Hosting Capacity Study

Network wide HV & LV Scenario based Hosting Capacity Analysis

April, 2022 – Version 1.1

Document Control

Change History

Version	Issue Date	Author	Description
0.1		Adam White	Outline
0.2	17/5/22	Adam White	Partial draft for review
0.3	23/5/22	William Tarlinton	Review and additional material
0.4	29/5/22	Adam White	Revise based on internal and external feedback
1.0	29/6/2022	Adam White	Revised based on feedback from Essential Energy and Baringa.
1.1	13/7/2022	Adam White	Minor revisions

Referenced Documents

Version	Issue Date	Author	Description

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Glossary of terms

Term	Definition
AEMO	Australian Energy Market Operator
ADMS	A term that has arisen recently and used in the industry to describe an Advanced DMS. The ADMS is the most significant operational technology used by DNSPs
Aggregator	An Aggregator is an organisation that provides an integration point and control mechanisms for many DER assets
CIM	Common Information Model, a standard for data exchange for network models, based on the IEC 61970, 61968 and 62325 family of standards.
DER	Distributed Energy Resource. Disruptive technologies being connected to distribution networks, including PV, EV, demand response solutions, battery storage and wind farms.
DNSP	Distribution Network Service Provider. These are the organisations that own and operate electricity distribution network infrastructure.
DOE	Dynamic Operating Envelop – a way of providing limits for DER to operate within to avoid voltage violations or thermal overload of the distribution network.
EV	Electric Vehicle.
EWB	Energy Workbench – a platform developed by Zepben to support network modelling and application development.
GIS	Geographic Information System. A computer system that incorporates geographical features with tabular data in order to help manage the assets in an electrical network.
Hosting Capacity	The ability for the network to accommodate a specific installed capacity of a particular DER technology
HV	High Voltage – 6.6kV to 66kv. Sometimes also referred to as MV. These are typical voltages used by distribution network to transport energy. This network forms part of the DNSP asset base.
ISP	Integrated System Plan is a whole-of-system plan produced by AEMO that provides an integrated roadmap for the efficient development of the National Electricity Market (NEM) over the next 20 years and beyond.
Load Flow Study	A numerical analysis of the flow of electric power in an interconnected system, providing the magnitude and phase

	angle of the voltage at each node, and the real and reactive power flowing in each line.
LV	Low Voltage – 400 V phase to phase. This is used for the last km of electricity reticulation in Australia. This network forms part of the DNSP asset base.
MV	Medium Voltage - 6.6kV to 66kv. Sometimes also referred to as HV. This network forms part of the DNSP asset base.
PV	Photovoltaic – refers to solar generation.
TNSP	Transmission Network Service Provider. These are the organisations that own and operate electricity transmission network infrastructure.
V2G	Vehicle to Grid – refers to Electric Vehicles exporting power to the grid.

1 Introduction

1.1 Executive Summary

As Australian consumers continue to rapidly adopt rooftop PV, residential scale battery storage systems and, increasingly electric vehicles, Essential Energy like all Electricity Distribution Networks needs to continue to adapt and develop its ability to provide two-way network services.

Along with this uptake in Distributed Energy Resources (DER), changing consumer preferences, innovative energy management platforms and ubiquitous internet-based data communications are making it possible for the DER to be orchestrated by aggregators. These innovative companies are changing the behaviour of DER to maximise the value of consumer owned DER through participation in emerging markets.

These trends are combining to impact the long-established assumptions that have historically acted as key inputs into the design and construction of electricity networks. In particular the simplifying assumptions of "after diversity maximum demand" (ADMD) that were used historically no longer hold, due to a mix of changes including the direction of energy flows, timing of energy flows, demand patterns, as well as overall energy consumption.

New concepts and techniques are needed for the planning and operation of electricity networks to ensure the assets are not overloaded and that voltage and other quality of supply requirements are being met.

Essential Energy understands these challenges and engaged Zepben to provide the electrical network modelling needed to extend strategic network planning from peak demand focused to power flow focused. This involved:

1. Undertaking a whole of network hosting capacity study, using various time-series power profiles of new DER devices, to discover at what levels of load and DER penetration the network assets move out of normal operating conditions and/or voltage violations occur, and

2. Analysing the benefit of interventions that could be adopted to increase the networks hosting capacity through strengthening the network, implementing new network asset control schemes, or changing the operating characteristics of DER connecting to the networks.

Zepben supplied these results to Essential Energy's economic modelling partner Baringa to develop a comprehensive Future Network Business Case as part of Essential Energy's overall planning for the 2024-29 regulatory period.

The key challenge with delivering on these outcomes was capturing the impact of DER uptake at the local level in a heterogeneous network that was originally built by around 50 local councils, over many decades. This required Zepben to move beyond a classic taxonomic approach to understand the magnitude and timing of DER impacts over the entire network.

Zepben was able to bring its extensive experience with the acquisition and curation of continuous network models in our Energy Workbench platform to support the data needs of the project. The load flow studies that underpinned the results were obtained using the OpenDSS[1] electric power distribution system simulator to run, literally, millions of individual load flow studies under different DER penetration scenarios.

The two key inputs that influence the modelled outcomes were the end-to-end network model provided by Essential Energy and the 15-year demand & DER forecast provided by Frontier Economics. This forecast is based around the Australian Energy Market Operators – Integrated System Plan scenarios, with a central scenario for roof top PV generation within Essential Energy's network projected to double from the current 1,900GWh per year, up to 4,000GWh per year by 2029.

Bringing together these inputs and the scale of cloud-based load flow calculations, the results captured and summarised the time-series performance of Essential Energy's network at the street level, providing highly granular insights into how Essential Energy will need to build and operate its electricity network to continue to efficiently deliver energy services to the community.

A clear implication from the analysis undertaken is that the efficient management of power flows from distributed generation is the key electrical network performance focus for the 2024-2029 period. One of the key outputs that inform this insight is Figure 1, which depicts how curtailment of distributed PV generation is predicted to change over the forecast period.

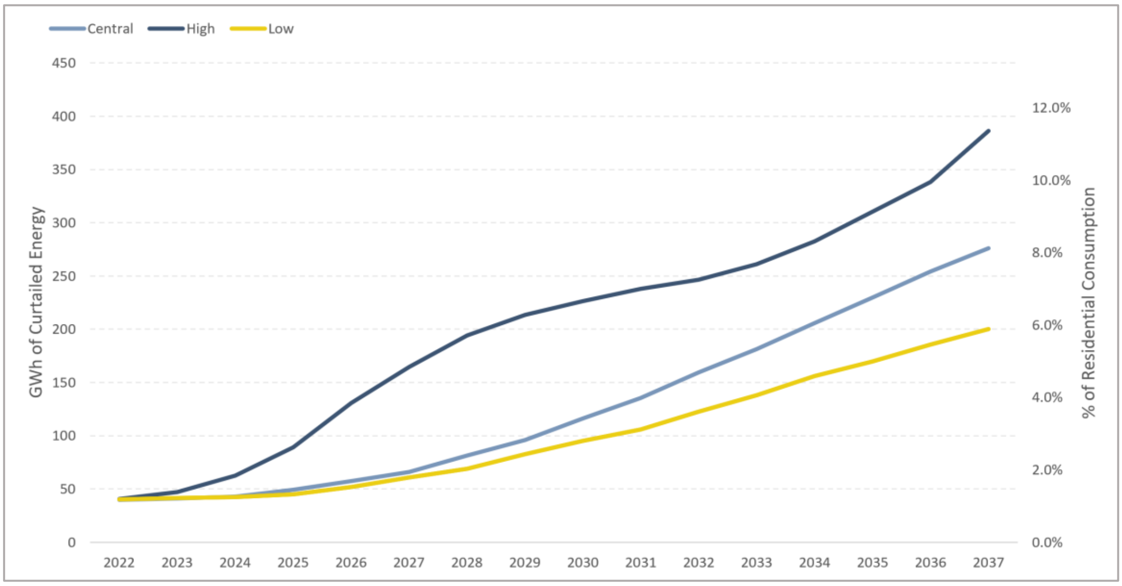


Figure 1 - Forecast Generation Curtailment under modelled scenarios

[1] https://smartgrid.epri.com/SimulationTool.aspx

Energy curtailed is set to at least double by 2029, with the potential high case to see curtailment quadruple over the same period. At these levels solar customers are set to experience solar curtailment as the norm rather than the exception during the 2024-2029 period.

A key implication of this result is how this curtailment eventuates, with the potential for the customer experience of this curtailment to range from high voltage limit inverter tripping, static year-round limits through to flexible dynamic limits applied in the shoulder seasons. Raising the importance of enabling an efficient move to more dynamic network capacity allocation mechanisms, such as Dynamic Operating Envelopes (DOEs) ahead of this forecast increase in curtailment.

Beyond 2030 the impact of changes in demand from the uptake of Electric vehicles (EV) layer on top of the curtailment challenges developed during the 2024-29 period. Figure 2 shows local network areas experience an acceleration in voltage non-compliance due to widening swings in network demand, from the dual trend of increasing local peak demand and increasing peak generation. This is forecast despite favourable modelling assumptions, such as a trend away from convenience charging and system wide levels of peak charging diversity occurring down into the distribution network.

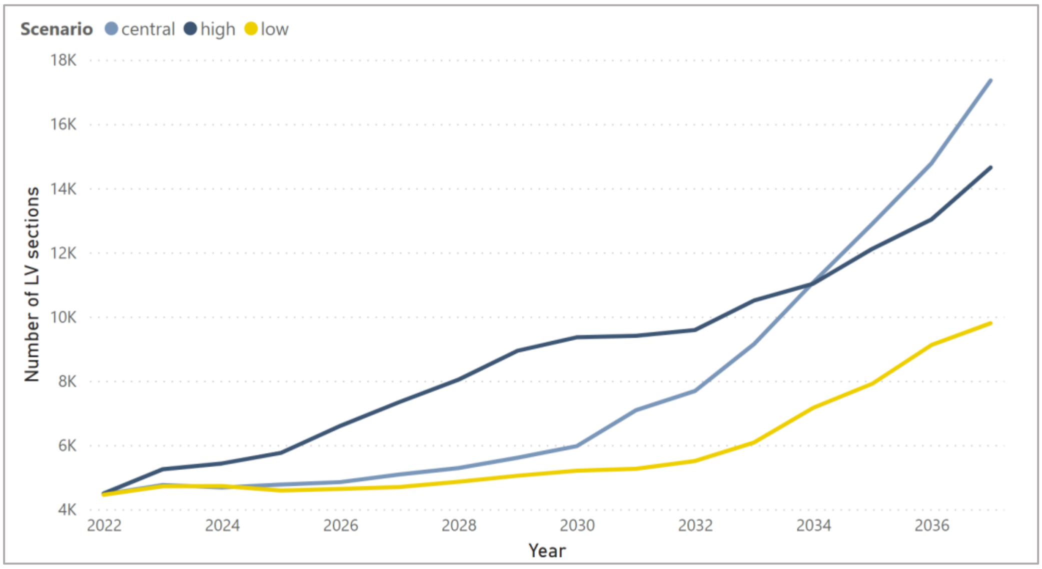


Figure 2 – Impact of growing delta between peak demand and minimum demand - Number of LV sections exceeding 16% voltage swing

The variation in scenarios across both Figure 1 and Figure 2 is also important to unpack, these scenarios are based on the AEMO ISP scenarios with the modelled high, central and low scenarios more than just scaled versions of the same scenarios. Each scenario has DER increasing in different mixes, and this becomes relevant when assessing the performance of the local distribution network. For example, the central scenario has a higher uptake of battery storage, relative to the other scenarios and DER assets, with installed battery storage capacity at the end of the forecast period set to equal current network peak demand ≈2.5GW. With penetrations of dynamic flexible assets this high, small discrepancies between local charging behaviour and local solar generation result in short swings in network demand that then impact network voltage performance.

The results of the forecast hosting capacity, particularly the modelled curtailment results then informed the subsequent focus on targeted intervention benefit assessment. Which investigated and quantified the specific solar hosting capacity uplift available for a mix of local network and non-network interventions.

These two complementary technical assessments provide significant insights into the changing nature of network performance and the high impact interventions that can be applied going forward. Enabling subsequent detailed economic modelling to inform the development of strategies to address the modelled network constraints & curtailment.

This modelling undertaken and the approaches applied are covered in detail in the subsequent chapters of this report, however the following section provides a summary of the key insights from these assessments:

- For the 2024-2029 period a focus on the **efficient management of uncontrolled generation at the consumer level** is critical to ensuring Essential Energy can meet technical standards around voltage, safety and performance.

- From 2028-2037, local pockets of EV uptake will give way to broader based uptake; The scale of this impact is highly dependent on the ability of broad-based incentives to convince customers to take up alternatives to convenience-based EV charging.

- **Local LV network thermal and voltage performance becomes highly sensitive to EV charging profiles beyond 2030.**

- **Residential areas continue the trend of declining annual energy imports** beyond 2030, despite the electrification of transport, due to the continued strong uptake of solar PV.

- Widespread benefits are likely to come from network-wide advanced voltage regulation schemes such as closed loop voltage control, which were identified to have the gross benefit **potential of between 240MW and 830MW of solar hosting capacity uplift**.

- Localised traditional network interventions can provide significant local capacity improvements. However, they are costly and limit delivered benefits to small groups of customers.

- Broad based interventions such as improved MV and HV voltage regulation and Dynamic Operating Envelopes (DOEs) have a large role in efficiently minimising the level of generation curtailment experienced by customers.

- The forecast scale of DER deployment and its dramatic impact on energy consumer load shapes highlight the importance of **focusing on a range of tools and approaches to influencing end consumer demand profiles** to shift energy consumption patterns.

- For the network sections that did breach maximum voltage limits or thermal constraints, the **average solar penetration level when this occurred varied significantly between network classifications**. With small rural substation network sections on average hosting 2.4kW of solar per customer before reaching voltage limits, compared to 5.3kW per customer for underground urban network sections.

2 APPROACH

2.1 SCOPE

The scope of work required:

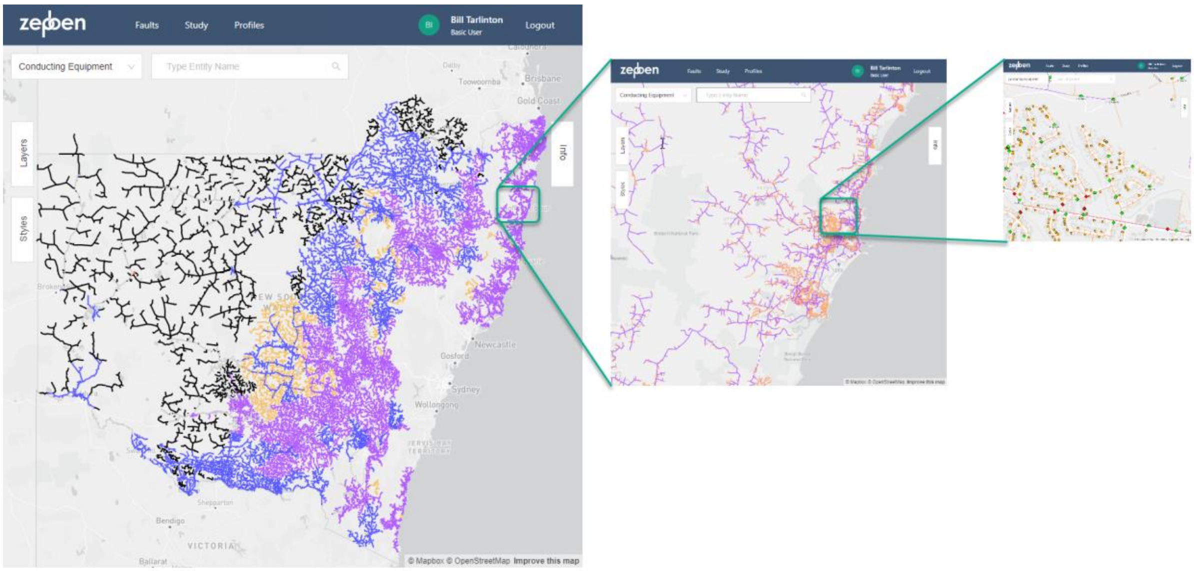
- MV and LV Hosting Capacity assessment for PV, battery storage and EV; forecasting the timing and location of constraints for the period 2022-2037.
- Analysis of the generation hosting capacity benefits for a range of network and non-network interventions.

These outcomes were required to be delivered against the 1456 distribution feeders that form Essential Energy's MV/LV network, comprising in total 189 thousand kilometres of conductors.

The modelling outcomes were required to be compiled into a suitable format to enable a Cost Benefit Analysis (CBA) to be formulated to determine the optimal network capacity-intervention cost balance over the 15-year forecast period.

2.1.1 Hosting Capacity Forecast

Each feeder was modelled from the MV busbar of the Zone Substation to each supply point in the LV network. In other words, the load flow studies were conducted for each feeder independently using a continuously connected MV and LV network, with the real and reactive power inputs supplied from each of the approximately 850,000 connection points in the model.



The load flow studies included:

- A baseline study to confirm each feeder model was calculating voltage and power correctly. This was achieved by comparing the voltages and power calculated by the models with available sensor data for both the LV and MV networks,
- A base year assessment of current network voltage issues and thermal constraints across the entire network, and
- 15-year forecast of voltage and thermal constraints under a set of forecast future DER scenarios. This forecast is aligned with the provided demand and DER forecast period 2022-2037.

2.1.2 Intervention modelling

Modelling was also undertaken to assess the effectiveness of several interventions to improve network hosting capacity outcomes. This included simulating changes to network construction and changes to voltage regulation, and testing the efficacy of various non-network interventions involving the simulation of DER asset orchestration to change the magnitude and timing of load and generation.

This modelling also utilised load flow studies but was only conducted on a subset of the total network feeders due to the limitation of making some manual. Refer to section 4.

2.2 Key Activities

There were four key activities undertaken to deliver the scope and develop the outcomes of this report:

- Data acquisition, model development and validation,
- Base case analysis to validate that the models were producing the correct outputs of power and voltage for electrical network and consumer behaviours,
- Hosting capacity analysis under Integrated System Plan (ISP) scenarios, and
- Intervention analysis

These four activities provided Essential Energy with a complete picture of the current and future performance of the distribution network, along with a view of the capacity benefits of various interventions that can be taken to optimise the network capacity available to customers.

2.3 Independent Validation of the Network Models

To provide added confidence in the OpenDSS models produced for the hosting capacity studies, the University of Melbourne, which has researchers with considerable experience using OpenDSS, was engaged to review several of the feeder models, through two iterations of the model development. This allowed Zepben to make several improvements to the production of the OpenDSS models and confirmed that OpenDSS was being used correctly for the load flow studies.

2.4 INPUTS

The modelling required a comprehensive set of digital asset information to represent Essential Energy's physical network and baseline consumer behaviour accurately. The following are the sources of data used to build up the base case 'digital twin' of Essential Energy's distribution network.

- HV Network Model - 11,22,33kV
- LV Network Model
- Sythetic Load Profiles - 30min energy profiles for each NMI
- DER Register
- Customer - Network Relationship from (PEACE)
- Feeder peak demand profiles - Forecasting Database
- Conductor library
- LV conductor specifications
- Distribution transformer tap settings and impedance.
- Zone Substation voltage regulation settings
- Zone Substation source impedance

In addition to the information needed to model the network, the hosting capacity studies needed forecasts of future consumer behaviours that could be translated to scenarios for how Essential Energy's network is expected to perform over the next 15 years in response to those forecast behaviours.

Zepben worked with Essential Energy and their forecasting partner, Frontier Economics, to include a comprehensive set of underlying load data, electrification and Distributed Energy resources forecasts into the forecast hosting capacity model.

The following inputs were ingested to develop the forecast load and generation inputs into the models.

- Zone Substation level underlying demand forecasts
- Zone Substation level electrification (residential gas and industry) forecasts
- PV panel capacity forecasts by Zone Substation
- Installed Consumer BESS numbers by Zone Substation
- Registered EVs by type per Zone Substation area
- Residential and Commerical EV charger demand profiles
- PV generation profiles
- BESS charging profile

Zepben combined this collection of inputs to create the information needed to support extending the base electrical model of Essential Energy's network over the forecast period. This enabled Zepben to define the performance of the physical network under the various versions of the future represented by the forecast inputs.

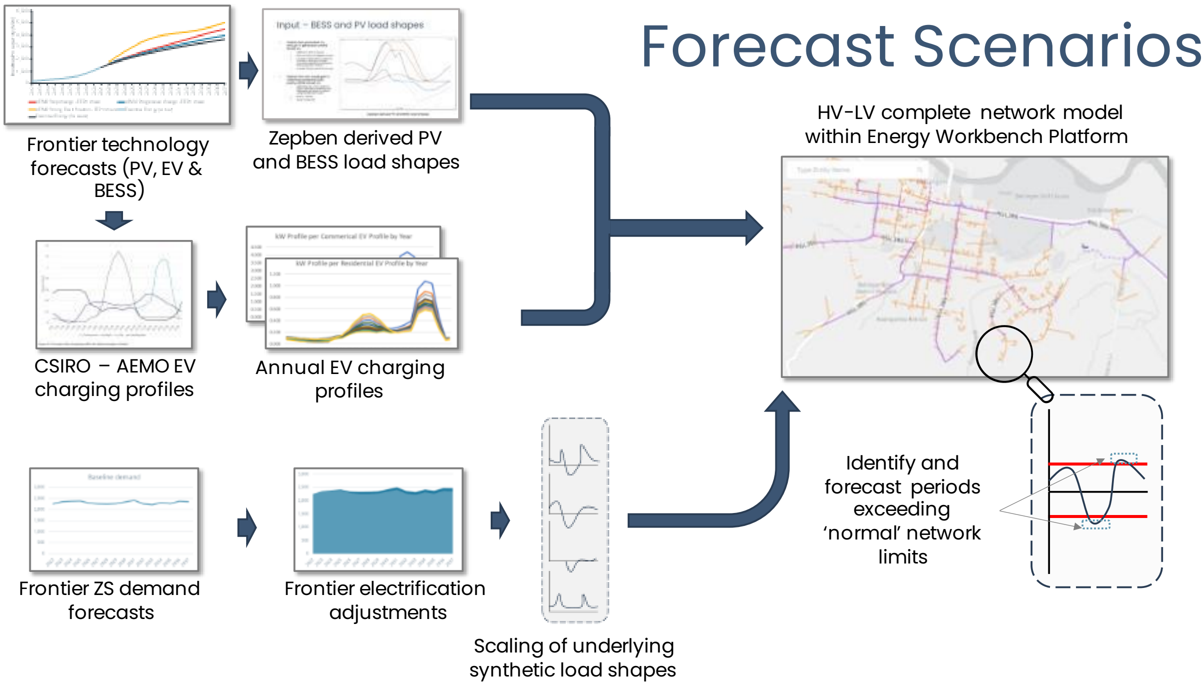


Figure 3 - This diagram illustrates how these inputs are combined to form valid future scenarios of electrical network performance

2.5 OUTPUTS

To meet the objectives of the Hosting Capacity Analysis project it was important to deliver a clear set of network performance metrics that accurately captured the time series network modelling results.

The raw time series analysis created a data set with a size of the order of peta-bytes, which would have been unmanageable as a useful input into Essential Energy's follow-on CBA project to determine the optimal balance of solutions. To make the model output useable, appropriately summarised metrics were created from the raw time series data.

The primary outputs were defined in combination with Baringa, the economic consulting partner engaged by Essential Energy to complete the Future Network Business Case, utilising the results of Zepben's network-wide Hosting Capacity work.

Table 1 describes the detailed breakdown of the summary output values provided by the Hosting Capacity Study. These results were provided for each of Essential Energy's approximately 136,000 distribution transformers, and represent a summary of the downstream network performance from the MV terminals of each of these transformers.

Figure 4 - Segmentation of recording network performance, below provides a graphical description of how the network was segmented to provide highly granular tracking of network performance.

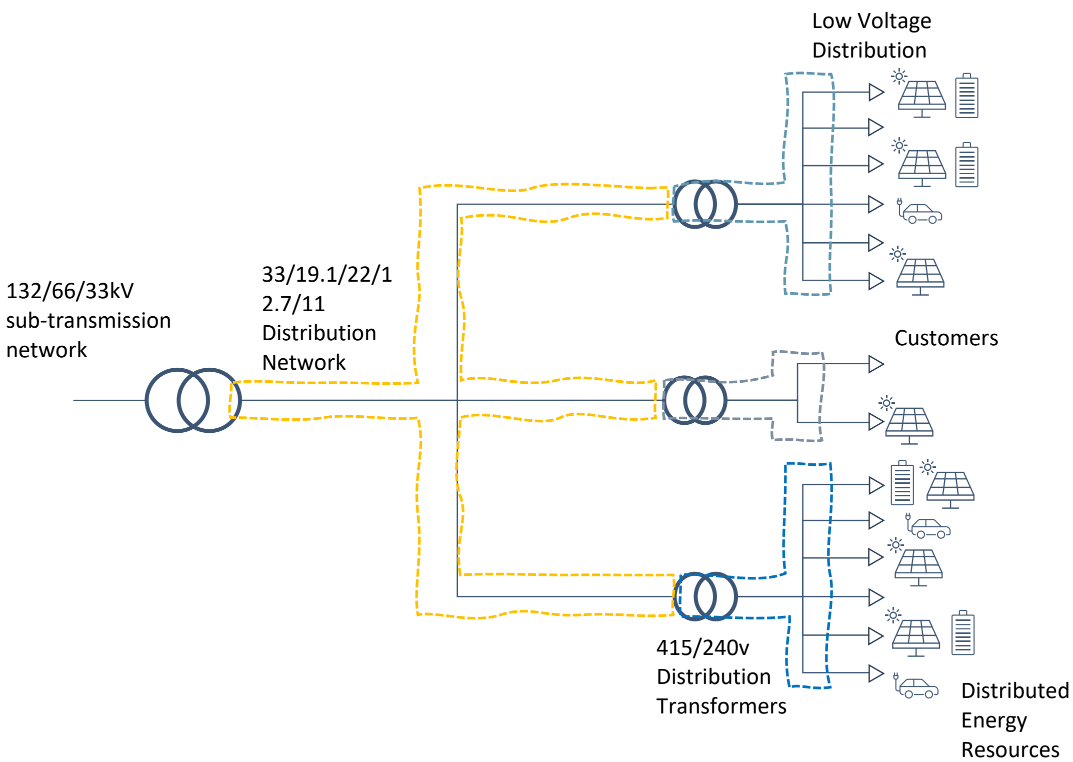


Figure 4 - Segmentation of recording network performance

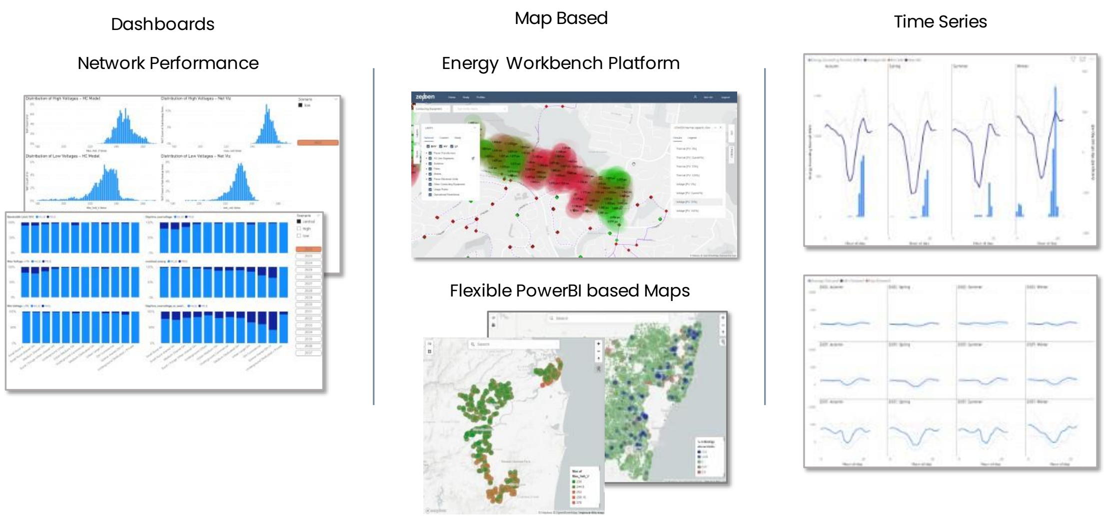
Table 1 - Key results metrics defined as modelling output

Metric	Description
id	Smallworld ID provided by EE via geoJSON
name	Transformer name as per geoJSON
day_time_maximum_voltage	Max voltage recorded during the day
maximum_voltage	Max voltage recorded during the day
minimum_voltage	Min voltage
day_time_voltage_percent_over_max	% of the daytime hours that the daytime voltage exceeds 253v (as defined peak solar gen window of 10am-4pm)
voltage_percent_over_max	% of the year voltage exceeds 253v
voltage_percent_under_min	% of the year voltage below 216v
load_exceeding_normal	Energy consumed by loads outside of 216v<>253v and any upstream asset thermal limits - Note: this is calculated as part of the OpenDSS load flow engine, it is defined by both thermal and voltage at the connection point and only considers consumption outside of limits.
overload_kw_normal_max	Peak kW loading above normal asset ratings
overload_kw_emerg_max	Peak kW loading above emergency asset ratings (where no value is provided 150% of normal rating used)
overload_kwh_normal_sum	Energy kWh above normal assets ratings - defined the energy flow within the section of network that exceeded normal assets ratings
voltage_driven_curtailment_kwh	sum of kWh where voltage limits are exceeded 216<>253
solar_voltage_thermal_curtailment	Total solar generation window network section energy flows outside of network limits -> Sum of the energy (kWh) flows outside the voltage thresholds 216v<>253v

	OR reverse network flows above normal thermal limits over the year. Note: outside of voltage limits, a linearly increasing % of energy is recorded as outside of the threshold up to 100% at 180v<>260v thresholds.
summer_solar_curtailment	summer kWh component of solar_voltage_thermal_curtailment
autumn_solar_curtailment	autumn kWh component of solar_voltage_thermal_curtailment
winter_solar_curtailment	winter kWh component of solar_voltage_thermal_curtailment
spring_solar_curtailment	spring kWh component of solar_voltage_thermal_curtailment
energy_exceeding_normal_kwh	Total network section energy flows outside of network limits -> Sum of the energy (kWh) flows outside the voltage thresholds 216v<>253v or reverse network flows above normal thermal limits over the year. Note: outside of voltage limits, a linearly increasing % of energy is recorded as outside of the threshold up to 100% at 180v<>260v thresholds.
worst_case_solar_voltage_thermal_curtailment_kwh	Total solar generation window network section energy flows outside of network limits -> Sum of the energy (kWh) flows outside the voltage thresholds 216v<>253v or reverse network flows above normal thermal limits over the year. Note: outside of voltage limits, all kWh of energy are counted.
overload_kw_normal_max_reverse	Reverse flow Peak kW loading above normal asset ratings
overload_kw_normal_sum_reverse	Reverse flow energy (kWh) above normal assets ratings - defined the energy flow within the section of network that exceeded normal assets ratings
longlats	Latitude and Longitude of start of network section

While the primary output as defined by Table 1 was the core deliverable, both the volume and complexity of the results required a series of reports and maps to enable review and analysis by Zepben, Baringa and Essential Energy teams.

Consequently, a range of network performance dashboards and interactive maps were created to help high-level network wide performance assessment as well as granular assessment of localised constraints.



This collection of outputs enables the immediate use of the results for assessment of efficient levels of curtailment within the Future Network Business Case, while also providing a comprehensive dataset to support BAU capacity planning and constraint analysis. Having this granular distribution substation level forecast to inform Essential Energy's constraint analysis and capacity planning, represents an uplift in BAU capability when compared to Zone Substation level analysis historically available.

2.6 Implementation of the Solution

The following approach was undertaken to initially implement the base network model assessing the performance of Essential Energy network for 2022.

This base model was then extended to build out the modelling of a 15-year forecast for the network constraints across the HV and LV network.

2.6.1 Ingestion of Essential Energy's full High Voltage and Low Voltage network model

Zepben received the complete network model held in Essential Energy's Smallworld Graphical Information System (GIS) in September 2021. This model held the following data:

- Underground and Overhead Lines, with length, connectivity, standard type, phase connections, voltage, identifier and, location,

- Transformers, with voltage, location, connectivity, standard type, rating, Estimated utilisation, identifier, number of phases,

- Switches, with connectivity, serviceability, status (closed/open) and type (fuse, link, cubical, LVL, switch etc), and

- Service points, with identifier, location, connectivity, solar status, inverter size and panel capacity.

The data was delivered as one file per MV feeder holding all the MV network assets, and one file per MV feeder holding all the LV assets. The data was expressed as geoJSON, a common way of exchanging geographic type data. The topology was exported by adding a “from” and “to” node attribute to all cables and overhead lines.

An example of the geoJSON used to represent a segment of overhead line is provided in the Figure 5 below.


```
{
    "type": "FeatureCollection",
    "features": [{
            "type": "Feature",
            "id": "cable4604457",
            "geometry": {
                "type": "LineString",
                "coordinates": [[152.920073, -31.4682914], [152.920461, -31.4683620], [152.920852, -31.4685328]]
            },
            "properties": {
                "class": "cable",
                "length": 79.6913258,
                "name": "4604457",
                "type": "Overhead",
                "network level": "11kV at 50C",
                "Service Status": "In Service",
                "Phases": "HV3",
                "Phase Connections": "Unknown",
                "Analysis Phase Connections": "ABC",
                "Tend SC": 200,
                "Standard Type": 37,
                "State Stand": 2,
                "ParSys": 1,
                "operating voltage": "11kV",
                "fromNode": "node332542652",
                "toNode": "node23378215"
            }
        },
```


Figure 5 - example geoJSON

The ingestion process converts the generic geoJSON formatted data into the CIM data profile used by the Energy Workbench.

The CIM profile used by the Energy Workbench is open source and can be viewed at the following URL:

[data model profile].

This enables the model to be stored in an open and standards aligned format, making it easily translatable into a range of other formats for a range of possible use cases. Figure 6 below graphically describes how the CIM data model relates the core elements of an electrical asset model.

Zepben's Software Development Kit (SDK) enabled programmatic manipulation of this CIM data model and provided an environment with the required flexibility for the engineering and data science teams to undertake the scope of work.

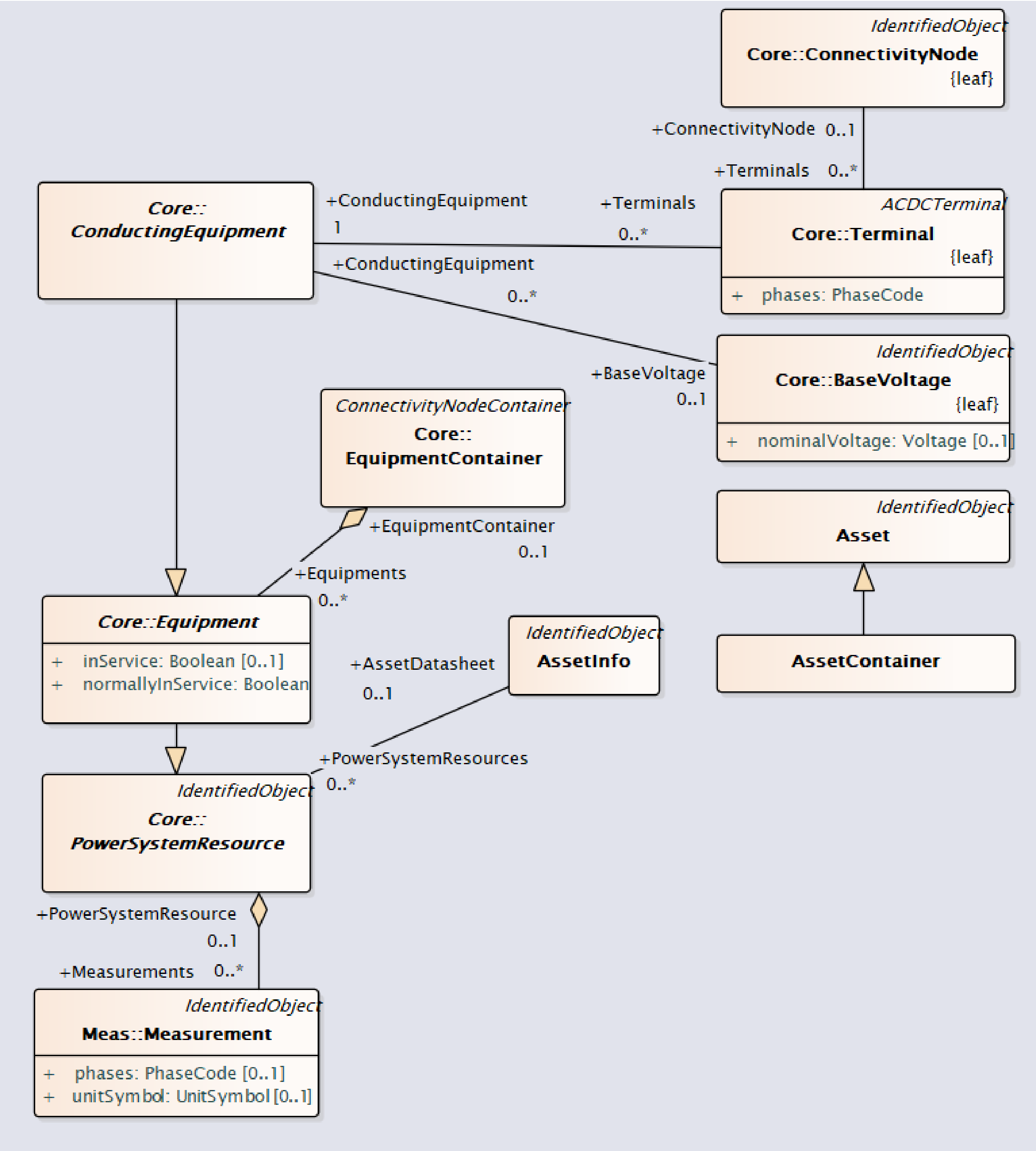


Figure 6 – CIM Data Model – Example of UML relationship diagram

2.6.2 Review of model completeness

Zepben undertook comprehensive analysis of the completeness of the Essential Energy network model. Some relevant findings included:

- Network voltages were complete for all the network,
- Non-zero network impedance values were available for 51% of cable sections, covering 94.34% of network length,

- Non-zero network impedance values were available for 99.86% of the MV network length,
- Non-zero network impedance values were available for 65.94% of the LV network length,
- 230km of LV network were defined with a high network resistance greater than 5 Ohms per km (3160 sections of line),
- 15.95% of services have their impedance defined, and
- Phase data was often missing or anomalous for the MV network.

In summary, the network models for the MV network (except for reliable phase data) were reasonably complete and suitable for use in electrical modelling, while the LV network required remediation.

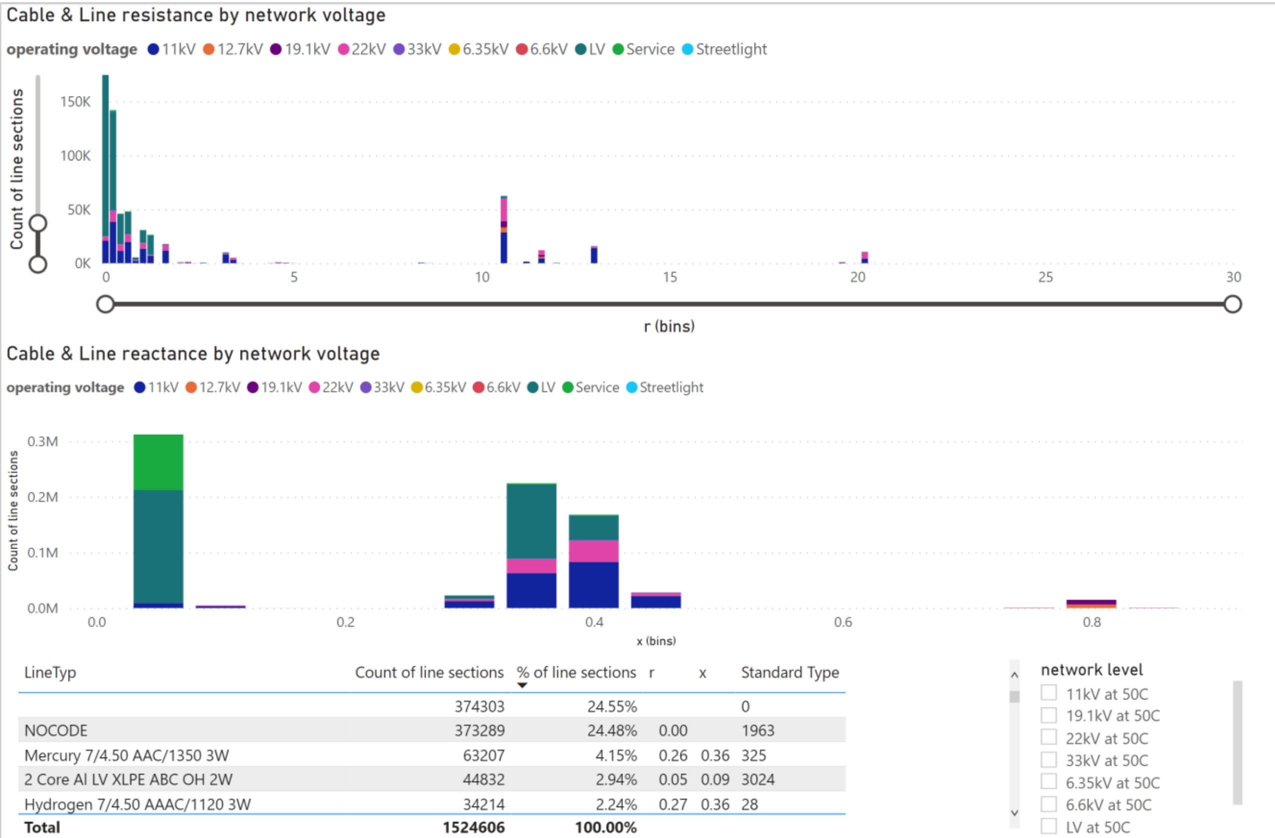


Figure 7 - Dashboard of line segments

The MV model is used by Essential Energy as an input into its business-as-usual planning activities, as well as real time operation of the network. This provides an explanation of why the MV network model was generally of good quality.

The LV network, on the other hand, has traditionally only been relied upon for asset location use cases. This means that certain key properties such as connectivity, phasing and impedance information have not been reliably captured or maintained, and so were not of sufficient quality to directly undertake electrical modelling.

A multistep process to patch missing information, refine incompatible connectivity and align inappropriate network phase connections was needed as a pre-requisite to running the load flow studies.

Through this work, Zepben developed a comprehensive set of algorithms capable of repairing the network models, using a combination of available attributes, business logic, location context, supporting asset information and standard assets library properties. Included in the data remediation were algorithms to:

- Infer consistent phasing in the MV network, and across MV-LV transformers for both HV and SWER networks,
- Detect and rectify false LV loops,
- Identify and deal with private substation connection point handling, and
- Identify and deal with missing service lines

Once in place these algorithms were able to build models suitable for the application of load flow engines for 98% of Essential Energy's ingested network.

2.6.3 Energy Consumer Load profiles

Essential Energy's network has limited penetration of smart metering infrastructure and network monitoring, with only around 30% of customers having interval meters capable of providing 30-minute energy consumption.

Essential Energy, as a consortium member of the evolve project[2], developed a synthetic load synthesis capability that utilised the clustering of both basic (90-day energy) metering customers and interval metering customers (30-minute energy) to provide a complete dataset of synthetic, but realistic consumer level load profiles that were inputs into the load flow models.

The profiles were validated by Essential Energy against available transformer monitoring. However, to assess the suitability of this dataset for use in the Hosting Capacity modelling, Zepben also used the time-series aggregation capabilities of the Energy Workbench platform to review the performance of the energy consumer level profiles when compared against the SCADA measurements taken at the start of the feeder.

Figure **8** is an example of the aggregate performance comparison between recorded SCADA values and the aggregate synthetic profile based on 30% interval meters.

We confirmed that the "bottom-up" shape showed good alignment with the measured "top-down" SCADA values over a broad range of feeders.

[2] https://arena.gov.au/projects/evolve-der-project/

The interval metering dataset is biased towards customers with solar as this is often the trigger for the change out of basic energy meters. This means the synthetic profiles do a particularly good job of representing the solar generation profile with the network loading.

One limitation identified upon review of the synthetic profiles was the ability to capture the pickup in controlled load that occurs as hot water systems are cycled on each night. The identified cause of this was the interval metering dataset bias to solar customers. These customers provide most of the interval meter data for each cluster of customer types, and these customers have often switched away from controlled tariffs for hot water heating and moved to use their solar energy for hot water heating.

While a limitation, this 'spike' in hot water demand is by design not the network peak demand value, and so we considered limited materiality in the impact of 'smearing' the spike in demand from controlled load hot water heating.

Zepben identified that the alignment of peak network loading was typically within 20% of the SCADA recorded values, and while this is impressive based on the low % of interval metering customers used to generate the profile it did need to be improved for use in the hosting capacity modelling.

Essential Energy provided the 2021 peak daily load profile and power factor for each of the 1456 distribution feeders to be modelled. Zepben then used this input to scale the aggregate feeder level load profile to align with the recorded 2021 peak values and set the power factor for all loads on the feeder to the recorded feeder value. When scaling loads to feeder peaks a 5% distribution loss factor was used to account for typical losses between HV feeder and LV connection points.

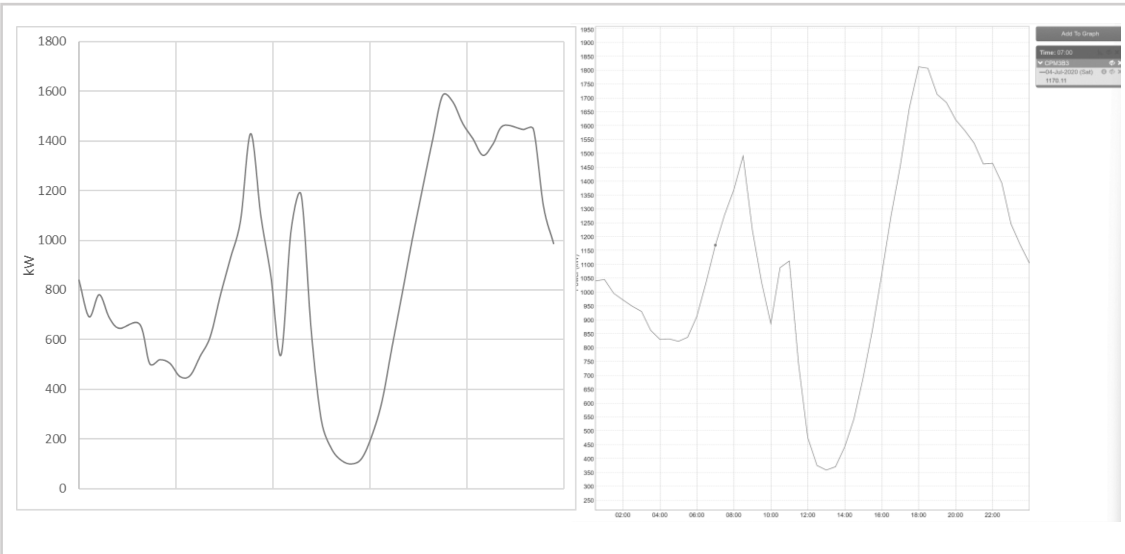


Figure 8 – left: SCADA measurements taken from the start of the feeder. Right: aggregate profile built up from the customer level. Both from 4/7/2020.

This process resulted in a 30-min interval load profile for each energy consumer for a complete year aligned with the network loading for 2021.

These profiles were stored within the Energy Workbench platform, and then broken down into a peak load value and a normalised demand profile, see Figure 9, suitable for being used by the OpenDSS load flow engine.

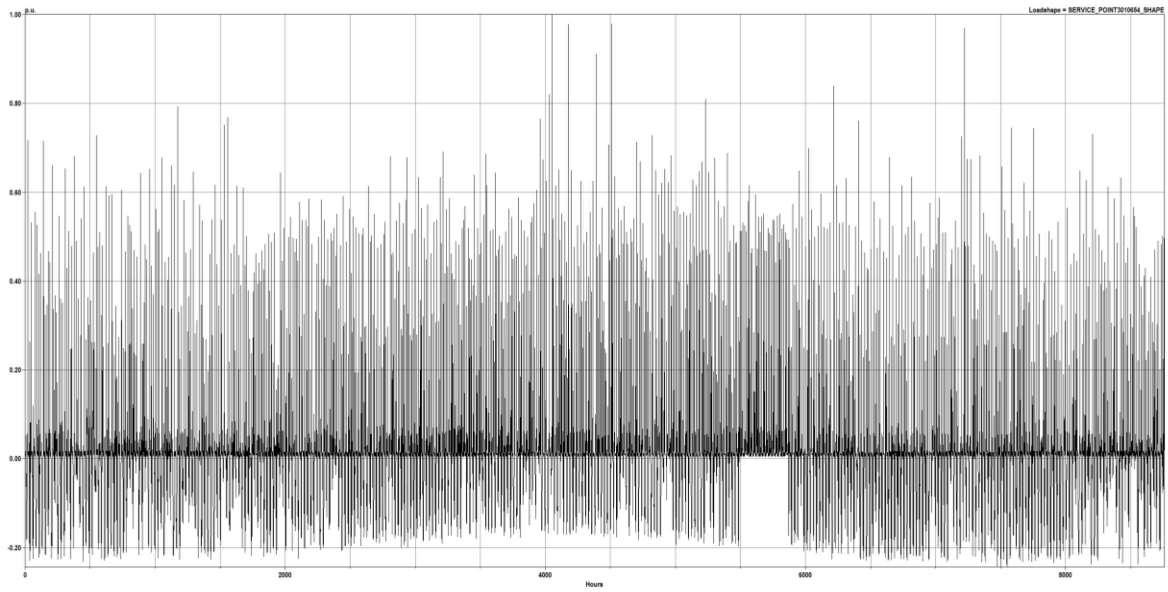


Figure 9 - Example of 30-min annual normalised loadshape that when combined with the recorded load peak value of kW=4.01 & PF=0.99 defines modelled load

Load.service_point3010654_LOAD bus1=XYZ kV=0.415 Phases=3 kW=4.006813042405478 PF=0.99 yearly=service_point3010654_SHAPE

The normalised load profile in Figure 9 represents the load factor for a particular energy consumer, with values ranging from 1 to -1 depending on the loading for a given 30min period. For example, the value of 0.5 represents the energy consumer using 0.5*4.1kW=2.05kW on average over an interval.

Note that as Essential Energy's energy customers have already embraced PV systems it is common for this profile to also have intervals of negative load, for example -0.2 represents the energy consumer exporting -0.2*4.1kW=-0.82kW on average over the interval i.e. 0.41kWh for the 30-min period.

This combined approach of using the highly granular energy consumer level profiles and feeder level demand for scaling, provided a good basis to use the model results to assess the distribution transformer level performance of the network. It is an improvement over the traditional industry approach of allocating local network consumption based on assumptions around transformer loading.

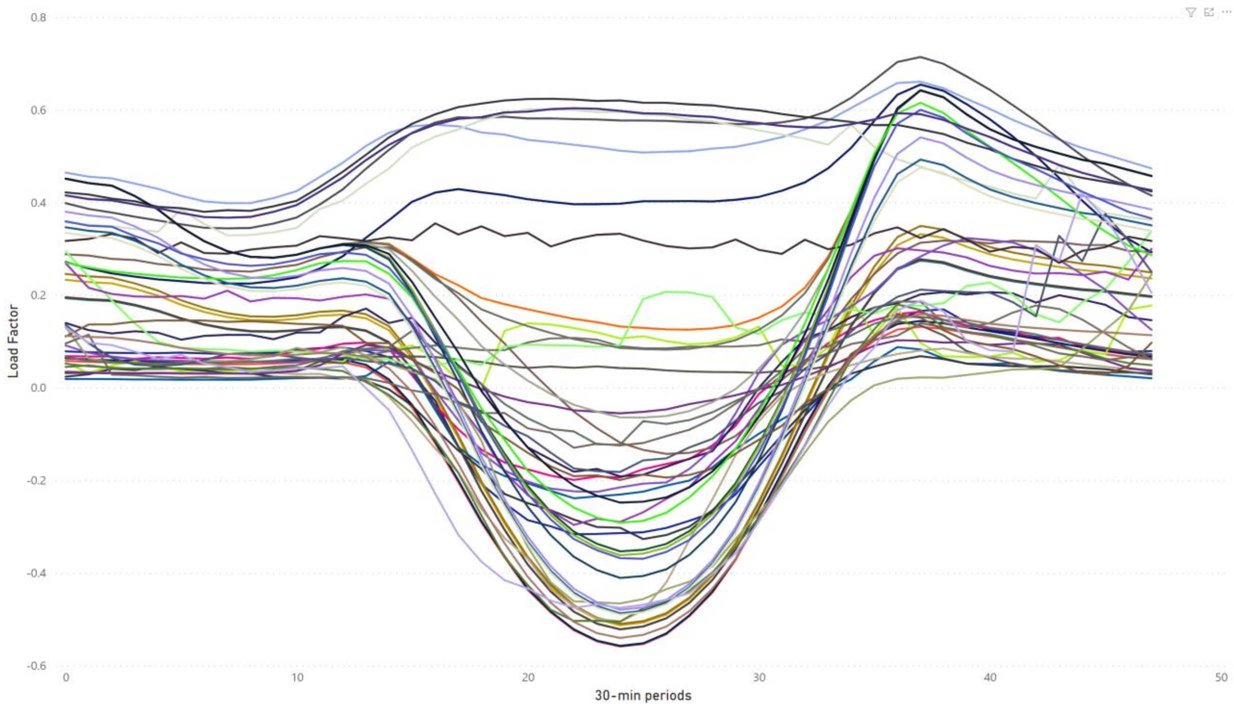


Figure 10 - Example of energy consumer profiles

2.6.4 Demand and DER Forecasts

Essential Energy commissioned Frontier Economics to produce a comprehensive set of forecasts for the next 15-year period. These forecasts included underlying network demand, electrification, PV uptake, electric vehicle uptake and consumer battery uptake, broken down to the level of Zone Substation.

These forecasts were used to create the load and generation inputs into the hosting capacity analysis. The forecasts included central, high and low scenarios. Each of these aligns with an Australian Energy Market (AEMO) integrated System Plan (ISP3) scenario, that is.

- Central: Step Change,
- Low: Progressive Change, and
- High: Strong Electrification.

The starting point for the base year network demand were the underlying demand profiles as outlined in section 2.6.3.

Beyond this, for each of the years of the forecast period, the underlying demand levels (i.e. the network loading before customer uptake of DER is considered) were adjusted based on the POE50 combined underlying and electrification growth trend provided by Frontier for

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

each of the forecasts scenarios. This approach was defined after engagement with Essential Energy's power system analysis lead and forecasting team.

2.6.5 DER Technology Forecasts

As part of the forecasting outcomes commission by Essential Energy, Frontier Economics provided DER technology forecasts[4] for the period 2022 to 2037 at the Zone Substation level that covered:

- PV panel capacity (MW)
- Battery Storage capacity (MW)
- Electric Vehicle numbers by type

Zepben used these forecasts to simulate the connection of DER devices at the energy consumer level within the Energy Workbench model of Essential Energy's distribution network to provide the equivalent DER capacity as the aggregate amount provided by the forecasts. This enabled bottom-up modelling of the impact of the DER on the network according to the top-down forecasts.

2.6.5.1 Modelling of PV forecast

The following approach was taken to model the forecast PV uptake at the Energy Consumer level.

- The Zone Substation level PV panel capacity (MW) forecast was broken down into the equivalent number of systems needed to make up the aggregate amount using a standard 6.6kW DC / 5kW AC system size assumption. This size was selected after reviewing the Australian PV Institute average system size tracker[5], Essential Energy's automatic connection levels and the expected trend in systems size. We determined that this size system was the most appropriate unit of capacity to allocate out PV panel capacity due to the following reasons:
    - It is the most common system size currently installed
    - It was less likely to substantially overload weak pockets of the network, impacting the ability of network models to converge.
    - It worked well with the allocation logic of assigning a second PV system once all customers had been allocated an initial system, resulting in a proportion of customers having a 13.2kW/10kW system which is the second most popular size of system according to Australian PV Institute data.

[4] Forecasts of customer numbers, energy consumption and demand - A report for Essential Energy - 8 April 2022

[5] https://pv-map.apvi.org.au/analyses

- The number of PV systems per feeder was calculated based on the number of customers connected to that feeder.

- Systems were then randomly allocated to customers that currently have no PV system or have a system less than 3.5kW. This reflected the likelihood that customers with existing PV are likely to upgrade if they were an early adopter with a small system.

- If all customers were allocated a PV system, the remaining PV systems were randomly allocated amongst customers irrespective of their currently installed capacity.

- If all customers on the feeder were allocated two new PV systems and there was still unallocated PV capacity, this capacity was left unallocated and written to a log file to be reported as a likely over allocation of PV during the forecasting process.

- Each PV system was assigned an annual generation profile based on the following characteristics

    - 6.6kW DC / 5kW AC system with phasing matched to phase connection in the model,

    - Roof mounted at 15 degrees & north,

    - Located in Coffs Harbour, on the mid north coast of NSW, based on a review of variability in irradiance across the state, see Figure 12, and consideration of EE's population centres, and

    - Includes historic typical cloud cover

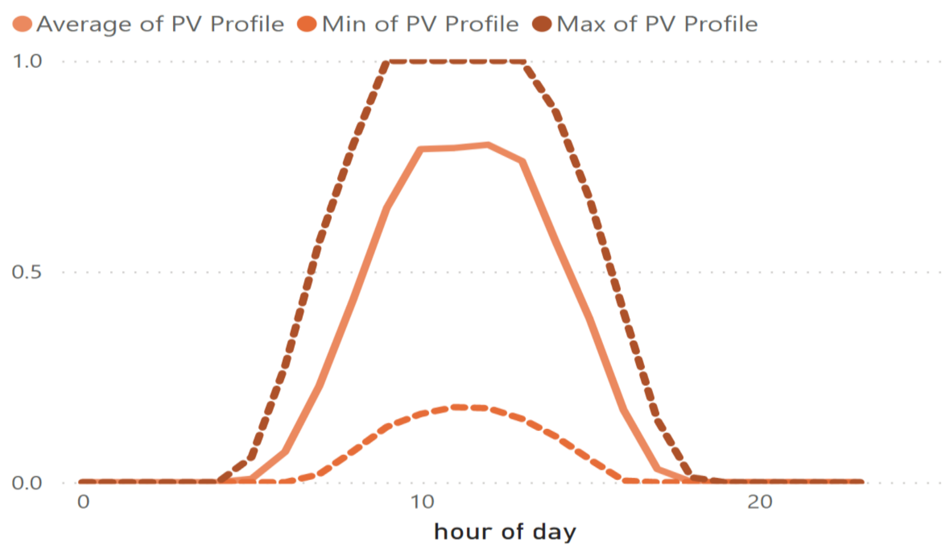


Figure 10 - Daily summary of PV generation profile used Figure 11 - Daily summary of PV generation profile used

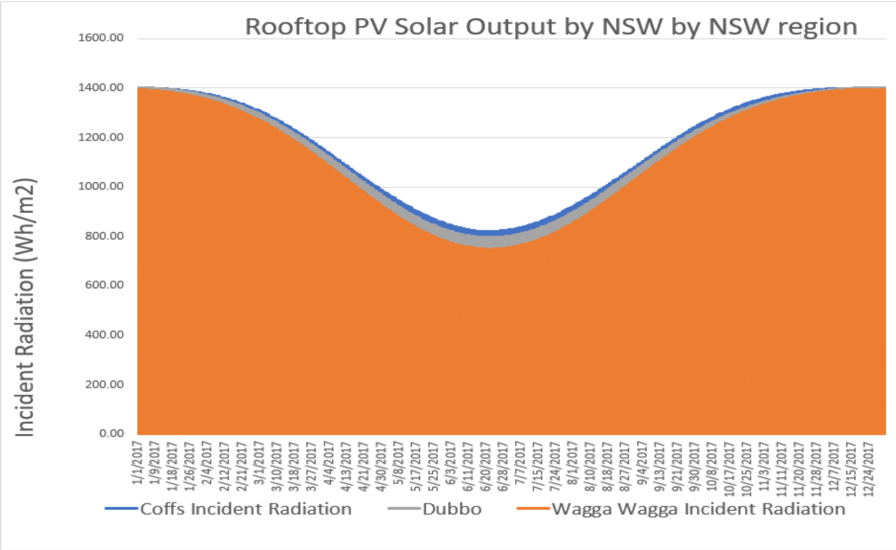


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Figure 12 - review of variation in solar irradiance across Essential Energy's network area

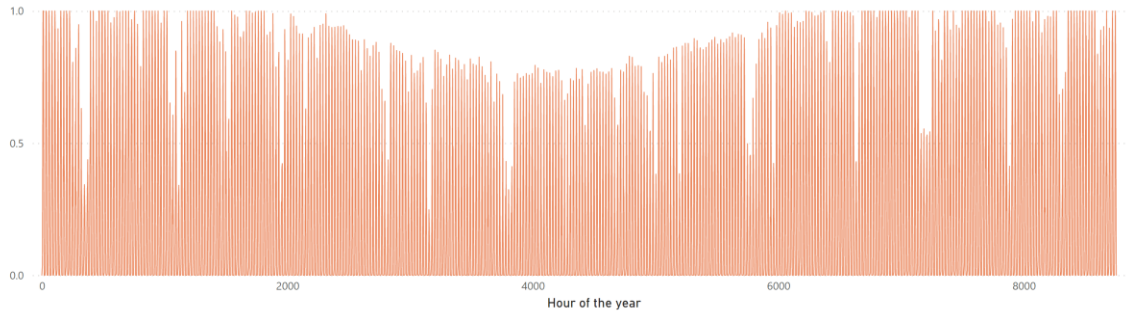


Figure 13 - Annual PV generation profile applied to new PV capacity added as part of the forecast scenarios

2.6.5.2 Modelling of Battery Storage forecast

The modelling of Battery Storage forecasts was done using a similar approach as for forecast PV uptake:

- Battery Energy Storage System (BESS) capacity (MW) forecasts at the Zone Substation level were broken down into a number of systems based on a standard system size of 5kW/10kWh. This level was based on a review of industry sources[6], with the typical range of grid interconnected systems being between 6-11kWh.

[6] https://www.sunwiz.com.au/wp-content/uploads/2022/03/SunWiz-Australian-Battery-Market-2022-purchaserA_Redacted-1.pdf & https://onestepoffthegrid.com.au/australians-installed-22661-home-battery-systems-in-2019/#:~:text=The%20report%20shows%20that%20the,various%20state%20government%20subsidy%20guidelines

- The number of battery systems per feeder was calculated based on the number of customers connected to that feeder.

- Battery systems were then randomly allocated to customers that also had PV, initially to those with system sizes greater than 3.5kW of panel capacity, and then to remaining customers once exhausted.

- Each battery system was assigned an annual profile based on the following characteristics

  - Battery control/dispatch based on targeting self-consumption using the typical diversified residential load shape, and the default PV profile – This analysis was completed using the NREL SAM model[7]

  - 5kW AC / 10kWh – with phasing is matched to customers current connection

  - System losses 14%

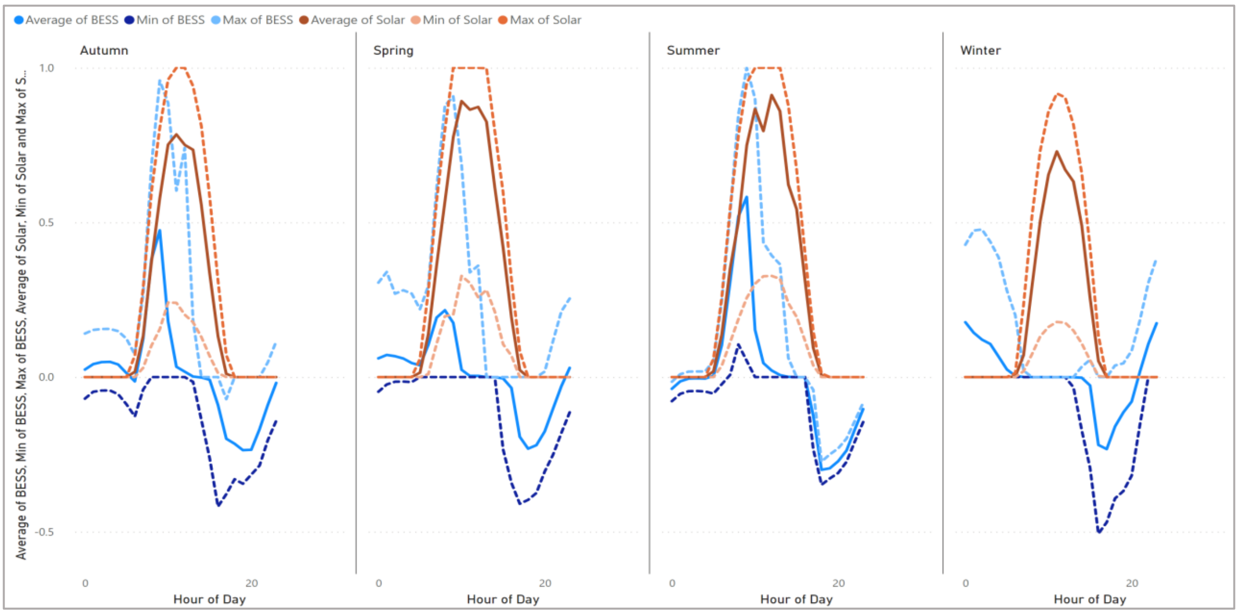


Figure 14 - Combined seasonal view of PV and battery storage load profiles plotted on the same axis

2.6.5.3 Modelling of Electric Vehicle forecast

The provided EV forecasts were broken down into three categories:

- Buses & Trucks 2%,

- Commercial 14% and

[7] https://sam.nrel.gov/

- Residential 84% (% as of 2030).

Based on the focus of this modelling being on the LV and current MV network, Zepben and Essential Energy agreed to limit the EV modelling to commercial and residential vehicle forecasts. The key driver for this decision is the way in which this type of load and charging infrastructure is likely to connect to the network.

Under Essential Energy's current capital contribution policy, connections of these large loads are subject to capital contribution requirements for impacts to the shared network in addition to direct connection infrastructure. The output of this hosting capacity modelling work is seeking to capture constraints that Essential Energy is required to address under the standard control expenditure framework, therefore it made sense to exclude the consideration of Buses and Trucks.

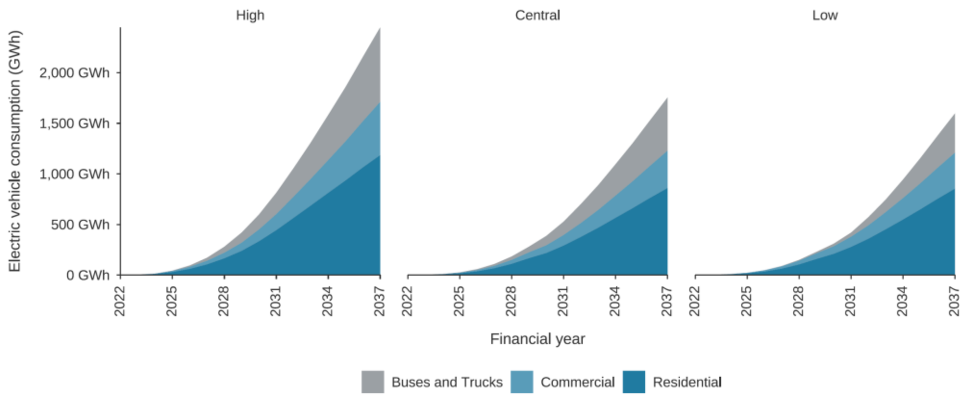


Figure 15 - EV consumption forecast by vehicle class, source Frontier Economics

The modelling of EV forecasts was done using a similar approach as for forecast PV and battery storage uptake:

- Zone Substation level forecast EV numbers were spread across feeders based on customer numbers
- Each forecast electric commercial vehicle was given a L2 7kW peak charger, and these were allocated randomly across existing customers that had > 15kW peak connection demand currently. Customers could be allocated multiple commercial EV L2 chargers.
- Residential vehicles were randomly allocated across all customers, each EV was allocated a L2 7kW charger with a residential charging profile.

Electric vehicle load is expected to make up half of all residential energy consumption, so it is critical that appropriate assumptions are used to represent the profile of this energy consumption when considering its impact on network performance.

To maintain alignment with AEMO's ISP scenarios, Zepben utilised the charging profiles developed by CSIRO[8] for AEMO as part of their input into the ISP; see Figure 16.

This dataset provides a year-by-year breakdown of how charging behaviour is expected to develop as progress continues towards more cost reflective tariffs and solar uptake continues to increase. However, the limitation with these charging profiles is that they are assumed to include diversity suited to modelling at a system level and are likely to understate the peak for a demand profile of a much smaller collection of EV chargers, when modelling their impact at the street level.

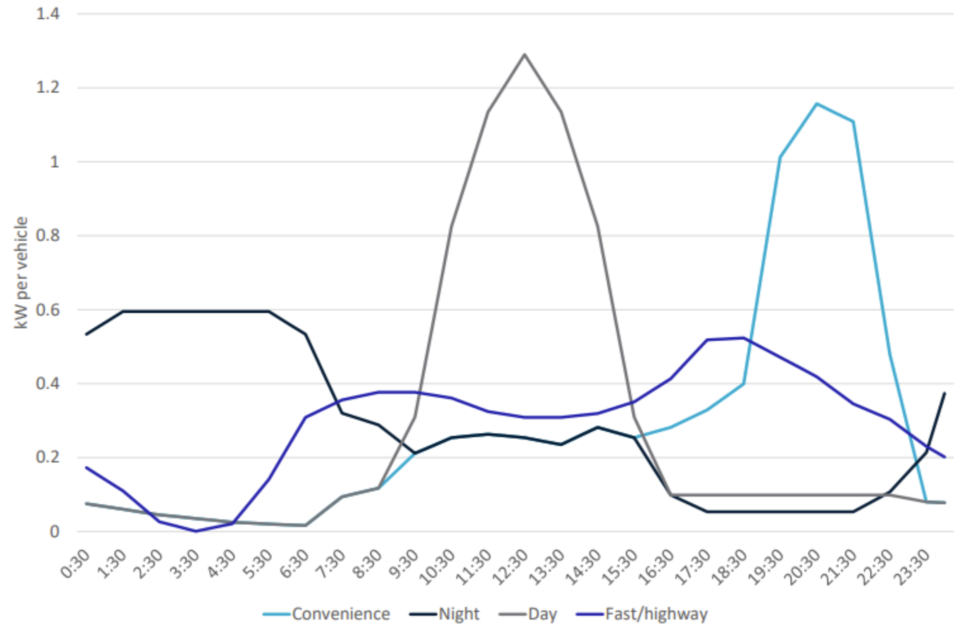


Figure 5-9 Average daily charging profiles for light passenger vehicles

Figure 16 - sperate types of charging profiles that form the input into the overall charging profile used within the model – CSIRO 2021[5]

A compromise was made to use the same profiles as used within the AEMO ISP scenarios, despite the potential to understate the peak demand contribution when considering the street level impact. This was considered reasonable based on the key period of interest being the period to 2029, and the material impact of this assumption not occurring until the 2030-2034 period. Future work could consider additional sensitivity analysis for specific EV charging behaviour and investment in improved data on customer EV charging behaviours.

The profiles used within the hosting capacity analysis are shown below. The commercial EV profile,

[8] https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/csiro-ev-forecast-report.pdf

Figure **18**, is initially defined with greater daily energy consumption, higher peak value and larger day time consumption when compared to the residential EV charging profile. The profiles start off in year 2022 with less diversity and more evening energy consumption, and over the forecast period respond to price signals, increasing daytime charging.

Residential EV profiles, Figure 17, follow a similar trend to the commercial profiles, with a gradual move each year from mostly convenience charging in the evening to much more daytime charging.

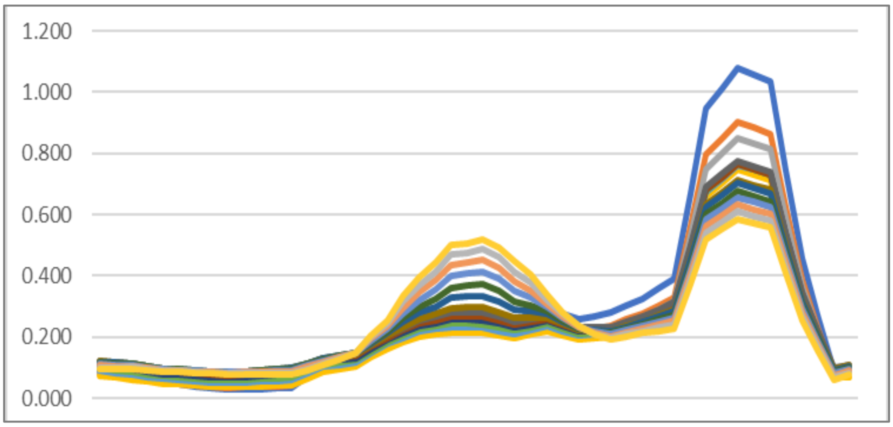


Figure 17 - Residential EV charging profile (kW) coloured by year, blue 2022, yellow 2037

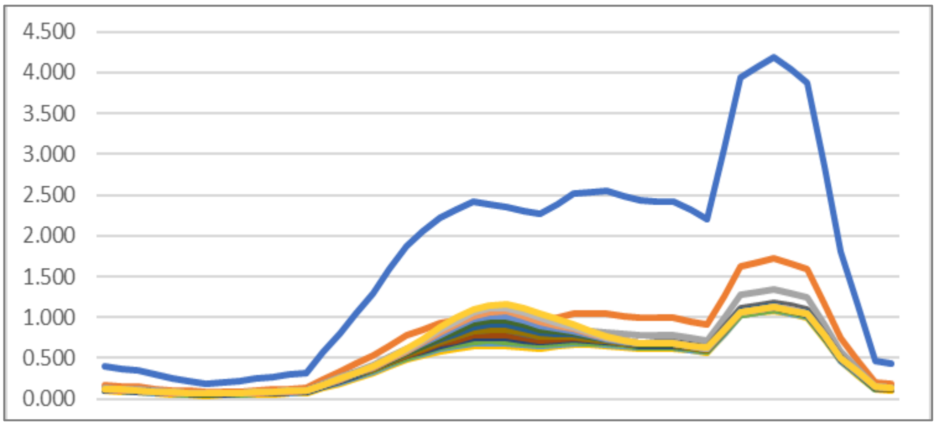


Figure 18 - Commercial EV charging profile (kW) coloured by year, blue 2022, yellow 2037

2.6.6 Modelling Assumptions

The following table provides a summary of the notable assumptions made when implementing the electrical asset models.

NETWORK	
ENERGY CONSUMERS	Energy consumers were connected as defined within Essential Energy's GIS. Where customers were defined as three phase their load was balanced across all three phases. Single phase customers with an unknown phase were randomly assigned a phase.
	Where customers were not connected to a node within the geospatial electrical model, the customer information system relationship between customer and substation was used to allocate the energy consumer to the LV terminals of the transformer, phasing of these customers were aligned to the transformer phasing.
SWER	Singe Wire Earth Return (SWER) transformers were modelled as 250v nominal split phase transformers as per the networks original design. Customer loads were all defined as single phase and only connected across one 'leg' of the split phase transformers secondary.
	SWER earth return was modelled as a 0 Ohm earth into 100 Ohm soil using the Deri earth model.
VOLTAGE REGULATORS	Voltage regulators were included within the modelling; all were operated to regulate the network normal downstream bus voltage. The regulation settings were defined as follows: float 1.023pu, bandwidth 200v (1.5-3%). Impedance and ratings for voltage regulators were provided as a separate dataset (to the geoJSON GIS extract) and were included within the model.
RATINGS	Line and transformer normal rating were defined by their standard type, referencing Essential Energy's provided standard transformer type dictionary. Where an emergency rating was not available the default was set to 150% of the normal rating.
SERVICE LINES	Missing service line impedance values were defined using Essential Energy's current standard conductor of 25mm^2 XLPE AL conductor, either 2-core of 4-core depending on the connection type (single or three phase).

TRANSFORMERS	Missing distribution transformer parameters: where ratings are unknown 234kVA was set as the default value, for missing impedance values 4% primary to secondary default was applied.
LINES	Missing line parameters were set based on the following logic - Apply the most common line type by voltage for that feeder. - If no known type is available for that voltage on that feeder, select from remaining conductor parameters based on the rating. - If the rating is not available assign default conductor parameters.

The following table provides a summary of the notable assumptions made when implementing Load and DER profiles, in addition to explanations previously provided on the implementation of DER and underlying load forecasts.

LOAD & DER	
NETWORK DEMAND	Overall feeder peak demand was aligned with 2021 measurement data.
	Privately owned substations (customer owned) were not modelled with customers attached, they were instead connected at the customers HV metering point. The result is that the appropriate upstream Essential Energy network loading is modelled, however constraints are not reported for the private assets downstream of the HV metering point.
DER	DER assets were modelled operating at unity power factor
LOADS	For the voltage range 0.85pu through to 1.15pu loads were modelled as constant power. Outside this range loads were changed to constant impedance to assist with convergence to a solution.

2.6.7 Model testing, refinement, and development

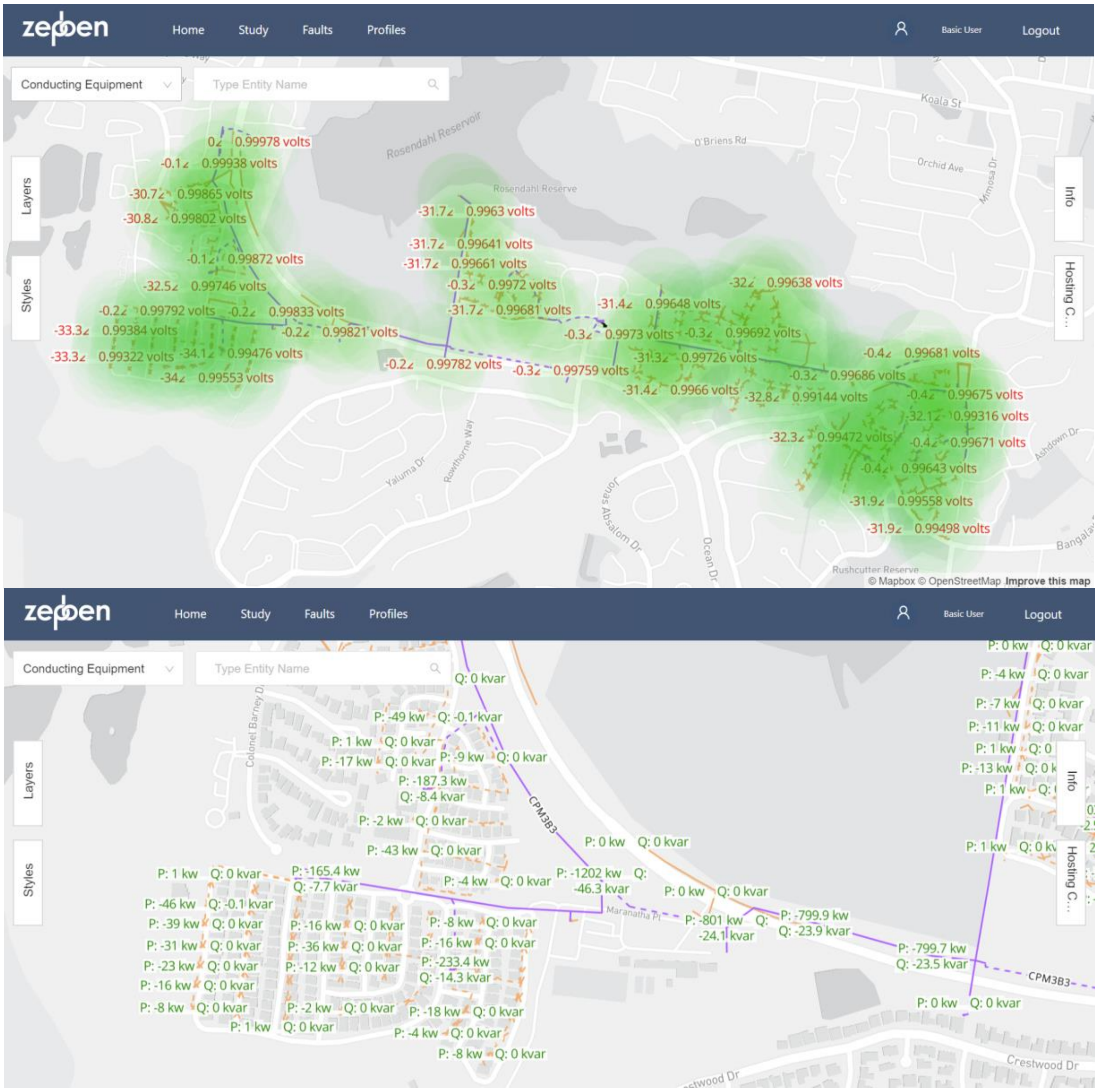


Figure 19 – screenshots showing analysis of feeder performance in Energy Workbench as part of model testing

Essential Energy made available smart meter voltage datasets in order to assist with validation of the Energy Workbench model's performance against real world measurements.

The voltages produced by the baseline models were compared with the available measured voltages. Real and reactive power inputs to the model were the same as those created and validated by the synthetic load profile work described earlier in this report.

Initial results, presented in Figure 21 and Figure 20, show the baseline network electrical model performance. They show reasonable alignment with measured low voltages, however showed poor alignment with measured high voltages.

Zepben investigated the contributing factors to this discrepancy and identified the following as additional opportunities to improve the model performance:

- Adding accurate transformer impedance values not provided in the GIS sourced geoJSON,
- Including specific tap settings for distribution transformers where available with the Asset Information System (AIS),
- Separating the treatment of service lines and LV network to provide tailored business logic for patching missing impedance data,
- Revision to some of Essential Energy's default LV conductor library values,
- Inclusion of upstream sub-transmission network source impedance, and
- Addition of OLTC to the start of the feeder electrical model with available voltage regulation settings applied.

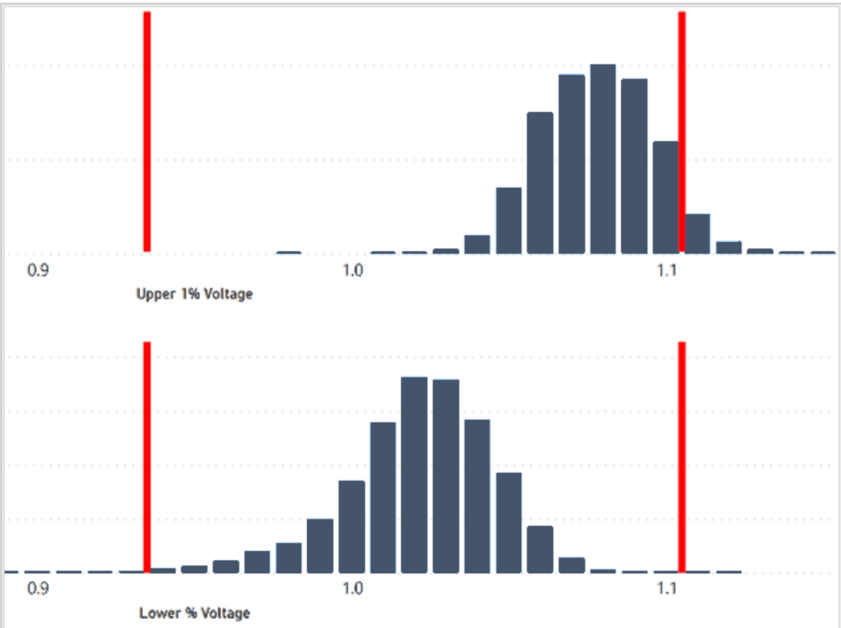


Figure 20 - Review of model voltage outcomes for LV network areas that have smart meter voltage measurement sites, upper chart - Highest voltage, lower chart – Lowest voltage (recorded for the year by network section)

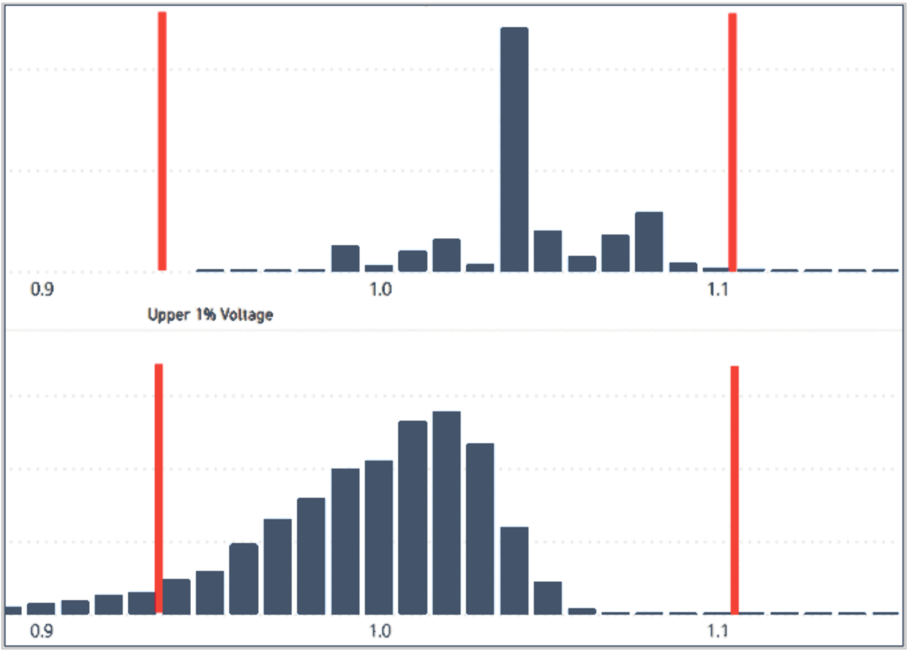


Figure 21 - Review of voltage performance of available measurement sites, upper chart - Highest voltage, lower chart – Lowest voltage (recorded for the year by network section)

Most of the information required to build an electrical model of Essential Energy's network; a "digital twin", was included within the GIS sourced geoJSON described in section 2.6.1.

However, to implement the identified improvements to the network model, additional detailed asset attributes had to be sourced from other Essential Energy systems.

Essential Energy provided a number of additional data sets that were ingested and included within the Energy Workbench CIM model, these included:

- Additional transformer attributes from WASP (AIS),
- Voltage regulation settings from the SCADA system records,
- Revised LV impedance information from Essential Energy's design standards,
- Additional voltage regulator attributes including rating, and
- Network normal Zone Substation source impedance values from CAPE system used to manage sub-transmission network protection.

2.6.7.1 Revised base model

Once the revised and additional information was incorporated into the CIM data model, a revised set of models and results were produced. The performance of these models was reviewed in a similar approach to the initial base models.

This review showed a marked improvement in the models alignment with measured voltages.

The distribution of high voltage showed the largest improvement, the revised model output showing a <2% error between the measured and modelled average high voltage level. The distribution does still show bias towards an underestimation of high voltage events, with the centre of the distribution shifted to the left slightly.

The most likely source of the model slightly underestimating the upper and lower worst case voltage performance values is the use of demand profiles synthesised from 30min energy profiles. These profiles, by definition, assume a constant demand over a 30min period. This 'smooths' out demand spikes below this level, for example a load that consumers 5kW for 30mins records the same 30min energy value as another load that consumes 15kW for 10mins. This 'smoothing' of spikes in generation and load is likely to cause the extremes in the network voltage performance to be 'softened'.

Overall, the voltage performance of the revised model approach provided sufficient validation to move forward and use the complete network models to provide a forecast view of network constraints.

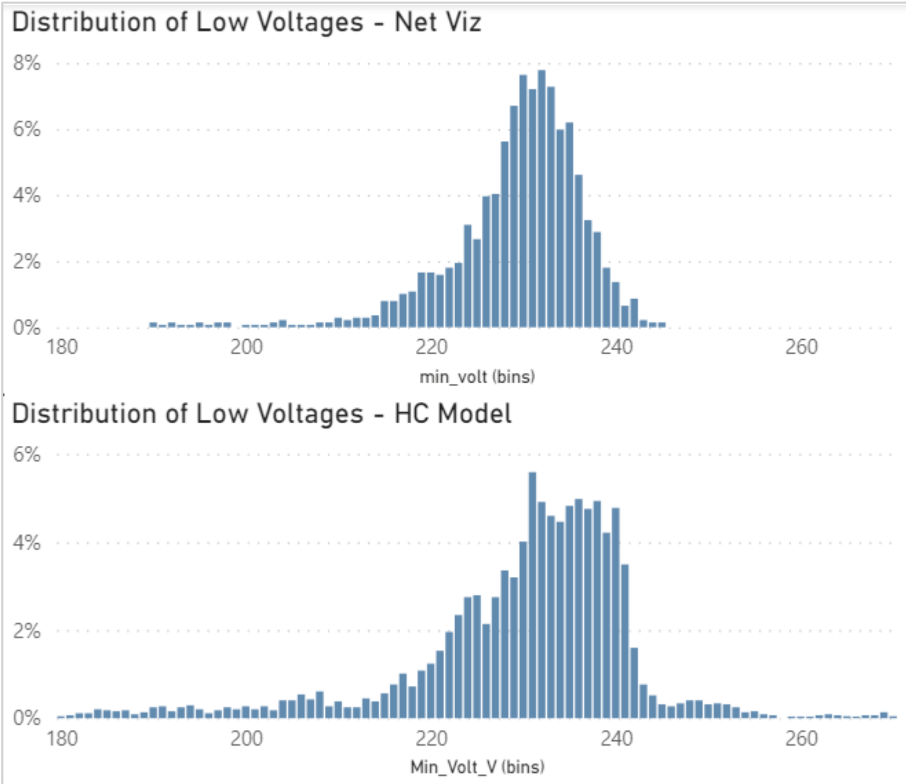


Figure 22 – Sample Review of model voltage outcomes for LV network areas that have smart meter voltage measurement sites, upper chart – measured values, lower chart – modelled values

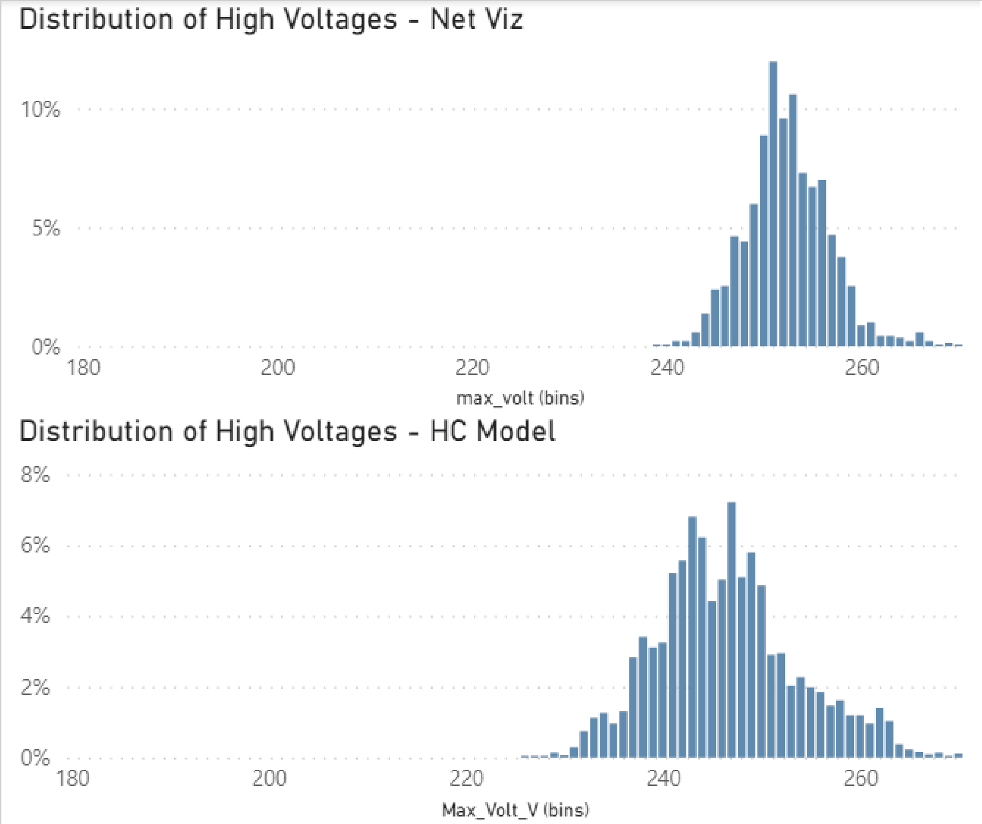


Figure 23 – Sample review of model voltage outcomes for LV network areas that have smart meter voltage measurement sites, upper chart – measured values, lower chart – modelled values

2.6.8 Cluster analysis

Zepben identified that with the large number of highly granular results being produced by the modelling, a new classification of network types would be required in order to assist in interpreting the large dataset.

The solution was to classify each transformer and downstream LV network section, see Figure 25, into categories that represented the characteristics of the group of assets. This enabled interpretation of how collections of like assets perform and allowed results to be compared between types of network construction. It also enables the subsequent economic analysis undertaken by Baringa as part of the Future Network Business Case to logically group the assessment of costs and benefits by network types.

The approach taken included the following:

- Based on the geoJSON network model ingested, Zepben developed a set of descriptive metrics using our own SDK to characterise each LV network section of EE network.
- Applying a machine learning algorithm (k-means clustering) to evaluate patterns within these metrics. All category metrics were converted to numeric values and normalised.
- The following metrics were found to provide a clear delineation and sensible grouping:
    - Number of Energy Consumers
    - Number of AC line segments
    - Total conductor length
    - Max energy consumer distance to the transformer
    - Min energy consumer distance to the transformer
    - Max AC line segment length
    - Average energy consumer distance to the transformer
    - Number of 3 phase customers
    - Number of 1 phase customers
    - Land use
    - Type (underground/Overhead)
- The following metrics were found not to assist with clustering:
    - Number of poles: AC line segments represented this characteristic and the inclusion of both skewed the definition of clusters
    - Average conductor length
    - Distance to ZS: this reduced the clear delineation between clusters
    - Population Density: better performance was observed with Land use

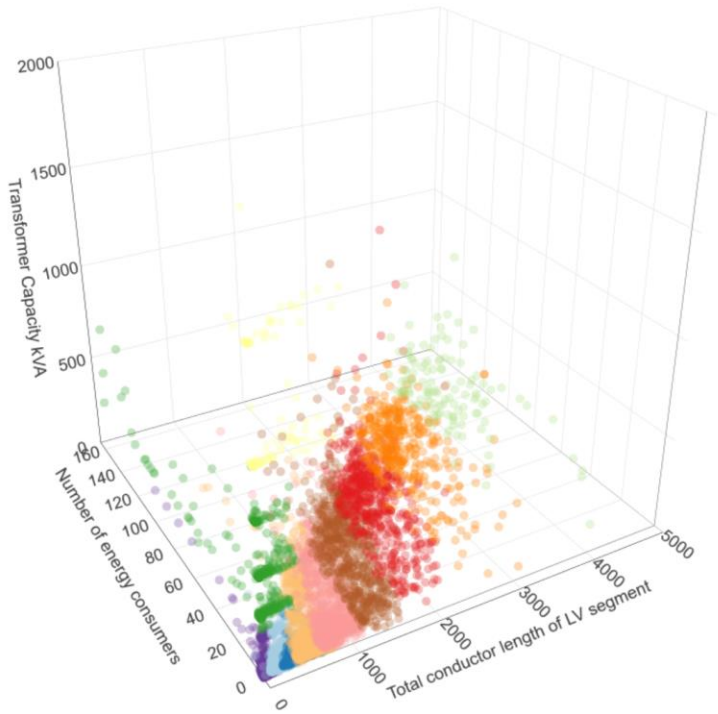


Figure 24 - Plot of categorised LV networks coloured by cluster type

Table 2 - Descriptive table of identified clusters

Cluster Description	% of Network	Mean Values for clusters							Type	% 3 Phase
		No. Ecs	KVA Capacity	No. Segments	Average length	total length	max ec distance	max length		
Medium Dedicated OH	2%	2.0	146	2.1	20	41	26	29	Overhead	99%
Rural / Fringe Urban shared OH	6%	8.8	97	20.5	61	848	298	199	Overhead	69%
Sparse shared OH LV	1%	76.4	284	138.3	43	3394	449	198	Overhead	98%
Underground Urban	2%	52.0	363	127.5	19	2240	369	131	Underground	100%
Underground Commercial	3%	9.9	595	27.5	10	356	103	59	Underground	99%
Underground Dedicated / Private	1%	0.1	861	3.1	1	29	0	8	Underground	99%
Small Rural shared OH	20%	1.7	25	4.2	60	204	101	122	Overhead	35%
Disconnected Customers*	4%	0.0	55	1.0	21	46	0	30	Overhead	54%
Urban Large OH	2%	48.6	245	92.4	29	2215	403	116	Overhead	99%
Medium Shared OH	11%	3.2	44	8.2	72	460	198	197	Overhead	46%
N/A - low count	0.03%	19.2	141	60.7	697	14231	207	4260	Overhead	35%
OH Commercial	2%	4.9	382	6.1	21	112	50	43	Overhead	100%
Small Rural dedicated OH	45%	1.1	19	1.6	25	40	29	32	Overhead	30%

Urban Medium OH	3%	24.8	181	51.3	38	1428	361	143	Overhead	94%

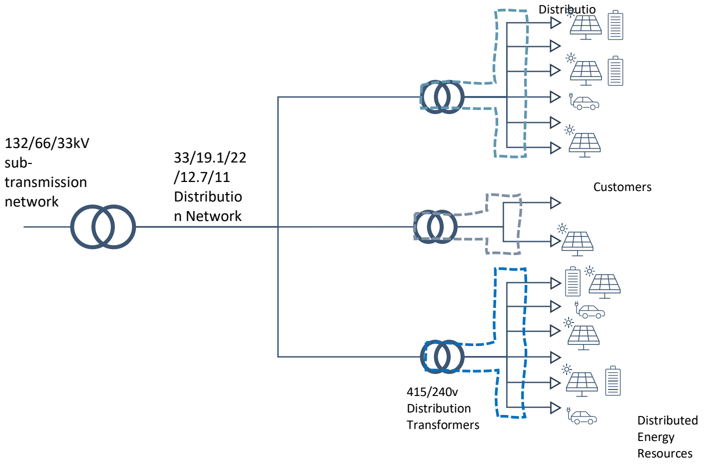


Figure 25 - Example of network sections that are defined by each cluster - total of

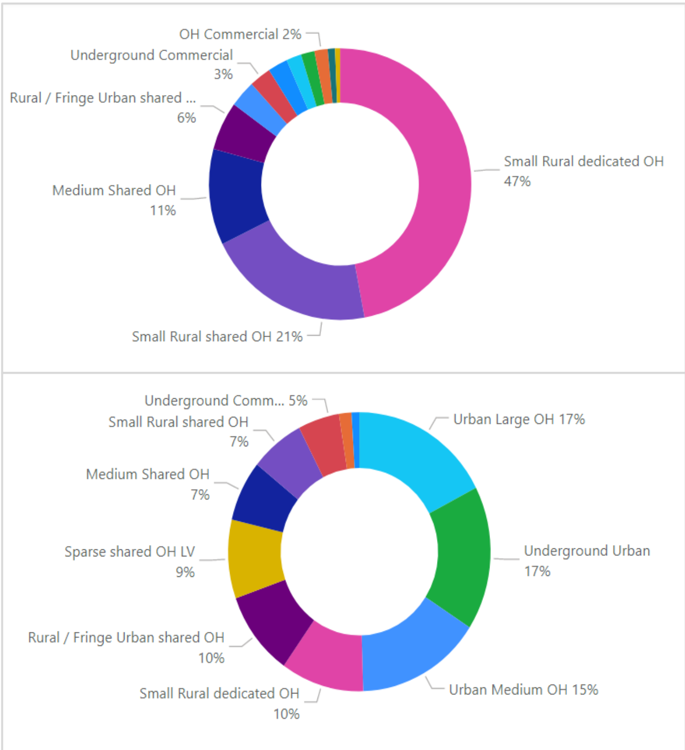


Figure 26 - Proportion of Substations (Above) and Proportion of Customers (Below) per each cluster type

A total of fourteen (14) cluster types were defined by this analysis. Twelve (12) of these cluster types were then used to define the representative network sections for the network wide analysis. The two categories that have not been included in the analysis are those referred to in the table above as:

1. ***N/A - low count:*** the clusters representing network with conductor length outliers not considered valid (0.03% of total network)

2. ***Disconnected Customers:*** the clusters with missing customers and/or network (4% of total network).

3 HOSTING CAPACITY FORECAST

3.1 KEY RESULTS

This section focuses on the modelled performance of the network under the input forecasts for future DER uptake. The key findings are as follows:

- **Network performance is not homogenous across the 12 assessed classifications of network types identified**. With network performance results ranging from constrained under current DER penetration levels, through to remaining un-constrained at the end of the forecast period – 2037.

- For the network sections that did breach maximum voltage limits or thermal constraints the **average solar penetration level when this occurred varied significantly between network classifications**. With small rural substation network sections on average hosting 2.4kW of solar per customer before reaching **voltage limits**, compared to 6.3kW per customer for underground commercial network sections.

- **The point at which voltage and thermal constraints are breached varied significantly within different network classifications**. For example, Medium shared Overhead network sections reached **voltage** limits at 3.2kW of solar per customer on average, but did not hit **thermal** limits until 6.4kW per customer on average.

- **Constraints identified over the 2024-2029 period are primarily driven by decreasing minimum demand and increasing reverse network flows**, making the efficient management of generation curtailment at the energy consumer level a key focus.

- From 2028-2037 EV uptake becomes broad based, at this point **local LV network thermal and voltage performance becomes highly sensitive to EV charging profiles.**

- **Uncoordinated or 'convenience' based EV charging would constrain between 50%-100% of network sections by 2037**, depending on the network classification.

- **Essential Energy's recent and current LV network designs can support EV charging demand** if transformer level contribution to after diversity maximum demand can be limited to around 1kW per energy consumer. While this level of 'smart charging' is possible, it is currently unprecedented for solutions running at scale to influence charging behaviours.

3.2 MODELLING SUMMARY

Summarising the approach outlined in section 2, the below graphic Figure 27, illustrates the workflow used to carry out the hosting capacity forecast.

- The base models capturing the physical assets and current network are created in a format suitable for applying the OpenDSS load flow engine, using the Energy Workbench platform
- These models are run using OpenDSS load flow engine for the whole network for each hour of the year to calculate both power flow and voltage performance
- Following modelling of the base year, the underlying network demand is adjusted for the forecast year to be modelled
- DER assets are then added to the network at the low voltage level based on quantity and in proportions defined by the forecasts
- Then power flow and voltage performance of the whole network are then modelled using the OpenDSS load flow engine for each hour of the forecast year
- This cycle is repeated for the 15-year forecast period

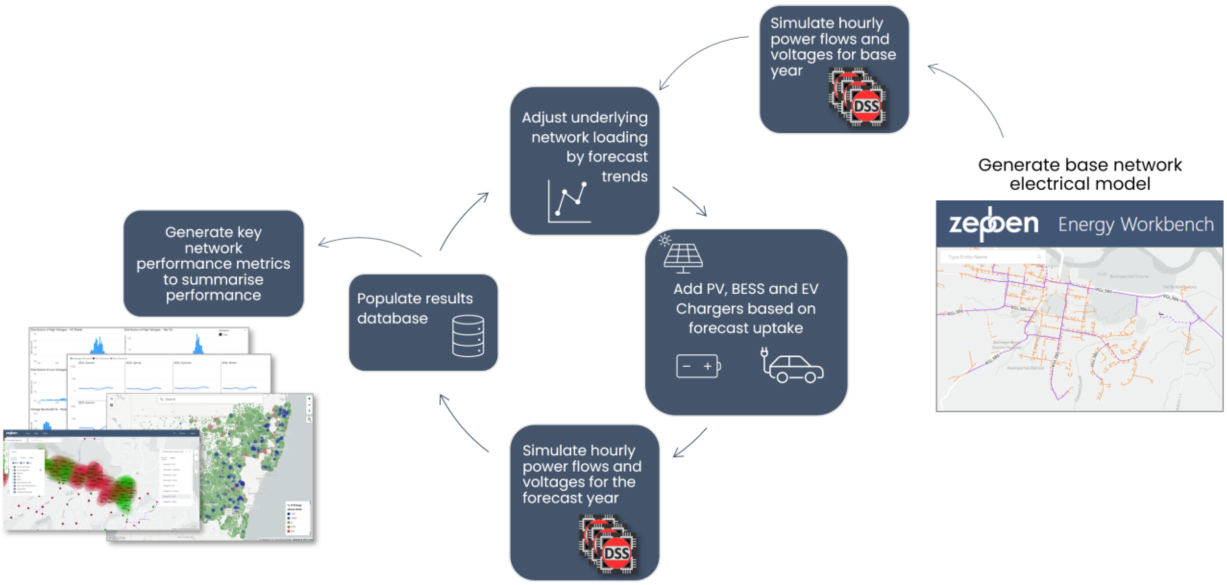


Figure 27 - Illustration of modelling process

3.3 BASE CASE RESULTS

The continuous HV and LV modelling approach used by the hosting capacity study provides some of the most granular insights possible into Essential Energy's network electrical performance, with the accuracy of the localised results limited only by the available data.

The base year results represent the impact of ***currently*** installed solar, battery and EVs. The key takeaway is the wide variation in performance across the approximately 136,000 network sections modelled. The results also show:

- Clustering of modelled sustained over voltages occurs, indicating MV voltage management should be a focus for the management of network performance.
- The legacy of the 240v voltage standard can be identified with sustained voltages biased to the high end of the allowable voltage envelope.
- A greater proportion of sustained over voltages occur outside of the major regional centres.
- Outside MV feeder-based clusters of over voltage, the causes are typically highly local and based on the characteristics of the network at the street level, such as long lengths of LV conductor and distribution substations supplying large numbers of customers over a large area. This is observed in the performance of the clustered network section types.

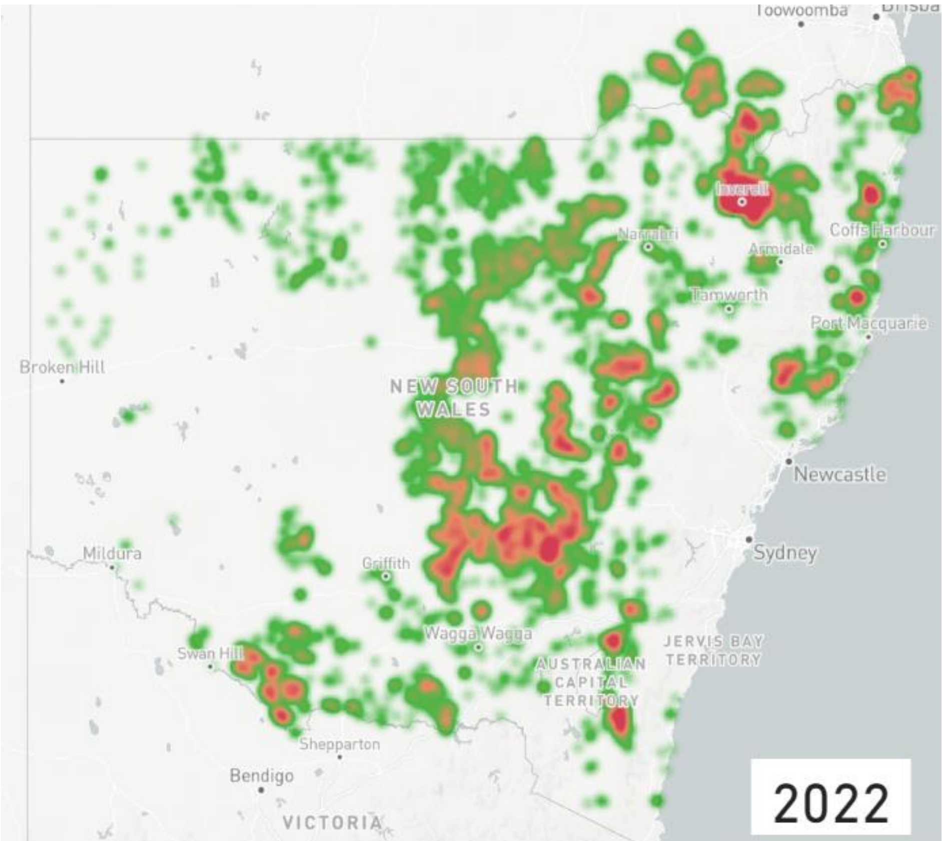


Figure 28 - Heatmap of modelled sustained over voltages, as defined by voltages exceeding 253v for >1% of the year. Red indicates a higher density of LV network sections that have recorded over voltages

3.3.1 Types of constraints identified

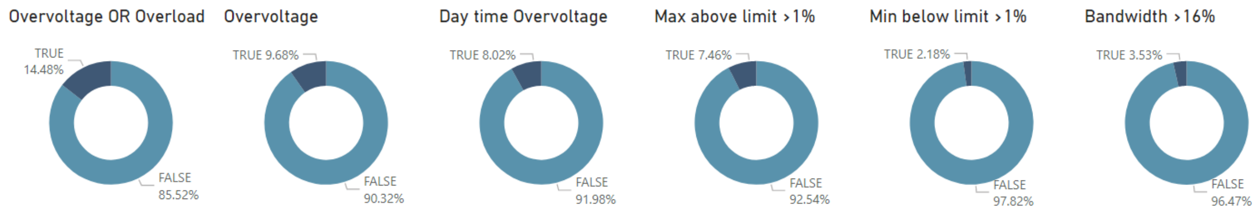


Figure 29 - Breakdown of constraints

Overall, 85.7% of the network was identified to perform within code for the whole of the base year. Where the limits for this analysis are defined as the normal thermal asset ratings provided by Essential Energy and within the voltages range of 216v to 253v.

Breaking down the types of constraints highlighted in Figure 29 the following was identified:

- For the network sections that were modelled to have periods outside these limits, **voltage constraints represented over two thirds of constraints identified**.
- 11.5% of network sections were modelled outside the voltage limits for one or more hours in the year
- 9.3% of network sections were modelled as overvoltage for one or more hours in the year
- **83% of network sections that were modelled with over voltage events reported over voltages during peak solar generation hours** 10am-4pm
- **7.2% of network sections recorded sustained (>1% of the year) over voltages**
- 3.5% of network sections had a variation in voltage over the year greater than 16%. 40% of these on the low voltage end of the range and 60% of these on the high voltage end of the range.

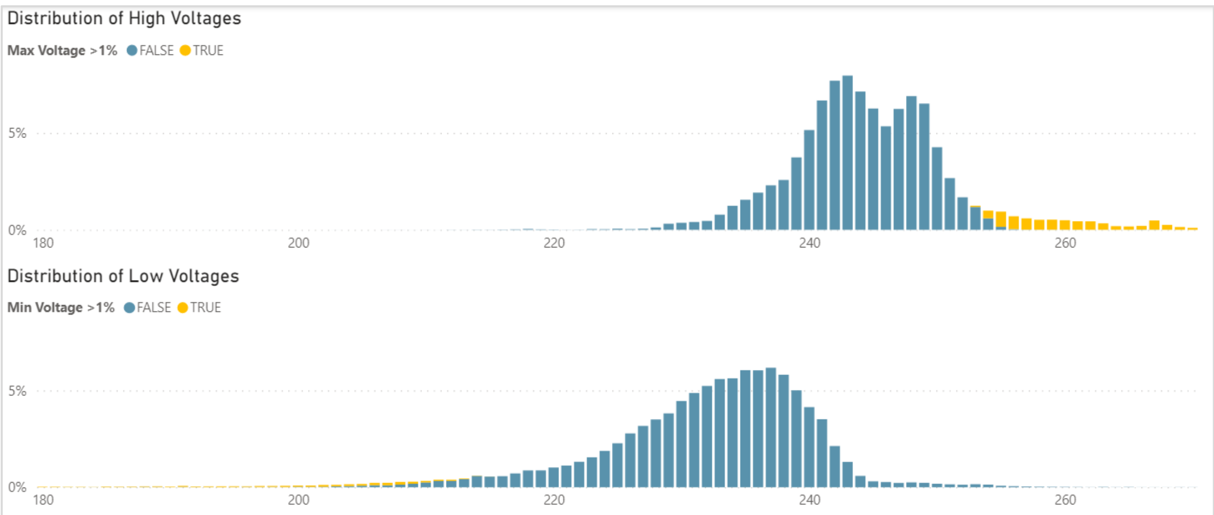


Figure 30 - Distribution of voltages with sustained over voltages highlighted

3.3.2 Impact of past practices on constraints identified

Distribution transformers are a critical component of the electricity distribution system and form the point of interface between the high voltage network and the low voltage network that connects to people's homes.

This interface point has historically been designed to meet the obsolete Australian Standard 2926, with a nominal low voltage standard of 240v +/-16% for single phase network and 415v +/- 6% for three phase networks. This has resulted in many older transformers still targeting this obsolete voltage standard. Most transformers with a rating >20kVA and all newer transformers have some ability to adjust the static ratio of voltage conversion using and off-load tap changer (this is a manually operated device, that can be adjusted once load has been removed from the transformer and it has been deenergised).

20% of Essential Energy's distribution transformers have been fully or partially adjusted to target the 230v nominal voltage standard defined by current AS60038 standard. Note this adjustment has been included within the model. This leaves a significant number of distribution transformers targeting the legacy 240v/415v nominal standard. The impact of this can be observed in the distribution of voltages modelled in Figure 30 and the calibration dataset plotted on Figure 22 and Figure 23.

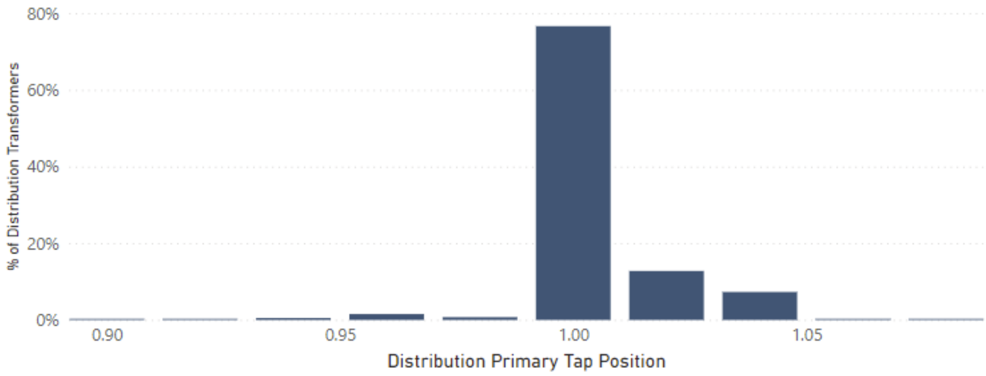


Figure 31 - Breakdown of tap position for Distribution Transformers

In addition, when closely reviewing Figure 30 a 'bump' is observed in the over voltage profile around the 250v point. This is a result of a network type specific to regional electricity networks; Single Wire Earth Return (SWER) networks.

These networks were designed to electrify remote Australia using cost effective high resistance steel conductors, that enabled large span between poles at the expense of significant voltage drop during distribution. Partly due to this, these networks were designed with transformers that supplied 250v/500v LV voltages to assist in compensating for voltage drop. When SWER networks were rolled out, the electricity system was only ever considered to be a one-way system, and so voltages slightly higher always resulted in maximum available system capacity for customers. However, this does leave a legacy challenge for rural networks seeking to maximize available headroom for export services on SWER networks.

3.3.3 Network section performance by network type

The cluster analysis defined in section 2.6.8 enables the performance of the network to be broken down across categories of like assets. This makes sense when considering how the local lines and transformers work together as a system to deliver hosting capacity, with the weakest element impacting the performance of the whole section.

Figure 32 shows the variability in voltage performance by network type, with urban networks performing well and smaller rural overhead network showing the worst performance.

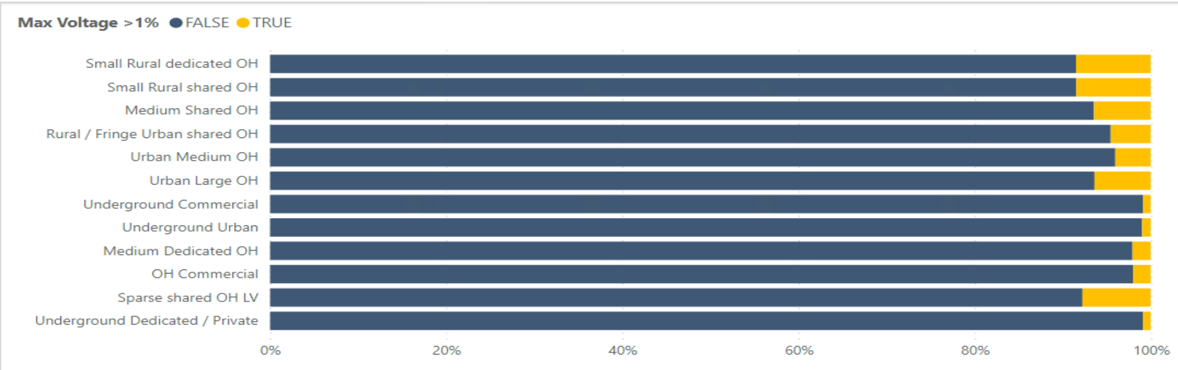


Figure 32 - Breakdown of network section over voltage performance by type

Digging deeper into what is driving the performance of these clusters, Figure 33 depicts the percentage of network sections that have recorded sustained over voltages on the y-axis, against the average total network length for each of the LV network section types on the x - axis. In addition, the points are sized by the number of customers supplied by that network section type.

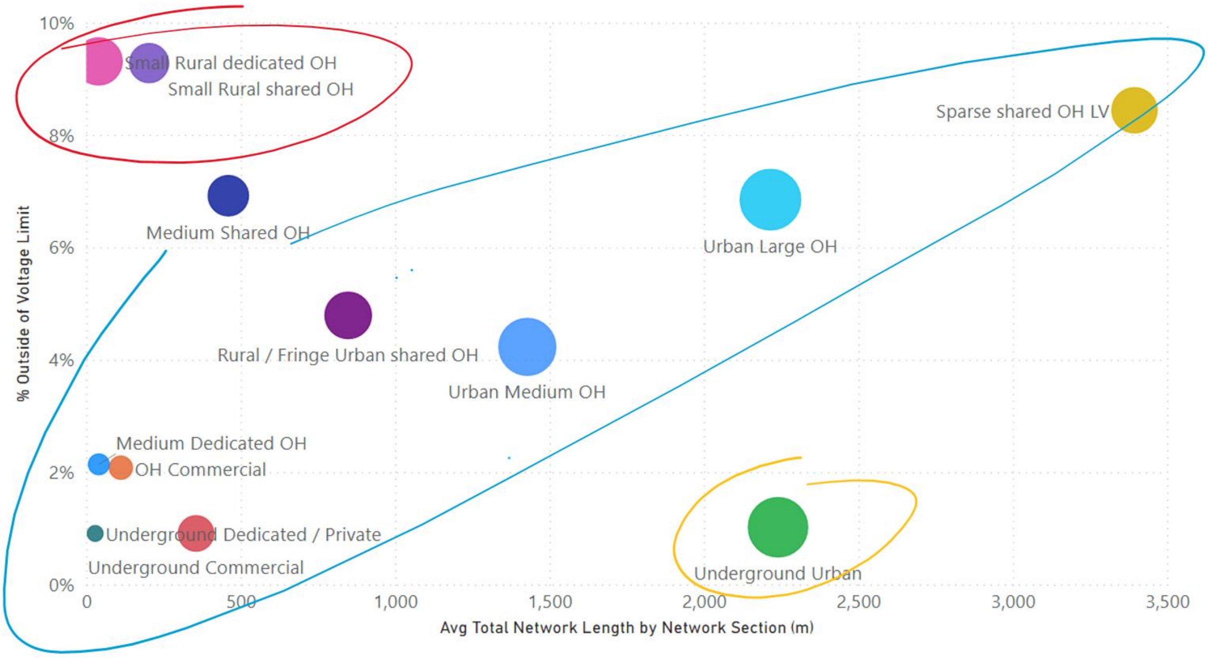


Figure 33 - correlation between network length and over voltage performance

Figure 33 shows:

- Small rural and dedicated rural network types, highlighted in red, have limited amounts of LV network associated with them. Their performance is driven by the voltage regulation performance of the MV network. This means a focus on improving MV and HV voltage regulation is likely to be an appropriate tool to address the performance of this network type.

- Overhead and underground shared networks, highlighted in blue, exhibit a strong correlation between LV network length and voltage performance. While these network types will benefit from MV and HV voltage regulation, some of these networks will require solutions that address the LV network voltage directly. These solutions include both network (additional or larger transformers, reconductoring etc) and non-network (battery, DOEs and tariffs to incentivise changes in customer load shapes).

- Underground Urban, highlighted in yellow, this network type performs well and does not exhibit the same link between performance and LV network length. This network type is the least likely to need investment to address voltage issues and is suited to fixed adjustments voltage using off-load tap changers.

Thermal performance was modelled against ratings provided by Essential Energy. For lines this data is part of the conductor library, for transformers, it was captured for each transformer individually as part of the network model, for more information see section 2.4.

Reviewing the thermal performance of the network types, while there are fewer overall thermal constraints than voltage, they are concentrated into particular network types. Reviewing the types of networks with the higher proportions of overloads, there are two trends; (1) those network types with long LV sections and (2) commercial network types. On face value the latter is unexpected, however commercial network sections often include non-standard cable types used for large customer connections, and in our experience these non-standard cable types can often be captured as *"unknown"* within source systems, and have been given "pessimistic" ratings in our modelling.

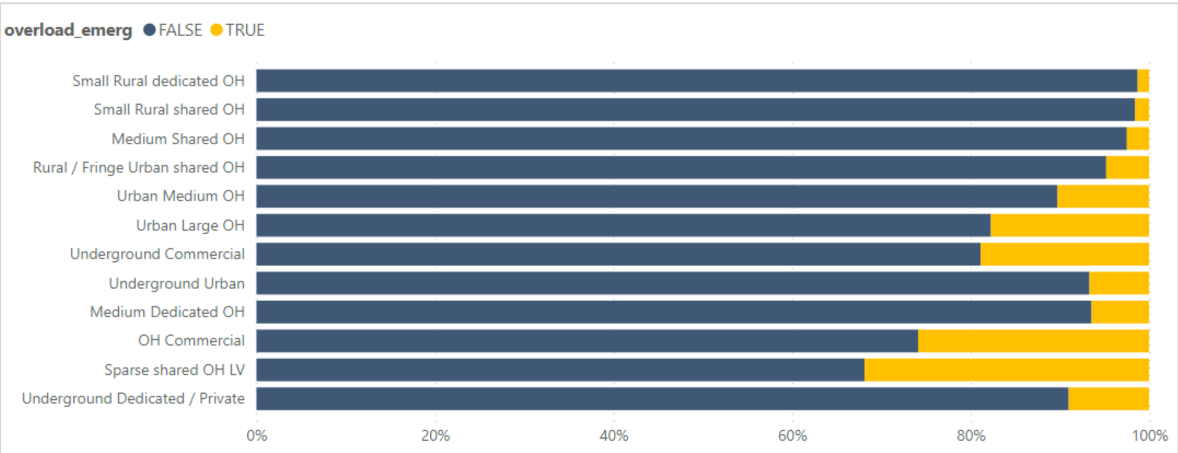


Figure 34 - Breakdown of network section thermal performance by type

Reviewing in detail the following characteristics were identified for thermal performance:

- 70% of overloaded elements were LV elements
- 95% of the overloaded LV assets had a rating of less than 125 Amps, indicating that incorrect classification of LV network lines may be impacting overload results.
- 90% of the HV overloaded elements are due to the elements having a rating of 0 amps[9]

This indicates that while the thermal results accurately highlight the areas of the network that are at risk of being overloaded caution is required when interpreting these results directly, due to data quality limitations. This is particularly the case for LV networks, that are not typically used for power flow modelling.

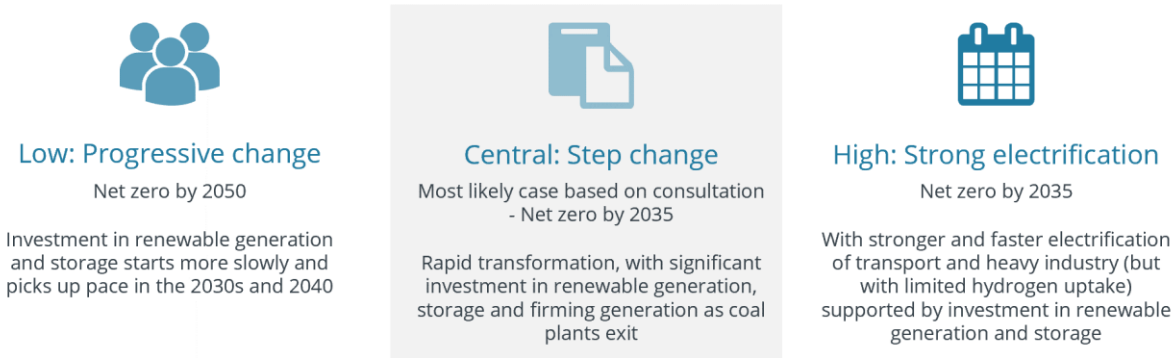
[9] note where values are missing rather than 0, these values are set to the most common conductor type for that feeder and that voltage class.

3.4 Forecast Scenarios Results

Building on the base case modelling, Zepben extended the approach to assess how network constraints are likely to occur over the period 2022-2037. The approach to setting up and undertaking this modelling is outlined in section 2.4 and section 2.6.

The modelling was done across three forecast versions of the future:

- Low: Based on AEMO's Progressive Change scenario (the scenario formerly known as Net Zero 2050).
- Central: Based on AEMO's Step Change scenario. AEMO's consultation with energy industry stakeholders found the Step Change scenario is widely considered to be the most likely[10].
- High: Based on AEMO's Strong Electrification sensitivity. This sensitivity is based on the Hydrogen Superpower scenario, but with limited hydrogen uptake and reduced energy efficiency.



These forecast versions of the future translate into the following technology uptake curves defined in Figure 35. The key differences being the rate of uptake across all technologies, and the various inflection points of the battery capacity uptake forecast.

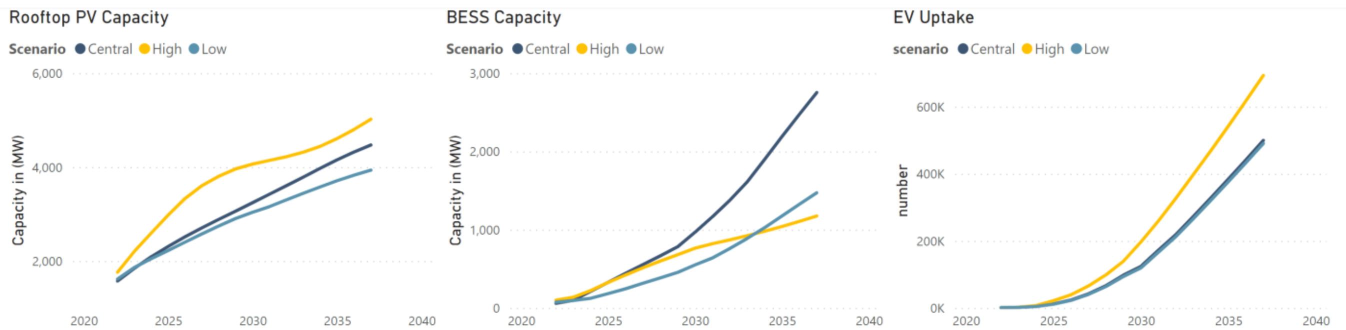


Figure 35 - Technology Uptake Curve

10 See Section 2.3 of AEMO' s Draft 2022 Integrated System Plan pp29-30

The forecast results presented in this section are all pre-intervention forecasts of how network performance would change over the planning horizon if Essential Energy did not intervene or invest to manage the network performance.

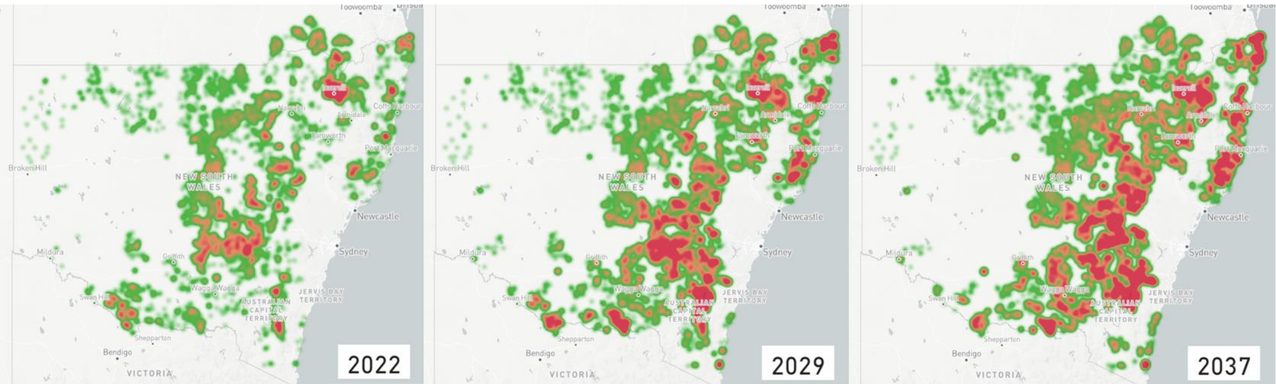


Figure 36 - Heatmap of how pre-intervention over voltage events change geospatially and over the forecast period

Geospatially Figure 36 shows how over voltage events in 2022 are localised and outside of the major regional population centres. Moving to the right-hand side the maps progress through the forecast period, highlighting a shift from localised over voltage events to being broad based over voltage events impacting all major population areas of Essential Energy's network.

3.4.1 Defining hosting capacity

'Hosting Capacity' is a well-known industry term, however there is no single clear common definition or metric that forms a suitable base for this work. To meet Essential Energy's requirements, Zepben has taken the approach of defining the collection of metrics outlined in Table 1 as the result set that provides the hosting capacity study outcome.

These metrics will enable analysis of forecast network performance and planning for efficient levels of generation curtailment and EV load shaping in the face of continued forecast PV and EV uptake.

Throughout this report we refer to the term Hosting Capacity, and so to assist in consistently interpreting this report we have defined Hosting Capacity for the purpose of this work, as:

the ability for the network to accommodate a specific installed capacity of a particular DER technology.

For example, where we refer to PV or Solar Hosting Capacity, we are referring to the kW of solar panel capacity that can be installed at a particular network level before voltage or thermal limits are breached.

3.4.2 Solar PV Update & Minimum Demand Constraints

Provision of network capacity for export services has traditionally been a by-product of capacity planning for customer load. However, the relentless uptake of rooftop PV by Australians and reforms across the National Electricity Market (NEM) have meant that this is no longer the case.

To meet both customer and regulator expectations DNSPs need to actively plan for export services and define efficient levels of economic curtailment.
The forecast scenario results are the key enabler of this change, providing a results dataset that breaks down the hosting capacity performance for various types of network section types.

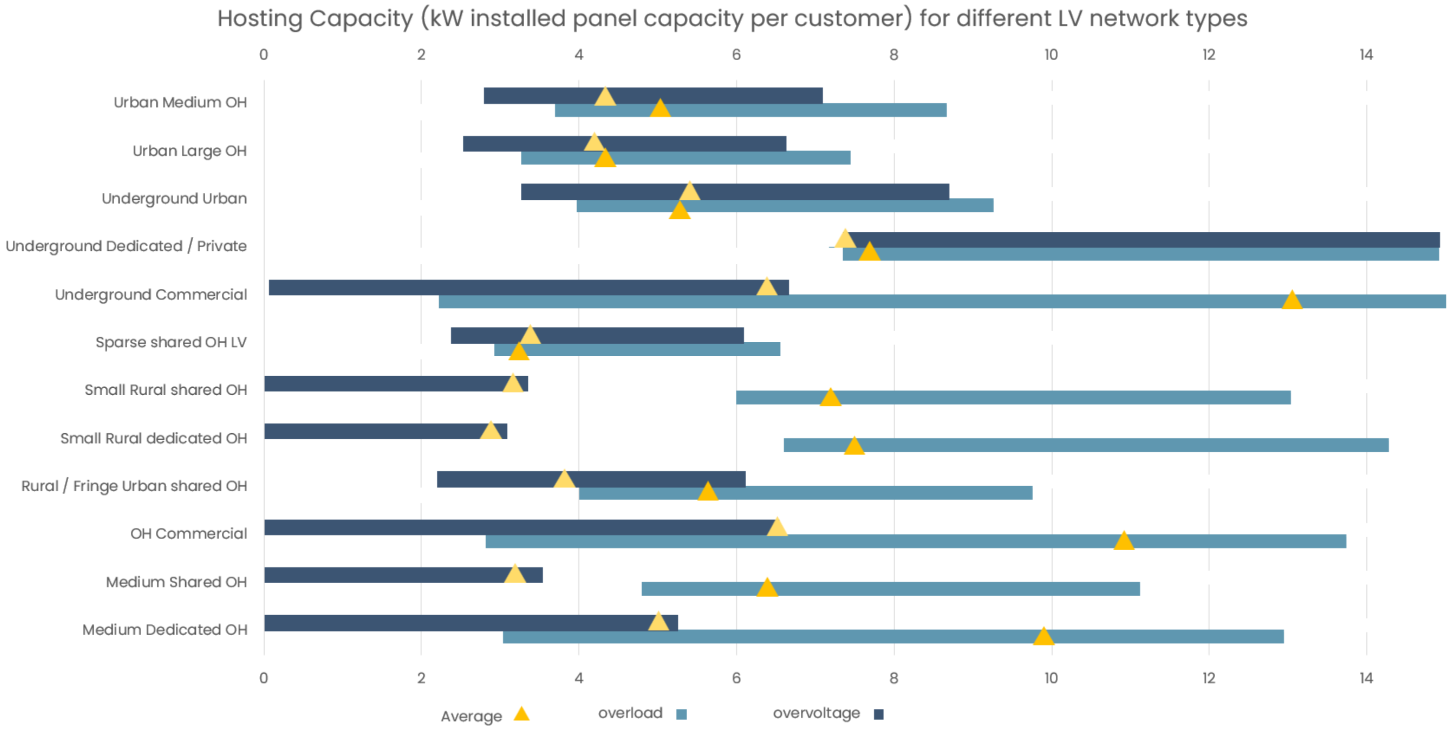


Figure 37 - Solar Hosting Capacity Performance by Network Type

Figure 37 shows the solar hosting capacity for various network types, providing a range of solar panel uptake capacities that can be hosted before breaching technical network limits. For both voltage and thermal capacity limits a range is provided along with a yellow triangle indicating the average capacity limit performance of each network type.

As expected, there is a wide range of variation between network types, highlighting the challenge DNSPs have providing standardised export services to customers. Generally, voltage limits are the binding limitation for solar hosting capacity. With a mix of small rural substations, and network types with long LV sections impacted the most by voltage performance. For Essential Energy's network the hosting capacity forecast indicates average export levels for these network types are between 2.4kW and 4kW. Both are below the automatic approved export limit of 3kW for rural and 5kW urban currently defined by Essential Energy.

Similarly, to the three types of overvoltage categories observed in Figure 33 there are different drivers of performance impacting the hosting capacity of these various network types. The voltage limits binding on small rural substations and commercial dedicated substations are impacted by the upstream MV network performance, as generally these LV networks are either short enough or of sufficient capacity for the LV network not to be the first limit reached. Whereas the urban overhead and underground network types are generally connected to MV feeders with lower voltage swing on the MV network, making LV voltage rise typically the first voltage limit to bind rather than the upstream MV voltage rise limiting performance.

Taking the solar hosting capacity limits defined in Figure 37, Zepben has compared these against the solar uptake forecasts too define when types of network are likely to reach solar hosting capacity limits. Figure 38 summaries these results by providing a forecast of when, on average, various network types would reach sustained over voltage thresholds. This result shows that for the 2024-2029 period the management of solar PV hosting capacity should be a key focus for the provision of standard control services.

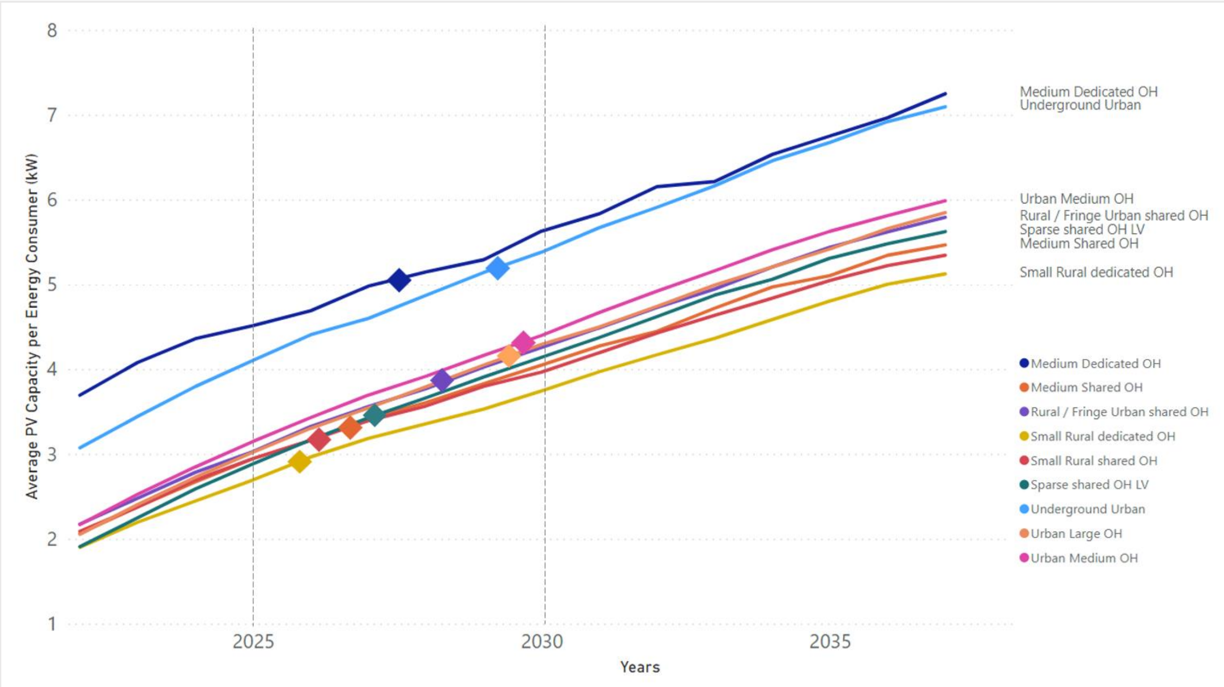


Figure 38 - Forecast timing for network types reaching average voltage defined hosting capacity limits

3.4.3 Time series Network Performance

Changes in modelled network performance are driven by changes in the customer load shapes over the forecast period. These load shape changes are driven by changes in underlying demand combined with the various combinations of DER technology.

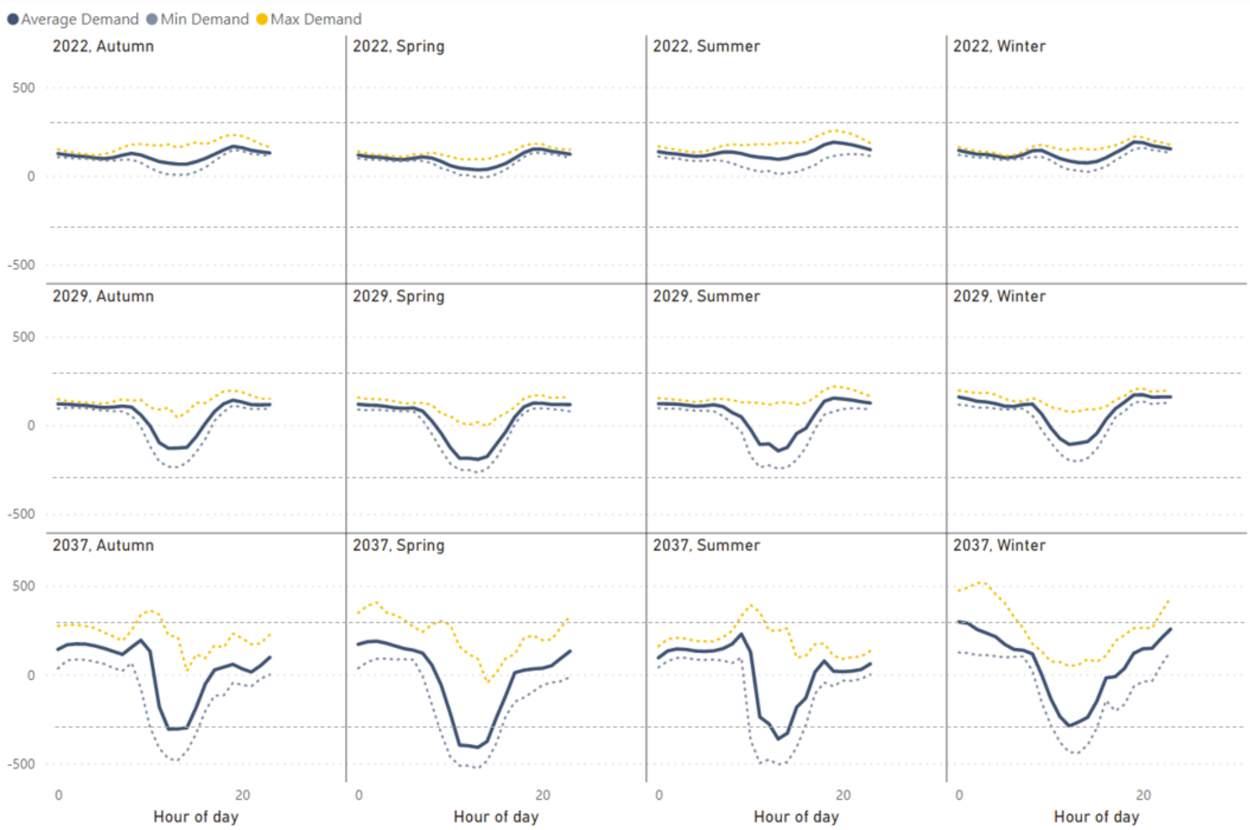


Figure 39 - Example of changes in load shape over the forecast period for a typical 315kVA Urban Distribution transformer

Reviewing the 315kVA substation example, Figure 39, of load shape changes provides a different perspective on how changes in technology uptake impact network performance.

- Out to 2029, the primary impact on network loading comes from the continued uptake of solar PV technology, with the rest of the typical daily load shape remaining similar.
- There is a large trend in increasing variability in network loading with the bandwidth between the min and max loading increasing significantly over the forecast period. This is driven primarily by variation in generation performance between 'clear sky' high production solar days and cloudy low production solar days. This presents a challenge to network voltage regulation.
- 2037 shows an increase in evening and overnight network loading as a result of electric vehicle uptake. Although the impact of this is moderated by the uptake of stationary battery systems that act to respond to peak evening pricing, supplying much of the forecast additional household peak energy demand.

4 MEASURES TO IMPROVE HOSTING CAPACITY

To support Essential Energy and their economic modelling partner, Baringa, to determine the appropriate mix of localised interventions suitable for unlocking network capacity for the management of forecast constraints identified in section 3, Zepben undertook electrical modelling of the solar hosting capacity benefit of various interventions, both network and non-network.

4.1 MODELLED INTERVENTIONS

The following interventions have been modelled for a range of relevant network section types (see 2.6.8 for more information on these network section types)

- LV reinforcement: - reconductor sections of LV network with conductors that have a minimum of 80% increase in thermal capacity.
- HV reinforcement: - reconductor sections of HV network with conductors that have a minimum of 80% increase in thermal capacity.
- Transformer upgrades: - replace distribution transformers with the next standard distribution transformer size that will increase capacity by at least 50%.
- OLTC transformers: - add On-Load Tap Changers to distribution transformers as part of a minimum 50% upgrade to transformer capacity.
- Additional transformer: – transformer added in a new location to share customers across transformers.
- Closed loop voltage control: - voltage measurements from the remote end of the feeder (LV network) are used to inform the appropriate starting voltage for the Zone Substation. This feedback loop replaces uncertainty in the outcome of traditional open loop voltage regulation and reduces any unused voltage bandwidth.
- Revised voltage regulation settings: - Setting the On-Load Tap Changer at the start of the feeder to regulate based on a 'co-gen' Line Drop Compensation (LDC) model, where the feeder starting point voltage is dropped as reverse power flows are detected, and then increased as forward power flows are detected.
- Community BESS: - are a promising technology solution that can provide a range of benefits across the energy system. In the context of this work, Zepben is assessing just the solar capacity enablement benefit provided by the addition of community BESS to LV network sections. Zepben would expect this benefit could be combined with the remainder of a community BESS value stack in order to be deployed; such as FCAS, wholesale energy, virtual cap, network capacity, losses.

All of the selected interventions are available commercially in some capacity.

Dynamic Operating Envelope's (DOEs) are another promising 'tool' in the 'toolbox' that have not been modelled within this scope of work. The reason for this is this analysis has focused on the technical network capacity benefit unlocked from taking interventions. While DOEs are similar they are also different, as rather than simply adding (kW) of network capacity they are a mechanism for efficient allocation of network capacity to unlock additional throughput (kWh). Therefore, DOEs have been directly modelled by Baringa using the network wide hosting capacity results (DER capacity and forecast curtailment) to determine the potential reduction in generation curtailment DOEs could unlock if implemented.

4.2 APPROACH

The list of interventions agreed between Essential Energy, Baringa and Zepben represented a mix between network and non-network interventions that required changes to the underlying network model, changes to the modelled network control approach and additional new elements.

To assess the capacity benefit of each intervention a sample of the clustered network section types were selected, see Table 3, to provide a representative sample of networks that where then assessed to determine the maximum pre and post intervention solar hosting capacity for each network section on the feeder. These networks were modelled as continuous HV/LV feeders, but the hosting capacity assessment was made for each specific network section individually.

Table 3 - List of feeders used for intervention modelling

FEEDER ID	TYPE
CPM3B3	Coastal Urban
NSK3B2	Mixed Urban / Rural / SWER
RGL3B6	Mixed Rural
OPM3B8	Regional Urban
GOG3B5	New Urban
DBS3B8	Regional Urban
NVE8B4	Remote
CNB8B4	Regional Urban/Rural
CNB8B1	Remote
CSO3B6	Long Rural

The delta between the modelled pre and post intervention solar hosting capacity defines the benefit of implementing each intervention on a particular network section.

These results were then reviewed and aggregated to the network section type level to define the average benefit that Essential Energy can expect to receive when applying these interventions to various network types. This aggregation also enables the intervention results to be readily applied to network section types as part of the economic modelling undertaken by Baringa within the Future Network Business Case. The workflow used as part of this approach is summarised in Figure 40.

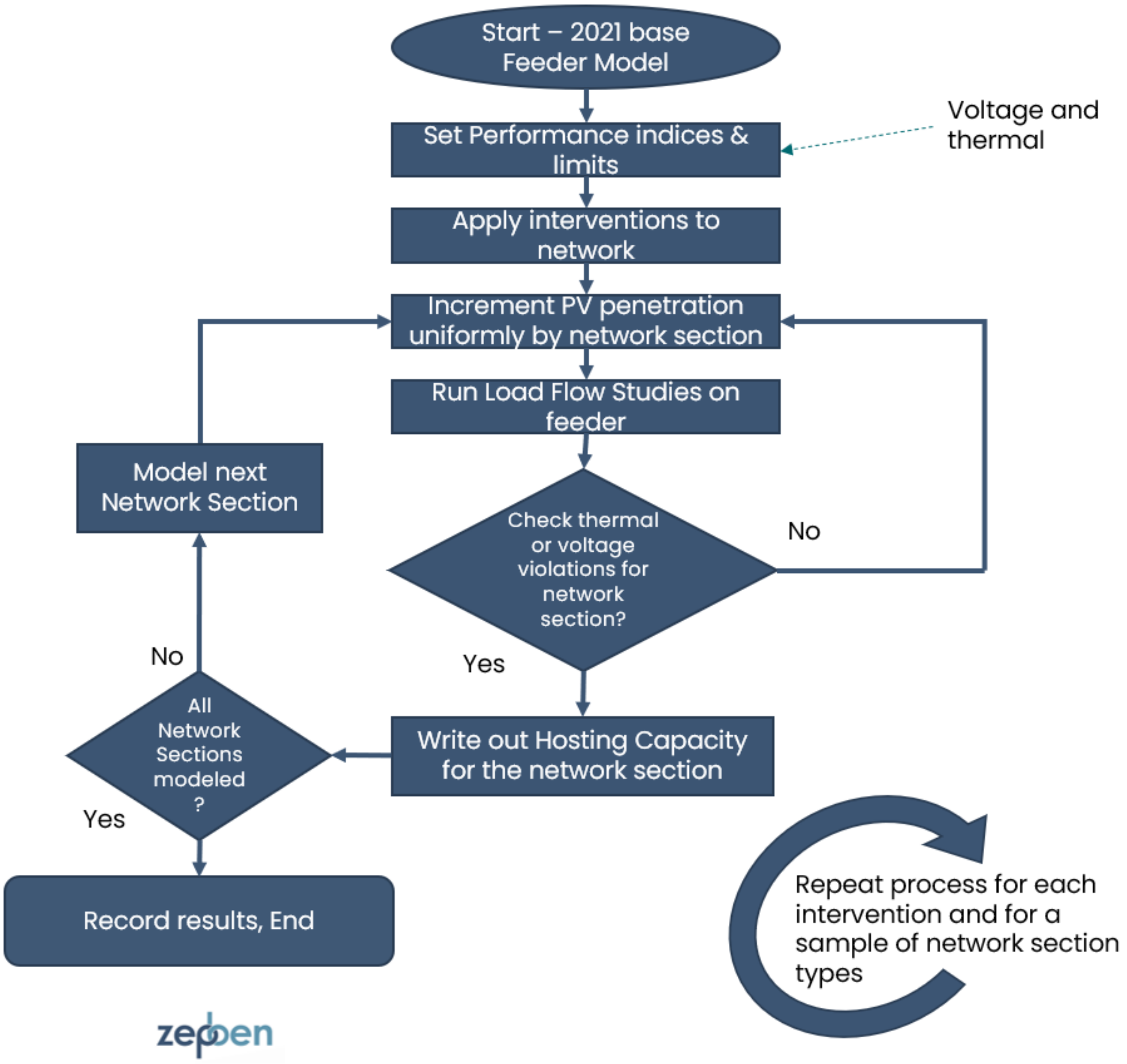


Figure 40 - Diagram of how the solar hosting capacity is calculated for each intervention type

4.2.1 Intervention specific approaches

4.2.1.1 Base model adjustments

This forms the reference case that all interventions are measured against and represents the current state of the network and consumer load profiles.

Due to the number of LV thermal overloads observed as a result of LV line ratings of less than 100 Amps, an adjustment was made to the base model. Where conductors were overloaded based on current PV 2021 penetrations, they were upgraded to the next conductor size that removed the overload to form a new base model. This decision was taken on the basis that it is likely that these overloads are the result of incorrect default conductor information and not genuine overloads. This adjustment enabled accurate measurement of the hosting capacity benefit of the non-LV reinforcement intervention; without this change the LV network is the first constraint in most cases and limits the measurement of the other intervention benefits.

4.2.1.2 LV Reinforcement

Sections of the network with high impedance and/or thermal rating were upgraded to a current Essential Energy standard conductor type with a minimum increase of 80% in thermal capacity.

4.2.1.3 HV Reinforcement

Sections of the network with high impedance and/or thermal rating were upgraded to a current Essential Energy standard conductor type with a minimum increase of 80% in thermal capacity.

4.2.1.4 Transformer upgrades

Transformers were upgraded to the next standard size that provided a minimum of 50% capacity increase, while maintaining the same phase and voltage characteristics. Essential Energy's standard library of transformers was used as the reference to select the appropriate transformers.

4.2.1.5 On-load Tap Changers – Distribution Transformers

Depending on the size of the transformer this intervention is available in different forms and different price points commercially. It is relatively new to the market and not standard equipment for many DNSPs. Based on this and the continued development of solutions in this space, Zepben decided to model the addition of OLTCs to all distribution transformers.

On-load Tap Changers were added to each distribution transformer. These tap changers were configured to regulate to a 230v float voltage and implemented 'co-gen' Line Drop Compensation. The LDC was configured to boost the voltage up to 253v when the transformer was operating at its full load rating, and buck down to 216v when operating at full rated power in reverse. The time-delay on these tap changers was set below that of the HV OLTCs to avoid "hunting" conflicts on the two voltage regulation schemes.

This intervention was modelled with and without upgrading the capacity of the transformer.

4.2.1.6 Additional transformer

Adding an additional transformer to a network section and splitting the original section of LV network into two sections often reduces both the average LV network length per customer while also increasing the transformer capacity available.

An LV switch or fuse was manually selected to open, and then an additional transformer of equal capacity was added at a location that enabled the new transformer to support around half of the network sections customers.

This intervention was modelled with and without upgrading the LV network.

4.2.1.7 Closed loop voltage control

The On-Load Tap Changer at the start of the feeder was reconfigured to regulate a voltage measurement from the remote end of the feeder.

To model this, the voltage at the end of the HV section of the feeder was selected, and the start of the feeder was adjusted so that the starting voltage ensured that the end of the feeder was regulated to 0.958pu, maximising the amount of solar generation that can be accommodated within the voltage performance of the feeder.

4.2.1.8 Revised voltage regulation settings

Setting the On-Load Tap Changer at the start of the feeder to regulate based on a 'co-gen' Line Drop Compensation (LDC) model. The forward power flow LDC setting were taken as a starting point, with the float voltage revised down where set above 1pu. The reverse LDC setting was set to reduce the HV feeder head voltage by up to 6% as reverse power flows on the feeder increased.

4.2.1.9 Community BESS

As the assessment was limited to just the solar capacity enablement benefit of community BESS to LV network sections, the dispatch of the BESS was pre-scheduled for the BESS to charge during the peak solar generation windows and discharge during the evening peak.

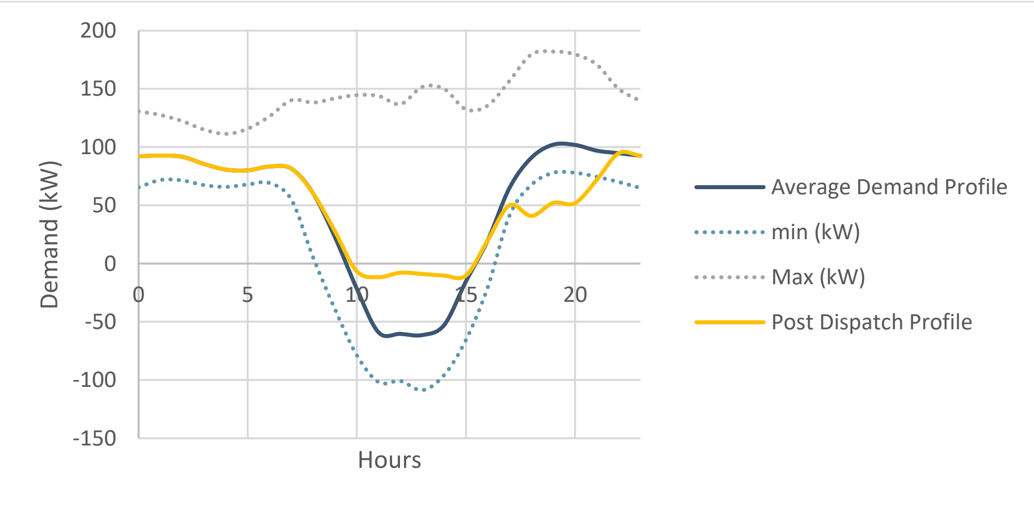


Figure 41 - Defined dispatch profile for assessment of Community BESS solar enablement benefit

This profile aligns with capturing higher average wholesale prices and provides a peak loping service to the local network. The inverter and energy storage size of the BESS was selected to coordinate with a typical 315kVA substation, with consideration of the typical physical space available for community BESS in existing neighbourhoods. While we considered that in practice a Community BESS dispatch curve is likely to be more complex to maximise benefits across a range of value streams, this profile represents a reasonable assessment of solar enablement benefit.

4.3 Performance of Measures

Table 4 provide a summary of the hosting capacity uplift for a given network section type.

Table 4 - Summary of intervention benefits

Intervention Capacity Benefits (kW)										
	LV[11]	HV[12]	Additional TX[11]	Upgrade TX[11]	OLTC Dist TX Upgraded[11]	Closed Loop Voltage Control[13]	Revised LDC Settings[13]	Community BESS[11]	OLTC Dist TX[11]	Additional Transformer Upgrade LV[11]
Medium Dedicated OH	N/A	N/A	N/A	N/A	9.9	4.7	0.0	N/A	9.9	N/A
Medium shared OH	16.5	3.1	15.6	13.7	12.4	7.7	4.2	N/A	12.4	15.6
OH Commercial	69.0	41.3	129.8	N/A	24.2	54.9	0.0	52.4	24.2	191.9
Rural / Fringe Urban shared OH	44.1	3.4	N/A	21.7	19.1	13.9	4.0	N/A	19.1	N/A
Small Rural dedicated OH	5.2	4.9	N/A	11.3	5.6	1.5	0.5	N/A	5.6	N/A
Small Rural shared OH	9.0	2.6	16.6	14.5	11.2	6.4	3.7	N/A	11.2	16.3
Sparse shared OH LV	157.9	0.0	112.9	N/A	121.8	0.0	0.0	N/A	121.8	205.5
Underground Commercial	131.6	0.0	N/A	190.3	84.8	0.0	0.0	39.2	0.3	N/A
Underground Urban	134.0	0.0	86.7	9.2	71.6	51.2	0.0	8.1	71.6	234.7
Urban Large OH	95.3	0.0	110.5	N/A	101.8	15.4	4.9	28.9	101.8	205.4
Urban Medium OH	91.2	0.7	103.8	31.9	25.4	18.2	2.9	13.4	25.4	189.3

Note: not all interventions were modelled for all network section types, due to a combination of suitability. For example, a community BESS is not suited to a single customer substation.

[11] Benefits per network section where the relationship between intervention and network section is one to one
[12] Benefits per network section where the relationship between intervention and network section is one to many
[13] Benefits per network section when implemented across the whole feeder

The results show a significant variation in solar hosting capacity benefit, with targeted LV upgrades providing significant benefits for targeted single network sections, compared to closed loop voltage control which provides a much lower per network section benefit but improves outcomes for hundreds of network sections per single implementation. Careful consideration of these capacity benefits alongside the costs of implementation is therefore critical in order to make an assessment of the appropriate mix of interventions suited to Essential Energy's network. This work will be undertaken by Essential Energy's economic consulting partner Baringa.

These intervention results have been structured to feed directly into the economic analysis of the Future Network Business Case, where the forecast constraints/curtailment, local intervention benefits and Dynamic Operating Envelopes (DOEs) will all be assessed, to define a forward-looking strategy for efficiently balancing customer demand for two-way network services.

5 APPENDIX

5.1 TECHNOLOGY SOLUTION – THE ENERGY WORKBENCH

A key requirement for the project was time-series electrical modelling across the whole of network Essential Energy's MV and LV network.

While traditional commercial solutions for running load flow studies support the analysis of load growth on individual feeders, they have limitations that made them unsuitable for the scale of modelling needed for this project.

These applications are designed to run on desktop PCs and are therefore limited by the computational power available on those single machines. This limits the amount of modelling that can be completed, forcing the use of a taxonomic approach to represent overall network performance.

To perform whole of network analysis over a 15-year forecasting period under different forecast scenarios for DER behaviour, the project needed to run models representing:

- 15 Years of hourly real and reactive power flows at the energy consumer level (350,400 time slots),
- Covering 3 future network development scenarios,
- For a total of 1456 feeders.

Multiplying this out gives a total of around 600 million Load Flow Studies that needed to be run to produce the results.

In addition to running the load flow studies, there was also significant computational and I/O resources needed to build the asset and load models used by the load flow engine, including algorithms to remediate missing or anomalous data.

To support this scale of computation and I/O, Zepben used its Energy Workbench platform, to provide the framework and parallel processing needed for this large-scale hosting capacity study.

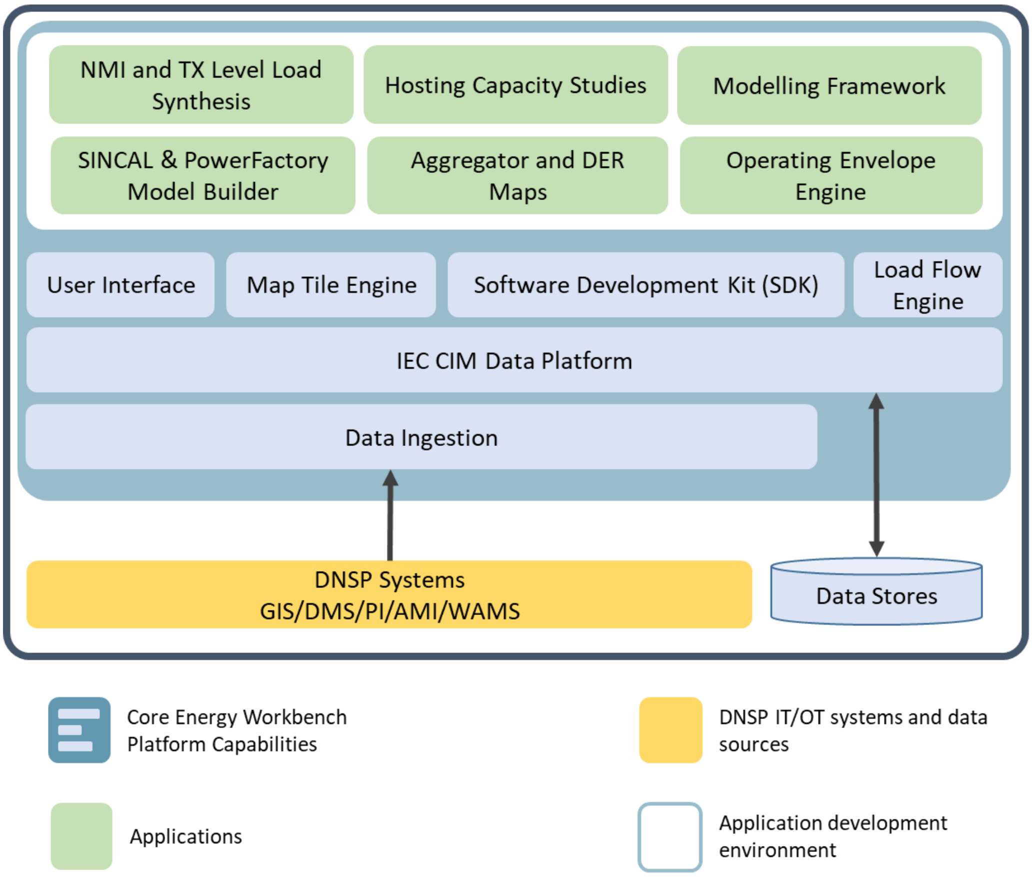
The functional components of the Energy Workbench (EWB) are illustrated below.

At its heart, the EWB has a memory resident model of the entire electrical distribution network, expressed using the IEC Common Information model (CIM).

The CIM is a standard that has been developed over many years and is now becoming widely used by the electricity sector to provide a common language for describing and modelling electricity networks. It was used to provide a standards-based approach to network modelling – providing benefits to the industry in terms of greater knowledge sharing, a reduction of barriers to the development of new applications and increased use of common decision support tools.

Much of the EWB code base is available under a permissive open-source licence, and can be accessed via GitHub.

https://github.com/zepben



Other key components of the Energy Workbench platform used for this project include:

- **Data ingestors:** to accept and translate the Essential Energy network model and load data into the IEC CIM data model.
- **Data Stores:** to store and access the network models and time-series annual load profiles for each of the approximately 850,000 customers connected to Essential Energy's network, and to accept the results of the modelling.
- **Software Development Kit (SDK)**: used as the integration point for the various process that needed to be run in the overall hosting capacity study, including the development of metrics to classify Essential Energy's network into types for better understanding network performance, the modelling of the capacity benefits of various interventions and the production of the actual network models used by the load flow engine.
- **Load Flow Engine:** the OpenDSS power simulation software, developed by EPRI, was used as the load flow engine for the hosting capacity study. OpenDSS was used because:

- It was possible to deploy many OpenDSS compute nodes in the cloud to run load flows concurrently, on different parts of the network,
- It was able to converge load flow studies with highly loaded, unbalanced three-phase networks,
- It had a variety of functionality to support quasi-static time series (QSTS) analysis to captures time-dependent aspects of power flow.

- **User Interface and Map Tile Engine**: These subsystems allow results to be visualised on a performance, vector-based map showing the spatial location of network assets.
- **SINCAL Model builder:** This was used to build network models in SINCAL to provide additional validation of the load flow analysis outputs of OpenDSS.

5.2 'CORNER CASES' & LIMITATIONS OF THE MODELLING

Overall, the modelling undertaken represents the most granular geospatial and time-series whole of network analysis of Essential Energy's network possible. With the scale of this analysis Zepben has identified some limitations that should be considered when interpreting the analysis presented:

- **LV Network condutors**: a significant proportion of the LV network conductor types 49%) were inferred from the known local conductor types. While the length of linear assets is well known, the exact impedance and ratings are not. We expect this to underrepresent the impact DER uptake has on some older unknown assets, and at the same time over represent the impact for non-standard higher capacity assets that are stored as unknown. The largest impact observed in the model results due to this imitation was on the LV line overloads. With a significant number of LV cable sections observed to be overloaded 365 days a year under the base network loading.
- **Phase unbalance**: the phase representation is not defined against field confirmed phasing. So, while the model provides a reasonable indication of areas of the network that are susceptible to phase imbalance due to large single-phase sections of network, the specific phases impacted in the model are not aligned to the phases in the field. Further, the phase connection in the LV network is not known. Customer phase connections were randomly distributed over all phases. In practise, there will be some areas of the LV network where load is not equally balanced over the three phases (the so called "short armed linesman" outcome) where the majority of sinlge phase premises are connected to the nearest phase the linesman can reach.
- **Voltage Regulation**: the model used provides the best available representation of Essential Energy's voltage settings, however specific setting for all 1456 feeders were not available and so some feeders were modelled with default voltage regulation settings.

5.3 DATA INSIGHTS

As a part of the development of the network wide hosting capacity model, Zepben ingested Essential Energy's full MV and LV network model, as well as supporting data sets. As part of this initial model ingestion, Zepben reviewed the completeness of the key dataset used in the project.

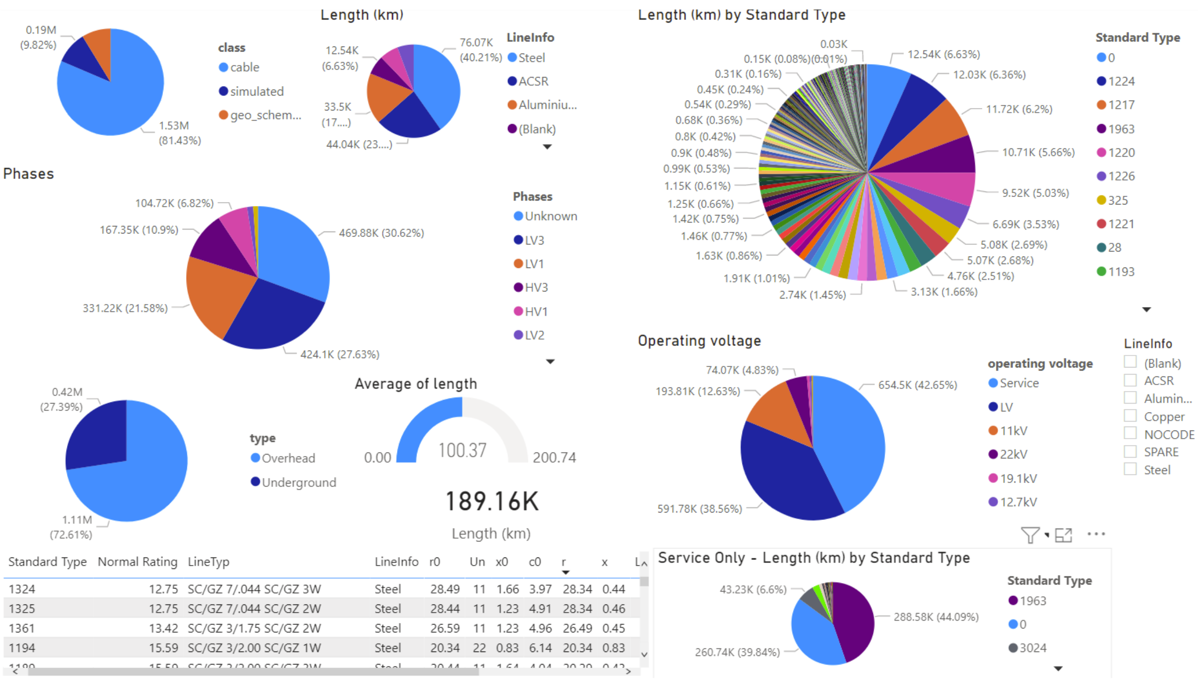


Figure 42 - Summary view of network line and cable dashboard

This review identified the varied data quality of different key network model parameters. Overall, the MV network model was found to be complete and well suited to load flow modelling, as expected, due to its use supporting BAU network planning outcomes. While the LV network and the phasing of the interface between the MV and LV networks was found to require assumptions in order to complete the overall combined HV/LV network model and support the network wide modelling outcomes. Table 5 summarises the specific review that was undertaken.

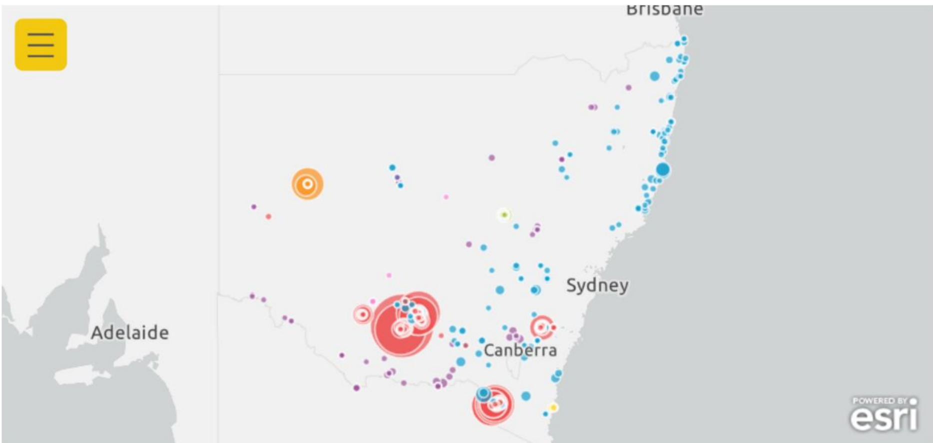


Figure 43 - Example of review identifying the localised impacts of HV lines with missing parameters – colour by voltage and size by segment length.

Table 5 - Summary table key Network Model parameters

ASSET TYPE	% and KM MISSING	% and KM 0Ω	% WITH PARAMETER OUTSIDE OF EXPECTED RANGE	ASSUMPTIONS USED WHERE PARAMETERS MISSING	IMPACT PRE-REMEDIATION	IMPACT POST-REMEDIATION
Hv Lines	0.13% 201km	0.13% 201km	0.13% 201km	Apply most common line type for specific feeders' voltage class->where not possible based line parameters on line rating -> where not possible apply default Zepben values.	The impact of missing values was localised and minimal.	Missing values were patched with locally common conductor type, but this updated was not material to the results.
LV LINES	19.4% 7,650km	34.06% 11,240km	65.1% 19,520km	Apply most common line type for specific feeders' voltage class->where not possible based line parameters on line rating -> where not possible apply default Zepben values.	Significant and material, LV voltage drop, and rise was materially underestimated and did not align with measured values. Rating missing and low thermal rating information also limited the usefulness of results	37.5% of LV km were assigned the most common LV line type by feeder. 27.6% of LV network remains with some parameters that are considered outside the expected range. Without other datasets to support remediation of this data is difficult and presents a challenge for DNSPs as they seek to operationalise new LV management approaches. Zepben considers that there is room for improvement in this dataset, and that there is a material impact on the accuracy of the LV overload results due to this input data quality.
SERVICE LINES	39.9% 4,670km	84.05% 11,750km	99.4% 13,580km	13,100km of service line had their parameters revised or added. 11,750km of service line had the default 0Ω parameters revised using the same replacement logic as for other unknown cables (outlined above). 1,350km of services lines that had line codes had their line parameters adjusted to be within the expected range, using parameters for 25mm AL ABC service line.	Significant and material, LV voltage drop, and rise was materially underestimated and did not align with measured values. Significant number of overloads underestimated the hosting capacity available.	96.4% of services are modelled with typically parameters. The impact of data accuracy for this asset type is considered acceptable. The uniform nature of service line types used reduces the impact of the assumptions used to complete the dataset.
TX LOAD	0%	0%	0%	Transformers with missing ratings are set to 234kVA (value selected at a level to not	None	None

				impact the majority of segments, but to be easily identifiable as a default value)		
TX PHASE	0.14% 197	0.14% 197	0%	Network phase information is primarily taken from the terminals of transformers, where missing the upstream network phasing is applied.	Not material	Small improvement, however not material.
TX VOLT	0%	0%	0%	Line voltage information is used to define transformer terminal voltages where unavailable	None	None

5.4 Forecast Scenarios

Summary of scenario parameters

Summary of parameters for scenarios in the 2021 IASR

Parameter	Progressive Change	Step Change	Hydrogen Superpower
Demand Drivers			
Economic growth and population outlook	Moderate	Moderate	High
Energy efficiency improvement	Moderate	High	High
DSP growth	Moderate	High	High
DER Uptake			
Distributed PV	Moderate	High	High
Battery storage installed capacity	Moderate	High	High
Battery storage aggregation / VPP deployment	Moderate	High	High
Battery Electric Vehicle (BEV) uptake	Moderate	High	Moderate/High
BEV charging time switch to coordinated dynamic charging	Moderate	High	Moderate/High
Electrification of other sectors (expected outcome)	Moderate	Moderate/High	Moderate/High
Hydrogen consumption	Potential for domestic consumption	Potential for domestic consumption	Large NEM-connected export and domestic consumption
Scenario alignment			
Shared Socioeconomic Pathway	SSP2	SSP1	SSP1
IEA 2020 World Energy Outlook Scenario	Stated Policy Scenario (STEPS)	Sustainable Development Scenario (SDS)	Net Zero Emissions by 2050 case (NZE2050)
Emission summary			
Climate change impacts based on assumed Representative Concentration Pathway (RCP) (mean temperature rise by 2100)*	RCP4.5 (~2.6°C)	RCP2.6 (~1.8°C)	RCP1.9 (<1.5°C)
Decarbonisation target	26-28% reduction by 2030. Economy-wide net zero target by 2050	Economy-wide net zero before 2050, exceeding 26-28% reduction by 2030. Pace of decarbonisation consistent with limiting temperature rise to 2 degrees, in line with global activities	Economy-wide net zero by early 2040s, exceeding 26-28% reduction by 2030. Pace of decarbonisation consistent with limiting temperature rise to 1.5 degrees, in line with global activities
Large-scale renewable build cost trajectories			
Generator and storage build costs	CSIRO GenCost Central	CSIRO GenCost High VRE	Hydrogen Superpower (see Note)
Investment and retirement considerations			
Generator retirements	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives beyond 2030.	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives
Fuel Price Settings			
Gas prices	Lewis Grey Advisory (2020), Central	Lewis Grey Advisory (2020), Step Change	Lewis Grey Advisory (2020), Step Change
Coal prices	Wood Mackenzie, Central	Wood Mackenzie, Step Change	Wood Mackenzie, Step Change
Gas Market Settings			
New gas supplies	Consistent with AEMO's 2021 GSOO Central scenario	Consistent with AEMO's 2021 GSOO Step Change scenario	Consistent with AEMO's 2021 GSOO Step Change scenario
All other gas market settings			

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[14] https://aemo.com.au/-/media/files/major-publications/isp/2021/2021-inputs-and-assumptions-workbook.xlsx?la=en