 15 (repeated in both tables). As already mentioned before, the Ideal OE, independent of being maximum or proportional allocation, is a very complex operating envelope to be implemented since it needs full monitoring of the LV network as well as highly accurate full electrical models of the LV networks. Therefore, it is also the costliest OE implementation.

Summary of Performance for All OE Implementations

The performance of the Fixed Export, Asset Capacity OE, Asset Capacity & Critical Voltage, Asset Capacity & Delta Voltage, and Ideal OE are presented in Table 16 and Table 17 for exports and imports, respectively. These results are presented here side-by-side to facilitate their visual comparison. No further discussions are provided as this one done previously.

5.1.4 Workshop with DNSPs and Feedback

After designing, implementing, and testing the OE implementations, a workshop was delivered to DNSPs to present the project findings and to receive their feedback. From the 16 DNSPs invited, 14 were present in the workshop, which shows their interest on the work developed in this project.

- In general, the OE implementations were well received by the DNSPs. They understood the general ideal on how to calculate and implement all the OEs. At some point some attendees even proposed how to improve the performance of two of the studied OEs. In this case, for the AC_CrV and AC_ΔV, they proposed to use one critical customer per feeder and per phase to improve the OE accuracy, and indeed it is one of the simple ways to improve these OE implementations. However, it requires more knowledge of the customers connected to the LV network, which may not be always available.
- Nevertheless, the difference between the AC_CrV and AC_ΔV was not clear to some of the attendees. As explained on this report, the big difference is that the AC_CrV does not capture well the voltage variations on the LV head of feeder throughout the day, while the AC_ΔV is designed to better capture this voltage variation.
- Furthermore, the attendees argued that the Volt-var standard on the PV systems of passive customers would inevitably help to regulate voltages for the active customers as well, which is correct. This might not be too fair with passive customers, which does not receive any money for regulating voltages, while the active customers would financially benefit from it.
- Another good point made by the attendees was that on the creation of the sensitivity curves for the AC_ΔV, if the historical data has a big variation around the linear midpoint, then it could lead to choose a conservative sensitivity curve to protect the network when the active power is way above the midpoint. This may occur in some cases, and it is important to note that the creation of the sensitivity curve will directly affect the accuracy of the calculated OE.

Table 16. Performance of all OE implementations (exports).

EXPORTS			OPERATING ENVELOPE																							
			FIXED EXPORT				ASSET CAPACITY				AC_ΔV				AC_CrV				IDEAL (PROPORTIONAL ALLOCATION)				IDEAL (MAXIMUM ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40	5	15	25	40	5	15	25	40	5	15	25	40	5	15	25	40
MAXIMUM VOLTAGE AT CUSTOMERS (V)			249	249	250	251	256	256	261	265	256	256	261	256	252	253	257	254	253	253	253	253	253	253	253	253
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	100	100	96	96	75	57	96	96	75	87	100	100	94	94	100	100	100	100	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		24	27	32	38	32	54	77	94	32	54	74	48	27	40	56	52	28	45	44	55	30	53	69	71
	LV HoF (%)		34	34	40	45	52	59	103	131	52	59	101	75	39	41	76	65	44	57	67	77	44	59	78	91
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	0.2	0.6	1	1.6	1.2	3.8	6.7	10.4	1.2	3.8	6.7	5	0.6	2.1	4	3.7	1.1	3.7	3.8	4.7	1.2	3.8	6.3	7.1
	POWER (kW)	8AM	7.5	24	42	67.5	50	160	280	450	50	160	280	203	25	88	168	156	50	160	168	225	50	160	268	292
		12PM	7.5	24	42	67.5	50	160	280	374	50	160	266	104	25	88	168	146	33	104	98	135	44	155	232	239
		8PM	7.5	24	42	67.5	50	160	280	437	50	160	280	257	25	88	168	144	50	160	210	270	50	232	273	322
TOTAL OE GAIN	ENERGY (MWh)	WHOLE DAY	0	0	0	0	1	3.3	5.7	8.8	1	3.3	5.7	3.4	0.4	1.5	3	2	1	3.1	2.8	3.1	1	3.2	5.3	5.5
	POWER (kW)	8AM	0	0	0	0	43	136	238	383	43	136	238	135	18	64	126	89	43	136	126	158	43	136	226	224
		12PM	0	0	0	0	43	136	238	305	43	136	224	35	18	64	126	79	25	80	56	68	36	131	190	172
		8PM	0	0	0	0	43	136	238	370	43	136	238	190	18	64	126	77	43	136	168	203	43	136	231	255
EQUITY / FAIRNESS (JFI)			1				1				1				1				1				0.93-1	0.98-1	0.88-1	0.83-0.99
IMPLEMENTATION	COMPLEXITY		-				Single-Point Monitoring				Two-Points Monitoring								Full Monitoring + Full Electrical Models							
	COST		-				$				$$								$$$$$							

Table 17. Comparison of performance of all OE implementations (imports).

IMPORTS			OPERATING ENVELOPE																			
			ASSET CAPACITY				AC_ΔV				AC_CrV				IDEAL (PROPORTIONAL ALLOCATION)				IDEAL (MAXIMUM ALLOCATION)			
PENETRATION OF ACTIVE CUSTOMERS (%)			5	15	25	40	5	15	25	40	5	15	25	40	5	15	25	40	5	15	25	40
MINIMUM VOLTAGE AT CUSTOMERS (V)			220	220	203	210	220	220	208	210	225	223	209	216	220	220	217	220	220	220	217	220
LV NETWORK VOLTAGE COMPLIANCE (%)			100	100	95	87	100	100	95	87	100	100	96	100	100	100	100	100	100	100	100	100
MAXIMUM UTILISATION	DISTR. TRANSF. (%)		31	62	98	107	31	62	88	107	26	53	85	83	31	62	70	76	31	62	70	76
	LV HoF (%)		64	107	154	155	64	107	139	155	50	90	131	115	64	100	100	100	64	100	100	100
AGGREGATED EXPORTS	ENERGY (MWh)	WHOLE DAY	1.7	5.4	9.4	10.5	1.7	5.4	9.0	10.5	1.2	4.4	8.1	7.9	1.7	5.4	7.1	7.5	1.7	5.4	7.1	7.5
	POWER (kW)	8AM	70	224	392	450	70	224	392	450	50	184	336	336	70	224	308	315	70	224	308	315
		12PM	70	224	378	374	70	224	375	374	50	184	334	326	70	224	364	360	70	224	364	360
		8PM	70	224	392	437	70	224	350	437	50	184	336	324	70	224	266	293	70	224	266	293
EQUITY / FAIRNESS (JFI)			1				1				1				1				1			
IMPLEMENTATION	COMPLEXITY		Single-Point Monitoring				Two-Points Monitoring								Full Monitoring + Full Electrical Models							
	COST		$				$$								$$$$$							

6 Recommendations

The following recommendations consider the OE implementations investigated in this project, their capacity on keeping the network within the required technical limits (i.e., voltages and thermal) according to the penetration of active customers, and which DNSPs currently have (or a close to have) the capabilities to use each OE implementation.

Asset Capacity OE

1. **Can be used by DNSPs that monitor distribution transformers**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy and South Australia Power Networks), Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy) and Step Transition cluster (Evoenergy), may already have the required capabilities to implement the Asset Capacity OE.
2. **Can be used in the short-term or in areas with low numbers of active customers**. Although the Asset Capacity OE implementation does not cater for voltage aspects, the latest PV inverter standard that combines Volt-Watt and Volt-var functions may help in areas with low numbers of active customers. However, it is not recommended in areas with medium or high numbers of active customers.
3. **Can be used in areas with thermal problems but not voltage problems**. The Asset Capacity OE implementation only consider thermal aspects on its calculation.

Asset Capacity & Critical Voltage OE

1. **Can be used by DNSPs that monitor distribution transformers and have historical non-market data from some LV customers (or critical points of the LV networks)**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy) and Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_CrV OE.
2. **Can be used by DNSPs with full monitoring of LV customers**. The full monitoring of LV customers could be used to estimate the power flow on the distribution transformer. The DNSPs that fall in this category are Ausnet Services, CitiPower, Horizon Power, Jemena, Powercor, and United Energy.
3. **Can be used in the medium-term or in areas with medium numbers of active customers**. The performance of the AC_CrV OE implementation may be enough for areas with a medium number of active customers, but it is not recommended in areas with high numbers.

Asset Capacity & Delta Voltage OE

1. **Can be used by DNSPs that monitor distribution transformers and have historical non-market data from some LV customers (or critical points of the LV networks)**. The DNSPs considered to be in the Fast Transition cluster (Endeavour Energy) and Very Fast Transition cluster (Ausgrid, Energex, and Ergon Energy), may already have the required capabilities to implement the AC_ΔV OE.
2. **Can be used in the medium-term or in areas with medium numbers of active customers**. The performance of the AC_ΔV OE implementation may be enough for areas with a medium number of active customers, but it is not recommended in areas with high numbers.

Ideal OE

1. **To be used in the long-term or in areas with high numbers of active customers**. The Ideal OE implementation is the most accurate OE approach, however, it is recommended to be used for high numbers of active customers. Since it requires full electrical LV network model and full monitoring of customers plus transformer monitoring, it is likely that DNSPs might require a few years to fully adopt this OE implementation.
2. Although none of the DNSPs have all the required capabilities to implement the Ideal OE today, the DNSPs of the Step Transition cluster (Evoenergy and Horizon Power) and some of the Very Fast Transition (Ausgrid, Citipower, Powercor, and United Energy) cluster are the ones with the highest potential to use it first in the near future in some parts of their network.

7 Conclusions

After surveying all DNSPs in Australia, it was possible to observe a large diversity on the available infrastructure/data they have (from electrical network models to network and customer monitoring to forecasting) which confirms the need to assess different OE implementations. In addition, the survey allowed to observe that all DNSPs are moving towards the modernisation of their infrastructure/data availability (e.g., more monitoring, better electrical models, etc.) but, as it can be expected, each one of them has their own pace, which is subject to their regional requirements and characteristics.

Four spectra were created to show the current available infrastructure/data of Australian DNSPs. These spectra are: *Available Electrical Models, Available Network Monitoring, Available Customer Monitoring, Available Forecast*.

From these four spectra an overall spectrum was created to cluster DNSPs according to their general level of available infrastructure/data. Four clusters were identified: *Moderate Transition, Fast Transition, Very Fast Transition, and Step Transition*.

Once the available infrastructure/data was identified, four different approaches to calculate OEs (or OE implementations) were produced, each one of them vary in terms of complexity and accuracy, they are:

1. Ideal OE (the benchmark)
2. Asset Capacity OE
3. Asset Capacity & Critical Voltage (AC_CrV) OE
4. Asset Capacity & Delta voltage (AC_ΔV) OE

The **Ideal OE is the most advanced** and, hence, **most accurate** operating envelope approach as it uses power flows to carry out calculations. However, it needs a full electrical LV network model and full monitoring of customers plus transformer monitoring, which makes its implementation very complex. If the model and monitoring data are correct, it can guarantee the operation of the network within technical limits (i.e., voltage and thermal) as well as the maximum possible export and/or import limits. Although this OE implementation approach is only used as benchmark in this report, it is interesting to highlight the DNSPs that are closer to be able use this option in the future.

The **Asset Capacity OE is the least advanced** and, hence, the **least accurate** operating envelope approach as it only considers the thermal aspect of the distribution transformer to calculate the spare capacity and split it among active customers. To do so, it only needs the monitoring and capacity of one element of the network (the distribution transformer), which makes its implementation very simple. Although the Asset Capacity OE implementation does not cater for voltage aspects, the latest PV inverter standard that combines Volt-Watt and Volt-var functions may help in areas with low numbers of active customers (those being given OEs). However, this OE implementation is not recommended in areas with medium or high numbers of active customers.

The **AC_CrV OE is more advanced than the Asset Capacity OE as both voltage and thermal issues are considered** instead of only thermal issues. Thermal issues are solved by calculating the spare capacity of the distribution transformer, while voltages issues are solved by estimating the voltage at the critical customer via a sensitivity curve (using historical active power and voltage of the critical customer). Although it needs more monitoring than the Asset Capacity OE, this extra requirement is minimal – only two points of the LV network, specifically the distribution transformer and the critical customer – which makes its implementation relatively simple. Given that the AC_CrV OE does not need the electrical models of the LV networks, this OE implementation has great potential to be used by DNSPs that have limited or no availability of such electrical models.

The **AC_ΔV OE is more advanced than the AC_CrV OE**, given that **it can capture better the daily voltage variations due to the interactions with the upstream HV network**. Thermal issues are solved by calculating the spare capacity of the distribution transformer, while voltages issues are solved by estimating the voltage at the critical customer via sensitivity curves (using historical aggregated active power on the LV network and voltage at the head of the LV feeder and at the critical customer). The monitoring requirements are the same as for the AC_CrV OE, which makes its implementation also relatively simple and has great potential to be used by DNSPs that has limited or no availability of such electrical models.

To assess the performance of these OE implementations nine metrics were defined: OE accuracy, voltage compliance, maximum voltage, minimum voltage, asset utilisation, total OE gain, aggregated exports/imports, equity/fairness, and complexity and cost of implementation. These metrics cover (to different extents) four interests and/or concerns from the stakeholders (i.e., DNSPs, AEMO, customers): network performance, impact on customers, service provision, and feasibility.

In conclusion, this project has demonstrated that full electrical LV network models and full monitoring of network/customers are not necessarily needed to calculate adequate OEs for low/medium number of active customers. Simpler OE implementations that require very limited knowledge of the electrical network and very limited monitoring may be good enough (not perfect though) to solve excessive voltage rise/drop and asset congestion on areas with low to medium number of active customers. This suggests that for the near future, complex OE implementations are not needed in most of the distribution network areas. Nevertheless, for the long-term, more advanced OE implementations will be required.

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