Hosting Capacity Study

Network wide HV & LV Scenario based Hosting Capacity Analysis

Dec, 2024 – Version 1.0

Document Control

Change History

Version	Issue Date	Author	Description
1.0	19 December	Adam White	First Issue

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 CER assets
CIM	Common Information Model, a standard for data exchange for network models, based on the IEC 61970, 61968 and 62325 family of standards.
CER	Consumer 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 CER 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 CER 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

Zepben has delivered a significant evolution in customer electrification modelling to CitiPower, Powercor, and United Energy. For the first time, near-complete AMI power quality data has been utilised in a comprehensive high-voltage (HV) to low-voltage (LV) power flow simulation, spanning from the zone substation bus to individual customer connection points. This model represents unprecedented capability, ensuring the customer electrification transition is technically informed and managed with confidence.

Key highlights of this evolution:

Unmatched power flow accuracy:

By utilising extensive AMI power quality data for each customer connection, along with detailed equipment control settings, the model has been able to determine unknown off load tap changer positions, removing a key uncertainty from the model that has impacted previous work in this space. This enables the model to achieve an accuracy of ±2% for 90% of customer connection points, making it the most precise and reliable model Zepben has developed to date.

Comprehensive Network Coverage:

The model used is a complete electrical 'digital twin' of the CitiPower, Powercor, and United Energy networks. Representing the 110,000 kms of HV and LV 'poles and wires' used in the delivery energy to the nearly two million customer network connection points.

The model executed hundreds of billions of power flow calculations, producing time-series results for nearly two million customer connection points at 30-minute intervals spanning a decade (2024–2034). Each time series is aligned to actual network observations and tailored forecasts for specific customer segmentation.

Industry Validation:

The Hosting Capacity Module developed and used by Zepben has had its approach to power flow modelling previously validated by the University of Melbourne, affirming the robustness, reliability of the approach.

Enhanced Analytical Capabilities:

Zepben collaborated with CitiPower, Powercor, and United Energy to enhance Zepben's modelling capabilities. The primary focus was on deploying analytics to raw timeseries power flow results to facilitate detailed economic modelling of compliance, curtailment, and energy at risk.

This collaboration led to the integration of voltage compliance analysis, identification of power quality improvement opportunities, and detailed valuation of curtailment by applying 30-minute timeseries forecasts for CECV. These advancements facilitated precise curtailment valuation and forecasting of power quality performance at individual customer supply points, ensuring alignment with Victorian Voltage Compliance obligations and supporting proactive network management strategies.

Confidence in future decisions:

The simulation results provided detailed performance insights, achieving comprehensive network coverage for each of the three networks, enabling effective decision-making and future planning.

This advanced model represents the most detailed and accurate simulation framework developed to date, providing unparalleled insights into current and future power quality performance and network reliability. The collaboration between CitiPower, Powercor, and United Energy, supported by cutting-edge technology and academic validation, sets a new industry benchmark for precision, scalability, and actionable intelligence.

A detailed dive into the development of this electrical 'digital twin', the application of the bottom up forecasts and the methodology is provided in the following chapters.

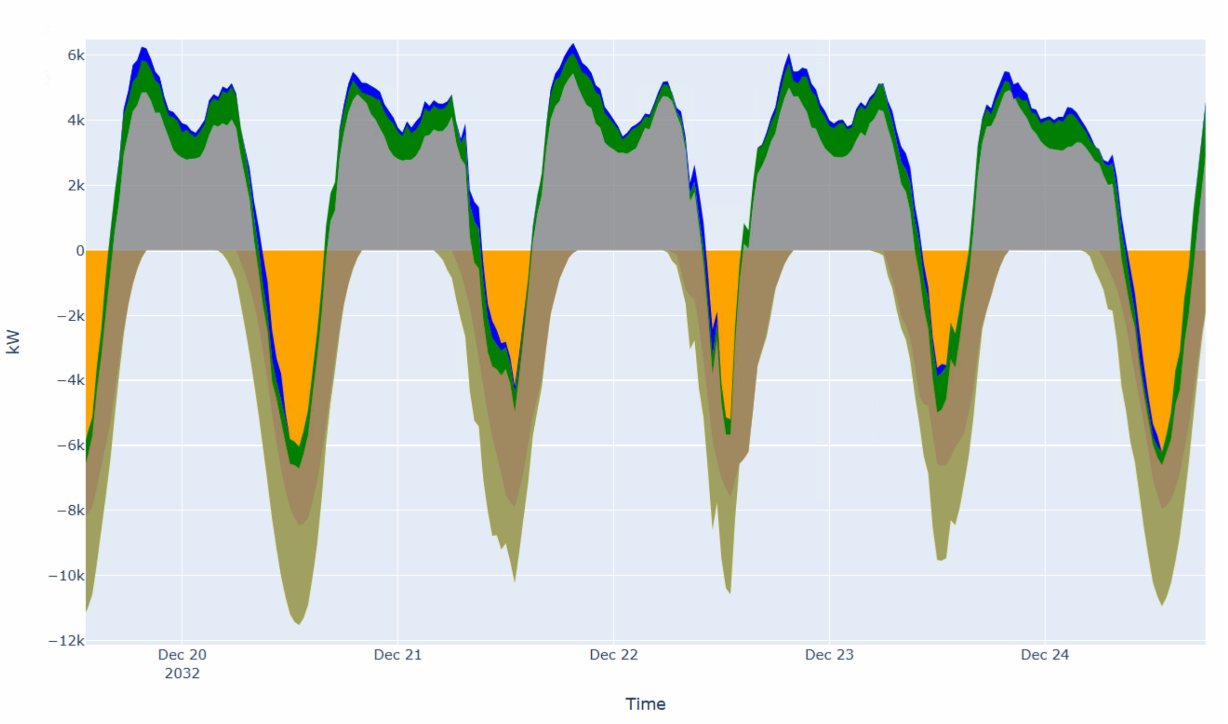

Figure 1 - Example of feeder level forecast network power flows 2032 – Orange forecast PV, Yellow existing exports, Green forecast EV Charging, Blue forecast BESS and Grey is underlying demand

2 OVERVIEW

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

CPPALUE understands these challenges and engaged Zepben to provide the electrical network modelling needed to extend strategic network planning from a pure peak demand focus to planning being built around customer compliance and timeseries curtailment. This involved undertaking a whole of network 'hosting capacity' study, to generate a constraint forecast from the LV network up into the HV network. Providing detailed output of both energy at risk and generation curtailment at the local 'street' level.

These results enabled CPPALUE to undertake detailed economic modelling to develop a comprehensive future network business case as part of CPPALUE's overall plan for the 2026-2031 regulatory period.

The key challenge with delivering on these outcomes was capturing the impact of CER uptake at the local level. The CPPALUE network covers large areas of rural Victoria, as well as the Melbourne CBD and many large inland cities. It is a heterogenous network that has been constructed over many decades. This, and the differing patterns of CER uptake predicted to occur regionally over the coming years, required moving beyond a classic taxonomic approach to an approach that provided an understanding of the magnitude and timing of CER impacts over the entire network by running time series load flow studies for multiple years into the future.

This outcome was achieved through the acquisition and curation of continuous network models 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 CER penetration scenarios. Cloud based horizontal and vertical scaling was used to provide the computational power to run the studies and aggregate and summarise the large amount of data produced.

The two key inputs that influence the modelled outcomes were the end-to-end network model provided by CPPALUE, and the 12-year demand & CER forecast provided by CPPALUE working with Blunomy. This forecast was based around the Australian Energy Market Operator's – Integrated System Plan scenarios, with a step-change scenario for roof top PV generation capacity within CPPALUE's network projected to more than double from the current 1,968MW of capacity, up to 5,300MW of capacity by 2035.

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

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

The modelling undertaken and the approaches applied are covered in detail in the subsequent chapters of this report.

2.1 SCOPE

The brief for the work was as follows:

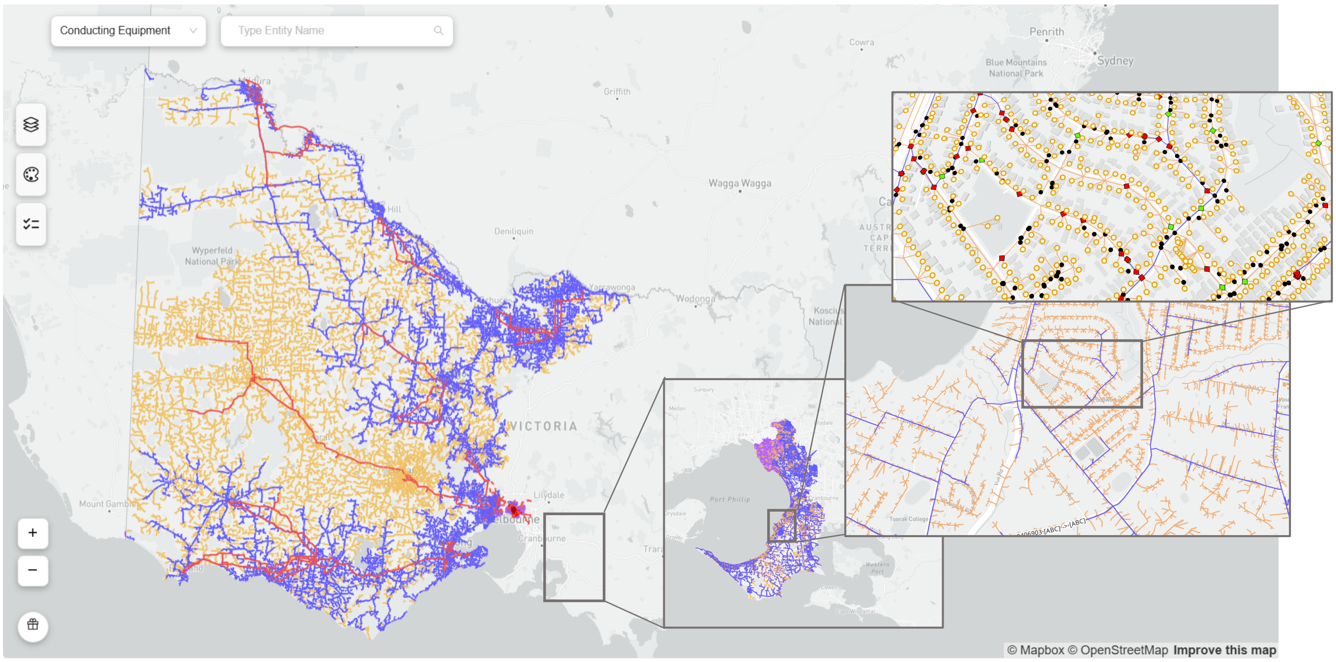
- *Complete a forecast hosting capacity assessment or 'curtailment forecast' across the Citipower, Powercor and United Energy networks (referred to in this report as CPPALUE) for the period 2023 - 2034 inclusive. Covering the MV and LV Network, and considering the impact of forecast PV, battery storage and EV uptake.*

The modelling outcomes were required to be compiled into a suitable format to enable a Cost Benefit Analysis (CBA) to be formulated around avoided curtailment, energy at risk and voltage compliance to determine the optimal network capacity-intervention cost balance over the 12-year forecast period.

2.1.1 Hosting Capacity Forecast

Each MV feeder was modelled from the MV busbar of the Zone Substation to each supply point in the LV network. "Supply Point" in this context means the last node in the LV network model, with one or more customer connection points attached to each supply point.

The time series load flow studies were conducted for each MV feeder in parallel, using this continuously connected MV and LV network, with the timeseries energy inputs supplied from each of the approximately 1,900,000 customer connection points in the model.



The load flow studies included:

- A baseline point in time load flow study for the whole network during a low demand period to set the tap position of all distribution transformer Off Load Tap Changers (OLTCs). This was achieved by modelling during a low demand period, minimising the influence of network impedance, using smart meter power quality data (Read, Reactive Power and Voltages) and feeder head power quality meter data. This enabled us to reduce the model unknown to be the network model and the transformer off load tap positions, allowing us to infer the estimation of the real world OLTC positions.

- Once the OLTC tap positions were set, a baseline timeseries study was undertaken to confirm the overall model was calculating voltage and power correctly. This was achieved by modelling a set of specific historic intervals with known real and reactive power and voltage per connection point. The real and reactive power inputs were used on the model and the voltages produced at each connection point were then compared with the measured actual voltages.

- A base year modelling of current network voltage issues and thermal constraints across the entire network.

- A 12-year forecast of voltage and thermal constraints under a set of forecast future CER scenarios. This forecast was aligned with the provided demand and CER forecast period 2023-2034.

2.2 KEY ACTIVITIES

There were three 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 each electrical network,

- Timeseries (30-minute interval) Hosting Capacity curtailment forecast for each year of the forecast provided by CPPALUE,

These three activities provided CPPALUE with a complete picture of the current and future performance of the distribution network.

2.3 INDEPENDENT VALIDATION OF THE NETWORK MODELS

To provide added confidence in the OpenDSS models produced by Zepben’s Hosting Capacity Module, the University of Melbourne, which has researchers with considerable experience using OpenDSS, has previously been engaged to review several of the feeder models built using Zepben’s Hosting Capacity Module, 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 CPPALUE'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 CPPALUE's distribution network.

- HV Network Model - 11,22,33kV
- LV Network Model
- 30min energy profiles for each AMI meter
- DER Register
- Customer - Network Relationship
- PQV data for calibration periods (real, reactive and voltage data)
- Feeder head voltages for calibration periods
- Conductor library (HV & LV)
- Line Regulator Voltage Settings
- Distribution transformer tap settings and impedance.
- Zone Substation voltage regulation settings
- Zone Substation source impedance
- Zone Substation Power transformer tap ranges & steps
- Pole top capacitors & control settings

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 CPPALUE's network is expected to perform over the next 12 years in response to those forecast behaviours.

Zepben worked with CPPALUE and their forecasting partner, Blunomy, to include a comprehensive set of underlying load data, electrification and CER forecasts into the 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
- PV inverter capacity forecasts by feeder
- Installed Consumer BESS numbers by feeder
- Registered EVs by feeder
- EV charger demand profiles by year
- PV generation profiles by feeder
- BESS charging profile by feeder

This collection of inputs were combined to create the information needed to support extending the base electrical model of CPPALUE's network over the forecast period. This enabled the performance of the physical network under the various versions of the future represented by the forecast inputs to be determined.

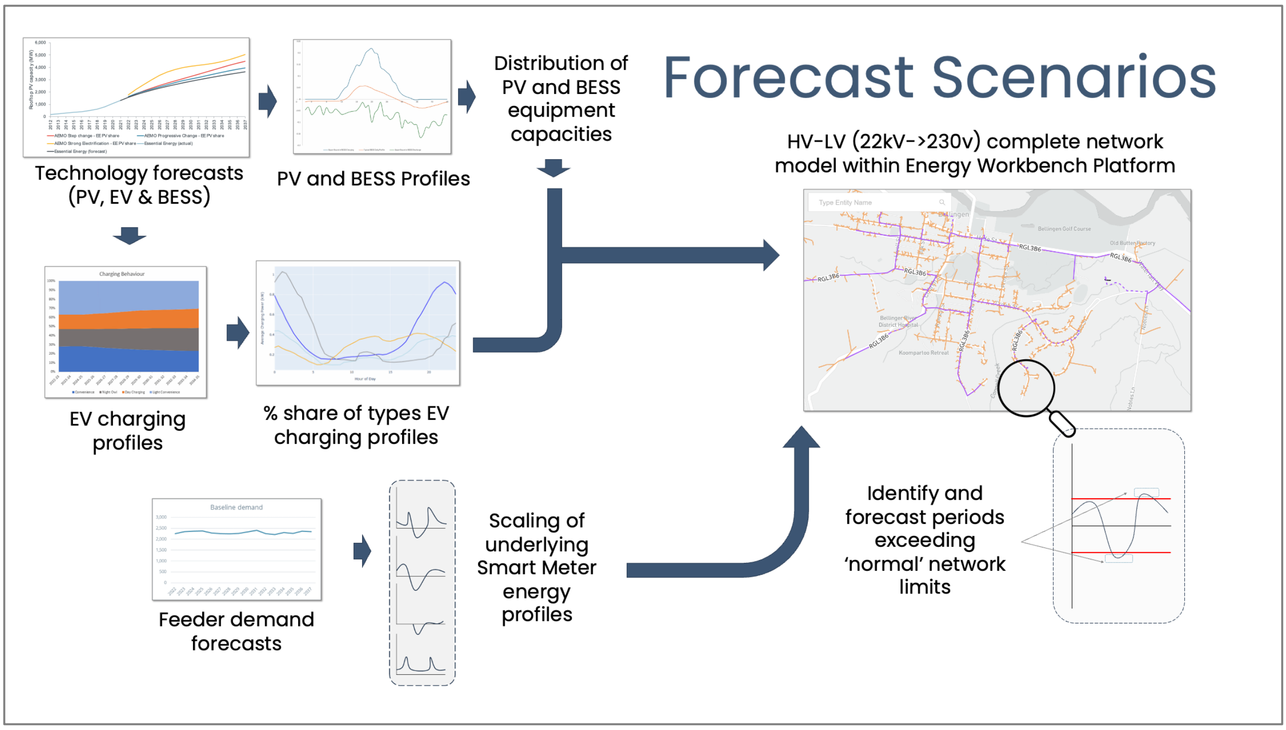


Figure 2 - This diagram illustrates how these inputs are combined to form valid future scenarios of electrical network performance

2.5 OUTPUTS

To meet the objectives of the Hosting Capacity Analysis project, Zepben collaborated with CPPALUE to develop a comprehensive set of network performance metrics that accurately captured the time-series network modelling results while addressing a range of operational scenarios. These metrics covered weekly, seasonal, and day/night-specific results, as well as on-demand constraint reporting and line-segment-level overload reporting.

The inclusion of these detailed metrics enhances the modelling approach by incorporating the valuation of energy flows at the outset into Zepben's Hosting Capacity Module. This enables the most granular 30-minute timeseries valuation of curtailment and energy at risk to be employed.

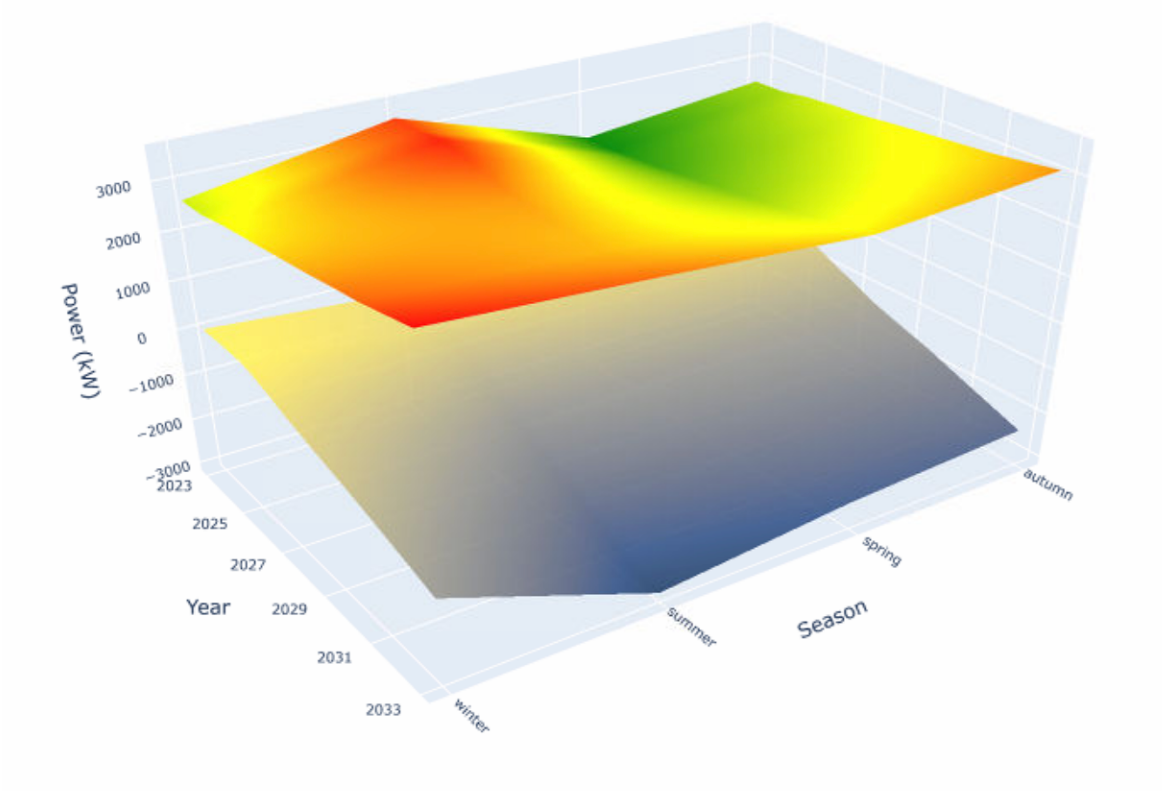


Figure 3 – Example of HV Feeder Level Forecast Peak Import and Peak Export by Season and Year

The raw time-series analysis generated a dataset of peta-byte scale, which was unmanageable as a direct input into CPPALUE's follow-on Cost-Benefit Analysis (CBA) project for determining the optimal balance of solutions. To ensure usability, the model outputs were transformed into appropriately summarized metrics. These Network Performance Metrics form the core output of the Hosting Capacity Module and are detailed in Table 1, with additional results defined in Appendix 4.2. They provide comprehensive summaries of downstream network performance for each of CPPALUE's MV feeders, distribution transformers, and LV circuit disconnectors.

Notably, these enhanced outputs introduced a comprehensive disaggregated valuation approach for time-series power flow results, applying a mix of well know industry standard and emerging valuation methodologies, including the Value of Customer Reliability (VCR), Customer Export Curtailment Values (CECV), avoided carbon emissions (CO_2), and Customer Value of Voltage Reduction (CVVR). These metrics provide deeper insights into network performance enabling customer impacts to be quantified and weight against investment options:

- **Value of Customer Reliability (VCR):** Quantifies the value customers place on electricity supply reliability, applied to customer imports exceeding thermal or voltage limits. This is applied as a constant value across the networks, based on share of end use consumption, in 2024 dollars.

- **Customer Export Curtailment Values (CECV):** Represents the economic value of renewable energy exports, applied to customer exports that exceed thermal or voltage limits. These values are imported directly from the Australian Energy Regulator (AER) website here[2]

- **CO_2 Avoidance Value:** Highlights the benefits of displacing carbon-based generation sources through avoided emissions, and aligns with CECV being applied to customer exports that exceed thermal or voltage limits. These values were provided by CPPALUE in the same format as CECV, a timeseries 30min value in 2024 dollars out to 2045.

- **Customer Value of Voltage Reduction (CVVR):** Captures the long-term costs to consumers from steady-state over-voltages, which reduce equipment lifetimes and appliance efficiency. While the capability was developed to apply this value, an industry agreed value is not defined to be able to apply there. Zepben is open to collaborating with organisations to continue to work towards defining this value in the interest of consumers.

Additionally, the project delivered a step-change in capability with the development of a voltage percentile-based measurement approach aligned with Victorian Voltage Compliance obligations. These obligations, traditionally applied to historical actuals from Victoria's extensive smart meter data, can now be forecast under various scenarios, offering a robust method for evaluating compliance and informing future network planning. Figure 4 provides an insight into the capability created by the detailed modelling of LV voltage compliance over the forecast planning horizon.

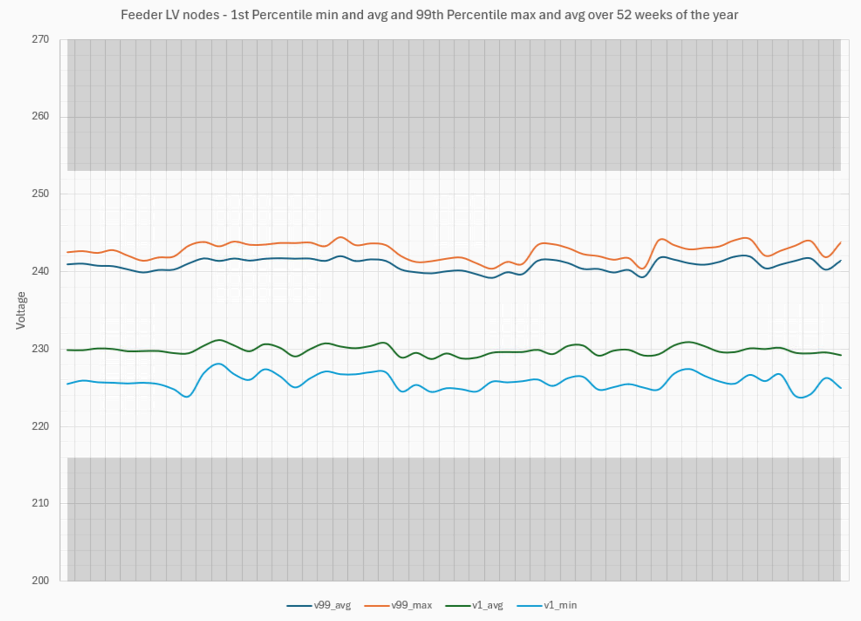


Figure 4 - Example of a Feeders annual LV node voltage compliance

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[2] https://www.aer.gov.au/system/files/2024-07/2024_CECV_VIC1.csv

All these key metrics discussed leverage the underlying segmentation of the network as described in Figure 5 below to enable analysis of the outputs alongside other external datasets, as well as providing a balance between overall modelling performance and modelling accuracy & detail. This diagram shows how the network was segmented to capture customer connection point voltages, energy at risk, and curtailment at the network level without double counting. This allows for accurate aggregation of results in subsequent economic analyses.

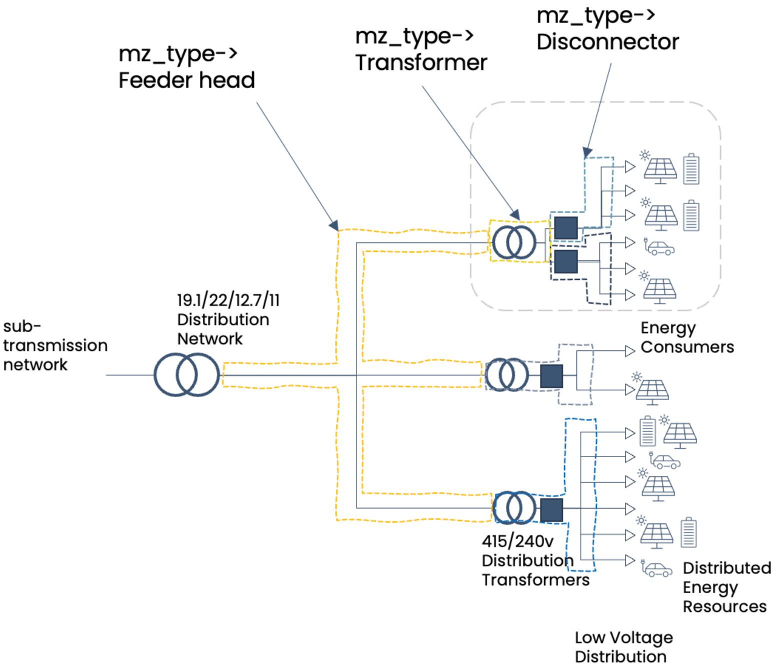


Figure 5 - Segmentation of recorded network performance

Table 1 - Key results metrics defined as modelling output

Metric	**Description**
work_package_id	The ID of the work package that was run
scenario	The scenario for this input
timestamp	Expressed in UTC
feeder	The feeder for this input
measurement_zone_name	The measurement zone name for this input (energy meter name)
mz_type	The type of asset class that forms the 'head' of the measurement zone

conducting_equipment_mrid	This is a unique identifier for the asset that forms the 'head' of the measurement zone
terminal_sequence_number	The identifier for the terminal of the conducting_equipment_mrid asset that forms the 'head' of the measurement zone. Where two measurement zones are present for a single conducting equipment mrid, this indicates a loop within the network. The terminal_sequence_number can be used to differentiate between them.
season	as per config - e.g. {spring, summer, autumn, winter, annual}
time_of_day	as per config - e.g. {day, solar_day, night, all}
interval_count	number of intervals covered by the metrics. Increment for every result timestep
v_base	voltage base of metrics - expressed in ph-ph voltage. For Transformers voltage base is reported as the secondary voltage. This field should be used to convert from per unit results into magnitudes
maximum_section_voltage	Maximum recorded voltage for a measurement_zone. This is the max voltage recorded across al the nodes and all phases within the measurement_zone. Note that the relevant time period is defined by the timestamp, season and time_of_day.
minimum_section_voltage	Minimum recorded voltage for a measurement_zone. This is the min voltage recorded across all the nodes and all phases within the measurement_zone. Note that the relevant time period is defined by the timestamp, season and time_of_day.
voltage_delta_avg	The average of the maximum voltage phase delta per time slot. This metric provides a view of the average voltage change across nodes within a measurement_zone for the relevant time period. Here the delta in voltage between nodes in a measurement_zone is calculated for each phase and each timestep. The average of this delta is then taken to show the typical voltage difference between nodes on the measurement_zone.

voltage_delta_max	The maximum voltage phase delta detected. Here the delta in voltage between nodes in a measurement_zone is calculated for each phase and each timestep. The maximum of this delta is then taken to show the worst case voltage difference between nodes on the measurement_zone.
v50_avg_section_voltage	The median voltage across all available phase voltage averages (this means averaging over circuit nodes and then median over the modelled time period)
v99_avg_section_voltage	99th percentile reading of all available phase voltage averages. (this means average voltage over circuit nodes and then percentile taken over the modelled time period)
v95_avg_section_voltage	95th percentile reading of all available phase voltage averages. (this means average voltage over circuit nodes and then percentile taken over the modelled time period)
v5_avg_section_voltage	5th percentile reading of all available phase voltage averages. (this means average voltage over circuit nodes and then percentile taken over the modelled time period)
v1_avg_section_voltage	1st percentile reading of all available phase voltage averages. (this means average voltage over circuit nodes and then percentile taken over the modelled time period)
voltage_over_limit_hours	Total hours where one or more phase voltages exceeds VH1
num_voltage_over_limit_events	Count of events, where an event occurs each time the voltage crosses over the VH1 limit
voltage_under_limit_hours	Total hours where one or more phase voltages are below VL1
num_voltage_under_limit_events	Count of events, where an event occurs each time the voltage falls below the VL1 limit
thermal_load_limit_hours	total hours of the modelled load has a thermal exceedance. Thermal exceedance is defined by normal/nominal asset ratings. Ratings are all assessed in terms of line current. Time is counted whenever a measurement_zone records a normal rating exceedance and the direction of power flow at the head of the measurement_zone is downstream.

thermal_emerg_load_limit_hours	total hours of the modelled load has an emergency thermal exceedance. Thermal exceedance is defined by emergency asset ratings. The default is 150% of the nominal rating. Ratings are all assessed in terms of line current. Time is counted whenever a measurement_zone records an emergency rating exceedance and the direction of power flow at the head of the measurement_zone is downstream.
num_thermal_load_limit_events	Count of events, where an event occurs each time the load has a thermal exceedance that was not present in the previous interval This metric can be used to understand the frequency of thermal load driven overloads. It is helpful to identify thermal constraints that might be due to inaccurate ratings, by identifying thermal constraints that bind for a large number of hours and are only made up of a few events i.e. where constraints are binding all but for min demand.
num_thermal_emerg_load_limit_events	Count of events, where an event occurs each time the load has a emergency thermal exceedance which was not present in the previous interval
thermal_gen_limit_hours	Total hours of the modelled generation has a thermal exceedance. Thermal exceedance is defined by normal/nominal asset ratings. Ratings are all assessed in terms of line current. Time is counted whenever a measurement_zone records a normal rating exceedance and the direction of power flow at the head of the measurement_zone is upstream.
thermal_emerg_gen_limit_hours	total hours of the modelled generation has a emergency thermal exceedance Thermal exceedance is defined by normal/nominal asset ratings. Ratings are all assessed in terms of line current. Time is counted whenever a measurement_zone records an emergency rating exceedance and the direction of power flow at the head of the measurement_zone is upstream.
num_thermal_gen_limit_events	Count of events, where an event occurs each time the generation has a thermal exceedance which was not present in the previous interval
num_thermal_emerg_gen_limit_events	Count of events, where an event occurs each time the generation has a emergency thermal exceedance which was not present in the previous interval

load_kwh	The sum of all energy consumed by elements modelled as loads (underlying demand, net BESS and EVs), within the measurement_zone during the relevant time period. Note this does not include energy that is supplied via the measurement_zone, or network losses, it is only energy delivered to consumers within the measurement_zone. This allows aggregation of measurement_zone results, as delivered energy is not double counted.
load_exceeding_normal_een_kwh	Sum Energy consumed by loads outside normal voltage limits 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.
load_exceeding_normal_een_vcr	Sum Energy consumed by loads outside normal voltage limits and any upstream asset thermal limits, multiplied by the Value for Customer Reliability 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. Due to a limitation within OpenDSS this metric is currently not being calculated correctly, this note will be removed once the limitation is no longer present.
load_overvoltage_kwh	Sum of energy consumed by loads whilst overvoltage Note: this does not use energy scaling, this means all energy delivered to loads for each interval where avg measurement_zone voltages exceed VH1 (default: 253v for 230v base) will be counted as at risk.
load_overvoltage_cvvr	load_overvoltage_cvvr is the same as load_overvoltage_kwh multiplied by CVVR (Customer Value Voltage Reduction). The logic behind the design of this metric is we are valuing the damage cause to all electrically connected appliance during an overvoltage event. This means that this metric is still conservative as not all connected appliances that are exposed to the overvoltage will be consuming energy during all intervals.
load_undervoltage_kwh	Sum of energy consumed by loads whilst undervoltage - does not use energy scaling. Note: this does not use energy scaling, this means all energy delivered to loads for each interval where avg measurement_zone voltages is below VL1 (default: 216v for 230v base) will be counted as at risk.

load_undervoltage_normal_kwh	This metric calculates the sum of kWh where the voltage is under normal voltage limits, the difference with load_undervoltage_kwh is that it uses energy scaling, to capture only a proportion of the circuit energy as at risk, depending on the magnitude of undervoltage. Measurement_zone energy is captured as a linearly increasing proportion between VL1 and VL2 (by default 216v -> 207v for 230v base), where once the average node voltage reaches VL2 100% of circuit energy is captured as 'at risk' or unserved.
load_exceeding_normal_voltage_kwh	This metric captures kWh of load that was delivered outside of the configured upper and lower thresholds. Includes energy scaling to capture energy based on the magnitude of voltage non-compliance. Default thresholds for 230v base are 216v <> 253v. This is the point at which part of the measurement_zone energy is counted. This energy linearly increases until the outer voltage thresholds are reached, which for 230v base are 207v <> 260v. At this level, 100% of measurement_zone energy for the relevant intervals is counted as energy 'at risk' or unserved.
load_exceeding_normal_voltage_vcr	This metric captures kWh of load that was delivered outside of the configured upper and lower thresholds, multiplied by the Value of Customer Reliability. Includes energy scaling to capture energy based on the magnitude of voltage non-compliance. This metric can be used to capture the value of addressing voltage constraints within a measurement_zone
load_exceeding_normal_thermal_kwh	This metric captures kWh of load 'at risk' due to power flows greater than the nominal/normal rating of power delivery assets within the measurement_zone. Defined the energy flow within the section of network that exceeded normal assets ratings. Warning: this group of thermal metrics captures energy flows through the measurement_zone that exceeds normal asset ratings, not just energy from load connected in the measurement_zone, energy from downstream measurement_zones is also include in the overload calculations. Overload energy for this metric is only captured when the direction of current flow is Downstream. See gen_exceeding_normal_thermal_kwh for upstream thermal overloads. The normal rating is defined by WireInfo ratedCurrent.

load_exceeding_emerg_thermal_kwh	This metric captures kWh of load 'at risk' due to power flows greater than the emergency rating of power delivery assets within the measurement_zone. Overload energy for this metric is only captured when the direction of current flow is Downstream. See gen_exceeding_emerg_thermal_kwh for upstream thermal overloads. The emergency rating is defined as a multiple of the WireInfo ratedCurrent. The default multiplier is 150% of nominal rating.
load_exceeding_normal_thermal_vcr	This metric is the same as the load_exceeding_normal_thermal_kwh defined above, multiplied by the Value of Customer Reliability. This metric can be used to capture the value of addressing thermal constraints within a measurement_zone.
load_exceeding_normal_thermal_voltage_kwh	This metric captures the total load at risk within a measurement_zone; voltage and thermal. Another way to view this metric is as the sum of the largest normal overload (voltage or thermal) on an interval-by-interval basis. Only accumulate the largest of each violation in each interval to avoid double counting. The voltage-driven energy used energy scaling as defined above.
load_exceeding_emerg_thermal_voltage_kwh	This metric captures the total load at risk within a measurement_zone; voltage and emergency thermal. The metric is as per load_exceeding_normal_thermal_voltage_kwh, except that the thermal overload component uses the emergency asset ratings.
load_exceeding_normal_thermal_voltage_vcr	This metric captures the total value of the load at risk within a measurement_zone; voltage and thermal. This value is the primary value that can be used for assessing the economic case for an intervention to manage the customer load energy at risk. The metric is defined as per load_exceeding_normal_thermal_voltage_kwh, multiplied by the Value of Customer Reliability.
load_exceeding_normal_thermal_max_kw	This metric is the complementary power metric to load_exceeding_normal_thermal_kwh. It captures the peak kW loading above normal asset ratings. This represents the largest delta between recorded power values and an normal asset rating within the measurement_zone in the relevant period.

load_exceeding_emerg_thermal_max_kw	Similar to the above metric this value represents the peak kW loading above emergency asset ratings. This represents the largest delta between recorded power values and an emergency asset rating within the measurement_zone in the relevant period. (where no emergency asset rating is provided 150% of normal rating used)
load_max_kw	This is the maximum recorded gross load/consumption recorded within the measurement_zone for loads connected within the measurement_zone. Only loads connected within the measurement_zone are included in this metric, downstream load is not captured.
load_max_timestamp	Timestamp of peak gross load/consumption within the relevant measurement_zone.
generation_kwh	Total generation over the measurement_zone. Where base year generation is defined by the AMI data export channels or equivalent data, and forecast generation is directly added to the model and so captured as gross generation connected.
gen_overvoltage_kwh	The sum of energy generated by PV systems whilst overvoltage event is recorded. Scaling is included to include partial generation energy from VH1 (default 253v for 230v base), and not include the full amount of measurement_zone energy until the average measurement_zone voltages reach VH2 (default 260v for 230v base).
gen_overvoltage_cecv	This metric is the same as gen_overvoltage_kwh defined above, multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overvoltage is present. Scaling is included to include partial generation energy from VH1 (default 253v for 230v base), and not include the full amount of measurement_zone energy until the average measurement_zone voltages reach VH2 (default 260v for 230v base)
gen_overvoltage_co2	This metric is the same as gen_overvoltage_kwh defined above, multiplied by the relevant the timeseries value of CO2 for each interval the overvoltage is present. Scaling is included to include partial generation energy from VH1 (default 253v for 230v base), and not include the full amount of measurement_zone energy until the average

	measurement_zone voltages reach VH2 (default 260v for 230v base)
gen_exceeding_normal_voltage_kwh	This metric builds on the overvoltage metrics above to include both over and under voltage events. It includes the sum of energy generated by PV systems whilst overvoltage or undervoltage event is recorded within the measurement_zone. Default thresholds for 230v base are 216v <> 253v. This is the point at which part of the measurement_zone energy is counted as curtailed. The curtailed energy then linearly increases until the outer voltage thresholds are reached, which for 230v base are 207v <> 260v. At this level, 100% of measurement_zone generated energy for the relevant intervals is counted as curtailed.
gen_exceeding_normal_voltage_cecv	This metric is the same as gen_exceeding_normal_voltage_kwh defined above, multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overvoltage is present.
gen_exceeding_normal_voltage_co2	This metric is the same as gen_exceeding_normal_voltage_kwh defined above, multiplied by the relevant the timeseries value of CO2 for each interval the overvoltage is present.
gen_exceeding_normal_thermal_kwh	This metric captures kWh of generation curtailed due to reverse power flows greater than the normal rating of power delivery assets within the measurement_zone. Overload energy for this metric is only captured when the direction of current flow is Upstream. See load_exceeding_normal_thermal_kwh for downstream thermal overloads.
gen_exceeding_emerg_thermal_kwh	This metric captures kWh of generation curtailed due to reverse power flows greater than the emergency rating of power delivery assets within the measurement_zone. Overload energy for this metric is only captured when the direction of current flow is Upstream. See load_exceeding_emerg_thermal_kwh for downstream thermal overloads. The emergency rating is defined as a multiple of the WireInfo ratedCurrent. The default multiplier is 150% of nominal rating.

gen_exceeding_normal_thermal_cecv	This is gen_exceeding_normal_thermal_kwh multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overload is present.
gen_exceeding_normal_thermal_co2	This is gen_exceeding_normal_thermal_kwh multiplied by the relevant timeseries value of CO2 for each interval the overload is present.
gen_exceeding_normal_thermal_voltage_kwh	This metric captures the total generation at risk within a measurement_zone due to breaching voltage and thermal limits. Another way to view this metric is as the sum of the largest normal generation overload (voltage or thermal) on an interval-by-interval basis. Only accumulate the largest of each violation in each interval to avoid double counting. The voltage-driven energy used energy scaling as defined above. Default thresholds for 230v base are 216v <> 253v. This is the point at which part of the measurement_zone energy is counted as curtailed. The curtailed energy then linearly increases until the outer voltage thresholds are reached, which for 230v base are 207v <> 260v. At this level, 100% of measurement_zone generated energy for the relevant intervals is counted as curtailed.
gen_exceeding_emerg_thermal_voltage_kwh	This metric captures the total generation at risk within a measurement_zone due to breaching voltage and emergency thermal limits. Another way to view this metric is as the sum of the largest emergency thermal generation overload or voltage limit breach on an interval-by-interval basis. Only accumulate the largest of each violation in each interval to avoid double counting. The voltage-driven energy used energy scaling as defined above. Default thresholds for 230v base are 216v <> 253v. This is the point at which part of the measurement_zone energy is counted as curtailed. The curtailed energy then linearly increases until the outer voltage thresholds are reached, which for 230v base are 207v <> 260v. At this level, 100% of measurement_zone generated energy for the relevant intervals is counted as curtailed.
gen_exceeding_normal_thermal_voltage_cecv	This is gen_exceeding_normal_thermal_voltage_kwh multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overload is present.

gen_exceeding_emerg_thermal_voltage_cecv	This is gen_exceeding_emerg_thermal_voltage_kwh multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overload is present.
gen_exceeding_normal_thermal_voltage_co2	This is gen_exceeding_normal_thermal_voltage_kwh multiplied by the relevant timeseries value of CO2 for each interval the overload is present.
gen_exceeding_emerg_thermal_voltage_co2	This is gen_exceeding_emerg_thermal_voltage_kwh multiplied by the relevant timeseries value of CO2 for each interval the overload is present.
gen_exceeding_normal_thermal_max_kw	This metric is the complementary power metric to gen_exceeding_normal_thermal_kwh. It captures the peak kW generation above normal asset ratings. This represents the largest delta between recorded power values and a normal asset rating within the measurement_zone in the relevant period, where the power flow direction is Upstream.
gen_exceeding_emerg_thermal_max_kw	Similar to the above metric this value represents the peak kW generation above emergency asset ratings. This represents the largest delta between recorded power values and an emergency asset rating within the measurement_zone in the relevant period, where the power flow direction is Upstream. (where no emergency asset rating is provided 150% of normal rating used)
gen_exceeding_emerg_thermal_cecv	This is gen_exceeding_emerg_thermal_kwh multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overload is present. This metric values thermal-based curtailment only.
gen_exceeding_emerg_thermal_co2	This is gen_exceeding_emerg_thermal_kwh multiplied by the relevant time-series value of CO2 for each interval the overload is present. This metric values thermal-based curtailment only.
gen_max_kw	This is the maximum recorded gross generation recorded within the measurement_zone for generators connected within the measurement_zone. Only generators connected within the measurement_zone are included in this metric, downstream generation is not captured. \n
gen_max_timestamp	Timestamp of gen_max_kw

peak_import	Peak_import is the maximum recorded downstream energy flow at the 'head' of the measurement_zone. This metric does not consider load and generation separately and captures the net peak import for the measurement_zone over the relevant period.
peak_export	Peak_export is the maximum recorded upstream energy flow at the 'head' of the measurement_zone. This metric does not consider load and generation separately and captures the net peak import for the measurement_zone over the relevant period.
transformer_utilisation	Ratio of installed TX capacity vs total energy delivered Note: This metric is currently only configured to operate for EE network based on a limitation for passing transformer ratings. This metric will be improved as part of planned updates.

While the primary output as defined by Table 1 was the core deliverable, there are a number of additional tables that define more detailed results. This includes the weekly results and the constraint table. Further details are available on these in Appendix 4.2.

2.6 MODELLING APPROACH

Zepben's approach to modelling is to maximise the use of source network model data, through the use of intelligent business/engineering logic algorithms that create an internally consistent model that is suitable for undertaking power flow analysis with forecast changes in load and generation as inputs.

2.6.1 Ingestion of CPPALUE's full Medium Voltage and Low Voltage network models

Zepben received the complete network models held in CPPALUE's Smallworld Graphical Information Systems (GIS) for May 2023. The Citipower and Powercor network models were of reasonable quality, with good overall quality for the MV and usable quality for the LV network.

The United Energy data model was initially of poor quality and was initially only able to support modelling a limited proportion of the United Energy network. Working with the United Energy team over a 6 month period we were able to resolved a significant proportion of the network connectivity, phasing and missing attribution issues.

These models held the following data:

- Underground and Overhead Lines, with length, connectivity, partial attributes that allow defining standard types, phase connections, voltage, identifier and, location,
- Transformers, with voltage, location, connectivity, rating, 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.

The data was delivered as one file per MV feeder holding all the MV network assets, and one file per LV distribution transformer holding the LV assets. The data was expressed as JSON, a common format for exchanging data. The topology was exported by adding a “from” and “to” node attribute to all cables and overhead lines.

An example of the JSON used to represent a segment of overhead line is provided in the Figure 6 below.

```
}, {
    "id": "93458992",
    "class": "transformer",
    "name": "",
    "attributes": [{
            "name": "Orientation",
            "value": -1.571890593
        }, {
            "name": "id",
            "value": 93458992
        }, {
            "name": "Functional Location",
            "value": "DS-000049950227-TX01"
        }, {
            "name": "status",
            "value": "in service"
        }, {
            "name": "transformer no",
            "value": "1"
        }, {
            "name": "position",
            "value": "u"
        }, {
            "name": "primary voltage",
            "value": "11kV"
        }, {
            "name": "rating",
            "value": 500
        }, {
            "name": "secondary voltage",
            "value": "lv"
        }, {
            "name": "Date Updated",
            "value": "13\/01\/2023"
        }, {
            "name": "Updated By",
            "value": "bturton"
        }, {
            "name": "Owner",
            "value": "UE"
        }, {
            "name": "Type",
            "value": "11KV CABLE ENTRY"
        }, {
            "name": "Feeder",
            "value": "AR 12"
        }, {
            "name": "Service Provider Region Id",
            "value": "R01"
        }, {
            "name": "Phases",
            "value": "A"
        }
    ]
```

```
}, {
    "id": "20549093",
    "class": "transformer",
    "name": "Transformer 22kV",
    "attributes": [{
            "name": "Orientation",
            "value": 3.017237663
        }, {
            "name": "Id",
            "value": 20549093
        }, {
            "name": "Equipment Number",
            "value": "41073806"
        }, {
            "name": "OMS Feeder",
            "value": "DDL021"
        }, {
            "name": "Name Plate",
            "value": "HARDING FENWICK 4"
        }, {
            "name": "Type",
            "value": "TD"
        }, {
            "name": "Name Plate Rating (kVA)",
            "value": "315 kVA"
        }, {
            "name": "Rating (kVA)",
            "value": "315 kVA"
        }, {
            "name": "Status",
            "value": "in service"
        }, {
            "name": "Primary Voltage",
            "value": "22kV"
        }, {
            "name": "Secondary Voltage",
            "value": "LV"
        }, {
            "name": "Tertiary (SWER) Voltage",
            "value": "None"
        }, {
            "name": "Date Installed",
            "value": "19\/07\/2001"
        }, {
            "name": "Serial Number",
            "value": "8605165"
        }, {
            "name": "Manufacturer Code",
            "value": "WET"
        }, {
            "name": "Technical Standard",
            "value": "Unknown"
        }, {
            "name": "Transformer Configuration",
            "value": "Three Phase"
        }, {
            "name": "Last Update Date",
            "value": "29\/04\/2010"
        }, {
            "name": "Last Update Name",
            "value": "skumar@skumar"
        }, {
            "name": "Business Code",
            "value": "8000"
        }, {
            "name": "Phase Vector",
            "value": "DY 11"
        }, {
            "name": "tapping_range_id",
            "value": 0
        }, {
            "name": "Transformer Position",
            "value": "1"
        }, {
            "name": "transformer_loading_id",
            "value": 0
        }, {
            "name": "Fire Area",
            "value": "Non Fire Area"
        }, {
            "name": "System Plan",
            "value": "MAP 242-1:E3"
        }, {
            "name": "Matchcode",
            "value": ""
        }, {
            "name": "Report",
            "value": ""
        }, {
            "name": "Melway\/VicRoads Ref",
            "value": "Melways 444 G7"
        }, {
            "name": "SAP Feeder",
            "value": "DDL021"
        }
    ]
```

Figure 6 - examples geoJSON (UE of left, Powercor/Citipower right)

The ingestion process converts the generic JSON 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 7 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 work.

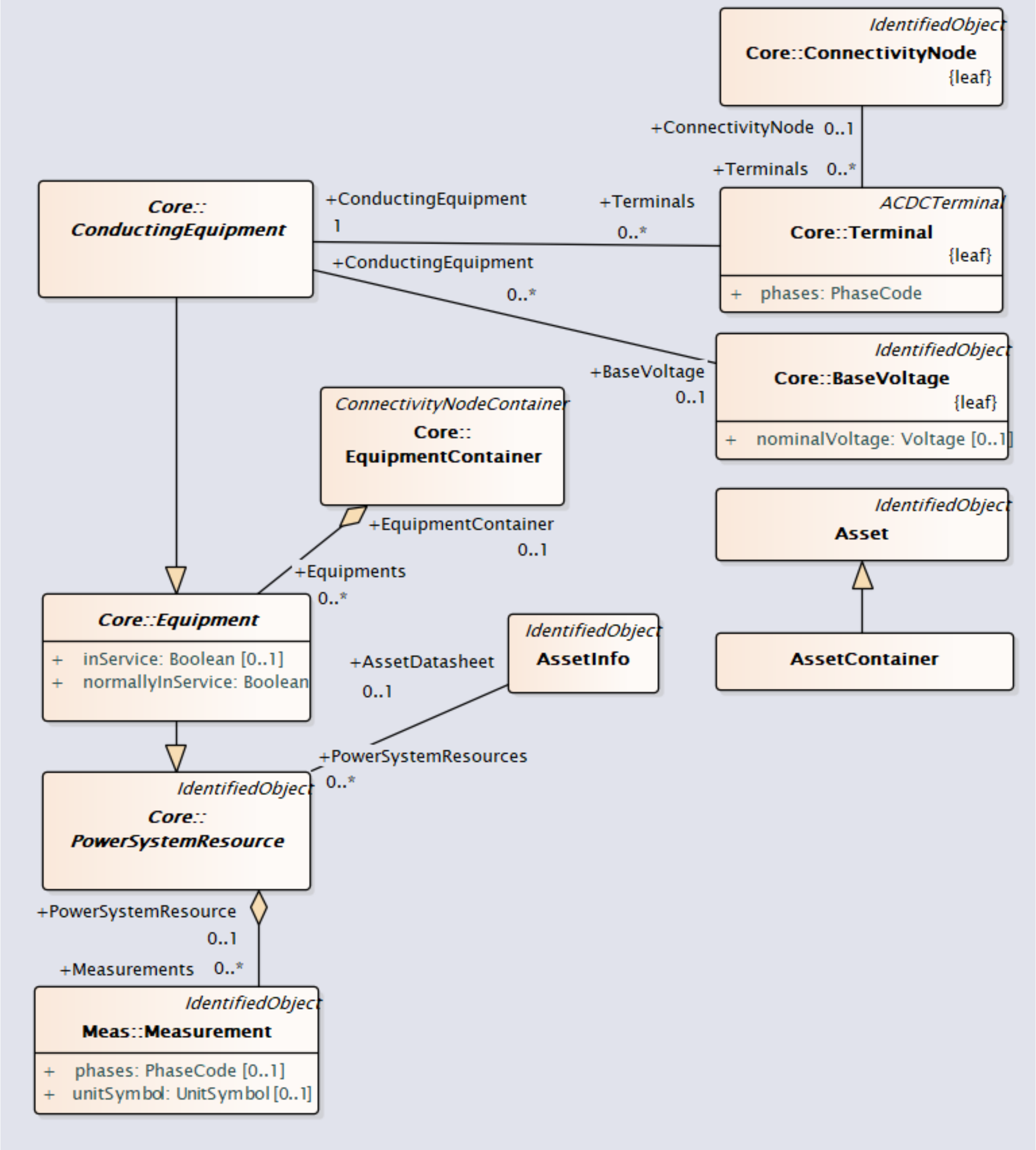


Figure 7 - CIM Data Model – Example of UML relationship diagram

2.6.2 Review of model completeness – Powercor & Citipower - CPPAL

Zepben undertook comprehensive analysis of the completeness of the Powercor and Citipower networks from the CPPALUE network models. Some relevant findings included:

- MV Network voltages were complete for all the network with a length > 0 meters, covering the range 11, 12.7, 22, 6.6kV.
- LV lines do not specify voltages, voltages are defined by transformer secondaries.
- 0.77% of MV network length has a blank line type, 5.89% of the MV network length is unable to be matched to a catalogue entry and are processed as an unknown conductor type.
- 60% MV network length was identified as high impedance conductor (where impedance > 6 Ohms per / km)
- Non-zero network impedance values were available for 99.23% of the MV network length,
- Non-zero network impedance values were available for 60% of the LV network length,
- 39% of LV network length contained unknown conductor types
- 100% of services were of unknown cable type, with partial identification coming from 30% of service length service conductor diameter only.
- Phase data was often missing or anomalous for the MV network.

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

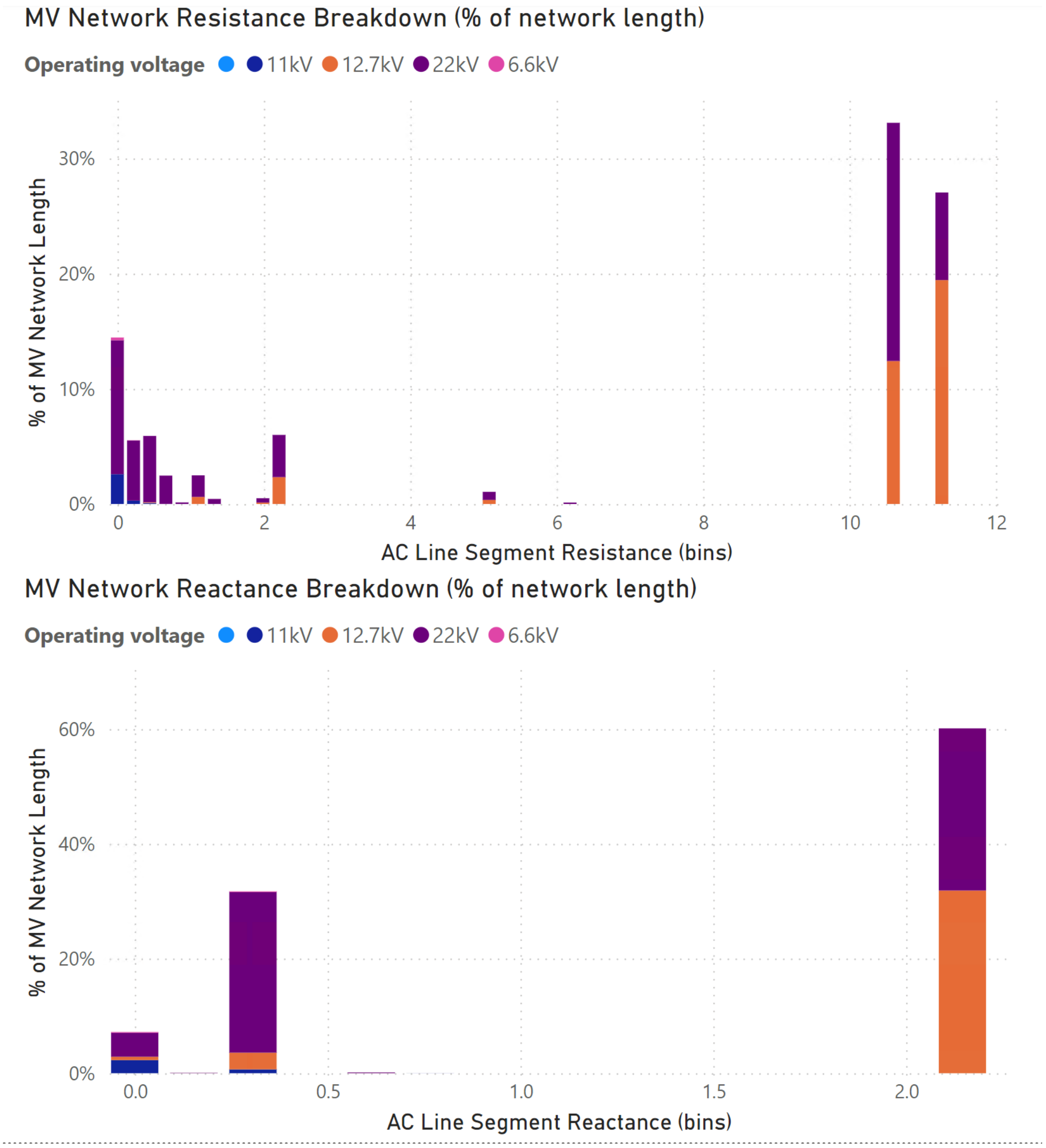


Figure 8 - Dashboard of CPPAL MV line ac segment Impedance by voltage

The MV model is used by CPPALUE 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 use cases that do not require conductor impedance characteristics, such as for asset location and for use by the Outage Management System. This means that properties such as phasing and impedance 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 and align inappropriate network phase connections was needed as a pre-requisite to running the load flow studies.

Through this work, 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 were developed.

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 combine series single phase regulators into regulator sites with grouped regulation settings.
- Assign default service lines types, which were then compared with the peak demand of the connecting customers to determine if the service line should be substituted for a service line of greater rating.

Once in place, these algorithms were able to build models suitable for the application of load flow engines for CPPALUE's network.

2.6.3 Review of model completeness – United Energy

Zepben undertook comprehensive analysis of the completeness of the United Energy network from the CPPALUE network models. Some relevant findings included:

- MV Network voltages were complete for all the network with a length > 0 meters, covering the range 11, 12.7, 22, 6.6kV.
- Line types available for 100% of MV segments, providing impedance and rating information
- 95% of service lines are unknown cable type.
- Phase data was often missing or anomalous for the MV network.
- Transformer attributes were more mixed:
    - Rating, Primary & Secondary voltages, are all complete and consistent
    - Phase data is inconsistent with 70% of transformers that are defined with Phase A having a rating greater than 50kVA. The secondary attribute 'number of phases' is only populated for a handful of transformers, and so is unable to be used as an alternative.
- LV Circuits where not identifiable within the GIS JSON payload. A separate data source was provided by UE team to enable Zepben to pre-process the network model data and rename LV switches that formed the head of LV Circuits

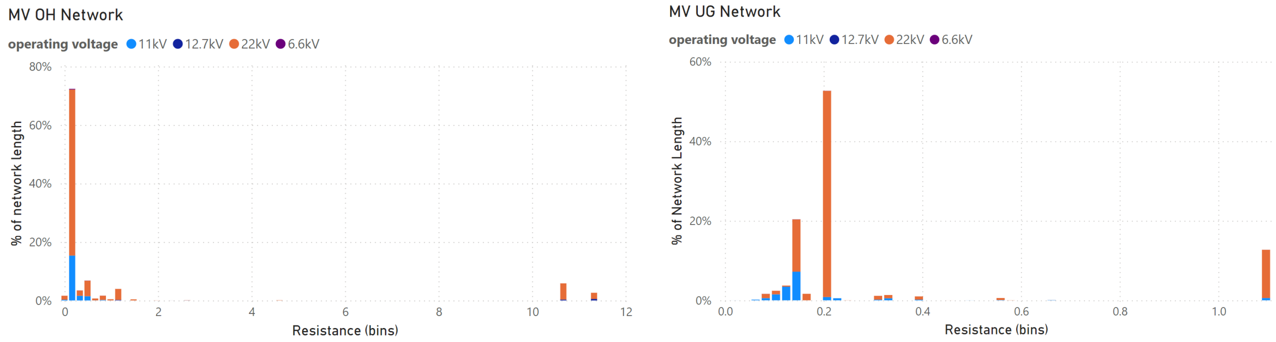


Figure 9 - Dashboard of UE MV line ac segment Impedance by voltage

2.6.4 Additional electrical model build processing

2.6.4.1 Line regulators

Multi-phase line regulators sites within the CPPAL network are often installed over multiple poles however electrically operate as a single site with common settings. To model these sites regulator collapsing logic was developed to identify these sites and create a single regulator for the relevant phases within the Energy Workbench CIM model.

This results in a single transformer and tap changer with an associated controller in the model.

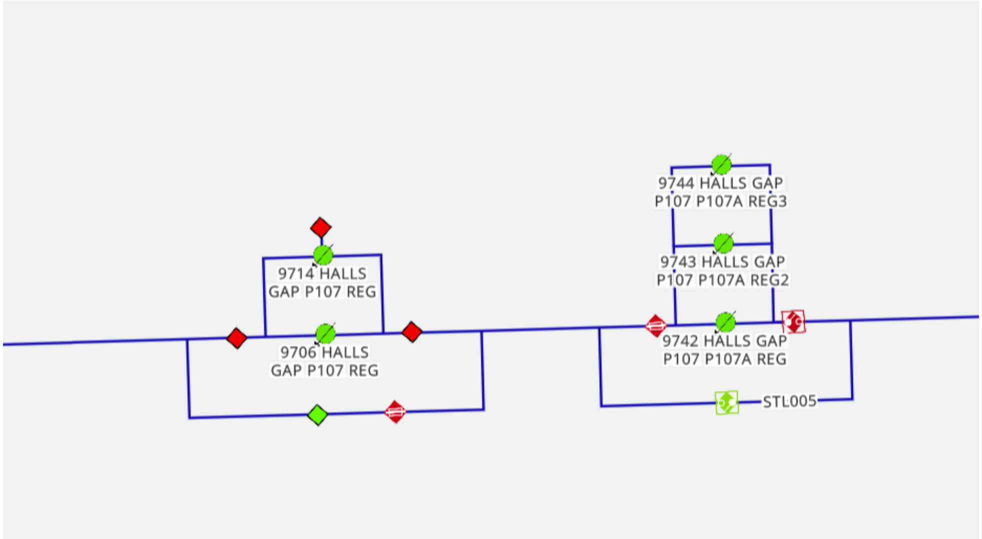


Figure 10 – Regulators as modelled in the CPPAL GIS

In terms of defining the associated controller, CPPALUE were able to provide a table that characterised the settings for the majority of regulator sites. These settings included:

Setting	Purpose
Site ID	Free text name used to link settings to topology model
Set Point	Target Voltage of the regulator site
Bandwidth	Controls the allowed difference between measured and target before regulator responds.
Delay	Time in seconds between tap changes
Line Drop Compensation Resistance	Defines in terms of the secondary voltage the amount of voltage 'boost' the regulator will apply for real power flow at CT rating, to compensate for line drop
Line Drop Compensation Reactance	Defines in terms of the secondary voltage the amount of voltage 'boost' the regulator will apply for reactive power flow at CT rating, to compensate for line drop
CT Primary	Used to translate setting expressed in terms of secondary
CT Ratio	Used to translate setting expressed in terms of secondary
Line Drop Compensation Mode	Define the direction the Line Drop Compensation settings apply for
VT ratio	Used to translate setting expressed in terms of secondary
Basis of settings MW and Power Factor	Define the point at which the Line Drop Compensation voltage applies.

Table 2 - Line Regulator Settings

2.6.4.2 Power Transformer On-Load Tap Changers

The Hosting Capacity Module is built around modelling the MV-LV network, this means that the upstream HV-MV network is modelled with a simplified representation. This simplified model includes the MV Zone Substation bus source impedance, on-load tap changer and aggregate load profile for the remainder of the substation MV feeders. This simplified model is captured in the diagram below.

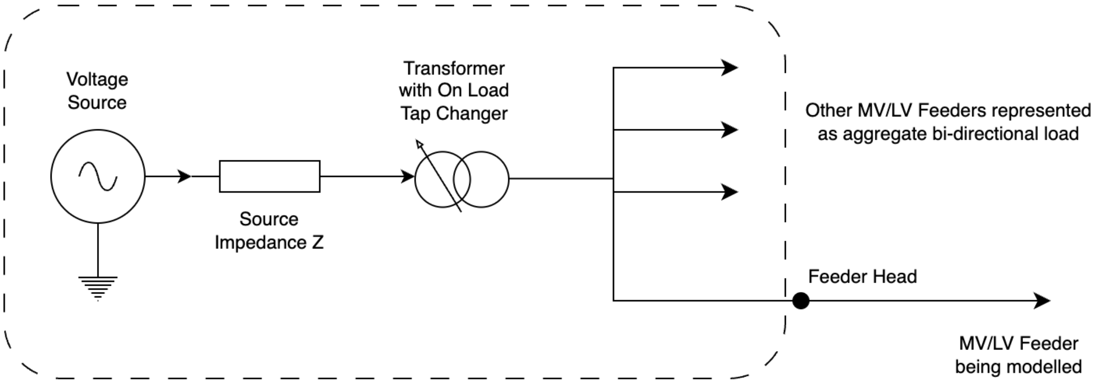


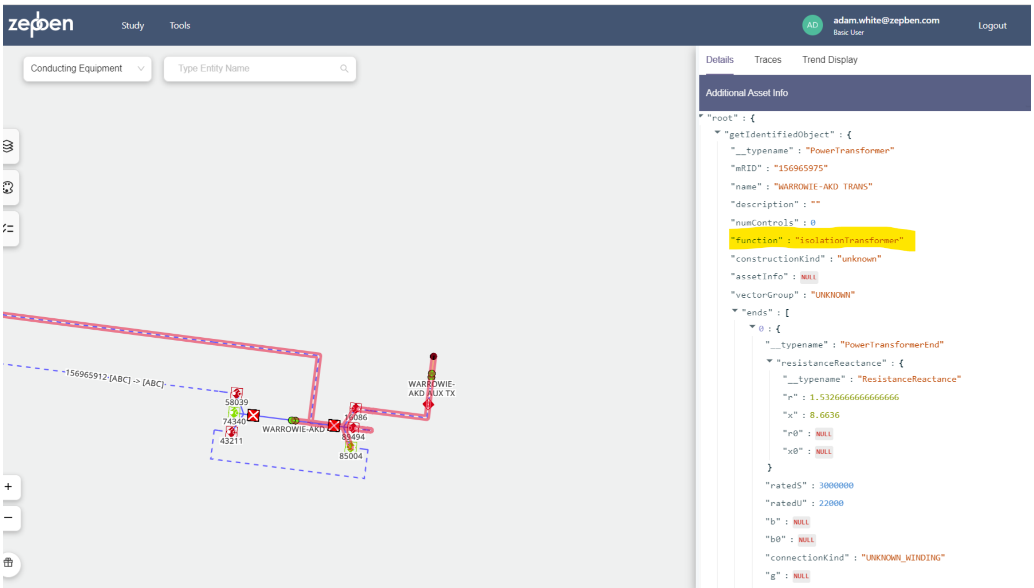
Figure 11 – Simplified Zone Substation model

To populate this simplified representation, several additional inputs to the JSON MV/LV topology model were captured from CPPALUE. This included:

- Source Impedance (sequence components)
    - These values where provided for the HV and MV bus of each Zone Substation transformer in the form of positive and zero sequence impedances. Zepben used the MV bus impedance referring it to the HV bus voltage due to its location on the primary side of the 'virtual' Zone Substation transformer. Where negative sequence impedance was not provided positive and negative are assumed to be equal.
- Tap Changer tap range, nominal position and step size
    - These values were provided for each Zone Substation in the form of several business rules that map between a transformer's voltage & rating and the applicable tap range, nominal tap and step size.
    - These rules were used to generate a standard supplementary input csv that mapped each site to the appropriate tap changer properties.
- On-Load Tap Changer controller settings
    - These setting were defined in two different ways for CPPAL and UE
        - For CPPAL, settings were extracted from source systems, this included both database and pdf data sources. The input template for these settings looks the same as the line regulator input template as defined in Table 2 above.
        - For UE, were closed loop voltage control was already in service across the network in the base year 2023, Zepben developed a basic closed loop voltage control approach that regulates the feeder head voltage using the end of HV line voltage as the controller input. This control model provided a simplified approximation of the in-service customer AMI data based closed loop control.

2.6.4.3 Isolation transformers

As part of the roll out of REFCL in the CPPAL network, large MV connected customers have been required to install isolation transformers[3] to isolate the customers installation from the REFCL system. These isolating transformers were provided with only partial details to enable electrical modelling of these assets, this is captured in the below screenshot.



```
"root" : {
  "getIdentifiedObject" : {
    "__typename" : "PowerTransformer"
    "mRID" : "156965975"
    "name" : "WARROWIE-AKD TRANS"
    "description" : ""
    "numControls" : 0
    "function" : "isolationTransformer"
    "constructionKind" : "unknown"
    "assetInfo" : NULL
    "vectorGroup" : "UNKNOWN"
    "ends" : [
      0 : {
        "__typename" : "PowerTransformerEnd"
        "resistanceReactance" : {
          "__typename" : "ResistanceReactance"
          "r" : 1.5326666666666666
          "x" : 8.6636
          "r0" : NULL
          "x0" : NULL
        }
        "ratedS" : 3000000
        "ratedU" : 22000
        "b" : NULL
        "b0" : NULL
        "connectionKind" : "UNKNOWN_WINDING"
        "g" : NULL
```

Figure 12 – Isolation transformer Model

Zepben developed transformer specific processing to identify these transformers based on, Phase, voltage and the transformer's function. This specific processing within the model builder creates an isolation transformer with a zigzag vector group which, within the OpenDSS model, is represented as three single phase transformers and neutral reactor connected to create a three phase transformer with vector group Dzn0. Below is an example of how a Dzn0 transformer is defined within the OpenDSS power flow model.

```
New Xfmrcode.isolatingDzn0 phases=1 windings=3 Xscarray=[5.37 5.37 5.37] kVs=[22 7.3333333
7.3333333] kVAs=[3000.0 3000.0 3000.0] %Loadloss=0.95 conns=[delta delta delta]

New Transformer.156965975_A Xfmrcode=isolatingDzn0
Buses=['156965975,156966077__156965975,156966077-t1__156965975,156966077-t2__etc.1.2'
'156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.4.6'
'156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.1.5']
New Transformer.156965975_B Xfmrcode=isolatingDzn0
Buses=['156965975,156966077__156965975,156966077-t1__156965975,156966077-t2__etc.2.3'
'156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.4.7'
'156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.2.6']
New Transformer.156965975_C Xfmrcode=isolatingDzn0
Buses=['156965975,156966077__156965975,156966077-t1__156965975,156966077-t2__etc.3.1'
```

---

[3] https://media.powercor.com.au/wp-content/uploads/2020/02/02001930/ESV-Guidance-for-HV-Customers-REFCL-readiness.pdf

```
'156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.4.5'
'156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.3.7']

New reactor.PrimBus_SecBusNeutral phases=1
Bus1='156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.4'
Bus2='156965975,156966026__156965975,156966026-t1__156965975,156966026-t2__etc.0'
R=12.7 X=0.00000000
```

2.6.4.4 Automatic model adjustments

This was an improvement developed by Zepben for the Hosting Capacity Module as a result of initial testing of the CPPALUE models that revealed many individual customer connections were significantly overloading their service lines, common LV network or distribution transformers. Analysis of several of these revealed problems with the assignment of energy consumers to supply points, that is, errors in the customer to supply point mapping data.

The impact of this was that these localised overloads would often be enough to cause model convergence issues impacting the timeseries results for complete feeder models. To overcome this Zepben developed a set of algorithms that utilise customer timeseries energy profile data to automictically adjust the network topology to create a power flow model representation of the network that is able to be solved. The adjustment algorithms included:

- **Service Line Adjustment:** Where a customer’s peak historic import or export is identified to be greater than ***n*** times the rating of the service line, it is upgraded to the next available standard service line size from CPPALUE catalogue that can support that customer peak import or export. Where ***n*** is a configurable threshold that was set to 1.0 in this project.
- **LV Mains Adjustment**: Where a customer’s peak historic import or export is identified to be greater than ***n*** times the rating of the LV mains (i.e. the shared LV network) between that customer and the distribution transformer the LV lines in that path are upgraded to the next available standard LV line size from CPPALUE catalogue that is able to support that customer peak import or export. Where ***n*** is a configurable threshold that was set to 2.0 in this project. Note this feature does not look at the aggregate customer import and export, it is assessing specific customers against asset ratings.
- **Customer Phasing**: Where a customer’s peak historic import or export is greater than a configured real power threshold ***n*** kW, that customer and its upstream network, to the nearest 3 phase asset, is upgraded to 3 phase. Where ***n*** is a configurable threshold that was set to 20kW in this project.
- **HV customer detection**: Where a customer’s historic peak import is greater than ***n*** times the rating of the upstream distribution transformer or a customer’s historic peak export is greater than ***n*** times the rating of the upstream distribution transformer, the customer is relocated within the model to the primary terminals of that upstream transformer. Where ***n*** is a configurable threshold, and for import this was set to 3.5 and for export this was set to 5.0 within this constraint forecasting undertaken in this project. This approach was designed to detect cases such as an

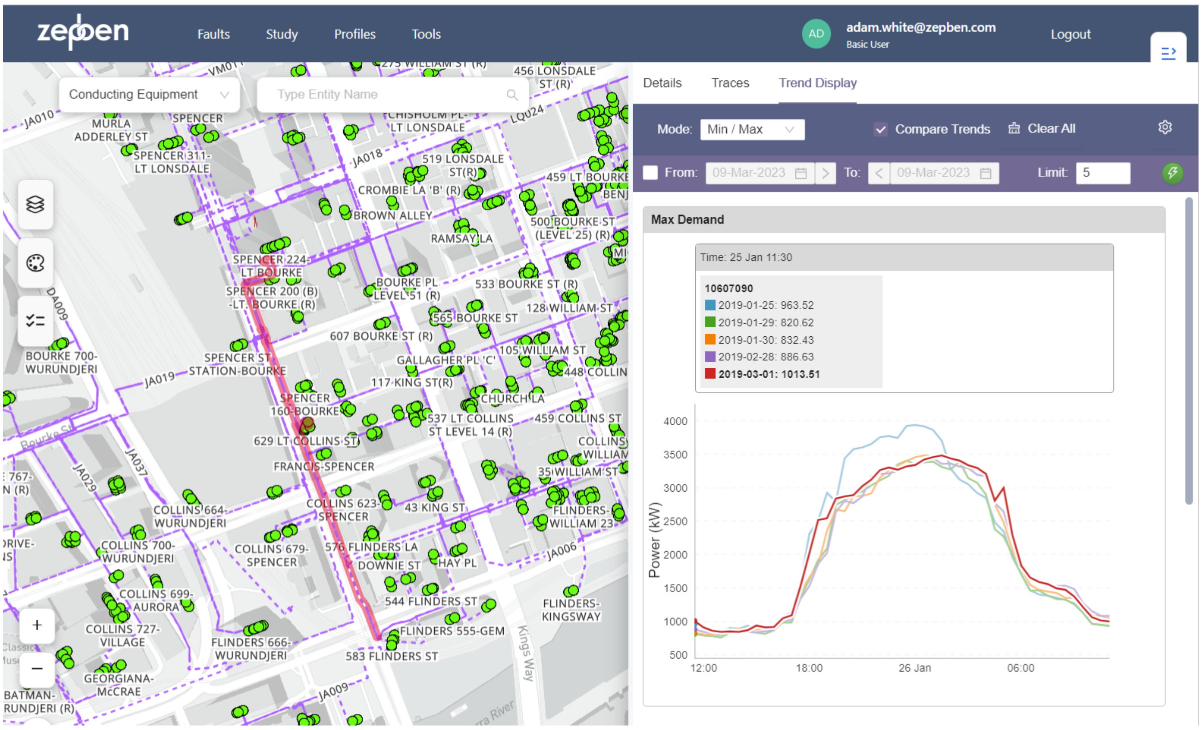
incorrect solar farm connection where the generators NMI was mapped against an existing farmhouse supply transformer rather than the MV metering point upstream.

Figure 13 – Incorrect mapping of a solar farm to a domestic transformer

2.6.5 Energy Consumer Load profiles

CPPALUE's networks have a high penetration of smart metering infrastructure that provides interval energy data at the individual customer level.

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 15, suitable for being used by the OpenDSS load flow engine.



Mode: Min / Max

☐ From: 09-Mar-2023 To: 09-Mar-2023 Limit: 5

Time: 25 Jan 11:30

10607090
🟦 2019-01-25: 963.52
🟩 2019-01-29: 820.62
🟧 2019-01-30: 832.43
🟪 2019-02-28: 886.63
🟥 **2019-03-01: 1013.51**

Figure 14 – Maximum demand trend display in the energy workbench

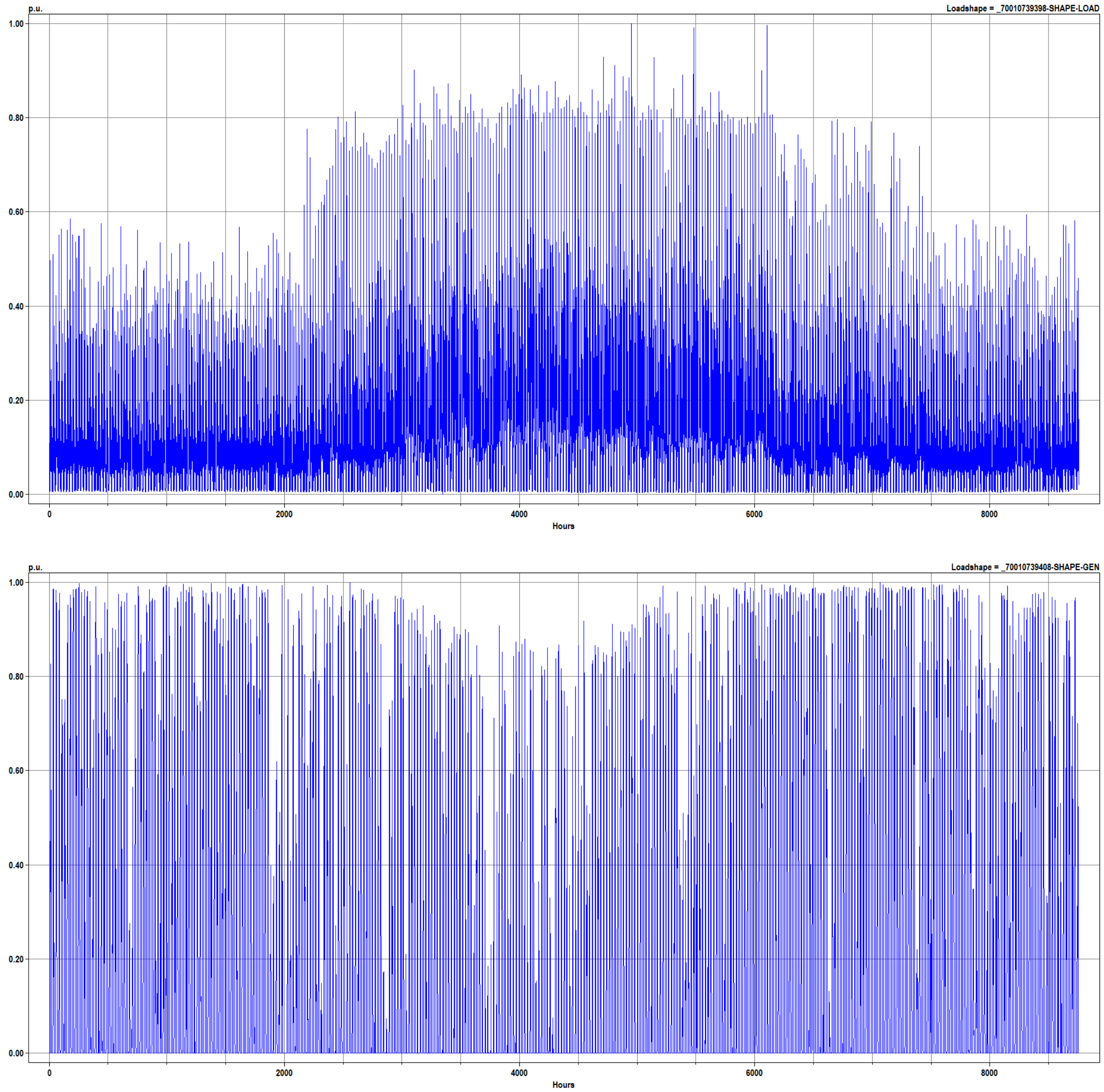


Figure 15 - Example of 30-min annual normalised loadshapes that when combined with the recorded load and generation peak values defines modelled customer

```
New 'Load.supply_point_id_gis-uuid-load' bus1='cn-105107202-t2.3' conn=wye Kv=0.2396 Phases=1 Vminpu=0.8 Vmaxpu=1.2 Kw=5.584983448431048 pf=1.0 Model=1 Yearly=’uuid-shape-load'
```

The normalised load profile in Figure 15 represents the load factor for a particular energy consumer, the ingress channels are mapped to loads within the power flow model and the egress channels are mapped to the generators within the power flow models.

Both the load and generation channels are normalised and are stored with their peak demand value. Each timestep has a value ranging from 0 to 1 depending on the demand 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.

This approach provides highly granular meter-channel level modelling for each energy consumer, while allowing feeder-level demand data to be incorporated for forecasting. This provides a good basis to use the model results to assess the low voltage circuit level performance of the network. This approach is a large improvement over the traditional industry approach of modelling the MV network and allocating local network consumption based on assumptions around transformer utilisation.

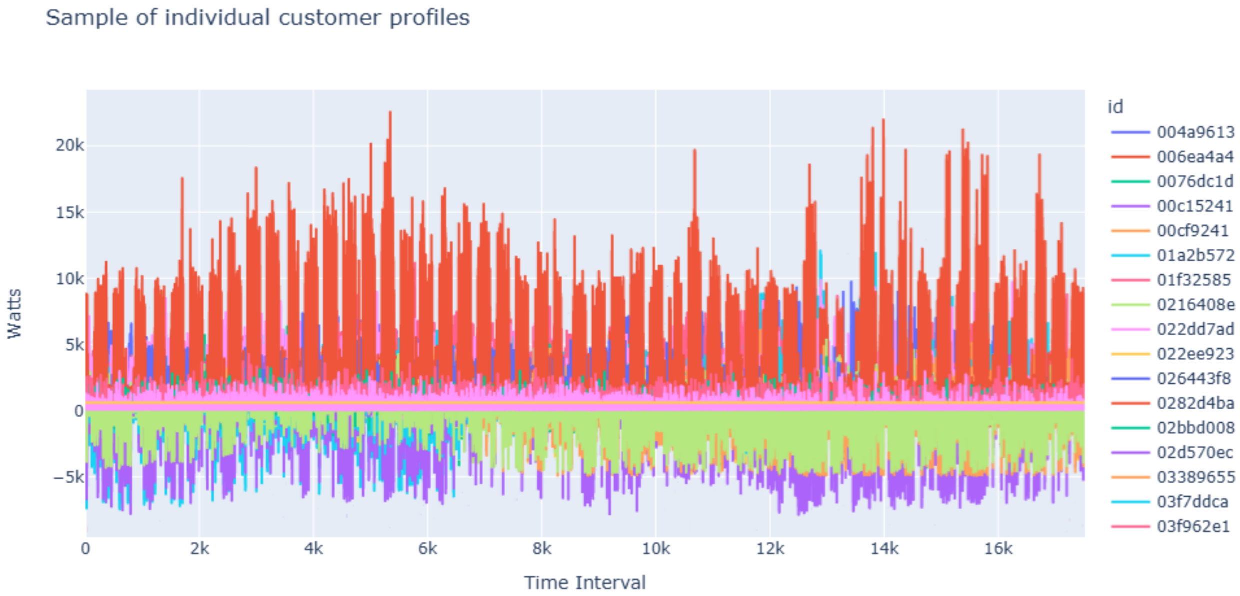


Figure 16 - Example of energy consumer profiles

2.6.6 Demand and CER Forecasts

CPPALUE commissioned Blunomy to produce a comprehensive set of forecasts for the next 12-year period. These forecasts included underlying network demand, electrification, PV uptake, electric vehicle uptake and consumer battery uptake, broken down to the level of Distribution Feeder.

These forecasts were used to create the load and generation inputs into the hosting capacity constraint forecast.

The forecast underlying demand (demand ex-EV load) is formed by combining the forecast year-on-year change in underlying demand with the individual customer level 'base year' demand profile. This is done for each of the years of the forecast period. The underlying demand levels (i.e. the network loading before customer uptake of CER is considered) are adjusted based on the feeder level POE50 demand trend for each year of the forecast period.

2.6.7 CER Technology Forecasts

As part of the forecasting outcomes commission by CPPALUE, Blunomy provided CER technology forecasts for the period 2024 to 2050 at the Zone Substation level that covered:

- PV inverter capacity (MW)
- Battery Storage capacity (MWh)
- Electric Vehicle numbers

Zepben used these forecasts to simulate the connection of CER devices at the energy consumer level within the Energy Workbench model of CPPALUE's distribution network to provide the equivalent CER capacity as the aggregate amount provided by the forecasts.

This enabled bottom-up modelling of the impact of the CER on the network according to the top-down forecasts: Over the forecast period, energy consumers were allocated new or upgraded PV systems such that in aggregate, the top down forecasts equated to the bottom up allocations.

2.6.7.1 Modelling of PV forecast

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

- The distribution feeder level PV inverter capacity (MW) forecast was broken down into the equivalent number of systems needed to make up the aggregate amount using three system sizes:
  - 5kW DC / 5kW AC – Single Phase
  - 10kW DC / 5kW AC – Single Phase
  - 10kW DC / 10kW AC – Three Phase
- Inverter capacity forecast was taken as the AC system capacity. These system sizes were selected by CPPALUE.
- CPPALUE also developed a PV system allocation approach for each distribution feeder that was used for the forecast period. This approach controlled the % allocation of system sizes within each feeder.

PV System Size	Average % allocation over the network
10kW DC / 5kW AC – Single Phase	4.5%
10kW DC / 10kW AC – Three Phase	10.5%
5kW DC / 5kW AC – Single Phase	85%

- Systems were then randomly allocated to customers that currently had no PV system or had 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 already allocated a PV system, the next allocations were modelled as system upgrades until the remaining PV forecast had been allocated.
- If all customers on the feeder were allocated two new PV systems (an initial system and then also an upgraded system) 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
    - Each system was connected at the customers supply point with phasing matched to the phase connection specified by the system type (1 phase or 3 phase).
    - Energy export was defined by a normalised solar generation profile provided by Blunomy for each distribution feeder within the CPPALUE network area.

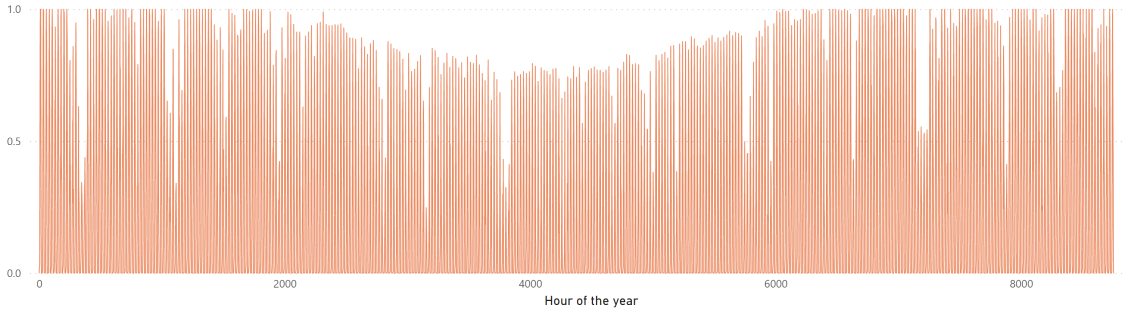


Figure 17 - Annual PV generation profile applied to new PV capacity added as part of the forecast scenarios

2.6.7.2 Modelling of Battery Storage forecast

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

1. Battery Energy Storage System (BESS) capacity forecasts were provided at the distribution feeder level in MWh.
    - A single BESS system size of 5kVA/13.5kWh was used for allocating forecast BESS capacity. This was provided as an input assumption by CPPALUE and corresponds to the most popular residential BESS size.
    - Customers with greater than 3.5kW of PV panel capacity where initial candidates for being allocated BESS. It was not until all these candidates were exhausted, that BESS systems were allocated to non-PV customers. This approach is

designed to follow trends observed within the industry and represent future changes in behaviour as increasingly cost reflective energy pricing incentivises residential BESS for non-solar customers eventually.

- Each battery system was assigned an annual 30min profile (17520 samples per year). These profiles were defined for each distribution feeder. The summary chart below shows a daily average demand profile with upper and lower limits over the year for a specific CPPALUE feeder.

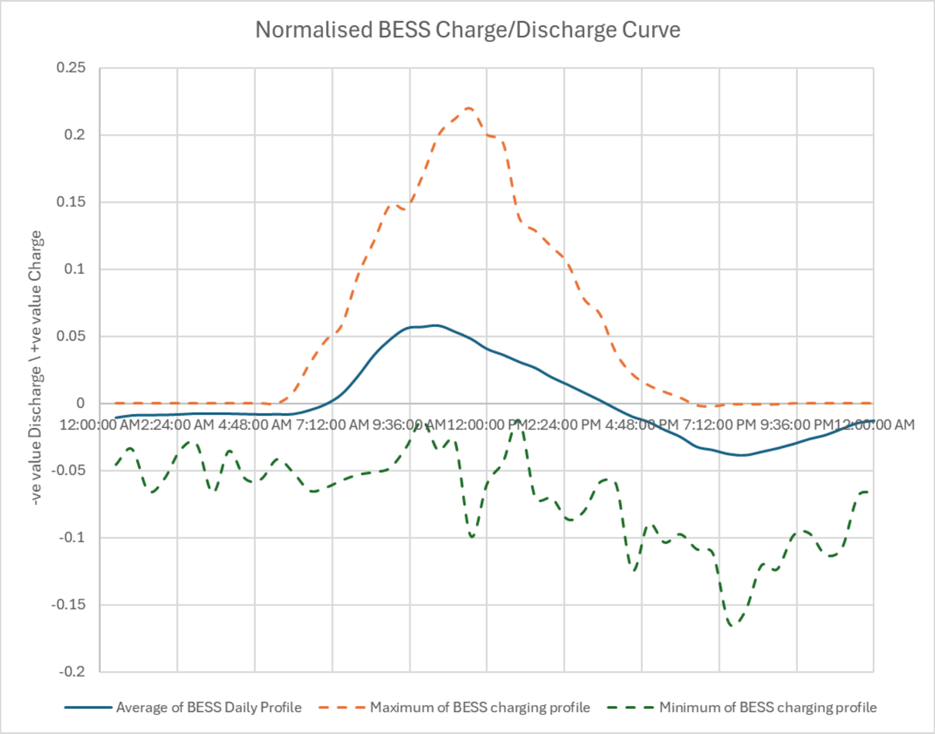


Figure 18 – BESS Charge/Discharge Curves

2.6.7.3 Modelling of Electric Vehicle forecast

The modelling of EV forecasts was done using a similar approach as for forecast PV and battery storage uptake. These profiles where provided by CPPALUE and were developed using available real world observed EV charging behaviour.

- EV forecast input was provided at the distribution feeder level, below this level random allocation of EV's and their charging profiles was done to align with the forecasts.

2. Four sizes of EV charger were associated with the EV profiles and allocated to customers within the model, these included 2.4kW single phase, 7.2kW single phase, 11kW three phase and 22kW three phase.

- Allocation of profiles within the feeder years followed the following splits defined by CPPALUE, as follows:

EV Charger Size	**% allocation over the network**
2.4kW single phase	30%
7.2kW single phase	59.5%
11kW three phase	10%
22kW three phase	0.5%

3. A range of real-world charging profiles were used to represent the range of customer charging behaviours, these profiles included:
    - Light convenience charging
    - Convenience
    - Night Owl charging
    - Day charging

To provide an overview of how EV charging profiles were allocated, the chart below shows how the modelled allocation changes over the forecast period. With a trend moving away from convenience-based charging towards the managed profiles of Night Owl and Solar Sponge.

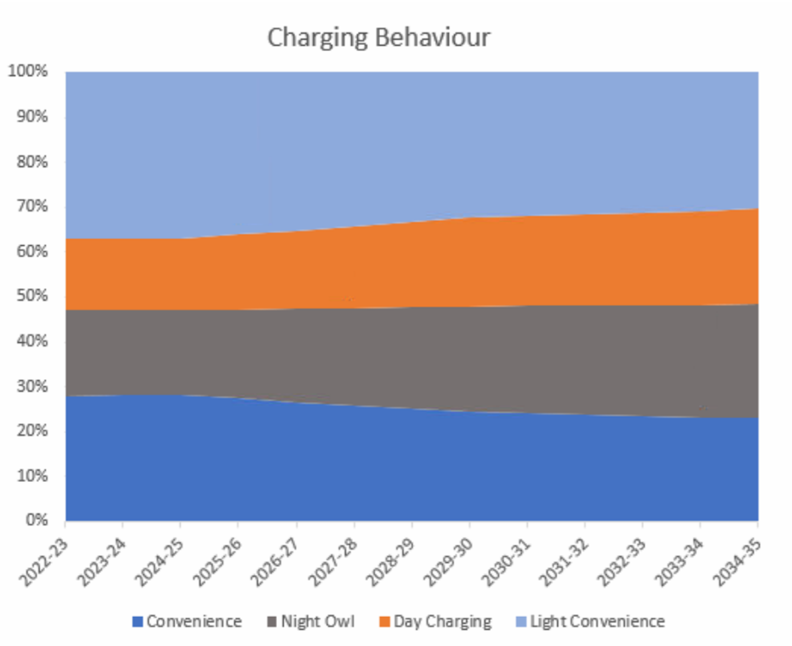


Figure 19 – Changing EV charger behaviour over time

To provide an overview of how these allocated profiles translate into modelled demand, the chart below provides a summary of the diversified behaviour of these profiles; the plotted profiles are of average daily power for the complete population of profiles.

However, to accurately model the LV network impact of EV charging the individual annual charging profiles allocated to customer connection points are not diversified.

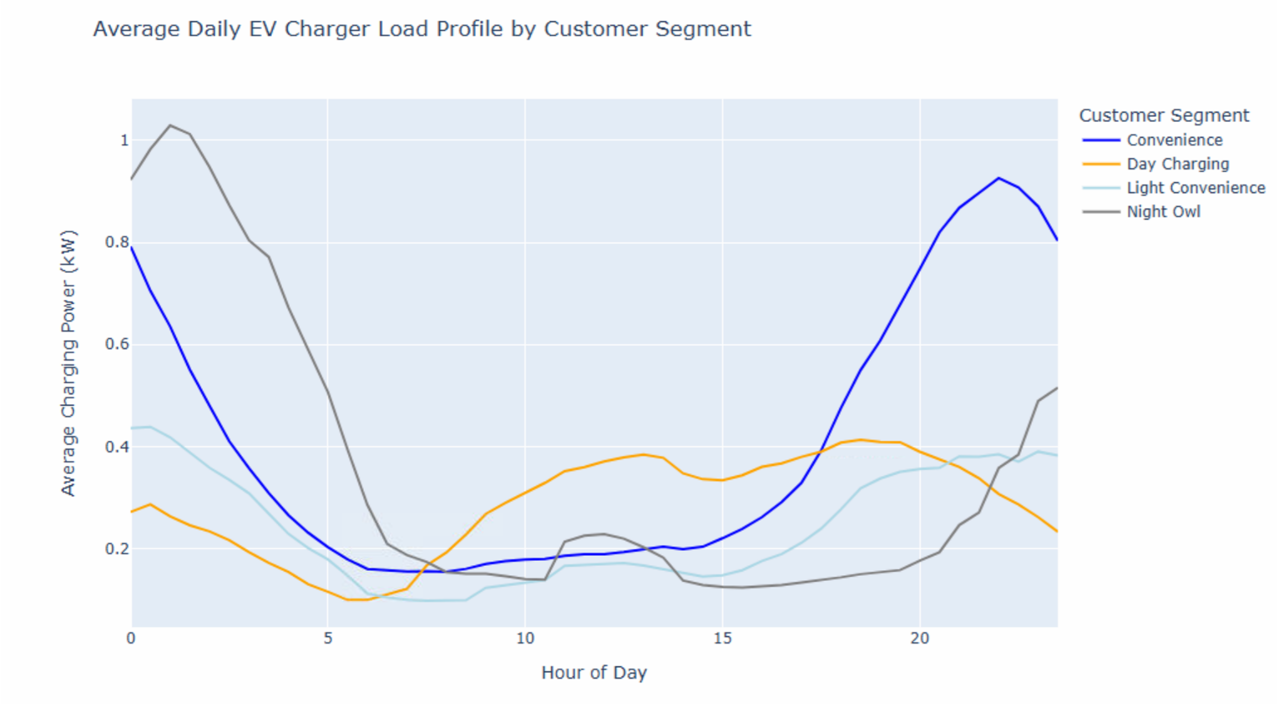


Figure 20 – Diversified EV charger behaviour

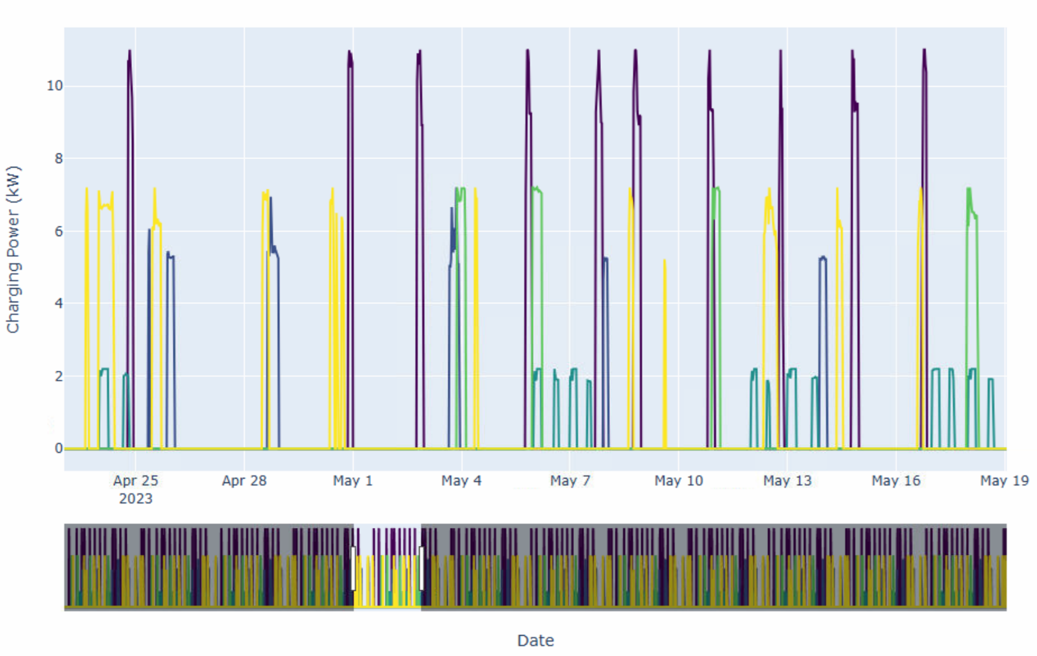


Figure 21 – Sample of five Individual charger behaviour from the yearly timeseries profiles

2.6.8 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 CPPALUE'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 typical Australian networks original design. Customer loads were all defined as single phase and connected between 'legs' 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	Line voltage regulators were included within the modelling; all were operated to regulate the network normal downstream bus voltage. The regulation settings were provided by CPPALUE, where they were extracted from a mix of source systems and documentation. The voltage regulator representation within the power flow model is able to support; setpoint, bandwidth, forward Line Drop Compensation for downstream current direction, reverse Line Drop Compensation for upstream current direction. The downstream voltage remains the measurement for regulating independent of the current flow.
RATINGS	Line and transformer normal rating were defined by ratings defined within the network topology model. 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 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 transformer impedance values these where estimated base on the transformer name plate rating, Zepben maintains a database of transformer types that defines a relationship between ratings and impedance for distribution transformers only.
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 CER profiles, in addition to explanations previously provided on the implementation of CER and underlying load forecasts.

LOAD & CER	
NETWORK DEMAND	30min interval energy data defines the modelled network demand.
	Privately owned substations (customer owned) were not modelled with customers attached downstream, as constraints on these transformers are not within scope of regulated standard control service. Customer loads/generation is modelled as connected to the primary terminals of the substation.
CER	CER assets were modelled as connected with phasing matching the existing customer phase connection.
LOADS	For the voltage range 0.8pu through to 1.25pu loads were modelled as constant power. Outside this range loads were changed to constant impedance to assist with convergence to a solution.

2.7 MODULE VALIDATION

2.7.1 Establishing 'Base year' Model

The 'base year' network model is a snapshot of the network MV/LV topology and the most recent 12-months of interval energy data that aligns with the CPALUE forecasting year, running from April 1st until March 31st.

As has been noted in sections 2.6.2 and 2.6.3, there are gaps in the properties and attributes of some network assets that make up the model, and one of these is unknown off-load tap positions. This is a material issue when it comes to modelling LV voltages on the distribution network, as the local tap position of each distribution transformer significantly impacts the voltages experienced by downstream customers. However, these tap positions were often not recorded at the time they were commissioned 40 years ago, and changes to the tap position since commissioning are also often not recorded.

CPPALUE made available smart meter power quality voltage datasets that enabled Zepben to undertake modelling to estimate these off-load distribution tap positions.

This data also supported the modelling of historic time periods to validate the models performance.

2.7.1.1 Workflow for determining Off-load Transformer Tap Positions

The detailed smart meter power quality data available to Victorian DNSPs created the opportunity to determine the local off load tap positions. The approach developed involved:

- Identifying a period of minimum demand outside of the solar generation window i.e. a period where the absolute value of network demand is as close to 0 as possible. This period is used as it is the period with the lowest voltage drop on the network, which helps to reduce the estimation error introduced by any inaccuracies in missing network line information.
- Building a power flow model for the identified low demand period timestamp with the customer real and reactive power set using the power quality dataset from smart meters.
- Running this power flow model for the identified low demand timestamp to generate voltage results at each customer connection point.
- Comparing the voltage results between the model output for each customer connection point with the measured voltages for the same connection point in the smart meter data.
- Aggregation of the customer level voltage delta to the distribution transformer level
- Estimation of transformer tap position adjustment to minimise the voltage delta calculated. Noting that specific available tap ranges for each transformer were not available, as a result all transformers were standardised to have 7 taps, 3 buck and 4 boost taps each adjusting the voltage 2.5%. The majority of taps allocated where either nominal or +/- one tap.

- Re-ingesting the calculated distribution transformer tap positions as the transformer tap positions for use in subsequent modelling work. These calculated tap positions, based on historic smart meter data, set the off-load tap positions used on the base network model.
- Lastly the model is re-run to assess the model's performance for a range of available timesteps within the available smart meter power quality voltage datasets.

In addition to determining the distribution transformer tap positions, Zepben then developed a 'calibration mode' specifically to make use of the detailed smart meter data available to Victorian DNSPs for a range of timestamps. This mode involved building models that utilised the measured real and reactive power values for each customer, along with the measured voltages. The calibration approach involved modelling a range of timesteps throughout the specific day of historic 5-min actuals used for calibration and comparing the modelled network wide customer voltage distribution with actual network customer voltage distribution for the same timestamps.

The chart below plots the voltage delta between modelled and measured voltages at each customer connection point, with the estimated off-load tap positions included in the model forming the baseline performance of the model. As you can see while there are 'tails' of connection points that sit outside +/- 2% the 90% of customers fall within this range.

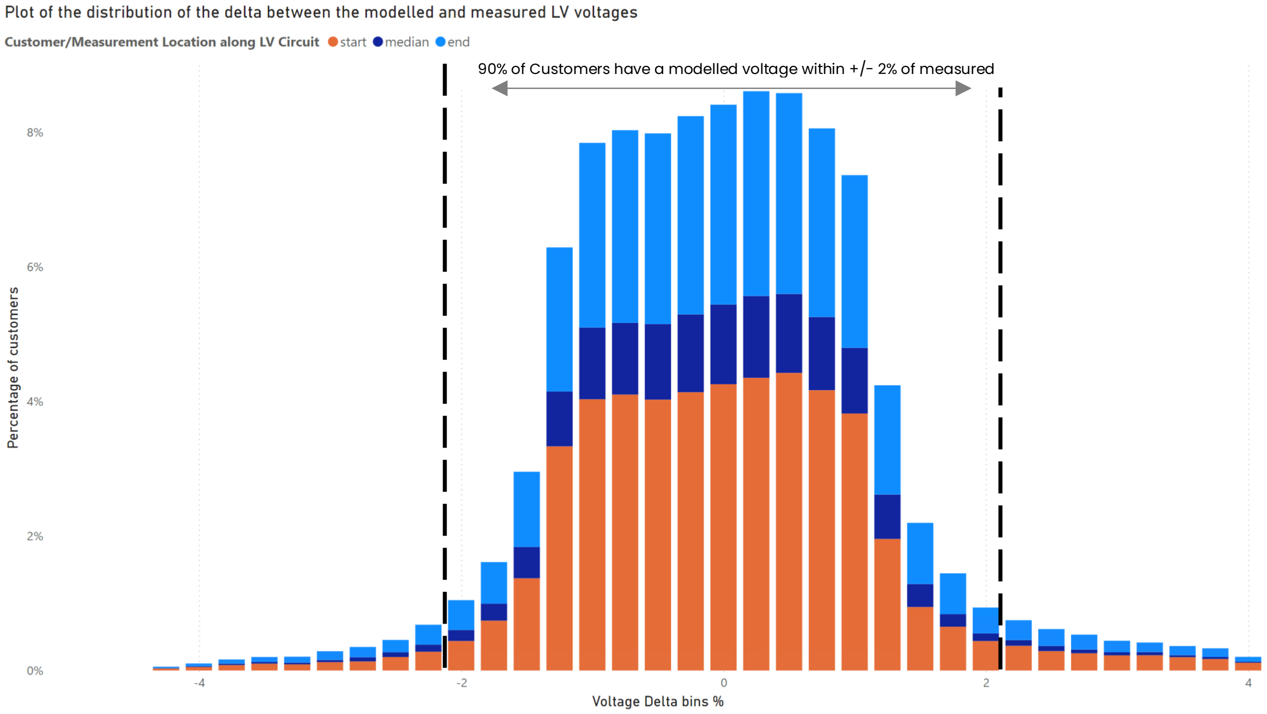


Figure 22 – Modelled and Measured voltage comparison

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

3 HOSTING CAPACITY FORECAST

The ‘Hosting Capacity Forecast’ undertaken as part of the scope of work was specifically designed to provide a forecast of curtailment and energy at risk under a base case scenario. Once the ‘base year’ model is established it forms a key input into generating the constraint forecast, which, as outlined earlier in this report, involves the timeseries modelling of CER uptake and profiles applied to the base year model.

The distribution feeder level charts below are snapshots of raw analysis that occurs within the Hosting Capacity Module to generate the key results metrics outlined earlier in Table 1. The first chart in **Figure 23** is of 2024 where we can observe that the model is made up of current underlying demand and existing customer exports; both defined by the customer level smart meter data.

The second chart in **Figure 24** jumps forward to 2029, where in this example the generation has tripled (new generation is orange) along with the addition of EV charging (green) and support from distributed energy storage (blue). The underlying demand (grey) is scaled based on the forecast trend in underlying demand being applied to the individual customer 2023 base year profiles. This is key as its this detailed timeseries data at the customer level that allows the model to calculate net flows at the LV level and apply timeseries curtailment values to net export flows that exceed thermal or voltage limits.

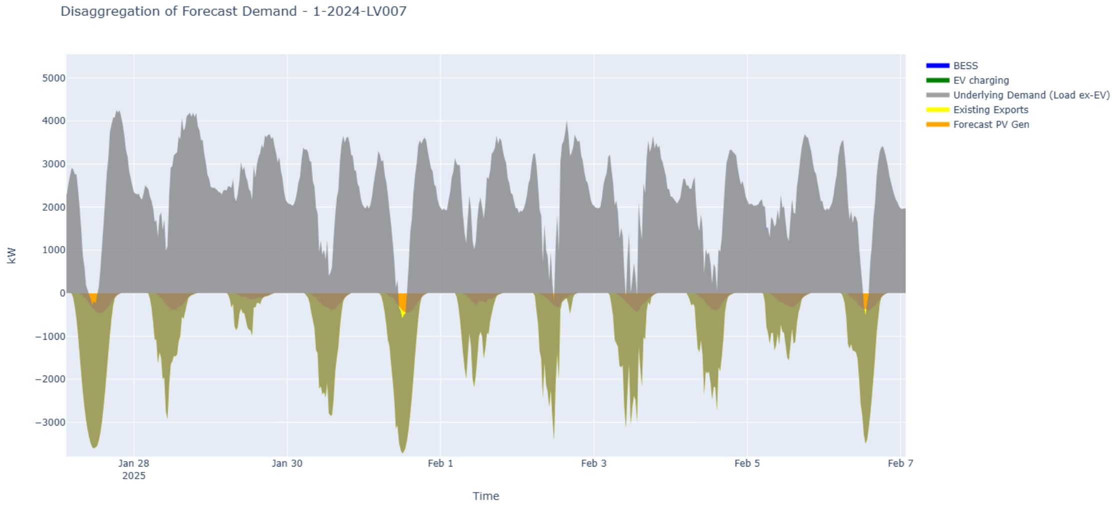


Figure 23 – Forecast load and generation 2024

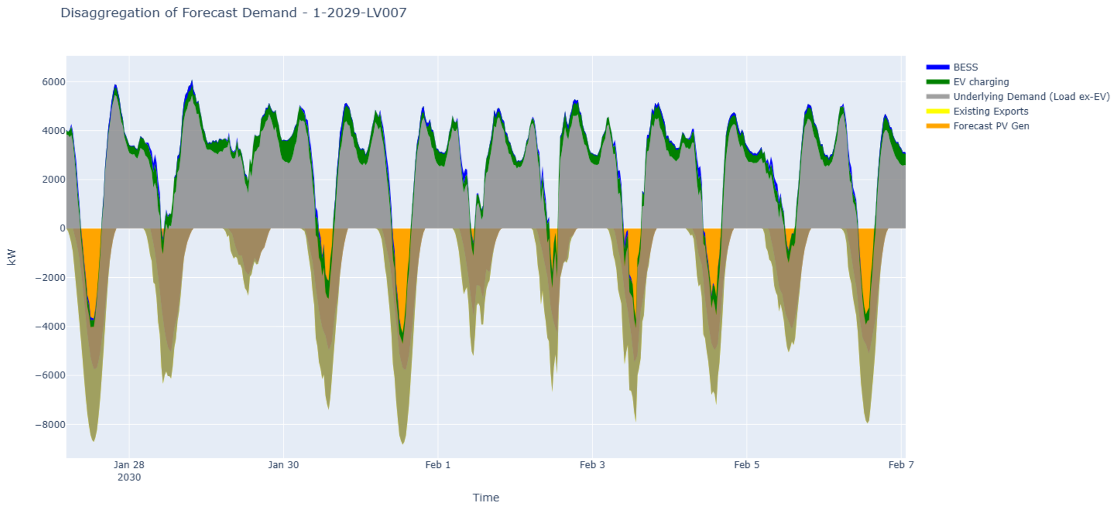


Figure 24 – Forecast load and generation 2029

3.1 MODELLING EXECUTION

Summarising the approach outlined in section 2.6, the graphic below illustrates the workflow used to carry out the hosting capacity forecast.

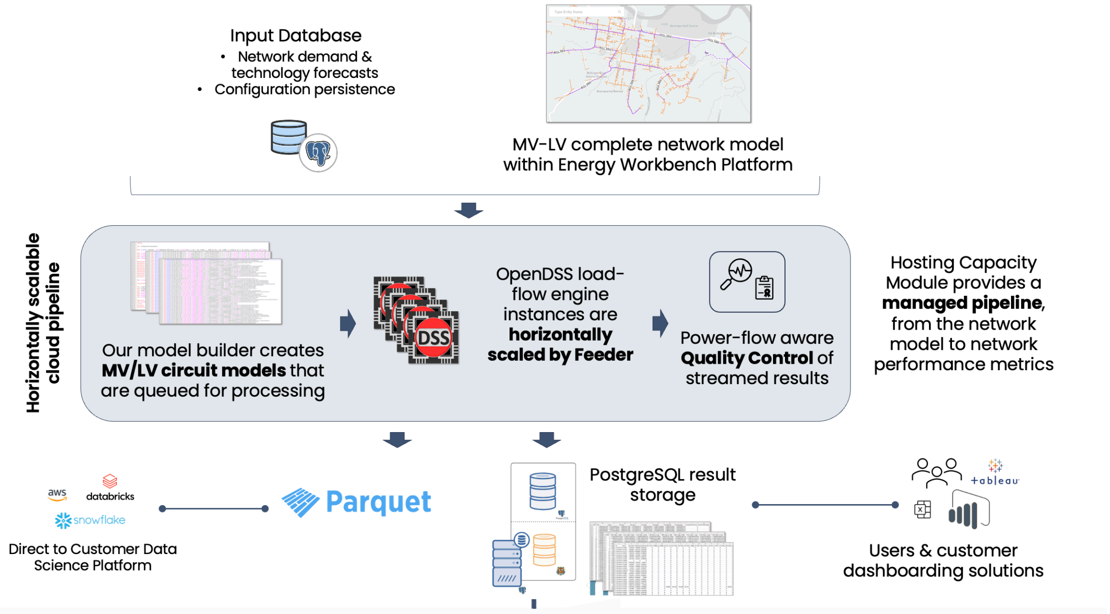


Figure 25 - Illustration of modelling process

- The Hosting Capacity Module is built around a horizontally scalable pipeline to enable solving of computationally intense power flow models.
- The module uses the as-built network model created within the Energy Workbench platform, this is the model that has been prepared for power flow modelling through the network ingestion process, see section 2.6.1.

- This ‘as-built’ base model that captures the physical assets and current network state are processed to generate a bus-branch model that is expressed in a format that is supported by the OpenDSS load flow engine.
- This base model is then extended to represent the forecast years by:
    - Scaling the underlying customer demand profiles from the base year to align with the forecast year to be modelled
    - CER assets are then added to the network at the low voltage level based on quantity and in proportions defined by the forecasts
- For each of the OpenDSS models that represents either a base or forecast year these are sent to a queue for execution. Modelling here can be scaled by varying the cloud resources applied.
- The output of the executed power flow model is a collection of raw timeseries energy flows and voltages that are streamed to a scalable results processing component.
- Within the results processor the network performance metrics are calculated from the raw timeseries data, determining the energy at risk and curtailment over various periods of interest, including time of day, season or week.
- While processing the results, the processor also checks the validity of the model output to identify models that have not met the convergence tolerance or for results that are outside of the possible range for valid results.

This end-to-end process is executed in a cloud environment for the whole network over the forecast period. With the final processed results streamed to a cloud object store to enable subsequent economic analysis.

4 APPENDIX

4.1 TECHNOLOGY SOLUTION – THE ENERGY WORKBENCH

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

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 traditional commercial solutions 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 time series analysis over a 12-year forecasting period under different forecast scenarios for CER behaviour, the project needed to run models representing:

- 12 Years of 30min real and reactive power flows at the energy consumer level (210,240 time slots),
- Covering base case with future network development scenario,
- For approximately 1500 feeders.

Multiplying this out gives a total of around 300 million Load Flow Studies per scenario, with approx. 1 billion iterations of the load flow engine in total, 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 required framework and parallel processing.

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 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

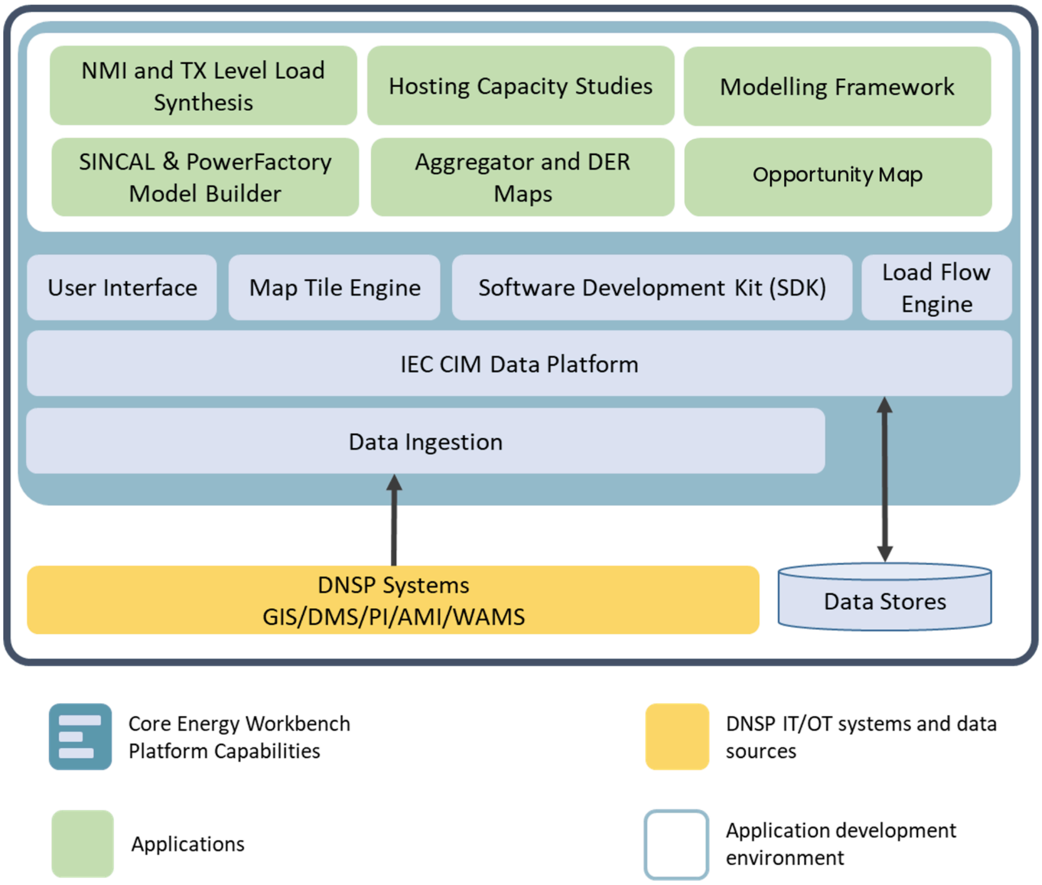


Figure 26 – Energy Workbench conceptual overview.

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

- **Data ingestors:** to accept and translate the CPPALUE 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 1,900,000 customers connected to CPPALUE's combined 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 CPPALUE'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.

4.2 ADDITIONAL RESULTS

As part of the scope of work, Zepben worked with CPPALUE to develop an additional set of detailed network metric to better understand network performance. The following table covers these additional metrics provided by the Hosting Capacity Module. The weekly performance metrics have been used to provide a forecast of customer voltage compliance as the methodology used to calculate the weekly voltage compliance in these forecast results as followed the Saturday-to-Saturday reporting period defined by Essential Services Commission[4].

4.2.1 Weekly Performance Metrics

Metric	Description
work_package_id	The ID of the work package that was run
scenario	The scenario for this input
timestamp	Expressed in UTC
feeder	The feeder for this input
measurement_zone_name	The measurement zone name for this input (energy meter name)
mz_type	The type of asset class that forms the 'head' of the measurement zone
conducting_equipment_mrid	This is a unique identifier for the asset that forms the 'head' of the measurement zone

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[4] https://www.esc.vic.gov.au/sites/default/files/documents/COD%20-%20Electricity%20Distribution%20Code%20of%20Practice%20%28version%202%20-%20updated%29%20-%2020230428.pdf

terminal_sequence_number	The identifier for the terminal of the conducting_equipment_mrid asset that forms the 'head' of the measurement zone. Where two measurement zones are present for a single conducting equipment mrid, this indicates a loop within the network. The terminal_sequence_number can be used to differentiate between them.
v_base	voltage base of metrics - expressed in ph-ph voltage. For Transformers voltage base is reported as the secondary voltage This field should be used to convert from per unit results into magnitudes
v99_avg	This boolean value is true if the 99th percentile for the average node and phase voltage over the relevant time period is greater than VH1 (default 253v) Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.
v99_max	This boolean value is true if the 99th percentile for the average node and maximum phase voltage over the relevant time period is greater than VH1 (default 253v) Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.
v1_avg	This boolean value is true if the 1st percentile for the average node and phase voltage over the relevant time period is below than VL1 (default 216v) Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.
v1_min	This boolean value is true if the 1st percentile for the average node and minimum phase voltage over the relevant time period is below than VL1 (default 216v). Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.

consecutive_vh2_avg	This boolean value is true if the 99th percentile for the average node and phase voltage is greater than VH1 (default 253v) for two consecutive weekly reporting periods. Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.
consecutive_vh2_max	This boolean value is true if the 99th percentile for the average node and maximum phase voltage is greater than VH1 (default 253v) for two consecutive weekly reporting periods. Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.
consecutive_vl2_avg	This boolean value is true if the 1st percentile for the average node and phase voltage is below VL1 (default 253v) for two consecutive weekly reporting periods. Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.
consecutive_vl2_min	This boolean value is true if the 1st percentile for the average node and minimum phase voltage is below VL1 (default 253v) for two consecutive weekly reporting periods. Reporting runs from Sunday to Saturday, starting the first Sunday of the modelling year. This aligns with VIC ESC reporting guidelines.
v99_avg_value	The 99th percentile for the average node and phase voltage over the relevant time period.
v99_max_value	The 99th percentile for the average node and maximum phase voltage over the relevant time period.
v1_avg_value	The 1st percentile for the average node and phase voltage over the relevant time period.
v1_min_value	The 1st percentile for the average node and minimum phase voltage over the relevant time period.
max_kw	This is an unsigned value that recorded the peak power value at the head of the measurement zone. This is the net power of the measurement zone, and captures the peak irrespective f the direction of current flow.

load_kwh	The sum of all energy consumed by elements modelled as loads (underlying demand, net BESS and EVs), within the measurement zone during the relevant time period. Note this does not include energy that is supplied via the measurement zone, or network losses, it is only energy delivered to consumers within the measurement zone. This allows aggregation of measurement zone results, as delivered energy is not double counted.
load_vcr	This metric is the total value of energy delivered to consumers within measurement zone during the relevant time period. It uses load_kwh.
load_energy_overvoltage_cvvr	load_overvoltage_cvvr is the value of CVVR (Customer Value Voltage Reduction) applied to the sum of energy consumed by loads whilst overvoltage. Note: this does not use energy scaling, this means all energy delivered to loads for each interval where avg measurement zone voltages exceed VH1 (default: 253v for 230v base) will be counted as at risk. The logic behind the design of this metric is we are valuing the damage cause to all electrically connected appliance during an overvoltage event. This means that this metric is still conservative as not all connected appliances that are exposed to the overvoltage will be consuming energy during all intervals.
load_exceeding_normal_thermal_voltage_vcr	This metric captures the total value of the load at risk within a measurement zone; voltage and thermal. This value is the primary value that can be used for assessing the economic case for an intervention to manage the customer load energy at risk. The metric is defined as per load_exceeding_normal_thermal_voltage_kwh, multiplied by the Value of Customer Reliability.

load_exceeding_emerg_thermal_voltage_vcr	This metric captures the total value of the load at risk within a measurement zone; normal voltage limits and emergency thermal ratings. This value is the primary value that can be used for assessing the economic case for an intervention to manage the customer load energy at risk. The metric is based on the sum of the largest emergency overload (voltage or thermal) on an interval-by-interval basis. The largest exceedance type is accumulated for each interval to avoid double counting. The voltage-driven energy used energy scaling. (where no emergency asset rating is provided 150% of normal rating used)
generation_kwh	Total generation over the measurement zone. Where base year generation is defined by the AMI data export channels or equivalent data, and forecast generation is directly added to the model and so captured as gross generation connected.
generation_cecv	This metric is the same as generation_kwh defined above, multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval. The metric represents the total economic value of avoided market generation.
generation_co2	This metric is the same as generation_kwh defined above, multiplied by the relevant the timeseries value of CO2 for each interval. The metric represents the total value of the CO2 avoided from the energy generation market from the generation of local clean energy.
gen_exceeding_normal_thermal_voltage_kwh	This metric captures the total generation at risk within a measurement zone due to breaching voltage and thermal limits. Another way to view this metric is as the sum of the largest normal generation overload (voltage or thermal) on an interval-by-interval basis. Only accumulate the largest of each violation in each interval to avoid double counting. The voltage-driven energy used energy scaling as defined above. Default thresholds for 230v base are 216v <> 253v. This is the point at which part of the measurement zone energy is counted as curtailed. The curtailed energy then linearly increases until the outer voltage thresholds are reached, which for 230v base are 207v <> 260v. At this level, 100% of measurement zone generated energy for the relevant intervals is counted as curtailed.

gen_exceeding_normal_thermal_voltage_cecv	This is gen_exceeding_normal_thermal_voltage_kwh multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overload is present.
gen_exceeding_normal_thermal_voltage_co2	This is gen_exceeding_normal_thermal_voltage_kwh multiplied by the relevant timeseries value of CO2 for each interval the overload is present.
gen_exceeding_emerg_thermal_voltage_kwh	This metric captures the total generation at risk within a measurement zone due to breaching voltage and emergency thermal limits. Another way to view this metric is as the sum of the largest emergency thermal generation overload or voltage limit breach on an interval-by-interval basis. Only accumulate the largest of each violation in each interval to avoid double counting. The voltage-driven energy used energy scaling as defined above. Default thresholds for 230v base are 216v <> 253v. This is the point at which part of the measurement zone energy is counted as curtailed. The curtailed energy then linearly increases until the outer voltage thresholds are reached, which for 230v base are 207v <> 260v. At this level, 100% of measurement zone generated energy for the relevant intervals is counted as curtailed.
gen_exceeding_emerg_thermal_voltage_cecv	This is gen_exceeding_emerg_thermal_voltage_kwh multiplied by the relevant Customer Export Curtailment Value (CECV) for each interval the overload is present.
gen_exceeding_emerg_thermal_voltage_co2	This is gen_exceeding_emerg_thermal_voltage_kwh multiplied by the relevant timeseries value of CO2 for each interval the overload is present.
peak_import	Peak_import is the maximum recorded downstream energy flow at the 'head' of the measurement zone. This metric does not consider load and generation separately and captures the **net** peak import for the measurement zone over the relevant period.
peak_export	Peak_export is the maximum recorded upstream energy flow at the 'head' of the measurement zone. This metric does not consider load and generation separately and captures the **net** peak import for the measurement zone over the relevant period.

4.2.2 Constraints Table

Column Name	Description
work_package_id	The ID of the work package that was run

scenario	The scenario for this input
timestamp	Expressed in UTC
feeder	The feeder for this input
measurement_zone_name	The measurement zone name for this input (energy meter name)
mz_type	The type of asset class that forms the 'head' of the measurement zone
conducting_equipment_mrid	This is a unique identifier for the asset that forms the 'head' of the measurement zone
terminal_sequence_number	The identifier for the terminal of the conducting_equipment_mrid asset that forms the 'head' of the measurement zone. Where two measurement zones are present for a single conducting equipment mrid, this indicates a loop within the network. The terminal_sequence_number can be used to differentiate between them.
constraint_type	Defines the type of constraints that are captured in the accompanying metrics. Multiple constraints can be active during the same interval. All metrics are populated for each constraint, although not all are relevant for defining each constraint. The values recorded relate to the metrics recorded between the constraint timestamps only. A measurement_zone can have no constraints.
ended	The end timestamp for the last interval where the constraint was binding. All timestamps are expressed in UTC
v_base	voltage base of metrics - expressed in ph-ph voltage. For Transformers voltage base is reported as the secondary voltage This field should be used to convert from per unit results into magnitudes
voltage_max	The voltage recorded in the constraint table is the average of the max phase voltages. This means that for the available phases the max voltages are captured from all nodes in the measurement_zone, then the average of the available phase voltage is taken, the maximum of this value during the constraint period is then recorded in the constraint table as voltage_max.
voltage_min	The voltage recorded in the constraint table is the average of the minimum phase voltages. This means that for the available phases the minimum voltages are captured from all nodes in the measurement_zone, then the average of the available phase voltage is taken, the minimum of this value during the constraint period is then recorded in the constraint table as voltage_min.

load_max_kw	This is the maximum recorded gross load/consumption recorded within the measurement_zone for loads connected within the measurement_zone. Only loads connected within the measurement_zone are included in this metric, downstream load is not captured.
load_delta_kw	The difference between the highest and lowest recorded gross load/consumption within the measurement_zone over the constraint period
gen_max_kw	This is the maximum recorded gross generation recorded within the measurement_zone for generators connected within the measurement_zone. Only generators connected within the measurement_zone are included in this metric, downstream generation is not captured.
gen_delta_kw	The difference between the highest and lowest recorded gross generation within the measurement_zone over the constraint period
thermal_max_kw	This metric captures the delta between the peak_import and the asset within the measurement_zone that is overloaded above its relevant rating. This will include the impact of downstream measurement_zone current flows.
energy_kwh	Estimate of energy exceeded relevant network limit in kWh. The calculation varies by constraint type. For voltage constraints scaling is included.
value_dollars	VCR and CECV applied to estimated energy exceeding network limits. Based on the direction of energy flow the relevant economic valuation is applied. For downstream energy flows VCR is applied to the calculated energy at risk. For upstream energy flows (CECV + CO2) is applied the curtailed energy.

4.3 'CORNER CASES' & LIMITATIONS OF THE MODELLING

Overall, the modelling undertaken represents the most granular geospatial and time-series whole of network analysis of CPPALUE'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 conductors**: a significant proportion of the LV network conductor types 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 CER 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.
- **Off-Load Tap Positions**: were not able to be provided from the systems of record, however the calibration approach used by Zepben has been able to account for this missing data, and establish a model that aligns with historic measurements. The main limitation through this process is error in network impedance from LV network uncertainty impacting tap position calculation. Further work to validate tap position information could be used as an additional form of external model verification.
- **Service Lines**: These were nearly all unknown type, this resulted in the addition of the service line upgrade automation that sizes service lines using standard types based on historic peak import and export. The limitation here is that the mode is assuming that service lines are all capable of delivering current customer loading, and only forecast constraint for service lines are modelled.
- **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 single-phase premises are connected to the nearest phase the linesman can reach.
- **Voltage Regulation**: the model used provides the best available representation of CPPALUE's voltage settings, however specific settings for all feeders were not available and so some feeders were modelled with default voltage regulation settings.