Shaped Operating Envelopes

Technical Design and Implementation Report

Prepared by

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CONVERGE

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Disclaimer

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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
CSIP	Common Smart Inverter Profile
DER	Distributed Energy Resources
DOE	Dynamic Operating Envelope
DNSP	Distribution Network Service Provider
DSO	Distribution System Operator
FCAS	Frequency Control Ancillary Services
FOE	Fixed Operating Envelope
IP	Internet Protocol
LV	Low Voltage
MV	Medium Voltage
NEM	National Energy Market
NMI	National Meter Identifier
NSW	New South Wales
OPF	Optimal Power Flow
SOE	Shaped Operating Envelope
PV	Photovoltaic
VPP	Virtual power plant
TLS	Transport Layer Security

Executive Summary

Project Converge is exploring an approach to calculating operating envelopes that factors in and integrates aggregator / customer preferences, the value of the wholesale market services they offer, and network support. The outcome is what we refer to as *shaped* operating envelopes, to reflect the fact that the operating envelopes are shaped by these values that go beyond pure network constraint management.

This report presents the shaped operating envelope concept, an overview of its implementation in the project and simulations to illustrate the potential benefits over a more conventional approach to operating envelopes. The second half of the report establishes a set of metrics that will be used for evaluating its performance in upcoming network trials, as well as addressing cybersecurity risks and some early lessons for future policy development in this space.

1 Concept

Dynamic operating envelopes (DOEs) are a class of techniques for allocating constrained distribution network capacity to aggregators and / or end customers. The key feature is the calculation and allocation of time-varying power envelopes either per customer or for regional aggregates of customers. With an appropriate allocation across many participants, DOEs can ensure the network does not become overloaded by distributed energy resources (DER).

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 DER have to act and how well-utilised the network is.

Shaped operating envelopes (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 DER. The concept comes out of 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 capabilities of the SOE concept and will implement it for live testing on Evoenergy's network in the ACT.

The improvements of SOEs over DOE proposals and implementations in related projects (Project Symphony [2], Project EDGE[1] [3], Evolve DER Project [4]) include:

1. The allocation of envelope capacity that jointly accounts for and balances:
    a) aggregator (and hence customer) intentions and preferences;
    b) benefits to wholesale market performance; and
    c) simple measures of envelope fairness.
2. The automatic 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 DER and 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

[1] The Project EDGE *Horizon 3* DOE proposal discussed in [12] has similar goals for optimising market participation with a more tightly coupled AEMO integration.

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

In the following, we discuss at a high level the key steps of the SOE calculation. We do this from the perspective of a "distribution system operator" (DSO) which encapsulates the capability that is being built in the project within Evoenergy, Zepben, and the 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. The implementation of the project is discussed more in the design and implementation section of the report.

1.1 Overview

The SOE framework has three key steps as presented in Figure 1. These steps run online every 5 minutes prior to the wholesale market dispatch. Day-ahead and pre-dispatch are also possible and will be discussed in the design and implementation section. The steps are:

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

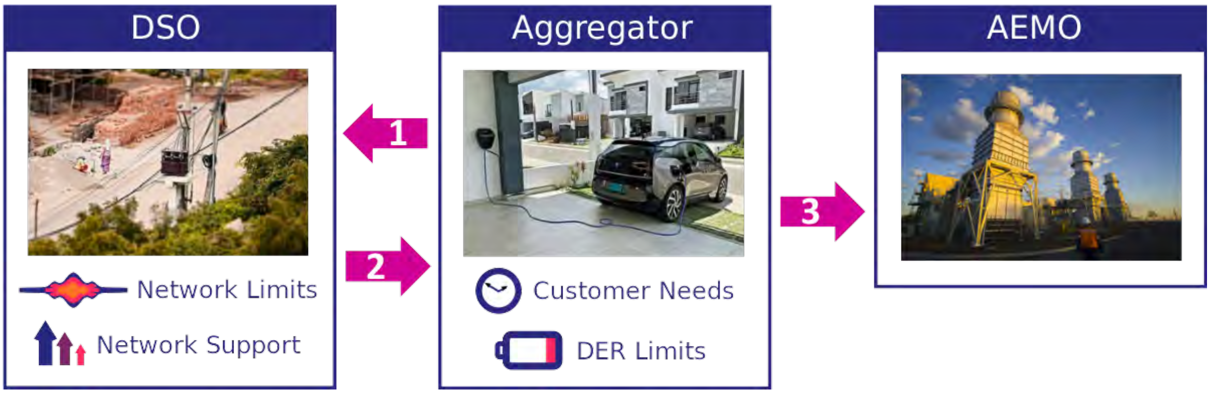

Figure 1. The flow of information for the key three steps of the SOE framework. Images sourced from [5–7].

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

1.2 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[2]. Each aggregator also sends a plan for how their customers individually will contribute to delivering the offered market services. For each NMI (National Meter Identifier) this plan is made up of:

- capacity contribution to each market and network support bid band; and
- forecast uncontrolled consumption / production (+ optional confidence interval).

This information allows the DSO to effectively disaggregate the wholesale bids, from NEM regions down to the LV distribution network level, enabling a more targeted optimisation of the envelopes to meet constraints within the distribution network.

1.3 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 (OPF) problem – a type of constrained optimisation problem that models network power flows and operating limits. We refer to this calculation as *shaping*[3] the bids and operating envelopes, with the outputs being **shaped rebids** and **shaped operating envelopes**.

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 NMIs of similar type.

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[2] Separate network support availability is not necessary if an aggregator is actively participating in the wholesale energy market, as is discussed in the design and implementation section.

[3] This terminology comes from the geometric interpretation of bids and operating envelopes that is sometimes employed to explain concepts. E.g., the bid *trapeziums* 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.

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

As part of this calculation, distribution network support instructions may be provisioned for customers where this will improve the objective. These instructions are a redirection of a part of the customer's energy market bid capacity toward network support (that will be provided irrespective of the energy market outcome). This is a form of short-term network support that is either compensated at one of several market-derived rates or based on pre-negotiated rates. The cost of this network support is factored into the SOE calculation.

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

1.4 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. In order to avoid manipulation, the resulting rebids must be *consistent* with the SOEs and the original bids that the DSO based its calculation on.

2 Design and Implementation

This section explores the SOE design in greater detail, focusing on the timing of communication and the data exchanged between aggregators and a DSO entity. The project implementation to date is also presented.

2.1 Timing

The three steps of the SOE algorithm run prior to every 5-minute wholesale market dispatch interval. In the following we label an arbitrary dispatch interval as **TD** and make use of the following times:

- **T1**: Latest time aggregator can send data to DSO as part of Step 1.
- **T2**: Latest time DSO can send data to the aggregator as part of Step 2.
- **T3**: Latest time aggregator can send data to AEMO as part of Step 3.

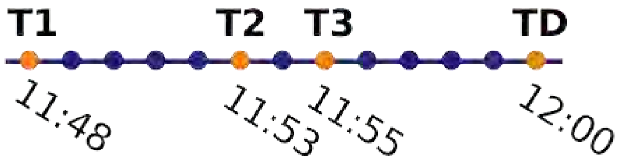

Figure 2. Relationship between important times T1, T2, T3 and TD using 12:00 as the dispatch interval.

Figure 2 shows the relationship between these times with example timestamps for a dispatch interval TD at 12:00. Note that the timestamps are for illustrative purposes only as the project will determine appropriate values for them.

The durations between these times are constrained in the following ways on top of communication delays:

- **TD − T3**: Minimum notice AEMO will accept for a rebid in relation to distribution network constraint management.
- **T3 − T2**: Maximum time aggregators require to process rebid and send to AEMO.
- **TD − T2**: Maximum time aggregators need to process and send envelopes to customers.

- **T2 − T1**: Maximum time the operating envelope engine needs to process input and run optimisation of operating envelopes.

The above hints at an online operation of the SOE approach where AEMO only becomes aware of the network effects on aggregator bids a short time (T3) prior to the dispatch interval. The concept can be extended to additionally calculate day-ahead and predispatch values to provide AEMO greater notice of distribution network effects. This will only become important for AEMO operations when DER and their market participation are deployed at scales where network constraints start to influence market prices. This will not be the case for the trials in this project, so we choose to simplify the presentation by focusing on the details of the online component of the proposal.

2.2 Data Flows

This section summarises the data that is communicated between aggregators, DSO and AEMO before giving a more detailed account of the data formats and contents. We omit data relating to the registration of customers and more slowly evolving or static information. Instead, we focus on the daily and intra-day data that is critical for the SOE operation.

The key data flows are listed below. From the perspective of a market participating aggregator, the significant *new* information they will need to gather and communicate is contained in D3 and D4.

- **Setup: Aggregator → DSO**
    - **D1. Day-ahead market bids**
      prices, capacities and inter-market constraints
- **Step 1: Aggregator → DSO**
    - **D2. Market rebids**
      updated capacities and inter-market constraints
    - **D3. Customer contributions**
      capacity contribution to each bid band for each customer
    - **D4. Customer reservations**
      interval of uncontrolled power and uncertainty for each customer
- **Step 2: DSO → Aggregator**

- **D5. Shaped rebids**
  updated capacities and inter-market constraints that reflect network constraints
- **D6. Shaped operating envelopes**
  operating envelope for each customer
- **D7. Network support**
  network support request for each customer

- **Step 3: Aggregator → AEMO**
  - **D8. Final rebids**
    shaped rebids of D5, forwarded to AEMO

2.2.1 Data formats

Aggregate market bids and rebids will be communicated to the DSO (in this project the Converge platform) leveraging AEMO's existing bid submission formats. This simplifies the implementation for aggregators who already integrate with AEMO's formats. In many cases, aggregators will have the option to simply duplicate existing messages and send them to the DSO (D1 and D2) or forward messages from the DSO to AEMO (D5 forwarded in D8).

The remaining data flows are per-customer. Project Evolve [4] has created a proposal to include operating envelopes in the 2023 version of the IEEE 2030.5 standard, which we intended to use as an extension for D6. While the remaining customer data D3, D4 and D7 could fit into further 2030.5 extensions, we propose for this project a separate and simpler REST API exchanging JSON. As of writing the specification is not finalised. We intend to release it and any learnings at the end of the project to inform future standardisation efforts.

In the following proposal, the DSO hosts a server with endpoints that aggregators interact with (the clients). As such the "Message" entries are written from the perspective of an aggregator.

2.2.2 D1. Day-ahead market bids

- Timing: Once a day, day-ahead
- Message: POST "submitBidsRequest" JSON (as defined by AEMO)

Day-ahead market bids sent to AEMO are also sent to the DSO. This includes the various market bid stack prices and quantities as well as cross-market constraints (e.g., FCAS trapeziums [8]).

Network support can be calculated using the wholesale energy market bid information as a reflection of the aggregator's preferences and capacity. However, in the case that an aggregator is not participating in the wholesale energy market (i.e., all aggregators in our trials), a separate mechanism to set network support prices is provided by the DSO. This takes the form of a day-ahead message that registers a set of up to 10 price bands for each network support direction: injection and consumption.

2.2.3 D2. Market rebids

- Timing: Ongoing as required, prior to T1 for upcoming interval
- Message: POST "submitBidsRequest" JSON (as defined by AEMO)

Any intra-day rebids sent to AEMO are also sent to the DSO. These will typically include adjustments to the quantities offered in each bid band and any additional constraints or capacity adjustments. The latest that the DSO can accept an update for the upcoming dispatch interval is T1.

The bids should be as granular as possible. That is, they would preferably be issued per feeder or even per category of DER per feeder. However, due to current market rules around minimum bid capacities, this might not be possible to test in this project. Instead per TNI or even regional bids for each aggregator will be used. This reduces the flexibility of the SOE calculation.

2.2.4 D3. Customer contributions

- Timing: Once per dispatch interval prior to T1
- Message: POST project-specific JSON with customer contributions

These contributions represent the capacity contribution of each customer to each market bid band. For each bid band, they should sum across all customers to a value equal to the aggregate band capacity, or a lesser value if the aggregator has other systems contributing to the band not participating in SOE.

An aggregator might want to over-subscribe their customers to a given market service. E.g., if an aggregator gets dispatched for 1MW of FCAS 6s raise, they might enable 1.2MW worth of systems so that statistically they guarantee at least 1MW after any failures. If this is the case, they can provide an additional number for each customer and market service called the *buffer multiplier.* It is a number greater or equal to 1 that represents the ratio between the power that needs to be enabled to achieve the power offered to the market.

2.2.5 D4. Customer reservations

- Timing: Once per dispatch interval prior to T1

- Message: POST project-specific JSON with customer reservations

The final component that an aggregator sends through is an interval that represents the uncontrollable or un-bid load / generation of each customer. It is an interval instead of a single number to allow aggregators to account for uncertainty. At its simplest, this can just be a forecast of the customer's uncontrolled load / generation for each 5-minute dispatch interval (e.g., 1kW production). If the aggregator is not confident in this forecast, they can reserve an interval of powers (e.g., from 1kW load to 3kW production).

This interval is considered in the SOE calculation. All else being equal, customers with wide intervals, representing inaccurate / highly uncertain estimates, will be more likely to have their market offers curtailed when the network reaches its limits. This indirectly provides a financial incentive for aggregators to submit more accurate reservation intervals.

2.2.6 D5. Shaped rebids

- Timing: Once per dispatch interval prior to T2
- Message: GET “submitBidsRequest” JSON (as defined by AEMO)

These rebid instructions represent how the aggregator needs to rebid its market bid band capacities in order to be consistent with the operating envelopes of its customers in D6. Following a set of rules, it would typically be possible for an aggregator to determine these shaped rebids on their own from the envelopes in D6. However, to simplify things and cover the general case the DSO will provide these as output from the SOE calculation.

This rebid is what the aggregator will forward to AEMO as the final rebid for the upcoming interval in D8. If network constraints are not active for the customers contributing to the market offering, then rebidding will not be necessary and the standing bids with AEMO can be used.

2.2.7 D6. Shaped operating envelopes

- Timing: Once per dispatch interval prior to T2
- Message: IEEE 2030.5-2018 with proposed 2023 operating envelope extension

These are per-customer operating envelopes which are an upper and lower limit on net real power transfer for the upcoming dispatch interval.

2.2.8 D7. Network support

- Timing: Once per dispatch interval prior to T2

- Message: GET project-specific JSON with network support

This communicates the network support each customer needs to provide as a positive or negative amount of real power for the upcoming dispatch interval. This capacity is reallocated from the customer's energy or network support bid capacity. Customers might not need to explicitly act on this signal, as remaining within their operating envelope (which already factors network support in) is sufficient to provide the requested network support.

Aggregators / customers will be remunerated based on the quantity of network support requested and the network support or energy market price bands they registered. The impact of settled wholesale energy prices will also be factored in if the aggregator is exposed to them.

Network support is required only in circumstances where the operating envelopes are restricted to the point of excluding some part of the customers' reservation interval. In these circumstances, in order to obey the operating envelope, the customer's DER might have to be dispatched in a way that runs counter to wholesale market dispatch. As such this capacity is reserved for network support purposes, and its provision is compensated.

2.2.9 D8. Final rebids

- Timing: Once per dispatch interval prior to T3
- Message: POST (to AEMO) "submitBidsRequest" JSON

Final rebids are sent to AEMO for the upcoming interval. These can be the shaped rebids from D5, or they can be recalculated by the aggregator in a way that is consistent with their SOEs (and the original bids they submitted to the DSO for SOE calculation).

2.3 Implementation

This section provides an overview of the internal systems of what we have been calling the DSO. The DSO function is performed by Evoenergym which operates the Converge platform. Figure 3 shows an overview of the architecture, emphasising the Converge-specific components.

A central database ("Converge Database") stores input, intermediate and output data. Input data stored in this database is taken from aggregator systems, Evoenergy's systems and other external sources. It comprises the following:

- Aggregator data, including per-NMI DER system information and per-NMI and aggregate network support price offers and market bids. This data is sourced from aggregators via the existing Evolve 2030.5 architecture and additional Converge-specific API calls;

- Load interval data sourced both from Evoenergy's smart meter data, as well as aggregator telemetry;
- Static data for loads sourced from Evoenergy's smart meter data;
- Market data sourced from AEMO;
- Weather time series data sourced from Visual Crossing.

Input data is gathered independently for each data source, using a modified version of the system that was first developed for Project Evolve [4].

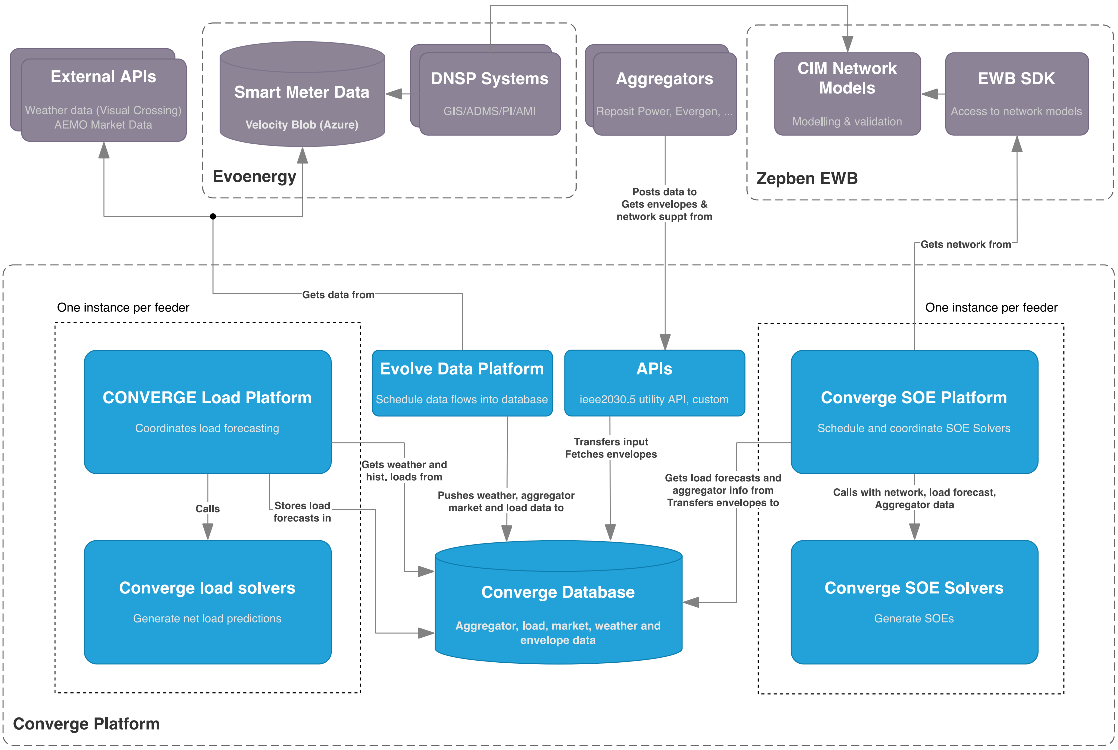

Figure 3. Overview of the Converge architecture. The Converge platform is shown with blue boxes, and external components are shown in grey.

Based on the stored load interval and weather data, load forecasts are then developed to cover the coming five-minute horizon. These forecasts are intended to cover all loads in the feeder of interest. The scheduling of load forecasting is handled by the Converge Load Platform shown to the left of the diagram. Forecasts are stored in the Converge database. In the case where detailed forecasts cannot be produced, a fallback forecast is provided instead. This may be an older (stale) forecast or even a rough forecast based on long-term averages.

The Converge SOE platform is responsible for scheduling and calculating the SOEs. In addition to the input data mentioned above, it requires network models. These are sourced from Zepben's EWB (Energy Workbench) platform, communicated via the GRPC protocol using Zepben's EWB python SDK. The network models are provided in a CIM-compliant form. They ultimately derive from Evoenergy's GIS and other systems. At the time of writing, Project Converge can successfully extract and process 227 out of 238 MV/LV feeders in the ACT.

For each 5-minute horizon, the Converge SOE platform generates envelopes and network support dispatch instructions for all DER participants. This information is again stored in the database and is provided to the aggregators via an API call initiated by the aggregators, either as an extension of the ieee2030.5 API or as a custom API call.

3 Examples

This section provides examples and simulations that demonstrate the capability of SOEs to manage network constraints while maximising market access for aggregators. It is contrasted with the behaviour of a simpler DOE calculation.

We start off with some small unrealistic but illustrative examples to build the intuition behind an SOE solution. We then jump to simulations involving hundreds of customers on real distribution feeders to demonstrate the relative benefits over alternatives.

3.1 Simple Examples

We start with a simple two-customer system as shown in Figure 4. These customers, labelled **A** and **B**, share a constrained network that requires the combined power flows to remain between 12 kW import and 12 kW export. We assume there are two aggregators, one for each customer.

In the following examples, we vary the aggregator market bids and customer reservations and compute the shaped operating envelopes and shaped reservations. In the illustrations, the symbols **[ ]** represent the lower and upper extremes of the shaped operating envelope interval, and the symbols ↓ ↑ represent the lower and upper extremes of the reservation interval.

Most examples only contain a single market bid and bid band per customer, and customers submit reservations of 0, 0 – a zero-width interval at 0 which equates to a situation where customers do not have any uncontrolled load or generation.

The envelope calculation needs to ensure that the 12 kW network limit is not exceeded. In this simple example, this translates to distributing the 12 kW of capacity between the two customers, in both the positive (generation) and negative (load) directions.

3.1.1 Example 1: Identical bids

A: 10 kW @ 10 ¢/kW, **B**: 10 kW @ 10 ¢/kW both 6-sec Raise

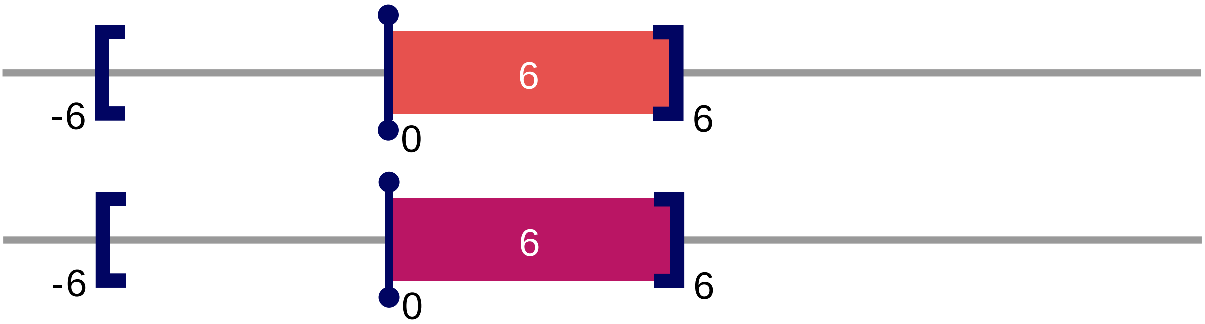

Figure 4. Example 1 – Identical bids.

In this first example, both **A** and **B** are bidding 10 kW at a price of 10 ¢/kW into the 6-sec Raise FCAS market. The resulting shaped operating envelopes and shaped bids are illustrated in the figure above for **A** and then **B**. Both are given a shaped envelope from -6 kW (load) to +6 kW (generation). To conform to this, their 10 kW raise bids are curtailed down to 6 kW each.

The two customers are identical, so it makes sense for them to have identical operating envelopes. The SOE optimisation sees that the bids offer the same value to the market, so the secondary objective to keep operating envelopes similar is dominant in this example.

Note that network capacity is still allocated on the negative side of the operating envelope despite no intentions for the customers to operate in that region. There is no reason not to allocate the capacity and it gives the customer some leeway if unforeseen uncontrollable loads materialise.

The outcome is the same that a simpler DOE would achieve. If customers are identical, then the extra market bid and reservation information cannot do anything to improve the outcome in the SOE calculation. It is only when there is some heterogeneity in customers, aggregators or the network that we expect a benefit over a simpler DOE. We will explore these cases next.

3.1.2 Example 2: Asymmetric bid quantities

A: 4 kW @ 10 ¢/kW, **B**: 10 kW @ 10 ¢/kW both 6-sec Raise

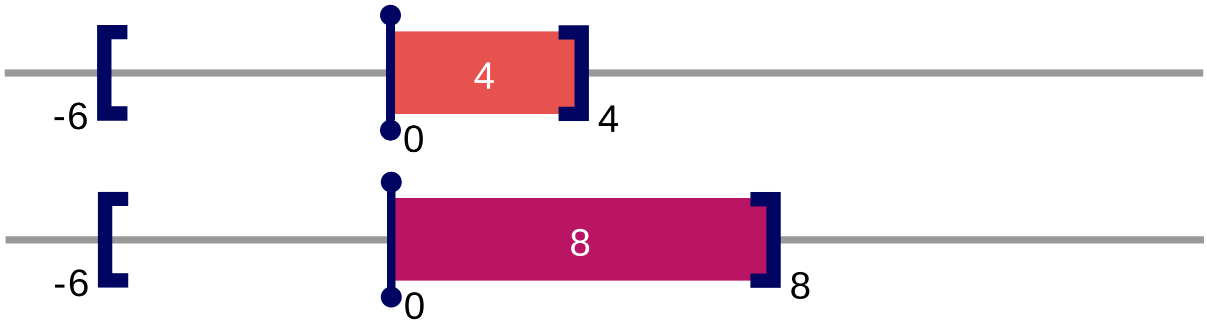

Figure 5. Example 2 – Asymmetric bid quantities.

The aggregator for **A** now only wants to bid 4 kW into the market. In practice, such an asymmetry between aggregator bid capacities could be the result of different DER capacities, state of charge, customer behaviour or aggregator bidding strategies. As the prices are the same, the fairness objective again tries to keep both customer envelopes similar; however, it will not waste envelope capacity on **A** that it cannot utilise so it stops at +4 kW.

The SOE outcome results in a total of 12 kW of 6-sec Raise making it to market across both aggregators. A simpler DOE approach does not have access to the bidding intentions of aggregators and therefore would likely allocate +6 kW envelopes to both customers, resulting in only 10 kW of 6-sec Raise making it to market.

3.1.3 Example 3: Asymmetric prices

A: 10 kW @ 30 ¢/kW, **B**: 10 kW @ 10 ¢/kW both 6-sec Raise

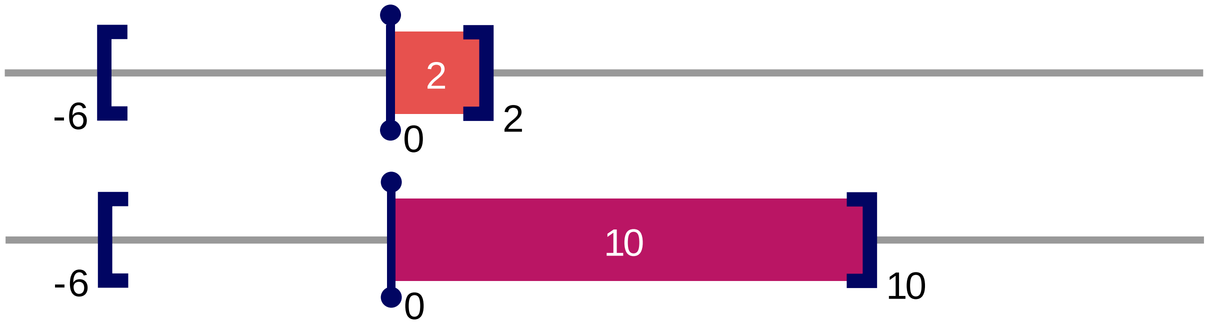

Figure 6. Example 3 – Asymmetric prices.

A's bid price is now much higher and is therefore less competitive in the market. For this reason, the SOE calculation favours allocating more capacity to **B**. A simpler DOE envelope would give equal capacity to each aggregator, which will mean a less competitive market offering and potentially underutilised network capacity if market prices are modest.

As discussed previously, the SOE calculation strikes a tuneable balance between market efficiency and the similarity of envelopes. In the above example, there is an extreme price difference where **B** gets all the capacity it requests. However, if **A**'s bid price was instead 12 ¢/kW, the calculation might provide **A** with a more comparable share of capacity (e.g., a 5 kW to 7 kW split instead of 2 kW to 10 kW). Ultimately this trade-off can be fine-tuned by the DSO to meet a set of principles or regulatory requirements.

3.1.4 Example 4: Energy and FCAS bids

A: 5 kW @ 3 ¢/kWh Load, **B**: 15 kW @ 5 ¢/kW 6-sec Raise, 15 kW @ 10 ¢/kWh Generation

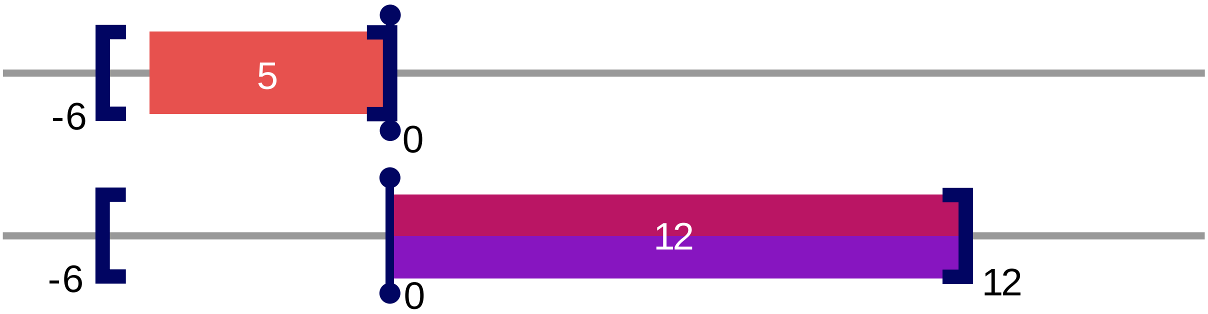

Figure 7. Example 4 – Energy and FCAS bids.

This example has a mixture of energy market (**A** Load, **B** Generation) and FCAS (**B** 6-sec Raise) bids. One extra piece of information not shown is that **B** has published cross-market constraints that restrict AEMO's market clearance so that the sum of the accepted generation and FCAS raise bids cannot exceed 15 kW. This is a common constraint that market participants can submit as part of their FCAS "trapeziums". The SOE calculation can account for these effects as illustrated above with the shaped energy and FCAS bids in parallel when fitting them into **B**'s envelope. With this result, the cross-market constraint will have to be updated so that AEMO is limited to accepting offers that sum to at most 12 kW.

3.1.5 Example 5: Network support

A: 5 kW @ 3 ¢/kWh Load, **B**: 15 kW @ 5 ¢/kW 6-sec Raise, 15 kW @ 10 ¢/kWh Generation

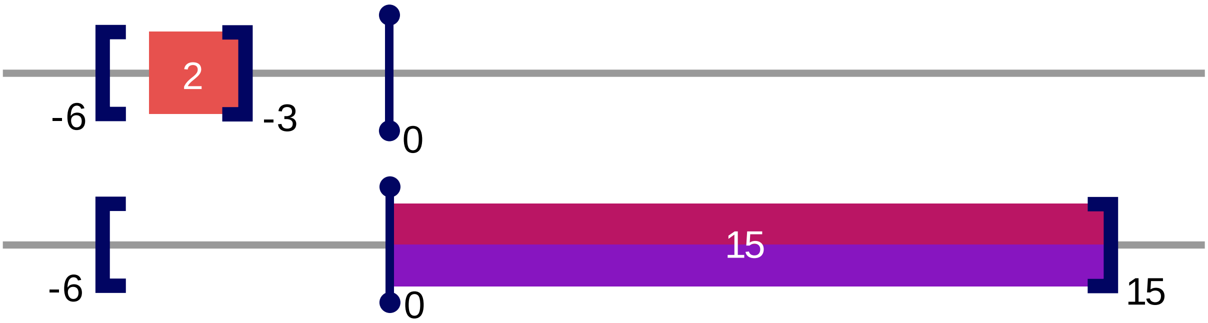

Figure 8. Example 5 – Network support.

This is the same set of bids as the previous example. The difference is that we assume that **A** has agreed to provide network support and that the market conditions are such that the benefit of maximising **B**'s access will be worth the network support cost. Network support materialises in the form of **A**'s operating envelope no longer containing the customer's reservation. To achieve this, 3 kW of capacity from **A**'s bid for scheduled load in the energy market must be redirected towards network support. To cover **A**'s opportunity cost, their network support should be compensated at a rate of at least 3 ¢/kWh (depending on settled market prices).

3.1.6 Example 6: Customer reservations

A: 10 kW @ 10 ¢/kW 6-sec Raise, **B**: 10 kW @ 10 ¢/kW 6-sec Raise, 3 kW @ 1 ¢/kW 6-sec Lower

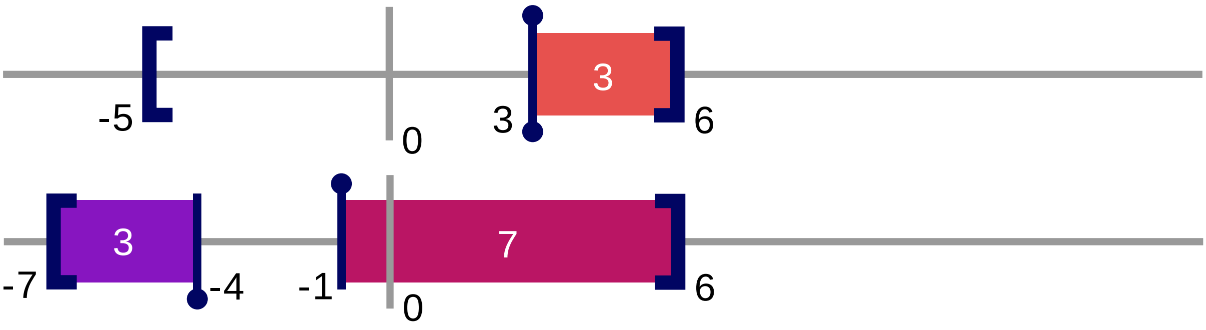

Figure 9. Example 6 – Customer reservations.

This final example demonstrates the impact of non-zero customer reservations. **B**'s reservation indicates they are uncertain about the behaviour of their uncontrolled loads but that they could be consuming somewhere between 1 and 4 kW in the upcoming interval. On the load (negative) side of the envelopes **B** is granted more access so that their 3 kW FCAS lower bid can make it to market. This is allocated accounting for the uncertainty in their uncontrolled loads.

A only gets 3 kW of raise market access due to their 3 kW of uncontrolled generation reducing their headroom.

No network support is required in this case, as the reservations remain within their respective operating envelopes.

3.2 Feeder Simulations

The previous examples were purposely simplified to highlight SOE behaviour. A more realistic heavily DER-laden feeder could have several aggregators with hundreds or even thousands of customers. Rather than a single price band, each aggregator could participate in up to 80 bid-bands when counting across the 8 energy and FCAS contingency markets. A further complication comes in the form of cross-market constraints and the power flow models that appropriately capture network voltage and thermal limits. The result is a much more complicated optimisation problem that requires a specialised approach to solve.

In this section we present the results of a more realistic SOE simulation, to better illustrate the potential network security and economic performance benefits. These and other simulations were done as part of testing our concept and implementation, in preparation for further testing in real-world trials. We will have a much more complete set of results at the end of the project after the approach is fully integrated with aggregators and trialled in the real world.

3.2.1 Test case

Our test case consists of a single ACT feeder using market and load data for February 2022. In this feeder we model several scenarios, starting from existing customer installations and then increased DER uptake. For the purposes of these simulations, we create two aggregators that each have a share of the customers and who both participate in energy and contingency FCAS markets.

We selected the ACT distribution feeder illustrated in Figure 10 for our simulations. This feeder was selected because it has a high number of customers with PV systems (33%) and smart meters (68%). The feeder covers MV and LV areas and has 1352 buses, 24 MV/LV transformers, and 803 customers (NMIs).

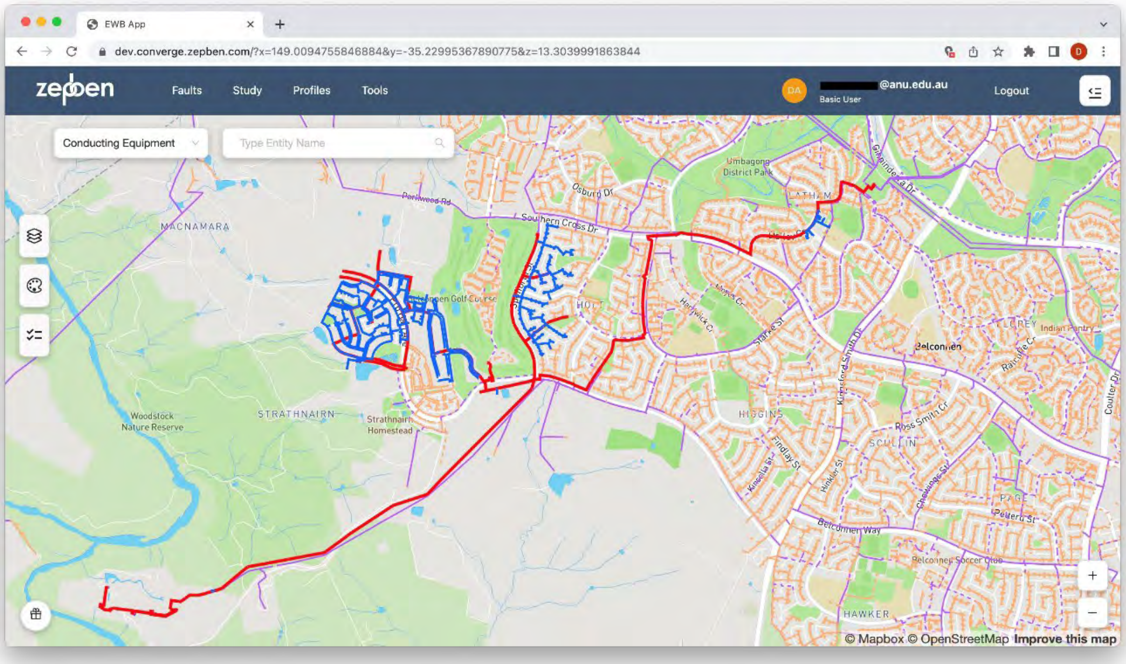

Figure 10. LATHAM_8TB_LWMLNGLOW feeder in the ACT, Australia. Blue and red lines denote LV and MV feeders, respectively.

The distribution network feeder data was directly extracted from Zepben's Energy Workbench (EWB) app. The bus voltage limits are fixed at 0.9 and 1.1 p.u. in the MV areas and at 0.94 and 1.1 p.u. in the LV areas, according to Australian standards AS 60038 and AS 61000.3.100.

DER owners connected to the distribution feeder can own PV systems ranging from 1 to 20 kW and battery systems of 5 kW / 13.5 kWh or 10 kW / 27 kWh with round trip efficiencies of 0.9. Table 1 presents the scenarios of DER participation considered in this report, listing the percentage of customers (i.e., NMIs) with PV and battery systems in each scenario. Note that all customers with batteries also have a PV system, but not necessarily the other way around. The P33B0 scenario represents the current integration of DER in the network area studied in the ACT, assuming that the current uptake of batteries is low and can be approximated as zero.

Table 1. DER scenarios.

DER scenario	Customers with PV	Customers with battery systems
P33B0	33%	-
P60B20	60%	20%
P80B40	80%	40%

Time series for background load and PV generation are generated from 30-minute smart meter data provided by Evoenergy, matching actual customers wherever possible and making appropriate substitutions in other cases.

3.2.2 Results of offline simulations

The results compare the network management performance under the proposed SOE framework to a more conventional DOE calculation that does not factor in aggregator / customer preferences. A comparison is also made to a fixed operating envelope (FOE) outcome which represents the current business practice, where customers are subjected to fixed power limits for exports (5 kW/phase) and imports (7-14 kW/phase)[4].

In the offline simulations, we assumed that aggregators behave as price-takers [9] in the NEM, which is in line with the current strategy of many aggregators in Australia. Under this assumption, aggregators optimise DER based on price forecasts to calculate energy and FCAS bids [10]. Afterwards, aggregators submit bids at price caps / floors to the markets. The bids are constrained by SOE, DOE, or FOE depending on the framework considered.

The results cover the network impact and economic performance of the mentioned frameworks.

Network impact

As expected, the SOE and DOE frameworks ensure the network secure operation of the feeder in all DER scenarios without causing any network problems. However, FOE causes several transformer overloads and voltage violations, namely in the P60B20 and P80B40 DER scenarios, as illustrated in Figure 11. To measure the network impact, we count voltage and thermal limit violations throughout the network, covering the entire simulated month. This is done assuming a worst-case activation of FCAS market bids from the DER. This means, a portion of the recorded violations would only occur under an FCAS contingency event, which is a low probability event. However, it is exactly under these circumstances that you do not want to trigger the protective equipment of the network, as it could remove the contingency response AEMO is expecting from aggregators.

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

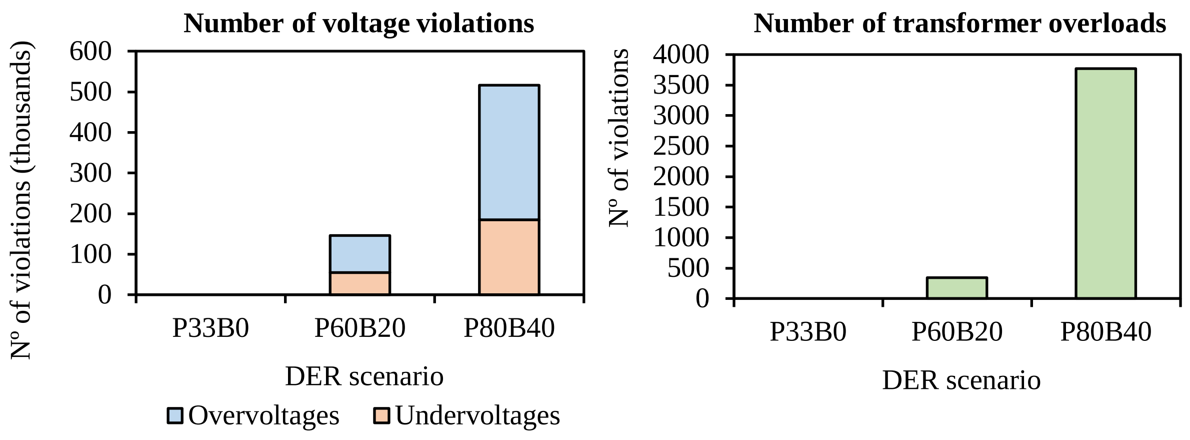

Figure 11. Network problems under FOE.

Economic performance

We compare the benefit to DER / aggregators under the two network-secure frameworks, i.e., SOE and DOE. The results are illustrated in Figure 12 and cover the DER profits generated by the participation of the two aggregators in energy and FCAS markets during February 2022. From these results, we can draw the following findings (which have been reproduced on several other feeders):

- SOE outperforms DOE in all DER scenarios. This is mainly because unlike SOE, DOE does not factor in the bidding intentions of aggregators. Instead, DOE allocates network capacity proportionally to DER sizes.
- The economic difference between SOE and DOE increases with an increase in DER installations. In the scenarios with low DER numbers, the difference between SOE and DOE is negligible. However, the difference increases significantly in scenarios of high DER penetration, such as in P80B40.

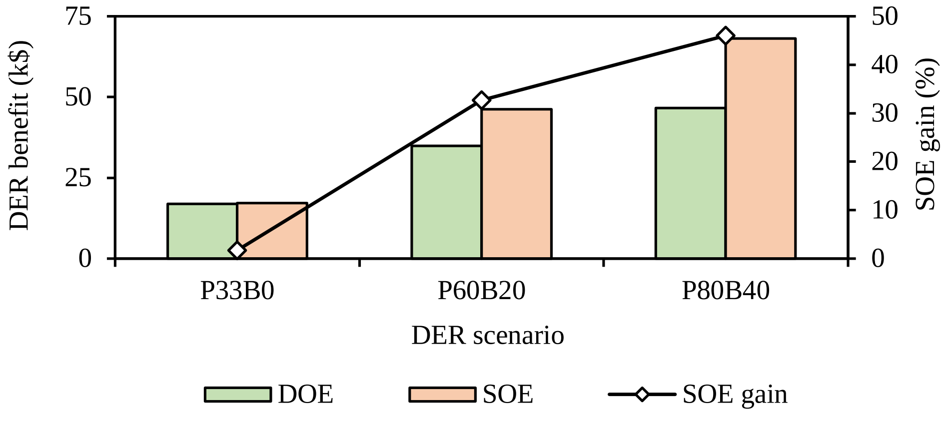

Figure 12. Benefit to DER / aggregators.

The economic differences between SOE and DOE are not the same every day, as illustrated in Figure 13. The difference is higher on days with high price volatility, like day 21. Days with high price volatility provide good opportunities for aggregators to orchestrate DER and maximise profits. The SOE approach has observability over this, which allows aggregators to maximise DER profit within network limits, contrary to the DOE approach.

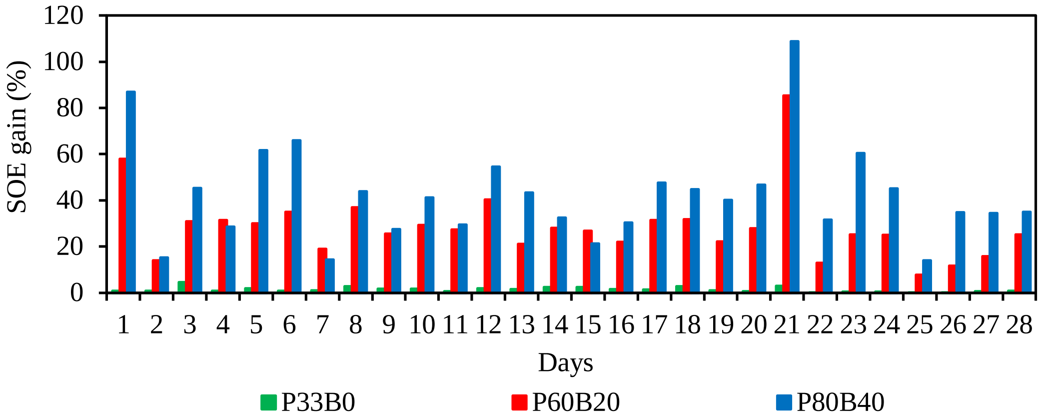

Figure 13. Daily SOE gains.

4 Trial Activities and Analyses

Project Converge aims to demonstrate through trial activities that SOEs can be used to enable the secure participation of DER aggregators in energy and FCAS markets and at the same time provide distribution network support services, such as voltage regulation and congestion management services.

This section outlines the key use cases for SOEs, establishes a set of metrics related to performance that will be measured, and presents our benchmarking approach. The finer details of the trials, including exact dates, durations, participating feeders and customers, are still being worked through as of writing this report.

The trial activities will happen in the distribution network managed by Evoenergy in the ACT and will have the participation of Reposit Power and Evergen, as aggregators / service providers.

Reposit Power provides retail optimisation services and aggregates customers into a virtual power plant (VPP) to provide contingency FCAS services in the ACT region. Their VPP operates across the entire NSW1 NEM region, of which the ACT systems are part. In addition, Reposit customers can provide distribution network support services.

Evergen provides retail optimisation services to customers in the ACT region. Evergen does not participate in wholesale markets. However, Evergen customers can provide distribution network support services.

As neither aggregator participates directly in the wholesale energy market, they will instead be able to make direct offers to provide network support to the Converge platform. This and the Reposit FCAS participation allow us to demonstrate a range of SOE benefits. These benefits will be demonstrated through the trial of use cases and benchmark analyses.

4.1 Use Cases

Project Converge is planning to demonstrate the four use cases described below.

4.1.1 **Use case 1:** Ensuring network security through SOEs

The aim of use case 1 is to demonstrate that SOEs can be used to ensure security in distribution networks with DER orchestration. We will use the metrics described in Table 2 to assess the effectiveness of SOEs and quantify impacts.

Table 2. Metrics for use case 1.

Metric ID – name	Description
Metric 1 - Fulfilment of voltage limits	Measurement of the voltage at the NMI level to check for compliance.
Metric 2 – Fulfilment of thermal limits	Estimation of transformer and line loadings to check for compliance.
Metric 3 – Network support services	Available volume of network support services.
Metric 4 – Network support provision	Volume of activated network support services.
Metric 5 – Network support cost	Cost/price to provide network support services.
Metric 6 – SOE capacity	SOE capacity per NMI.

4.1.2 **Use case 2:** Provision of FCAS services under network-constrained conditions

The aim of use case 2 is to demonstrate that SOEs can be used to ensure the reliable delivery of FCAS services under network-constrained conditions. We will use the metrics described in Table 3 to assess the effectiveness of SOEs and quantify impacts.

Table 3. Metrics for use case 2.

Metric ID – name	Description
Metric 1 - Fulfilment of voltage limits	Measurement of the voltage at the NMI level to check for compliance.
Metric 2 – Fulfilment of thermal limits	Estimation of transformer and line loadings to check for compliance.
Metric 3 – Network support services	Available volume of network support services.
Metric 4 – Network support provision	Volume of activated network support services.
Metric 5 – Network support cost	Cost/price to provide network support services.
Metric 6 – SOE capacity	SOE capacity per NMI.
Metric 7 – Unconstrained FCAS bids	Volume of FCAS bids submitted to the market.
Metric 8 – Constrained FCAS bids	Volume of constrained FCAS bids.

4.1.3 **Use case 3:** Provision of voltage regulation services

The aim of use case 3 is to demonstrate the provision of voltage regulation services using SOEs. We will use the metrics described in Table 4 to assess the effectiveness of SOEs in the provision of this service and quantify impacts.

Table 4. Metrics for use case 3.

Metric ID – name	Description
Metric 1 - Fulfilment of voltage limits	Measurement of the voltage at the NMI level to check for compliance.
Metric 3 – Network support services	Available volume of network support services.
Metric 4 – Network support provision	Volume of activated network support services.
Metric 5 – Network support cost	Cost/price to provide network support services.
Metric 6 – SOE capacity	SOE capacity per NMI.

4.1.4 **Use case 4:** Provision of congestion management services

The aim of Use case 4 is to demonstrate the provision of congestion management services using SOEs. We will use the metrics described in Table 5 to assess the effectiveness of SOEs in the provision of this service and quantify impacts.

Table 5. Metrics for use case 4.

Metric ID – name	Description
Metric 2 – Fulfilment of thermal limits	Estimation of transformer and line loadings to check for compliance.
Metric 3 – Network support services	Available volume of network support services.
Metric 4 – Network support provision	Volume of activated network support services.
Metric 5 – Network support cost	Cost/price to provide network support services.
Metric 6 – SOE capacity	SOE capacity per NMI.
Metric 9 – Load change	Measurement of the active power per NMI to check for compliance.

4.2 Benchmark Analyses

The benchmark analyses aim to compare the performance of SOEs against DOEs and FOEs. To perform these analyses, we will trial SOEs and at the same time simulate the operation of FOEs and DOEs using trial data.

4.2.1 Benchmark analysis 1: Comparison of SOEs to FOEs

The aim is to benchmark SOEs against FOEs. We will use the metrics described in Table 6 to compare the technical and economic performance of SOEs and DOEs. The economic performance will be analysed from the point of view of our key participants: aggregators, the DNSP and the wholesale market. The analysis of the economic impact on DER owners will be more limited because it will ultimately depend on the agreements they have with their aggregator – something the SOE approach does not prescribe.

Table 6. Metrics for benchmark analyses 1 and 2.

Metric ID – name	Description
Metric 10 – Network problems	Estimation of network problems (e.g., voltage violations, transformer and line overloads).
Metric 11 – Curtailment of DER services	Volume of curtailed DER services (e.g., PV generation, and FCAS).
Metric 12 – Economic performance	Calculation of DER economic performance.

4.2.2 Benchmark analysis 2: Comparison of SOEs to DOEs

The aim is to benchmark SOEs against DOEs. We will use the metrics described in Table 6 to compare the technical and economic performance of SOEs and DOEs.

4.3 Trial Challenges

Demonstrating these use cases will be limited by the kinds of trials we can perform. One key problem is the lack of concentration of *controllable* DER in the network. While a significant proportion of residential customers have rooftop solar, few are equipped or connected in a way where they can provide curtailment on-call. Those battery systems that are ready for control are similarly few and spread out across the network such that it becomes difficult to have an appreciable influence locally on the network.

The challenges that will limit how effective the trials will be at demonstrating the use cases include:

- low concentrations of controllable DER;
- incomplete or lagging metering data;
- inaccurate network phasing information;
- limited set of types of network problems;
- aggregators not directly participating in energy markets;

- simplified inelastic aggregator bidding practices; and
- limited un-aggregated data from aggregators.

The quality of data is one of the themes that emerges from this list.

Fortunately, computer simulations can be run on scenarios where some of these limitations are lifted, to establish the potential future benefit of the SOE approach. Simulations will be used to supplement the live trials to form a more complete picture.

5 Cyber Security

This section outlines cybersecurity requirements in the DER space. It starts by describing general DER cybersecurity requirements and ends by discussing some Converge-specific considerations.

Cybersecurity requirements exist across all actors in DER management – at the device level, with aggregators, and with DNSPs/utilities. Implementation at the aggregator or device level, as well as any proprietary communication methods between them, is in general not standardised and is outside of the scope of this report. Additionally, DNSPs already manage sensitive data within their operational systems – for example, network topology, SCADA, and advanced metering infrastructure data. The new cybersecurity challenges in the DSO role primarily relate to the communication and coordination between the utility server and potentially large numbers of DER devices (either directly or through an aggregator). This has implications for data protection and, significantly, electrical network security – particularly as the management of increasing numbers of devices plays a greater role in the safe operation of the network.

While each DER system may be quite small relative to the overall network load, the management of large numbers of these devices may represent a significant generation (or load) capability. These devices may be managed very differently from a single generator, and it is important to understand the implications of cybersecurity in terms of network security.

5.1 Standards for Communication

The importance of standards in this space has been identified in Project Evolve [4], promoting interoperability both as a means of lowering barriers to entry for interested parties and ensuring a consistent approach to securing communications. This project team has also been actively involved in the development of the Common Smart Inverter Profile – Australia (CSIP-Aus), both through the Interoperability Steering Committee and through Standards Australia subcommittees. CSIP-Aus is itself based on the Common Smart Inverter Profile (CSIP) and IEEE 2030.5-2018, which is also under a proposal for identical adoption by Standards Australia[5]. IEEE 2030.5-2018 is an interoperability standard for communication with IoT devices such as inverters, and its implementation in relation to DER management is described in CSIP/CSIP-Aus.

[5] AS 5385 open for public comment as of 1 February 2023.

5.2 IEEE 2030.5 Security Overview

IEEE 2030.5 is an application-layer protocol that uses TCP/IP to provide the underlying transport layer functionality and HTTPS as the (secure) application data exchange protocol. This protocol stack is common to most internet communications and its properties are well known.

The security features of IEEE 2030.5 are predominantly provided by the TLS specification. The choice of TLS 1.2[6] and the particular cipher suite provide a high level of cybersecurity, provided the implementation is sound. In particular:

- minimum TLS version and choice of single cipher suite provides resistance against downgrade attacks;
- the cipher suite chosen[7] provides forward secrecy
- mutual TLS (mTLS) means that both server and client are authenticated to each other.

5.2.1 Information Assurance in IEEE 2030.5

Confidentiality and communications integrity are provided by the choice of mTLS. Note that the compromise of any particular originator of communications is a separate concern – the premise in assuring communications integrity is that the integrity of each party is also assured. In particular, the assumption that the party supplying the issued credentials is the legitimate holder of those credentials, and that they have not been compromised in any other way. While the general security of IoT devices is of importance, the unique aspect of these communications as they relate to network security is in certificate management, which will be discussed in a later section.

5.2.2 Authentication and Authorisation

Client-server authentication is achieved through mutual TLS authentication, which involves the exchange of X.509 certificates, verifying integrity, and establishing that the certificate chain matches the root certificate authority. The device identifier for the client is inextricably linked to the X.509 certificate presented. In order to authorise a

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[6] Note that, while a newer version of TLS (1.3) has been released. The cipher suite chosen remains available in the later version of TLS. It is anticipated that, while the standard requires TLS 1.2, a transition to TLS 1.3 will require minimal changes in the specification.

[7] TLS_ECDHE_ECDSA_WITH_AES_128_CCM_8

client, this device identifier is compared to a server access control list[8], and appropriate resources are made available to that client.

5.2.3 Availability

Ensuring the availability of communications channels for DER management is complicated by the fact that there may be multiple physical transport media that support communications with a diverse range of devices. For example, in an aggregator-mediated scenario, the aggregator and utility server may communicate between clouds, with aggregator to device communications over residential internet (including residential Wi-Fi) or by a dedicated mobile channel. This means that there are multiple points of failure and multiple failure modes. These failure modes may relate to physical or environmental factors (such as storms and blackouts), technical factors (such as changes in network connectivity) or could be a product of adversarial actions (such as Denial-of-Service attacks). Of particular interest are how these systems may fail, and the impact of those failures on network management.

5.3 Cybersecurity considerations for Converge

This subsection covers Converge-specific considerations for the deployment of an internet-facing utility server to communicate with participating aggregators.

5.3.1 Denial of Service

For a general-purpose utility server that may communicate directly with many devices connecting over different communications channels, there is necessarily a large communications surface area that makes such a system susceptible to (intentional or otherwise) Denial of Service attacks.

In Project Converge, all communications with the utility server originate from a small number of aggregators with known IP address ranges. As such, additional cybersecurity measures (such as IP address whitelisting) can be applied to reduce the exposure of (secured) API endpoints to the broader internet. In the general scenario where end devices may talk directly to the utility server, these measures would need to be modified.

5.3.2 Certificate Management

[8] As discussed in later sections, this requires out-of-band communication and maintenance between the server and clients. CSIP-Aus contains revisions that allow for authorisation to take place as connections are established as an extension to the IEEE 2030.5 standard.

The converge project uses self-signed certificates for mutual TLS purposes. This is considered appropriate for trial purposes; however, a production system would need to use an established certificate authority that has the responsibility to manage certificate issuance for DER and utility servers in Australia. Ongoing work in the Interoperability Steering Committee aims to establish the relevant pathways for achieving this.

Any transition to new root certificate authorities would require a complex certificate management and rollout process – particularly if end devices are communicating directly with the utility server. For aggregator-mediated communication, this process would be significantly more manageable[9].

[9] Since device identifiers are linked directly to the certificate, a transition between certificate authorities would necessitate a change in device identifiers, which may have downstream effects as well. In the aggregator-mediated scenario, only aggregator identifiers will change, which will limit the impact of a change like this.

6 Insights for Future Policy

Project Converge aims to inform the policy and regulatory discussions surrounding the participation of DER in markets, including DNSP-level network support markets. There are many broad learnings that have been discussed from similar projects that Converge supports as well as unique insights from the project implementation.

Project Converge is also undertaking specific Social Science research. The interim findings of this work will be made available in [11].

6.1 General Insights

At this stage in the project, several initial policy, regulatory and market discussion points have been identified. The key findings are described below:

- SOEs bring overall system benefits, however, these benefits only become material once DER penetration levels get high. Whilst this indicates that DOEs are sufficient in the short term, the learnings of Project Converge are useful in providing a pathway beyond DOEs, providing greater clarity on a final DER market optimisation framework.
- There is still general industry confusion on the range of functions of DOEs. As pointed out in this report, there are many variations to DOEs that can include market access. Discussions with stakeholders around DOEs show there is increasing awareness of the concept of DOEs, however knowledge and awareness of the calculation methods, inputs and objectives are still developing. This has created a barrier when discussing the concept such as DOEs, SOEs, network support and market participation. Greater industry consistency in terminology, definitions and processes will aid research and policy development in key areas.
- Project Converge proposes a framework consistent with the current market roles and re-enforces the need for DSO functions performed by DNSPs. The definition of the DSO functions requires further work to ensure consistency across the NEM, especially as the DSO functions move to include network support, and/or techniques such as SOEs that have material interaction with the wholesale and ancillary markets. Project Converge calls for a consistent approach for all market-interacting DSO functions across DNSPs, however, the implementation timeframes should be staggered based on need.
- SOEs and indeed all operating envelope variations will need to consider concepts of fairness and/or equity. SOEs have been designed with this in mind

and have factored in some of these concepts in the SOE Optimisation Algorithm. However, a broadly accepted definition of equity and/or fairness has not been determined within the project, therefore the settings required to implement them are unknown. Further discussion of this topic will be provided by the Social Science research.

- The technology implementation is consistent with using IEEE 2030.5 including the CSIP-Aus extensions for DOEs to implement the required data transfers between the aggregator and DSO. New data endpoints have been defined for the trial and this may be transitioned existing IEEE 2030.5 functions or propose new standard interface endpoints at the end of the project.

6.2 Insights Arising from Implementation

There are several complex issues arising from the technical implementation, in a large part due to the complex problem that is being solved. To recap, the SOE solution explored in Converge is a technique that aims to solve the distribution network optimal power flow problem for a general case where millions of DER are participating in wholesale markets that change every 5 minutes. It is a complex problem, necessitating a solution that can handle this complexity. At a physical level, we recognise the interconnected power system, however, the current market constructs do not adequately consider distribution-level power flows and constraints. For example, DER behaviour under high wholesale events may exceed distribution network capacity in certain areas. One of the DSO functions is to advise the network capacity through operating envelopes. DOEs provide this advice without aiming to maximise market benefits, however, SOEs aim to maximise market benefits, hence linking DSO actions to wholesale and ancillary market outcomes. This is a significant regulatory and policy-level insight that requires consideration by energy regulators and policymakers.

To handle the complexity, there is a general recognition within the trial projects considering DER market participation that greater coordination is required between AEMO and the DSO functions.

- SOEs rely on sufficient NMI-level information from aggregators on individual system behaviour. This is challenging to obtain, and other projects have not been able to obtain sufficiently granular information to proceed. Aggregated DER Fleets by definition provide aggregated bids that combine systems at a NEM region level. This level of detail provides some direction on the intended behaviour of individual systems, but not enough for the DSO to predict the network impacts. Project Converge is continuing to work with the DER partners to resolve this issue, based on available granular data. The final report will aim to confirm the current availability of this data and analyse the options to obtain this data.

- The DSO function under SOEs includes the accountabilities for local network support procurement and settlement. SOEs effectively create a market mechanism for procuring network support, where aggregators send network support availability capacities every 5 mins as part of the submission for an SOE. The SOE algorithm calculates the network support and encodes that as part of the envelope. The DSO settles directly with the aggregator. Converge has thus far focussed on the technology to facilitate SOEs and hence network support and hasn't explored the future commercial and contractual requirements around this yet. At this point, aggregators are commercially contracted to Evoenergy to provide network support at agreed prices.

The DSO function under the SOE processes has new accountabilities to include and utilise distribution network capacity for maximised market benefits. This function has the effect of coordinating DER behaviour in local areas to achieve a broader goal. This function should be considered as an additional network optimisation function step within the current AEMO rebid process, rather than a new or different approach. As such this requires minimal reforms to implement.

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