Trial of Shaped Operating Envelopes

Final Technical Knowledge Sharing Report

Prepared by

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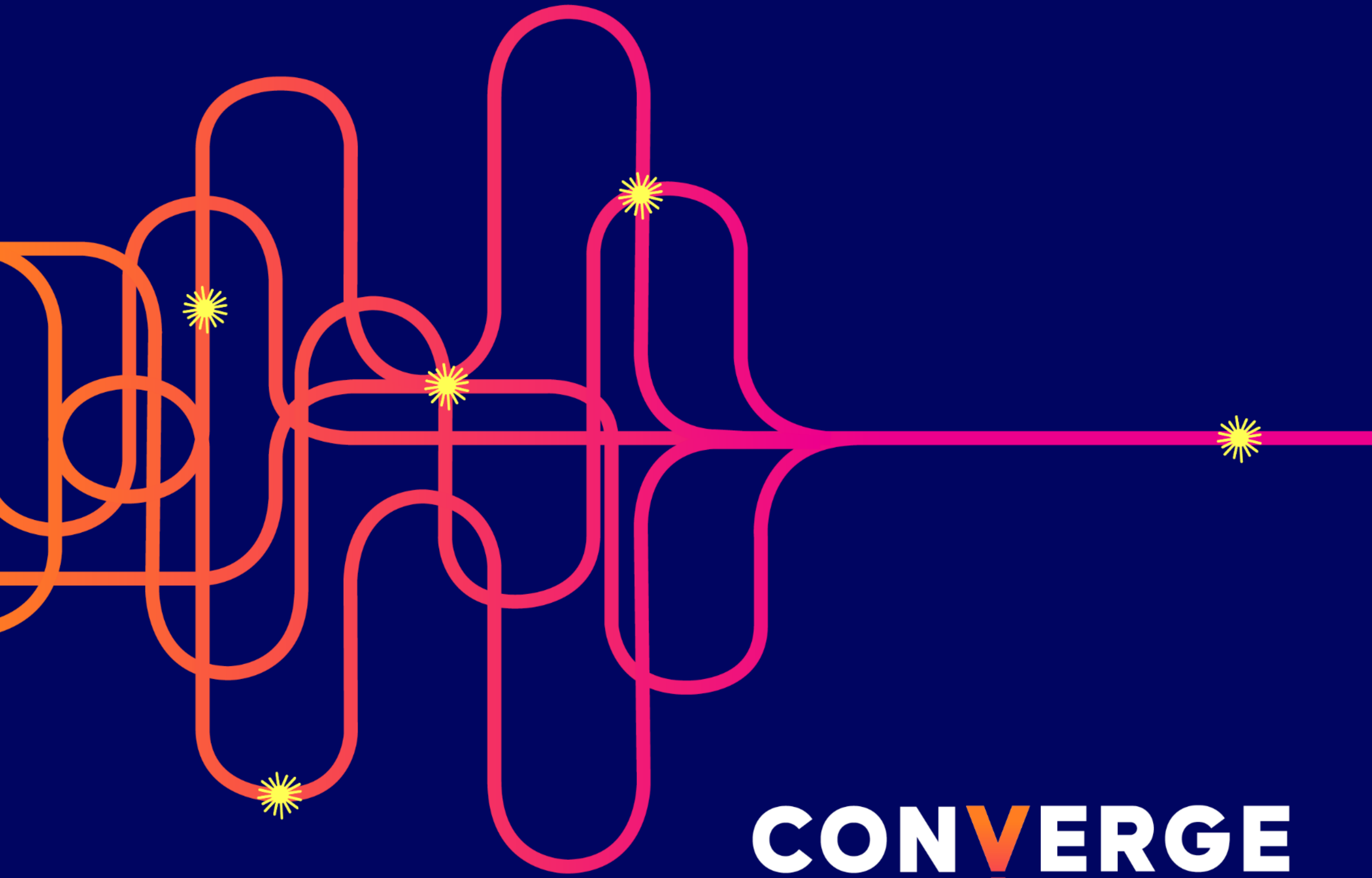

CONVERGE

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Disclaimer

The views expressed herein are not necessarily the views of the Australian and ACT Governments. The Australian and ACT Governments do not accept responsibility for any information or advice contained within this report.

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List of Abbreviations

AEMO	Australian Energy Market Operator
ACT	Australian Capital Territory
ANU	Australian National University
API	Application Programming Interface
ARENA	Australian Renewable Energy Agency
CIM	Common Information Model
DER	Distributed Energy Resource
DOE	Dynamic Operating Envelope
DSO	Distribution System Operator
EV	Electric Vehicle
FCAS	Frequency Control Ancillary Service
FOE	Fixed Operating Envelope
IT	Information Technology
LV	Low Voltage
MV	Medium Voltage
NEM	National Energy Market
NMI	National Meter Identifier
OLTC	On-Load Tap Changer
RIT-D	Regulatory Investment Test for Distribution
RT	Real-Time
SOE	Shaped Operating Envelope
PV	Photovoltaic

Executive Summary

Distributed energy resources (DERs) are changing the way electricity is generated, managed, and consumed. Traditionally, electricity has been generated by big power plants, such as coal and gas power plants. Today, it is increasingly being generated by DERs located in millions of homes and businesses in Australia.

Project Converge aims to address the issues and enhance the advantages created by the increasing deployment of DERs, including rooftop photovoltaic (PV) systems, batteries, and electric vehicles (EVs). These distribution network-connected assets can contribute to power system reliability through their participation in energy and ancillary service markets, such as frequency control ancillary service (FCAS) markets. However, without orchestration, DERs can also threaten the security of distribution networks.

To address this issue, Project Converge has developed and demonstrated new capabilities that we refer to as shaped operating envelopes (SOEs). SOEs allow DERs to provide network support services to reduce distribution network congestion while also allowing them to maximize their value in energy and FCAS markets. These SOE capabilities represent a next step beyond the capabilities being demonstrated by previous ARENA-funded projects [1–4] involving dynamic operating envelopes (DOEs).

This report presents the main technical findings of Project Converge, including the results of the trials and offline simulations conducted in the Australian Capital Territory (ACT) with the support of Evoenergy, as distribution system operator (DSO), and Reposit Power and Evergen, as DER aggregators.

The report is divided into 6 sections. Sections 1 and 2 provide a review of the SOE concept and its implementation, initially outlined in [5]. Section 3 reports the SOE trial results, while Section 4 discusses the results of the offline simulations. Section 5 describes an RT RIT-D toolbox developed to identify the most cost-effective DER owners capable of providing distribution network support services, so, DSOs can avoid network augmentations through the recruitment of DER owners to their SOE programs. Finally, Section 6 presents the main technical findings and lessons learnt.

The main technical findings and lessons produced by Project Converge can be divided into general and trial lessons. The general lessons were drawn from the development and testing of the SOE and RT RIT-D solutions. They include the following:

- **Moving beyond current practices:** current DSO practices, such as fixed import and export limits at the customer connection point, are unsuitable for ensuring distribution network security without relying on significant network augmentations. The work of Project Converge shows that SOEs can ensure distribution network security when enough controllable DER capacity is available to provide network support services.
- **SOE benefits:** SOEs produce superior overall system benefits when compared to DOE approaches in offline simulations. However, these benefits only become significant once DER penetration levels become high. This suggests that DOEs may be sufficient in the short term.
- **DER-based network support vs network augmentation:** Our RT RIT-D experiments on the ACT distribution network show that using DERs can be more cost-effective than network augmentation options. Project Converge calls for policymakers to develop/change regulation to incentivise DSOs to use DERs when they are the most cost-effective solution. The current regulation does not provide the right incentives for DSOs prioritising the use of DERs or even for aggregators developing business models to provide these network support services. In other words, without the right regulatory environment, DSOs will continue to favour the network augmentation option, since they can only intervene as the regulatory environment allows and their business model incentivises.

The trial lessons were derived from the experience gained during the trialling of SOEs. They include the following:

- **Demonstrated SOE functionalities**: SOEs can deliver network support services, such as voltage regulation and congestion management, as demonstrated in the trials.
- **Impact of lack of network support capacity:** SOEs can be used to ensure network security. However, SOEs can only maintain the network within its secure limits if enough controllable[1] DER capacity is available, as observed in the trials.
- **Relevance of network data quality:** High-quality network data is key to accurately calculate SOEs, since their calculation is done using optimal power flow models. Project Converge calls for the improvement of network data quality. Common issues found in network datasets are for example missing network parameters and inaccurate information about network components.

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[1] DERs capable of coping with control actions applied by operating envelopes.

- **Importance of smart meter data:** Smart meter data is one of the key inputs for the calculation of SOEs. Project Converge calls for the deployment of smart meters in all customers.
- **Impact of customer-level forecasts on envelope compliance:** The calculation of SOEs requires customer-level forecasts, such as active and reactive netload forecasts. Forecasting errors can lead to envelope violations on both import and export sides of the envelope, as observed in the trials. To overcome this problem, Project Converge calls for the development of tools capable of producing high-quality point or interval forecasts, so customers can comply with envelopes. Interval forecasts were identified in the project as a promising solution to improve the robustness of SOEs. However, aggregators preferred the use of point forecasts for their clients.

A more detailed description of the technical findings and lessons learned is presented in Section 6.

1 SOE Concept

Dynamic Operating Envelopes (DOEs) are a class of techniques for allocating distribution network capacity to aggregators and/or customers. The key feature is the calculation and allocation of time-varying power envelopes per customer. With an appropriate allocation across many participants, DOEs can ensure the network does not become overloaded by DERs.

In most networks there is not just one way to allocate envelopes while ensuring that network limits are met; rather, there is an uncountable number of ways. Some of these envelope allocations are objectively better than others when considering impacts beyond network constraints. Particularly, the choice affects how much freedom DERs have to act and how well-utilised the network is.

SOEs are a form of DOE that refines the concept to factor in aggregator/customer preferences and network support, with the goal of improved network utilisation and market access for DERs. The SOE concept comes from the ARENA-funded Optimal DER Scheduling for Frequency Stability Study [1], where it was found to strike a good balance between performance and practicalities. Project Converge further enhances the SOE concept.

The improvements of SOEs over DOE proposals and implementations in related projects (Project Symphony [2], Project EDGE[2] [3], Evolve DER Project [4]) include:

- The allocation of envelope capacity that jointly accounts for and balances:
    - aggregator (and hence customer) intentions and preferences;
    - benefits to wholesale market performance; and
    - simple measures of envelope fairness when suitable.
- The provision of short-term network support actions in cases where this can satisfy the objectives listed above.

Through these enhancements, SOEs enable aggregators and DER owners to extract more value from their DERs and to offer more services. When enacted at scale, the wholesale market will be able to operate more efficiently through more participation and greater competition. Envelopes that better align with customer intentions mean that higher levels of network throughput can be achieved, and, in many cases, this has the potential to avoid the need for network augmentation. These indirect benefits help

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[2] The Project EDGE *Horizon 3* DOE proposal discussed in [21] has similar goals for optimising market participation with a more tightly coupled AEMO integration.

to put downward pressure on electricity prices for all customers not just those with large amounts of DERs.

In the following, we discuss at a high level the key steps of the SOE calculation. We do this from the perspective of a DSO which encapsulates the capability that is being built in the project within Evoenergy, Zepben, and the Australian National University (ANU). This enables us to set aside the details of network data and models for now and focus on the key parts of the SOE framework that make it unique.

1.1 Overview

The SOE framework has three key steps as presented in Figure 1. These steps run online every 5 minutes before the wholesale market dispatch. Day-ahead and pre-dispatch are also possible, as discussed in [5]. The steps are:

- **Step 1:** Aggregators send their network support availability, aggregated market bids and customer contributions to the DSO.
- **Step 2:** SOEs and network support requests are calculated and sent back to aggregators.
- **Step 3:** Aggregators submit their final rebids to the wholesale market.

Figure 1. The flow of information for the key three steps of the SOE framework. Images sourced from [6–8].

We further break down the SOE steps in the sections that follow.

Step 1: Bids and Contributions

This first step is where aggregators inform the DSO of their intentions and capabilities. The Aggregator provides their AEMO day-ahead wholesale bids and rebids to the DSO (before sending them to AEMO), along with aggregator network support availability[3]. Each aggregator also sends a plan for how their customers individually will contribute to delivering the offered market services. For each customer identified by an NMI (national meter identifier), this plan is made up of:

- capacity contribution to each market and network support bid band; and
- forecast background netload in the form of a point or interval. This is known as reservation in the trials.

This information allows the DSO to effectively disaggregate the wholesale bids, from national energy market (NEM) regions down to the low-voltage (LV) distribution network level, enabling a more targeted optimisation of the envelopes to meet constraints within the distribution network.

Step 2: Envelope Calculation

For each feeder of interest, the DSO solves an optimisation problem to constrain the wholesale bids of aggregators and allocate operating envelopes for customers. This is done by solving a specially formulated optimal power flow problem – a type of constrained optimisation problem that models network power flows and operating limits. We refer to this calculation as shaping[4] the bids and operating envelopes, with the outputs being **shaped rebids** and **shaped operating envelopes (SOEs)**.

The calculation takes in wholesale market pre-dispatch prices and price sensitivity information to select a subset of aggregator bids that stay within network constraints. This is done to maximise the following objectives:

- expected value of the bids to the wholesale market, after accounting for any network support costs; and
- similarity of envelopes across customers of similar types when suitable.

This is a multi-objective problem that in practice is solved by weighting the importance of these two objectives. At times the objectives can conflict, so it will be up to the DSO to set an appropriate weighting between them, possibly under the direction of the regulator.

The resulting shaped rebids, shaped operating envelopes, and network support are communicated back to the aggregator.

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[3] Separate network support availability is not necessary if an aggregator is actively participating in the wholesale energy market.

[4] This terminology comes from the geometric interpretation of bids and operating envelopes that is sometimes employed to explain concepts. E.g., the bid trapeziums [22] that AEMO use to represent energy and FCAS cross-market constraints. The SOE calculation shapes these objects into a new form that is consistent with network operating limits.

Step 3: Final Rebids

As a final step, the aggregator submits their final rebids for the upcoming dispatch interval to the wholesale market. In theory, the shaped rebids calculated by the DSO could be forwarded to AEMO. Alternatively, an aggregator can independently calculate their final rebids. To avoid manipulation, the resulting rebids must be *consistent* with the SOEs and the original bids that the DSO based its calculation on.

2 SOE Implementation

In this section, we discuss details of how the SOE concept was put into practice in the trials. The trials focused on demonstrating the network support capabilities of SOEs. The capabilities relating to the wholesale market were evaluated through offline simulations alone in Section 4, as participating aggregators were unable to provide wholesale market bids for the trials.

In broad terms, the SOE concept is implemented in Project Converge as an automated exchange of data between aggregators (**Reposit Power** and **Evergen**) and IT systems maintained by the ANU (Converge Dagster platform and Converge API, see Figure 2). This exchange takes place every 5 minutes. To allow time for data exchange, the calculation of SOEs is performed up to 15 minutes ahead of time in each interval. For each interval, the following steps take place:

- Aggregators provide data, via the Converge API, about the reservations and network support offers of all their customers. For each customer, this data comprises the following:
    - A reservation consisting of a forecast netload for the 5-minute interval. It can be provided in the form of a single value or as a range of values. Ranges enable SOEs to better handle uncertainty. However, aggregators preferred the use of point forecasts.
    - A set of network support injection and consumption offers. Under normal circumstances, SOEs, as implemented in project Converge, are not allowed to restrict the reservation. However, aggregators are given the option to provide network support offers to alter a participant's reservation for a price. Network support offers consist of quantity and price pairs. For example, an injection offer of 3 kW and $1/kWh indicates that the customer is willing to increase their injection/generation (or, equivalently, decrease their load), relative to their reservation, by up to 3 kW, for which they will be paid $1/kWh. Multiple injection or consumption offers may be stacked, like bid-stacking in the NEM.
- Using the data provided by aggregators, network models, and netload forecasts of non-aggregator customers, the SOE engine calculates SOEs for each participating customer. SOEs are calculated to best comply with voltage and thermal constraints in the network while minimising the total cost of network support. Beyond this, the calculation of SOEs also considers the following factors:

  - SOEs must permit customers to consume or generate within their reservation unless there is a network support offer.
  - Assuming a generation convention, the “injection” dispatch is defined as the amount by which the lower bound of the envelope exceeds the lower bound of the reservation, and the “consumption” dispatch as the amount by which the upper bound of the envelope falls below the upper bound of the reservation. Dispatch must not exceed the offered amount, and payment is calculated based on dispatch and the offer cost.
  - A further constraint is that SOEs must contain the zero point, i.e. the lower bound must be non-positive, and the upper bound must be non-negative[5].
- Just before the upcoming interval, aggregators submit a request to the Converge API to provide SOEs for each customer, as well as any payment data that might apply. They are then responsible for ensuring (as far as is made physically possible using controllable DERs) that SOEs are obeyed.

The discussion above describes interactions between aggregators and the Converge platform, however, two other stakeholders participate in this process:

- **Evoenergy (ACT DSO)** provides network and smart meter data. The smart meter data is used to forecast the netload of customers.
- **Zepben** provides CIM[6] compliant network models computed based on the network data provided by Evoenergy.

The software systems used to implement this process are shown in Figure 2. At the heart of the platform are two databases, the Converge TBD database, and the Converge evolveapi database. These contain all data that goes into the calculation of the SOEs: netload data for the former, and aggregator offers for the latter.

The management of data and the calculation of SOEs are orchestrated by the Converge Dagster platform – the large grey box taking up the lower half of the figure. This is based on a framework for orchestrating data pipelines called Dagster [9].

The Converge API directly manages the flow of data between aggregators and the Converge evolveapi database. Any data exchanges involving aggregators must be initiated by aggregators, in the form of HTTP POST or GET requests. Aggregators

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[5] This constraint is related to the expectation that an envelope should not force a customer to consume/generate electricity. Project Converge was implemented in part using the APIs and infrastructure developed for Evolve DER Project [4], which implemented a DOE solution. This project applied the constraint of forcing the DOE to include zero, as a desirable feature.

[6] CIM (Common Information Model) is a standard for electricity network models.

post their data to the Converge API service, which directly inserts it into the Converge evolveapi database, and they query the Converge API to retrieve envelopes for the upcoming interval.

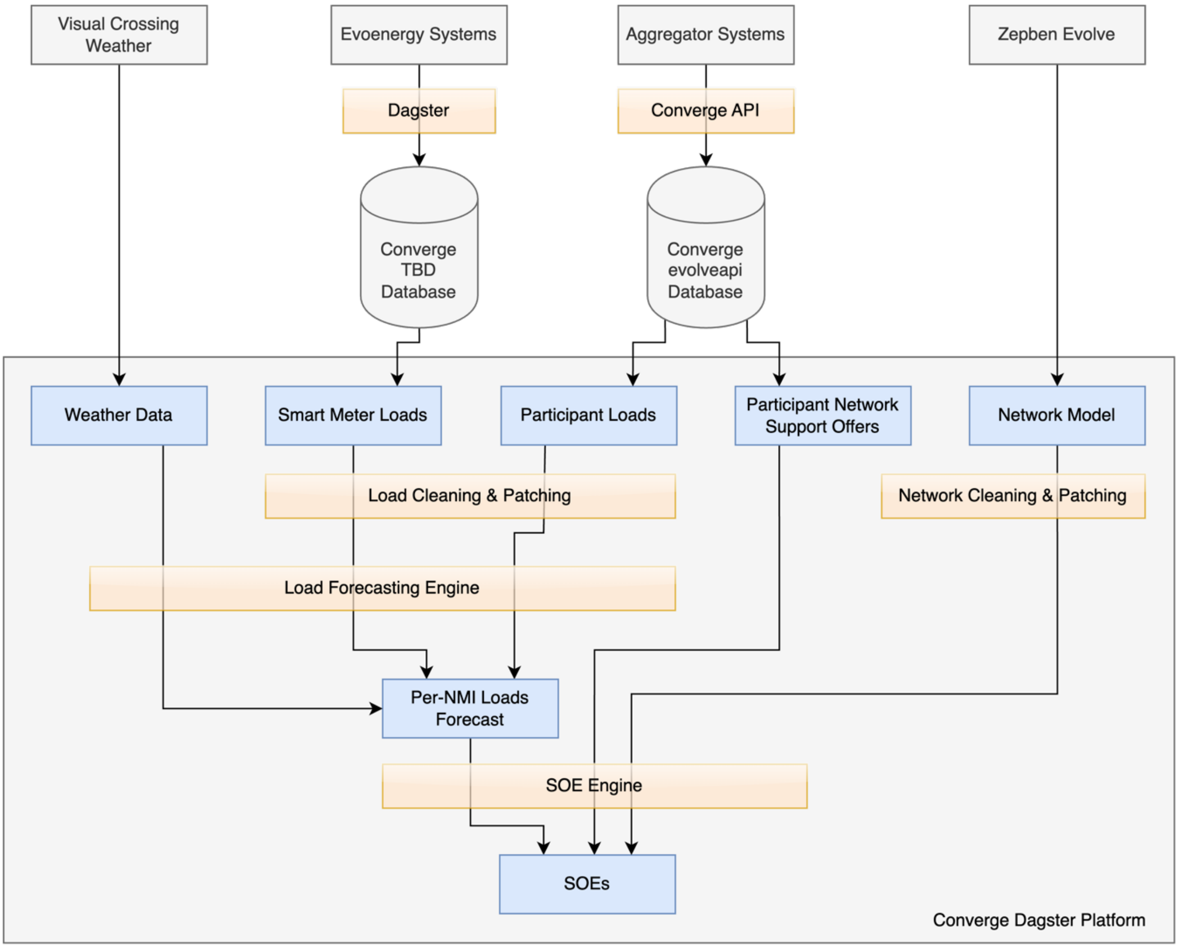

Figure 2. Data and workflows that go into SOE generation.

The other two main data streams that go into the SOE calculation are the smart meter data and network models retrieved from Zepben's energy workbench platform [10] (i.e., Zepben Evolve) by the Converge Dagster platform.

Smart meter data, aggregator telemetry, and weather data are used to calculate netload forecasts for all customers in the ACT network using the approach described in [11]. These forecasts, together with network models and participant offers (including reservation and network support offers of aggregators' customers) are then input into the SOE engine to calculate SOEs. The SOE engine solves the SOE optimisation problem modelled in Pyomo [12] using the IPOPT optimiser.

The SOEs are then stored in the Converge evolveapi database and are provided on request to the aggregators via the Converge API.

3 SOE Trials

A series of trials were performed over November and December 2023 in the ACT, to evaluate the SOE approach in live operation with real customers, aggregators, and networks. The following subsections present the results of the trials.

3.1 Trial Participants and Network Areas

The main motivation for the SOE concept is to enable higher concentrations of controllable DERs to be safely integrated into our networks. One major challenge for the trials was to demonstrate a capability with only existing, relatively low concentrations of controllable DERs. The trials were designed to maximise the learnings despite this limitation, starting with the registration of participating customers.

Two aggregators, Reposit Power and Evergen, participated in the trials. The project provided them with a prioritised list of customers within their existing ACT customer bases to register for trial participation. Preference was given to customers on feeders that had a good combination of:

- existing / historical network issues;
- controllable DERs; and
- smart meter data.

A total of 1001 customers were registered from the participation through the two aggregators. This is around 1% of the customers on any feeder; a low concentration relative to the intended use case of SOEs.

Five MV-LV feeders were selected to be the focus of the trials based on the same selection criteria that were applied to the prioritisation of customers. 82 of the registered participants connect to these five feeders. The remaining 919 participants are used in trials that emulate higher DER concentrations. Table 1 presents the main characteristics of the five feeders.

More detailed information about the network data can be found in appendix A. Network visualisations of the five feeders are also presented in this appendix.

Table 1. Characteristics of the MV-LV test networks.

Feeder	Buses	MV/LV transformers	Total customers	Participating customers
CITYEA_8LB_EBDEN	2834	27	1900	22
CIVIC_8FB_BELCWAYSTH	1837	23	1217	12
LATHAM_8TB_LWMLNGLOW	1884	24	796	7
WANNIA_8KB_BISSHAWK	4373	57	2621	18
WODEN_8_NB_STREETON	2964	35	2184	23

3.2 Trials

The trials focused on demonstrating the network support capabilities of the SOE approach. The capabilities relating to the wholesale market were evaluated through offline simulations alone in Section 4, as the participating aggregators were unable to provide wholesale market bids for the trials.

Three trials were performed. The first two use the real customer connections on the five feeders outlined in the previous section:

- **Trial 1:** Network Support for Voltage Management.
- **Trial 2:** Network Support for Congestion Management.

The third trial is partly synthetic to demonstrate high DER network concentrations. The true network location of the 1001 participating customers is discarded, and instead, they are considered connected to a single feeder:

- **Trial 3:** Network Support under High DER Concentrations.

The first two trials were run for 4 days each, and the third trial was run for 13 days in total, for 2+ days per feeder.

Network Support Events

In total, 8599 network support customer “events” were triggered, and 5.1 MWh of network support response. Many of these network support events were artificially induced by changing the values of some network components, such as the tap positions of transformers, the voltage limits of buses, or the limits of transformers, so we could demonstrate the network support functionalities of SOEs.

Figure 3 shows an overview of these dispatch events by time and participant. In the top (time series) plot, the dramatic rise in total dispatch towards the end of the trial periods indicates that trial 3 is in effect, where all participating households are given a synthetic location in single feeders to test the behaviour and performance with larger numbers of participants. In the bottom histograms, we see that most participants were dispatched on many occasions. There was a large variation in both the total amount of dispatch and the number of events per participant, and the pattern was different depending on the aggregator. This can be explained by the fact that the two aggregators had different payment structures, with aggregator 1 providing a per kWh payment rate and aggregator 2 providing a flat payment for the whole trial; the optimisation engine took these differences into account when generating network support dispatches.

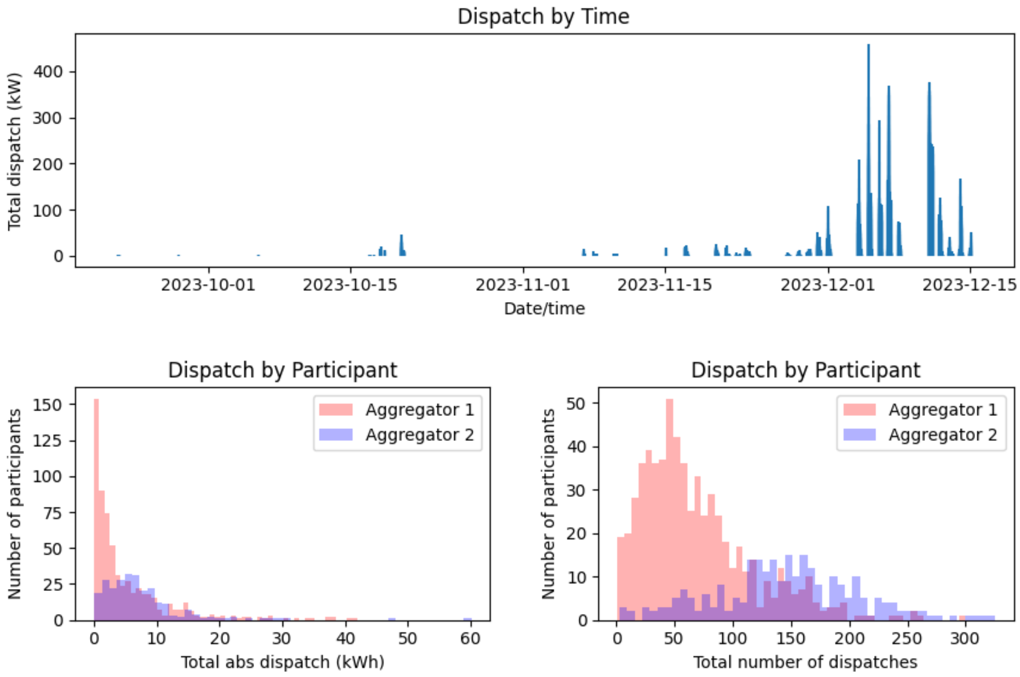

Figure 3. Overview of network support dispatch during the trials. Top: dispatch by time. Bottom left: total dispatch kWh by participant / aggregator. Bottom right: total number of dispatches by participant/ aggregator.

3.3 Overview of Participant Offers

This section considers the amount of network support offered by participants during the trials. We analyse 7 days of offers that were received during Trial 3. Offers from 912 out of the 1001 registered participants were received during this period, with the remaining 89 participants likely being offline.

The 7 days of offer data were combined into an average day. Figure 4 presents the offer capacity for each hour of the day, averaged over participants who submitted offers. The capacity is split between injection and consumption offers. Furthermore, the offer capacities are shown in their “raw” and “enforceable” forms which we will explain next.

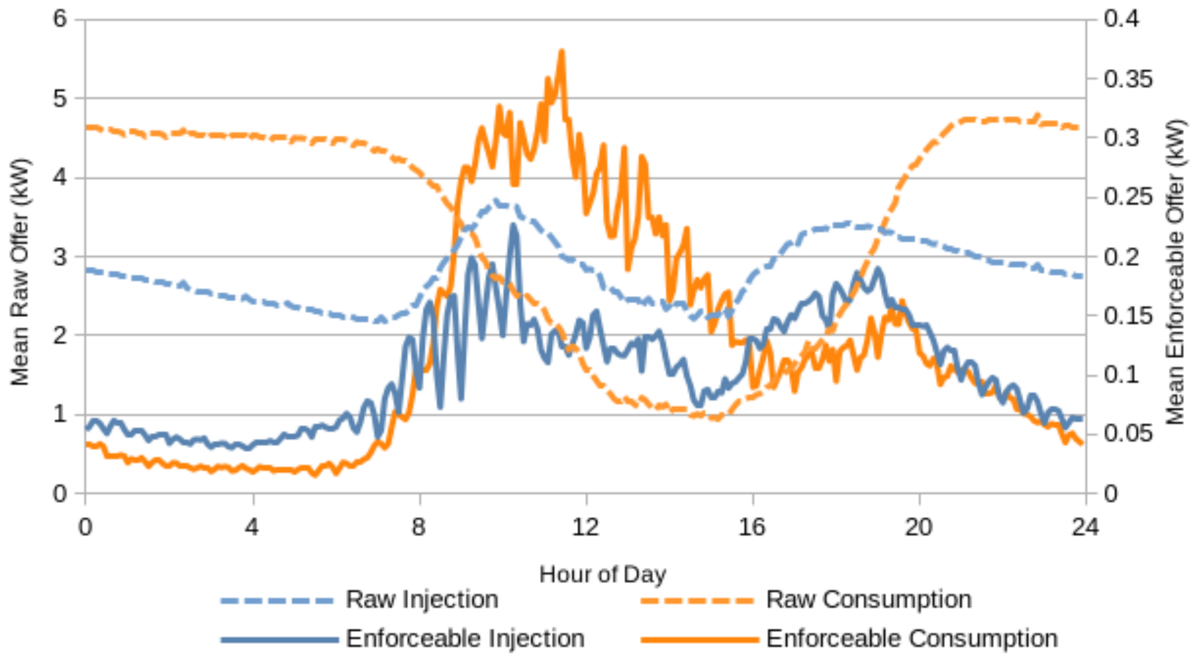

Figure 4. Mean network support offer for each hour of day, averaged over 7 days of offers. The “raw” offers are around an order of magnitude higher than the “enforceable” offers that the SOE engine works with for the trials.

The Converge API was used to interface with aggregators. Part of this API is used for publishing operating envelopes to aggregators. As defined, operating envelopes applied at a connection point must permit the possibility of having zero consumption/generation, meaning the lower real power limit must not go above zero, and the upper real power limit must not go below zero. The consequence of this is that customers generation or consumption can only be curtailed toward zero, and customers with connection point forecast close to zero cannot have their behaviour much altered through operating envelopes.

The trial implementation relied on operating envelopes to communicate the acceptance of network support offers and to enforce their enactment. As such, while a participant might provide a large network support capacity offer (the “raw” capacity), the forecast connection point power of each participant influenced how much of this capacity could be accepted / enforced (the “enforceable” capacity) during the trials.

The enforceable capacity was typically an order of magnitude less, as seen in Figure 4, which indicates that much of the time the forecast connection point power of the participants was not far enough away from zero to make full use of the raw offers being provided. This is understandable, as most customers on conventional retail offerings will be operating their batteries to store their excess solar during the day and to meet their consumption during the peak periods. This tends to bring their connection point power close to zero.

The API could be adapted, e.g., by allowing a more flexible definition of operating envelopes or by implementing a separate “network support” category, to enable the full raw network support offers to be accepted. However, the existing design is potentially sufficient for a future scenario where participants are providing wholesale market services either directly through their aggregator or through a retailer offering greater wholesale market price exposure. In this scenario, extreme connection point powers (far from zero) are the key challenge that the SOE concept is designed to address.

The above observations should be carefully interpreted within the wider context that Project Converge was focused on using envelopes as a means of limiting the potential harmful behaviour caused by DERs, rather than on network support as a means of fixing existing underlying network issues. These two concepts are only partially aligned. Envelopes are generally seen as a means of preventing DER behaviour that might have adverse impacts, while network support is also concerned with proactively fixing existing issues. If a DER site’s power is close to zero, then it is not contributing to network problems, and, within a harm prevention framework, does not need to modify its behaviour. We should also note that, even in cases discussed above, where the full network support offer cannot be dispatched, the presence of envelopes can still lead to a more robust network by preventing any harmful deviations from the forecast.

3.4 Envelope Compliance

One of the first results we can consider for the trials is how well the participants complied with the envelopes they were given. In the trials, SOEs are calculated factoring in aggregator reported network support offers and reservations for each customer. The reservation represents the forecast connection point power of a customer for the dispatch interval of interest, assuming no network support actions. If the reservation is accurately forecasted and the offered capacity reflects the physical capability of on-site DERs, then customers will be able to physically comply with all generated SOEs. However, in practice, these assumptions do not always hold, and, in addition, there are other likely sources of error such as misconfigured systems and communications failures.

This project does not have the level of visibility over customers to fully analyse the source of envelope compliance issues; however, we expect the single biggest likely cause to be the inevitable deviations between reservation forecasts and actual consumption. For the trial implementation, aggregators forecast the customer connection point powers 15 minutes (or more) in advance of a dispatch interval, which can lead to significant errors. While the trial implementation allowed aggregators to communicate a measure of uncertainty about their reservation forecast, which the

SOE engine could factor into its calculations, the aggregators did not elect to provide this information during the trials. This meant that the envelopes calculated in the trials were oblivious to forecasting errors, and participants could be exposed to envelopes they might not be able to physically conform to.

To measure compliance, we look for violations in the envelope real power limits (upper and lower) using measurements on the connection point power of each participant as reported by the aggregators. We consider the metered real power averaged over each 5-minute dispatch interval as the relevant quantity for envelope compliance. One aggregator provided *instantaneous* 5-minute readings, which we interpolated as an approximation to an interval average.

To present the results on envelope compliance, we first split the data into two parts, one for each envelope limit. Figure 5 shows the load-limiting real power envelope and Figure 6 shows the generation-limiting real power envelope. The envelopes are further binned based on how "tight" they are. This envelope "tightness" is measured in kW and is the difference between the customer reservation forecast and the relevant envelope limit. It estimates how much a customer will need to act to keep their connection point within the envelope. A tightness that is zero or negative should not need any participant action so long as the reservation was accurate. A positive tightness will require participant action, and it is equivalent to the amount of network support that is being accepted.

The boxplots in Figure 5 and Figure 6 show the 25th, 50th and 75th percentiles, with the whiskers showing the 2nd and 98th percentiles. The thresholds below the 50th percentile (median) sit on zero and so are generally not visible. The compliance is generally a bit better on the load-limiting side of the envelope than the generation side. It is possible that solar is being underestimated and its volatility is causing larger problems.

We expect these results to largely be a measure of how well aggregators can forecast their customer behaviour 15 minutes out from an interval. It demonstrates the importance of being able to quantify and communicate forecasting error through reservations, otherwise it will be very difficult for aggregators to conform to operating envelopes consistently.

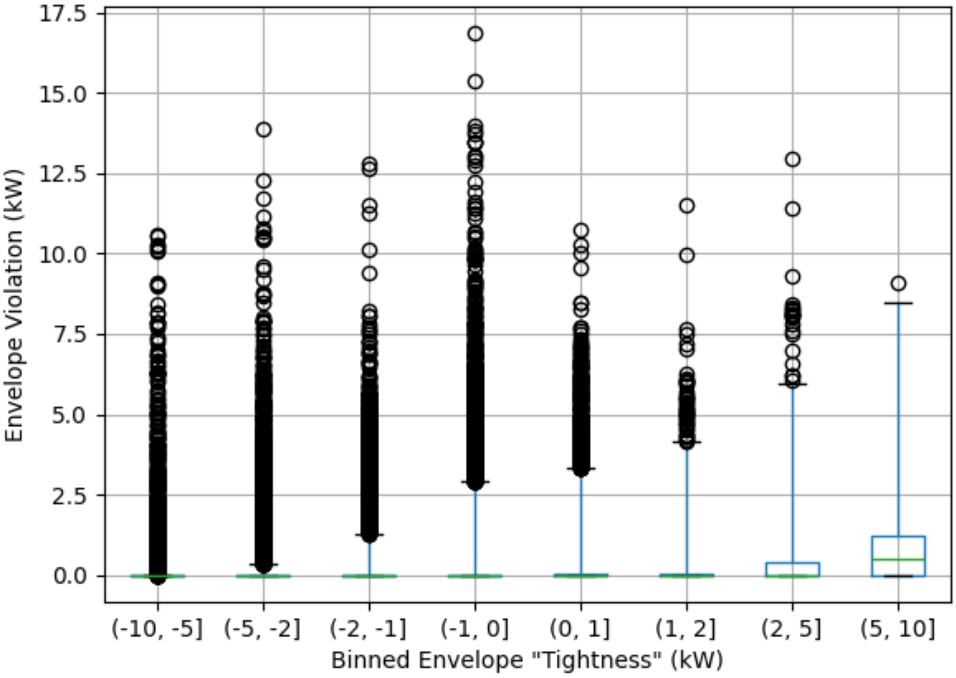

Figure 5. Load-limiting envelope violations. Whiskers represent the 2nd and 98th percentiles.

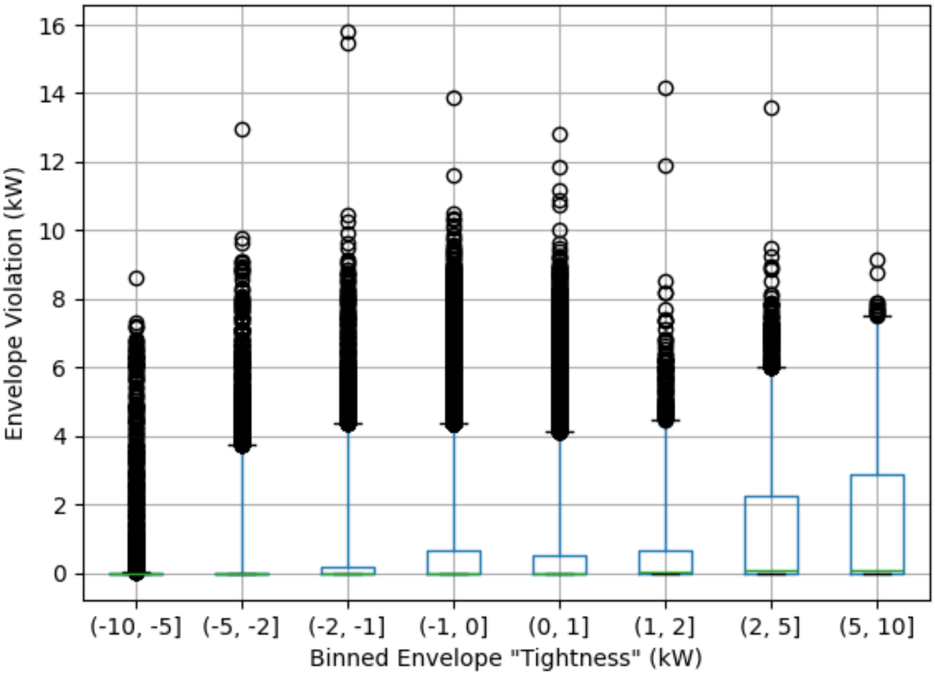

Figure 6. Generation-limiting envelope violations. Whiskers represent the 2nd and 98th percentiles.

3.5 Voltage and Congestion Response

In this section, we analyse the network support that was initiated in response to active network voltage (Trial 1) and thermal (Trial 2) limits. For some feeders, the LV voltage and MV-LV transformer thermal limits were set stricter than their defaults to elicit a network support response during the trial period.

Our analysis of the trials relies on a combination of the inputs and outputs of the SOE engine, the aggregator reported connection point power of participants and network simulations to estimate the network performance. We were not able to access network telemetry outside of the reported values for the participant. Regardless, the unknown phasing of customer connections and transformer tap configurations would have made it difficult to make use of direct network measurements. Instead, we estimate the network impact by simulating the network behaviour with and without the SOE response generated during the trials. For the non-participating network customers, we feed these simulations with our connection-point power forecasts, since we only have smart meter readings for a subset of these customers, and it is 30-minute intervals instead of 5 minutes as used in the trials.

Figure 7 and Figure 8 show results from Trial 1 on two separate days on the WODEN_8_NB_STREETON feeder. The blue forecast voltage region represents the anticipated range of LV voltages, before any network support, given the network model and a day-ahead forecast combined with participant forecasted reservations. The horizontal dashed grey lines represent the voltage limits set in the model, where both figures have the forecast voltage region violating the upper voltage envelope. As expected, the SOE engine accepts negative network support during times of violation, which corresponds to a tighter limit on the export side of participant operating envelopes. This will have participants curtailing their exports to bring down voltages.

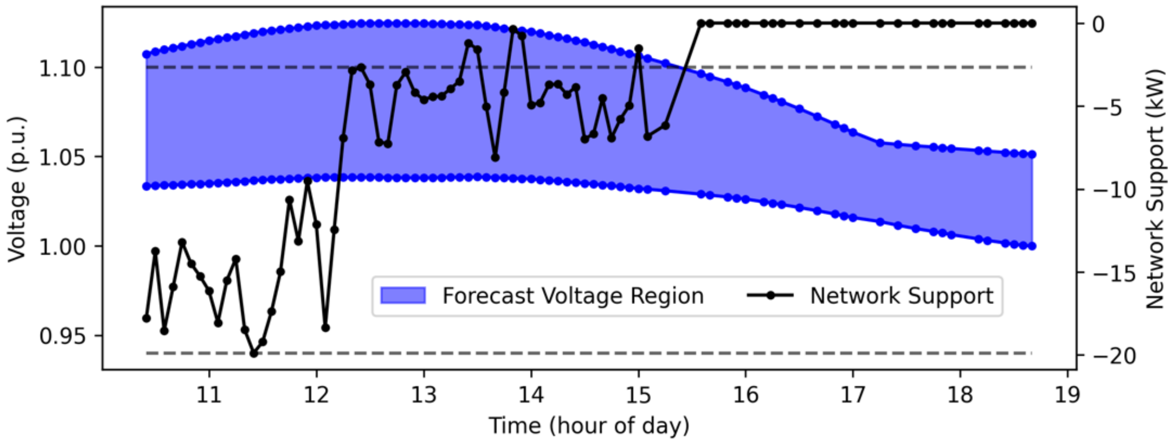

Figure 7. The forecast voltage region and SOE network support. Results of Trial 1 for WODEN_8_NB_STREETON on 17/11/2023.

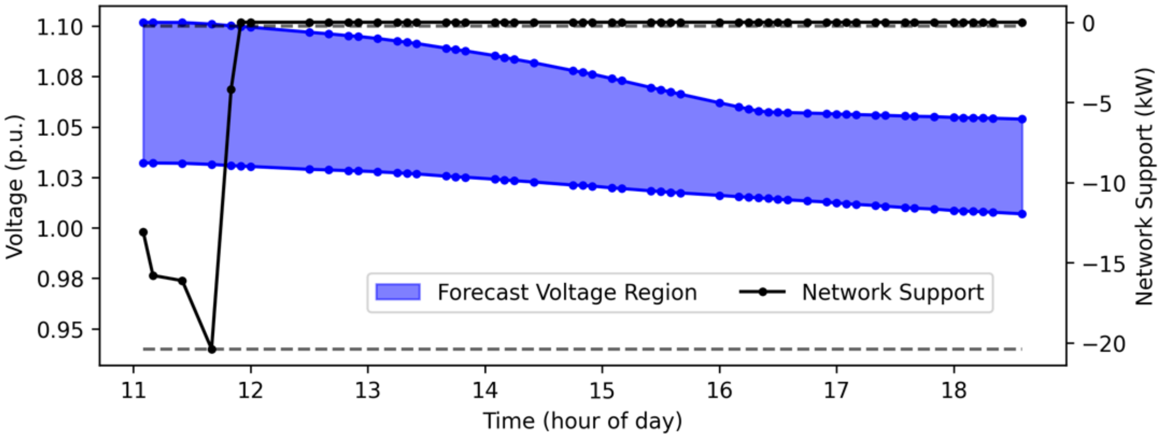

Figure 8. The forecast voltage region and SOE network support. Results of Trial 1 for WODEN_8_NB_STREETON on 21/11/2023.

Figure 9 and Figure 10 show similar results for Trial 2, but where the voltage region is replaced with a forecast loading of the most loaded MV-LV transformer. Again, network support is provided during times when the limits are violated. Figure 9 represents a situation where export needs to be curtailed, and Figure 10 represents the opposite case where load needs to be reduced with an import limit.

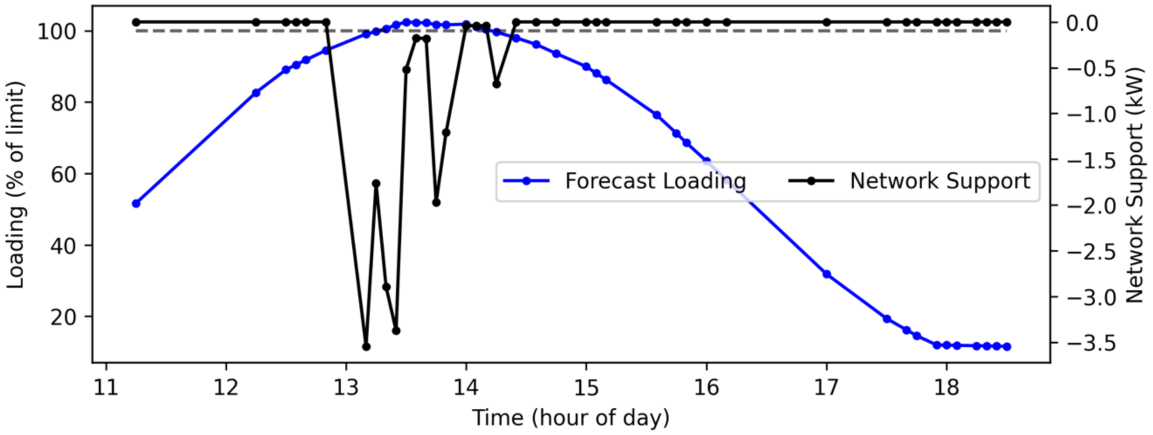

Figure 9. The forecast voltage region and SOE network support. Results of Trial 2 for CITYEA_8LB_EBDEN on 28/11/2023.

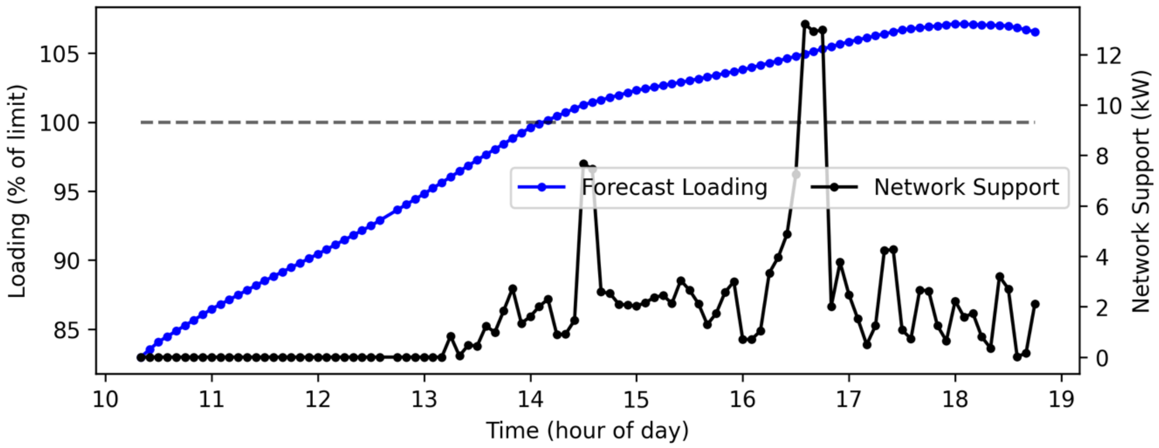

Figure 10. The forecast voltage region and SOE network support. Results of Trial 2 for CIVIC_8FB_BELCWAYSTH on 28/11/2023.

Figure 11 and Figure 12 show Trial 1 and Trial 2 results for two different feeders, focusing on the 100 most significant events in terms of network constraint violation. It shows the ordered violation alongside the corresponding network support for the event. There is no easily identifiable relationship between the significance of the event and the strength of the network support. This relates to the fact that the participants (23 on the first feeder and 12 on the second) are too few and their network support offerings are too small to have enough of an impact to bring the feeder voltages / loading back within limits. Under these circumstances the SOE engine behaves in an "all or nothing" manner: when there is a constraint violation it throws all available network support at the problem, and where there is no violation no network support is used. This can be compared to the results where all available participants were mapped to a single feeder to test the effect of greater DER penetration, see Section 3.6, below.

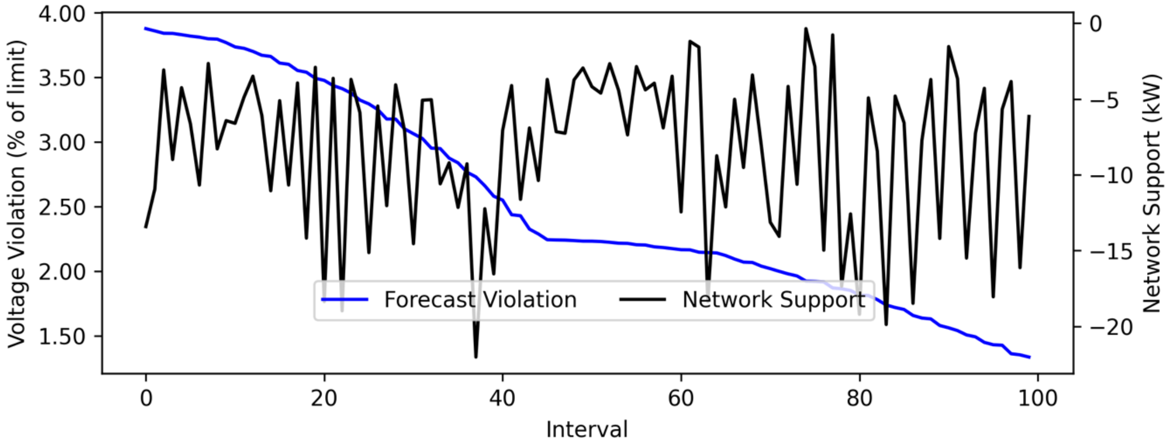

Figure 11. Voltage violation and SOE network support for the 100 largest voltage violation events. Results of Trial 1 for WODEN_8_NB_STREETON.

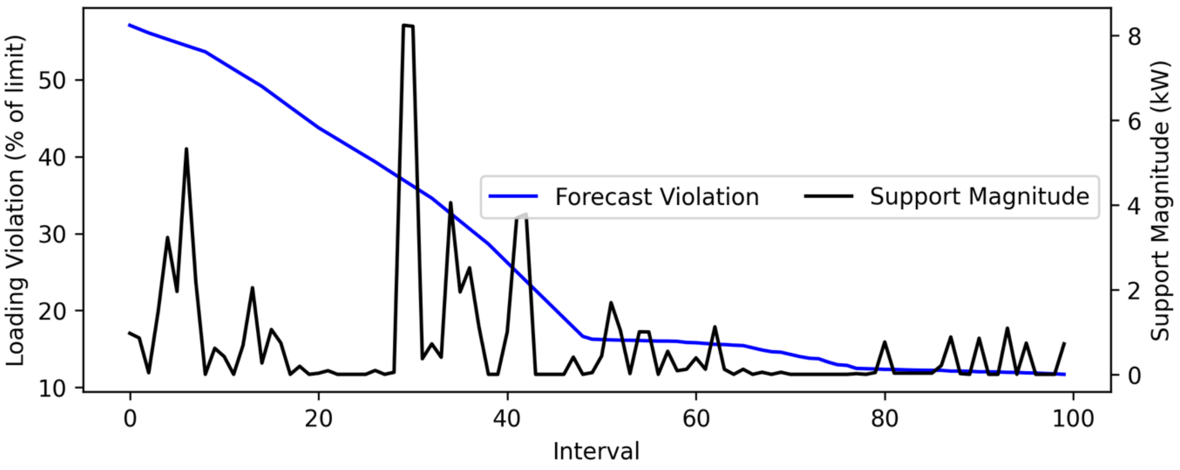

Figure 12. Transformer loading violation and SOE network support for the 100 largest thermal violation events. Results of Trial 2 for CIVIC_8FB_BELCWAYSTH.

3.6 High DER Concentration Response

Recall that Trial 3 synthetically mapped *all* participants onto a single feeder, to test the effect of high concentrations of DER. Trial 3 results therefore show a much stronger network support. However, as shown in Figure 13, the overall impact on the network was still difficult to separate from background noise. In this case, there is a large forecast violation of the upper voltage bound. The SOE engine dispatches all network support on offer, which peaks at over 300 kW in generation curtailment. This feeder has 2621 customers on it, of which around 34% are the trial participants submitting offers. 300 kW spread across 2621 customers is only just over 100 W per customer. In context, the response is unlikely to have a large network impact, and indeed forecasting error in load and generation far outweighs the observable network impact. This can be seen in Figure 13 by observing how the green voltage region is sometimes above and sometimes below the blue voltage region.

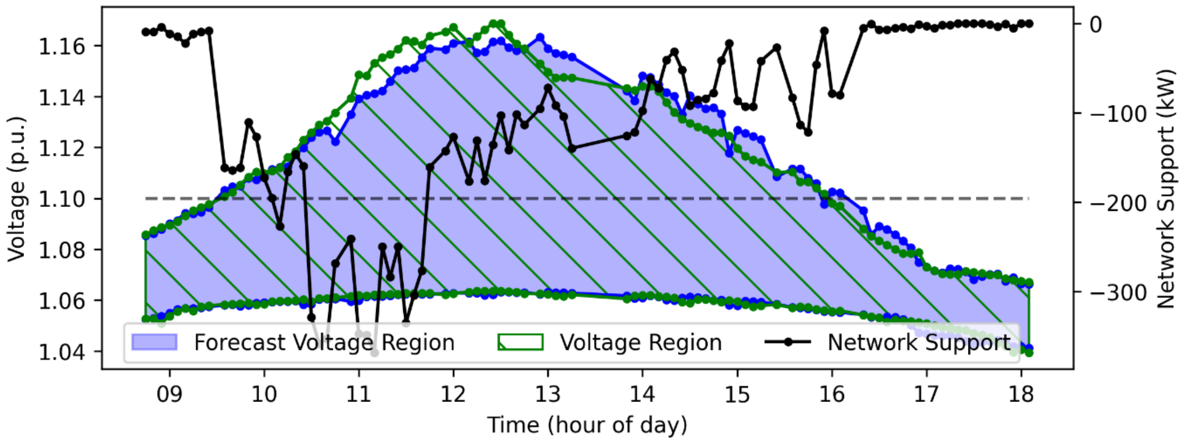

Figure 13. Forecast (no support) and resulting voltage regions. Results of Trial 3 for WANNIA_8KB_BISSHAWK on 17/12/2023.

To dilute these forecasting errors, we focus on a smaller network where the available network response will have a larger impact. Figure 14 shows the same plot but for the LATHAM_8TB_LWMLNGLOW feeder, where the 1001 active customers artificially allocated to the feeder are providing offers. The reduction is more consistent as the resulting voltage region is in green with the network support active mostly now sitting below the forecast voltage region that has no support applied to it.

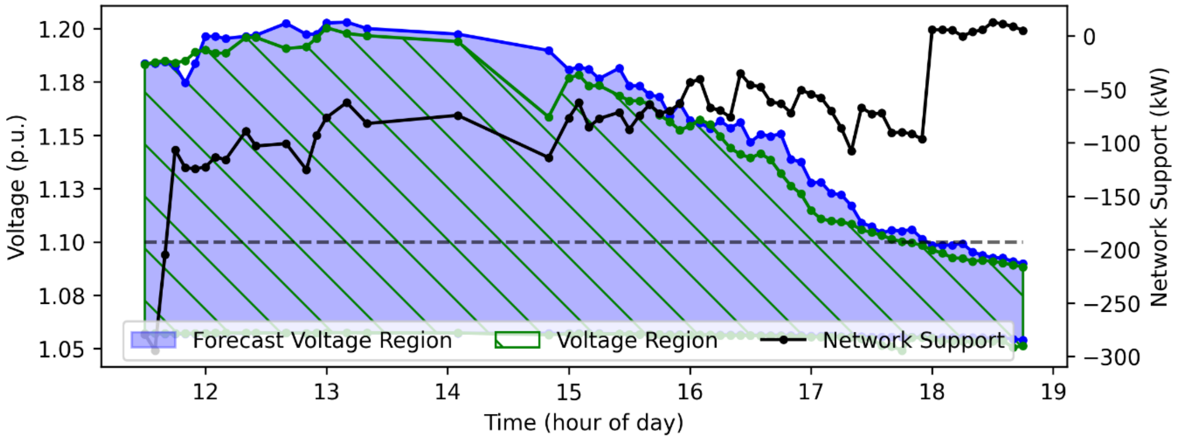

Figure 14. Trial 3: Forecast (no support) and resulting voltage regions alongside network support. Results of Trial 3 for LATHAM_8TB_LWMLNGLOW on 06/12/2023.

To further isolate the network support impact from forecasting error we compare the difference in voltage violation with and without the dispatched network support in a way that cancels out errors in forecasting. Figure 15 shows the top 50 voltage violations for the LATHAM_8TB_LWMLNGLOW feeder. This plot shows a reduction in voltage violation by up to 0.5 percentage points. The peak network support in the way of 300 kW generation curtailment is around 300 W per customer.

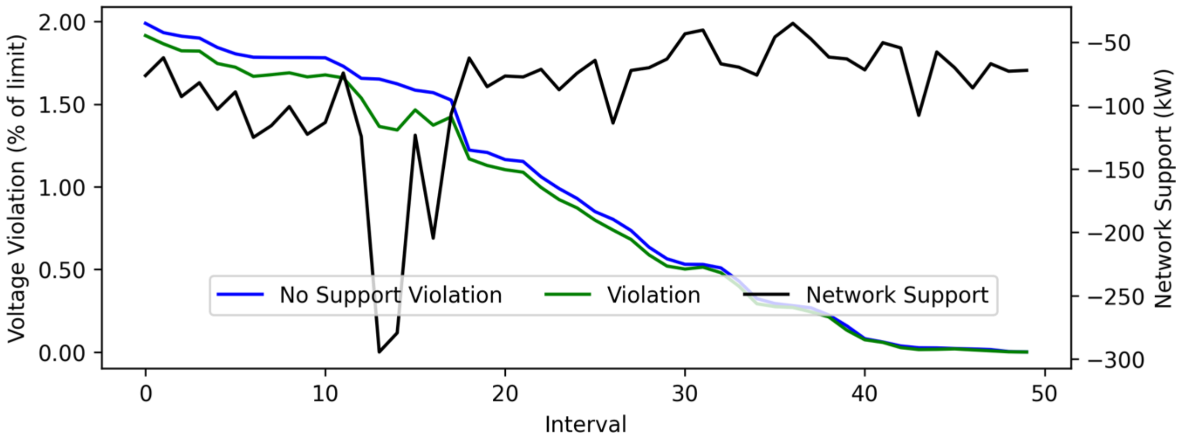

Figure 15. Voltage violation (with and without network support) and SOE network support for the 50 largest voltage violation events. Results of Trial 3 for LATHAM_8TB_LWMLNGLOW on 06/12/2023.

Figure 16 plots a time series of the average operating envelope for the same day on the LATHAM_8TB_LWMLNGLOW feeder. This feeder exceeds the voltage upper bound in the middle of the day, with a peak violation around 13:30. However, this is precisely where the upper side of the operating envelope is at its highest, the opposite of what is required to reduce voltages. The upper envelope is only able to be tightened at around 17:00 as the voltage event is nearing its end. This shows that the offers aggregators are generating do not align with what the SOE engine needs to manage network limits. Uncurtailable solar generation is likely a big factor in this.

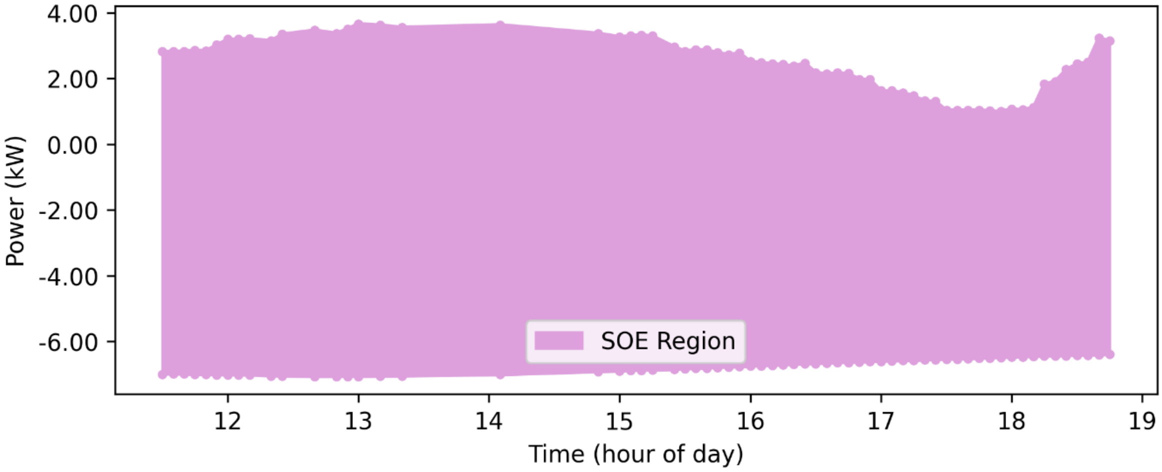

Figure 16. The average operating envelope for the trial participants where positive is generation. Results of Trial 3 for LATHAM_8TB_LWMLNGLOW on 06/12/2023.

Those customers that can provide larger offers to soak up solar of other customers are likely being held back by what the SOE engine can enforce through operating envelopes, as implemented in the Converge API. To explore this, we plot the voltage regions that would have been achievable if the full raw consumption offers could be accepted (allowing envelopes to cross the zero point of the connection point). Figure 17 shows the expected outcome for this hypothetical case. While a much larger network response is achieved, it is largely limited to times after the voltage event is over. Within the voltage event itself, there is only a modest improvement over what was achieved when restricted to enforceable envelopes. This suggests that, for this scenario, there was simply too much uncontrollable solar and not enough flexible curtailment or battery storage capacity at the right time.

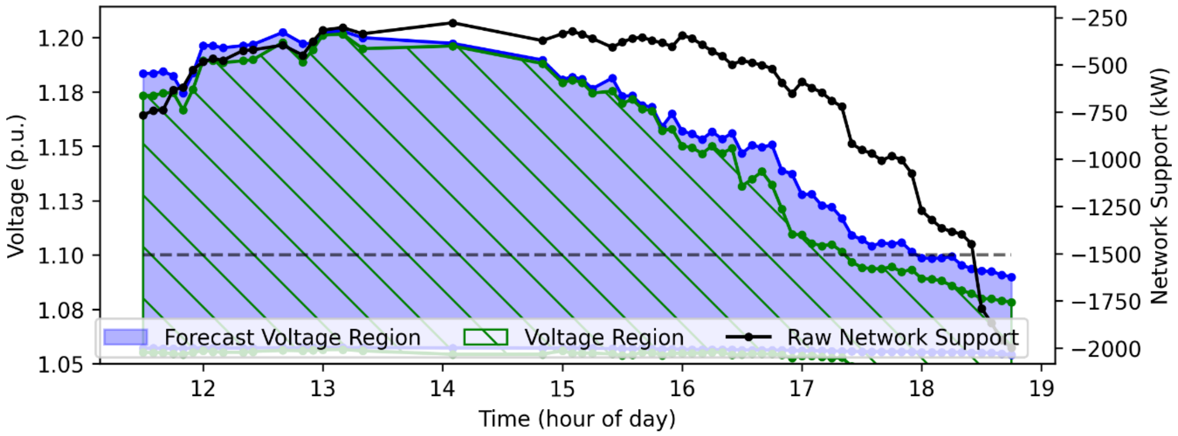

Figure 17. Forecast (no support) and resulting voltage regions if (zero-point crossing) envelopes, i.e. raw network support could be achieved. Results of Trial 3 on LATHAM_8TB_LWMLNGLOW and 06/12/2023.

A similar trend holds in Figure 18 which is for the WODEN_8_NB_STREETON feeder. In this case, the available raw network support is again the largest at times when it is least useful. In this case, there is just enough network support available in the middle of the day to keep the voltages within the upper voltage limit.

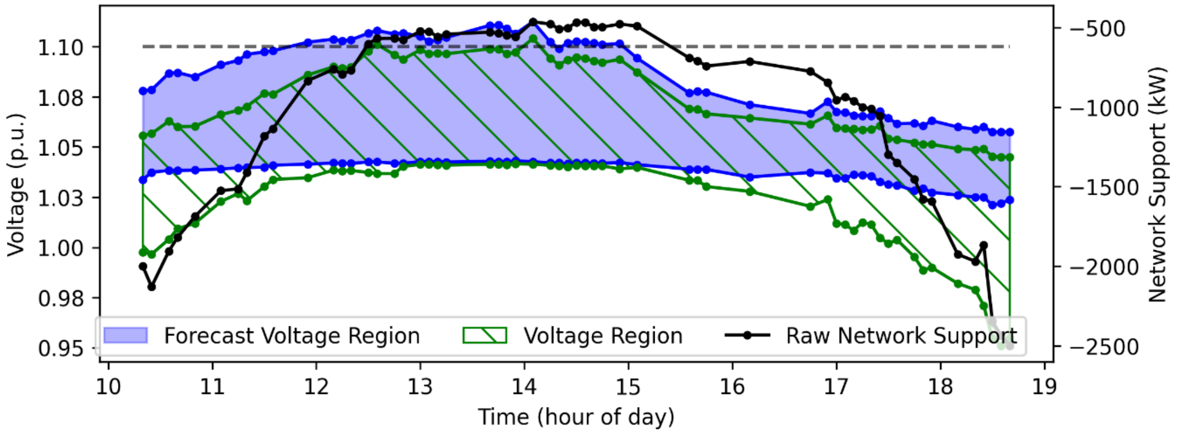

Figure 18. Forecast (no support) and resulting voltage regions if (zero-point crossing) envelopes, i.e. raw network support could be achieved. Results of Trial 3 for WODEN_8_NB_STREETON on 12/12/2023.

4 Comparison of SOEs against Other Approaches

In this section, we evaluate and compare the performance of SOEs against DOEs and fixed operating envelopes (FOEs) using offline simulations. This analysis is made for multiple DER scenarios, and covers the following topics:

- **Network security:** We evaluate the network performance of SOEs, DOEs, and FOEs. In other words, we evaluate if the mentioned approaches can ensure network security.
- **Unlocked DER capacity:** We quantify the DER capacity that can reach wholesale markets under the mentioned approaches. This analysis helps to understand the potential to unlock DER capacity under DOEs and SOEs.
- **Unlocked DER value:** We quantify and discuss the DER value unlocked by DOEs and SOEs in wholesale markets.

In the offline simulations, we use the full implementation of the SOE concept described in Section 1, which enables active wholesale market participation and network support delivery.

4.1 Experimental Setup

Our experimental setup revolves around aggregators actively participating in energy and FCAS markets, specifically focusing on the raise and lower of 6sec, 60sec, and 5min contingency markets. We assume that aggregators behave as price-takers in the NEM, which is in line with the current strategy of many aggregators in Australia. Under this assumption, aggregators optimise DERs based on price forecasts to calculate energy and FCAS bids, as described in [13]. The bids are constrained by SOEs, DOEs, or FOEs depending on the approach considered. Note that FOEs represent the current business practice, where customers are subjected to fixed power limits for exports (5 kW/phase) and imports (7-14 kW/phase)[7].

We chose this business model for the aggregators in our offline simulations so that we can discuss the system-level benefits introduced by SOEs compared to the other two approaches.

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[7] This limit can vary depending on the installation.

4.2 Test Case

The test case describes the data used to conduct the offline simulations for one month. We used the data from September of 2023.

Network Data

The aggregators' customers are connected to an MV-LV network region in ACT. This network region covers the following five MV-LV feeders:

- CITYEA_8LB_EBDEN.
- CIVIC_8FB_BELCWAYSTH.
- WANNIA_8KB_BISSHAWK.
- LATHAM_8TB_LWMLNGLOW.
- WODEN_8_NB_STREETON.

The five network feeders include a total of 13892 buses, 13892 lines, 166 MV/LV transformers and 8718 customers (2168 with DER, mostly PV).

The network data was provided by Evoenergy to Zepben which made data available through its energy workbench platform [10]. The voltage limits were set according to the Australian standard 60038. In LV areas, the voltage limits are fixed at 0.94 and 1.1 p.u., while in MV areas, they are set at 0.9 and 1.1 p.u. More detailed information about the feeders can be found in Section 3.1 and Appendix A.

DER Scenarios

Table 2 presents the scenarios of DER market participation considered in our offline simulations, listing the number and percentage of customers with PV and batteries in each scenario. The first scenario (P25B2) represents the current level of DER penetration in the 5 feeders.

Customers with DER can own PV systems ranging from 0.5 to 30 kW and battery systems of 5 kW / 13.5 kWh or 10 kW / 27 kWh. Note that all customers with batteries also have PV, but not necessarily the other way around.

Table 2. DER scenarios.

DER scenario	Customers with PV	Customers with batteries
P25B2	2168 (25%)	152 (2%)
P40B20	3546 (40%)	1769 (20%)
P60B40	5282 (60%)	3520 (40%)

Smart Meter Data

We generated time series of background load and PV generation for September 2023 using 30-minute smart meter data provided by Evoenergy, matching actual customers wherever possible and making appropriate substitutions in other cases. These time series were used as inputs in the optimisation model [13] used to compute aggregators' bids for energy and FCAS markets.

NEM Data

The NEM data (energy and FCAS prices) was sourced from the AEMO website [14] to be used as input in the aggregators' optimisation problems.

4.3 Results

The results compare and discuss the performance of SOEs, DOEs, and FOEs in three categories: network security; unlocked DER capacity; and unlocked DER value.

Network Security

As expected, SOEs and DOEs ensure network security in the 5 feeders and all DER scenarios without causing any network problems. However, FOE causes several transformer overloads and voltage violations at both LV and MV levels, especially in P40B20 and P60B40 scenarios, as illustrated in Figure 19, Figure 20, Figure 21, Figure 22, and Figure 23. To measure the network violations, we count voltage and thermal limit violations throughout the 5 feeders and the entire month. This is done assuming a worst-case activation of FCAS bids. This means, that a part of the violations would only occur under FCAS contingency events, which have a low probability of occurrence. However, these are exactly the circumstances that we do not want to trigger the protection functions of DERs, as it could block the essential FCAS services from being delivered, as expected by AEMO.

In our offline simulations, we assumed that aggregators have perfect control over all DERs, which makes it possible for SOEs and DOEs to mitigate all potential network problems. In a real-world setting, this level of controllability can be limited, which reduces the amount of DER capacity available for SOEs and DOEs to act on. In other words, SOEs and DOEs may not be able to ensure network security in scenarios where not enough controllable DER capacity is available.

Another important factor is the accuracy of customer-level forecasts for active and reactive power, which we assumed to be perfect in offline simulations. In a real-world setting, forecasts provided by aggregators are not perfect, which impacts the quality of SOEs and DOEs. This kind of uncertainty is an intrinsic part of forecasting individual loads. However, the aggregate load from many households is expected to be far more predictable, so envelopes should in aggregate do a reasonable job. Nonetheless, design changes (such as separate metering for DER and household loads combined with more accurate weather-based PV prediction) and a careful framing of rules around compliance with envelopes could be considered in future implementations.

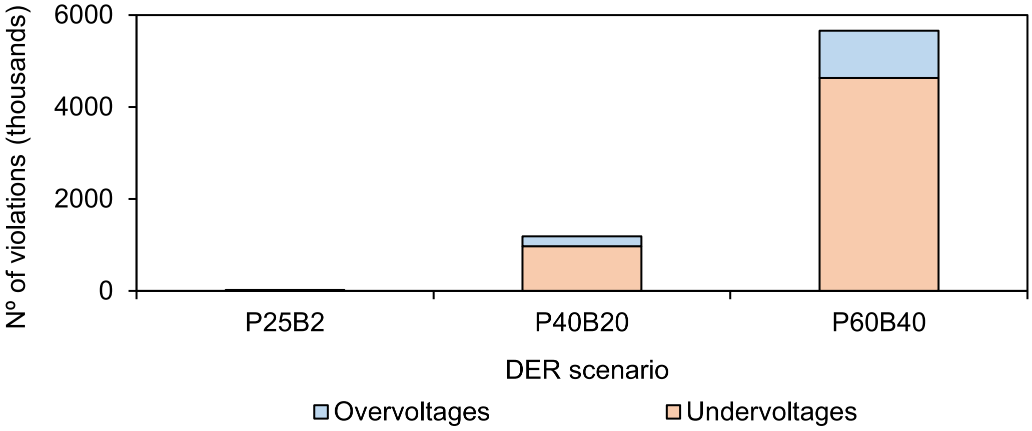

Figure 19. Number of LV violations under FOE[8].

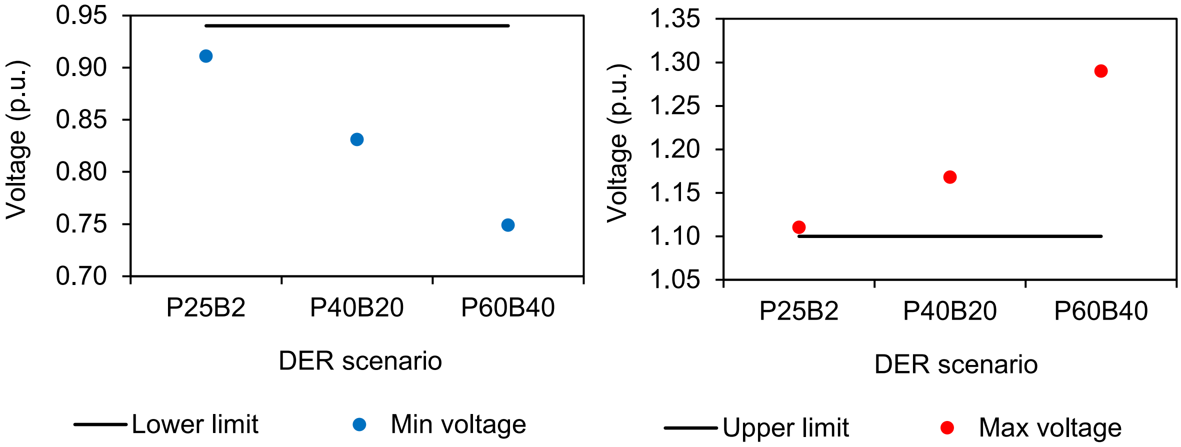

Figure 20. Severity of LV violations under FOE.

The network results illustrated in Figure 19 - Figure 23 also show that the number of network violations increases with the increased number of DERs. The severity of the violations also increases, showing that it would be very insecure to operate the feeders in such conditions.

Another interesting observation is that voltage problems arise first in LV areas, and only reach MV areas when DER penetration levels are high, like in the P60B40

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[8] Note that 500 overvoltages and 13544 undervoltages were counted in P25B2.

scenario. This highlights the importance of DSOs accounting for both MV and LV feeders in network planning and operation, as reported in previous studies [15].

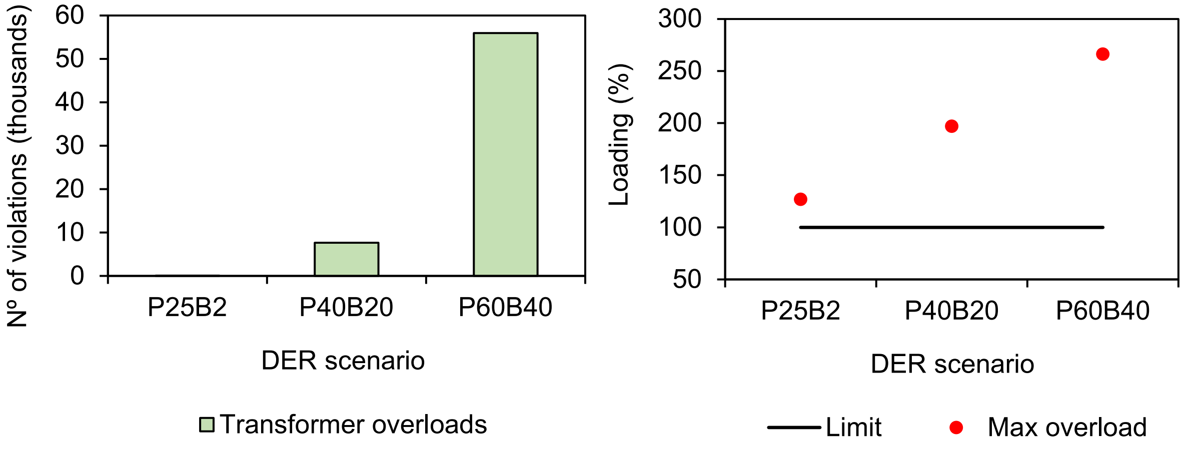

Figure 21. MV/LV transformer violations under FOE[9].

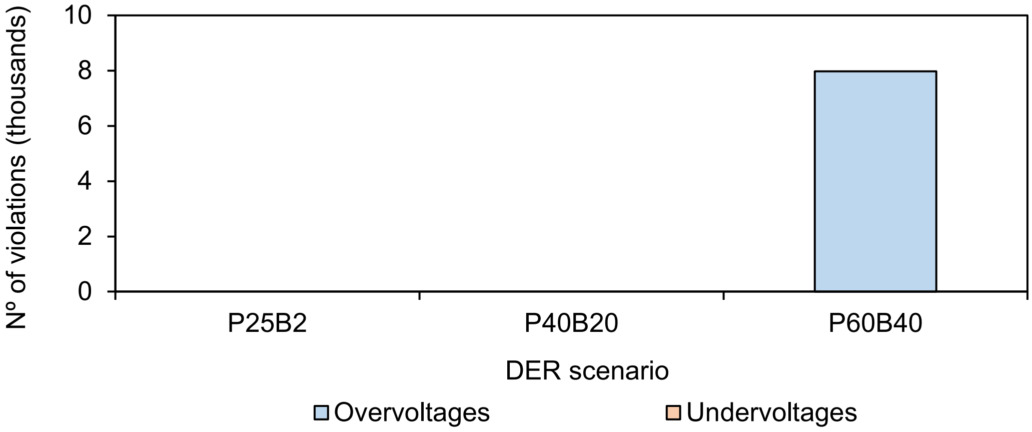

Figure 22. Number of MV violations under FOE[10].

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[9] Note that 35 transformer overloads were counted in P25B2.

[10] Note that 8 undervoltages were counted in P60B40.

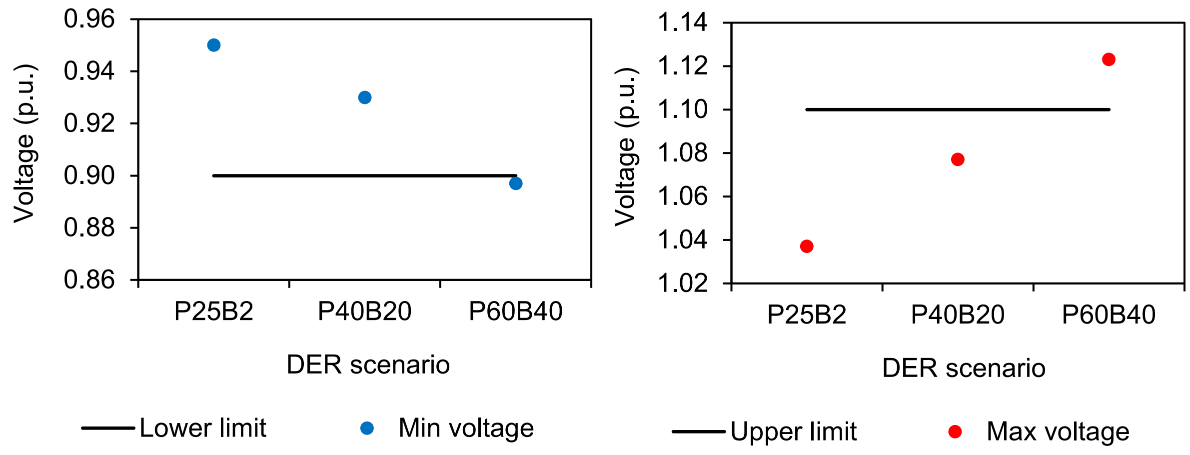

Figure 23. Severity of MV violations under FOE.

Unlocked DER Capacity

The DER capacity unlocked by SOEs and DOEs in the wholesale markets is illustrated in Figure 24, as the volume of services traded in energy and FCAS markets. The results show that SOEs allow more DER services / capacity to reach energy and FCAS markets than DOEs, potentially increasing the benefits for DER owners. In addition, they also show that the difference between them increases with the increase in the number of DER installations. This happens because, unlike SOEs, DOEs do not factor in the bidding intentions of aggregators. Instead, DOEs allocate network capacity proportionally to DER sizes, which has shown to be a less efficient method for network capacity allocation.

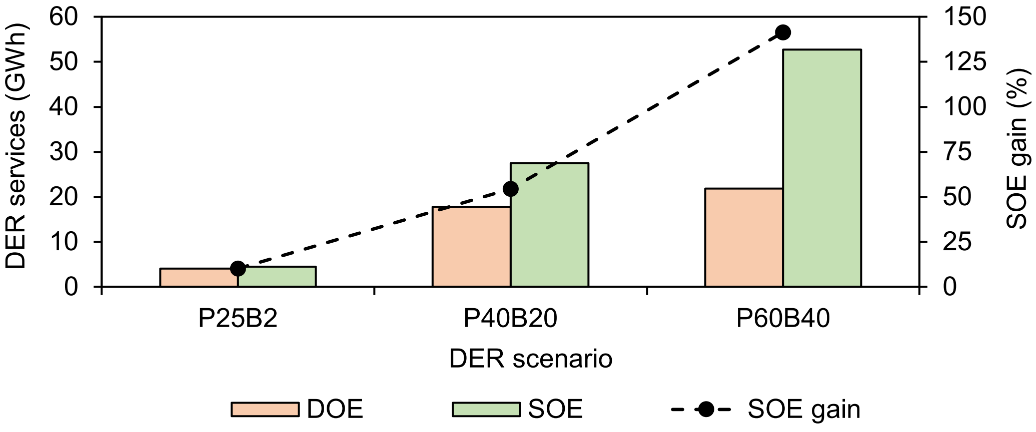

Figure 24. Unlocked DER capacity under SOEs and DOEs.

We only considered the approaches that ensure network security in this analysis. Because of this reason, FOE was not included.

Unlocked DER Value

The DER market value unlocked by SOEs and DOEs is illustrated in Figure 25. The results in Figure 25 reflect the value of the DER services traded in energy and FCAS markets. As expected, these results follow the same trend as the results illustrated in Figure 24, where SOEs outperform DOEs in all DER scenarios. As mentioned before, SOEs outperform DOEs because the calculation of SOEs factors in the bidding intentions of aggregators, unlike DOEs. These bidding intentions include both quantities and prices of services.

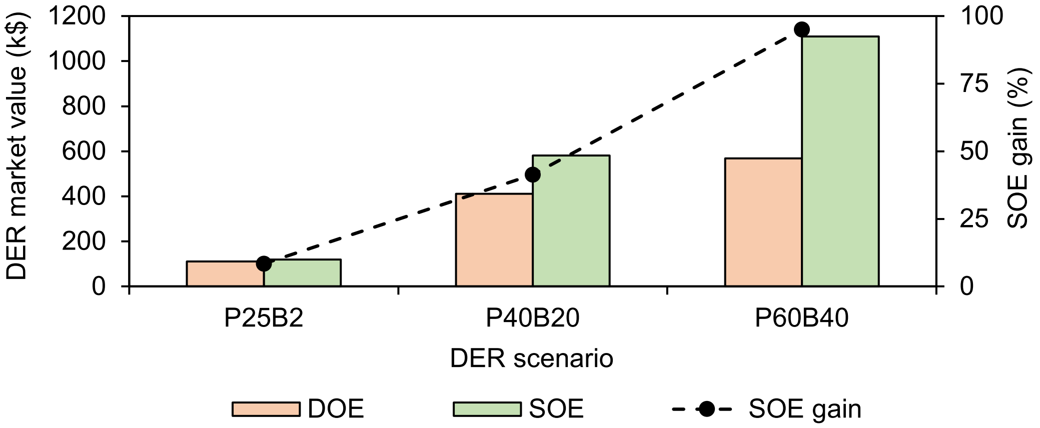

Figure 25. Unlocked DER value under SOEs and DOEs.

The extra market value unlocked by SOEs can be passed from aggregators to customers, increasing the benefits for customers and reducing the payback times of DERs. This extra market value depends mainly on how the network is constrained. Under highly constrained network conditions, SOEs perform significantly better than DOEs, as illustrated by the P60B40 scenario. However, when the network is not heavily constrained, the market value generated by DOEs and SOEs can be similar.

5 Real-Time RIT-D

5.1 Toolbox Description

The Real-time (RT) RIT-D toolbox aims to identify the most cost-effective DER owners capable of providing distribution network support services, such as voltage regulation and congestion management. DSOs can avoid network augmentations through the recruitment of DER owners to their network support programs (SOE programs).

The RT RIT-D toolbox includes three interconnected tools, as illustrated in Figure 26:

- The **Power flow tool** forecasts possible network violations. The outputs include the network locations, types, times, and values of all network violations. These are used as inputs by the other two tools.
- The **DER mapping tool** identifies the most cost-effective DER owners capable of providing network support services. The outputs include NMIs, network support services (type and kWh/year), and cost.
- The **Network augmentation tool** identifies the avoided network augmentations, due to the use of DERs to provide network support services. The outputs are the technologies, costs, and locations of the avoided augmentations.

The RT RIT-D toolbox uses as inputs: network data; DER and netload scenarios from 1 month-ahead to 1 year-ahead; and network support services data.

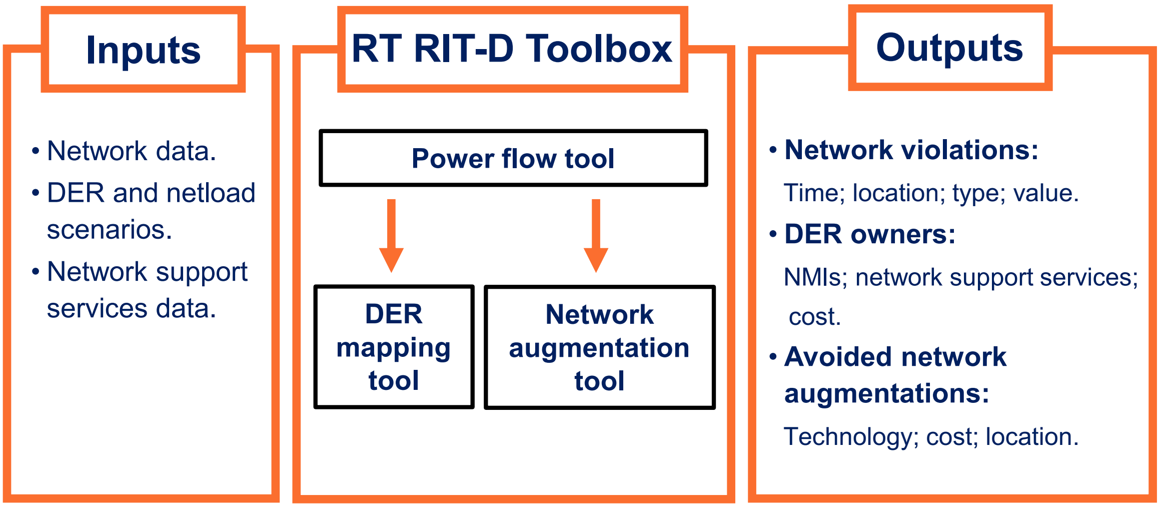

Figure 26. RT RIT-D Toolbox.

The RT RIT-D toolbox should be run periodically (e.g., every week or month) so that the list of relevant DER owners is updated regularly based on updated forecasts of network conditions and scenarios.

5.2 Test Case: Inputs of the Toolbox

This section describes the test case selected from the ACT region to evaluate the RT RIT-D toolbox. The test case describes the input data used by the toolbox.

Network Data

We considered an MV-LV network region covering LATHAM_8TB_LWMLNGLOW and WODEN_8_NB_STREETON feeders. This network region includes a total of 4848 buses, 4787 lines, 59 MV/LV transformers and 1980 customers.

The voltage limits were set according to the Australian standard 60038. In the LV areas, the voltage limits are fixed at 0.94 and 1.1 p.u., while in the MV areas, they are set at 0.9 and 1.1 p.u.

DER and Netload Scenarios

We generated DER adoption scenarios for 1 year-ahead using as a base the current percentage of DER penetration in the network. Table 3 presents the DER scenarios, listing the percentage of customers with PV, batteries, and EV in each scenario. DER owners can own PV systems ranging from 0.5 to 26 kW, battery systems of 5 kW / 13.5 kWh or 10 kW / 27 kWh, and EVs. Note that all customers with batteries also have PV systems, but not necessarily the other way around.

Table 3. DER scenarios.

DER scenario	Customers with PVs	Customers with batteries	Customers with EVs
P30B3EV0	892 (30%)	91 (3%)	-
P30B3EV3	892 (30%)	91 (3%)	91 (3%)
P33B5EV5	983 (33%)	151 (5%)	151 (5%)

We computed 30-minute netload scenarios for 1 year-ahead using historical smart meter data provided by Evoenergy and assumptions regarding the operation of the new PVs, batteries, and EVs introduced in each DER scenario.

Network Support Services Data

The network support services data includes the availability for DER owners to increase and decrease generation and load through the orchestration of DERs by aggregators.

We computed 30-minute time series of network services for 1 year-ahead using a bespoke optimisation model for each DER scenario. The total network support services per month are illustrated in Figure 27 for the P33B5EV5 scenario. Note that raise is the availability to increase generation and decrease load, while lower is the opposite.

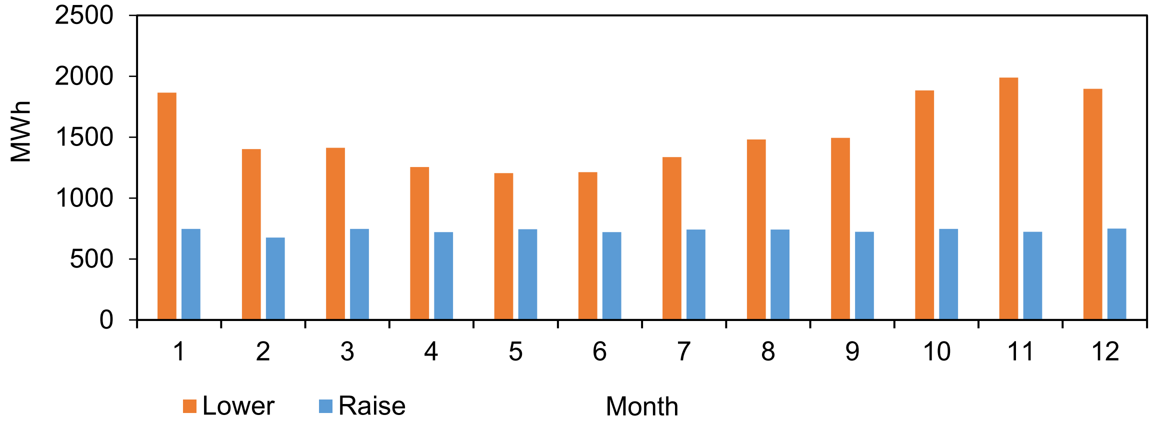

Figure 27. Network support services data for P33B5EV5 scenario.

5.3 Results: Outputs of the Toolbox

This section describes the results obtained using the RT RIT-D Toolbox. The results illustrate the outputs of the RT RIT-D Toolbox.

Network Violations

We used the Power flow tool from the toolbox to forecast and identify possible network violations in each DER scenario. The outputs of this analysis include the network locations, types, times, and values of all violations.

Figure 28 illustrates the number of overvoltages and undervoltages identified under each DER scenario. To count voltage violations, we evaluated the voltage values throughout the 4848 buses and the 17,520 30-minute intervals of the entire year. We only identified voltage violations in LV feeders, predominantly overvoltage violations. These are caused by rooftop PV, while undervoltages are mainly caused by batteries and EVs.

We can also observe in Figure 28 that the number of voltage violations increased with the increase of the DER numbers. Higher DER numbers increase the load and generation in the network and consequently the number of violations, but also the severity of these, as illustrated in Figure 29.

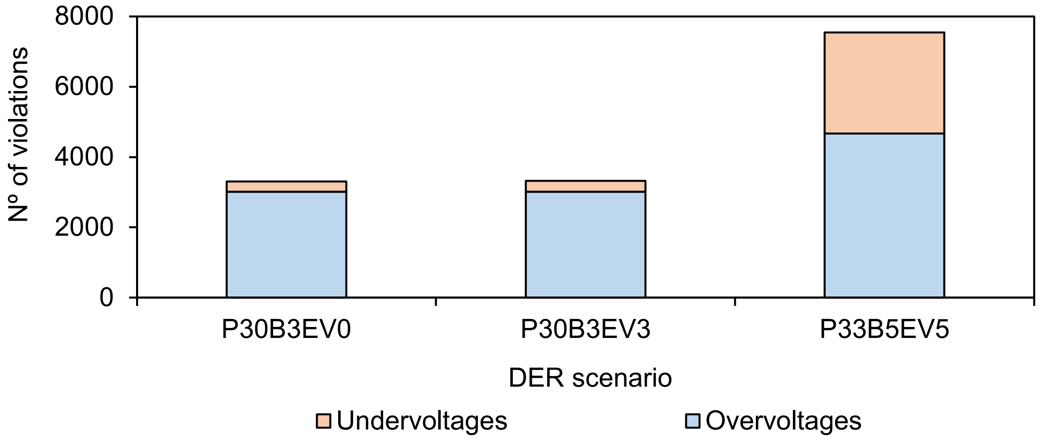

Figure 28. Number of LV violations over 1 year.

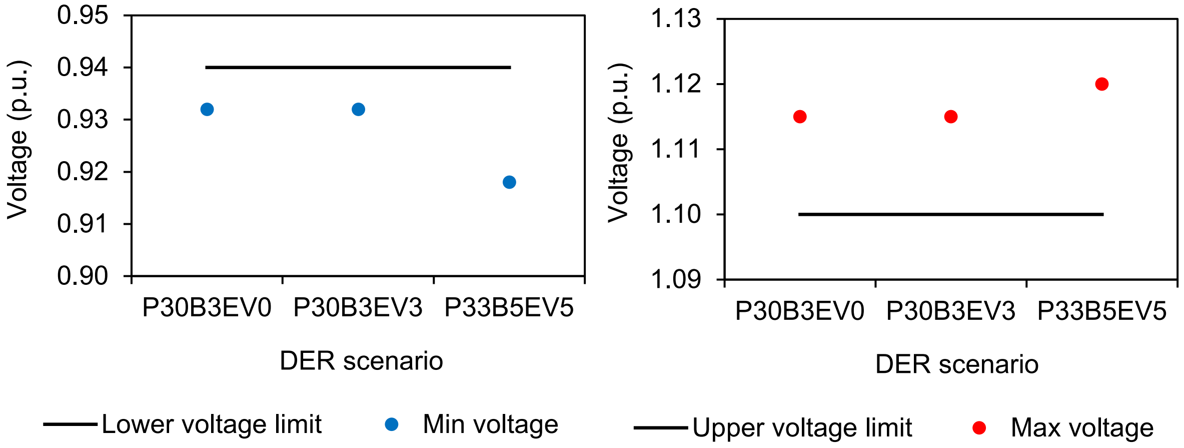

Figure 29. Severity of the LV violations.

Identification of DER Owners

The network problems forecasted and identified by the Power flow tool should be addressed, so that the DSO can operate the network safely. To achieve this goal, the DSO can recruit DER owners to maintain the distribution network secure.

The challenge here is to identify the most cost-effective DER owners to provide the required voltage regulation services. To do this, we can use the DER mapping tool from the RT RIT-D Toolbox. This tool uses as inputs: prices to recruit DER owners (AUD100/year and AUD0.1/kWh); and the outputs of the Power flow tool.

Table 4 presents the outputs of the DER mapping tool for each DER scenario. The outputs include the number of DER owners, the amount of raise and lower services, and the cost of using DER owners to provide the necessary voltage regulation services to maintain network security. In other words, the DER owners that the DSO needs to recruit and their respective remuneration. The geographic location of the DER owners for P33B5EV5 is presented in Figure 30 for illustrative purposes.

The results of Table 4 show that the requirements to maintain the network secure increase from P30B3EV0 to P33B5EV5, i.e., with the increase of DER numbers and network problems. This is an expected result since the increase of foreseen network problems typically increases the requirements for network support services.

Table 4. DER network support service requirements.

DER scenario	Number of DER owners	Raise services (kWh/year)	Lower services (kWh/year)	Cost (AUD/year)
P30B3EV0	4	75	705	478
P30B3EV3	5	81	705	579
P33B5EV5	20	732	1227	2196

Avoided Network Augmentations

The recruitment of DER owners to provide network support services, such as voltage regulation, can avoid investments in traditional network solutions, such as on-load tap changer (OLTC) transformers.

The Network augmentation tool allows us to identify the network augmentations avoided by the recruitment of DER owners. Table 5 shows that the use of DERs to provide voltage regulation services can avoid the installation of MV/LV OLTC transformers and consequently their installation costs (AUD 218,000/OLTC[11]). In the most extreme scenario, the installation of 9 MV/LV OLTC transformers can be avoided. The geographic location of these OLTC transformers is illustrated in Figure 30 for the P33B5EV5 scenario.

Table 5. Avoided network augmentations and costs.

DER scenario	Number of MV/LV OLTC transformers	Installation cost (AUD)
P30B3EV0	3	654,000
P30B3EV3	4	872,000
P33B5EV5	9	1,962,000

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[11] Value provided by Evoenergy for a pad-mount substation with an OLTC.

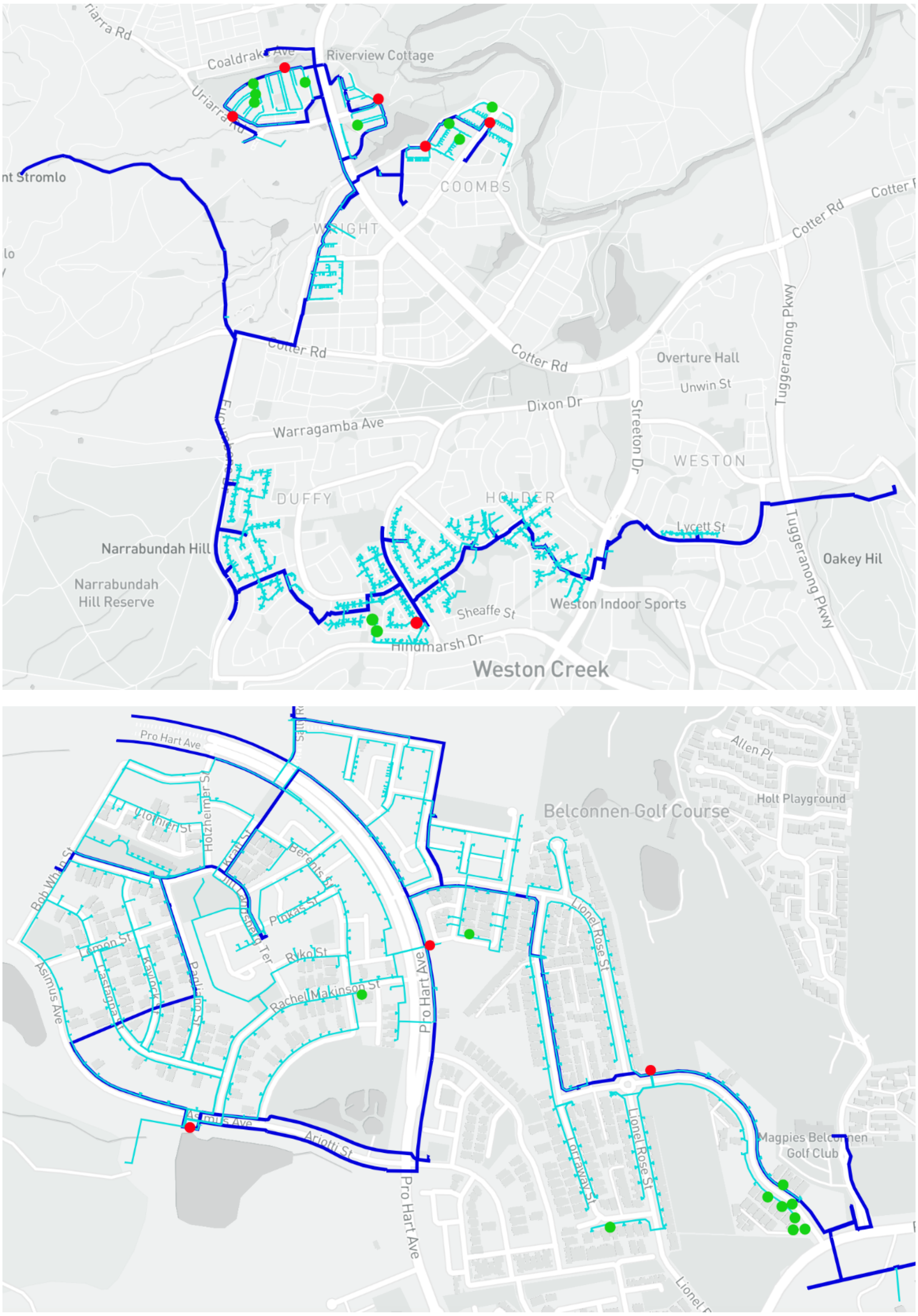

Figure 30. Geographic location of the 20 DER owners (green dots) and 9 avoided MV/LV OLTC transformers (red dots) in P33B5EV5. MV and LV lines are coloured dark and light blue, respectively.

The economic comparison between the use of DERs and the installation of MV/LV OLTC transformers can be done by computing the net present value of each solution for each scenario. Table 6 presents a simplified net present value calculation for both DER and OLTC options for a period of 30 years with a 7% discount rate[12]. The results show a clear and significant economic benefit for the use of DERs.

The calculation of OLTC transformers' net present value only considered their installation costs since this augmentation action would replace current transformers with similar maintenance and operating costs. In other words, these costs are common to both options. For this reason, they were not factored in in the calculation of avoided costs.

Table 6. Net-present value evaluation: avoided costs due to the use of DERs.

DER scenario	Recruitment and utilisation of DER owners (AUD)	MV/LV OLTC transformers (AUD)	Avoided cost (AUD)
P30B3EV0	5,931	654,000	648,069
P30B3EV3	7,179	872,000	864,821
P33B5EV5	27,250	1,962,000	1,934,750

An important aspect worth highlighting, when comparing the use of DERs to the installation of traditional network solutions, is that DER owners can be recruited in a short period of time, as opposed to network expansion that can take many months or even years. Consequently, installing traditional network solutions may not be a viable approach to address foreseen network issues in the near future.

As a final remark, the results show that the RT RIT-D Toolbox identifies the most cost-effective DER owners capable of providing distribution network support services. This information can support DSOs in making investment decisions closer to real-time operations, and with this avoid network augmentations.

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[12] A detailed analysis might consider the rate of increase of DER penetration over the 30 year period.

6 Lessons Learnt

Project Converge produced insights and lessons for future policy and trial initiatives in the DER / DOE space from the development, testing, and trialling of the SOE and RT RIT-D solutions. Our lessons are divided into:

- **General lessons** derived from the development and testing of the SOE and RT RIT-D solutions.
- **Trial lessons** derived from the experience gained during the trialling of SOEs.

There are many broad learnings that have been discussed from similar DOE projects that Converge supports, as well as unique insights from the project development and implementation.

6.1 General Lessons

The key general lessons learnt from the development and testing of the SOE and RT RIT-D solutions are discussed below:

- **Moving beyond current practices:** current DSO practices, such as fixed import and export limits at the customer connection point, are unsuitable for ensuring distribution network security without relying on significant network augmentations. The research of Project Converge shows that SOEs can deliver distribution network security when enough controllable[13] DER capacity is available.
- **SOE benefits:** SOEs produce superior overall system benefits when compared to DOE approaches in offline simulations. However, these benefits only become significant once DER penetration levels get high. This suggests that DOEs may be sufficient in the short term. Therefore, the lessons from Project Converge are useful in providing a pathway beyond DOEs, providing greater clarity for a future scenario where DERs actively participate in wholesale and ancillary markets.
- **Network support pricing:** SOEs create a market mechanism for procuring network support services from aggregators. In Project Converge, network support prices were agreed between the DSO (Evoenergy) and aggregators (Reposit Power and Evergen) before the trials, so that the project could focus on the technical demonstration of SOEs. Future work is required to investigate

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[13] DERs capable of coping with control actions applied by operating envelopes.

the most cost-effective market mechanism to set network support prices in the SOE context, as well as the regulation to govern this[14].

- **Linking DSO functions to market outcomes:** Project Converge proposes a framework consistent with the current market design and re-enforces the need for the expansion and enhancement of DSO functions. The definition of the DSO functions requires further work to ensure consistency across the NEM, particularly when DSO functions move to include approaches, such as SOEs, which link DSO functions to outcomes in wholesale and ancillary markets. Project Converge calls for policymakers to develop regulation[15] to govern market-interacting DSO functions so that all SOE capabilities can be successfully implemented, allowing aggregators to maximise market benefits.
- **Standardisation and consistency:** In the last years, several versions of DOEs with different functions have been proposed and piloted in Australia [16,17]. Discussions with stakeholders around DOEs and SOEs show there is increasing awareness of the concepts, however, knowledge and awareness of the calculation methods, inputs and objectives are still developing. This has created a barrier when discussing concepts, such as DOEs, SOEs, network support and market participation. Greater standardisation and consistency in terminology, definitions and processes will aid research and policy development in key areas.
- **DER-based network support vs network augmentation:** The RT RIT-D toolbox allows us to identify the most cost-effective DER owners capable of providing network support services through SOE programs and with this avoid expensive network augmentations. Our experiments on ACT MV-LV feeders show that using DERs to provide network support is more cost-effective than network augmentation solutions. Project Converge calls for policymakers to develop/change regulation to incentivise DSOs to use DERs instead of network augment solutions when DERs are the most cost-effective solutions. The current regulation does not provide the right incentives for DSOs prioritising the use of DERs or even for aggregators developing business models to provide these network support services. In other words, without the right regulatory environment, DSOs will continue to favour the network augmentation option, since they can only intervene as the regulatory environment allows and their business model incentivises.

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[14] It is worth mentioning that research has been conducted in the DOE space to investigate pricing mechanisms [23].

[15] An example is regulation to govern actions and data flows between aggregators, DSOs, and AEMO, having in mind data privacy and confidentiality.

6.2 Trial Lessons

There are several complex issues arising from the trialling of SOEs, in large part due to the complexity of such task. We learnt several lessons that can be useful to guide future SOE / DOE initiatives. The key lessons are the following:

- **Demonstrated SOE functionalities**: SOEs can deliver network support services, such as voltage regulation and congestion management, as demonstrated in the trials. In the trials, we artificially induced voltage and congestion problems by changing the values of some network components (e.g., tap positions of transformers, voltage limits of buses, or limits of transformers), so we could demonstrate these functionalities.
- **Impact of lack of network support capacity:** SOEs can be used to ensure network security. However, SOEs can only maintain the network within its secure limits if enough controllable DER capacity is available. We observed this in the trials, where not enough controllable DER capacity was available at some times. Because of this, Project Converge calls for the upgrade of DER standards, so that all DERs connected to the network can respond to SOEs and provide network support services when required.
- **Relevance of network data quality:** High-quality network data is key to accurately calculate SOEs since their calculation is done using optimal power flow models. Project Converge calls for the improvement of network data quality. Common issues found in network datasets are for example missing network parameters and inaccurate information about customers' connection points and phases and tap positions of transformers. Some of these issues have been reported across different DSOs in Australia [18].
- **Importance of smart meter data:** Smart meter data is one of the key inputs for the calculation of SOEs. Project Converge calls for the acceleration of the deployment of smart meters so that the uptake reaches 100% as soon as possible.
- **Relevance of high-quality customer-level forecasts:** The calculation of SOEs requires customer-level forecasts, such as active and reactive netload forecasts. Forecasting this data accurately is considerably challenging for aggregators and DSOs since customer-level netload is highly volatile and dependent on weather and human behaviour. In addition, forecasting tools require extensive historical smart meter data, which is not always available. Project Converge identifies as key the development of tools capable of producing high-quality netload forecasts for active and reactive power so that SOEs can better represent the export and import limits of customers.

- **Envelope compliance:** Trial results show that customers do not always comply with the export and import limits set by SOEs. The reasons for this can be diverse, but one of the main causes is due to forecasting errors of netload, known as reservation in the project. In the trials, aggregators provided a reservation point value for each customer, However, they could have provided the reservation as an interval, which could have potentially mitigated the impact of the forecasting errors. Project Converge identified this interval reservation, as a potential solution to mitigate SOE compliance issues. However, aggregators preferred the use of point forecasts for the reservation.
- **Converge API limitations:** The Converge API sets a zero-point limit for the export and import limits of SOEs, meaning that the export limit cannot be specified below zero and the import limit above zero (using a generation is positive convention). In our experiments, we found that removing this zero-point limit can bring benefits to network operation by allowing DER owners to offer a wider range of network support offers.

The Project Converge solution was designed with the complete set of functionalities of the SOE concept in mind. However, the trials only tested the network support functionality due to restrictions imposed by aggregators. To test the complete set of functionalities, aggregators would need to start publishing their wholesale market intentions, so they could be factored in the calculation of SOEs.

References

[1] E. Franklin, K. Alam, R. Amin, M. Negnevitsky, P. Scott, J. Iria, D. Gordon, A. Attarha, S. Thiebaux, Optimal DER Scheduling for Frequency Stability Study Report, 2022. https://arena.gov.au/knowledge-bank/optimal-der-scheduling-for-frequency-stability-study-report/.

[2] Project Symphony, (2021). https://arena.gov.au/projects/western-australia-distributed-energy-resources-orchestration-pilot/.

[3] Project EDGE, (2020). https://arena.gov.au/projects/project-edge-energy-demand-and-generation-exchange/.

[4] Evolve DER Project, (2019). https://arena.gov.au/projects/evolve-der-project/.

[5] P. Scott, J. Iria, D. Gordon, A. Fraser, B. Weise, A. Attarha, S.M.N. R. A., Shaped Operating Envelopes: Technical Design and Implementation Report, 2023. https://arena.gov.au/assets/2023/02/shaped-operating-envelopes-technical-design-implementation-report.pdf.

[6] Mariordo (Mario Roberto Durán Ortiz), BMW i3 home charging, CC BY-SA 4.0 <https://Creativecommons.Org/Licenses/by-Sa/4.0>, via Wikimedia Commons. (n.d.).

[7] iMahesh, An electric transformer, CC BY-SA 4.0 <https://Creativecommons.Org/Licenses/by-Sa/4.0>, via Wikimedia Commons. (n.d.).

[8] Steven Bradley, Braemar Power Station, CC BY-SA 3.0 <https://Creativecommons.Org/Licenses/by-Sa/3.0>, via Wikimedia Commons. (n.d.).

[9] Dagster, (n.d.). https://dagster.io/.

[10] Zepben's Energy Workbench, (n.d.). https://www.zepben.com/solutions/energy-workbench.

[11] S.M.N. R. A., A. Attarha, M. Mahmoodi, J. Iria, D. Gordon, P. Scott, Multi-Step Ahead Electrical Load Forecasting: An Australian Case-Study, (n.d.). https://raw.githubusercontent.com/SeyyedMahdiNoori/converge_load_forecasting_data/main/Forecasting.pdf.

[12] W.E. Hart, C.D. Laird, J.-P. Watson, D.L. Woodruff, G.A. Hackebeil, B.L. Nicholson, J.D. Siirola, Pyomo — Optimization Modeling in Python, Springer International Publishing, Cham, 2017. https://doi.org/10.1007/978-3-319-58821-6.

[13] J. Iria, F. Soares, An energy-as-a-service business model for aggregators of prosumers, Applied Energy. 347 (2023) 121487. https://doi.org/10.1016/j.apenergy.2023.121487.

[14] Australian Energy Market Operator (AEMO), Market Data - NEMWEB, (n.d.).

https://www.nemweb.com.au/.

[15] J. Iria, P. Scott, A. Attarha, D. Gordon, E. Franklin, MV-LV network-secure bidding optimisation of an aggregator of prosumers in real-time energy and reserve markets, Energy. 242 (2022) 122962. https://doi.org/10.1016/j.energy.2021.122962.

[16] J. Iria, P. Scott, A. Attarha, F. Soares, Comparison of network-(in)secure bidding strategies to coordinate distributed energy resources in distribution networks, Sustainable Energy, Grids and Networks. 36 (2023) 101209. https://doi.org/10.1016/j.segan.2023.101209.

[17] Distributed Energy Integration Program (DEIP), DER Market Integration Trials Summary Report, 2022. https://arena.gov.au/knowledge-bank/deip-der-market-integration-trials-summary-report/.

[18] M.Z. Liu, A. Simonovska, L.F. Ochoa, P.K.C. Wong, K. Chew, J. Theunissen, Validating real LV feeder models using smart meter data: a practical experience from project EDGE, in: 27th International Conference on Electricity Distribution (CIRED 2023), Institution of Engineering and Technology, 2023: pp. 1924–1928. https://doi.org/10.1049/icp.2023.1074.

[19] Zepben's evolve SDK, (n.d.). https://zepben.github.io/evolve/docs/python-sdk/0.37.0/.

[20] SmartGridToolbox software, (n.d.). https://gitlab.com/SmartGridToolbox/SmartGridToolbox.

[21] The University of Melbourne, Project EDGE Research Plan, (2022). https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/der-demonstrations/project-edge.

[22] A. Attarha, P. Scott, J. Iria, S. Thiebaux, Network-Secure and Price-Elastic Aggregator Bidding in Energy and Reserve Markets, IEEE Transactions on Smart Grid. 12 (2021) 2284–2294. https://doi.org/10.1109/TSG.2021.3049464.

[23] A. Attarha, M. Mahmoodi, S.M.N. R. A., P. Scott, J. Iria, S. Thiébaux, Adjustable Price-Sensitive DER Bidding Within Network Envelopes, IEEE Transactions on Energy Markets, Policy and Regulation. 1 (2023) 248–258. https://doi.org/10.1109/TEMPR.2023.3303911.

Appendix A Network Data

Network data was provided by Evoenergy to Zepben which made CIM-compliant network models available via the energy workbench platform [10]. The network models cover ACT, across high voltage, MV, and LV network areas.

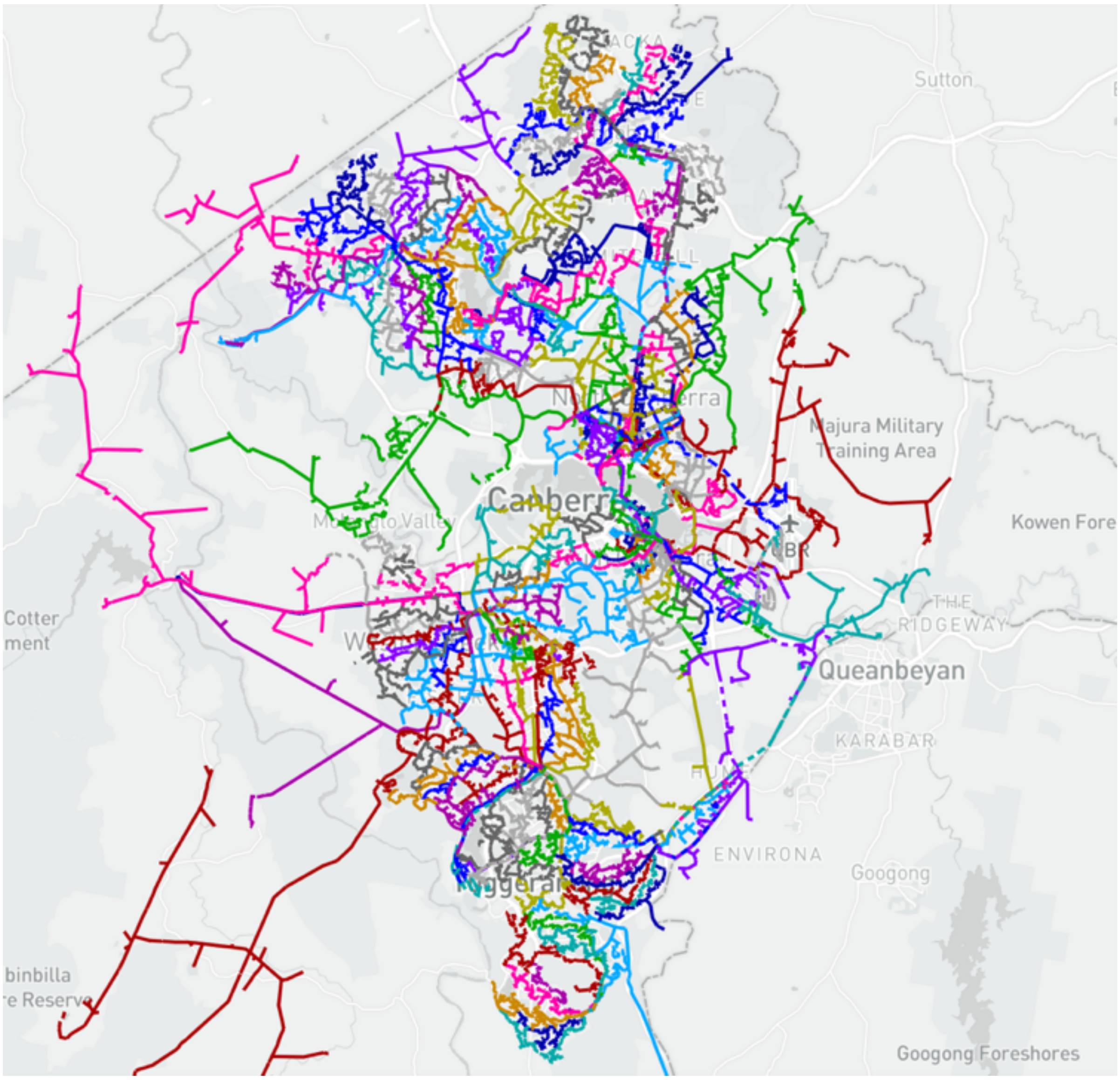


Figure 31. A screenshot from Zepben's energy workbench platform, showing the extent of the modelled network. For clarity, only high voltage and MV lines are shown. Lines are coloured according to the feeder.

In Project Converge, we worked only with MV-LV feeders. These consist of downstream network equipment originating at a zone substation. There are 241 such feeders in the dataset. Each feeder was treated completely independently as far as calculations were concerned, and in what follows we describe the process used for extracting and processing network data for a single feeder.

We began by extracting feeder data, using Zepben's Evolve SDK [19]. This resulted in a CIM compliant representation of all objects and connections in the network. Network data of interest typically included the following objects:

- **Infeeder (zone substation):** voltage settings, etc.
- **Transformers:** vector group, transformer ratio, phasing, tap configuration and settings, power rating, series, and shunt impedances, etc.
- **Lines:** phasing, presence of a neutral, thermal rating, series impedance characteristics, length, shunt impedance, etc.
- **Switches and protection:** switch type, switch state, etc.
- **Loads (aggregated to a connection point):** phasing, associated customers (NMIs), etc.

We then translated this model from Zepben's python model into an internal data format (e-JSON), which was used in our software tools.

Various data sanitisation and processing steps were then applied:

- The network was audited for issues, and these were fixed where possible. Such issues included missing base voltages at network nodes, inconsistent phasing, and missing line impedances.
- Various processing steps were applied to normalise the network:
    - elements were ordered from the substation downwards,
    - unconnected or islanded sections were removed,
    - standard base voltages were applied (22 kV / 11 kV / 230 V), and various quantities were updated in terms of these standard voltages,
    - voltage limits were added to all nodes (-6% - +10% for LV, -10% - +10% for MV), and
    - loads were separated on a per-customer (NMI) basis.
- Special location-specific fixes were then applied to the network. For example, the LATHAM_8TB_LWMLNGLOW feeder has an issue with how the loads in a water treatment plant are modelled. We chose to delete this load.
- Another issue was transformer taps. The network models come with static tap settings supplied, but due to the occasional manual shifting of taps and other factors, there was some concern about their accuracy at any given time. We took the approach of assuming that taps were already in near-optimal positions

before calculating envelopes. To apply this assumption, a tap optimisation algorithm was used to set taps so voltages could be maintained with the allowable band as nearly as possible over several months.

- Finally, we chose to work with a balanced, radial version of the network. This involved reducing the three-phase model to a single-phase equivalent. The choice to work with a single-phase/balanced reduction was not so much reflective of the limitations of our calculations but was rather a response to the lack of reliable phasing data in LV distribution networks.

The resulting 241 feeders were validated at various points during the project, mainly using load flow studies carried out using ANU's SmartGridToolbox software [20]. Initial validation showed that most of these networks were amenable to a power flow solution, but with varying degrees of issues with very high or low voltages, for example.

In our studies, we narrowed the list of feeders to the following five: CITYEA_8LB_EBDEN; CIVIC_8FB_BELCWAYSTH; WANNIA_8KB_BISSHAWK; LATHAM_8TB_LWMLNGLOW; and WODEN_8_NB_STREETON. The main characteristics of these feeders are presented in Table 1, and their visual representations are illustrated in the figures below.

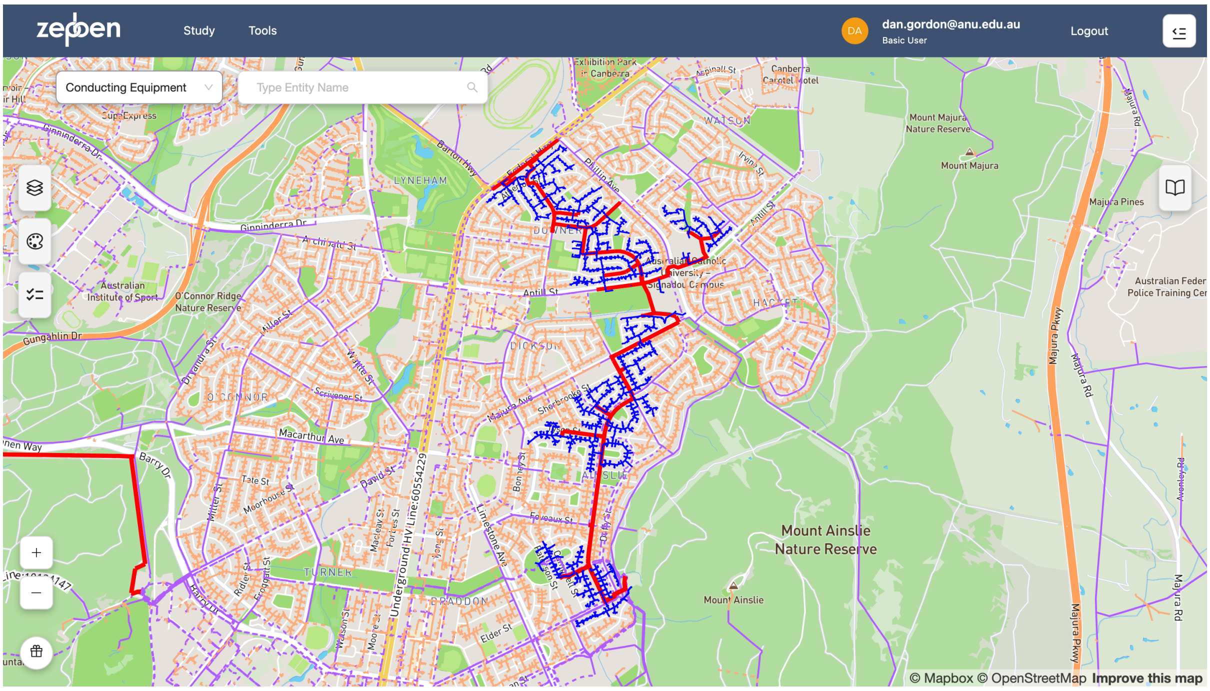


Figure 32. CITYEA_8LB_EBDEN feeder. Blue and red lines denote LV and MV lines, respectively.

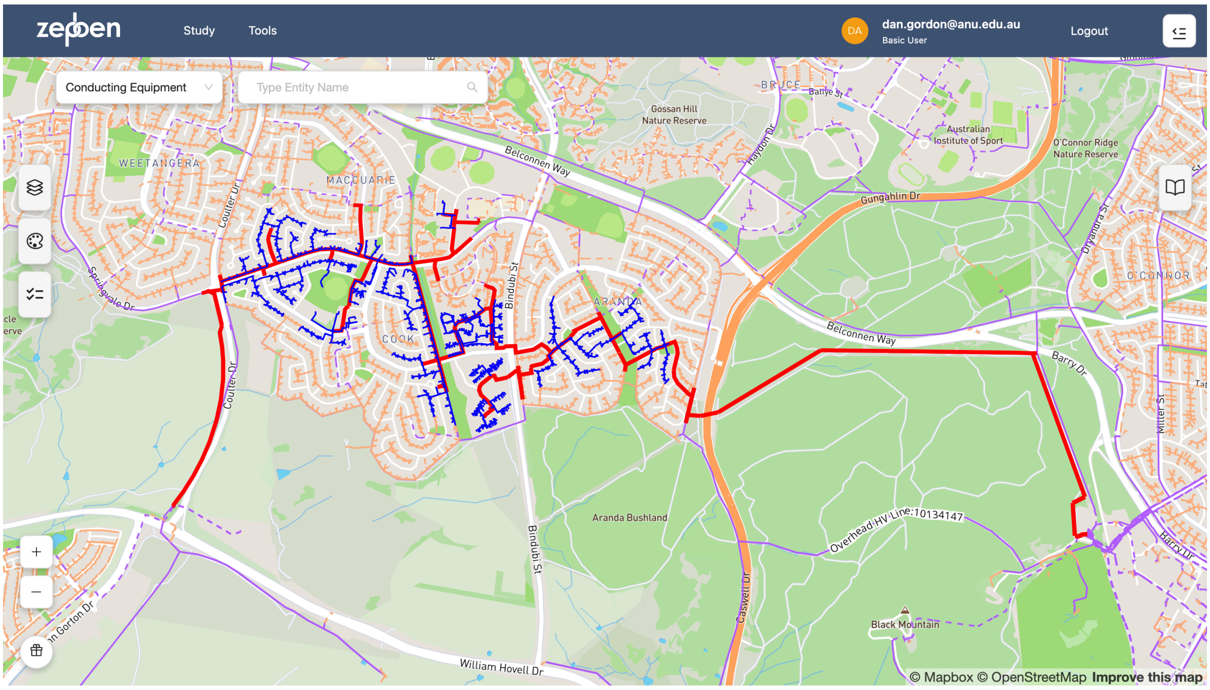


Figure 33. CIVIC_8FB_BELCWAYSTH feeder. Blue and red lines denote LV and MV feeders, respectively.

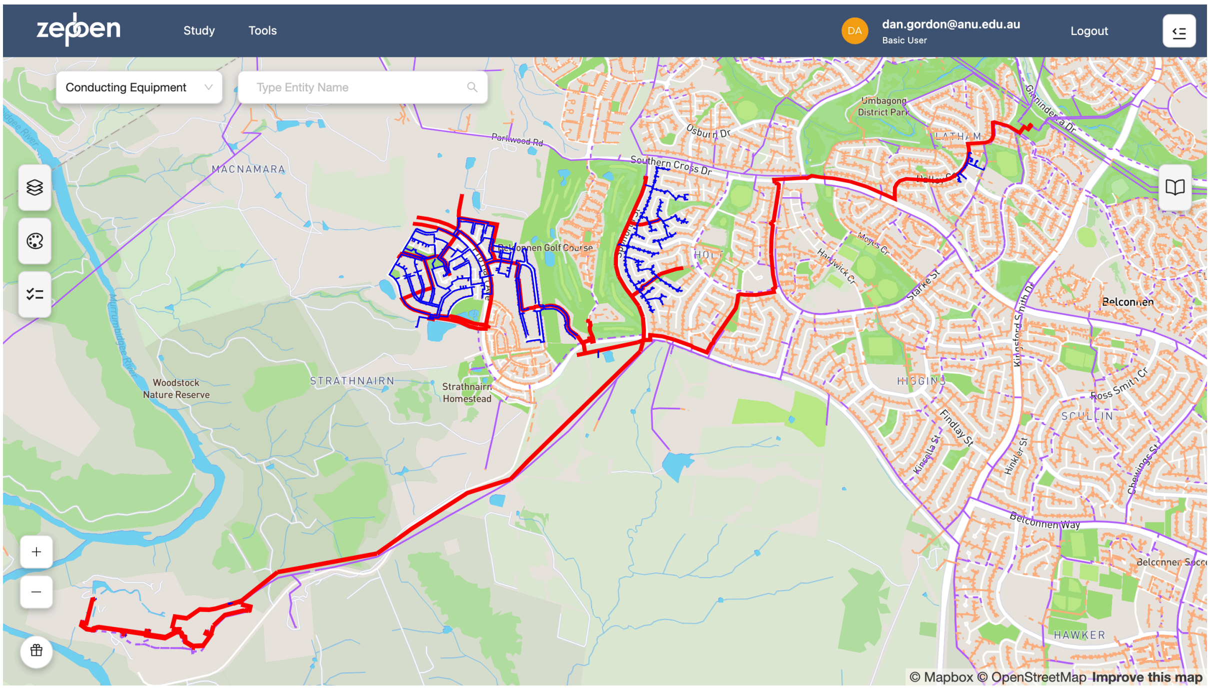


Figure 34. LATHAM_8TB_LWMLNGLOW feeder. Blue and red lines denote LV and MV feeders, respectively.

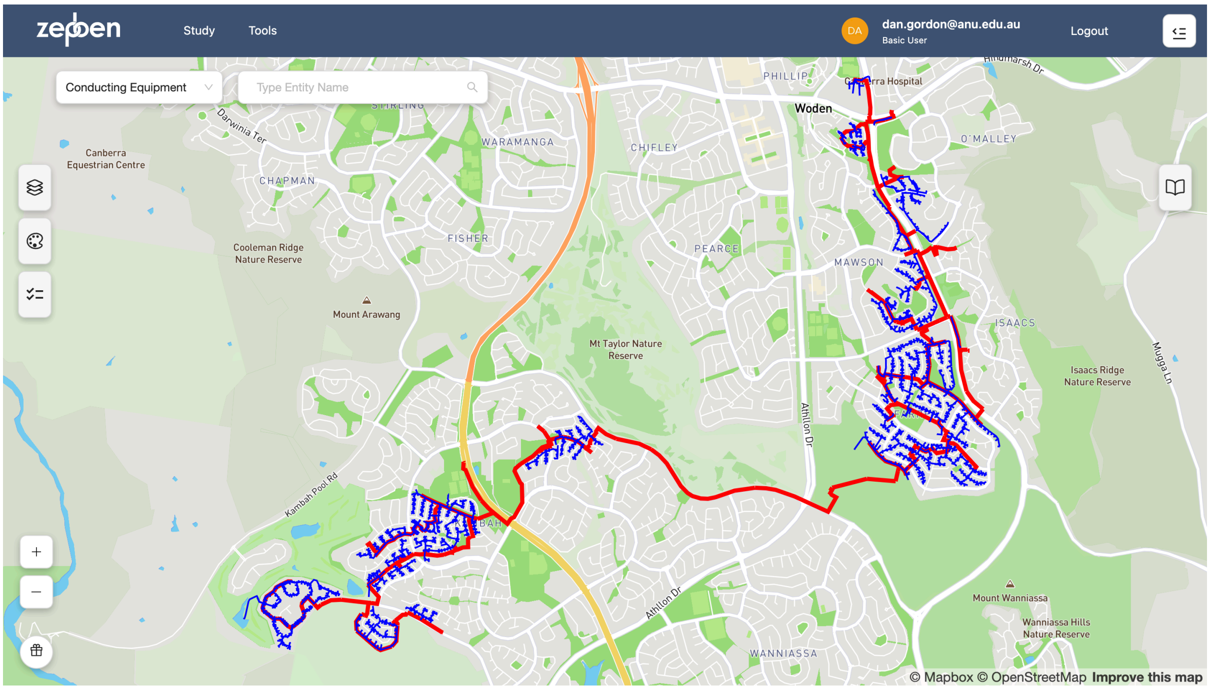


Figure 35. WANNIA_8KB_BISSHAWK feeder. Blue and red lines denote LV and MV feeders, respectively.

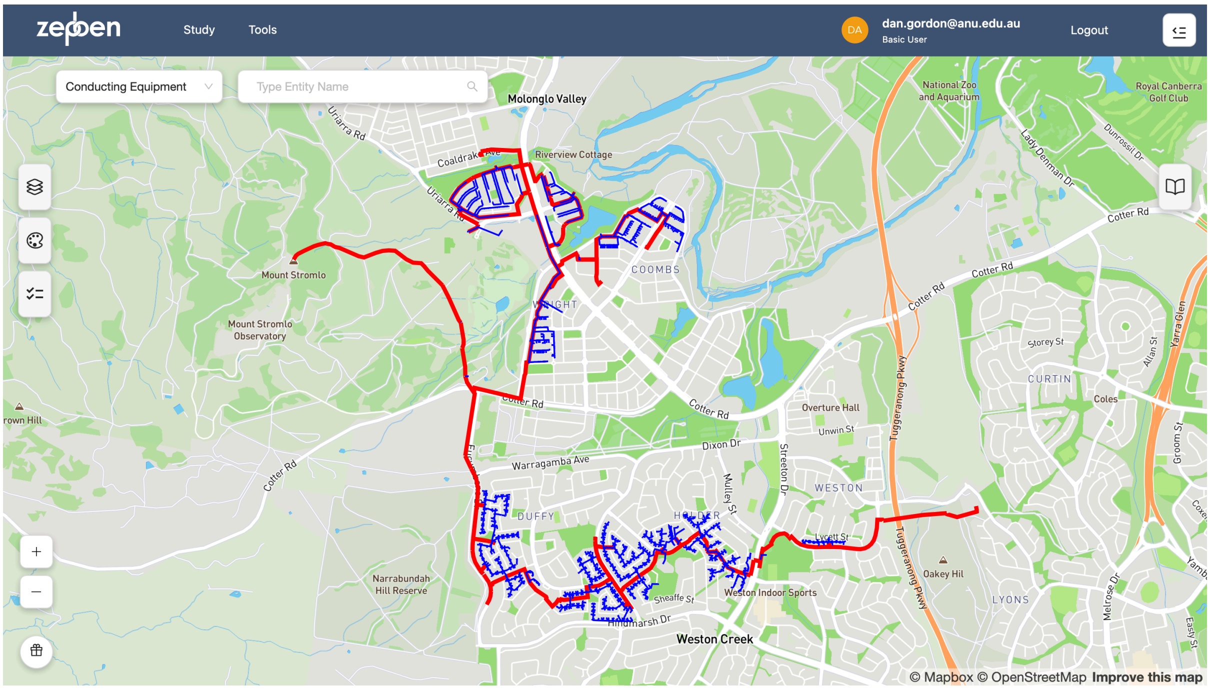
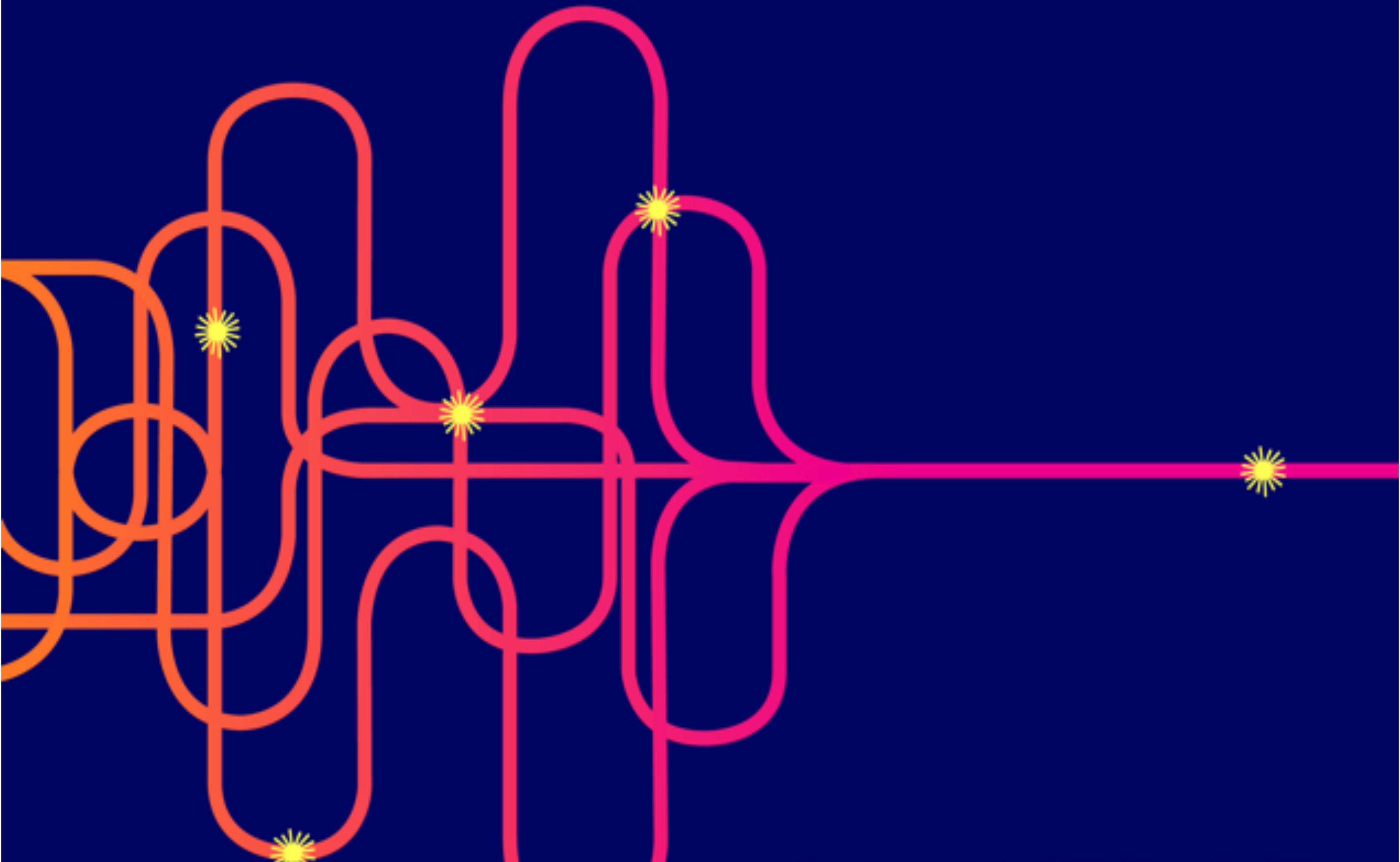


Figure 36. WODEN_8_NB_STREETON feeder. Blue and red lines denote LV and MV feeders, respectively.



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