Title:

Milestone 6: Network Modelling and EV Impact Assessment

Synopsis:

This report investigates the impact of residential electric vehicle (EV) charging on Integrated HV-LV Feeders. This report presents the modelling considerations and results of a highly-granular, detailed EV hosting capacity assessment done on urban and rural networks in Tasmania, New South Wales, and Victoria. This involves fully-modelled high voltage (HV) (22kV and 11kV) feeders and pseudo low voltage (LV) (0.4kV) networks to capture the effects close to end users as well as 1-min resolution time-series analyses and growing penetrations of EVs.

Document ID: UoM-ENA-C4NET-EV_Integration_M6_v02

Date: 20th October 2021

Prepared For:
Energy Networks Australia (ENA)
Australian Power Institute (API)
Centre for New Energy Technologies (C4NET)

Prepared By:
Dr William J. Nacmanson
Jing Zhu
Prof Luis(Nando) Ochoa
Department of Electrical and Electronic Engineering
The University of Melbourne

Revised By:
Prof Luis(Nando) Ochoa
Department of Electrical and Electronic Engineering
The University of Melbourne

Contact:
Prof Luis(Nando) Ochoa
+61 3 9035 4570
luis.ochoa@unimelb.edu.au

Executive Summary

The report at hand corresponds to Milestone 6 “EV Impact Assessment in Distribution Networks”, part of the 2 year collaborative project on ‘EV integration into the electricity grid’ between Energy Networks Australia (ENA), the Australian Power Institute (API), the Centre for New Energy Technologies (C4NET), and The University of Melbourne, as part of the ENA and API’s Australian Strategic Technology Program. This report presents the modelling considerations and results of a highly-granular, detailed EV hosting capacity assessment done on urban and rural networks in Tasmania, New South Wales, and Victoria. This involves fully-modelled high voltage (HV) (22kV and 11kV) feeders, pseudo low voltage (LV) (0.4kV) networks to capture the effects close to end users as well as 1-min resolution time-series analyses and growing penetrations of EVs.

The following summarise the key points and findings of this report.

HV-LV Feeder Modelling

The table below some of the characteristics of the HV-LV feeders modelled within OpenDSS and used in this project.

Feeder	Voltage Level (Total HV length)	No. Customers (HV Peak Demand)	No. LV Dist. Tx	Avg Residential Peak Size (kW)	Residential Data Used	ADMD (kW)	PV Penetration for Base Case (%)	Avg PV Size (kW)
Rural NSW (Hazelbrook)	11kV (20km)	1,401 (3.14MW)	39	2.0	VIC Smart Meter	6.5	24	3.8
Urban NSW (Preston)	11kV (6km)	616 (1.62MW)	17	2.0	VIC Smart Meter	6.5	30	5.8
Rural TAS (Norwood)	22kV (11km)	1,506 (6.15MW)	33	3.0	Avg Profile	5.0	0	-
Urban TAS (West Hobart)	11kV (6km)	620 (5.41MW)	12	3.5	Avg Profile	5.0	0	-
Rural VIC (SMR8)	22kV (486km)	3,669 (14.7MW)	765	2.0	VIC Smart Meter	4.0	0	-
Urban VIC (CRE21)	22kV (30km)	3,383 (7.80MW)	80	2.0	VIC Smart Meter	4.0	0	-

- Selected HV Feeders. The six HV feeders were identified and selected by the DNSPs using their know-how and expert views and considering several characteristics (rural, urban, length, number of customers, etc.) to capture an adequate spectrum across Australia within the timeframe available. There is an inherent trade-off between the quality and availability of data (conductor information, SCADA measurements, GIS coordinates, customer information, etc.) as well as the corresponding data extraction complexity and associated time restrictions, both in finding and extracting this data as well as converting it into HV-LV network models.
- Integrated HV-LV Feeders. These feeders were modelled using the software OpenDSS (developed by the Electric Power Research Institute - EPRI, USA). Since LV feeder information is not readily available from most DNSPs (unlike the HV feeder models which are available), LV networks are modelled based on the number of customers per distribution transformer, planning residential after diversity maximum demand (ADMD) values used by DNSPs and design principles (e.g., length, conductor, distribution of customers, etc.). By modelling the LV networks, even if not exactly as in reality, it is possible to have a better quantification of the impacts closer to LV customers, in particular, voltages at the customer connection points. These form so-called pseudo-LV feeder models.
- Validation of HV-LV Feeders. Validation of the modelled integrated HV-LV feeders is required. The objective is to ensure that the demand and generation (where applicable) profiles of residential and non-residential customers connected to the pseudo LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements. This ensures that the integrated HV-LV models mimic the real behaviour to the extent that is possible (given the limited data availability). The validated integrated HV-LV models will therefore represent the base case from which the impacts of different EV penetrations will be assessed.

EV Modelling

- EV Data. Realistic EV profiles are derived from the UK EV trial Electric Nation with nearly 700 EV owners taking part, with data found to be applicable for Australia. Four pools of time-series 1-min resolution EV demand profiles have been created by type of day (weekday/weekend) and charger size (Level 1/Level 2), each with 1,200 profiles.
- Weekdays. From the perspective of EV impact analyses, the EV demand of interest corresponds to weekdays. Therefore, in this project, weekday profiles (from both level 1 and level 2 pools) will be used assess the effects of EVs on the integrated HV-LV feeders.
- Charger Size. 80% of EVs are assumed to be equipped with Level 2 chargers (7.36kW), 20% of EVs are assumed to be equipped with Level 1 chargers (3.68kW).
- EV Penetration. EV penetration is defined in this project as the percentage of houses with a single EV. Since it is expected that eventually around 60% of houses will have two EVs (similar to regular cars), the maximum EV penetration to be considered in this project is 160%, i.e., every house has one EV, and 60% of them have a second EV.
- Multiple EVs per House. To create profiles for multiple EVs per household, the charging setup for each house must be considered. Two Level 1 chargers or a single Level 1 charger and a single Level 2 charger will not cause an issue for a typical residential single-phase connection and, therefore, can be directly assigned demand profiles. For two Level 2 chargers, a dual-headed Level 2 charger is considered which results in an adapted profile in which the excess demand (above 7.36kW) is deferred, thus extending the total charging duration.
- Diversified EV Demand. Based on the individual EV profiles created, no matter the type of day, the diversified peak demand of Level 2 charging (around 2kW during weekdays and 1.5kW during weekends) is approximately twice that of Level 1. For houses with two EVs, the largest diversified peak corresponds to the use of dual-headed Level 2 charges (around 4kW during weekdays and 3kW during weekends) and is nearly twice the values of a single Level 2 charger. It should be noted that EVs were modelled individually using the aforementioned pool of profiles, but this information is presented for completeness.
- Daily Charging Coincidence Factor. Not all the EVs in a given area will have a charging event every day. Assuming that EVs will charge up to 4 days in a week, it is estimated that 70% or less of the existing EVs will have a charging event on the same day.
- Power Factor. A power factor of 0.99 (lagging) is used for all EV demand profiles.

EV Impact Assessment

To assess the impacts for different EV penetrations, each of the six integrated HV-LV feeders considers nine EV penetrations: from the base case (0%) up to a maximum of 160% in 20% steps. Houses with a second EV are only considered after all houses have one EV (i.e., 100% of EV penetration). The maximum EV penetration of 160% assumes that 60% of houses have a second EV. EV location is randomly assigned across and within the LV feeders up to the EV penetration being investigated. Voltage compliance and asset utilization are used as performance metrics to quantify the technical impacts caused by different penetrations of EVs.

It is important to note that no EV management techniques or time-of-use tariffs that alter EV charging behaviour are considered in this report. This report focuses on the impacts of unmanaged EVs, e.g., following a standard tariff. These aspects will be investigated in the next stage of the project.

A summary of the residential EV charging impacts on integrated HV-LV feeders modelled as part of this project is presented below, split into rural/ urban and then compared by region.

Rural Feeders

- Overall, **rural feeders were found to have an EV hosting capacity of up to 40% of residential customers with an EV**. LV transformer utilisation issues can appear with as little as 20% EV penetration for Rural VIC and become wider at 40% for Rural NSW and TAS, including significant customer voltage drops and LV conductor issues.
- The larger number and smaller size of LV transformers typically used in rural feeders results in many congested transformers with relatively low EV penetrations. Furthermore, the length of the rural feeders and resulting higher impedances lead to lower voltages with relatively low EV penetrations.

Urban Feeders

- Overall, **urban feeders were found to have an EV hosting capacity of up to 80% of residential customers with an EV**. The first limiting factor was asset congestion (LV conductors, HV conductors or LV distribution transformers).
- While voltage issues are not significant for urban feeders until high EV penetrations, the high density of residential customers inevitably leads to a much larger peak demand even with modest EV penetrations, resulting in asset congestion.

New South Wales (NSW) Feeders

- Overall NSW feeders were found to have an EV hosting capacity of 0-80% before problems are encountered. The rural feeder was unable to host a 20% EV penetration and is first limited by LV distribution transformers becoming congested followed by voltage problems at 60%. For the urban feeder, the hosting capacity reached 80% before LV conductors become a problem and limit hosting capacity and is followed by LV distribution transformers limiting hosting capacity at 140%.

Tasmanian (TAS) Feeders

- Overall, it was found TAS feeders have an EV hosting capacity of 0-40% before problems are encountered. The urban feeder is unable to host 20% of customers with an EV with LV conductors being the first limiting factor. The next limiting factor for the urban feeder was the congestion of HV conductors which begin to overload at 40% EV penetration, followed by LV distribution transformers at 80%. The rural feeder on the other hand has a hosting capacity limit of 40% EV penetration, LV conductor problems and a small number of customers with a voltage problem being the limiting factor. The next limiting factor for the rural feeder is the LV transformer utilisation at 60% EV penetration.

Victorian (VIC) Feeders

- Overall, it is found that the EV hosting capacity of VIC feeders is 0%, with problems occurring at 20% EV penetration for both the rural and urban feeder. For the urban feeder, the limiting factor is LV distribution transformers with some overloading at 20% EV penetration. Beyond this, the next limiting factors are the HV, LV and customer voltages all becoming problematic at 80% EV penetration and beyond. For the rural feeder, the limiting factor is customer voltages and HV conductor overloads that first occur in the base case when considering the peak demand day. This rural feeder is much larger than other feeders considered and contains a significant number of single wire earth return networks that are much more sensitive to voltages. The next limiting factor is LV distribution transformers that begin to overload at 20% EV penetration.

The table below summarises the network impacts from unmanaged residential EV charging. Green indicates the parameter (e.g., customer voltages, LV transformer utilisation, etc.) is within limits, yellow indicates marginally exceeding limits whilst red indicates the limit was significantly exceeded.

Feeder	EV Hosting Capacity							
	20%	**40%**	**60%**	**80%**	**100%**	**120%**	**140%**	**160%**
Rural NSW (Hazelbrook)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Urban NSW (Preston)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Rural TAS (Norwood)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Urban TAS (West Hobart)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Rural VIC (SMR8)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Urban VIC (CRE21)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**

Limitations of the Study

- Fast charging stations. Fast charging stations were not considered. However, depending on their location, their demand in addition to that of residential EV charging could exacerbate problems, particularly for the HV feeder.
- Peak demand day. This study considers a peak demand day (modelled with 1-min resolution profiles) as it represents the worst-case scenario to quantify the EV impacts on the networks. While this is useful to capture the EV hosting capacity of a HV feeder, seasonal or annual-related aspects such as energy losses, cannot be quantified.
- Assignment of EVs to residential customers. EVs were randomly assigned to residential customers. There would be variations in impacts depending on the distribution of EVs. For instance, EV clusters could lead to voltage issues faster for those residential customers as well as congestion for the corresponding assets.
- LV feeders. In practice, LV conductors will use different specifications to those adopted in this project. As a consequence, the exact impacts on LV feeders versus those seen in the pseudo-LV feeders will vary. Depending on the age of the LV feeder and the ADMD used at the time of it being built (e.g., older feeders typically were designed with a lower ADMD and LV conductor specification, etc.), impacts could be slightly higher or lower.
- Uptake of Level 1 and Level 2 chargers. Factors such as subsidies that promote the use of Level 2 chargers may decrease EV hosting capacity (if more than 80% of EV users end up with a Level 2 charger). Conversely, a lack of Level 2 charger uptake may increase EV hosting capacity (higher percentage of Level 1 chargers).
- Cyclic ratings of transformers and conductors. This study did not consider cyclic ratings for transformers and conductors, only seasonal ratings. The consideration of cyclic ratings could increase EV hosting capacity. However, the peak hours might last longer.
- PV systems uptake in combination with EV uptake. The presence of residential PV systems was limited to the existing/available information when modelling the HV feeders. However, PV uptake is likely to increase with EV uptake. Whilst there is some small mitigation of EV impacts during daylight hours, the majority of EV demand will occur after daylight hours. Therefore, DNSPs may find a situation of voltage rise issues during the day and voltage drop issues once the sun has set.
- Residential Batteries. This study did not consider residential batteries. This technology could be used by customers to charge their EVs at night using energy captured from PV generation, thus reducing imports from the grid and the corresponding impacts.

Table of Contents

List of Figures

List of Tables

1 Introduction

The increasing adoption of light-duty electric vehicles (EVs, primarily used for the transport of passengers) will pose significant technical and economic challenges on the power grid, particularly on the very infrastructure they are connected to: the electricity distribution network.

Distribution networks were originally designed to cope with peak demand. Depending on the State or Territory in Australia, that design value can vary from 3 to 7kW per house (single phase) which accounts for diversity (we all use electricity at different times) and demographics (larger houses or colder places without access to gas consume more). Although distribution networks have been engineered to withstand demand growth, this does not include EVs.

The trend around the world is for EVs charged at home to use the fast Level 2 chargers (around 7kW of demand). While all EVs will not be charged at the same time, they clearly are a concern for distribution companies (known as Distribution Network Service Providers [DNSPs]) as the extra demand could easily exceed what the infrastructure has been designed for. Therefore, we need to understand the extent to which our distribution networks can host EVs.

This report presents the modelling considerations and results of a highly-granular, detailed EV hosting capacity assessment done on urban and rural networks in Tasmania, New South Wales, and Victoria. This involves fully-modelled high voltage (HV) (22kV and 11kV) feeders and pseudo low voltage (LV) (0.4kV) networks to capture the effects close to end users as well as 1-min resolution time-series analyses and growing penetrations of EVs. It should be noted that this report considers the hosting capacity and impacts of unmanaged EVs. Therefore, aspects such as time-of-use tariffs and other EV management techniques (that will help increase hosting capacity) are not considered in this report.

Validation of the HV-LV networks is performed with the objective of ensuring that the demand and generation (where applicable) profiles of residential and non-residential customers connected to the pseudo LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements. This ensures that the integrated HV-LV models mimic the real behaviour to the extent that is possible (given the limited data availability). The validated integrated HV-LV models represent the base case from which the impacts of different EV penetrations are assessed.

EVs are modelled based on real EV data from the UK EV trial “Electric Nation”, which when launched in 2017 was the world’s largest home smart charging trial with nearly 700 EV owners. Having assessed its suitability for Australia, data is used from this trial to construct realistic 1-min resolution time-series EV profiles based on the real plug-in times and charging durations. The profiles are divided into four pools separated by type of day (weekday/weekend) and charger size (Level 1/Level 2), each with 1,200 profiles. Considerations are also made relating to houses with more than one EV, the numbers of EVs likely to be charged per day, and the power factor.

This report corresponds to Milestone 6 “Network Modelling and EV Impact Assessment”, part of the 2 year collaborative project on “EV Integration” between Energy Networks Australia (ENA), the Australian Power Institute (API), the Centre for New Energy Technologies (C4NET), and The University of Melbourne, as part of the ENA and API’s Australian Strategic Technology Program.

The report is structured as follows: Chapter 2 presents the processes adopted by The University of Melbourne to validate and produce detailed three-phase models for six HV (e.g., 22kV, 11kV) feeders selected by the DNSPs TasNetworks, Endeavour Energy and AusNet Services as part of this project. This includes an overview of the parameters used to model the pseudo-LV (400V) feeders, a key feature to fully capture the effects of EVs on end customers. Chapter 3 then presents the different modelling aspects and considerations to produce realistic time-series demand profiles for light-duty EVs. Chapter 4 presents data associated with demand and PV generations as well as corresponding considerations used for case studies in this project. Chapters 5-10 present the impacts related to residential EV charging for the selected HV feeders modelled as HV-LV integrated networks. Finally, conclusions are drawn in Chapter 11.

2 Selected HV Feeders and HV-LV Feeder Modelling

This chapter presents the key characteristics and processes adopted by The University of Melbourne to validate and produce detailed three-phase models for six HV (e.g., 22kV, 11kV) feeders selected by the DNSPs TasNetworks, Endeavour Energy and AusNet Services as part of this project. This includes an overview of the parameters used to model the pseudo LV (400V) feeders, a key feature to fully capture the effects of EVs on end customers.

The six HV feeders were identified and selected by the DNSPs using their know-how and expert views and considering several characteristics (rural, urban, length, number of customers, etc.) to capture an adequate spectrum across Australia within the timeframe available. There is an inherent trade-off between the quality and availability of data (conductor information, SCADA measurements, GIS coordinates, customer information, etc.) as well as the corresponding data extraction complexity and associated time restrictions, both in finding and extracting this data as well as converting it into HV-LV network models.

These feeders were modelled using the software OpenDSS (developed by the Electric Power Research Institute - EPRI, USA). Since LV feeder information is not readily available from most DNSPs (unlike the HV feeder models which are available), LV networks are modelled based on the number of customers per distribution transformer, planning residential after diversity maximum demand (ADMD) values used by DNSPs and design principles (e.g., length, conductor, distribution of customers, etc.). By modelling the LV networks, even if not exactly as in reality, it is possible to have a better quantification of the impacts closer to LV customers, in particular, voltages at the customer connection points. These form so-called pseudo-LV feeder models.

2.1 Characteristics and Information

HV Feeders can vary significantly and can be described using key characteristics which are vital for producing an equivalent model. For example, while feeders may lie generally within an urban or rural setting, in reality, HV feeders can vary significantly in terms of length, number of customers, etc.

The following are some of the key characteristics used in this project to help with the selection of HV feeders and corresponding modelling of HV-LV feeders. It should be highlighted that some of these characteristics might not be readily available or difficult/time-consuming to extract from DNSP databases and feeders are selected where data is available to be shared.

- **Geography/Type.** The feeder type in terms of location and structure (e.g., rural, urban).
- **Length and Topology.** Total conductor length within the HV feeder and the topology of the HV feeder.
- **Availability/Quality of Head of Feeder SCADA data**. Although this is not a direct characteristic, it allows identifying those feeders that have good availability of recorded data, hence enabling a validation of network models for the corresponding analyses. Furthermore, it provides a maximum or average loading (i.e., MVA, Mvar, MW) of the feeder.
- **LV Transformers.** The size and location of LV transformers connected to HV feeder.
- **Number of customers.** The number of customers connected and supplied by the HV feeder. Ideally information related to how many of these customers are connected to each of the corresponding connected LV distribution transformers. Furthermore, the information includes the type of customer (e.g., residential, commercial, industrial etc.). This information is important in building realistic pseudo-LV models to attach to the HV feeder, since LV feeder models and information are commonly not readily available by DNSPs.
- **Extent of PV installations.** This corresponds to the extent of already existing residential rooftop PV within the feeder and is important information used to model the HV-LV feeders net demand before EVs are considered.
- **Design voltage.** The rated voltage at which the feeder is operated (e.g., 22kV, 11kV).
- **Line ratings.** The rated ampacity of HV conductors, as well as necessary conductor information (positive and zero sequence resistance, reactance and capacitance per unit length) required for modelling.

2.2 Selected HV Feeders and Data Provided

This section presents a general overview of the selected HV feeders and the data provided.

Table 2-1 presents the overview of the selected HV feeders, including their name, location and corresponding DNSP providing the original data. They are a mix of HV feeder types covering both urban and rural feeders as well as different voltage levels (11kV and 22kV). Data related to feeders from Endeavour Energy and TasNetworks were supplied as part of this project, whereas the AusNet Services HV feeders were already fully modelled in a previous project ("Advanced Planning of PV-Rich Distribution Networks" [1-6]).

Table 2-1. General Overview of Selected HV Feeders

Feeder Name	Type	Location	DNSP
Rural NSW (Hazelbrook)	Rural	Blue Mountains, New South Wales	Endeavour Energy
Urban NSW (Preston)	Urban	Greater Sydney, New South Wales	Endeavour Energy
Rural TAS (Norwood)	Rural	Northern Tasmania	TasNetworks
Urban TAS (West Hobart)	Urban	Greater Hobart, Tasmania	TasNetworks
Rural VIC (SMR8)	Rural	Victoria	AusNet Services
Urban VIC (CRE21)	Urban	Victoria	AusNet Services

Table 2-2. HV Feeder Technical Information Summary

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)
Rural NSW (Hazelbrook)	11kV	1401	39	20	6.5	2.0	24%	3.8
Urban NSW (Preston)	11kV	616	17	6	6.5	2.0	30%	5.8
Rural TAS (Norwood)	22kV	1506	33	11	5.0	3.0	0%	-
Urban TAS (West Hobart)	11kV	620	12	6	5.0	3.5	0%	-
Rural VIC (SMR8)	22kV	3669	765	486	4.0	2.0	0%	-
Urban VIC (CRE21)	22kV	3383	80	30	4.0	2.0	0%	-

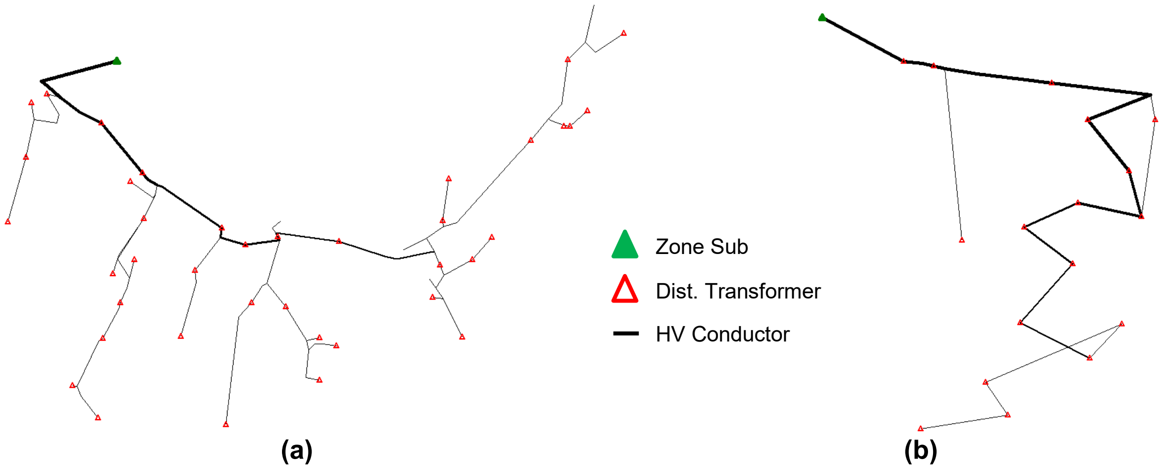
Table 2-2 presents more technical information about the HV feeders. From a modelling perspective, in particular, to produce the pseudo LV feeders, the residential ADMD and the number of residential customers per LV transformer (not included in the table and availability depends on the HV feeder) are key inputs (as discussed in section 2.4). From a validation perspective, the number of residential customers, their corresponding average peak demand, the number of PV installations and their average size, are also key inputs to be used for comparisons with the demand recorded by SCADA measurements at the head of the HV feeder.

It is worth highlighting that the average peak of 2.0kW for the VIC HV feeders is based on anonymised smart meter data from [7]. The same value was considered reasonable for the NSW HV feeders. In the case of the TAS HV feeders, however, TasNetworks provided specific values that reflect the higher use of electricity (for heating purposes).

The original models (used by the DNSPs) of the selected HV feeders were passed onto The University of Melbourne along with other important data to enable the production and validation of the integrated HV-LV feeders. More details about the original models and other data are listed below.

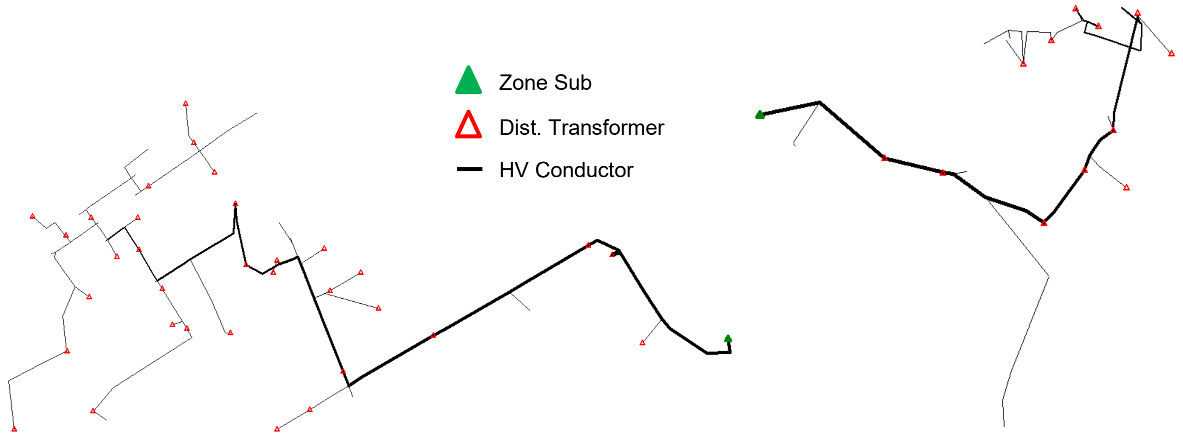
1. **Original models for each selected HV Feeder.** The models produced correspond to the information to the databases and tables used by the specialised software packages that contain all the required details for each HV feeder (i.e., conductor specifications, connection, topology, transformers, coordinates, etc.).
2. **Distribution Transformer Information.** These files correspond to the details of the distribution substations (i.e., Substation ID, Substation Name, Substation Number, Transformer Size, number of customers, type of customers such as residential or non-residential) and for some DNSPs number of customers with solar PV, installed capacity and the average size of PV installations. This information is equally important as it is not included in the original model files or databases and are required to model pseudo LV feeders.
3. **Residential Profiles.** For the TAS HV feeders, TasNetworks provided a half-hourly daily average profile for residential customers. For the VIC and NSW feeders, anonymised smart meter profiles from [7] were considered adequate.
4. **SCADA Data.** These files contain SCADA measurements at the head of the selected HV feeder and include current, voltage, active power, reactive power and apparent power measurements of 15 or 30-minute intervals over the previous few years. These are used for validation of the HV-LV feeder models.

Figure 2-1 to Figure 2-3 present the topologies of the selected HV feeders based on the coordinates available in the original model files. Connected to each distribution LV transformer, denoted by a red triangle, will be pseudo LV feeders (not shown as coordinates do not exist). The HV feeder is fed from the zone substation shown with a green triangle. Finally, the black lines represent the HV conductors, with the thickness indicating the approximate level of relative power expected to flow.



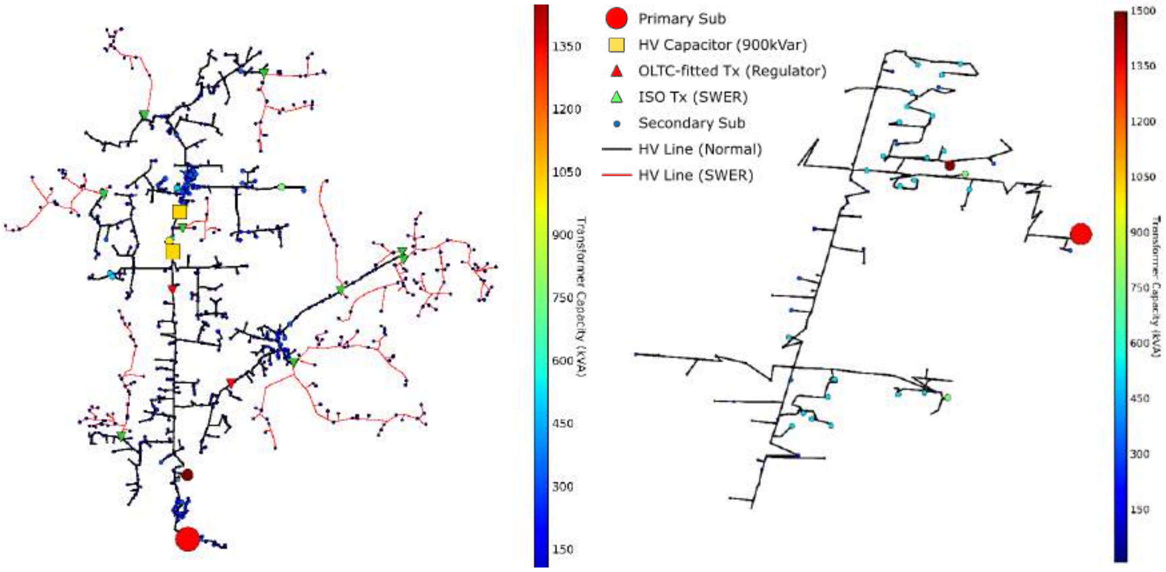
(a) (b)

Figure 2-1. (a) Rural NSW (Hazelbrook, 11kV); (b) Urban NSW (Preston, 11kV)



(a) (b)

Figure 2-2. (a) Rural TAS (Norwood, 22kV); (b) Urban TAS (West Hobart, 11kV)



(a) (b)

Figure 2-3. (a) Rural VIC (SMR8, 22kV); (b) Urban VIC (CRE21, 22kV)

2.3 Modelling of HV Feeders

This section presents the general process to translate the original HV feeder models (files or export files from power system analysis software commonly used by DNSPs) into HV feeder models within OpenDSS. Data from all the elements representing the HV feeder need to be extracted (from the corresponding database, e.g., as done for PSS Sincal in [1], or through the user graphical interface). Further details are provided below.

Overhead Lines and Underground Cables

Depending on how the lines are defined they will either have unique identifiers (IDs) for each of the two nodes (aka ports, terminals, buses, etc.) or not.

- With Unique Node Identifiers. These can be directly extracted into the bus definitions of the OpenDSS line object. While these arbitrary (anonymized) node IDs are for the original software's own modelling, they can also serve the same use in OpenDSS (which uses nodes directly in model creation).
- Without Unique Node Identifiers. A series of line objects need to be created in OpenDSS:

1. For the first line (e.g., line A), it is defined within OpenDSS with the same line name (for connection of other elements later) and assigned arbitrary sequential node IDS (e.g., HV1 and HV2) for the node identifications.
2. For all the line objects connected to the second terminal of the first line object (e.g., line B and C), new line objects within OpenDSS would be created. The first node ID within OpenDSS for these new line object definitions (e.g., line B and C) would be the second node ID from the previous line object that was connected to it (e.g., HV2).
3. This process picks the first of several options if the feeder branches (e.g., line B first), assigning a new node ID to the second terminal (e.g., HV3), and repeats until ultimately the feeder branch will end and line IDs and node IDs are created for that branch (i.e., the topology is recorded).
4. The process repeats for other unchecked lines from branches until all line objects have been translated and assigned arbitrary node IDs.

Then, the length of each line needs to be extracted (e.g., in km). Generally, it will be within the respective database that contains the line object definitions.

Finally, the electrical characteristics of the conductors need to be extracted. These can be found within the line type (or line code) within the database. Depending on the type of conductor used in each line object, it will be assigned a set of physical characteristics per unit length (e.g., positive and zero sequence resistance, reactance, and capacitance) as well as the maximum ampacity (or current rating) of the line or cable per phase. In some instances, there may be more than one value of rated ampacity, typically, the higher value is a summer rating and lower value is a winter rating.

Zone Substation

The zone substation information will be within either a database for network elements containing one node or a list of transformers. It may be the case that it is simply defined as an in-feeder and the transformer is not modelled. Either way, the connection to the HV feeder must be extracted, either by using the node ID of the element or the connected line name. If available, the physical characteristics of the zone substation (e.g., reactance, percentage load loss, percentage no load loss, rated power, etc) will be in the corresponding entry of transformer types.

LV Distribution Transformers

The LV distribution transformers will be in a database for either two node network elements, one node network elements or simply a list of transformers, depending on the software and modelling procedures use by each DNSP. In some instances, the LV transformer may not be modelled and instead modelled directly as a load on the HV feeder. In this case, the ID of the load element should be taken as it will likely correspond to an LV transformer on information provided separately to the model that contains transformer size, number of customers, etc. It is worth noting that the off-load tap position (if applicable) is not commonly available and, thus, the nominal position is considered.

As was the case with the primary transformer, the node ID or line name needs to be recorded for the connection point to the HV feeder. If using the line name, then the corresponding node ID for that terminal must be used for OpenDSS. The characteristics of the LV transformer are extracted from the transformer type database. Where LV transformers are not modelled directly and are instead loads, then supplementary information would be required (e.g., based on a known model of a similar size).

Coordinates

Depending on the software, coordinates will either be defined per node ID, which can be directly translated into OpenDSS, or defined for line objects, connector/fuses etc. In the latter case, the coordinates of the line objects need to be recorded and if plotted within OpenDSS (and not externally) translated into corresponding node ID coordinates for both ends of the line object. Finally, the coordinates of LV transformer (or loads) and of the primary transformer should also be noted (either directly or via the node IDs they are connected to.

Additional Information

Any other network element should be recorded (e.g., capacitor banks, in-line transformer etc) if they are modelled, including the coordinates, characteristics, and location within the HV feeder.

2.4 Modelling of LV Feeders

Modelling the LV feeders allows quantification of the impacts closer to LV customers, in particular, voltages at the customer connection points. These factors, when considered together with the HV feeder, have big implications on getting closer to accurately estimating the EV hosting capacity of various feeders. Noting that LV network models are not readily available from (in general, from DNSPs), LV feeders can be modelled based on:

- The number of residential customers for each LV distribution transformer (i.e., either provided or estimated). Residential customers are used for the LV feeders since non-residential customers are modelled connected to the busbar of the LV distribution transformer.
- The planning residential ADMD value used by each DNSP.
- LV design principles, as specified by the industry [8-12] (e.g., length, conductor, distribution of customers, etc.).

In some instances, there may be a LV transformer within the HV feeder model that did not appear within the HV model. In this instance, the average number of residential customers per kVA of transformer is calculated and used to estimate the number of customers (only if corresponding LV transformer information data is not found).

Finally, the nominal position of the off-load tap changers used by LV distribution transformers is considered in all the six integrated HV-LV feeders. This is due to a lack of information but is also aligned with DNSP practice. Consequently, those distribution transformers will be effectively providing the original natural boost (approximately 8%) due to the transformation ratio used in Australia (e.g., 22kV to 433V or 11kV to 433V). The steps followed to model the LV networks for each of the HV feeders LV distribution transformer is described in this section and are based on the method originally used for the “Advance Planning of PV-rich Distribution Networks” project [1-6].

2.4.1 Number of LV Feeders and Connected Customers

Depending on the conductor going to be used, the maximum number of customers allowed to be connected on each feeder can be calculated using the conductor’s ampacity using (1). This allows defining the total number of feeders to be connected at the secondary distribution substation.

$$\boldsymbol{C^F} = \left\lfloor \frac{I_{AMP} \times 3 \times V_{L-N}}{C^{ADMD}} \right\rfloor \tag{1}$$

Where $\boldsymbol{C^F}$ the total number of customers per feeder, I_{AMP} is the rated ampacity of the cable used and V_{L-N} is the line-to-neutral voltage.

Then, using $\boldsymbol{C^F}$, the number of feeders connected to the TX can be defined using (2)

$$\boldsymbol{F} = \left\lceil \frac{\boldsymbol{C^{TX}}}{\boldsymbol{C^F}} \right\rceil \tag{2}$$

where $\boldsymbol{F}$ is the total number of feeders connected to the TX and the brackets, ⌈ ⌉, denote that the number is rounded up to the nearest integer. $\boldsymbol{C^{TX}}$ is the total number of customers the secondary distribution transformer is supplying, TX^{kVA} is the transformer’s rated capacity and C^{ADMD} is the assumed ADMD for a single customer (i.e., Villa, Townhouse, Apartment)

The LV feeder conductor to be considered in the analyses throughout this project is a 240mm^2 with the following details:

R1	X1	B1	R0	X0	B0	I_{AMP}
0.127	0.0272	0.0001	0.342	0.089	0.0001	280

2.4.2 Length of LV Feeder and Distribution of Customers

To calculate the length of each feeder, design specifications adopted by Horizon Power [11, 12] are used. These design specifications define the maximum length of an LV feeder based on a maximum equivalent length defined by a 95mm^2 cable which is also based on the transformer's size and feeder's LV fuse size as shown in Figure 2-4 and Figure 2-5.

Once the maximum equivalent length is defined, using (3) it is converted to the actual maximum length of the feeder going to be modelled by reversing the procedure shown in Figure 2-5 and defined in [11].

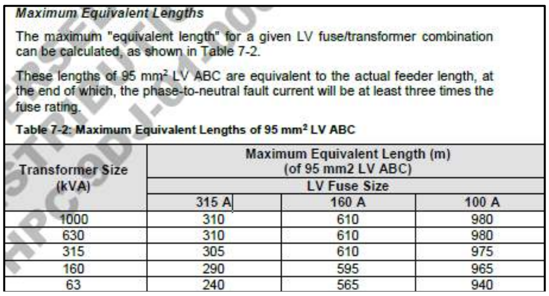
$$F^{l}_{max\_act} = F^{l}_{max\_eq} \times sf \tag{3}$$

where $F^{l}_{max\_act}$ is the feeder actual maximum length in meters, $F^{l}_{max\_eq}$ is the feeder equivalent maximum length in meters and sf is the equivalent length conductor scaling factor which is based on the conductor's size.

Once the feeders' actual maximum length ($F^{l}_{max\_act}$) is defined, the actual length of each feeder is calculated as a proportional to the number of houses connected to it. For example, considering that the maximum number of customers a feeder can supply is $\boldsymbol{C^F}$ then this means that for this number the length of feeder will be equal to the maximum length i.e., $F^{l}_{max\_act}$. Considering this, the length of each feeder will be calculated using (4).

$$F^{l}_{i} = F^{l}_{max\_act} \times \left(\frac{C^{F}_{i}}{\boldsymbol{C^F}}\right) \tag{4}$$

where F^{l}_{i} is the length of feeder i.



Maximum Equivalent Lengths

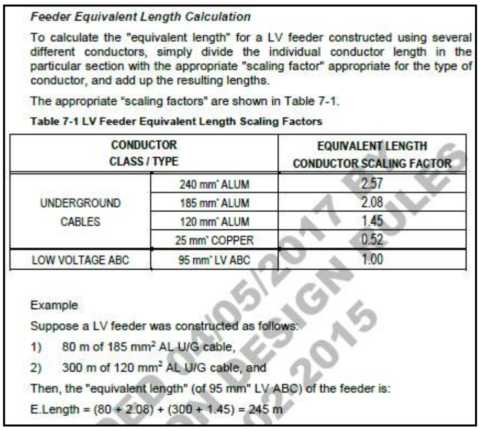
The maximum "equivalent length" for a given LV fuse/transformer combination can be calculated, as shown in Table 7-2.

These lengths of 95 mm^2 LV ABC are equivalent to the actual feeder length, at the end of which, the phase-to-neutral fault current will be at least three times the fuse rating.

Table 7-2: Maximum Equivalent Lengths of 95 mm^2 LV ABC

Transformer Size (kVA)	Maximum Equivalent Length (m) (of 95 mm2 LV ABC)		
	LV Fuse Size		
	315 A	160 A	100 A
1000	310	610	980
630	310	610	980
315	305	610	975
160	290	595	965
63	240	565	940

Figure 2-4 Equivalent Maximum Lengths [11]



Feeder Equivalent Length Calculation

To calculate the "equivalent length" for a LV feeder constructed using several different conductors, simply divide the individual conductor length in the particular section with the appropriate "scaling factor" appropriate for the type of conductor, and add up the resulting lengths.

The appropriate "scaling factors" are shown in Table 7-1.

Table 7-1 LV Feeder Equivalent Length Scaling Factors

CONDUCTOR CLASS / TYPE		EQUIVALENT LENGTH CONDUCTOR SCALING FACTOR
UNDERGROUND CABLES	240 mm^2 ALUM	2.57
	185 mm^2 ALUM	2.08
	120 mm^2 ALUM	1.45
	25 mm^2 COPPER	0.52
LOW VOLTAGE ABC	95 mm^2 LV ABC	1.00

Example

Suppose a LV feeder was constructed as follows:

1) 80 m of 185 mm^2 AL U/G cable,

2) 300 m of 120 mm^2 AL U/G cable, and

Then, the "equivalent length" (of 95 mm" LV ABC) of the feeder is:

E.Length = (80 + 2.08) + (300 + 1.45) = 245 m

Figure 2-5 Feeder Equivalent Length Calculation [11]

Once the length of each feeder is calculated, houses (i.e., loads) are evenly distributed across the whole feeder. Each house is connected through a 10m service cable.

The lengths of the LV feeders in the analyses throughout this project will be defined considering a 95mm^2 maximum equivalent length based on [11]. The LV service cable to be considered in the analyses throughout this project is a 16mm^2 and has the following characteristics:

R1	**X1**	**B1**	**R0**	**X0**	**B0**	I_{AMP}
1.149	0.08	0.0001	4.26	0.092	0.0001	100

2.5 HV-LV Feeder Validation

This section presents the steps to validate the four integrated HV-LV models produced in this project created using the HV feeder models and associated data provided by Endeavour Energy (Rural NSW and Urban NSW) and TasNetworks (Rural TAS and Urban TAS). The validation process used for the feeders from AusNet Services (Rural and Urban VIC) is presented in [1].

The objective is to ensure that the demand and generation (where applicable) profiles of residential and non-residential customers connected to the pseudo LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements. This ensures that the integrated HV-LV models mimic the real behaviour to the extent that is possible (given the limited data availability). Where no or incomplete information exists, worst-case scenario considerations have been made to avoid over-optimistic results when assessing the effects of EVs. The validated integrated HV-LV models will therefore represent the base case from which the impacts of different EV penetrations will be assessed.

To validate the HV-LV models for a 24-hour period the following steps are conducted. Given that the active power demand of non-residential customers was not available, the process first estimates that demand based on the gap between known residential demand and SCADA measurements at the head of the feeder. The steps are as follows:

1. Select a peak demand day from the SCADA data. In the context of the project, this day will be the worst-case scenario for EV impacts due to the increase in demand.
2. Assign residential demand to residential customers. This is done with available data, i.e., anonymised smart meter profiles for Rural and Urban NSW feeders, and average daily residential profiles for Rural and Urban TAS feeders.
3. Assign residential PV profiles based on available data. This combines PV penetration, average PV size and clear-sky irradiance for the corresponding day (see section 4.2).
4. Tune non-residential active power demand profiles (associated with each distribution transformer) such that the active power of the OpenDSS power flow simulation at the head of the feeder is aligned with the SCADA measurement.
    - For simplicity, loads are modelled as constant power. Therefore, to ensure a close match of currents seen at the head of the HV feeder the most appropriate voltage from the SCADA measurements is selected (and fixed throughout the day).
5. Tune reactive power of all customers such that the reactive power of the OpenDSS power flow simulation at the head of the feeder is aligned with the SCADA measurements. Since no reactive power data is available for residential customers, an acceptable inductive (lagging) power factor range is assumed.
    - Tune the inductive reactive power profile of non-residential customers such that the reactive power of the OpenDSS power flow simulation at the head of the feeder is aligned with the SCADA measurement.
    - For cases when SCADA measurements show a very low inductive reactive power or even capacitive, a capacitor located at the head of the HV feeder is sized and operated to achieve the corresponding SCADA measurements. While, in practice, customers can show capacitive behaviours (leading power factor), this assumption creates a worst-case scenario for EVs as larger voltage drops are expected. Furthermore, the reactive power profile of non-residential customers might require a final tuning.

Once the above validation process is completed for a given HV-LV feeder, it is also possible to check whether the customer voltage profiles and asset utilisation behave as expected for an existing distribution network (e.g., voltages are generally within statutory limits and assets are not overloaded).

3 EV Modelling

This chapter presents the different modelling aspects and considerations to produce realistic time-series demand profiles for light-duty EVs (primarily used for the transport of passengers).

First, the key EV parameters and steps for the creation of EV profiles are presented. Then, an analysis is presented on the UK EV trial Electric Nation [13-15] data which is used as a basis for EV modelling. A comparison on Australian and UK vehicle behaviours is carried out to confirm that UK trial data is also valid for Australia. Finally, the process to take this data from the UK EV Trial Electric Nation and create EV profiles that can be used to assess the effects on the integrated HV-LV feeders, along with necessary modelling considerations, is presented.

3.1 Parameters and Steps for the Creation of EV Profiles

This section presents the overall key parameters and methodology to achieve adequate EV models for an EV impact analysis. Considering the demand is influenced by human behaviours and limited by charger capacity, there are multiple parameters and characteristics need to be defined in a proper EV demand model:

1) **Charging Start Time and Duration.** The most critical parameters used to describe a certain charging event is the charging 'start time' and 'duration' which reflect the timeframe from charging beginning to end.
2) **Daily Charging Times.** Another important characteristic is the number of times per day EVs are plugged in, as people may choose to charge their EVs more than once in a day. Therefore, subsequent plug-ins (i.e., more than one) should also need to be taken into consideration in EV modelling.
3) **Daily Charging Coincidence Factor.** Given the usage pattern and longer EV range, most of EVs are not charged every single day. Thus, there is a coincidence factor used to estimate the percentages of EVs that will be charged for a certain day.
4) **Types of EV Charger.** The parameters above can only help to define charging status (ON/OFF), while the actual demand is decided by the type of EV charger. For residential charging, there are normally two types of EV chargers available in the market: Level 1 and Level 2. Each country has different regulations for voltages, and in Australia, the resulting demands are approximately 3.68kW for Level 1 (16A, 230V) and 7.36kW for Level 2 (32A, 230V) [16]. Therefore, EV charger size must be considered.
5) **EV Penetration.** Percentage of residential customers with a single EV. Since some customers might have more than one EV, penetration levels can go above 100%.
6) **Power Factor.** Power factor describes the ratio of active power to apparent power drawn by EV chargers. An EV charger contains an AC/DC converter and has a power factor which needs to be represented.

Considering the key parameters above, a set of charging profiles must be created from a pool of EV charging data.

A general EV charging profile is a binary profile with ON/OFF (1/0) status corresponding to the plug-in events. Each plug-in event can be characterised by charging 'start time' and 'duration'. Thus, if the EV data can define start time and duration, then a binary EV profile can be created as shown in Figure 3-1. If a binary EV profile can be created, then when assigned to the corresponding charger size, the EV demand profile (for both active and reactive power) per house can also be created.

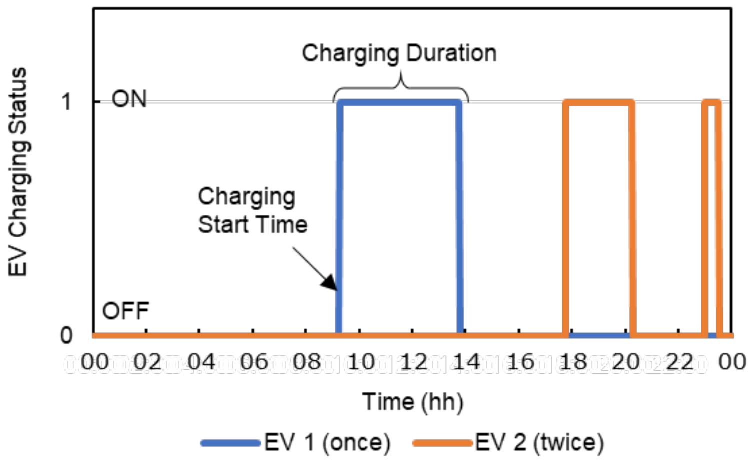


Figure 3-1. Charging Profiles Example

The creation of EV profiles from any EV dataset can be conducted using the following steps:

Step 0) Analyse and check EV data.
Step 1) Define residential EV charger sizes.
Step 2) Consider the implications of multiple EVs per house.
Step 3) Divide data into subsets (if applicable).
Step 4) Extract probability distributions.
Step 5) Produce EV binary profiles.
Step 6) Translate into EV demand profiles.
Step 7) Create EV demand profiles considering charging limitations (if applicable).
Step 8) Extract the daily charging coincidence factor.
Step 9) Consider a power factor.
Step 10) Consider EV penetrations.

Each of the above steps will be demonstrated in section 3.4 using the Electric Nation data.

3.2 Analysis of Electric Nation Data

This section presents an overview of the data from the EV trial “Electric Nation”, which is used to model EVs for this project. When launched, Electric Nation [13-15], located in the UK, was the world’s largest home smart charging trial with nearly 700 EV owners taking part in the 18-month trial (2017-2018). Between them, trial participants provided data for more than 2 million hours of car charging with over 157,000 charging events are recorded in total.

This trial was processed in 3 stages, and data from Stage 1 is used for this project to model EVs and understand their potential impacts on Australian HV-LV feeders.

- **Stage 1: Blind**. Users did not know if or when their vehicle was having its charge limited.
- **Stage 2: Interactive**. Interaction with customers is introduced through phone apps that would allow them to have control over their charging.
- **Stage 3: Incentivised**. Vouchers are introduced so incentivise customers to charge outside of peak hours.

Different EV models were considered in the Electric Nation trial, with different charger sizes, battery capacities, etc. It can be seen from Figure 3-2 (from the trial), that the majority of cars that make up the trial are electric battery EVs (BEV). The battery capacity on the other hand corresponds to all types of vehicles considered, with range extender (REX) and plug-in hybrids (PHEV) requiring smaller batteries on average.

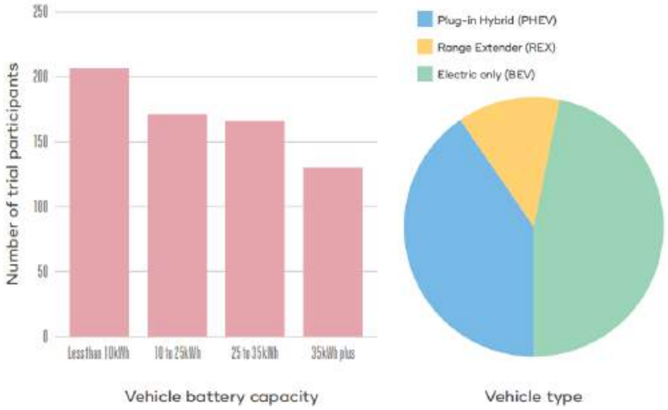


Figure 3-2 Vehicles in Electric Nation Trial [15]

In the trial database, key elements in each charging record were captured for analysis:

- **Transaction ID.** Added in the database to identify each transaction.
- **Participant ID.** ID number for the participant linked to each charger.
- **Participant Car W/kWh**. Rating/battery capacity of the participant's vehicle.
- **Weekday or Weekend**. Used to identify the plug-in day.
- **Active Charging Start**. Time when charging began.
- **Charging Duration.** Time between ‘ActiveChargingStart’ and ‘EndCharge’ in minutes.
- **Managed**. ‘Yes’ if the transaction was constrained during charging. ‘No’ if it wasn’t.

To understand both human and technical factors behind the Electric Nation EV database, a charging analysis behaviour is carried out. This is done considering the subset of the stage 1 database (with) that corresponds to unmanaged EVs (no smart charging, more than 33,000 EV charging events) and removing entries with errors.

The analysis of the charging data is done focusing on three key factors.

- Charging Level.
- Battery Size.
- Vehicle Type.

For each charging event, both charging start time and charging duration are extracted, then probability distribution plots are provided to sketch the resulting behaviours for each of the key factors.

3.2.1 Charging Level

There are around 60% of EVs using Level 1 chargers (3.68kW) at home with the other 40% using Level 2 chargers (7.36kW).

As seen in Figure 3-3, there is no prominent difference on charging start time for Level 1 and Level 2 EVs. However, it is noteworthy that the curve of plug-in times during the weekend is flatter, likely due to having less time constraints (e.g., due to work) compared to weekdays.

As for duration, shown in Figure 3-4, Level 2 EVs tend to charge longer than Level 1, despite the higher charging power, with more than 20% increment on the average. The reason behind is those Level 2 EVs are usually equipped with large sized battery also, and despite the higher charging power of Level 2 helping to accelerate the rate of charging, ultimately it still requires a longer duration to get fully charged.

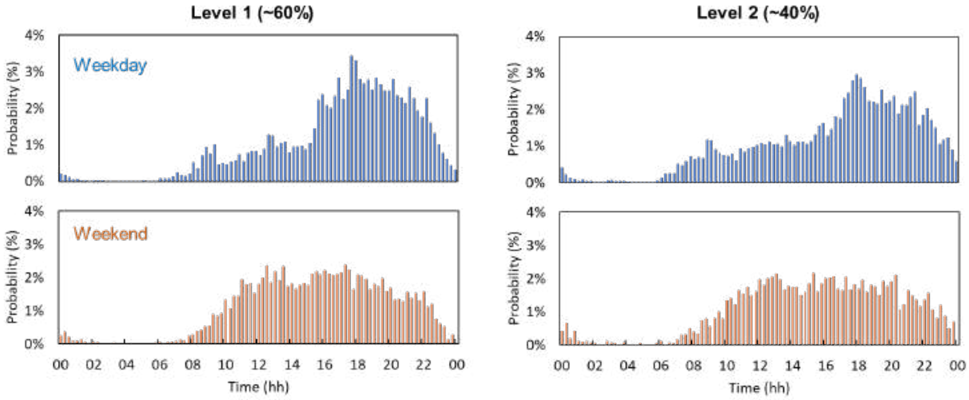


Figure 3-3. Charging Start Time split by EV Charger Size

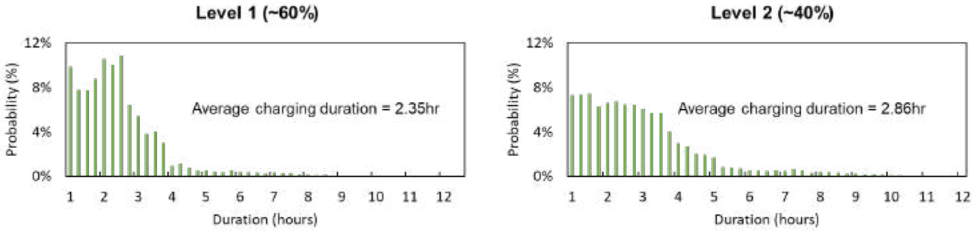


Figure 3-4. Charging Duration split by EV Charger Size

3.2.2 Battery Size

Battery size is another important factor that influences EV charging profiles, typically the charging duration. As provided in “Participant Car W/kWh”, the battery size can be categorized from short range to extra-long range:

- **Short range.** Less than 10kWh.
- **Medium range.** 10 to 25 kWh.
- **Long range.** 25 to 35 kWh.
- **Extra-long range.** Larger than 35kWh.

As seen in Figure 3-5, when comparing the charging start time, the extra-long ranged category shows a small difference with lower charging during the daytime. Those participants likely purchased extra-long range EVs knowing charging opportunities are limited or perform long distance journeys. On the contrary, short, ranged EV owners are more concentrated with charging events. For example, as seen just after work hours (17:00), likely due to short commutes.

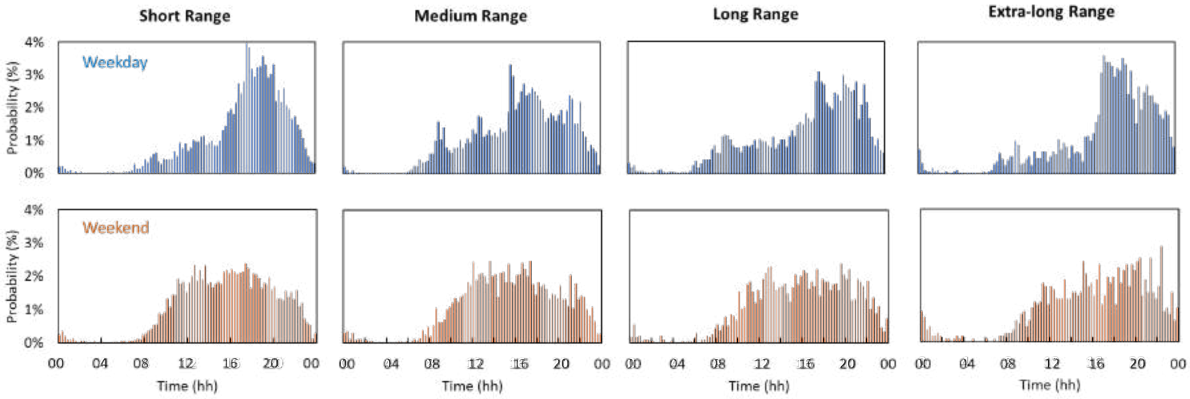


Figure 3-5. Charging Start Time split by Battery Size

The insights related to charging duration, shown in Figure 3-6, are aligned with the analysis on charging levels seen in Figure 3-4, whereby long range and extra-long ranged EVs (i.e., also cars with larger batteries), despite being connected with Level 2 chargers, need more time to get fully charged.

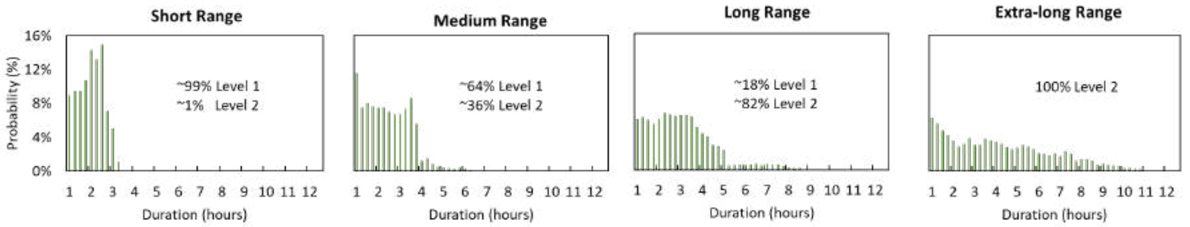


Figure 3-6. Battery Size: Charging Duration

3.2.3 Vehicle Type

According to the vehicle type, EVs can be classified as BEV, PHEV and REX as their dependency on the electricity is different.

- **Battery electric vehicles (BEV).** A purely electric vehicle that is powered by a battery and an electric motor, with no internal combustion engine.
- **Plug-in hybrid (PHEV).** A combustion engine vehicle with a battery-powered electric motor, each of which can power the wheels independently or together. The battery can be charged by plugging in, and the vehicle itself can charge the battery when in use.
- **Range extended (REX).** A plug-in electric battery and motor powers the vehicle, but there is a small combustion engine that acts solely as a generator to charge the battery if required.

It can be seen in Figure 3-7 that the plug-in times for all vehicle types are very similar.

Considering that PHEV and REX can still operate after the battery is empty, it is equipped typically with smaller sized battery compared to BEV, so the charging duration is shorter. This can be seen in as seen in Figure 3-8, with charging duration for BEV is slightly longer on average.

However, it was also noted from the dataset that most Level 1 chargers are used for PHEV, so it is important to include the PHEV type in Level 1 charging.

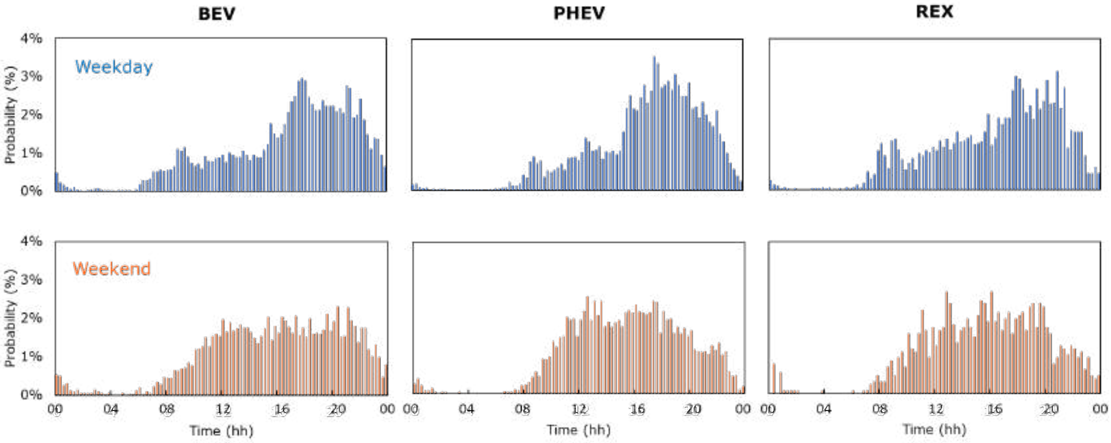


Figure 3-7. Engine type: Charging Start Time

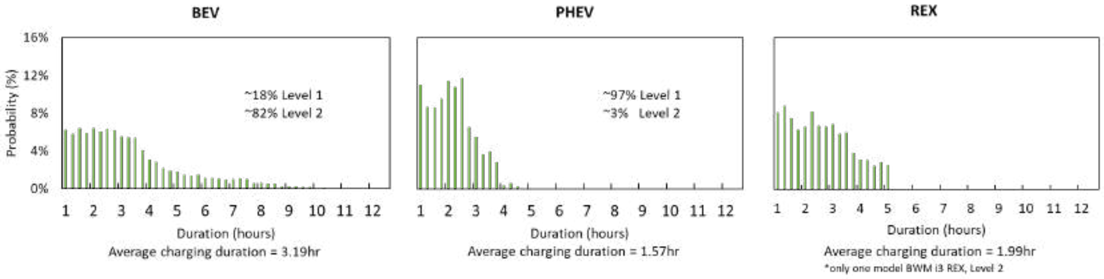


Figure 3-8. Engine type: Charging Duration

3.2.4 Key Remarks

The following are the key remarks from the charging behaviour analysis:

- Weekday/Weekend is a key factor to influence charging start time. During the weekday there is a larger coincidence of plug-in time during the early evening (which is likely to coincide with load demand). Whereas during the weekend, EV owners show a more distributed behaviour during the weekend**.** Weekday can be considered the worst-case scenario.
- Charging levels, battery sizes and types of vehicles are key factors to influence charging duration. As such these must be accounted for in modelling. BEV are usually equipped with larger sized battery, and thus need higher charging power (Level 2).

Based on the above, to reflect the diversity of charging behaviours, the Electric Nation database needs to be divided into several subsets: weekday/weekend and Level 1/Level 2. There is no necessity to further categorise the subsets by battery size and vehicle type, as this is captured by the charging level (as discussed in this section).

3.3 Applicability to Australia

This section discusses the applicability of using data from the UK Electric Nation trial to produce EV profiles that will be used to carry out EV studies on Australian HV-LV feeders.

Australian EV uptake has a lower trajectory than global EV sale trends and lacks information characterising its current EV owners [17]. Nonetheless, the behaviour of Australian EV users could be similar to other countries.

To answer this, the Australian car usage behaviour is compared with those involved in the UK Electric Nation trial. The comparison is conducted considering four key aspects:

1) Travel Mileage.

2) Plug-in Time.
3) EV Model Diversity.
4) Other EV Usage Behaviours.

3.3.1 Travel Mileage

From the Electric Nation trial, participants reported their travel mileage in a typical week, most of which travel around 300 km per week, as shown in Figure 3-9. In Australia, we can refer to Survey of Motor Vehicle Use [18], summarised in Table 3-1, given the lack of EV usage characteristics.

The statistics show that light-duty vehicles travel 212 km in average with little variance between each region. Therefore, we can deduce that EV travel mileage in Australia will be equivalent to the UK, considering the Australian survey value is slightly under-estimated. Those early EV adopters in New South Wales, also summarised in Table 3-1, report 190 to 380 km travel mileage per week [19]. It is conceivable that this behaviour will be seen in more EV owners in the future. This, again, generally aligns with the UK.

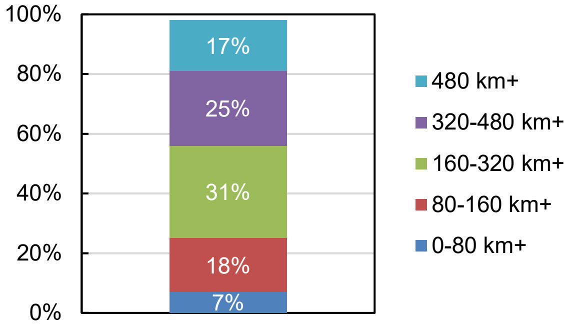


Figure 3-9. UK EV Weekly Mileage Survey in Electric Nation Trial [15]

Table 3-1. Australian EV Weekly Mileage Survey

Survey of Motor Vehicle Use [18]										**NSW EV Owners Survey [19]**
Region	NSW	VIC	QLD	SA	WA	TAS	NT	ACT	Australia	56% of users travel 10,000-20,000 km/year (~190-380 km/week)
Avg. km per week	206	219	213	208	217	195	232	217	212*	
*Includes registered vehicles did not travel in the period (under-estimated)										

3.3.2 Plug-in Time

The Electric Nation trial report provides a distribution of plug-in times, and a prominent surge is observed for plug-in events from 5pm as shown in Figure 3-10. The plug-in time is related to vehicle travelling time, typically for those who charge their EVs at home (83%), since there is a strong intention to plug in cars when people are back at home. As such, traffic volume information is used in lieu of residential EV plug in time information.

In Australia, the typical hourly traffic volume [20], as seen in Figure 3-11, can be used to estimate the likely EV connection times. In particular, the traffic volume starts to decrease after 5pm and, therefore, it is safe to assume that EVs are likely to be charged after this time as it suggests arrival to the destination (home). This mirrors the spike in EV connections seen in the UK after 5pm. Thus, it can be concluded that Australia EV users will follow a similar plug-in behaviour to those in the UK.

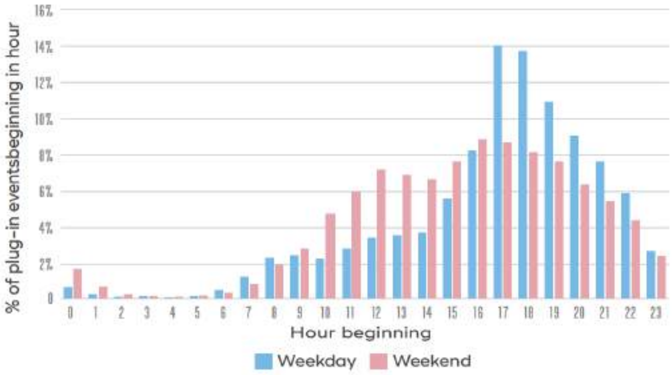


Figure 3-10. UK Distribution of Plug-in Times in the Electric Nation Trial [15]

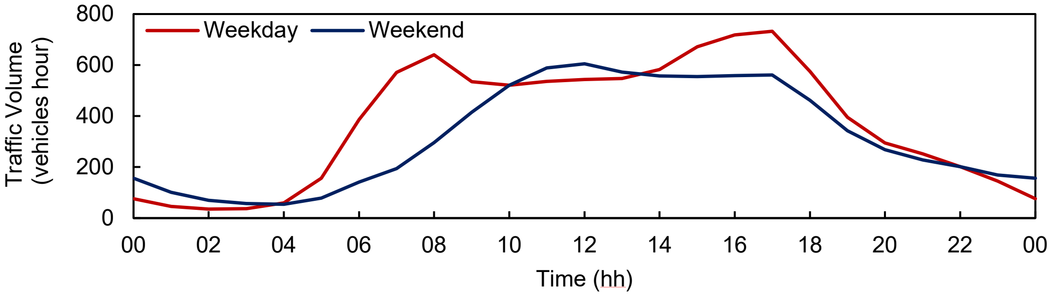


Figure 3-11. Australian Typical Hourly Traffic Volume [20]

3.3.3 EV Model Diversity

As shown by Figure 3-12, there are various types of EV models involved in the Electric Nation trial, implying market diversity in the UK. In comparison, for Australia, as shown in Figure 3-13, the choice is limited with fewer manufactures and fewer models. In this project, because future EV penetrations are considered, potential market developments need to be included, which is very likely to follow a similar trend as in the UK with an increase in choice of EVs.

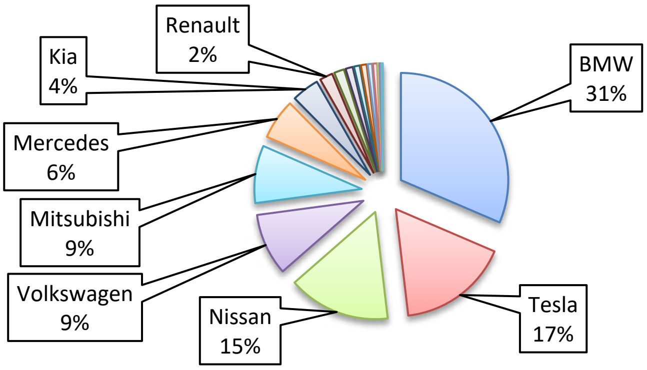


Figure 3-12 UK EV Models Distribution in the Electric Nation Trial [15]

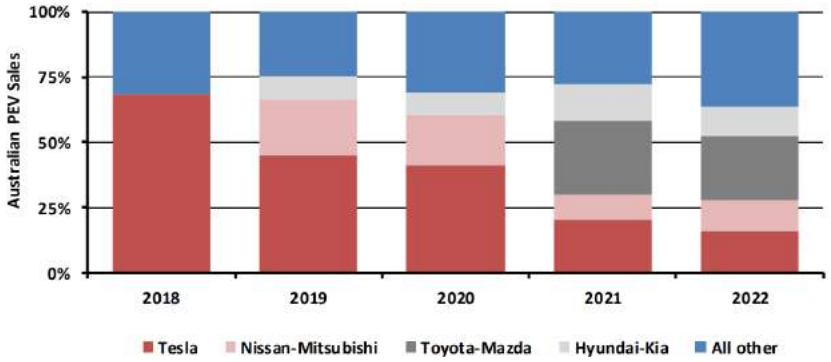


Figure 3-13 Australian EV Market Share, 2018-2022 [21]

3.3.4 Other EV Usage Behaviours

Besides the previously mentioned aspects, there are other behaviours found in common for the UK and Australia, as stated in travel surveys and reports and summarised in Table 3-2.

Table 3-2. UK vs Australia: Other EV Usage Behaviours

Behaviour	UK (Electric Nation [15])	Australia
Charging Frequency	3-4 times per week	3-4 times per week [19]
Peak Charging Time	Peak EV charging demand was observed between 5pm to midnight	10pm-7am was the most popular time for home charging (65%). Mostly taking place between 5pm and midnight. [22]
Charging Duration	BEV have a slightly longer charging duration than PHEV/REX	The duration of charging events does not vary significantly among different types of EVs. [22]
PV Adoption	Over one fifth of participants had solar PV panels fitted to their properties.	Majority already do (18%) or would consider (58%) using a solar power system to charge their EV [19].

3.3.5 Key Remarks

Based on the above analysis, the UK Electric Nation trial data is considered adequate for Australian EV analyses. The following are some of the key remarks:

- EV customers (and normal car drivers) in Australia and the UK tend to have similar travel mileage, thereby we can deduce that the usage of EV battery is also similar, i.e., equivalent charging demand quantity/charging duration.
- Australian traffic times are aligned with the UK EV plug-in time. For those who charge EVs at home in Australia, a similar plug-in trend to that in the UK will be likely followed.
- The Australian EV market is expected to grow and be as diversified as in the UK with various battery sizes and charging levels.

3.4 Realistic EV Profiles and Considerations

This section presents the process for the creation of realistic EV profiles and the necessary considerations required when implementing these EV profiles to conduct an EV impact assessment on distribution networks. Following the analysis of the EV data in the previous sections, the process for the creation of EV profiles is conducted following the steps presented in section 3.1 (repeated for convenience below).

Step 1) Define residential EV charger sizes.

Step 2) Consider the implications of multiple EVs per house.

Step 3) Divide data into subsets (if applicable).

Step 4) Extract probability distributions.

Step 5) Produce EV binary profiles.

Step 6) Translate into EV demand profiles.

Step 7) Create EV demand profiles considering charging limitations (if applicable).

Step 8) Extract the daily charging coincidence factor.

Step 9) Consider a power factor.

Step 10) Consider EV penetrations.

Step 1) Define residential EV charger sizes

For residential charging, there are normally two types of EV chargers available in the market: Level 1 and Level 2. Each country has different regulations for voltages, and in Australia, the resulting demands are approximately 3.68kW for Level 1 (16A, 230V) and 7.36kW for Level 2 (32A, 230V) [16].

Since Level 1 provides very slow charging, it is always applied on EVs from the data with smaller battery sizes (e.g., PHEVs and short-ranged BEV). The Electric Nation data has Level 1 and Level 2 split by 60% and 40%, respectively. However, when considering engine type in the data, it is shown that for BEV only (shown previously in Figure 3-8 in section 3.2.4) 82% of BEV customers were charged with a Level 2 charger, whilst 97% of PHEVs were charged with a Level 1 charger. The market share of PHEV and short-ranged BEV is estimated to be around 20% in 2050 [23]. In contrast, long-ranged BEV equipped with Level 2 charger will likely dominate the market and subsequently increase the percentage of customers with a Level 2 charger beyond the 40% currently seen in the Electric Nation data. This is likely because newly released models are increasing in battery size and mostly equipped to use a Level 2 charger. This, combined with an increased preference to BEV and particularly long ranged BEV, suggests that customers will likely install a Level 2 charger at home. Finally, from a survey which was conducted in a previous part of this project [24], it was found that two thirds of current EV owners contacted in Australia have a Level 2 charger installed at their house.

Therefore, based on these assumptions:

- 80% of EVs are assumed to be equipped with Level 2 chargers (7.36kW).
- 20% of EVs are assumed to be equipped with Level 1 chargers (3.68kW).

Step 2) Consider the implications of multiple EVs per House

In this project, residential customers with two EVs (i.e., a second car) are also considered. This is only implemented, however, once every residential customer has one EV (i.e., once 100% penetration is reached). Therefore, considerations need to be drawn for when multiple EVs are connected to a single house and are charged concurrently (according to their assigned profiles).

Given that most single-phase connected houses in Australia will likely have import limits ranging from 30 to 60A (approximately 7 to 14kW), it is therefore possible to install:

- Case A: Two separate Level 1 chargers; and,
- Case B: One Level 1 charger and one Level 2 charger.

As such, the peak demand for these cases is simply the addition of both EVs. Since the aggregated power of two Level 2 chargers (14.72kW) is likely to exceed import limits, a dual-headed Level 2 charger (Case C) is considered. In this case, if one EV is connected (or two are connected and one is full), it gets the full Level 2 charge of 7.36kW. However, if charging overlaps, then this is halved until one battery is full (or disconnected).

The three cases are summarised below in Table 3-3. Profiles for Case C are created in Step 8.

Table 3-3. Charging Alternatives for House with Two EVs

Case	1st EV	2nd EV	Chargers	Max Power
Case A	Level 1	Level 1	Separate chargers	3.68+3.68=7.36 kW
Case B	Level 1	Level 2	Separate chargers	3.68+7.36=11.04 kW
Case C	Level 2	Level 2	Dual-headed Level 2 charger	7.36 kW

Step 3) Divide data into subsets

According to the charging records, summarised in Figure 3-14 showing the distribution of the number of times EVs are plugged in per day, 96% of EVs plug-in up to twice a day. Therefore, before any division of the data, a filter needs to be applied to extract only charging events for EV that were plugged in either once or twice per day. This will simplify the corresponding modelling task.

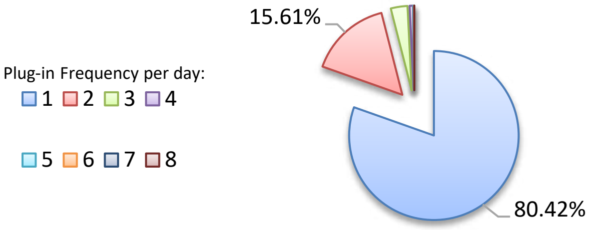


Figure 3-14 Frequency of Plug-in Events from the Electric Nation EV Trial

Given the findings from the analysis carried out in section 3.2, the data is divided into four subsets differentiating day type (weekday/weekend) and charging level (1/2), as shown in Figure 3-15.

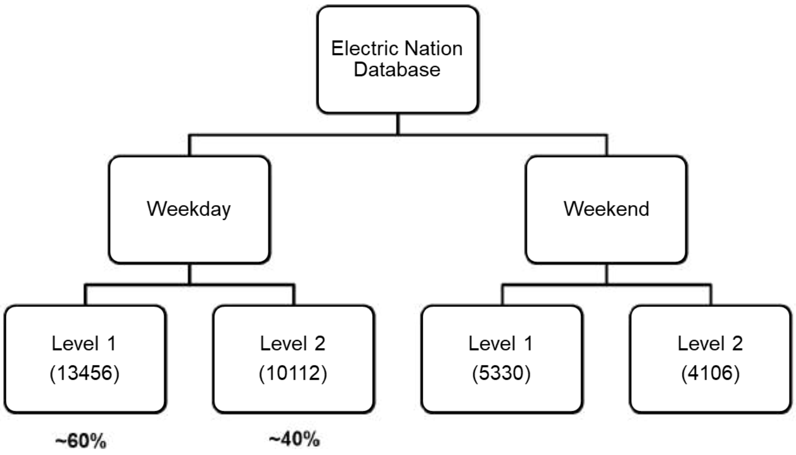


Figure 3-15 Creation of Subset through Division of Electric Nation Data

Step 4) Extract probability distributions

For each of the four subsets presented previously, probability distributions for charging 'start time' and 'duration' are extracted. These probability distributions are plotted in Figure 3-16 to Figure 3-19. For the cases when charging occurs twice a day, the plots are presented separately for the 1st and 2nd plug-in events. A prominent start time lag is observed on the 2nd plug-in event.

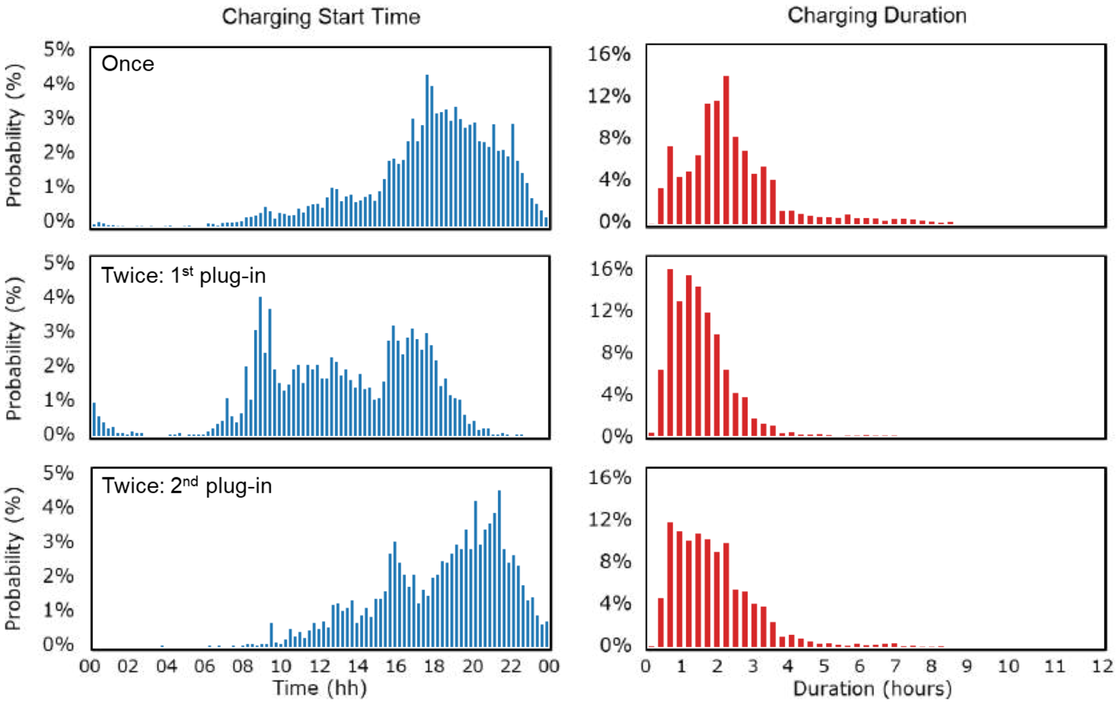


Figure 3-16. Probability Distributions: Weekday Level 1

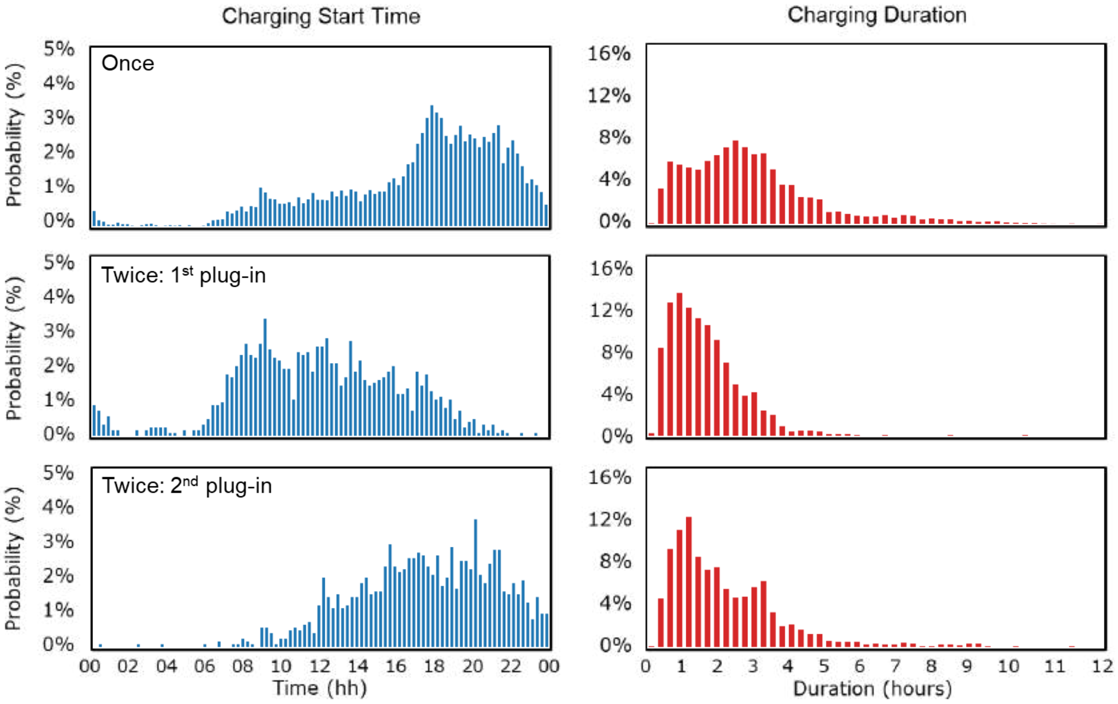


Figure 3-17. Probability Distributions: Weekday Level 2

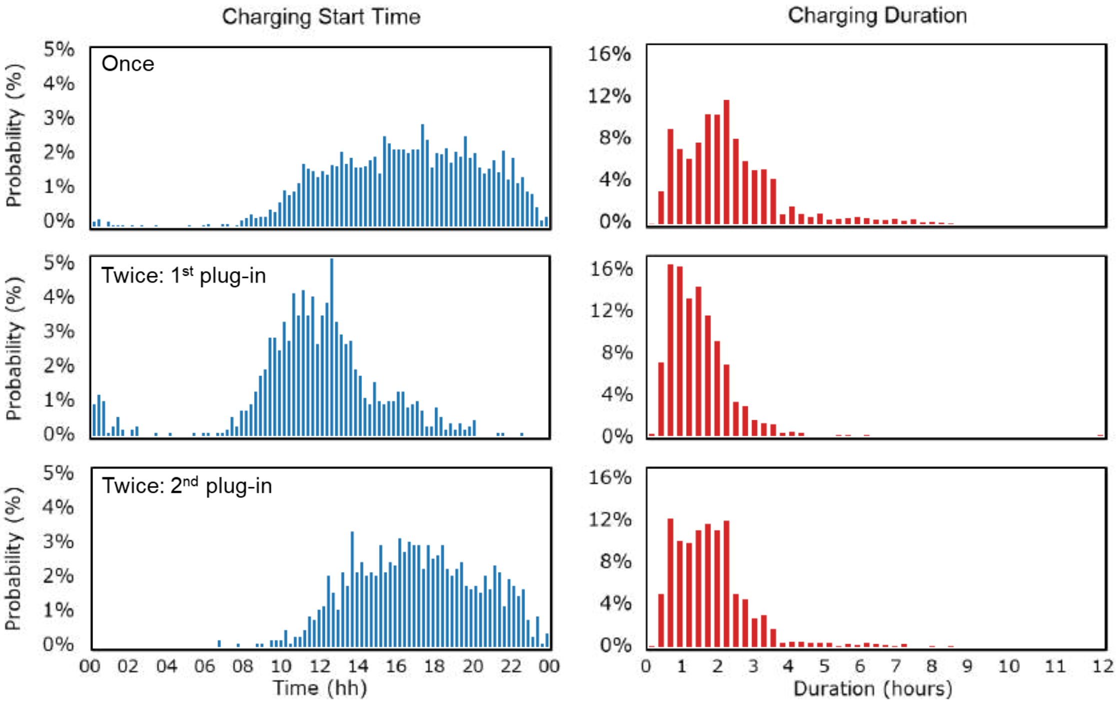


Figure 3-18. Probability Distributions: Weekend Level 1

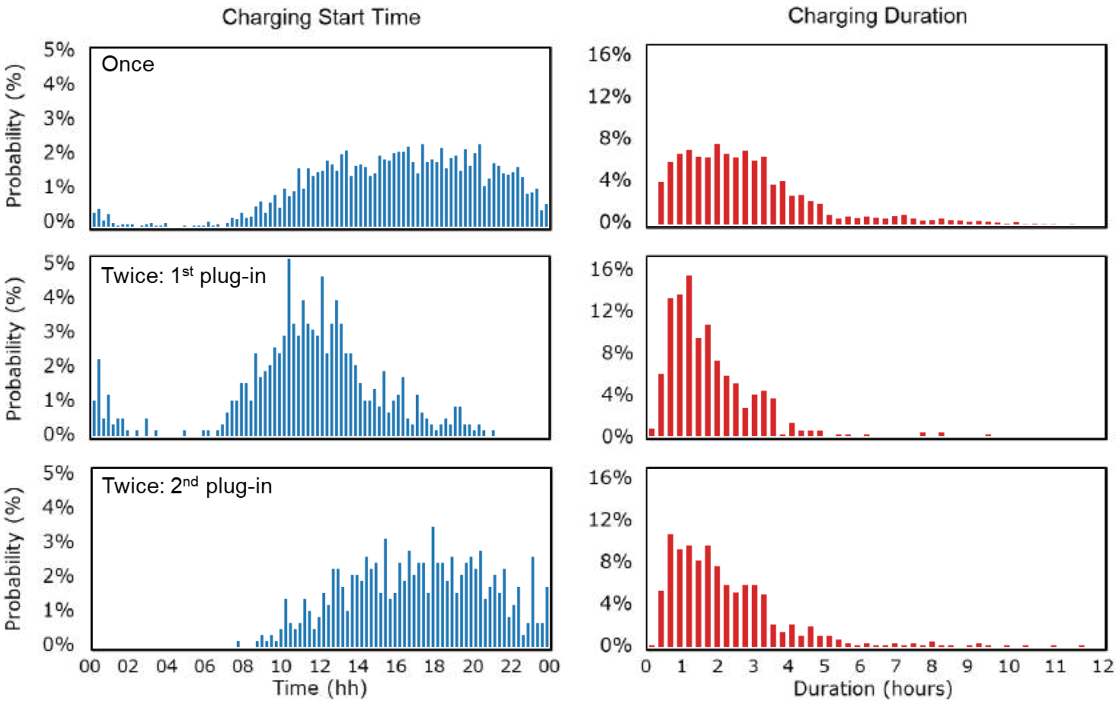


Figure 3-19. Probability Distributions: Weekend Level 2

Step 5) Produce EV binary profiles

With the probability distributions, the charging 'start time' and 'duration' are randomly selected and combined to produce 1-min resolution EV binary profiles. There are 4,800 profiles produced in total, 1,200 profiles (1,000 for plug-in once, 200 for plug-in twice) in each subset. As introduced in section 3.1 in Figure 3-1, a general charging profile has two statuses: ON/OFF → 1/0. Therefore, we need to translate time information into binary profiles. More specifically, assign value ‘1’ to the time-period plug-in and assign value ‘0’ to plug-out.

Step 6) Translate into EV demand profiles

The binary profiles only contain the ‘ON/OFF’ information. However, a demand profile is needed to model EVs in distribution networks. Therefore, the last step is to assign the charging levels (Level1: 3.68kW, Level 2: 7.36kW) to the binary profiles to translate them into active power demand profiles.

The resulting diversified active power demand for each of the four subsets (each with 1,200 EV profiles) is shown in Figure 3-20.

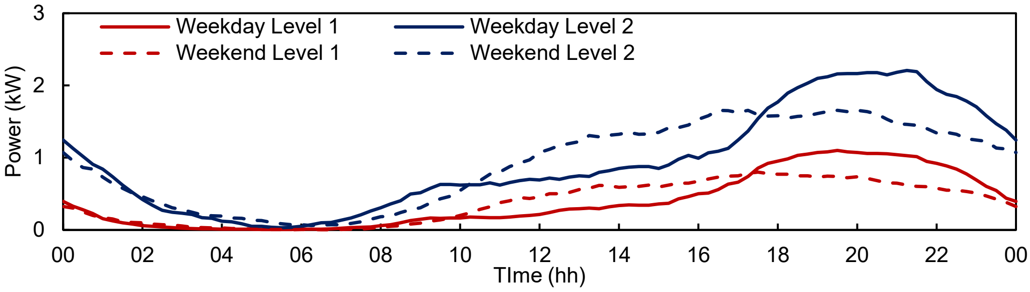


Figure 3-20. Diversified EV Demand Profiles

It can be seen in Figure 3-20 that there is more coincident charging during the weekdays (solid lines); likely due to people coming back home after work. This is also reflected in the plug-in distribution data that was extracted earlier in step 4. Overall, no matter the type of day, the diversified peak demand of Level 2 charging (around 2kW during weekdays and 1.5kW during weekends) is approximately twice that of Level 1.

Based on the above, from the perspective of EV impact analyses, the EV demand of interest corresponds to weekdays. Therefore, in this project, weekday profiles will be used assess the effects of EVs on the integrated HV-LV feeders.

Step 7) Create EV demand profiles considering charging limitations

To create profiles for multiple EVs per household, the charging setup for each house must be considered. As shown in step 2, two Level 1 chargers (Case A in Table 3-3) for a house is unlikely to be a problem and, therefore, charging profiles can be assigned simultaneously. This is the same for a single Level 1 charger and a single Level 2 charger (Case B Table 3-3). However, given that two Level 2 chargers can cause problems for a typical house with a single-phase connection, a dual headed Level 2 charger is considered (Case C in Table 3-3).

The use of a dual headed charger requires adaptation of profiles since charging the EVs at half power (each drawing 3.68kW) will increase the charging duration. Figure 3-21 demonstrates the ‘overlap method’ adopted for creating these new profiles. In summary, two single Level 2 profiles are aggregated, and the excess demand (above 7.36kW) is deferred, thus extending the total charging duration.

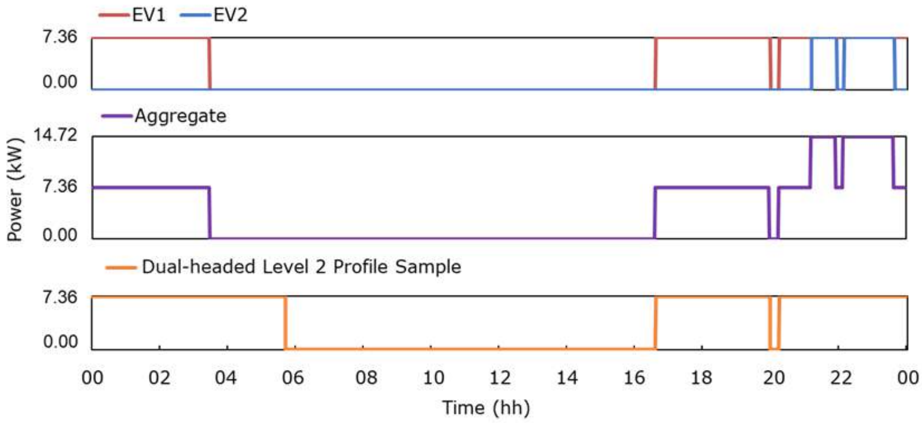


Figure 3-21. Dual Level 2 Profiles Creation Sample

The resulting diversified active power demand for each of the two subsets for Level 2 (each with 1,200 EV profiles) is shown in Figure 3-22. It should be noted that despite the shared charging, this still results in peak values for weekdays (around 4kW) and weekends (around 3kW) that are nearly twice those of a single Level 2 charger.

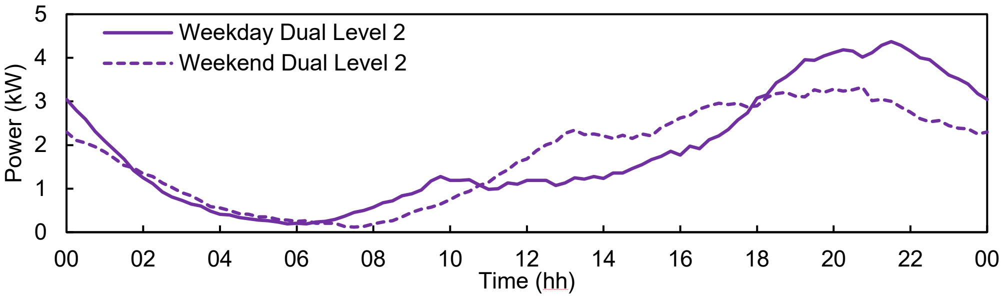


Figure 3-22 Diversified EV Demand Profiles for a Dual-Headed Level 2 Charger

Step 8) Extract the Daily Charging Coincidence Factor

As reported in the NSW Electric Vehicle Owners Survey [19], EVs are charged only 3 to 4 days of the week. From the perspective of the distribution networks, this means that the number of EVs charging in a particular day is always less than the actual EV penetration, i.e., not all the EVs in a given area will have a charging event every day.

Assuming that EVs in Australia will be charged up to 4 days out of the 7 days in the week, and that every day has the same charging probability, the cumulative distribution function can be used to calculate the probability of having an X (or less) number of EVs charging on the same day. For a 99% probability, it is found that 70% or less of the existing EVs will have a charging event on the same day. Figure 3-23 illustrates this with 100 EVs. Up to 70 EVs will charge on the same day (day 5). In this project, this value is referred to as the Daily Charging Coincidence Factor.

Therefore, to realistically assess the effects of EVs on distribution networks, a daily charging coincidence factor of 70% will be used. This is implemented in the EV impact analysis by considering only the fraction of EV users represented by this factor. For instance, for a HV-LV network with 1,000 houses and an EV penetration of 40% (i.e., 400 houses with a single EV), only 280 EVs would be considered to have a charging event in a given day.

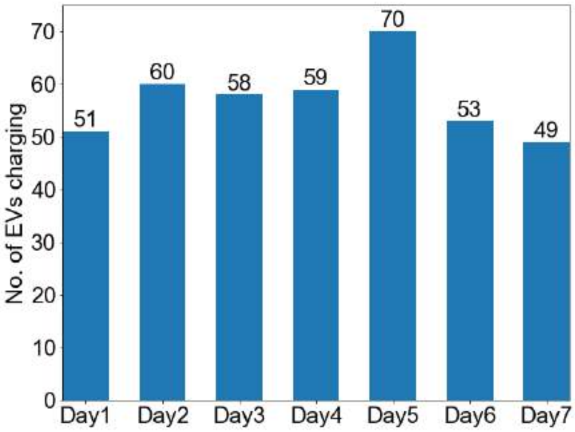


Figure 3-23 Daily Number of EVs Plugged-in

Step 9) Consider a Power Factor

With the development of power factor correction devices embedded in chargers and EVs, the power factor of EV demand can range from 0.98 to 1.0 (lagging) for both Level 1 and Level 2 chargers [25]. For modelling purposes, the value of 0.99 will be used to simulate reactive power absorption.

Step 10) Consider EV Penetrations

EV penetration is defined in this project as the percentage of houses with a single EV. This means that with a 100% EV penetration all houses will be considered to have one EV. However, since it is expected that eventually around 60% of houses will have two EVs (similar to regular cars [23]), the maximum EV penetration to be considered in this project is 160%, i.e., every house has one EV, and 60% of them have a second EV.

3.4.1 Key Remarks

The following are key remarks for the EV modelling considerations adopted in this project:

- Four pools of time-series 1-min resolution EV demand profiles have been created by type of day (weekday/weekend) and charger size (Level 1/Level 2), each with 1,200 profiles.
- From the perspective of EV impact analyses, the EV demand of interest corresponds to weekdays. Therefore, in this project, weekday profiles (from both level 1 and level 2 pools) will be used assess the effects of EVs on the integrated HV-LV feeders.
- 80% of EVs are assumed to be equipped with Level 2 chargers (7.36kW), 20% of EVs are assumed to be equipped with Level 1 chargers (3.68kW).
- EV penetration is defined in this project as the percentage of houses with a single EV. Since it is expected that eventually around 60% of houses will have two EVs (similar to regular cars), the maximum EV penetration to be considered in this project is 160%, i.e., every house has one EV, and 60% of them have a second EV.
- To create profiles for multiple EVs per household, the charging setup for each house must be considered. Two Level 1 chargers or a single Level 1 charger and a single Level 2 charger will not cause an issue for a typical residential single-phase connection and, therefore, can be directly assigned demand profiles. For two Level 2 chargers, a dual-headed Level 2 charger is considered which results in an adapted profile in which the excess demand (above 7.36kW) is deferred, thus extending the total charging duration.
- Based on the individual EV profiles created, no matter the type of day, the diversified peak demand of Level 2 charging (around 2kW during weekdays and 1.5kW during weekends) is approximately twice that of Level 1. For houses with two EVs, the largest diversified peak corresponds to the use of dual-headed Level 2 charges (around 4kW during weekdays and 3kW during weekends) and is nearly twice the values of a single Level 2 charger.
- Not all the EVs in a given area will have a charging event every day. Assuming that EVs will charge up to 4 days in a week, it is estimated that 70% or less of the existing EVs will have a charging event on the same day.
- A power factor of 0.99 (lagging) is used for all EV demand profiles.

4 Demand Modelling, PV Modelling and Case Studies

This chapter presents the data associated with demand and PV generations as well as corresponding considerations used for the analysis performed in this project. First, the residential and non-residential demand used for the analyses are described. Then, the modelling of solar PV including irradiance profiles, penetrations and panel sizes are detailed. Finally, the case studies to be considered later in this report (full results in Chapter 5-10) are described.

4.1 Demand Modelling

This section presents the data and considerations for both residential and non-residential demand modelled within the HV-LV feeders. All residential customers are assigned an inductive power factor that is randomly distributed uniformly between 0.95 and 0.99.

4.1.1 Residential Smart Meter Data for VIC and NSW

For the feeders located in New South Wales (Endeavour Energy) and Victoria (AusNet Services), Victorian smart meter data is used to model residential customers. In the case of the New South Wales feeders, Victorian smart meter profiles were considered as adequate. A pool of 30-min resolution, year-long (i.e., 17,520 points), anonymized smart meter demand data (i.e., P and Q), collected from 342 individual residential customers in the year of 2014 is used. This data was facilitated to the University of Melbourne for the purposes of a previous project “AusNet Mini Grid Clusters” [7] and “Solar PV Penetration and HV-LV Network Impacts” [26-28]. Using this pool, the yearly demand profiles were broken down in daily profiles, resulting in a pool of ~30,000 profiles. For illustration purposes, sample residential demand profiles are presented in Figure 4-1.

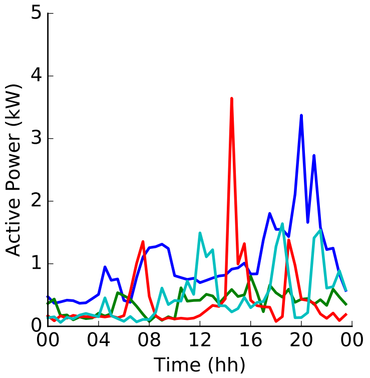


Figure 4-1. Sample Smart Meter Data

Since the worst-case scenario in the context of EVs is high loading conditions, the day with the highest average demand (14th of January) is selected for residential demand. Individual load profiles from this day within the pool of load profiles are randomly assigned to residential customers. The average demand from the pool of smart meter data on that day is shown in Figure 4-2.

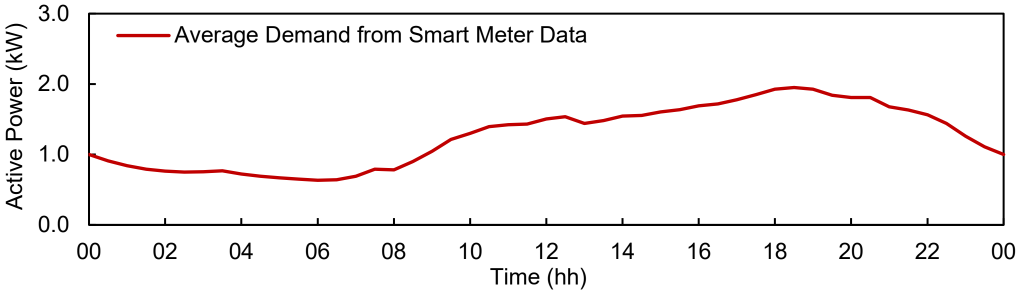


Figure 4-2. Average Residential Demand on Highest Demand Day

4.1.2 Residential Average Profile for TAS

For the feeders located in Tasmania, after discussion with TasNetworks, it was decided that due to the characteristics of their residential demand which includes the widespread use of electric heating, Victorian smart meter data (with a diversified peak of 2kW per customer) would not be suitable. An aggregated residential profile based on measurements in inner Hobart in 2020 was provided by TasNetworks for use in both the Rural and Urban TAS feeders.

This aggregated residential profile from inner Hobart was normalized for application to an appropriately sized average residential peak load value. This profile can be seen in Figure 4-3 and is used for the Urban TAS feeder (West Hobart). However, whilst this average residential profile was found to match up closely to the Urban TAS feeder's SCADA measurement data on the peak demand day, it did not fit as closely for the Rural TAS feeder (Norwood). This was due to a larger morning peak and a smaller evening peak seen for the rural area versus the urban area. To address this, the residential profile's morning and evening peaks are scaled to better fit what is seen in the Rural TAS feeder, as seen in Figure 4-3 where after scaling the peak residential demand is moved from the evening to the morning.

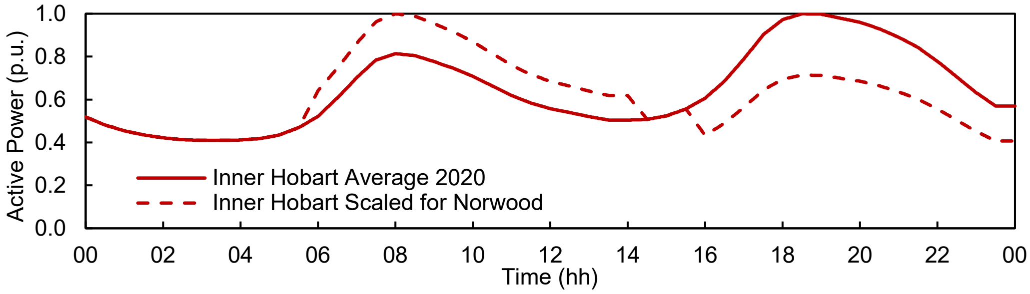


Figure 4-3. Normalised Average Residential Demand from Inner Hobart and Scaled for Norwood

Following the DNSP's local know-how, a value of 3.5kW was decided to be an appropriate value as a diversified peak demand for residential customers in the Urban TAS feeder, whereas a value of 3.0kW for the Rural TAS feeder was decided upon. The normalized profiles from Figure 4-3 are then applied to the corresponding load value; thereby forming the residential profiles for each feeder. The residential profiles for both feeders can be seen in Figure 4-4.

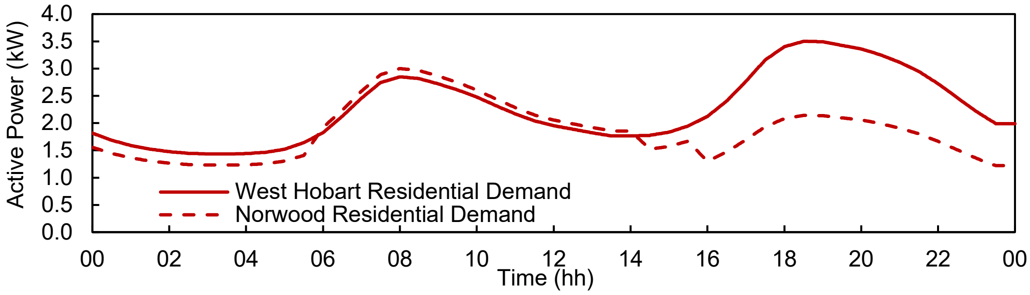


Figure 4-4. Average Residential Demand for West Hobart and Norwood per Customer

4.1.3 Non-Residential Demand

Non-residential demand (corresponding to commercial and industrial loads) is modelled at the secondary busbar of the LV transformers within the HV-LV feeder. After residential demand is modelled in time-series (either with smart meter data or an average residential profile), the profile for non-residential demand is tuned following the steps in section 2.5 per HV feeder.

Non-residential demand is distributed across the many different sized LV transformers, for each HV-LV feeder, as a percentage of the spare capacity of the LV transformer after the peak residential demand is considered (e.g., 3.5kW per residential customer). This is done to assign the majority of non-residential demand to larger transformers with a few residential customers, which are likely to contain larger non-residential customers (thereby also helping to prevent LV transformer overloads compared with if it were uniformly distributed).

The result is a unique non-residential behaviour for each HV feeder, unevenly distributed, which can account for the inflexible nature of the data available for residential load modelling within the LV feeders for each HV feeder and still enable a validated HV-LV feeder (as explained in section 2.5).

4.2 PV Modelling

This section details the modelling aspects of the solar PV such as irradiance profiles, penetrations levels and definitions and panel sizes. This is required because some HV feeders already have data on customers with a PV system and as such are considered as part of the validation process which forms the base case (before EVs are added in the impact analysis).

4.2.1 PV Profiles using Clear-Sky Irradiance

Datasets of PV irradiance are used in this task to model the solar PV generation for the day of interest (e.g., peak demand day). The clear-sky irradiance is used for simplicity but also to capture the highest PV generation. The resulting voltage rise issues can trigger the need for changes in voltage regulation devices (such as the tap position of off-load tap changers [3]) which in turn can exacerbate voltage drop issues due to EVs.

The dataset consists of a pool of 1-min resolution, year-long normalised PV generation profiles based on clear-sky irradiance profiles presented in Figure 4-5 for Melbourne [3, 4]. These profiles are modelled using an available tool developed by the University of Loughborough, Centre for Renewable Energy Systems Technology (CREST) [29, 30]. In this tool, once the day and the configuration information of the installed PV panel (e.g., location, efficiency, area, etc.) are determined, 1-min resolution PV generation profiles can be produced which can then be normalised and applied to different PV sizes.

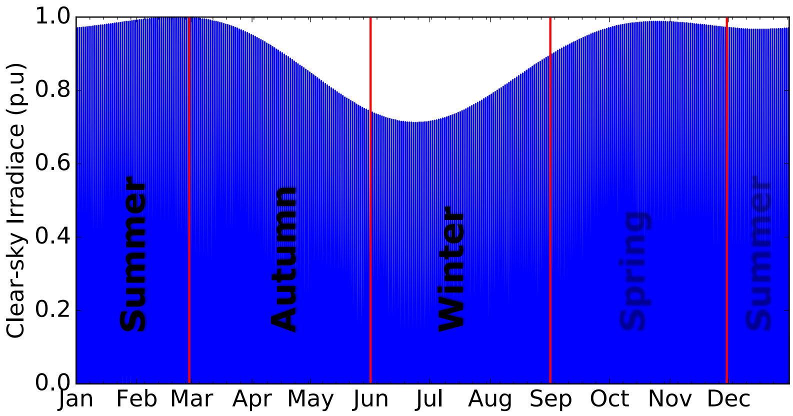


Figure 4-5. Normalised Daily Clear-sky Irradiance

4.2.2 PV Penetration and PV System Sizes

This section presents the average PV penetration and the size of the residential rooftop PV installation for each HV feeder as reported by the DNSPs and, therefore, representing the base case for each of the HV feeders. A summary of this information can be found in Table 4-1. PV penetration is defined as the percentage of residential customers with a solar PV system.

For simplicity, for the NSW HV feeders, the PV systems are randomly assigned to residential customers across the corresponding HV feeders. For the TAS feeders, no PV information was available, thus, no PV installations are considered in the base case for these two feeders. For the VIC feeders, since they were produced by ("Advanced Planning of PV-Rich Distribution Networks" [1-6]), the original models without PV were also considered.

Table 4-1. Case Study Residential PV Information

Feeder Name	Residential PV Penetration for the Base Case (%)	Average Residential PV Size (kW)
Rural NSW (Hazelbrook)	24	3.8
Urban NSW (Preston)	30	5.9
Rural TAS (Norwood)	0	-
Urban TAS (West Hobart)	0	-
Rural VIC (SMR8)	0	-
Urban VIC (CRE21)	0	-

It should be noted that at this stage of the project the PV installations are not considering an export limit or inverter size limit. Furthermore, no implementation of AS/NZS 4777.2 (e.g., Volt-Watt or Volt-var responses) were considered.

4.3 Case Studies

This section presents some of the key considerations in the processes involving the validation, the corresponding base case (i.e., no EVs), and the EV impact assessment to be carried out using the integrated HV-LV feeders. The results for each of the six feeders will are presented in Chapters 5 to 10, accordingly.

4.3.1 HV-LV Feeder Validation

As mentioned in Chapter 2, only four integrated HV-LV feeders will be validated in this project using the corresponding SCADA data and the steps described in section 2.5. The peak demand days (extracted from the SCADA data) for each of the feeders is presented in Table 4-2.

Table 4-2. SCADA Peak Demand Day for each HV feeder

Feeder Name	Peak Demand Day
Rural NSW	22/06/2019 (Winter)
Urban NSW	18/08/2019 (Winter)
Rural TAS	08/11/2019 (Spring)
Urban TAS	22/05/2018 (Autumn)

4.3.2 Base Case

To understand the relative impact of EVs, the base case behaviour (i.e., without EVs) of the six integrated HV-LV feeders is illustrated first. This is done using daily simulations and considering the identified peak demand days for each of them (presented in a more generic way in Table 4-3) and the demand (and PV generation where applicable) profiles described in sections 4.1 and 4.2. For the NSW and TAS feeders, the days are based on SCADA data. For the VIC feeders, the days are based on anonymised smart meter data.

The voltage considered for all simulations (base case and with EVs) at the head of the HV feeder is fixed and corresponds to the value used for validation. In practice, this voltage will change throughout the day depending on the upstream network, the net demand of other HV feeders connected to the same zone substation, and the characteristics of the on-load tap changer. However, given that information was limited to only the investigated HV feeder, the fixed value was deemed to be adequate.

Finally, the nominal position of the off-load tap changers used by LV distribution transformers is considered in all the six integrated HV-LV feeders. This is due to a lack of information but is also aligned with DNSP practice. Consequently, those distribution transformers will be effectively providing the original natural boost (approximately 8%) due to the transformation ratio used in Australia (e.g., 22kV to 433V or 11kV to 433V).

Table 4-3. Base Case Peak Demand Day of for each HV feeder

Feeder Name	Peak Demand Day
Rural NSW	June (Winter)
Urban NSW	August (Winter)
Rural TAS	November (Spring)
Urban TAS	May (Autumn)
Rural VIC	January (Summer)
Urban VIC	January (Summer)

4.3.3 EV Impact Assessment

In this project, EV penetration is defined as the percentage of residential customers with a single EV. Thus, to assess the impacts for different EV penetrations, each of the six integrated HV-LV feeders will consider nine EV penetrations: from the base case (0%) up to a maximum of 160% in 20% steps. Houses with a second EV are only considered after all houses have one EV (i.e., 100% of EV penetration) The maximum EV penetration of 160% assumes that 60% of houses have a second EV.

EV location is randomly assigned across and within the LV feeders up to the EV penetration being investigated.

The time-series 1-min resolution EV demand profiles (active and reactive power) follow the considerations presented in section 3.4. Some of them are summarised below:

- The EV demand of interest corresponds to weekdays.
- The daily charging coincidence factor is 70% (no more than 70% of the EVs have a charging event on the same day).
- Both Level 1 (3.68kW) and Level 2 (7.36kW) EV chargers are considered, with a 20/80 split respectively.
- Houses with two EVs which are both Level 2 use profiles that consider dual-headed chargers.
- Power factor is 0.99 (lagging).

To capture and illustrate the impacts of residential EV charging on the integrated HV-LV feeders, a 24-hour analysis is performed for each of the EV penetrations. The performance metrics adopted are described in the following section.

Finally, EV Hosting capacity is defined as the maximum amount of EVs that a given distribution network (or part of it) can host without negatively affecting its normal operation at any point in time.

It is important to note that no EV management techniques or time-of-use tariffs that alter EV charging behaviour are considered in this report. This report focuses on the impacts of unmanaged EVs, e.g., following a standard tariff. These aspects will be investigated in the next stage of the project.

4.3.4 Performance Metrics

To quantify the technical impacts caused by different penetrations of EVs, the performance metrics presented in this section are adopted.

4.3.4.1 Voltage Compliance

To understand the impacts of residential EV charging in terms of the voltage performance, the number of customers with voltage issues will be calculated for each of the days analysed.

- **Number of non-compliant customers:** This metric takes the voltage profile calculated for each customer connection point from the power flow simulation to then check if the Australian standard AS 61000.3.100 is satisfied. If the customer's voltage does not comply with the standard, then this costumer is considered to have a voltage issue. Thus, the total number of AS 61000.3.100 non-compliant customers in the HV-LV feeder is calculated.

  The AS 61000.3.100 indicates that the nominal voltage of customers in LV networks is 230V (phase to neutral) and under normal operating conditions customer voltages should be ranging between +10% and -6% of the nominal value.

It is important to clarify that the compliance of customer connection points with the AS 61000.3.100 standard is used here for quantification purposes. Consequently, the quantification of non-compliant customers as adopted in this work is a good metric but does not necessarily mean that the corresponding customers will actually experience issues associated with high or low voltages.

***Note*:** While the AS 61000.3.100 is considered throughout this project, it should be noted that a revised Electricity Distribution Code [31] was issued in April 2020 in Victoria, stating that customer voltages should be ranging between +13% and -10% of the nominal value.

4.3.4.2 Asset Congestion

To understand the impacts of residential EV charging in the adequacy (capacity to supply demand) of distribution networks, the utilisation level of all HV conductors, LV conductors and LV transformers is calculated for each of the days analysed.

- **Maximum utilisation level of conductors:** This metric assesses the utilisation level of all conductors. This metric is calculated as the maximum daily current divided by the ampacity (conductor rating) of the corresponding segment of the HV or LV feeder.

- **Maximum utilisation level of transformers:** This metric assesses the utilisation level of the distribution transformers. This metric is calculated as the maximum daily power divided by the transformer capacity.

The idea behind these metrics is to show how the utilisation of the most important and expensive assets (i.e., conductors, transformers) of the network behaves with different EV penetration levels.

These metrics allow visualising the assets' maximum utilisation levels and therefore identifying if they increase above their maximum specified limits (i.e., thermal limits). It is important to highlight that increasing the utilisation level of the assets above their limits might lead to the increment of their insulation temperature above their operational limit which may result in damaging or accelerating the ageing of the corresponding assets. Crucially, these metrics help understanding how the increasing penetrations of EVs impact the utilisation level of the assets.

5 Case Study: Rural NSW (Hazelbrook)

This chapter presents the validation results for Rural NSW (Hazelbrook), the base case analysis and the results from the EV impact analysis across different increasing EV penetrations (described in section 4.3.3 and Chapter 3). A summary of the technical information is shown in Table 5-1.

Table 5-1. HV-LV Feeder Technical Information Summary

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)	HV Feeder Peak (MW)
Rural NSW *Hazelbrook*	11kV	1401	39	20	6.5	2.0	24%	3.8	3.14

5.1 HV-LV Feeder Validation

Table 5-2 shows key considerations in validating the Rural NSW feeder.

Table 5-2. Key Considerations for Validating the Rural NSW Feeder

Avg Res Peak Size	Res Data Used	ADMD for LV Networks	PV Penetration	Avg PV Size	Head of Feeder Voltage
2.0kW	VIC Smart Meter	6.5kW	24%	3.8kW	10.95kV (0.99pu)

Figure 5-1 to Figure 5-4 presents the comparison of head of HV feeder SCADA measurements from the peak demand day with that of equivalent values obtained in the (validated) OpenDSS integrated HV-LV feeder model. The objective was to ensure that the net demand of residential and non-residential customers connected to the pseudo LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements (following section 2.5.).

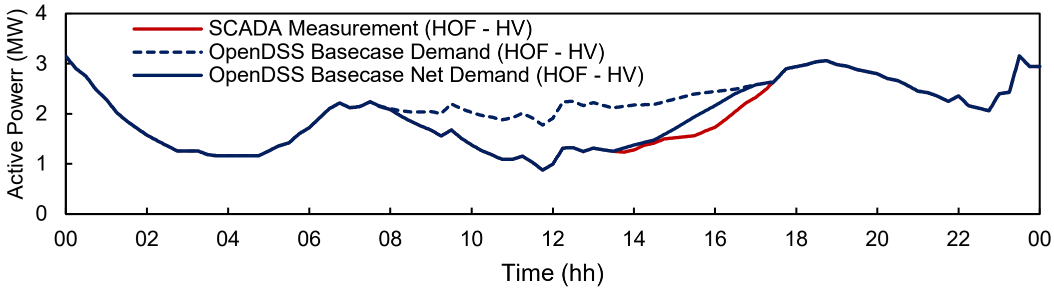


Figure 5-1. Rural NSW Active Power at Head of the HV Feeder

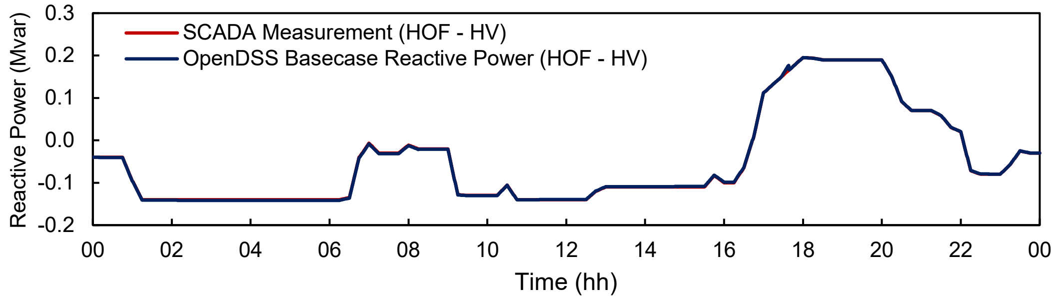


Figure 5-2. Rural NSW Reactive Power at Head of the HV Feeder

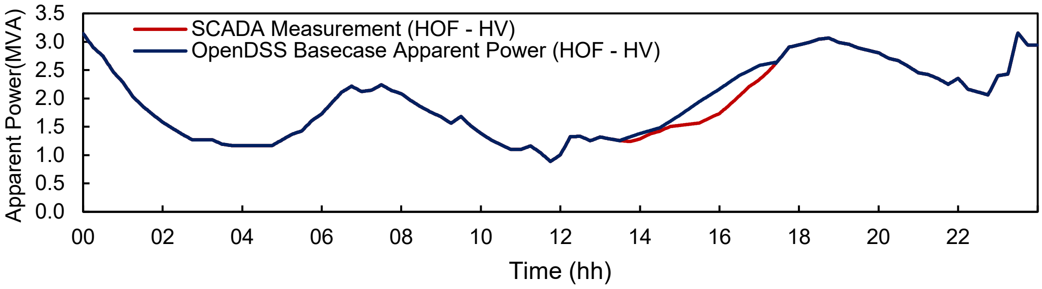


Figure 5-3. Rural NSW Apparent Power at Head of the HV Feeder

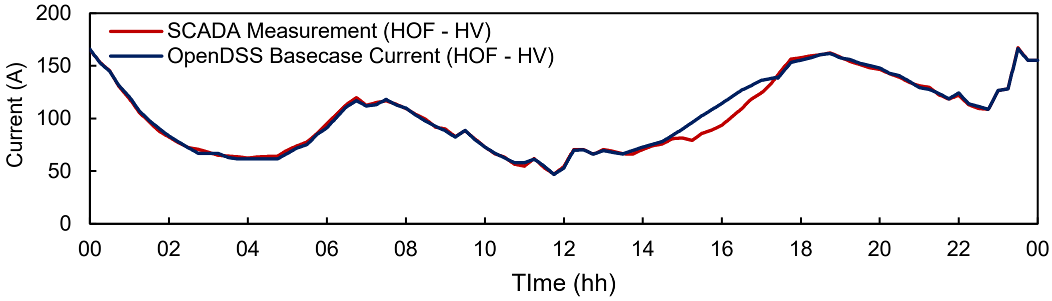


Figure 5-4. Rural NSW Current at Head of the HV Feeder

Overall, it can be seen in Figure 5-1 to Figure 5-4 that the OpenDSS model is following the SCADA measurements well. There is some deviation between the net demand from the OpenDSS simulation and the SCADA during the early afternoon. This is because there is a large load component during these hours within the residential VIC smart meter data (from the peak demand day) used for residential demand which is not seen in the SCADA. Consequently, there is only so much adjustment (reduction), following the validation steps in section 2.5, that can be made with the non-residential demand to compensate.

Table 5-3 summarises the percentage errors for the active power, reactive power, apparent power and current for the values obtained at the head of the HV feeder in OpenDSS when compared with the corresponding SCADA measurements from the head of the HV feeder. Overall, it can be concluded that the model of the HV-LV feeder is performing acceptably close to SCADA measurements.

Table 5-3. Summary of Percentage Errors Between Head of Feeder SCADA Measurements and OpenDSS Simulation Values

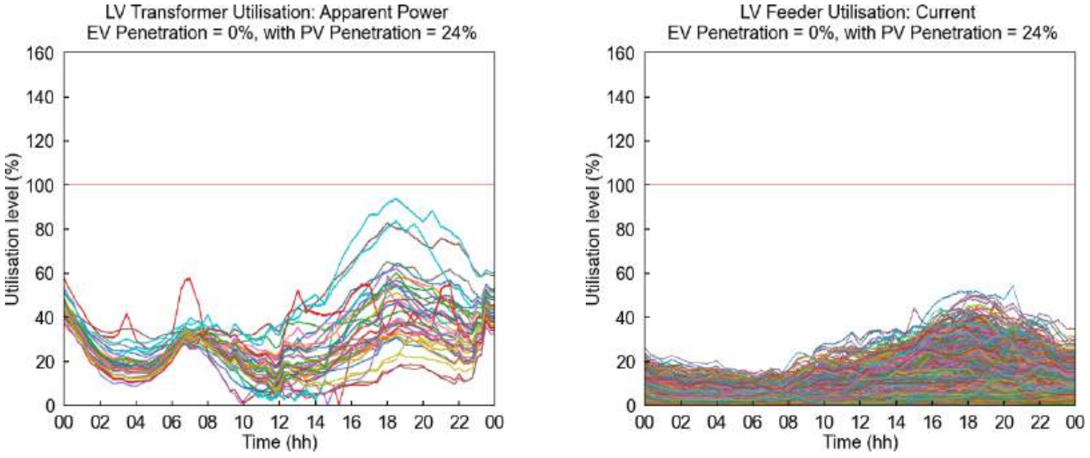
Error Metric	Active Power Error (%)	Reactive Power Error (%)	Apparent Power Error (%)	Current Error (%)
Minimum	0.00	0.00	0.00	0.00
Median	0.04	0.87	0.01	1.29
Mean	0.04	1.46	2.07	2.86
Maximum	0.09	51.55	24.89	22.27

5.2 Base Case

This section presents the performance metrics for Rural NSW when considering the base case, i.e., no EVs. These performance metrics are assessed to provide a reference point for the EV impact analysis.

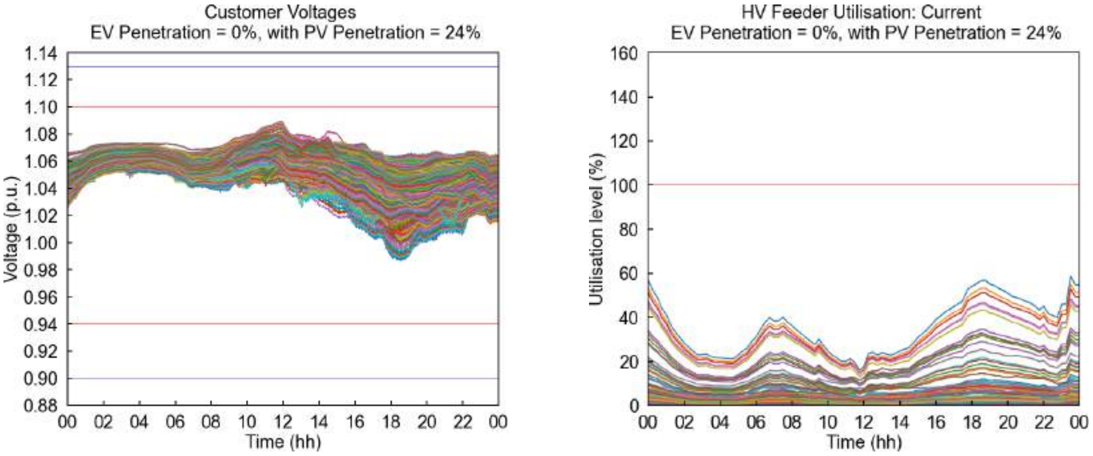
LV distribution transformer and LV feeder utilisation are shown in Figure 5-5 whilst customer voltages and HV feeder utilisation are shown in Figure 5-6.

It can be seen in Figure 5-5 that the LV transformer utilisation and the LV feeder utilisation are, as expected, within limits. Figure 5-6 (a) shows that the LV customer voltages are also within limits. The red line reflects the Australian standard AS 61000.3.100, whilst the blue line reflects the updated (as of April 2020) Victorian LV voltage limits [31]. A voltage rise can be observed during peak daylight hours (11:00-14-00) which is caused by reverse power flows from residential PV systems (there is a 24% PV penetration). On the other hand, a drop in voltages can be seen once the sun has started to set and demand increases during the mid-evening hours. Finally, Figure 5-6 (b) shows that HV transformer utilisation for the base case is within their respective ratings.



(a) (b)

Figure 5-5. Rural NSW Base Case (a) LV Transformer Utilisation and (b) LV Feeder Utilisation



(a) (b)

Figure 5-6. Rural NSW Base Case (a) Customer Voltages and (b) HV Feeder Utilisation

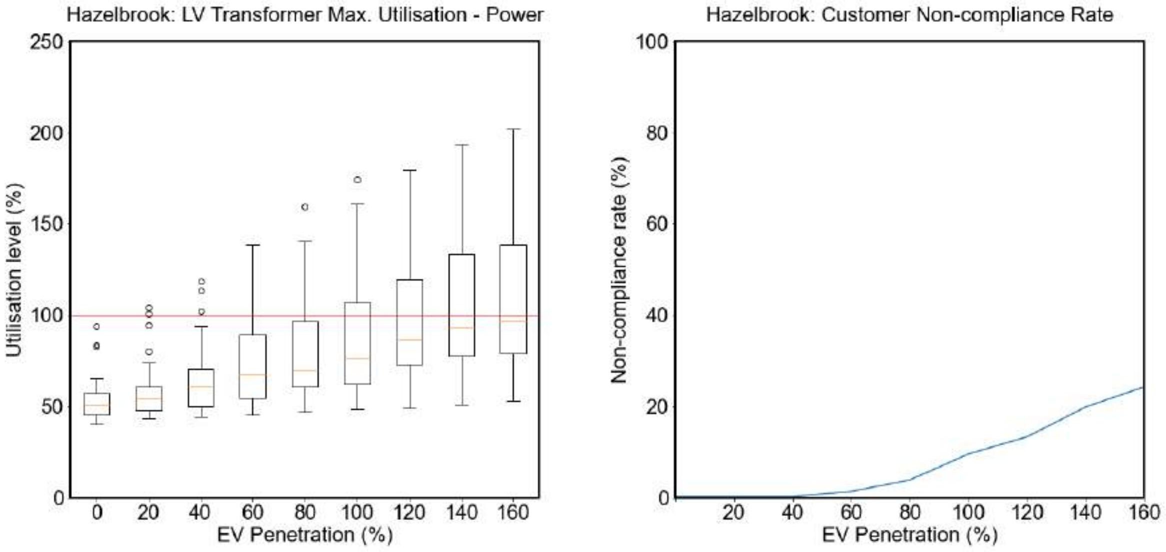
5.3 EV Impact Assessment

This section presents the different impacts that residential EV charging can have on the Rural NSW feeder considering a 24-hour time-series analysis of the HV-LV feeder for each of the penetration levels, considering the worst-case scenario of a peak demand day.

An overview of the results is presented first. Further details corresponding to LV distribution transformer utilisation, customer voltages, LV feeder utilisation, and HV feeder utilisation are presented in the subsequent sections.

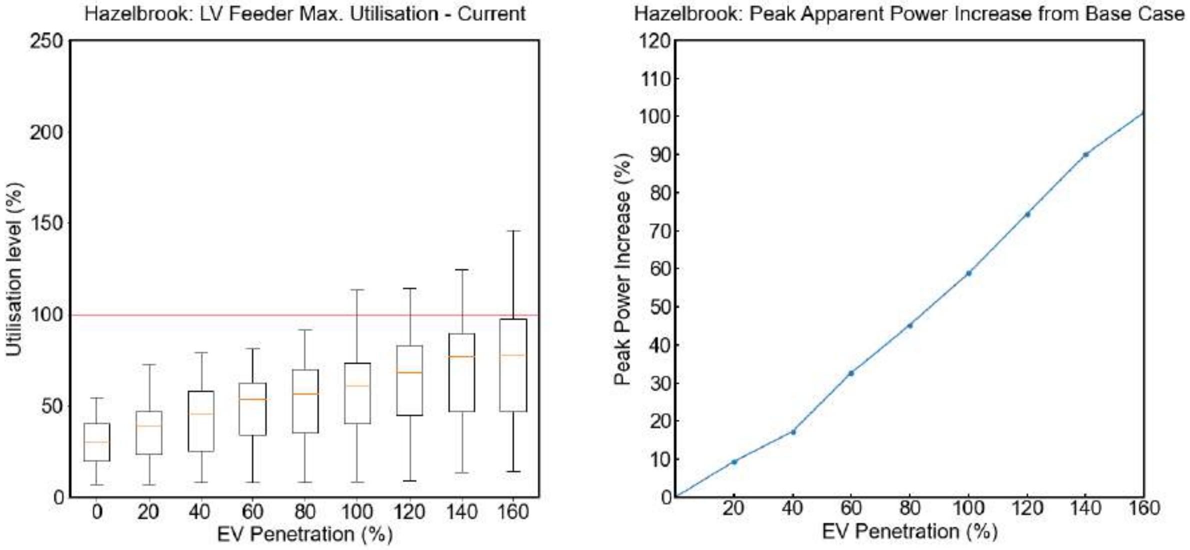
5.3.1 Overview of Results

Figure 5-7 (a) presents the LV distribution transformer maximum utilisation for a 24-hour period considering the assessed EV penetrations, whilst Figure 5-7 (b) presents the percentage of customers that violated the Australian standard AS 61000.3.100 voltage limits. Figure 5-8 (a) presents the maximum LV feeder maximum utilisation per LV feeder, for a 24-hour period considering the assessed EV penetrations, whilst Figure 5-8 (b) presents the increase of peak apparent power relative from the base case.



(a) **(b)**

Figure 5-7. Rural NSW Base Case (a) LV Transformer Maximum Utilisation and (b) Percentage of Customers with Non-Compliant Voltages



(a) **(b)**

Figure 5-8. Rural NSW Base Case (a) LV Feeder Maximum Utilisation and (b) Relative Increase in Peak Apparent Power

Two of the LV distribution transformers, shown in Figure 5-7 (a), can be overloaded at just 20% of EV penetration. By 80% close to a quarter of LV distribution transformers are overloaded and by the maximum penetration, approximately half of the LV distribution transformers are overloaded.

Problems at 60% EV penetration and beyond is also reflected in the percentage of customers with non-compliant voltages shown in Figure 5-7 (b). By 80% of customers with an EV, voltage problems start to accelerate, reaching over 1 in 5 residential customers with non-compliant voltages at the maximum penetration of 160% (every house with an EV plus 60% with a second EV).

It can be seen in Figure 5-8 (a) that the LV feeders start to have overloads of their conductors from 100% EV penetration, which steadily grows in severity up to the maximum penetration, where nearly a quarter of LV feeders have an overloaded segment within them.

Figure 5-8 (b) shows there is up to just over a 100% increase in peak apparent power demand when considering the maximum EV penetration. This may become significant for the zone substation and upstream, when aggregated with other HV feeders.

Figure 5-9 presents the EV impact on the top five utilised HV line segments within the HV feeder. Overloads of an HV conductor segment starts to occur at 120% EV penetration. This increases to all fives segments by 140% EV penetration and beyond. Figure 5-10 (a) presents the location of these top five utilised segments in relation to the network topology. As expected, due to the aggregation of demand, all these overloads occur either direct at or somewhat close to the head of the HV feeder. Finally, Figure 5-10 (b) presents the total length in kilometres of overloaded HV conductors, reaching 1km of overloaded conductors at 160% EV penetration.

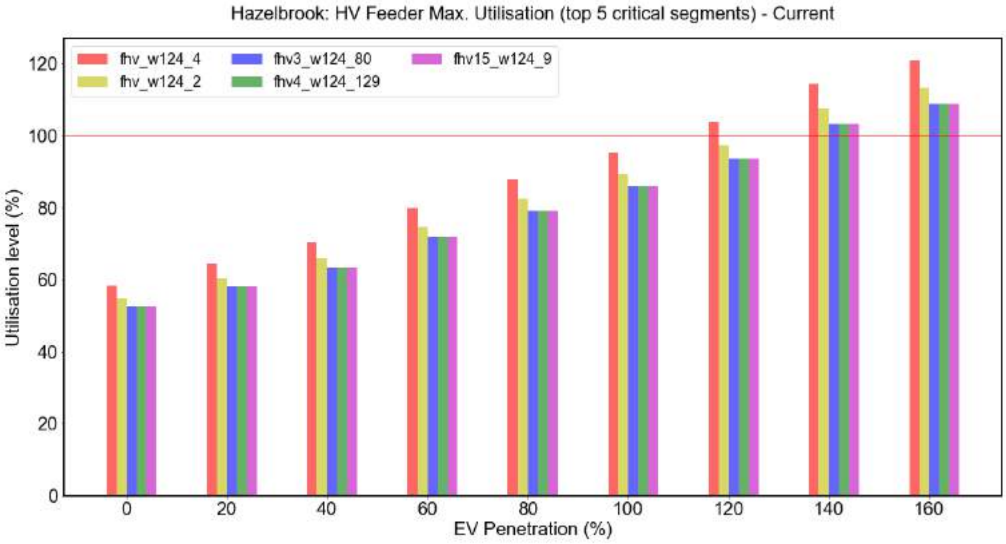
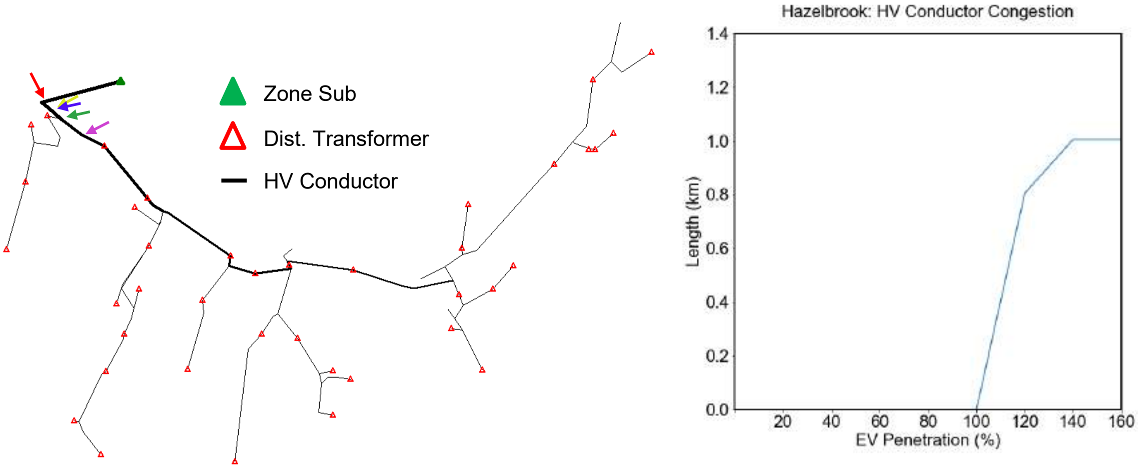


Figure 5-9. Rural NSW Base Case. EV Impact on the Top Five Utilised HV Line Segments

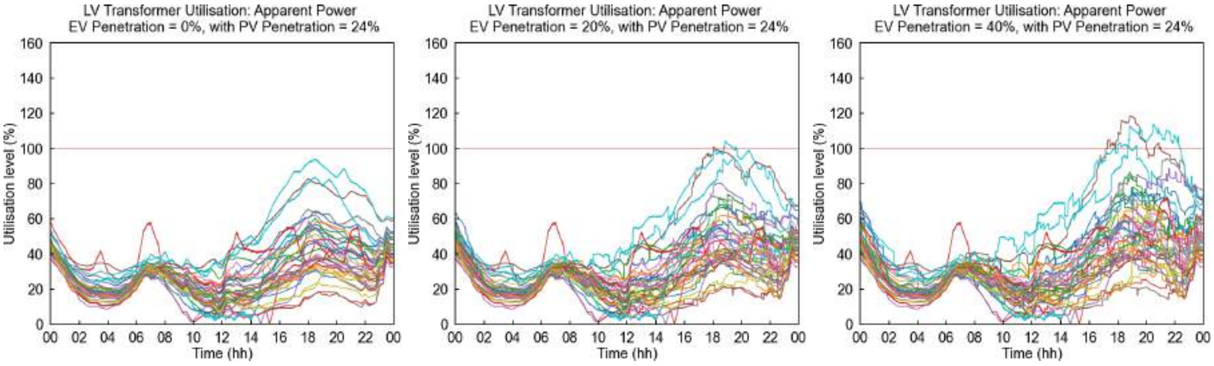


(a) (b)

Figure 5-10. Rural NSW Base Case (a) Position of the Top Five Utilised HV Line Segments and (b) Total length of HV Conductor Congestion

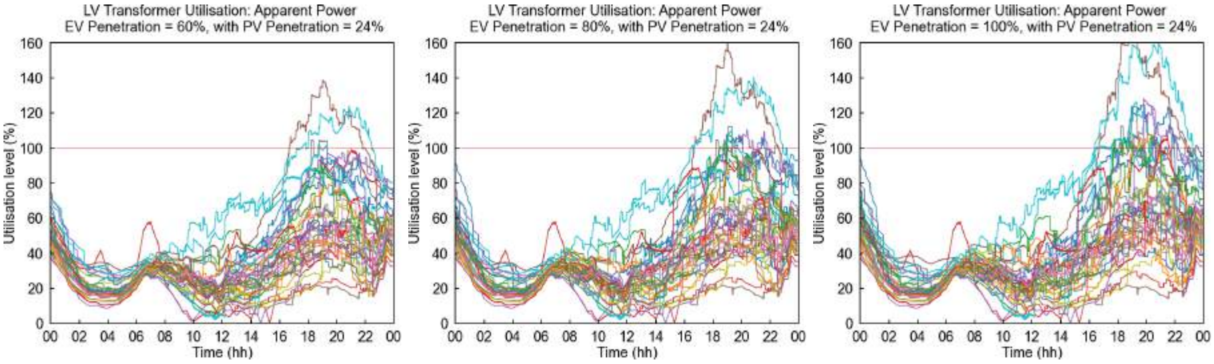
5.3.2 LV Distribution Transformer Utilisation

Figure 5-11 to Figure 5-13 presents the impacts of EVs on the utilisation of LV Distribution Transformers (Tx) for Rural NSW, considering the increase of EV penetrations up to 160%.



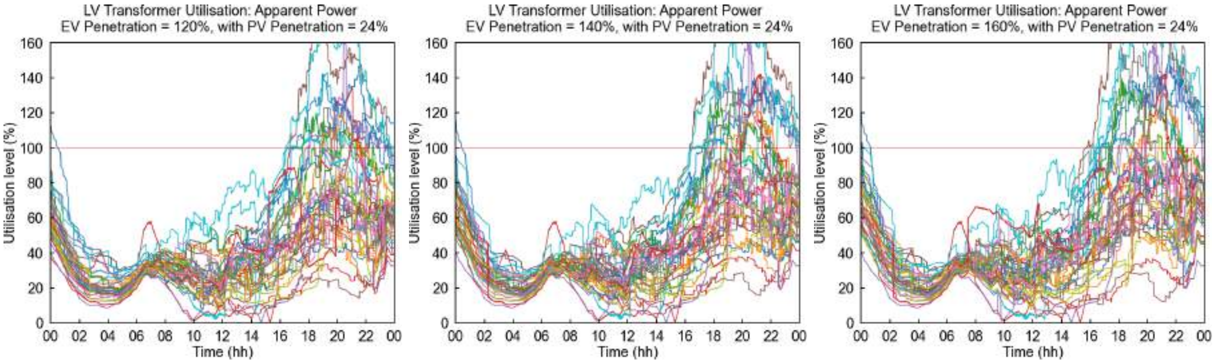
(a) **(b)** **(c)**

Figure 5-11. Rural NSW Base Case LV Tx Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) **(b)** **(c)**

Figure 5-12. Rural NSW Base Case LV Tx Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



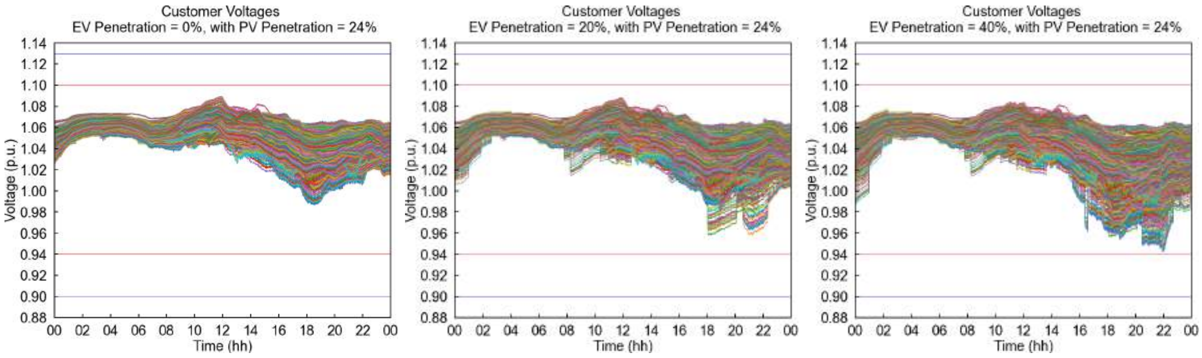
(a) **(b)** **(c)**

Figure 5-13. Rural NSW Base Case LV Tx Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

LV transformer overloads for the Rural NSW feeder begin at 20% EV with two transformers overloading slightly during the peak loading hours for residential customers (which occurs between 6pm-8pm). This impact quickly increases with EV penetration both in terms of severity of the overload and number of transformers that overload. Whilst the overloads start off small (around 20% above the rated capacity for 40% EVs), these quickly grow to more than 60% at 100% EV penetration (when every residential customer has 1 EV).

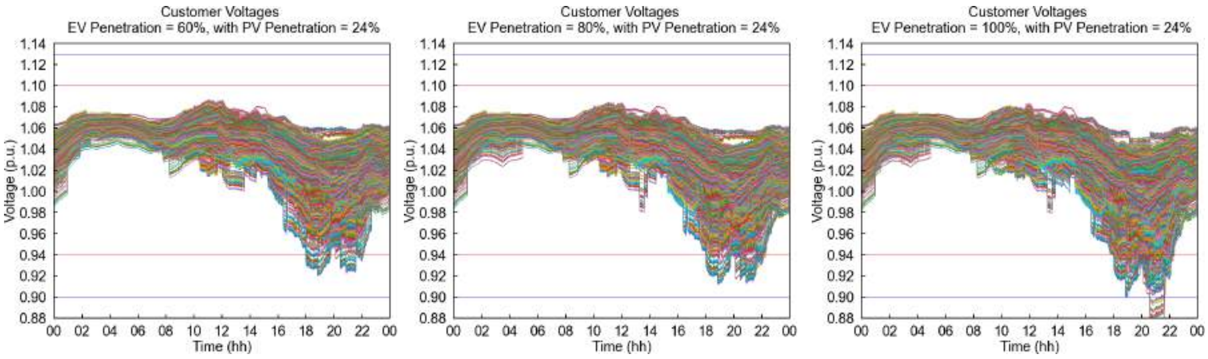
5.3.3 Residential Customer Voltages

Figure 5-14 to Figure 5-16 presents the impacts of EVs on the residential customer voltages for Rural NSW, considering the increase of EV penetrations up to 160%.



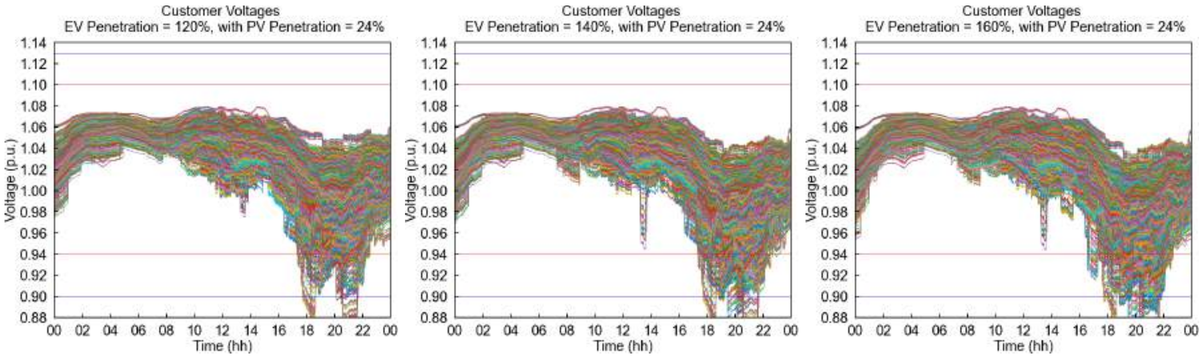
(a) **(b)** **(c)**

Figure 5-14. Rural NSW Base Case Customer Voltages with EVs: (a) 0%, (b) 20% and (c) 40%



(a) **(b)** **(c)**

Figure 5-15. Rural NSW Base Case Customer Voltages with EVs: (a) 60%, (b) 80% and (c) 100%



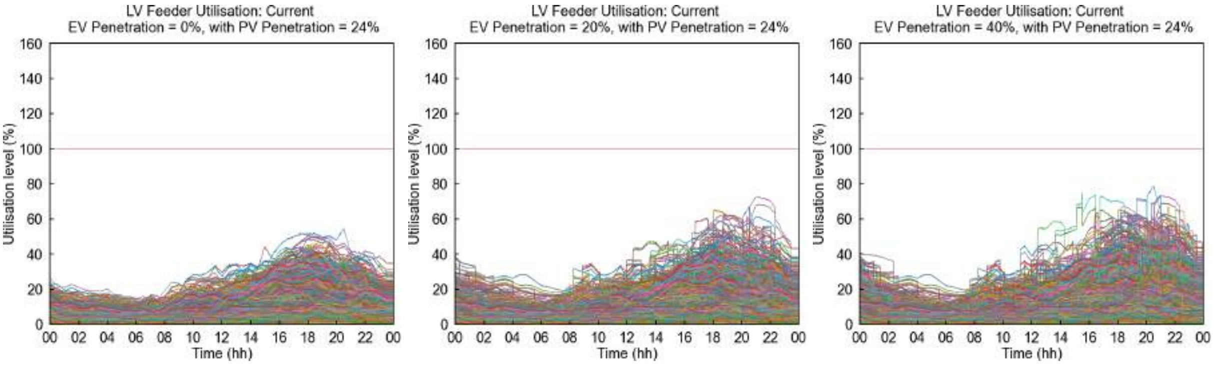
(a) **(b)** **(c)**

Figure 5-16. Rural NSW Base Case Customer Voltages with EVs: (a) 120%, (b) 140% and (c) 160%

It can be observed that issues of customer voltages start occurring from 60% of residential customers with an EV, exceeding the Australian standard AS 61000.3.100 shown by the red line. As the penetration increases, so does the severity of voltage problems. As the penetrations increases beyond 100% EV penetration (and second EVs are considered), the voltage problems get significantly worse with many customers now below the lower voltage limit of 0.90p.u. The voltage rise from the PV considered as part of the base case scenario can be seen during the peak daylight hours of 11am-2pm.

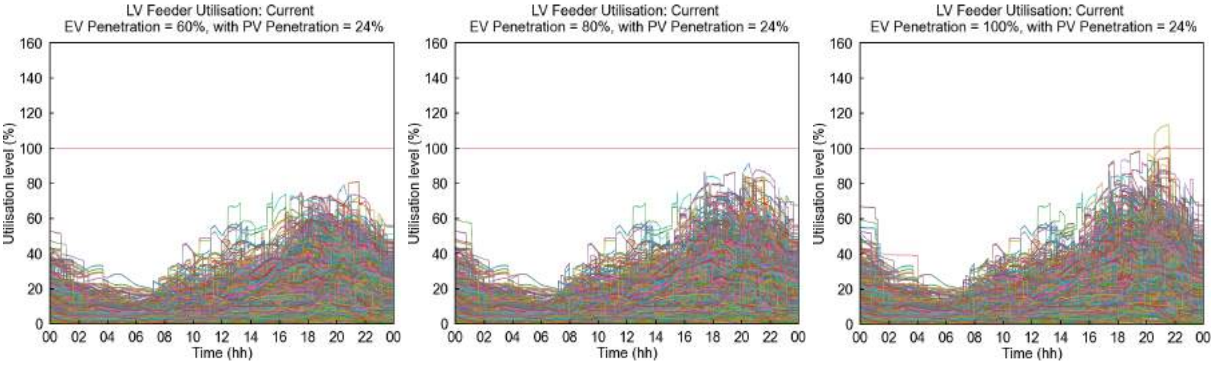
5.3.4 LV Feeder Utilisation

Figure 5-17 to Figure 5-19 presents the impacts of EVs on the utilisation of LV conductors for Rural NSW, considering the increase of EV penetrations up to 160%.



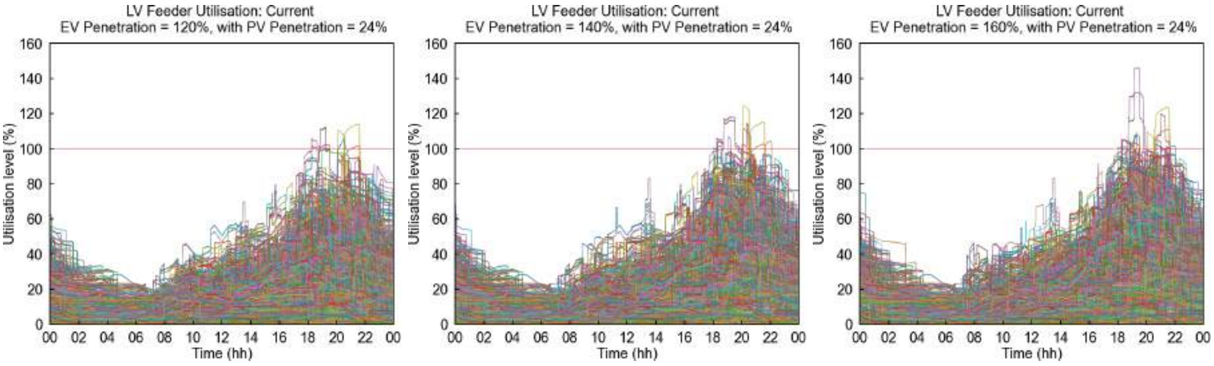
(a) (b) (c)

Figure 5-17. Rural NSW Base Case LV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 5-18. Rural NSW Base Case LV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



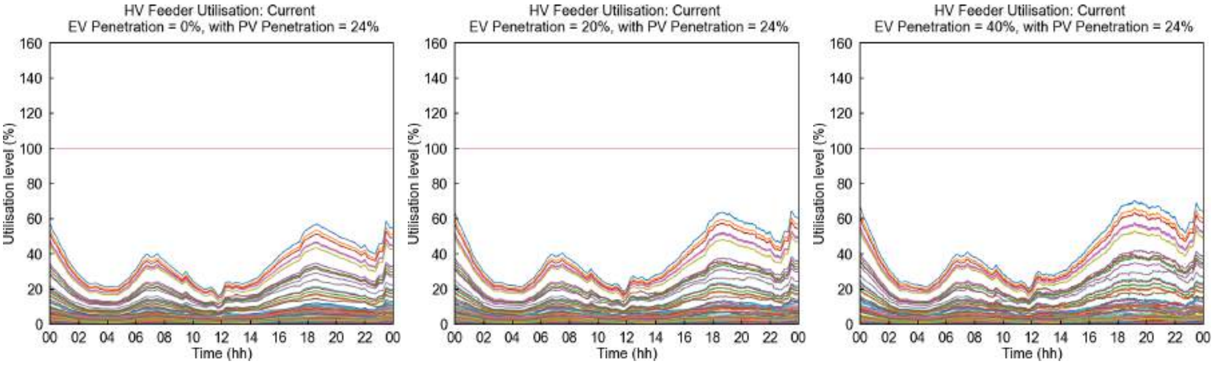
(a) (b) (c)

Figure 5-19. Rural NSW Base Case LV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

From the results it can be seen that LV feeder utilisation issues occur from 60% of homes with an EV, with a slight overload in a couple of segments within the LV feeders. From 120% EV penetration and beyond, these impacts start to become more frequency with many more conductors overloading, but rarely reaching an overload of greater than 120% of the rated ampacity and a peak of 140% at maximum EV penetration.

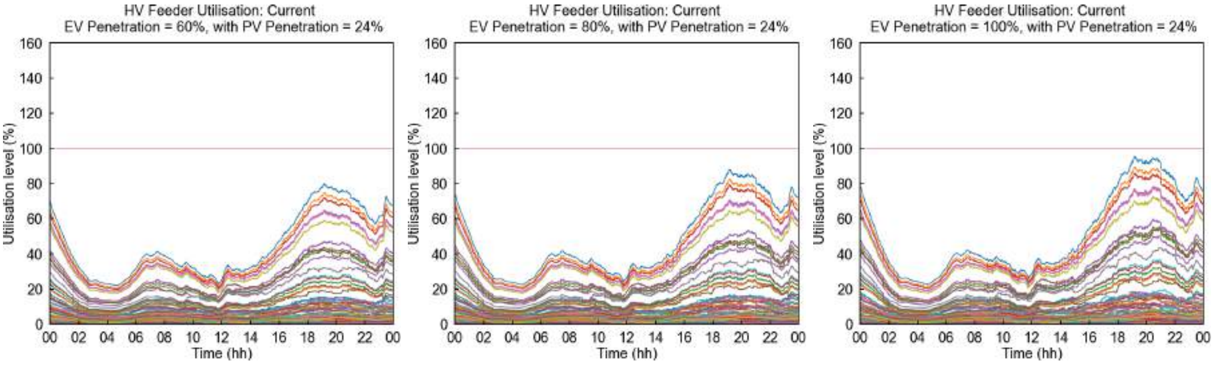
5.3.5 HV Feeder Utilisation

Figure 5-20 to Figure 5-22 presents the impacts of EVs on the utilisation of HV conductors for Rural NSW, considering the increase of EV penetrations up to 160%.



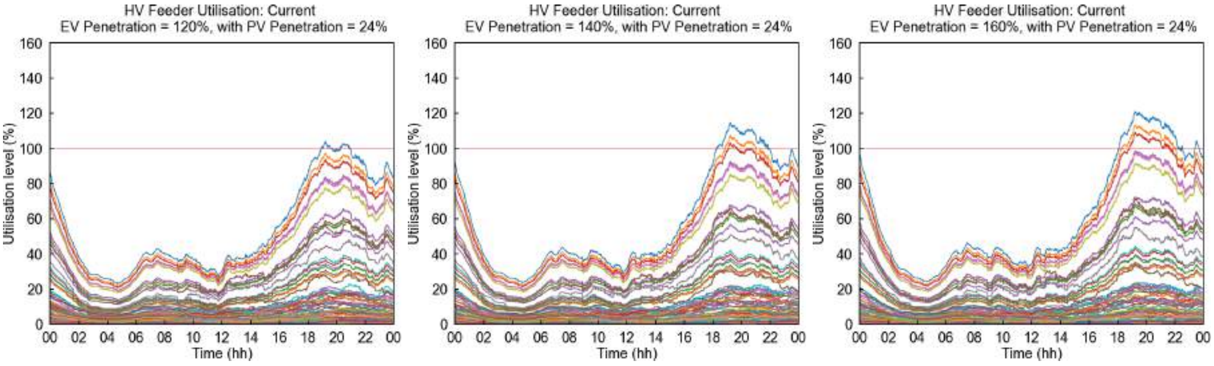
(a) (b) (c)

Figure 5-20. Rural NSW Base Case HV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 5-21. Rural NSW Base Case HV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



(a) (b) (c)

Figure 5-22. Rural NSW Base Case HV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

From the results it is observed that HV conductor overload issues begin from 120% of residential customers with an EV (20% with 2 EVs). However, this only occurs with one segment of the HV feeder at 120%, increasing to a handful of segments at 160% At maximum EV penetration, the largest utilisation for any segment of the HV feeder is 120% utilisation (or overload of 20%).

5.4 Key Remarks

- Two LV distribution transformer have asset utilisation problems at just 20% EV penetration. This impact increases in severity continuously as EV penetration increases, reaching nearly a quarter of LV distribution transformers by 80% EV penetration and nearly half of all LV transformers close to overloading at maximum EV penetration (160%).
- Customers exceeding the lower voltage standard become a problem at 60% EV penetration and beyond, becoming increasingly severe after 100% EV penetration. At maximum EV penetration (160%) just over 1 in 5 residential customers will have a lower voltage standard violation.
- During peak daylight hours there is some voltage rise from PV towards the ends of the LV feeders. The network could be constrained by both voltage rise and voltage drop issues at different times of the same day if PV and EV penetrations increase together.
- A small number of LV feeders begin to have some conductors with utilisation problems at 100% EV penetration and beyond. Close to 25% of all LV feeders have conductors that are close to or are exceeding their ratings by the maximum EV penetration of 160%.
- HV conductor utilisation issues occur at 120% EV penetration and beyond. In total 1km of HV conductors is congested by the max EV penetration of 160% (5% of total HV feeder length).
- The increase in peak apparent power for Rural NSW, when considering the maximum EV penetration, is just over 100%. When considering other HV-LV feeders also connected to the same network assets upstream, this could have serious implications for the zone substation and beyond.
- Considering the above, the **EV hosting capacity of the Rural NSW feeder was found to be less than 20% of residential customers with an EV**, with the LV distribution transformers being the first limiting factor at 20%. However, considering this is just one transformer and the potential of uneven EV distribution, the hosting capacity could potentially increase to approximately 20-40%.

6 Case Study: Urban NSW (Preston)

This chapter presents the validation results for Urban NSW (Preston), the base case analysis and the results from the EV impact analysis across different increasing EV penetrations (described in section 4.3.3 and Chapter 3). A summary of the technical information is shown in Table 6-1.

Table 6-1. HV-LV Feeder Technical Information Summary

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)	HV Feeder Peak (MW)
Urban NSW *Preston*	11kV	616	17	6	6.5	2.0	30%	5.8	1.62

6.1 HV-LV Feeder Validation

Table 6-2 shows key considerations in validating Urban NSW (Preston).

Table 6-2. Key Considerations for Validating the Urban NSW Feeder

Avg Res Peak Size	Res Data Used	ADMD for LV Networks	PV Penetration	Avg PV Size	Head of Feeder Voltage
2.0kW	VIC Smart Meter	6.5kW	30%	2.0kW	10.9kV (0.99pu)

Figure 6-1 to Figure 6-4 presents the comparison of head of HV feeder SCADA measurements from the peak demand day with that of equivalent values obtained in the (validated) OpenDSS integrated HV-LV feeder model. The objective was to ensure that the net demand of residential and non-residential customers connected to the pseudo LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements (following section 2.5.).

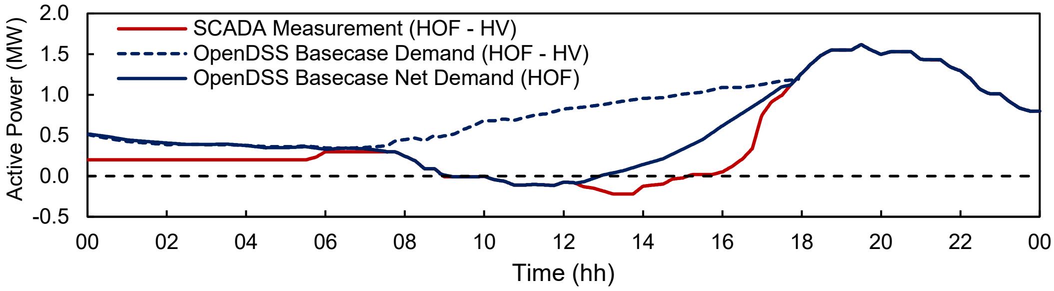


Figure 6-1. Urban NSW Active Power at Head of the HV Feeder

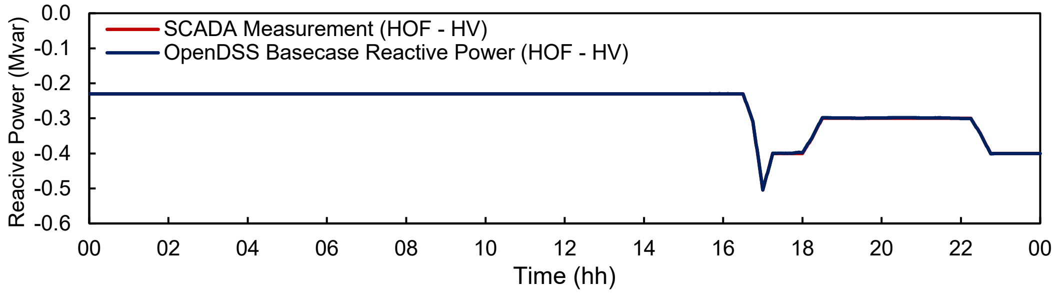


Figure 6-2. Urban NSW Reactive Power at Head of the HV Feeder

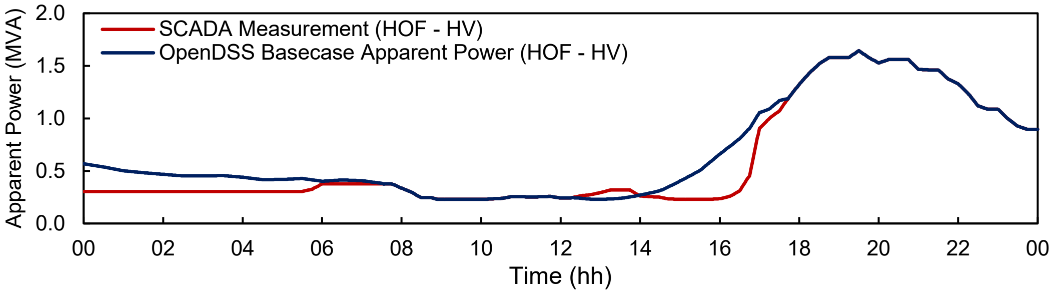


Figure 6-3. Urban NSW Apparent Power at Head of the HV Feeder

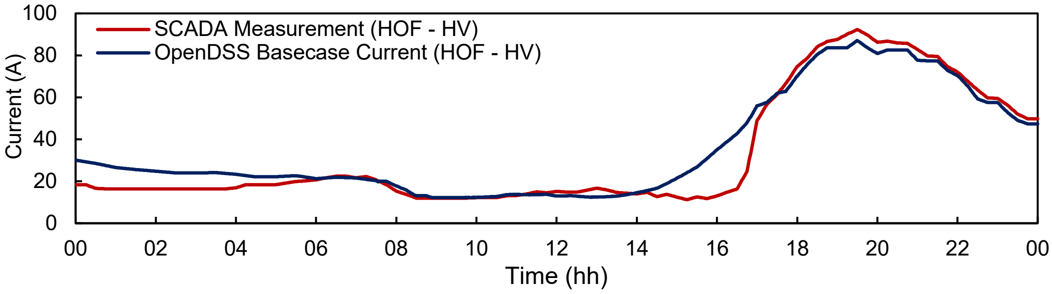


Figure 6-4. Urban NSW Current at Head of the HV Feeder

Overall, it can be seen in Figure 6-1 to Figure 6-4 that the OpenDSS model is following the SCADA measurements well. It can be noted that the installed residential PV in this feeder results in a reverse power flow out of the HV feeder during peak daylight hours. The deviations in seen are due to differences in the residential smart meter data profiles versus the SCADA measurements, with limits in the minimum tuning of non-residential demand. The summary of percentage errors is presented below in Table 6-3. Overall, it can be concluded that the model of the HV-LV feeder is performing acceptably close to SCADA measurements.

Table 6-3. Summary of Percentage Errors Between Head of Feeder SCADA Measurements and OpenDSS Simulation Values

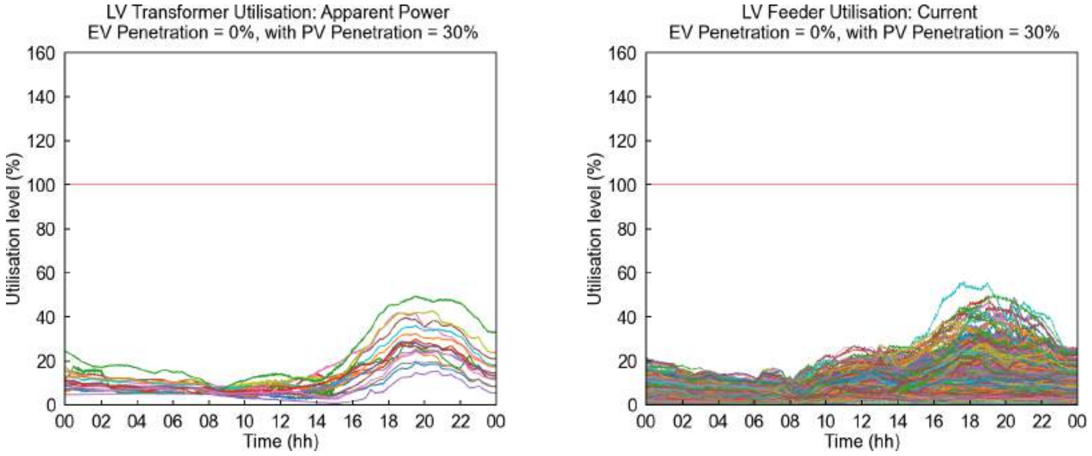
Error Metric	Active Power Error (%)	Reactive Power Error (%)	Apparent Power Error (%)	Current Error (%)
Minimum	0.00	0.00	0.03	0.00
Median	11.89	0.04	6.84	6.52
Mean	282.63	0.12	25.82	26.6
Maximum	-	0.83	168.79	183.71

6.2 Base Case

This section presents the performance metrics for Urban NSW when considering the base case, i.e., no EVs. These performance metrics are assessed to provide a reference point for the EV impact analysis.

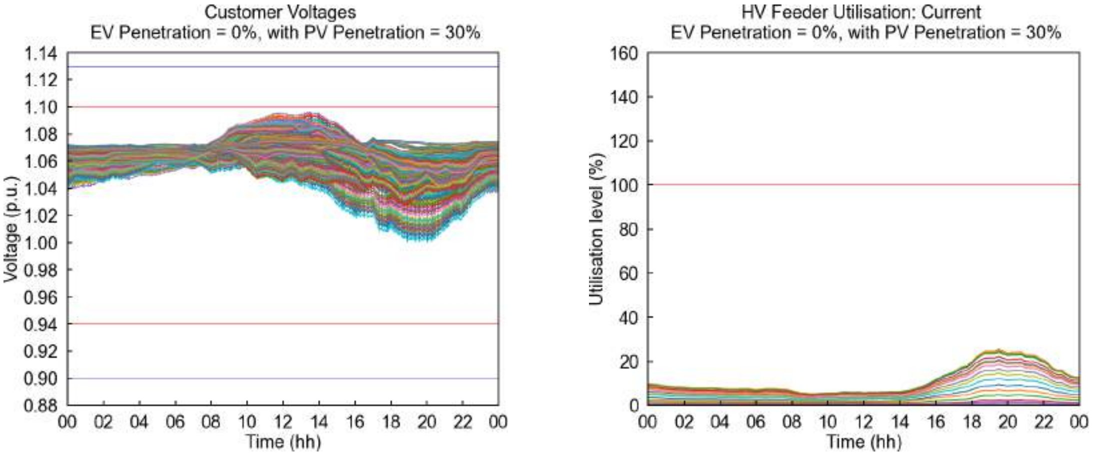
LV distribution transformer and LV feeder utilisation are shown in Figure 6-5 whilst customer voltages and HV feeder utilisation are shown in Figure 6-6.

It can be seen in Figure 6-5 (a) and (b) that the LV transformer utilisation and the LV Feeder utilisation are within limits for the base case scenario. As shown in Figure 6-6 (a) the customer voltages (within the LV feeder) are also within limits. The red line reflects the Australian standard AS 61000.3.100, whilst the blue line reflects the updated (as of April 2020) Victorian LV voltage limits as defined in the Electricity Distribution Code [31]. A voltage rise can be observed during peak daylight hours (11:00-14-00) which is caused by reverse power flows from residential PV systems. On the other hand, a drop in voltages can be seen once the sun has started to set and demand increases during the mid-evening hours. Finally, Figure 6-6 (b) shows that HV transformer utilisation for the base case is within their respective ratings.



(a) **(b)**

Figure 6-5. Urban NSW Base Case (a) LV Transformer Utilisation and (b) LV Feeder Utilisation



(a) **(b)**

Figure 6-6. Urban NSW Base Case (a) Customer Voltages and (b) HV Feeder Utilisation

6.3 EV Impact Assessment

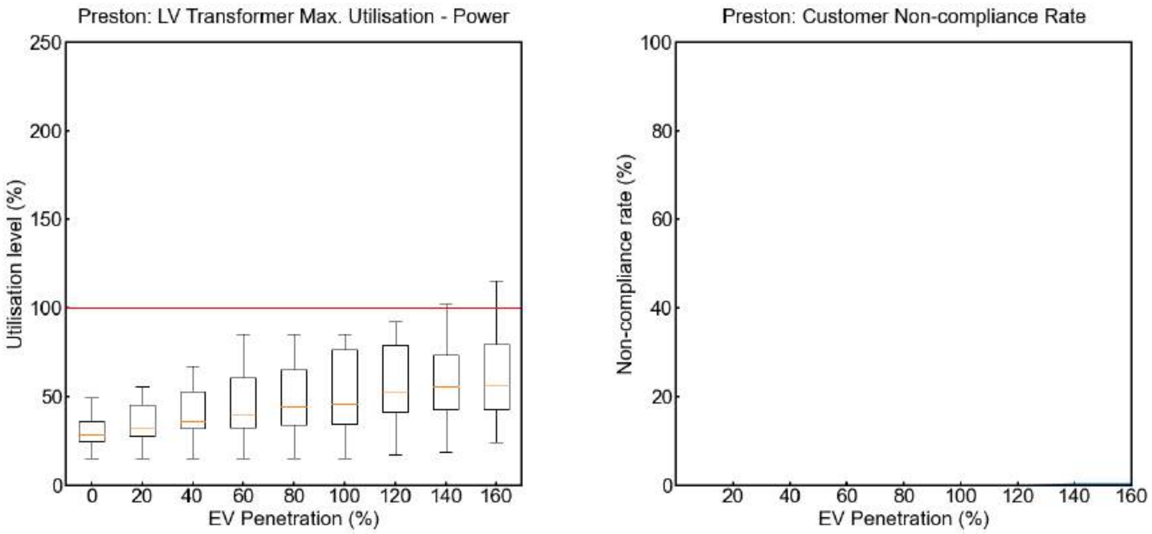
This section presents the different impacts that residential EV charging can have on the Urban NSW feeder considering a 24-hour time-series analysis of the HV-LV feeder for each of the penetration levels, considering the worst-case scenario of a peak demand day.

An overview of the results is presented first. Further details corresponding to LV distribution transformer utilisation, customer voltages, LV feeder utilisation, and HV feeder utilisation are presented in the subsequent sections.

6.3.1 Overview of Results

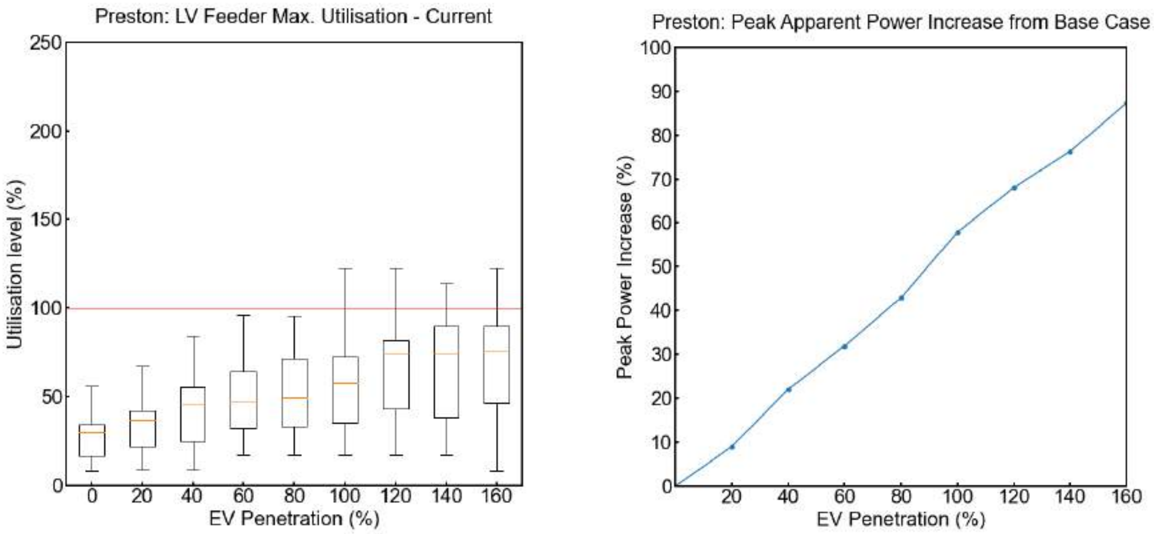
This section presents the overview of results for Urban NSW (Preston) considering EV penetrations from 0% up to 160% of residential customers with an EV (100% + 60% with a second EV).

Figure 6-7 (a) presents the LV distribution transformer maximum utilisation for a 24-hour period considering the assessed EV penetrations, whilst Figure 6-7 (b) presents the percentage of customers that violated the Australian standard AS 61000.3.100 voltage limits. Figure 6-8 (a) presents the presents the maximum LV feeder maximum utilisation per LV feeder, for a 24-hour period per EV penetration, whilst Figure 6-8 (b) presents the increase of peak apparent power.



(a) **(b)**

Figure 6-7. Urban NSW Base Case (a) LV Transformer Maximum Utilisation and (b) Percentage of Customers with Non-Compliant Voltages



(a) **(b)**

Figure 6-8. Urban NSW Base Case (a) LV Feeder Maximum Utilisation and (b) Relative Increase in Peak Apparent Power

It can be seen in Figure 6-7 (a) that that LV transformers for Urban NSW (Preston) start to overload at 100% EV penetration, however very few LV transformers overload relative to the feeder. Whilst Figure 6-7 (b) shows that there are no voltage violations seen for any EV penetration, voltages get very close to both the upper and lower limits for higher EV penetrations.

As shown in Figure 6-8 (a) the LV feeder conductors start to overload from 100% with the average peak of the LV feeders continuously edge higher to the 100% utilisation limit, suggesting a greater impact on conductors than feeders for (Preston). Figure 6-8 (b) shows there is up to a nearly 90% increase in peak apparent power demand at the head of the feeder when considering the maximum EV penetration, which could be significant for the zone substation and beyond further up the network when aggregated with other HV-LV feeders.

Figure 6-9 presents the EV impact on the top five utilised HV line segments within the HV feeder. The HV conductors do not overload of any EV penetration. Figure 6-10 (a) presents the location of these top five utilised segments in relation to the network topology. As expected, considering the aggregation of net demand, all these occur near to the head of the HV feeder. Finally, Figure 6-10 (b) presents the total length in kilometres of overloaded HV conductors, but since no HV conductors overload, this remains at 0km.

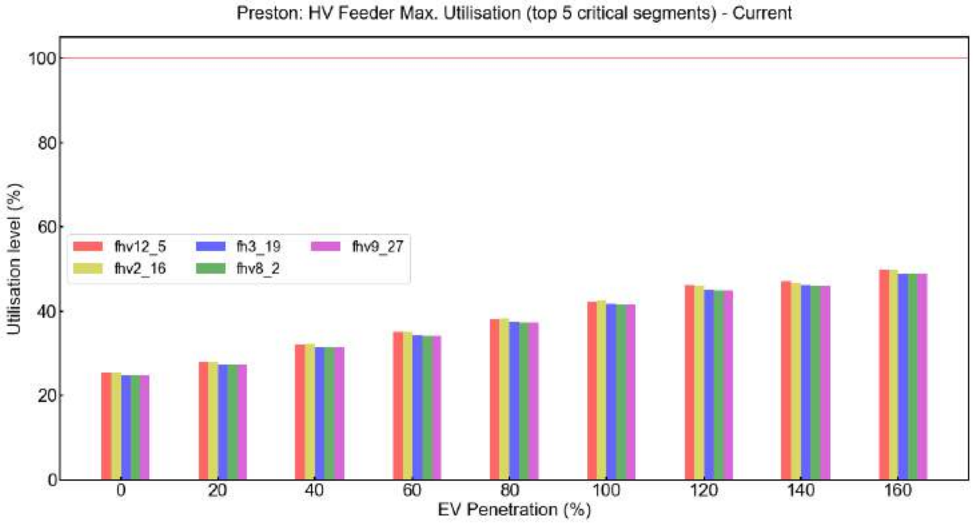
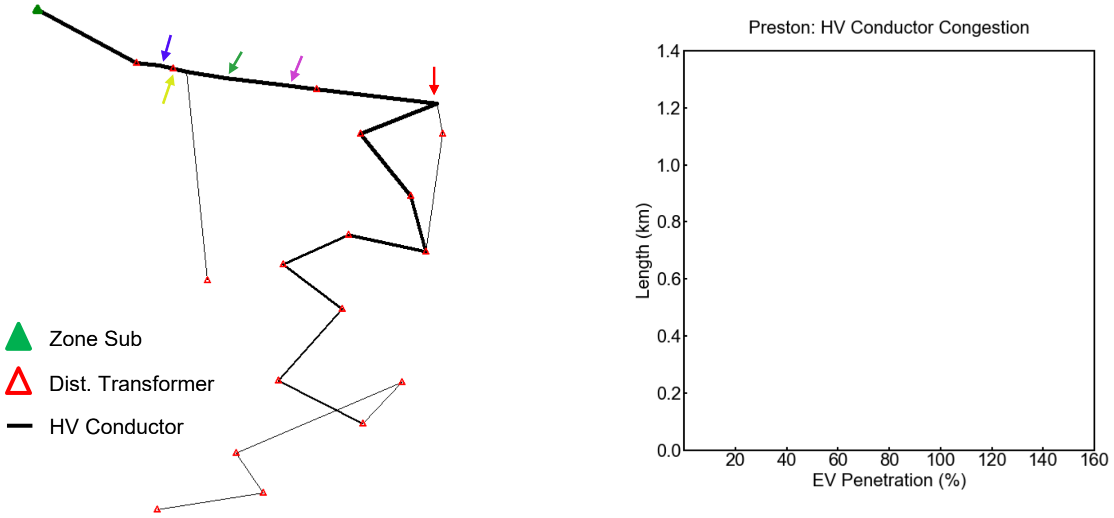


Figure 6-9. Urban NSW Base Case. EV Impact on the Top Five Utilised HV Line Segments

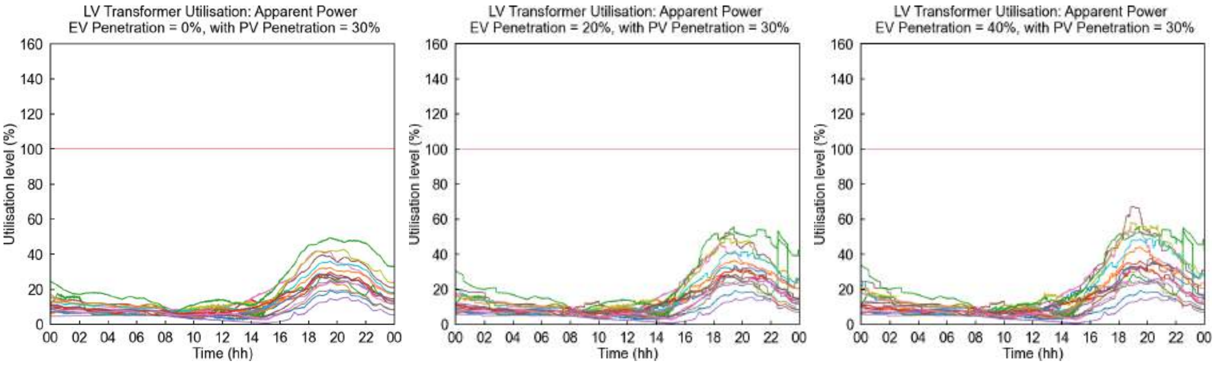


(a) (b)

Figure 6-10. Urban NSW Base Case (a) Position of the Top Five Utilised HV Line Segments and (b) Total length of HV Conductor Congestion

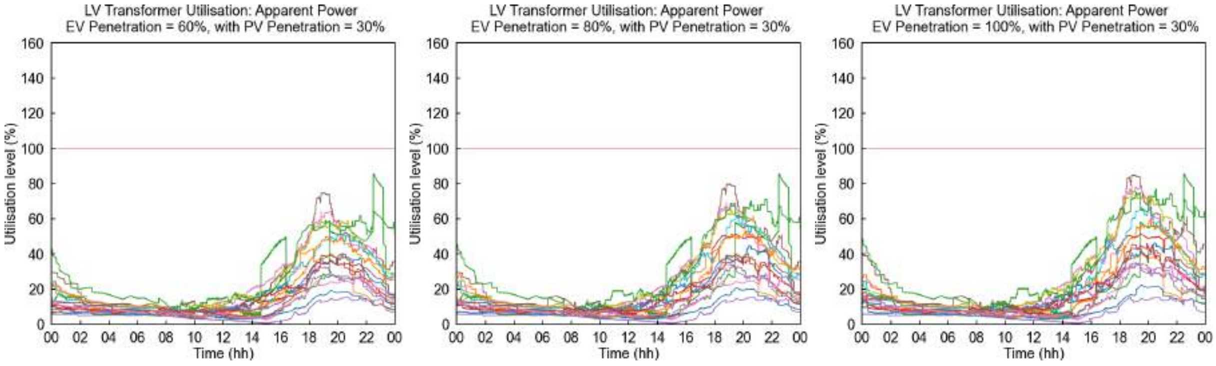
6.3.2 LV Distribution Transformer Utilisation

Figure 6-11 to Figure 6-13 presents the impacts of EVs on the utilisation of LV Distribution Transformers (Tx) for Urban NSW, considering the increase of EV penetrations up to 160%.



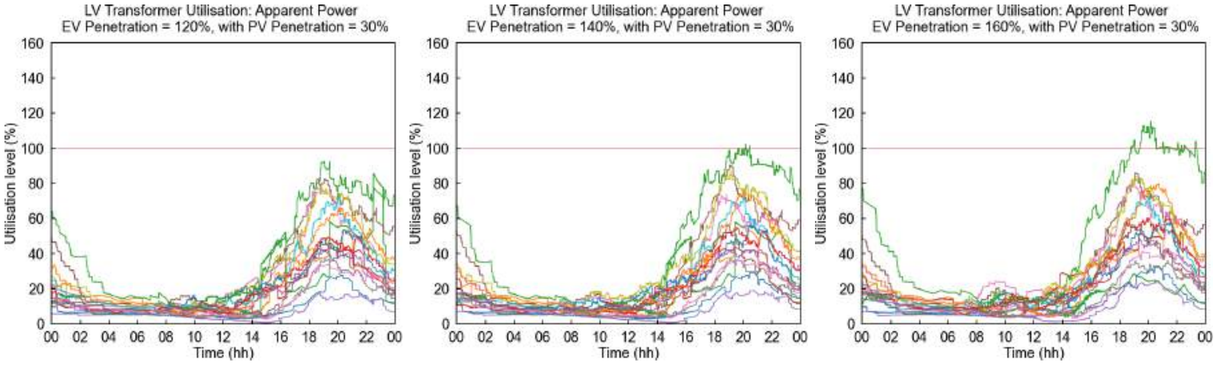
(a) (b) (c)

Figure 6-11. Urban NSW Base Case LV Tx Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 6-12. Urban NSW Base Case LV Tx Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



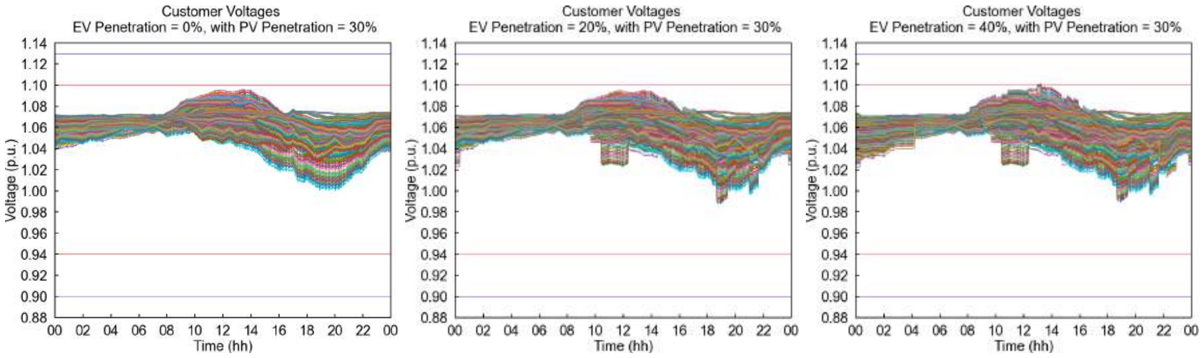
(a) (b) (c)

Figure 6-13. Urban NSW Base Case LV Tx Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen Figure 6-13 (b) and (c) that one LV distribution transformers overloads at 140% EV penetration and beyond. Meanwhile, the other LV distribution transformer have no utilisation issues.

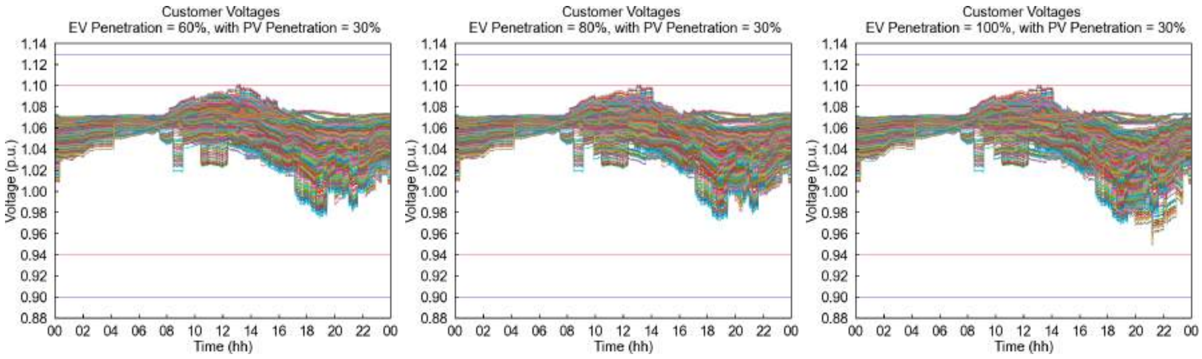
6.3.3 Residential Customer Voltages

Figure 6-14 to Figure 6-16 presents the impacts of EVs on the residential customer voltages for Urban NSW, considering the increase of EV penetrations up to 160%.



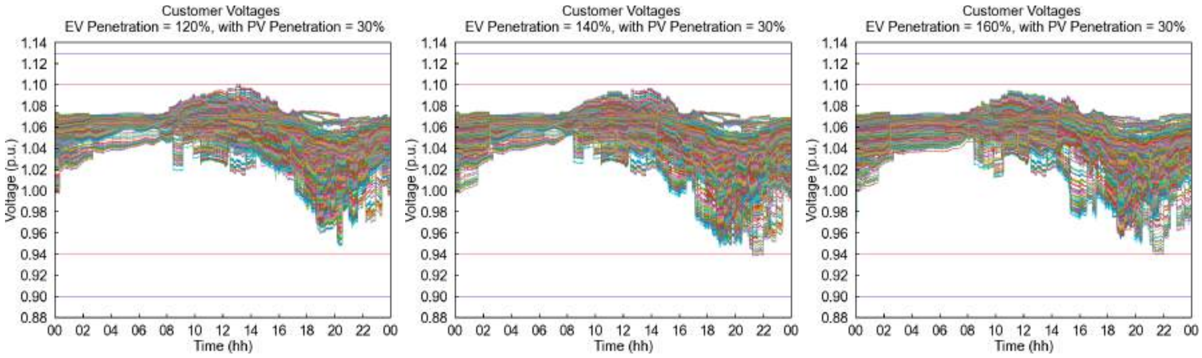
(a) (b) (c)

Figure 6-14. Urban NSW Base Case Customer Voltages with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 6-15. Urban NSW Base Case Customer Voltages with EVs: (a) 60%, (b) 80% and (c) 100%



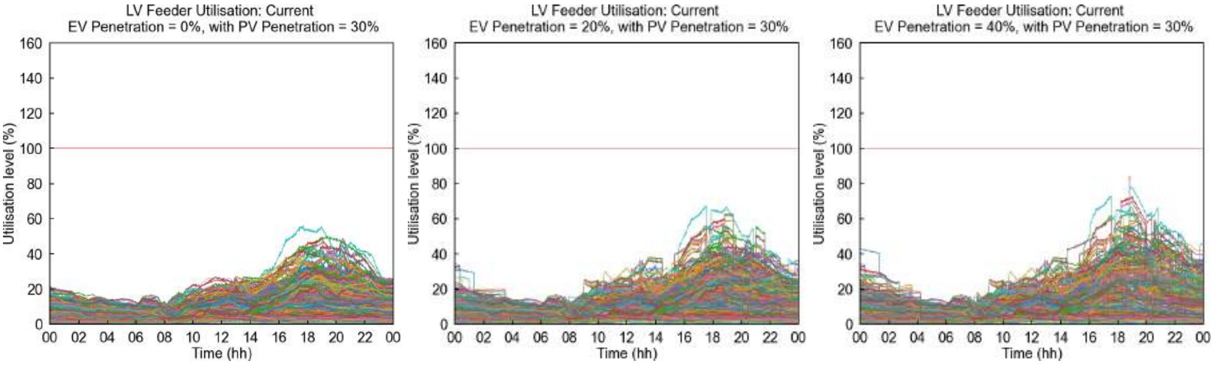
(a) (b) (c)

Figure 6-16. Urban NSW Base Case Customer Voltages with EVs: (a) 120%, (b) 140% and (c) 160%

As shown by the results, Urban NSW does not have voltage drop issues from the introduction of EVs. However, it can be noted for the higher penetrations that voltages do get quite close to the lower limit. Meanwhile considering the voltage rise from PV and the upper voltage limit, it can be seen that Urban NSW is now heavily voltage constrained both by the upper and lower voltage limits, leaving little room for further PV induced voltage rise or further EV induced voltage drops.

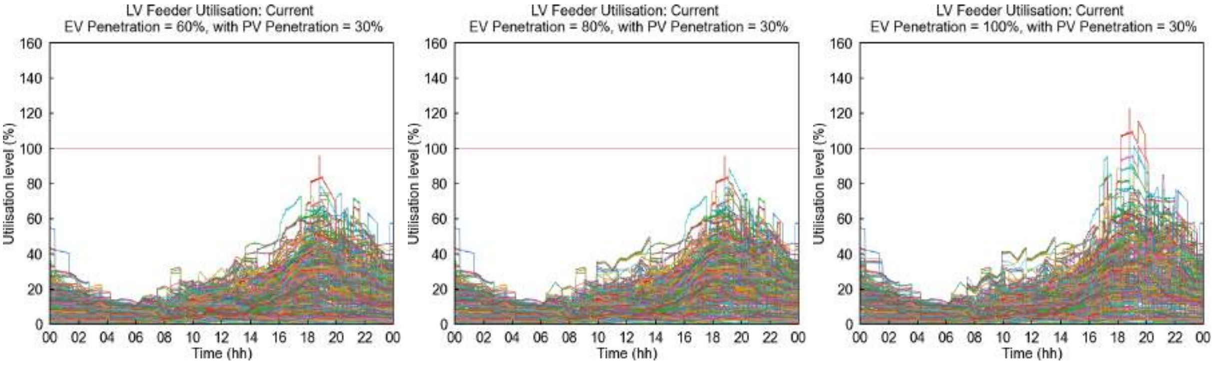
6.3.4 LV Feeder Utilisation

Figure 6-17 to Figure 6-19 presents the impacts of EVs on the utilisation of LV conductors for Urban NSW, considering the increase of EV penetrations up to 160%.



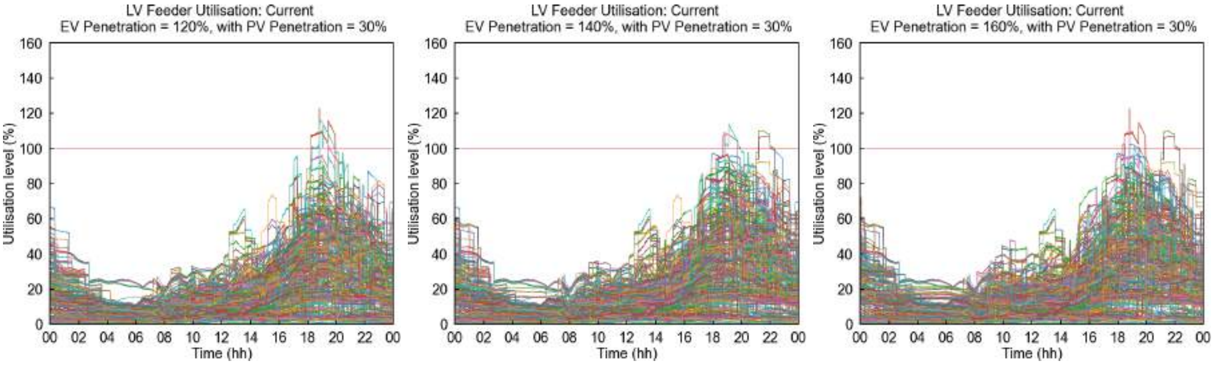
(a) (b) (c)

Figure 6-17. Urban NSW Base Case LV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 6-18. Urban NSW Base Case LV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



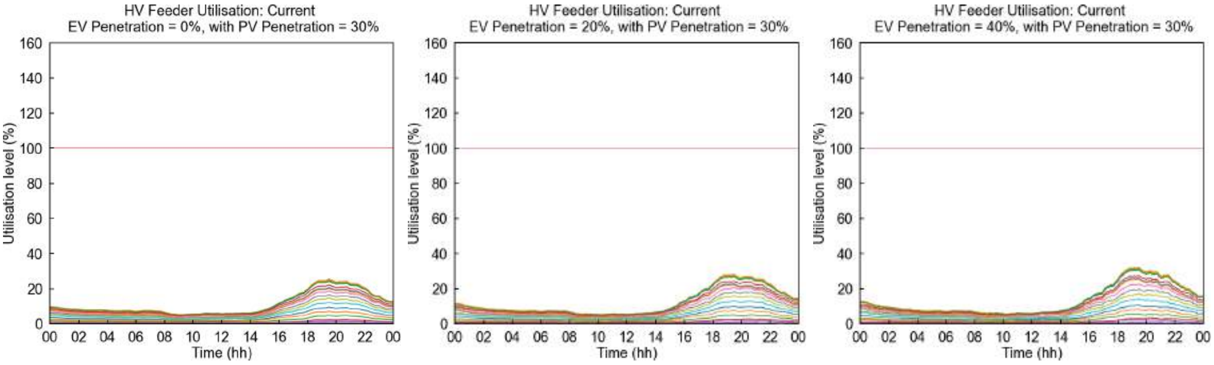
(a) (b) (c)

Figure 6-19. Urban NSW Base Case LV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen in the results that LV feeder overloads begin in a small-scale for 100% and increase slightly up to 160% EV penetration. However, this will only affect a small number of LV conductors and feeders within the integrated HV-LV feeder.

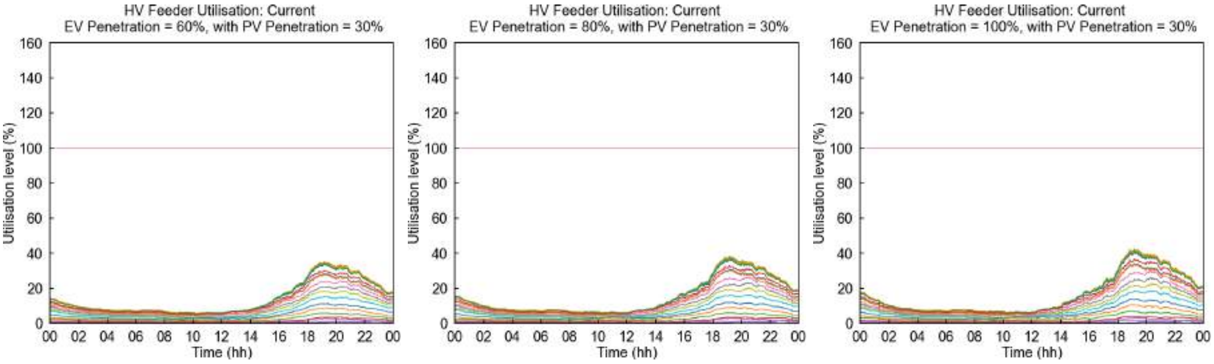
6.3.5 HV Feeder Utilisation

Figure 6-20 to Figure 6-22 presents the impacts of EVs on the utilisation of HV conductors for Urban NSW, considering the increase of EV penetrations up to 160%.



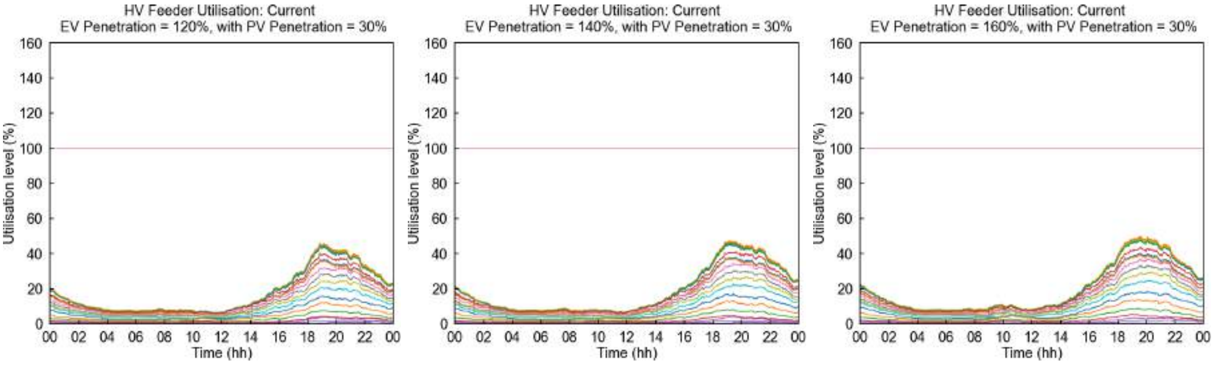
(a) (b) (c)

Figure 6-20. Urban NSW Base Case HV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 6-21. Urban NSW Base Case HV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



(a) (b) (c)

Figure 6-22. Urban NSW Base Case HV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen from the results that there are no HV feeder overloads for Urban NSW (Preston) at any EV penetration considered.

6.3.6 Key Remarks

- Only one LV distribution transformer has asset utilisation problems at 140% EV and beyond.
- No lower voltage standard limit violations from residential customers due to EVs. However, Urban NSW (Preston) is now heavily constrained with voltage both near the upper voltage limit during peak daylight hours, and voltage near the lower limit during evening hours.
- A small number of LV feeders begin to have conductor utilisation problems within them at 100% EV penetration and beyond.
- No HV conductor utilisation issues for any EV penetration.
- The increase in peak apparent power for Urban NSW when considering the maximum EV penetration is nearly 90%. This could have serious implications for the zone substation and further upstream in the network when considering other HV-LV feeders also connected to the same network assets.
- Considering the above, **the EV hosting capacity of the Urban NSW feeder would be approximately 80% of residential customers with an EV**, with LV conductors the first limiting factor followed by LV distribution transformers at 140%, with no voltage issues or HV conductor issues.

7 Case Study: Rural TAS (Norwood)

This chapter presents the validation results for Rural TAS (Norwood), the base case analysis and the results from the EV impact analysis across different increasing EV penetrations (described in section 4.3.3 and Chapter 3). A summary of the technical information is shown in Table 7-1.

Table 7-1. HV-LV Feeder Technical Information Summary

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)	HV Feeder Peak (MW)
Rural TAS *Norwood*	22kV	1506	33	11	5.0	3.0	0%	N/A	6.15

7.1 HV-LV Feeder Validation

Table 7-2 shows key considerations in validating Rural TAS.

Table 7-2. Key Considerations for Validating the Rural TAS Feeder

Avg Res Peak Size	Res Data Used	ADMD for LV Networks	PV Penetration	Head of Feeder Voltage
3.0kW	Avg Res Profile	5.0kW	0%	21.9kV (0.99pu)

Figure 7-1 to Figure 7-4 presents the comparison of head of HV feeder SCADA measurements from the peak demand day with that of equivalent values obtained in the (validated) OpenDSS integrated HV-LV feeder model. The objective was to ensure that the net demand of residential and non-residential customers connected to the pseudo LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements (following section 2.5.).

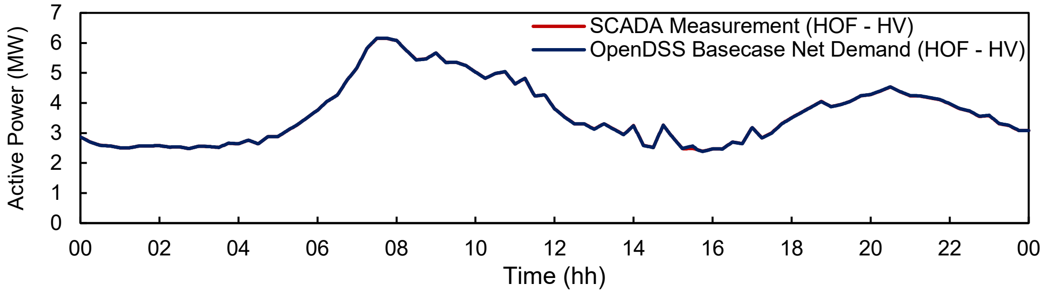


Figure 7-1. Rural TAS Active Power at Head of the HV Feeder

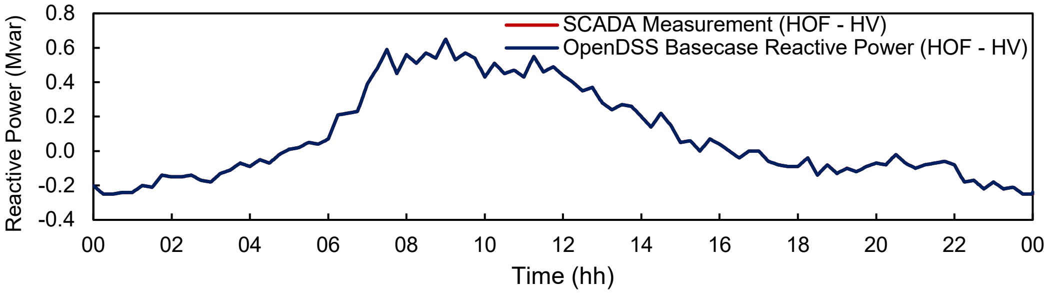


Figure 7-2. Rural TAS Reactive Power at Head of the HV Feeder

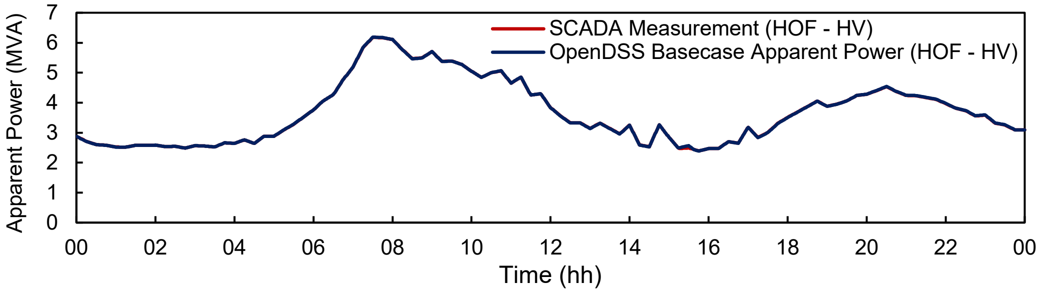


Figure 7-3. Rural TAS Apparent Power at Head of the HV Feeder

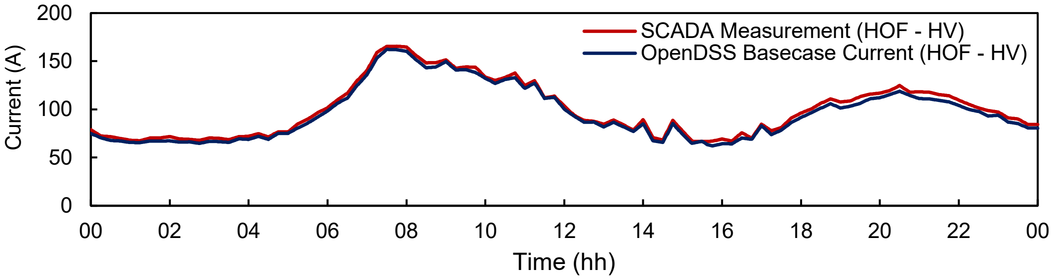


Figure 7-4. Rural TAS at Head of the HV Feeder

Overall, it can be seen in Figure 7-1 to Figure 7-4 that the OpenDSS model is following the SCADA measurements well. The summary of percentage errors is presented below in Table 7-3

Table 7-3. Summary of Percentage Errors Between Head of Feeder SCADA Measurements and OpenDSS Simulation Values

Error Metric	Active Power Error (%)	Reactive Power Error (%)	Apparent Power Error (%)	Current Error (%)
Minimum	0.00	0.02	0.00	0.00
Median	0.09	0.04	0.09	3.90
Mean	0.13	0.11	0.13	3.74
Maximum	3.08	3.87	3.08	7.31

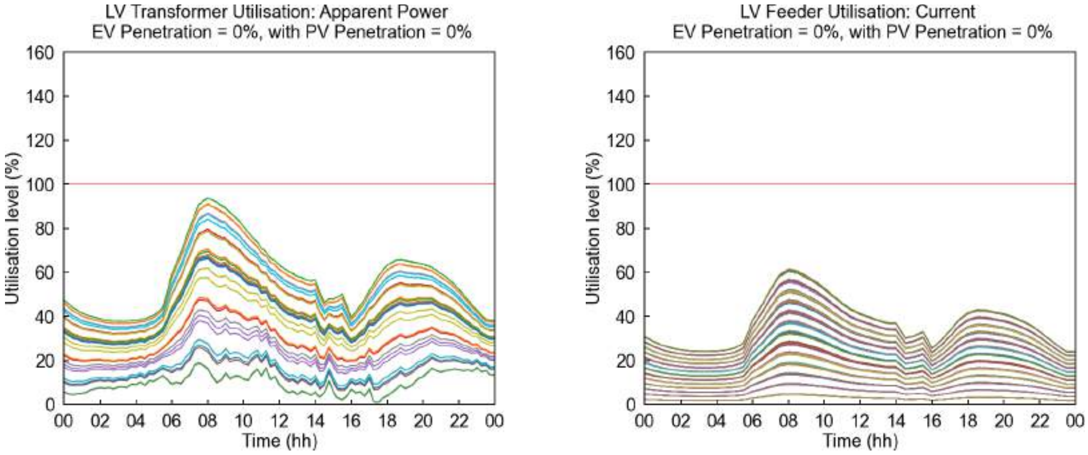
7.2 Base Case

This section presents the performance metrics for Rural TAS when considering the base case, i.e., no EVs. These performance metrics are assessed to provide a reference point for the EV impact analysis.

Figure 7-5 shows the LV transformer and LV feeder utilisation whilst Figure 7-6 shows customer voltages and HV feeder utilisation for the base case.

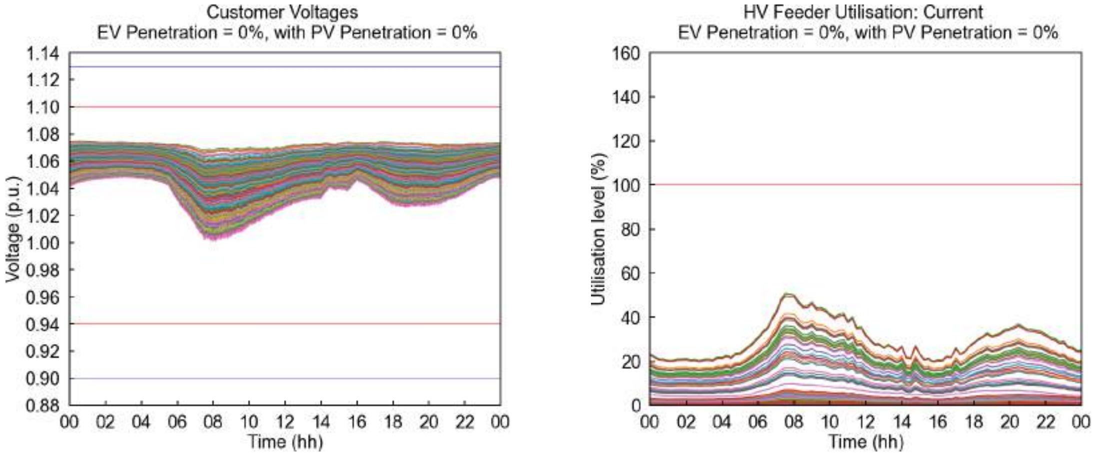
It can be seen in Figure 7-5 (a) and (b) that the LV transformer utilisation and the LV Feeder utilisation are within limits for the base case scenario.

As shown in Figure 7-6 (a) the customer voltages (within the LV feeder) are also within limits. The red line reflects the Australian standard AS 61000.3.100, whilst the blue line reflects the updated (as of April 2020) Victorian LV voltage limits as defined in the Electricity Distribution Code [31]. Finally, Figure 7-6 (b) shows that HV transformer utilisation for the base case is within their respective ratings.



(a) (b)

Figure 7-5. Rural TAS Base Case (a) LV Transformer Utilisation and (b) LV Feeder Utilisation



(a) (b)

Figure 7-6. Rural TAS Base Case (a) Customer Voltages and (b) HV Feeder Utilisation

7.3 EV Impact Assessment

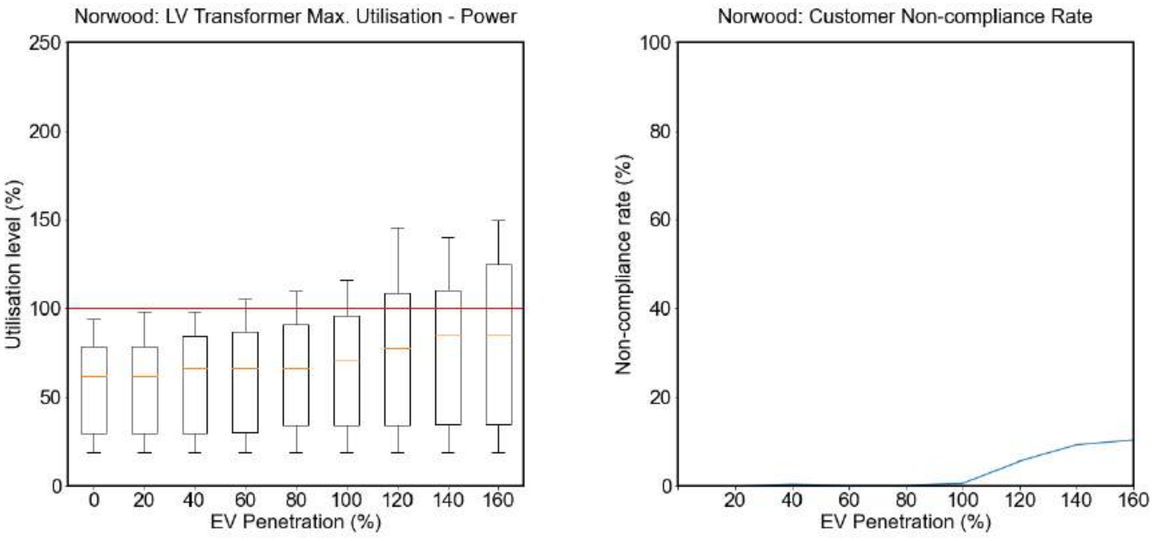
This section presents the different impacts that residential EV charging can have on the Rural TAS feeder considering a 24-hour time-series analysis of the HV-LV feeder for each of the penetration levels, considering the worst-case scenario of a peak demand day.

An overview of the results is presented first. Further details corresponding to LV distribution transformer utilisation, customer voltages, LV feeder utilisation, and HV feeder utilisation are presented in the subsequent sections.

7.3.1 Overview of Results

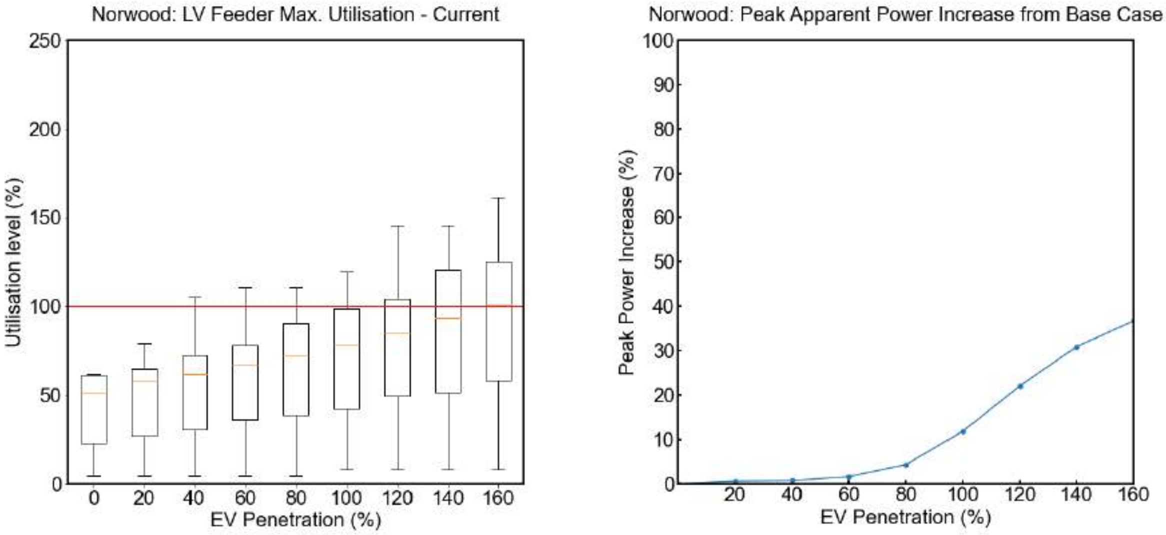
This section presents the overview of results for Rural TAS (Norwood) considering EV penetrations from 0% up to 160% of residential customers with an EV (100% + 60% with a second EV).

Figure 7-7 (a) presents the LV distribution transformer maximum utilisation for a 24-hour period considering the assessed EV penetrations, whilst Figure 7-7 (b) presents the percentage of customers that violated the Australian standard AS 61000.3.100 voltage limits. Figure 7-8 (a) presents the presents the maximum LV feeder maximum utilisation per LV feeder, for a 24-hour period per EV penetration, whilst Figure 7-8 (b) presents the increase of peak apparent power.



(a) (b)

Figure 7-7. Rural TAS Base Case (a) LV Transformer Maximum Utilisation and (b) Percentage of Customers with Non-Compliant Voltages



(a) (b)

Figure 7-8. Rural TAS Base Case (a) LV Feeder Maximum Utilisation and (b) Relative Increase in Peak Apparent Power

It can be seen in Figure 7-7 (a) that the LV transformers begin to overload at 60% EV penetration, and it increases in severity as the EV penetrations. At 100% EV penetration, close to a quarter of LV distribution transformers are overloaded. Whilst it can be seen in Figure 7-7 (b) that voltage issues start at 40% EV penetration but for a very small number of customers (two). Voltage problems become more widespread at 120% EV penetration and by the maximum EV penetration close to 1 in 10 customers have a lower voltage standard violation issue.

Figure 7-8 (a) shows that conductors within LV feeders start to overload by 40% EV penetration. By 100% EV penetration, close to a quarter of LV feeders having LV conductors within them overload and reaches the mean (or nearly half) of LV feeders with problematic LV conductors at 160%. Figure 7-8 (b) shows that the increase in peak apparent power at the head of the feeder reaches nearly 40% by maximum EV penetration. The increase is slower for the early penetrations due to the peak demand occurring initially during the morning hours whereas most of the EV demand occurs later. For a similar feeder with a high evening demand, or feeders with more residential customers, this peak power increase will grow. However, the already high residential demand relative to other regions inevitably also will lower this figure.

Figure 7-9 illustrates the EV impacts on the top five utilised HV line segments within the HV feeder, whilst Figure 7-10 (a) shows the location of these segments and Figure 7-10 (b) shows the total length of all congested HV feeders. Overall, it can be seen that there are no HV conductor issues within the HV feeder and as expected the most utilised HV line segments are at the head of the feeder where demand is aggregated.

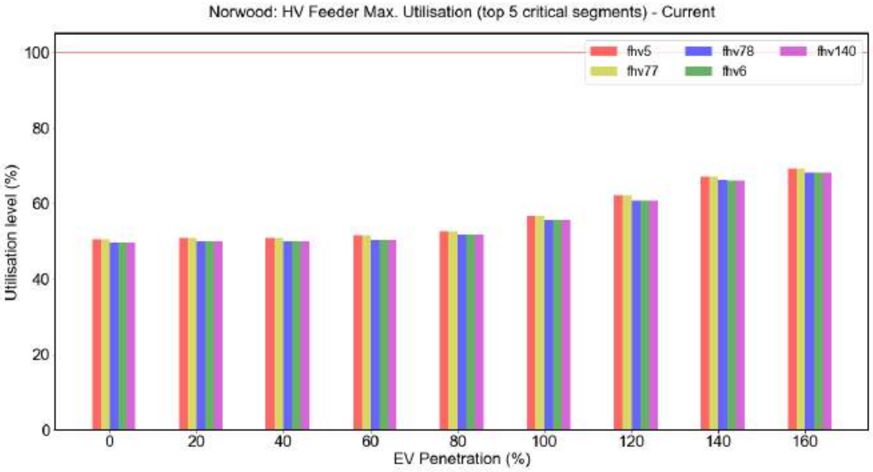
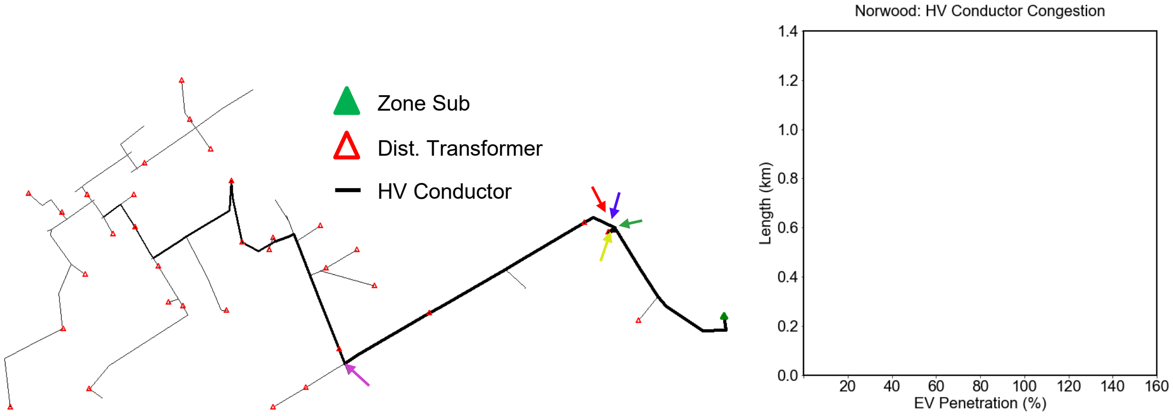


Figure 7-9. Rural TAS Base Case. EV Impact on the Top Five Utilised HV Line Segments

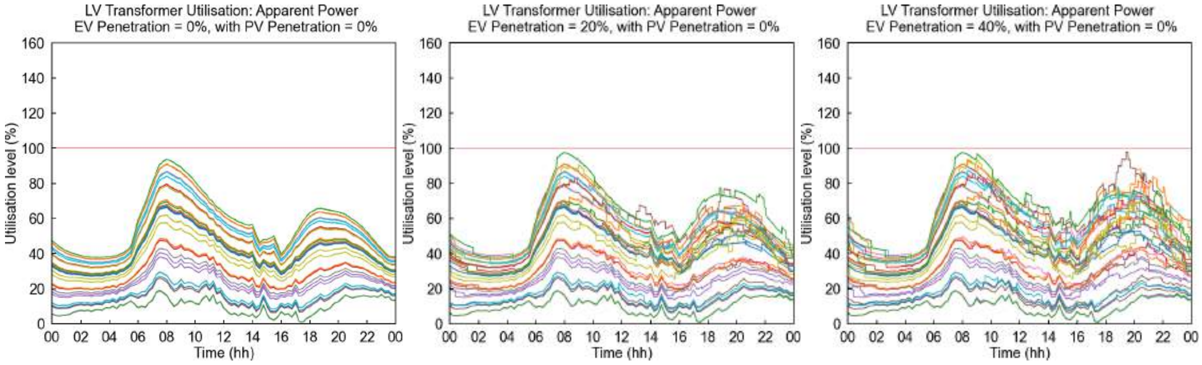


(a) (b)

Figure 7-10. Rural TAS Base Case (a) Position of the Top Five Utilised HV Line Segments and (b) Total length of HV Conductor Congestion

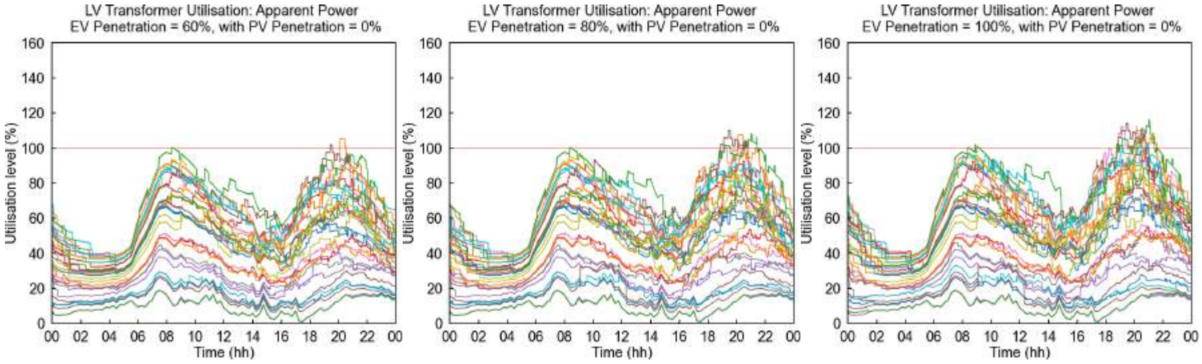
7.3.2 LV Distribution Transformer Utilisation

Figure 7-11 to Figure 7-13 presents the impacts of EVs on the utilisation of LV Distribution Transformers (Tx) for Rural TAS, considering the increase of EV penetrations up to 160%.



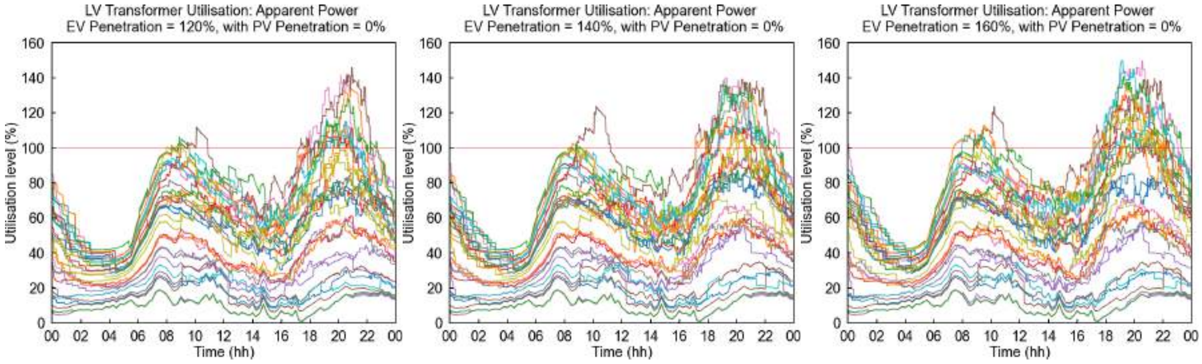
(a) (b) (c)

Figure 7-11. Rural TAS Base Case LV Tx Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 7-12. Rural TAS Base Case LV Tx Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



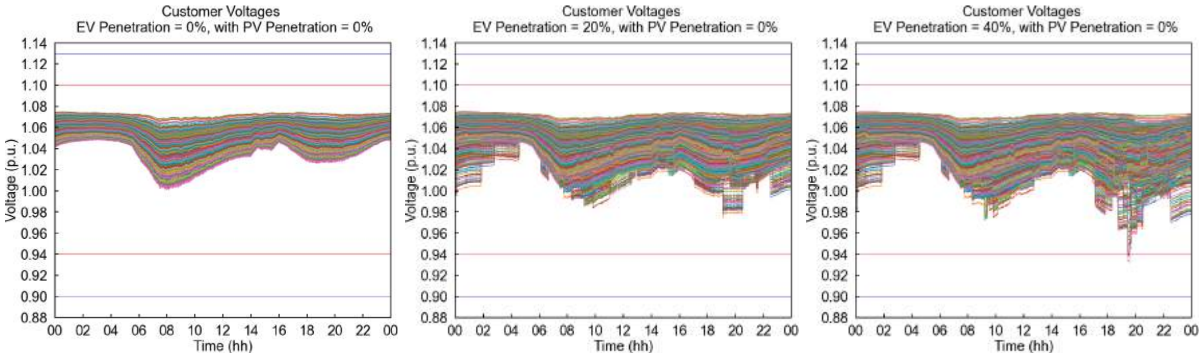
(a) (b) (c)

Figure 7-13. Rural TAS Base Case LV Tx Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

The results show that LV transformer utilisation problems occur at 60% EV penetration with just two LV distribution transformers overloading. However, as the EV penetration grows, so does the number of LV distribution transformers that are overloaded. By 100% EV penetration, overloads occur both for the morning and evening peak.

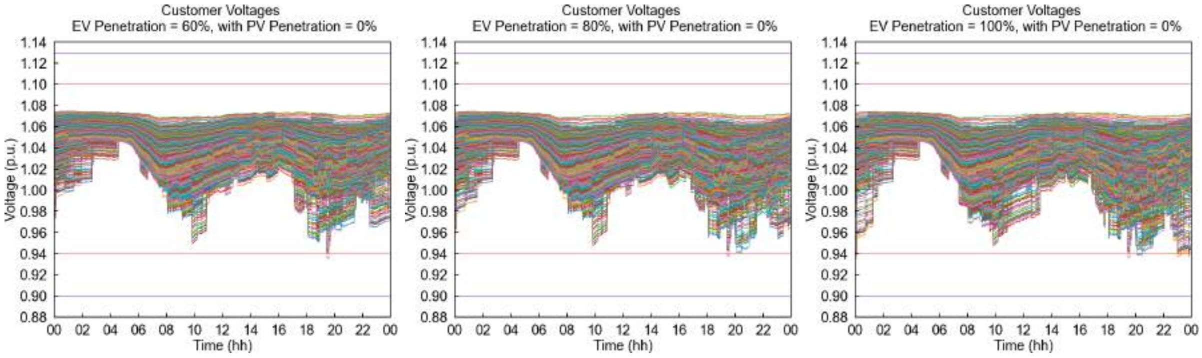
7.3.3 Residential Customer Voltages

Figure 7-14 to Figure 7-16 presents the impacts of EVs on the residential customer voltages for Rural TAS, considering the increase of EV penetrations up to 160%.



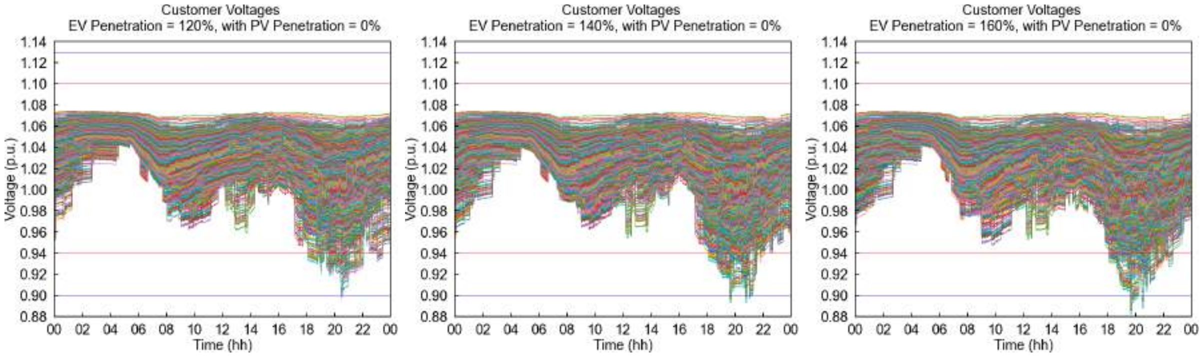
(a) (b) (c)

Figure 7-14. Rural TAS Base Case Customer Voltages with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 7-15. Rural TAS Base Case Customer Voltages with EVs: (a) 60%, (b) 80% and (c) 100%



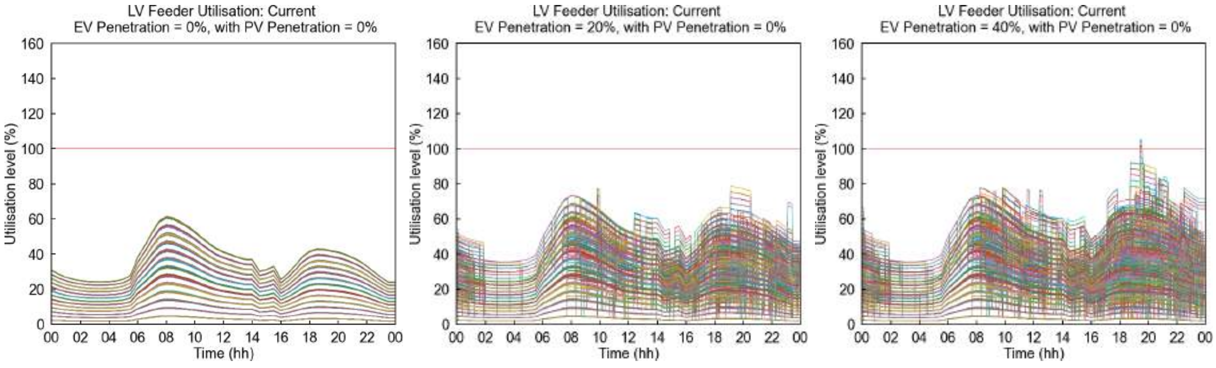
(a) (b) (c)

Figure 7-16. Rural TAS Base Case Customer Voltages with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen in the results that customer voltage issues first occur for a very small number of customers between 40 to 100% EV penetration. This is where voltages exceed the red line which represents the Australian standard AS 61000.3.100. However, it can be seen that beyond 120% EV penetration, customer voltage problems become much more widespread.

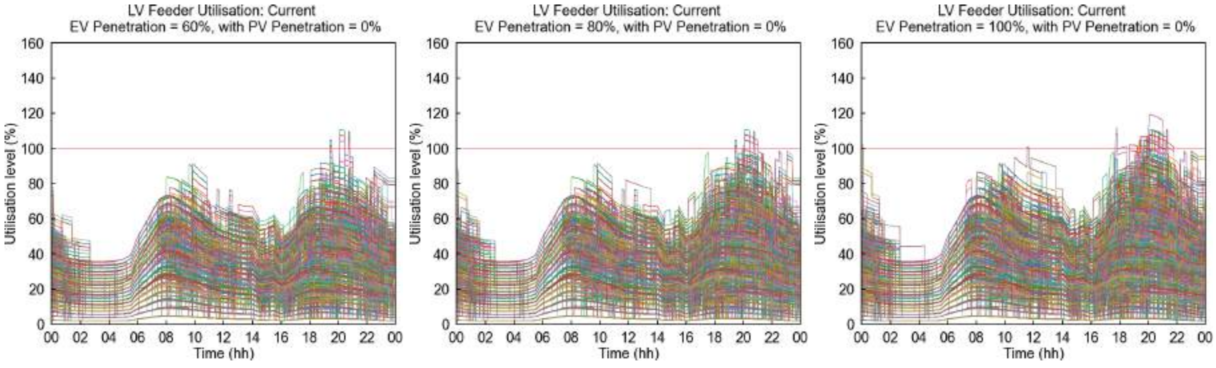
7.3.4 LV Feeder Utilisation

Figure 7-17 to Figure 7-19 presents the impacts of EVs on the utilisation of LV conductors for Rural TAS, considering the increase of EV penetrations up to 160%.



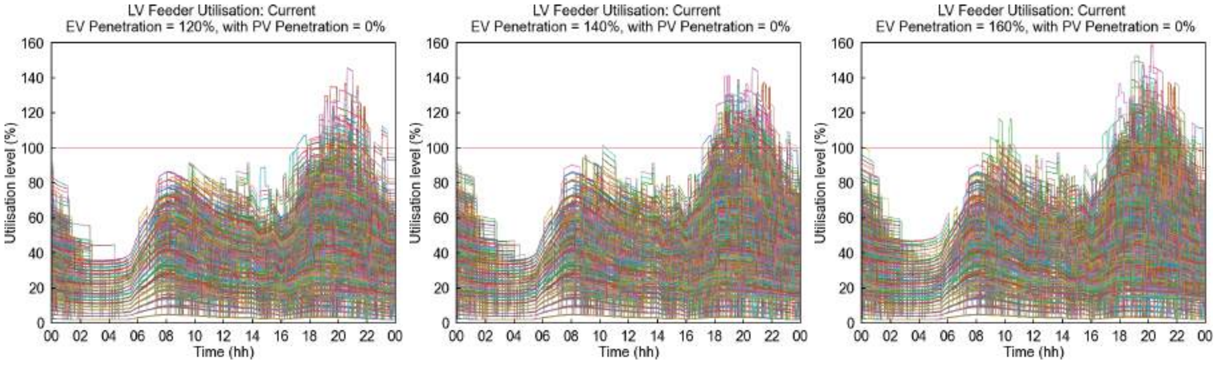
(a) (b) (c)

Figure 7-17. Rural TAS Base Case LV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 7-18. Rural TAS Base Case LV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



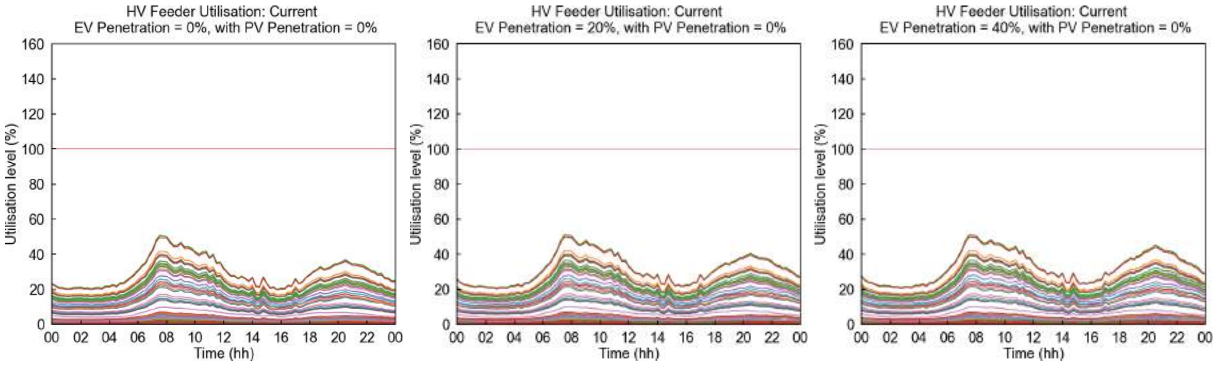
(a) (b) (c)

Figure 7-19. Rural TAS Base Case LV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen that for a small number of LV conductors, overloads first occur at 40% EV penetration. As the EV penetration increases, so does the number of conductors that overload. From 120% and beyond, the number of conductors that are overloaded starts to increase significantly. As was the case for the LV distribution transformers, for higher EV penetrations the mornings can also start to see overload problems.

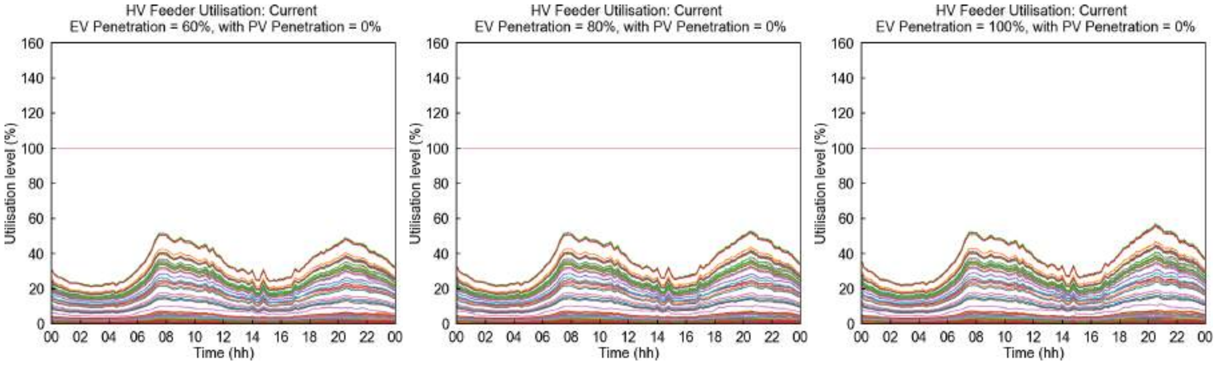
7.3.5 HV Feeder Utilisation

Figure 7-20 to Figure 7-22 presents the impacts of EVs on the utilisation of HV conductors for Rural TAS, considering the increase of EV penetrations up to 160%.



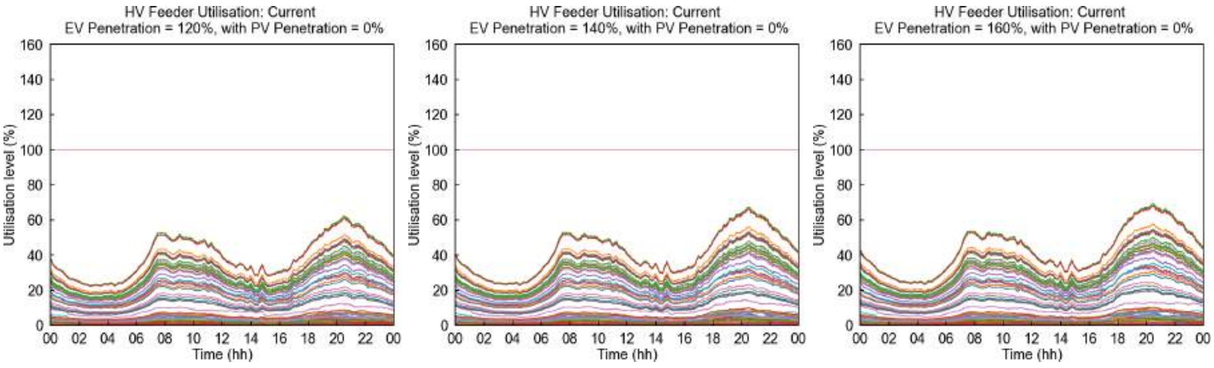
(a) **(b)** **(c)**

Figure 7-20. Rural TAS Base Case HV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) **(b)** **(c)**

Figure 7-21. Rural TAS Base Case HV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



(a) **(b)** **(c)**

Figure 7-22. Rural TAS Base Case HV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

The results show that there are no HV feeder utilisation problems for Rural TAS (Norwood).

7.3.6 Key Remarks

- LV distribution transformers begin to encounter asset congestion issues at 60% EV, with the impact increasing in severity as EV penetration increases. By 100% EV penetration, nearly one quarter of LV distribution transformers are at or very close to 100% utilisation. Also, for over 100% EV penetration, asset utilisation issues start to occur both in the morning and the evening.
- Whilst there is a couple of lower voltage standard violations as early as 40% EV penetration, voltage issues start to really increase from 120% EV penetration and beyond by max EV penetration, with nearly 1 in 10 customers have a lower voltage standard violation.
- Some LV feeders start to have conductors within them that have utilisation problems at 40% EV penetration. By 100% EV penetration nearly 25% of LV feeders will have an LV conductor issue within It and at 160% penetration this can reach nearly half of the LV feeders.
- There is an increase of nearly 40% of peak apparent power when considering the maximum EV penetration. For HV feeders with larger evening peaks and a small number of non-residential customers, this would potentially increase.
- There are no HV conductor utilisation issues for Rural TAS.
- Considering the above, the **EV hosting capacity of the Rural TAS feeder is approximately 20% of residential customers with an EV**, with LV feeder utilisation issues and minor customer voltage standard violation issue being the first limiting factors. By 60% EV penetration, LV transformers start to encounter asset congestion issues and lower voltage standard violations start to increase in volume.

8 Case Study: Urban TAS (West Hobart)

This chapter presents the validation results for Urban TAS (West Hobart), the base case analysis and the results from the EV impact analysis across different increasing EV penetrations (described in section 4.3.3 and Chapter 3). A summary of the technical information is shown in Table 8-1.

Table 8-1. HV Feeder Technical Information Summary

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)	HV Feeder Peak (MW)
Urban TAS *West Hobart*	11kV	620	12	6	5.0	3.5	0%	-	5.41

8.1 HV-LV Feeder Validation

Table 8-2 shows key considerations in validating Urban TAS.

Table 8-2. Key Considerations for Validating the Urban TAS Feeder

Avg Res Peak Size	Res Data Used	ADMD for LV Networks	PV Penetration	Head of Feeder Voltage
3.5kW	Avg Res Profile	5.0kW	0%	11.1kV (1.01pu)

Figure 8-1 to Figure 8-4 presents the comparison of head of HV feeder SCADA measurements from the peak demand day with that of equivalent values obtained in the (validated) OpenDSS integrated HV-LV feeder model. The objective was to ensure that the net demand of residential and non-residential customers connected to the pseudo-LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements (following section 2.5.).

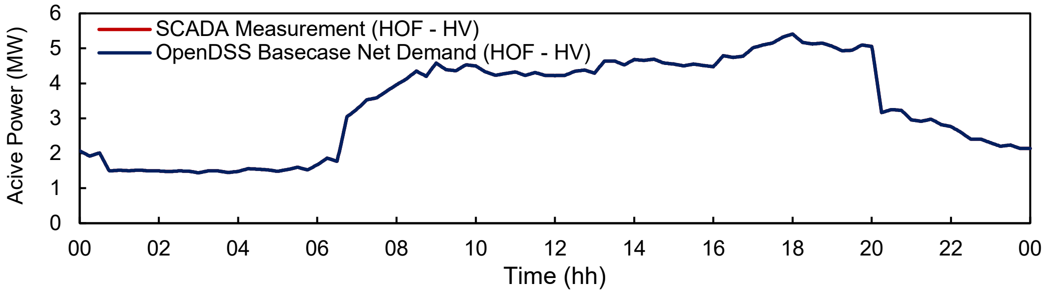


Figure 8-1. Urban TAS Active Power at Head of the HV Feeder

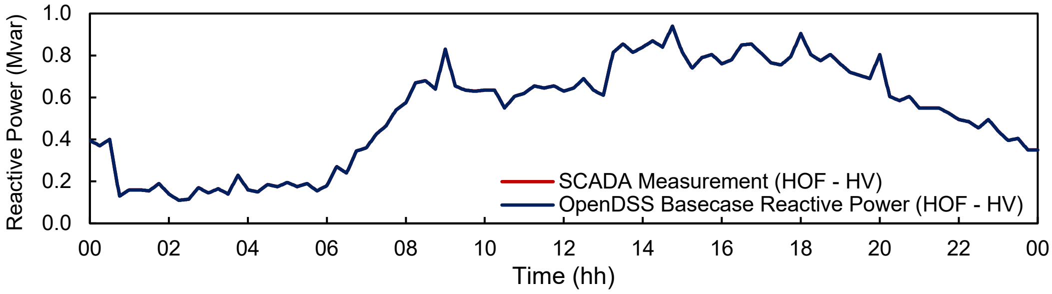


Figure 8-2. Urban TAS Reactive Power at Head of the HV Feeder

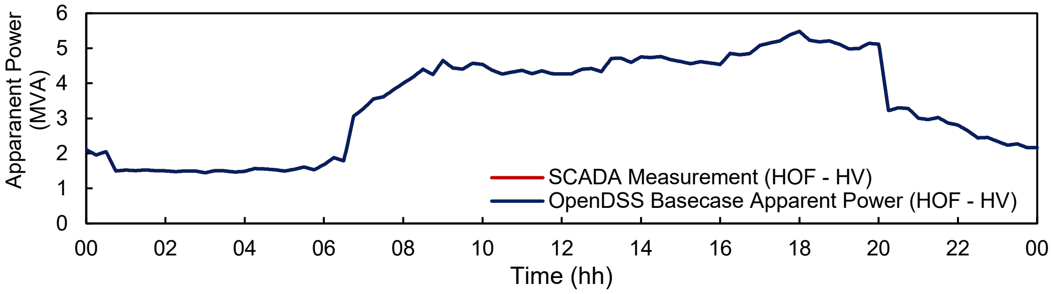


Figure 8-3. Urban TAS (West Hobart) Apparent Power at Head of the HV Feeder

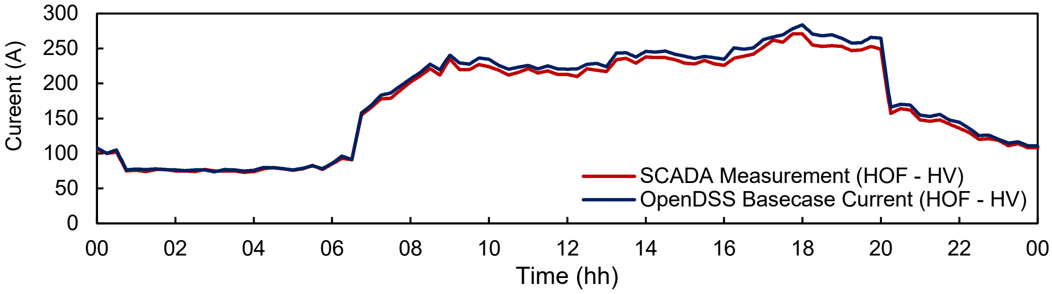


Figure 8-4. Urban TAS at Head of the HV Feeder

Overall, it can be seen in Figure 8-1 to Figure 8-4 that the OpenDSS model is following the SCADA measurements well. The summary of percentage errors is presented below in Table 8-3

Table 8-3. Summary of Percentage Errors Between Head of Feeder SCADA Measurements and OpenDSS Simulation Values

Error Metric	Active Power Error (%)	Reactive Power Error (%)	Apparent Power Error (%)	Current Error (%)
Minimum	0.00	0.00	0.00	0.00
Median	0.00	0.01	0.00	3.24
Mean	0.00	0.01	0.00	3.08
Maximum	0.01	0.02	0.01	5.96

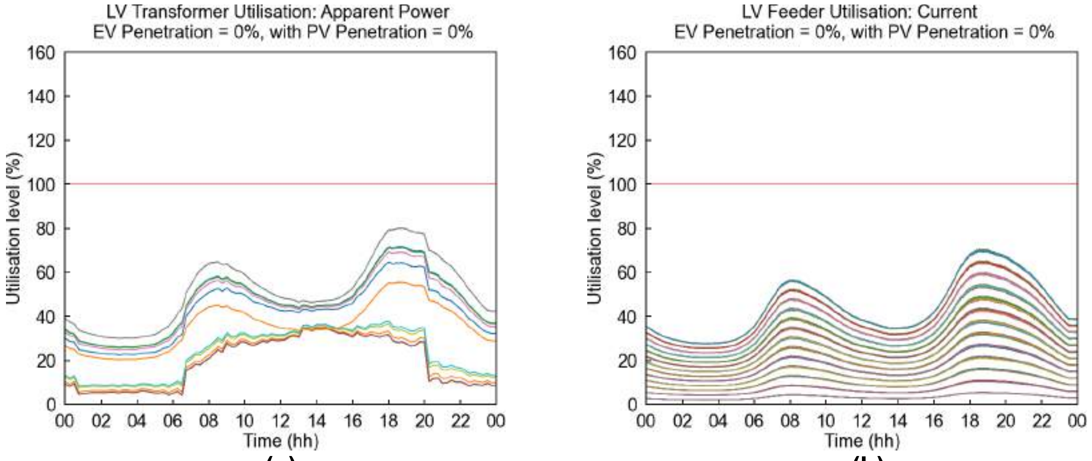
8.2 Base Case

This section presents the performance metrics for Urban TAS when considering the base case, i.e., no EVs. These performance metrics are assessed to provide a reference point for the EV impact analysis.

LV transformer and LV feeder utilisation are shown in Figure 8-5, whilst Figure 8-6 shows customer voltages and HV feeder utilisation for the base case.

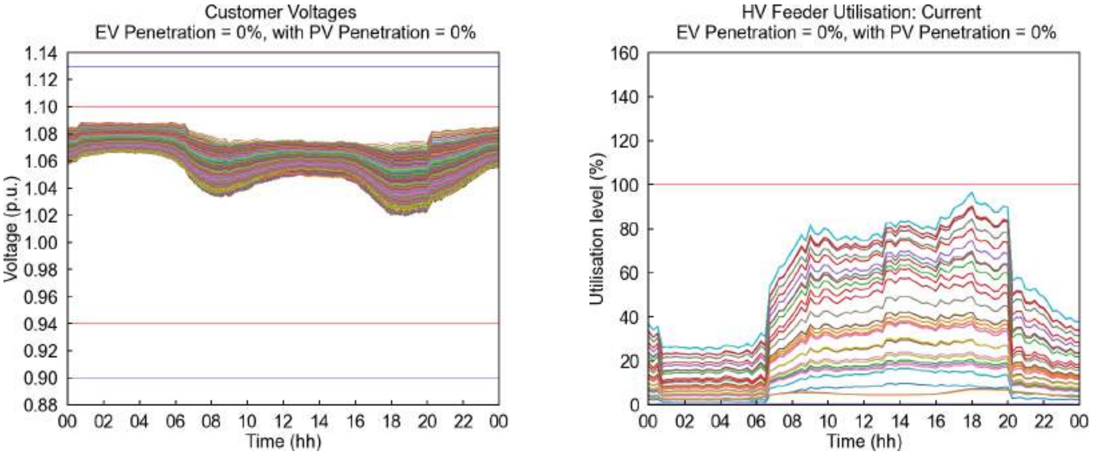
It can be seen in Figure 8-5 (a) and (b) that the LV transformer utilisation and the LV Feeder utilisation are within limits for the base case scenario.

As shown in Figure 8-6 (a) the customer voltages (within the LV feeder) are also within limits. The red line reflects the Australian standard AS 61000.3.100, whilst the blue line reflects the updated (as of April 2020) Victorian LV voltage limits as defined in the Electricity Distribution Code [31]. Finally, Figure 8-6 (b) shows that HV transformer utilisation for the base case is within their respective ratings.



(a) (b)

Figure 8-5. Urban TAS Base Case (a) LV Transformer Utilisation and (b) LV Feeder Utilisation



(a) (b)

Figure 8-6. Urban TAS Base Case (a) Customer Voltages and (b) HV Feeder Utilisation

8.3 EV Impact Assessment

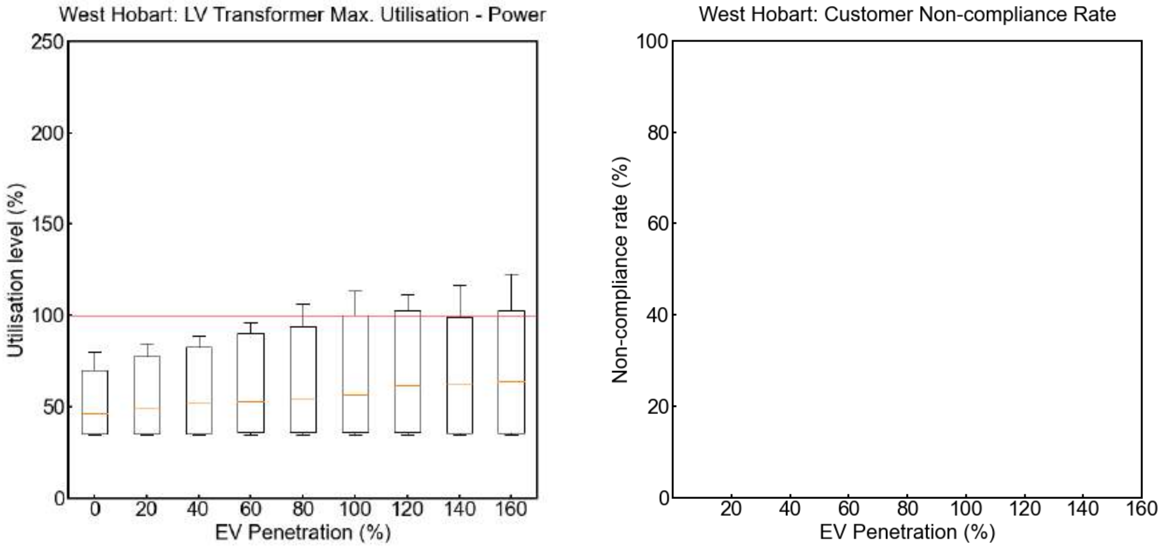
This section presents the different impacts that residential EV charging can have on the Urban TAS feeder considering a 24-hour time-series analysis of the HV-LV feeder for each of the penetration levels, considering the worst-case scenario of a peak demand day.

An overview of the results is presented first. Further details corresponding to LV distribution transformer utilisation, customer voltages, LV feeder utilisation, and HV feeder utilisation are presented in the subsequent sections.

8.3.1 Overview of Results

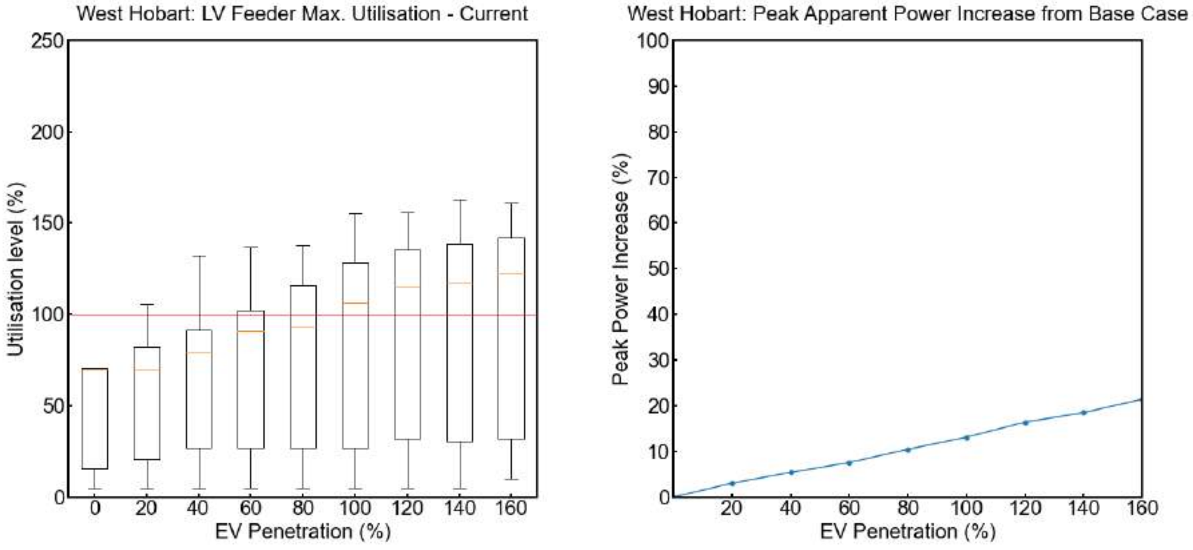
This section presents the overview of results for Urban TAS (West Hobart) considering EV penetrations from 0% up to 160% of residential customers with an EV (100% + 60% with a second EV).

Figure 8-7 (a) presents the LV distribution transformer maximum utilisation for a 24-hour period considering the assessed EV penetrations, whilst Figure 8-7 (b) presents the percentage of customers that violated the Australian standard AS 61000.3.100 voltage limits. Figure 8-8 (a) presents the maximum LV feeder maximum utilisation per LV feeder, for a 24-hour period considering the assessed EV penetrations, whilst Figure 8-8 (b) presents the increase of peak apparent power relative from the base case.



(a) **(b)**

Figure 8-7. Urban TAS Base Case (a) LV Transformer Maximum Utilisation and (b) Percentage of Customers with Non-Compliant Voltages



(a) **(b)**

Figure 8-8. Urban TAS Base Case (a) LV Feeder Maximum Utilisation and (b) Relative Increase in Peak Apparent Power

It can be seen in Figure 8-7 (a) that LV distribution transformers start to overload at 80% EV penetration and a quarter of the transformers are overloaded by 100% EV penetration. Meanwhile there are no customer voltage issues for any EV penetration as shown in Figure 8-7 (b).

Conductors within the LV feeders start to overload from just 20% EV penetration, shown in Figure 8-8 (a), reaching over a quarter of LV conductors by 60%. By 100% EV penetration this reaches to over half of the LV feeders and continues to grow up to the maximum EV penetration. Figure 8-8 (b) shows that at the head of the head of the peak HV feeder apparent power increases by over 20% from the base case to the maximum EV penetration (160%).

Figure 8-9 presents the EV impact on the top five utilised HV line segments within the HV feeder. It can be seen that overloads of the HV conductors within the HV feeder start to occur from 40% EV penetration and beyond.

Figure 8-10 (a) presents the location of these top five utilised segments in relation to the network topology. As expected, considering the aggregation of net demand, all these occur near to the head of the HV feeder. Finally, Figure 8-10 (b) presents the total length in kilometres of overloaded HV conductors, reaching over 0.6km for 40% EV penetration and over 1.2km for 140% EV penetration.

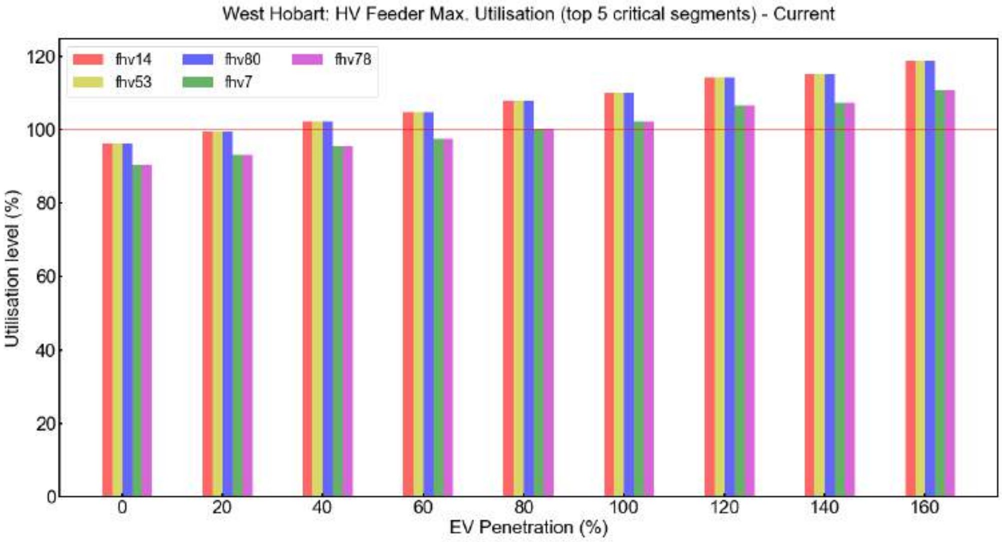


Figure 8-9. Urban TAS Base Case. EV Impact on the Top Five Utilised HV Line Segments

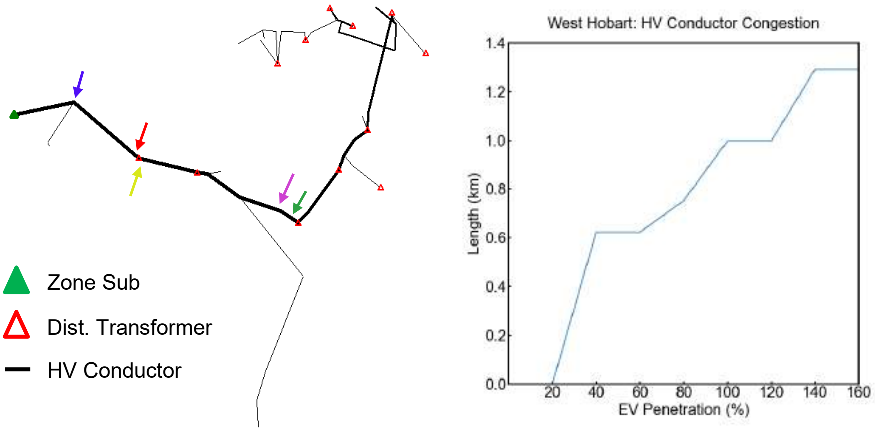
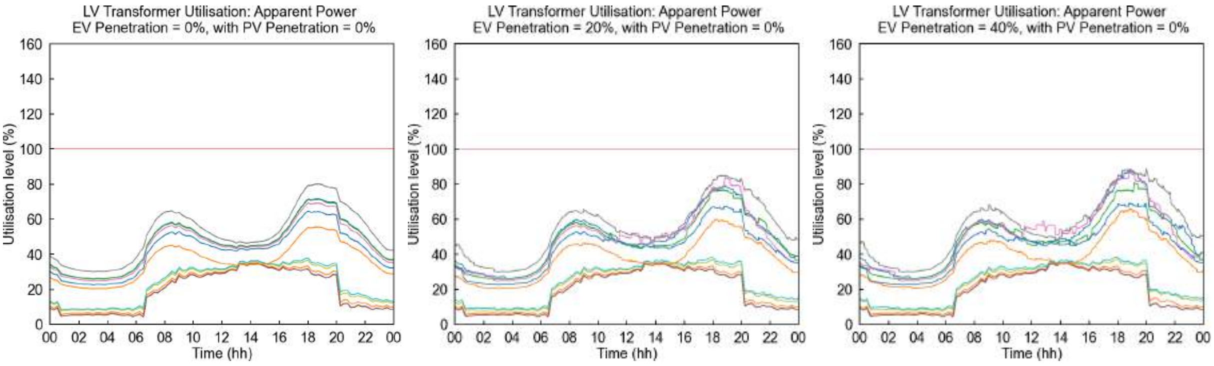


Figure 8-10. Urban TAS Base Case (a) Position of the Top Five Utilised HV Line Segments and (b) Total length of HV Conductor Congestion

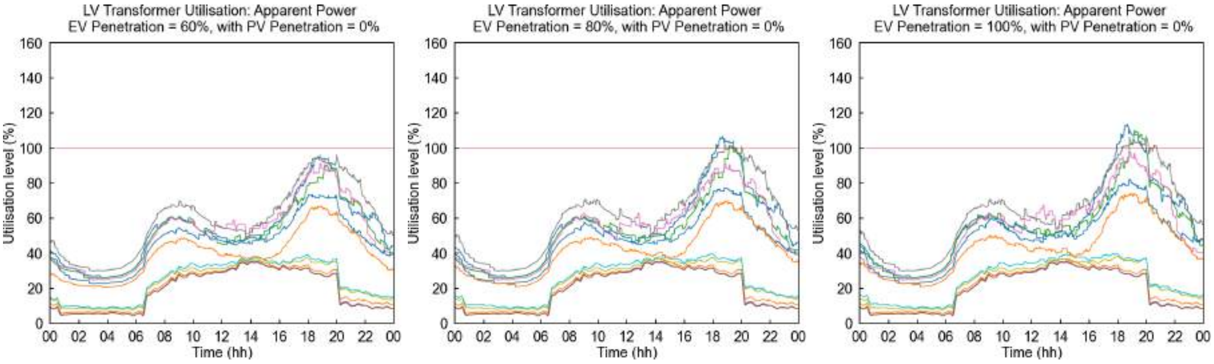
8.3.2 LV Distribution Transformer Utilisation

Figure 8-11 to Figure 8-13 presents the impacts of EVs on the utilisation of LV Distribution Transformers (Tx) for Urban TAS, considering the increase of EV penetrations up to 160%.



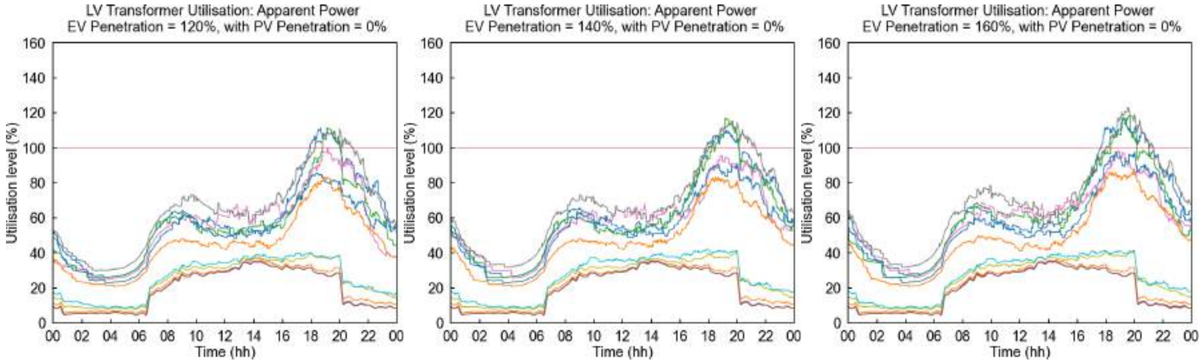
(a) (b) (c)

Figure 8-11. Urban TAS Base Case LV Tx Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 8-12. Urban TAS Base Case LV Tx Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



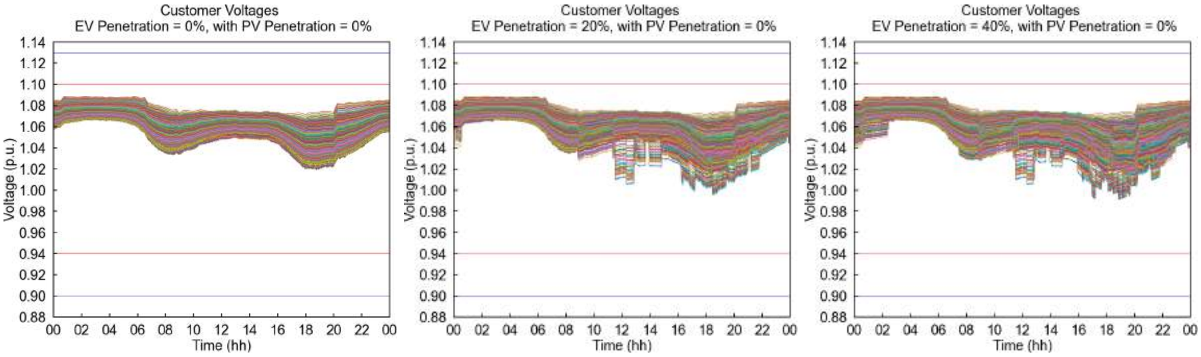
(a) (b) (c)

Figure 8-13. Urban TAS Base Case LV Tx Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen in the results that three LV transformers start to overload at 80% EV penetration. This impact increases in both severity and slightly the number of overloaded LV transformers, as the EV penetration also increases.

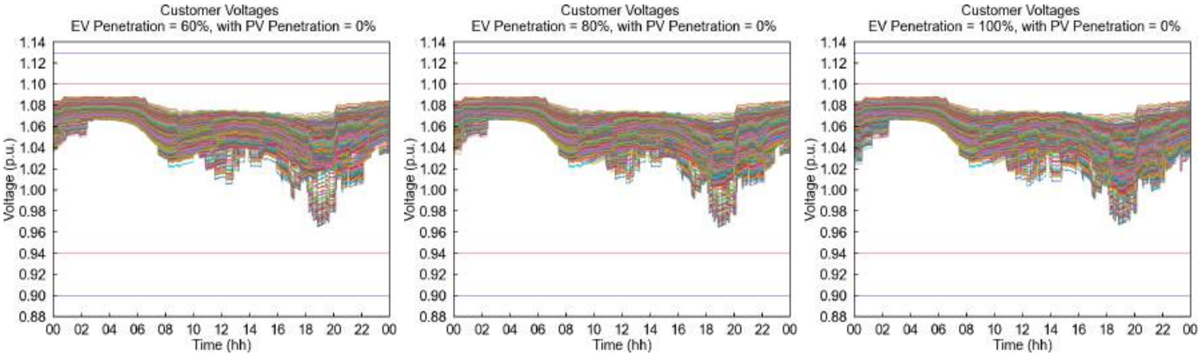
8.3.3 Residential Customer Voltages

Figure 8-14 to Figure 8-16 presents the impacts of EVs on the residential customer voltages for Urban TAS, considering the increase of EV penetrations up to 160%.



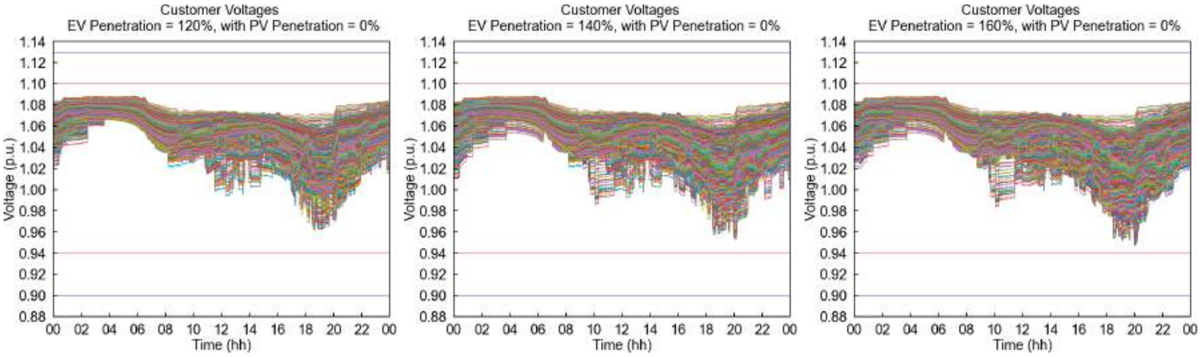
(a) **(b)** **(c)**

Figure 8-14. Urban TAS Base Case Customer Voltages with EVs: (a) 0%, (b) 20% and (c) 40%



(a) **(b)** **(c)**

Figure 8-15. Urban TAS Base Case Customer Voltages with EVs: (a) 60%, (b) 80% and (c) 100%



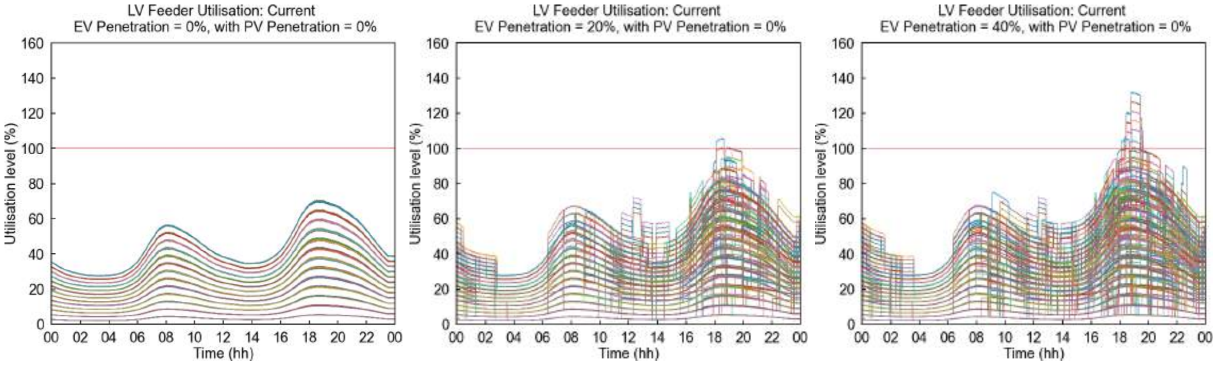
(a) **(b)** **(c)**

Figure 8-16. Urban TAS Base Case Customer Voltages with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen in the results that there are no customer voltage standard violations for Urban TAS. However, voltages are very close to the limits and any significant change in off-load tap positions to accommodate high penetrations of PV in the future will cause voltage drop standard violations.

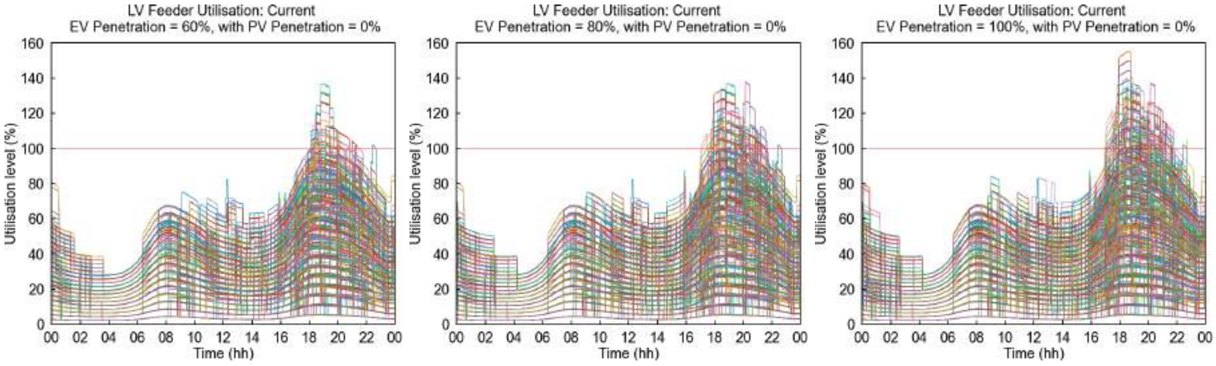
8.3.4 LV Feeder Utilisation

Figure 8-17 to Figure 8-19 presents the impacts of EVs on the utilisation of LV conductors for Urban TAS, considering the increase of EV penetrations up to 160%.



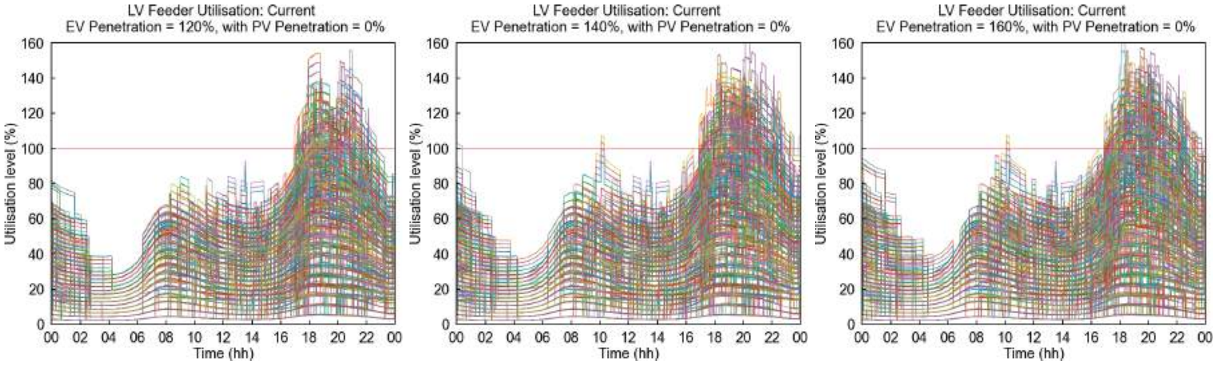
(a) (b) (c)

Figure 8-17. Urban TAS Base Case LV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 8-18. Urban TAS Base Case LV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



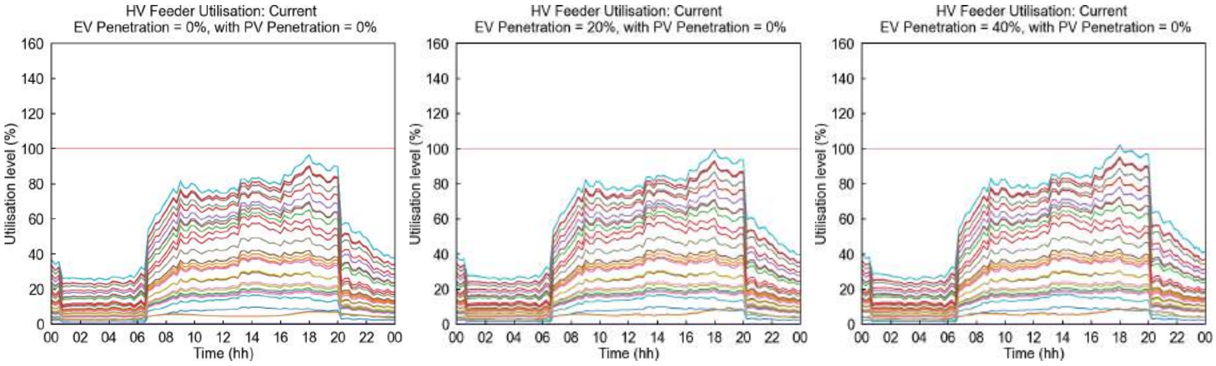
(a) (b) (c)

Figure 8-19. Urban TAS Base Case LV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

As seen in the results a very small number of LV conductors overload at 20% EV penetration. As the EV penetration grows, so does both the number of LV conductors that overload and the severity of the overloads. By 140% EV penetration, overloads also start to occur during the morning hours.

8.3.5 HV Feeder Utilisation

Figure 8-20 to Figure 8-22 presents the impacts of EVs on the utilisation of HV conductors for Urban TAS, considering the increase of EV penetrations up to 160%.

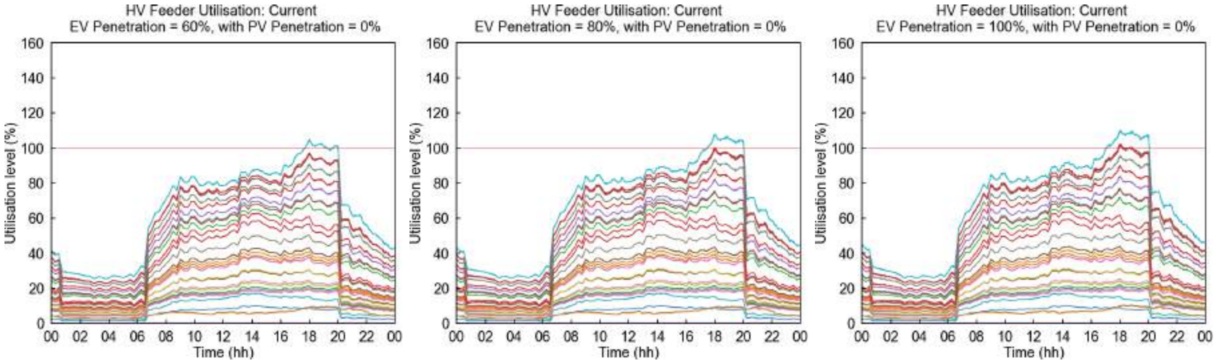

HV Feeder Utilisation: Current EV Penetration = 0%, with PV Penetration = 0%

HV Feeder Utilisation: Current EV Penetration = 20%, with PV Penetration = 0%

HV Feeder Utilisation: Current EV Penetration = 40%, with PV Penetration = 0%

(a) (b) (c)

Figure 8-20. Urban TAS Base Case HV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%

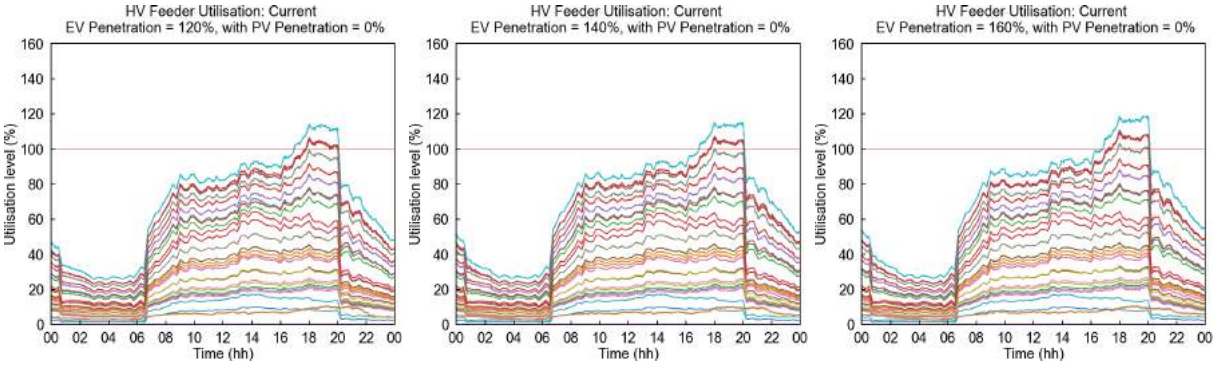

HV Feeder Utilisation: Current EV Penetration = 60%, with PV Penetration = 0%

HV Feeder Utilisation: Current EV Penetration = 80%, with PV Penetration = 0%

HV Feeder Utilisation: Current EV Penetration = 100%, with PV Penetration = 0%

(a) (b) (c)

Figure 8-21. Urban TAS Base Case HV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%


HV Feeder Utilisation: Current EV Penetration = 120%, with PV Penetration = 0%

HV Feeder Utilisation: Current EV Penetration = 140%, with PV Penetration = 0%

HV Feeder Utilisation: Current EV Penetration = 160%, with PV Penetration = 0%

(a) (b) (c)

Figure 8-22. Urban TAS Base Case HV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen in the results that HV feeder utilisation problems occur first at just 20% EV penetration and grows steadily as EV penetration increases. It should be noted that these conductors overloads occur towards the head of the HV feeder as demand aggregates.

8.3.6 Key Remarks

- LV Distribution Transformers start to overload at 80% EV Penetration and beyond. By 100% EV penetration, nearly a quarter of LV distribution transformers are overloaded and stays at a similar percentage to the maximum EV penetration at 160%.
- No lower voltage standard limit violations from residential customers due to EVs.
- LV conductors can overload from as early as 20% EV penetration, rising to over half of LV feeders having overloaded conductors within them at 100% EV penetration.
- The increase in peak apparent power for Urban TAS increases by over 20% by the maximum 160% EV penetration. For feeders with lower non-residential demand and more residential customers, this figure would be expected to increase.
- HV conductor overloads become problematic at 40% EV penetration and beyond. These overloads occur towards the head of the HV feeder as demand aggregates. By the maximum EV penetration, over 1.2km of HV conductors are overloaded (20% of the total length of HV conductors). This could have serious implications for the zone substation and further upstream in the network when considering other HV-LV feeders also connected to the same network assets.
- Considering the above, the **EV hosting capacity of the Urban TAS feeder is limited to less than 20% of residential customers with an EV** due to overloads in some LV feeder's conductor's utilisation. Whilst there are no voltage issues, HV conductors become problematic at 40% and LV transformers start to limit hosting capacity at 80%.

9 Case Study: Rural VIC (SMR8)

This chapter presents the validation results for Rural VIC (SMR8), the base case analysis and the results from the EV impact analysis across different increasing EV penetrations (described in section 4.3.3 and Chapter 3). A summary of the technical information is shown in Table 9-1.

Table 9-1. HV-LV Feeder Technical Information Summary

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)	HV Feeder Peak (MW)
Rural NSW *Hazelbrook*	11kV	1401	39	20	6.5	2.0	24%	3.8	14.7

This HV-LV integrated feeder was modelled in OpenDSS from a previous project ("Advanced Planning of PV-Rich Distribution Networks" [1-6]). As such, the base case from these networks is used and data from the peak demand day is applied, with everything else remaining unchanged (except for the addition of EVs for impact analysis). Head of feeder voltage is set to 1.0p.u. (22kV).

Because these feeders are located in Victoria, non-compliant customer voltages are assessed considering the voltage limits defined in the Electricity Distribution Code [31], instead of the Australian standard AS 61000.3.100 (used in the other feeders). This means a voltage limit of +13%/-10%, instead of +10%/-6%.

9.1 Base Case

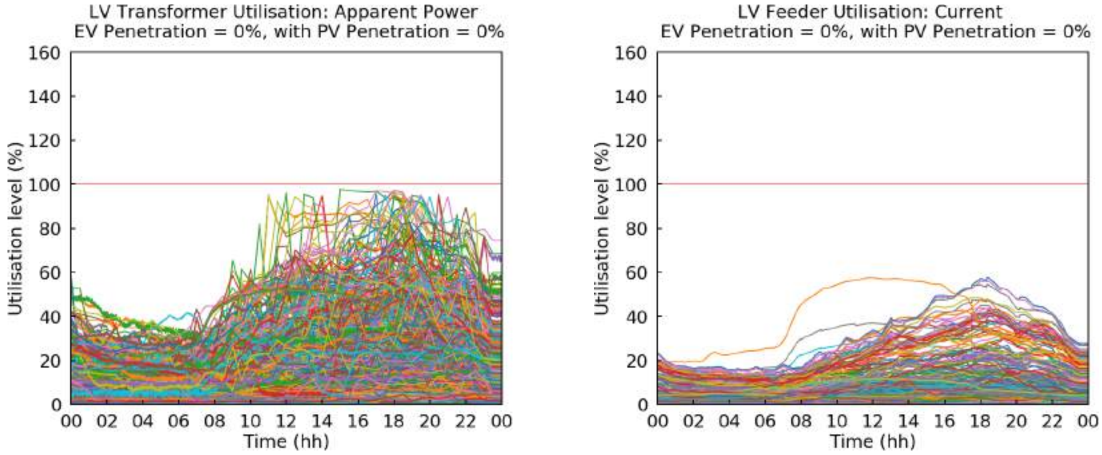
This section presents the performance metrics for Rural VIC when considering the base case, i.e., no EVs. These performance metrics are assessed to provide a reference point for the EV impact analysis.

Figure 9-1 shows the LV transformer and LV feeder utilisation whilst Figure 9-2 shows customer voltages and HV feeder utilisation for the base case.

It can be seen in Figure 9-1 (a) that LV transformer utilisation is within limits for the base case, whilst Figure 9-1 (b) shows the LV feeder utilisation is also within the respective asset ratings.

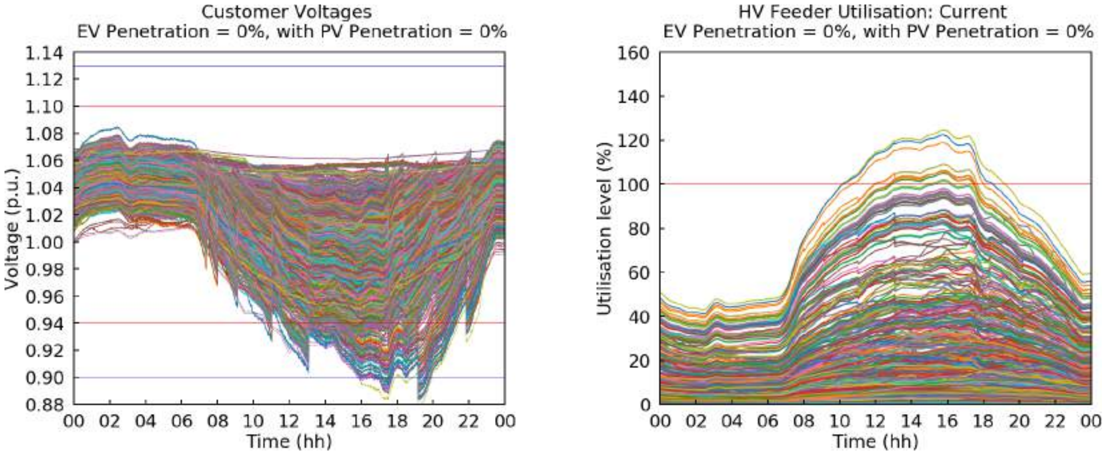
Figure 9-2 (a) shows that the majority of customer voltages are within limits, where the red line reflects the Australian standard AS 61000.3.100, whilst the blue line reflects the updated (as of April 2020) Victorian LV voltage limits as defined in the Electricity Distribution Code [31]. However, because of the voltage at the head of the HV feeder (a proxy of the voltage target of the OLTC) and the nominal position of the off-load tap changers considered for the base case, there are voltage issues during the peak day. There might also be an effect due to simplifications done in the modelling of the Single-Wire Earth Return (SWER) lines. Further analysis will be carried out to determine more adequate off-load tap positions and potentially a more adequate voltage at the head of the HV feeder. Nonetheless, voltage issues are known to exist in rural areas.

Finally, Figure 9-2 (b) shows there is a 20% overload in 3 conductors for the peak demand day, whilst a minor overload in a few more conductors can also be observed. The vast majority of HV conductors are within their respective ratings for the base case of the peak demand day.



(a) (b)

Figure 9-1. Rural VIC Base Case (a) LV Transformer Utilisation and (b) LV Feeder Utilisation



(a) (b)

Figure 9-2. Rural VIC Base Case (a) Customer Voltages and (b) HV Feeder Utilisation

9.2 EV Impact Assessment

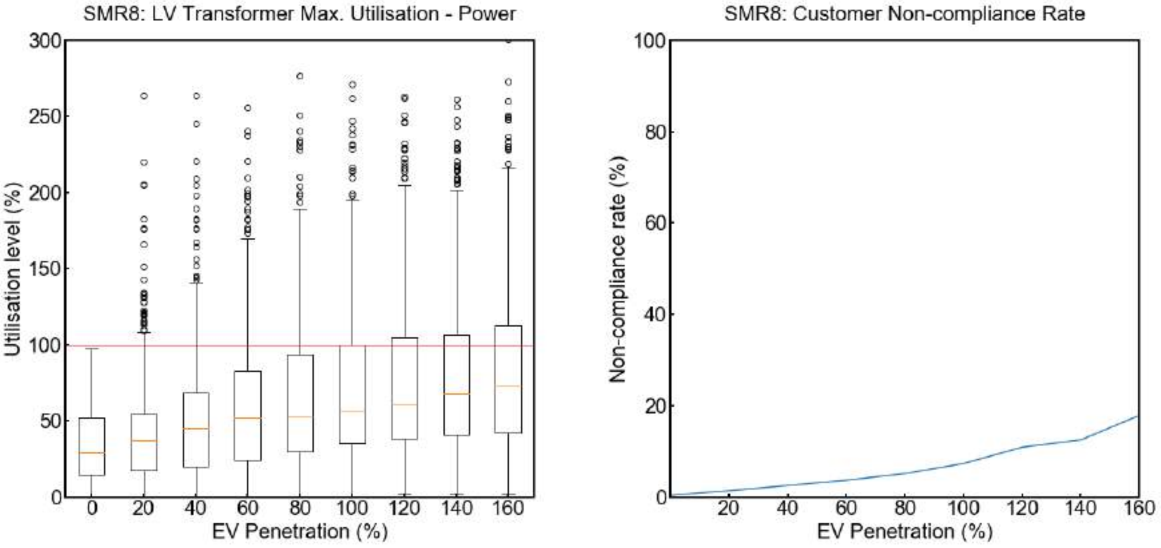
This section presents the different impacts that residential EV charging can have on the Rural VIC feeder considering a 24-hour time-series analysis of the HV-LV feeder for each of the penetration levels, considering the worst-case scenario of a peak demand day.

An overview of the results is presented first. Further details corresponding to LV distribution transformer utilisation, customer voltages, LV feeder utilisation, and HV feeder utilisation are presented in the subsequent sections.

9.2.1 Overview of Results

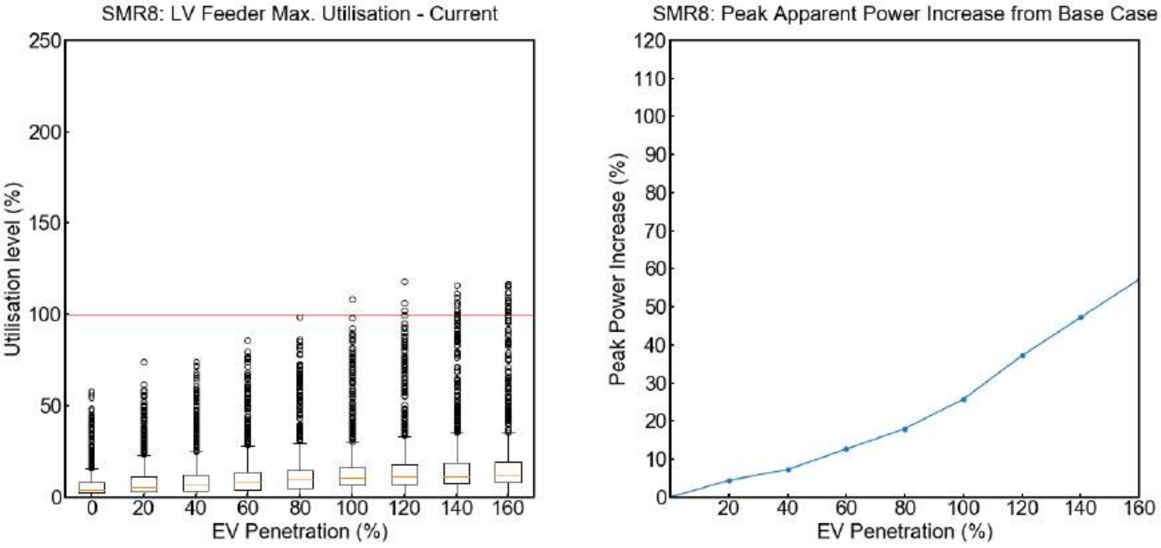
This section presents the overview of results for Rural VIC (SMR8) considering EV penetrations from 0% up to 160% of residential customers with an EV (100% + 60% with a second EV).

Figure 9-3 (a) presents the LV distribution transformer maximum utilisation for a 24-hour period considering the assessed EV penetrations, whilst Figure 9-3 (b) presents the percentage of customers that violated the Victorian LV voltage limits as defined in the Electricity Distribution Code [31]. This limit is used instead of the Australian standard AS 61000.3.100 for the Victorian Feeders (lower limit of 0.90p.u. vs 0.94p.u. respectively). Figure 9-4 (a) presents the maximum LV feeder maximum utilisation per LV feeder, for a 24-hour period considering the assessed EV penetrations, whilst Figure 9-4 (b) presents the increase of peak apparent power relative from the base case.



(a) (b)

Figure 9-3. Rural VIC Base Case (a) LV Transformer Maximum Utilisation and (b) Percentage of Customers with Non-Compliant Voltages



(a) (b)

Figure 9-4. Rural VIC Base Case (a) LV Feeder Maximum Utilisation and (b) Relative Increase in Peak Apparent Power

LV distribution transformers begin to have congestion issues, shown in Figure 9-3 (a), from 20% EV penetration and beyond. By 100% EV penetration, a quarter of LV distribution transformers have congestion issues. Whilst voltage issues were seen in the base case, Figure 9-3 (b) highlights that this is a very small percentage of customers within the feeder. By maximum EV penetration, approximately 1 in 5 customers are exceeding the Victorian LV voltage limits as defined in the Electricity Distribution Code [31].

It can be seen in Figure 9-4 (a) that the LV feeders start to have LV conductors within them that have congestion issues at 100% EV penetration and beyond. However, considering the size of this feeder and the higher number of LV distribution transformers/LV feeders per customer relative to the other feeders (over 700 LV distribution transformers in total), this is not a significant portion of LV feeders.

Finally, Figure 9-4 (b) shows there is approximately a 55% increase in the peak apparent power increase by the maximum EV penetration (160%), this may become significant for the zone substation and other assets upstream, when aggregated with other HV-LV feeders.

Figure 9-5 presents the EV impact on the top five utilised HV line segments within the HV feeder. Overloads of an HV conductor segment starts to overload for the base case. By maximum EV penetration, all top five utilised HV conductors are overloaded by approximately 180-200%. It should be noted that the top five segments are taken at maximum EV penetration.

Figure 9-6 (a) recaps the network topology for context, whilst Figure 9-6 (b) presents the total length in kilometres of overloaded HV conductors, reaching approximately 25km of overloaded conductors at 100% EV penetration and 35km at 160% EV penetration. However, considering the size of this feeder, 35km still only represents less than 10% of the total length of HV conductors.

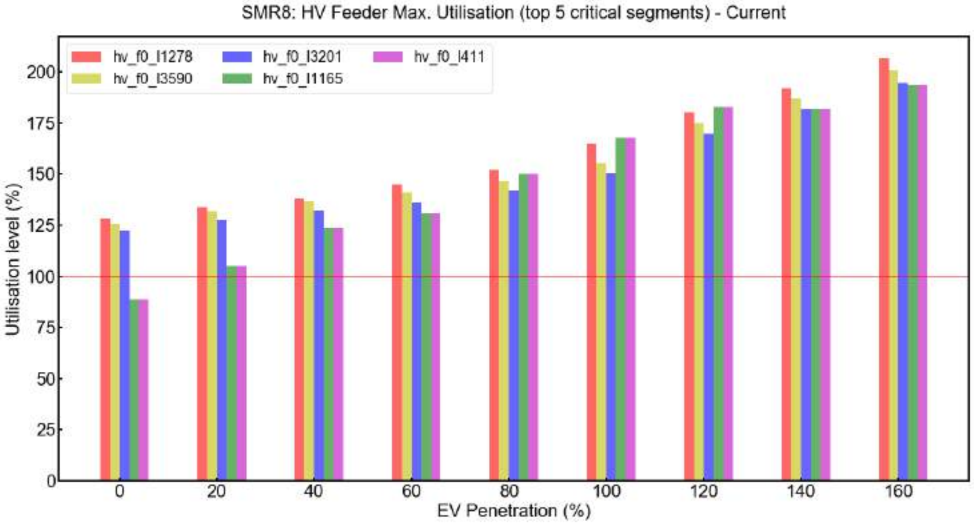
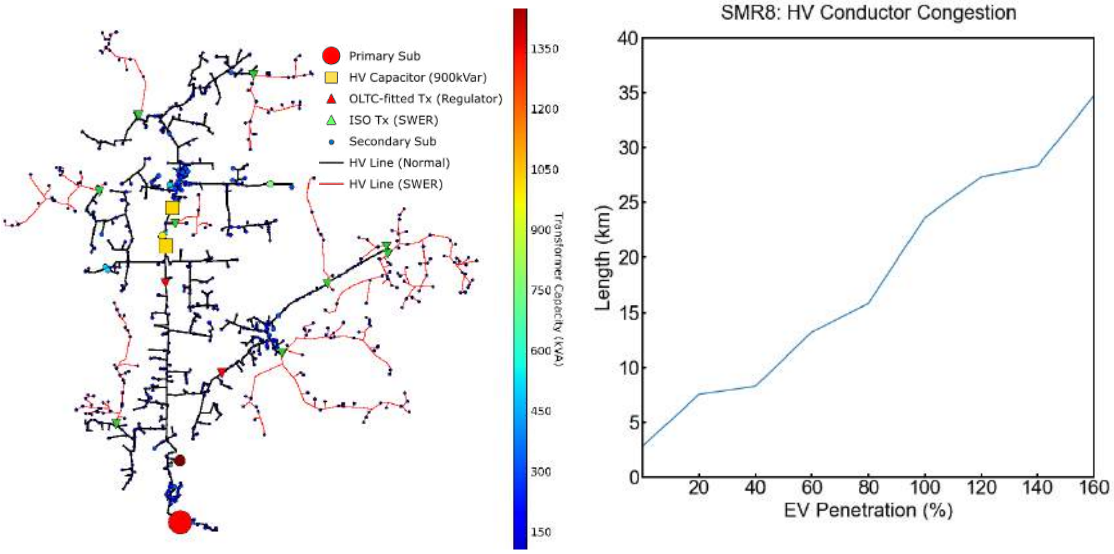


Figure 9-5. Rural VIC Base Case. EV Impact on the Top Five Utilised HV Line Segments

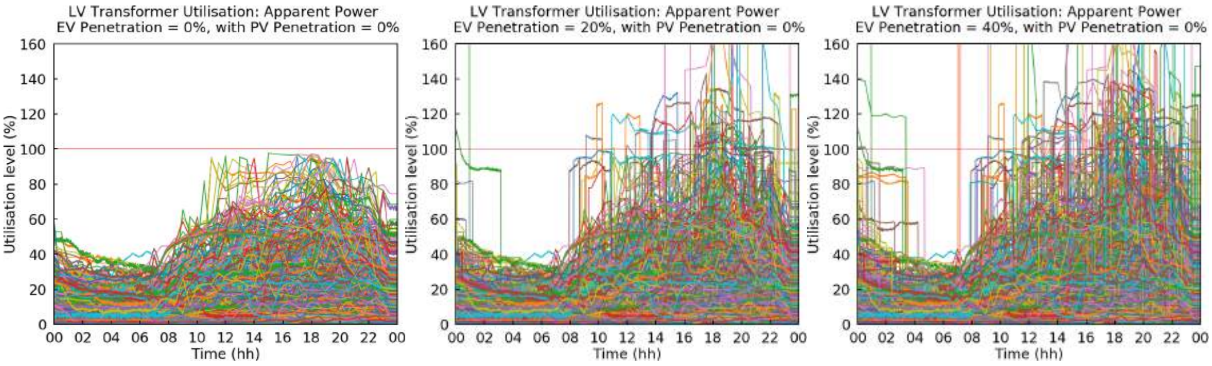


(a) (b)

Figure 9-6. Rural VIC Base Case (a) Network Topology and (b) Total length of HV Conductor Congestion

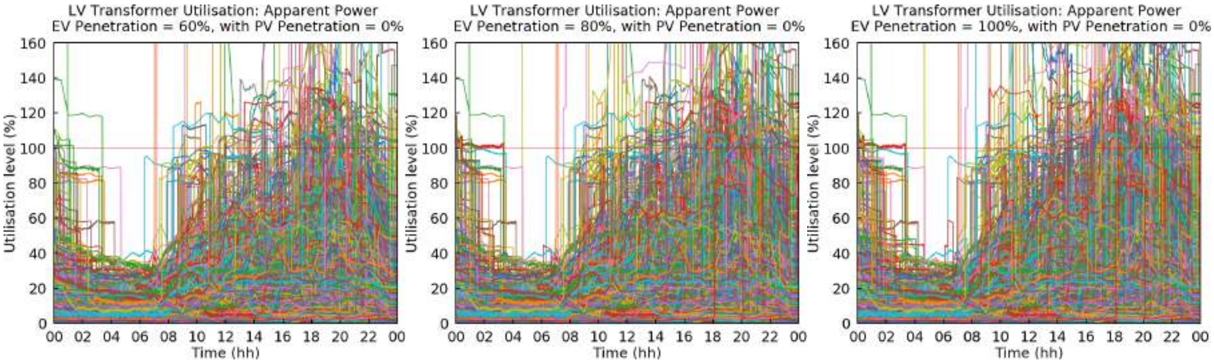
9.2.2 LV Distribution Transformer Utilisation

Figure 9-7 to Figure 9-9 presents the impacts of EVs on the utilisation of LV Distribution Transformers (Tx) for Rural VIC, considering the increase of EV penetrations up to 160%.



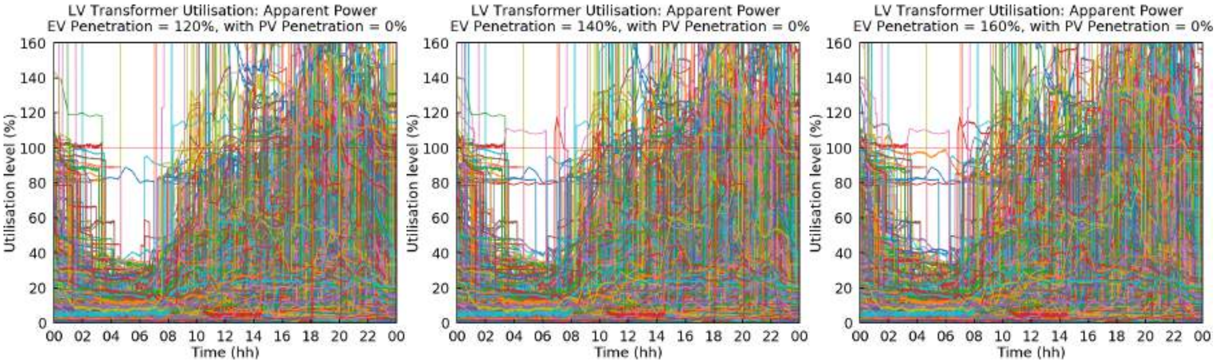
(a) (b) (c)

Figure 9-7. Rural VIC Base Case LV Tx Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 9-8. Rural VIC Base Case LV Tx Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



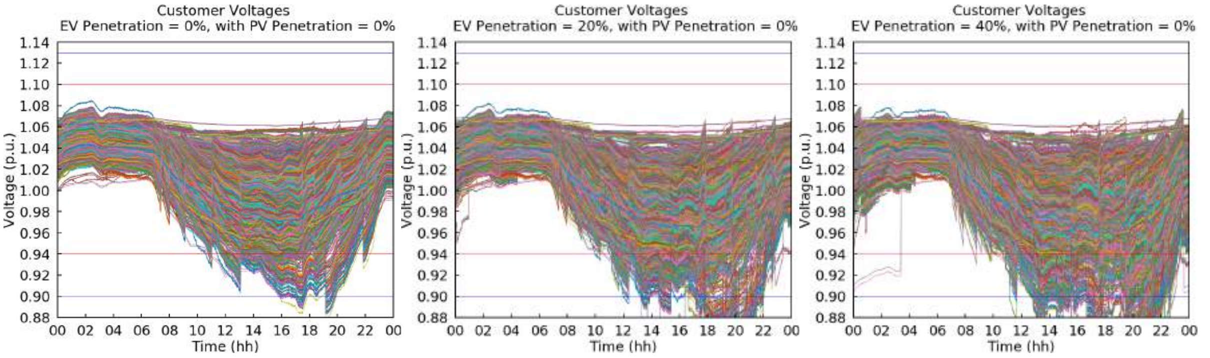
(a) (b) (c)

Figure 9-9. Rural VIC Base Case LV Tx Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

For the base case in Figure 9-7 (a) there are no LV distribution transformer utilisation issues. However, from just 20% EV penetration LV distribution overload issues start to occur. This quickly increase in the number of transformers and the severity. It should be noted that this LV transformer has over 700 LV distribution transformers, and as such the plots of each individual LV distribution transformer gets quite full quickly once overloads occur. However as shown in the overview, at 100% EV penetration, a quarter of LV distribution transformers are overloaded.

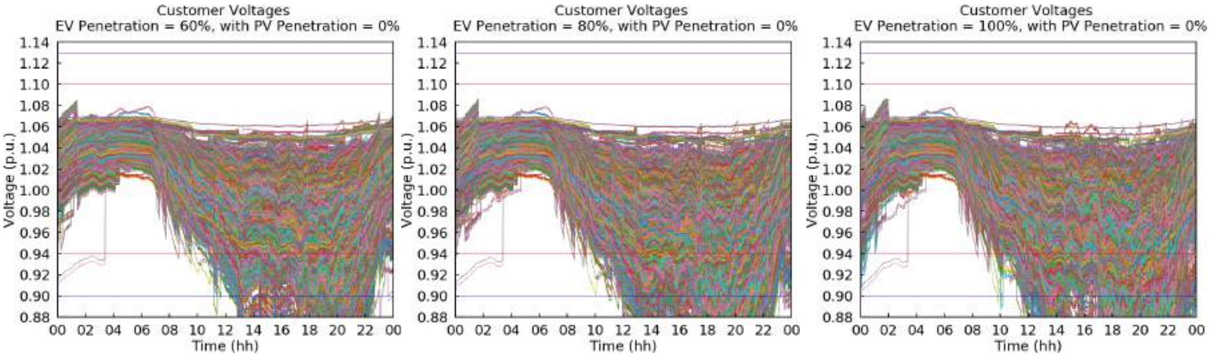
9.2.3 Residential Customer Voltages

Figure 9-10 to Figure 9-12 presents the impacts of EVs on the residential customer voltages for Urban VIC, considering the increase of EV penetrations up to 160%.



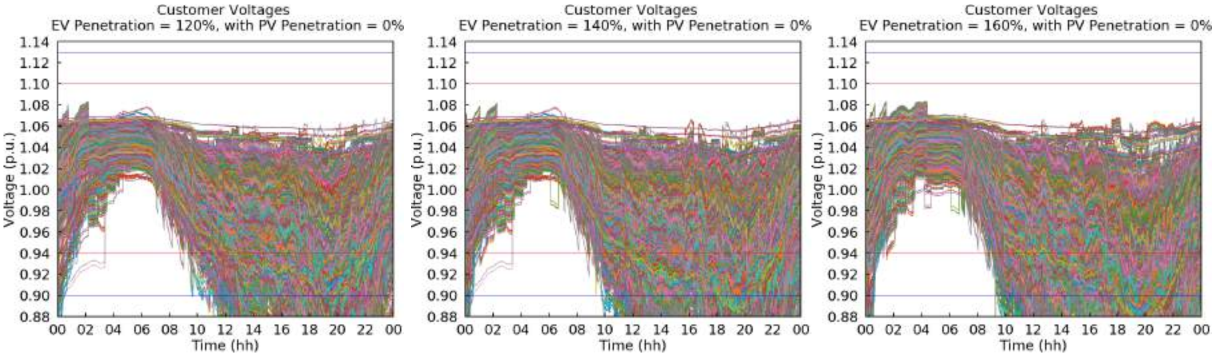
(a) **(b)** **(c)**

Figure 9-10. Rural VIC Base Case Customer Voltages with EVs: (a) 0%, (b) 20% and (c) 40%



(a) **(b)** **(c)**

Figure 9-11. Rural VIC Base Case Customer Voltages with EVs: (a) 60%, (b) 80% and (c) 100%



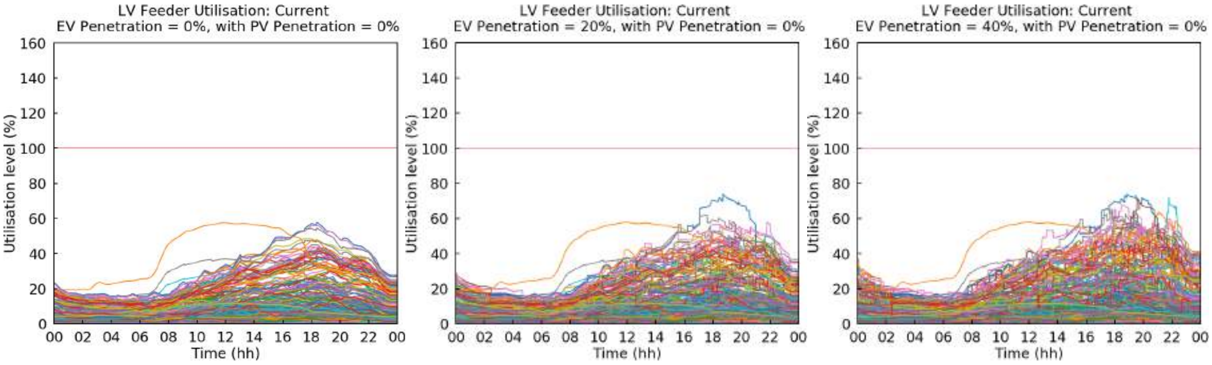
(a) **(b)** **(c)**

Figure 9-12. Urban VIC Base Case Customer Voltages with EVs: (a) 120%, (b) 140% and (c) 160%

Overall it can be seen that there are a few customers exceeding the Victorian LV voltage limits as defined in the Electricity Distribution Code [31], shown by the blue lines. The voltage drop problem caused by EVs becomes quite serious at 20-60% EV penetration and beyond. From the Advance Planning of PV-rich Distribution Networks project [3], it is known also that this feeder has hosting capacity problems for 20% customers with PV systems and as such options with the LV distribution transformer off-load tap positions, whilst can be adjusted to improve the base case, may still introduce problems during peak daylight hours once PV is considered. However, adjustments to the head of the feeder voltage (e.g., zone sub tap position) can still improve voltage.

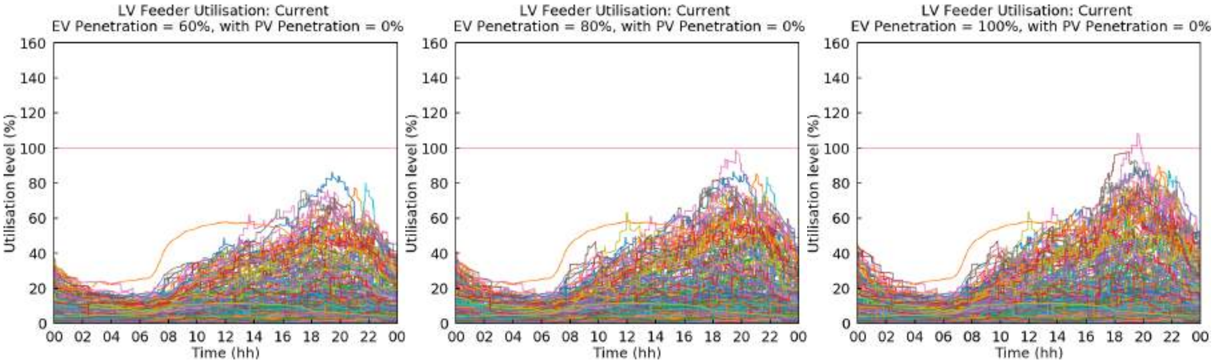
9.2.4 LV Feeder Utilisation

Figure 9-13 to Figure 9-15 presents the impacts of EVs on the utilisation of LV conductors for Rural VIC, considering the increase of EV penetrations up to 160%.



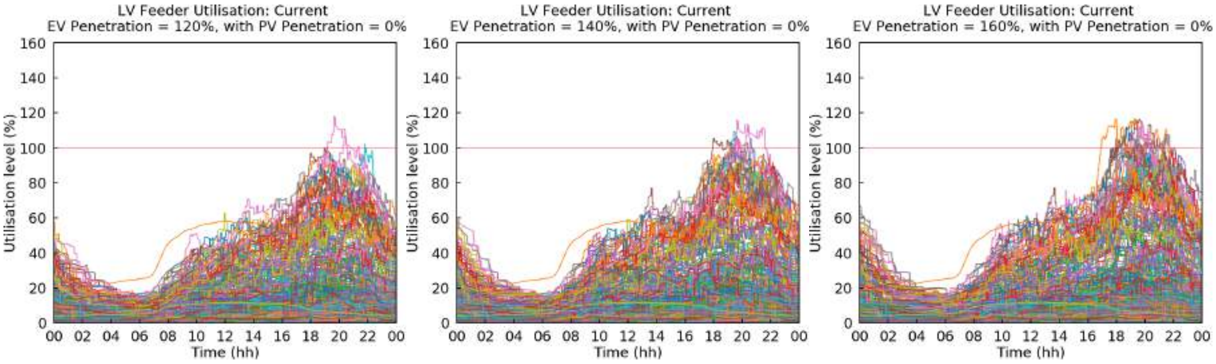
(a) (b) (c)

Figure 9-13. Rural VIC Base Case LV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 9-14. Rural VIC Base Case LV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



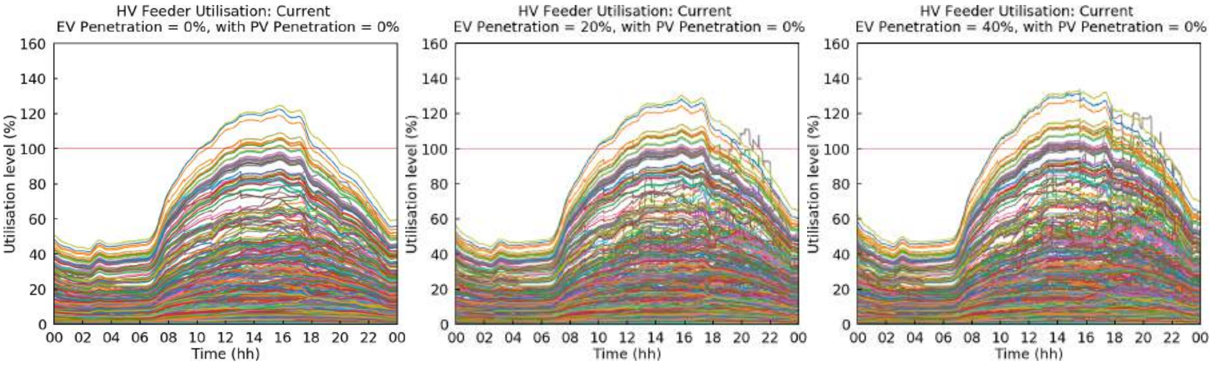
(a) (b) (c)

Figure 9-15. Rural VIC Base Case LV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

The results show in Figure 9-14 and Figure 9-15 that LV feeder utilisation problems occur for a few feeders from 60% EV penetration and grow in number by 160% EV penetration. Due to the spread-out nature of this very large feeder (over 700 LV distribution transformers), there are relatively few customers per LV feeder and as such, considering the fixed ampacity rating of the LV conductors used in the pseudo-LV feeders, only a minority of LV feeders have asset utilisation problems, and the overloads are not too high.

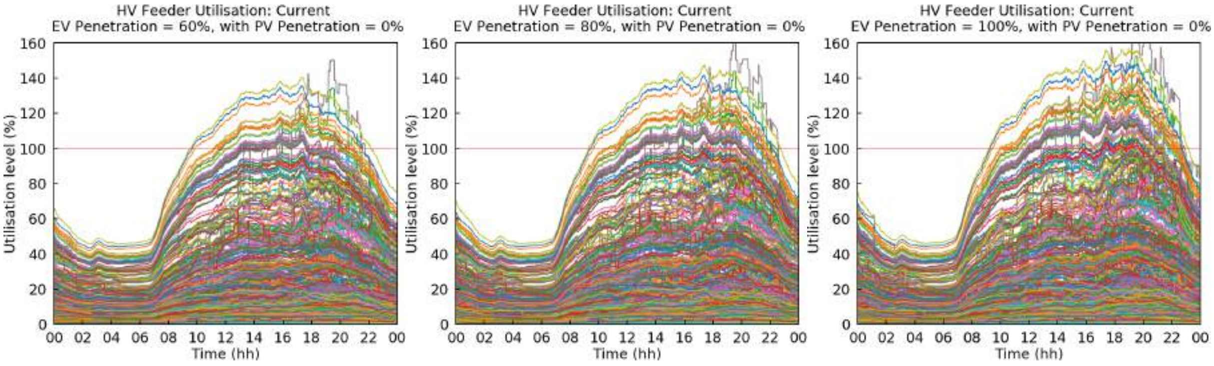
9.2.5 HV Feeder Utilisation

Figure 9-16 to Figure 9-18 presents the impacts of EVs on the utilisation of HV conductors for Rural VIC, considering the increase of EV penetrations up to 160%.



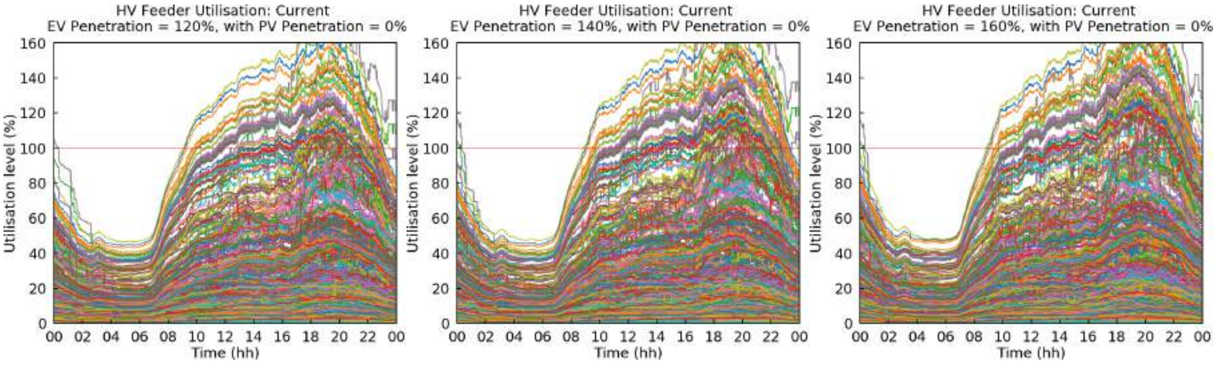
(a) (b) (c)

Figure 9-16. Rural VIC Base Case HV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 9-17. Rural VIC Base Case HV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



(a) (b) (c)

Figure 9-18. Urban VIC Base Case HV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

As seen in the results, overloads of HV conductor segment occur within the base case which considers a peak demand day. As EV penetration increases, the severity and number of HV conductors that are overloaded increases significantly. Considering that this feeder has a total conductor length of 400km, at maximum EV penetration the overloaded HV conductors still only form less than 10% of all HV conductors within the feeder.

9.2.6 Key Remarks

- LV distribution transformers start to overload at 20% EV penetration and beyond. By 100% EV penetration, approximately a quarter of LV distribution transformers are overloaded.
- Due to simplifications associated with SWER lines in the HV-LV feeder model, the base case (peak demand without EVs) suggests there might already be a small percentage of customers with voltage problems; even when considering the new Victorian limits as defined in the Electricity Distribution Code [31]. As EV penetration increases, the number of customers with voltage issues grows as does the severity of the voltage problem. By the maximum EV penetration (160%), approximately 1 in 5 residential customers might have a (Victorian) voltage standard violation.
- LV feeders were found to have asset utilisation problems within the LV conductors at 100% EV penetration and beyond. However, this only affects a small portion of LV feeders.
- A few segments of the HV feeder already have overload issues (up to 20%) when considering the base case (which can occur in practice). As EV penetration increases the severity and number of overloaded HV conductors increases. By 100% EV penetration close to 25km of HV conductor could be overloaded, and at maximum penetration this is approximately just under 35km (less than 10% of the total length of HV conductors).
- The increase in peak apparent power for Rural VIC increases by approximately 55% by the maximum 160% EV penetration. For feeders with lower non-residential demand and more residential customers, this figure would be expected to increase. This could have serious implications for the zone substation and further upstream in the network when considering other HV-LV feeders also connected to the same network assets.
- Overall, considering the above, the **EV hosting capacity of the Rural VIC feeder is less than 20% of residential customers with an EV**, with customer voltages and the HV feeder being the first issue that would need to be addressed with issues already being seen for the peak demand day. The next limiting factor is LV distribution transformers that begin to overload at 20% EV penetration.

10 Case Study: Urban VIC (CRE21)

This chapter presents the validation results for Urban VIC (SMR8), the base case analysis and the results from the EV impact analysis across different increasing EV penetrations (described in section 4.3.3 and Chapter 3). A summary of the technical information is shown in Table 10-1.

Table 10-1. HV-LV Feeder Technical Information Summary

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)	HV Feeder Peak (MW)
Urban VIC *CRE21*	22kV	3383	80	30	4.0	2.0	0%	-	7.80

This HV-LV integrated feeder was modelled in OpenDSS from a previous project ("Advanced Planning of PV-Rich Distribution Networks" [1-6]). As such, the base case from these networks is used and data from the peak demand day is applied, with everything else remaining unchanged (except for the addition of EVs for impact analysis). Head of feeder voltage is set to 1.0p.u. (22kV).

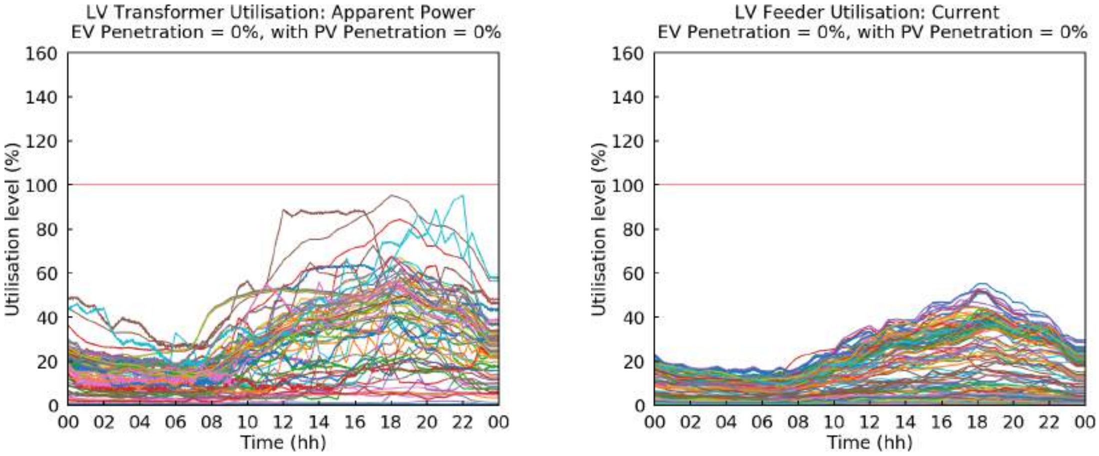
Because these feeders are located in Victoria, non-compliant customer voltages are assessed considering the voltage limits defined in the Electricity Distribution Code [31], instead of the Australian standard AS 61000.3.100 (used in the other feeders). This means a voltage limit of +13%/-10%, instead of +10%/-6%.

10.1 Base Case

This section presents the performance metrics for Urban VIC when considering the base case, i.e., no EVs. These performance metrics are assessed to provide a reference point for the EV impact analysis.

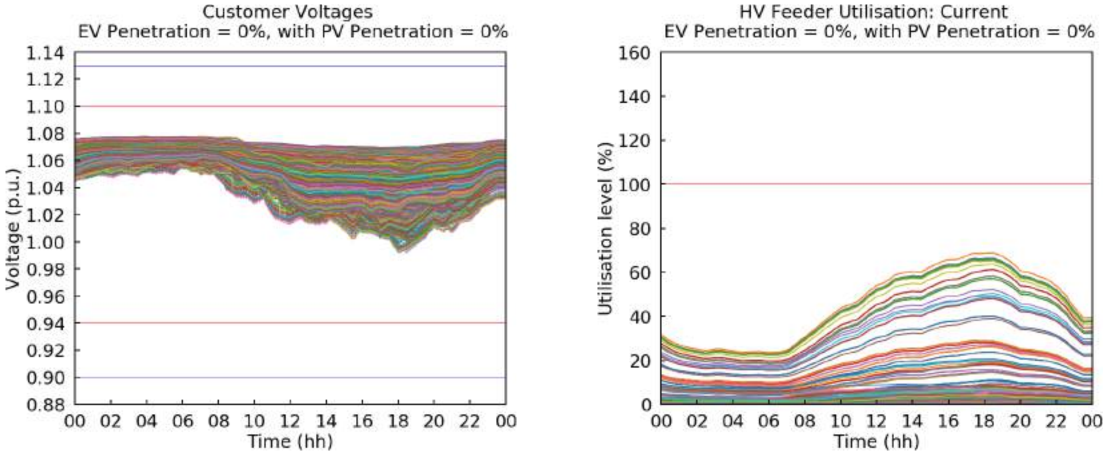
Figure 10-1 shows the LV transformer and LV feeder utilisation whilst Figure 10-2 shows customer voltages and HV feeder utilisation for the base case.

It can be seen in Figure 10-1 (a) that the LV transformer utilisation is within limits, as is the LV feeder utilisation shown in Figure 10-1 (b). Furthermore, the customer voltages shown in Figure 10-2 (a) are also within limits, where the red line reflects the Australian standard AS 61000.3.100, whilst the blue line reflects the updated (as of April 2020) Victorian LV voltage limits as defined in the Electricity Distribution Code [31]. Finally, as seen in Figure 10-2 (b), all the HV conductors are within limits.



(a) (b)

Figure 10-1. Urban VIC Base Case (a) LV Transformer Utilisation and (b) LV Feeder Utilisation



(a) **(b)**

Figure 10-2. Urban VIC Base Case (a) Customer Voltages and (b) HV Feeder Utilisation

10.2 EV Impact Assessment

This section presents the different impacts that residential EV charging can have on the Urban VIC feeder considering a 24-hour time-series analysis of the HV-LV feeder for each of the penetration levels, considering the worst-case scenario of a peak demand day.

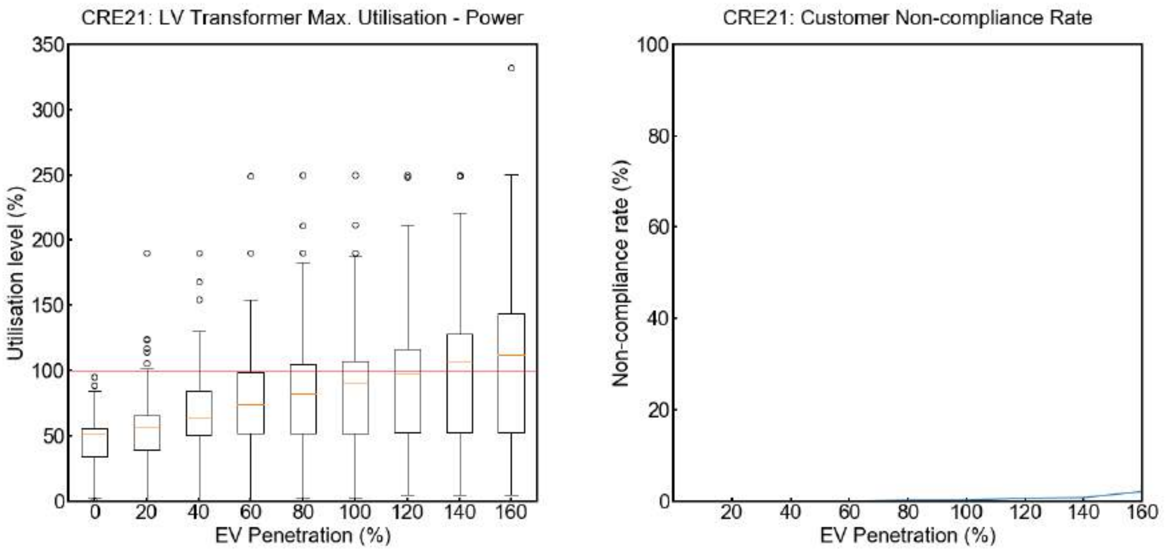
An overview of the results is presented first. Further details corresponding to LV distribution transformer utilisation, customer voltages, LV feeder utilisation, and HV feeder utilisation are presented in the subsequent sections.

10.2.1 Overview of Results

This section presents the overview of results for Urban VIC (CRE21) considering EV penetrations from 0% up to 160% of residential customers with an EV (100% + 60% with a second EV).

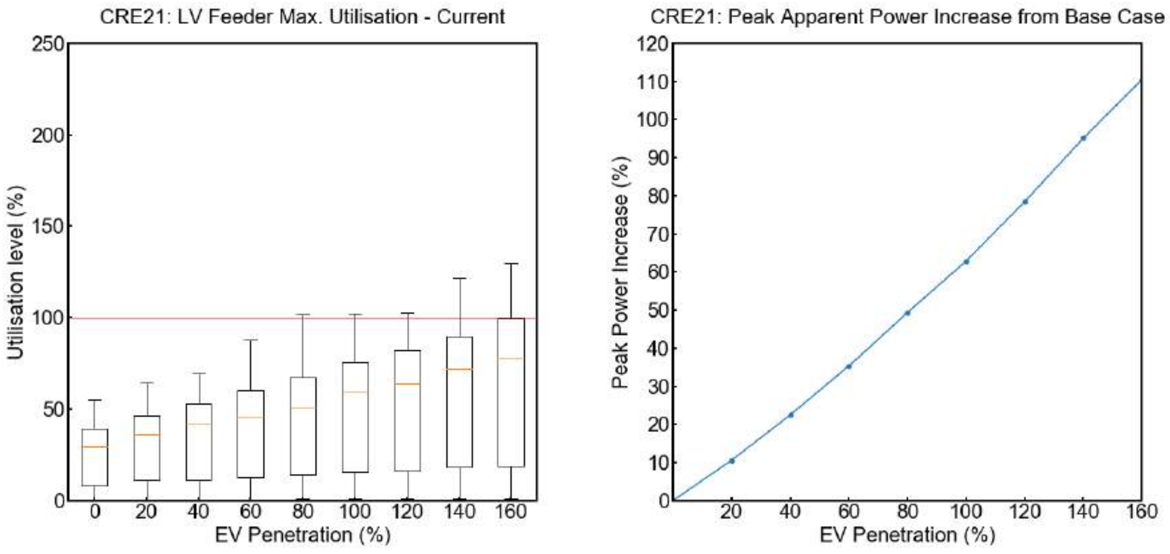
Figure 10-3 (a) presents the LV distribution transformer maximum utilisation for a 24-hour period considering the assessed EV penetrations, whilst Figure 10-3 (b) presents the percentage of customers that violated the Victorian LV voltage limits as defined in the Electricity Distribution Code [31]. This limit is used instead of the Australian standard AS 61000.3.100 for the Victorian Feeders (lower limit of 0.90p.u. vs 0.94p.u. respectively). Figure 10-4 (a) presents the maximum LV feeder maximum utilisation per LV feeder, for a 24-hour period considering the assessed EV penetrations, whilst Figure 10-4 (b) presents the increase of peak apparent power relative from the base case.

LV distribution transformers for the Urban VIC feeder start to overload at 20% EV penetration as seen in Figure 10-3 (a). By 60% EV penetration approximately a quarter of LV distribution transformers are overloaded. By 120% EV penetration, this reaches over half of LV distribution transformers. Customer voltage issues shown in Figure 10-3 (b), whilst do occur from 80% EV penetration, are not widespread, with only a very small percentage of customers with voltage issues at maximum EV penetration. As seen in Figure 10-4 (a) LV Feeder utilisation issues first occur at 80% EV penetration and by the maximum EV penetration, approximately a quarter of LV feeders have overloaded LV conductors within them. Finally, Figure 10-4 (b) shows that the peak apparent power increase from the base case to the maximum EV penetration is approximately 110% percent. This can have significant implications for both the zone substation and assets further upstream, when considering other HV-LV feeders that may also be connected to the same zone substation.



(a) **(b)**

Figure 10-3. Urban VIC Base Case (a) LV Transformer Maximum Utilisation and (b) Percentage of Customers with Non-Compliant Voltages



(a) **(b)**

Figure 10-4. Urban VIC Base Case (a) LV Feeder Maximum Utilisation and (b) Relative Increase in Peak Apparent Power

Figure 10-5 presents the EV impact on the top five utilised HV line segments within the HV feeder. Overloads of an HV conductor segment starts to overload for the base case. It should be noted that the top five segments are taken at maximum EV penetration. Congestion of HV conductors first occur at 80% EV penetration, and by the maximum EV penetration, the overloads are above 140%.

Figure 10-6 (a) recaps the network topology for context, whilst Figure 10-6 (b) presents the total length in kilometres of overloaded HV conductors, reaching approximately just over 2.5km at 100% EV penetration and over 3.5km at the maximum EV penetration (just over 10% of total length).

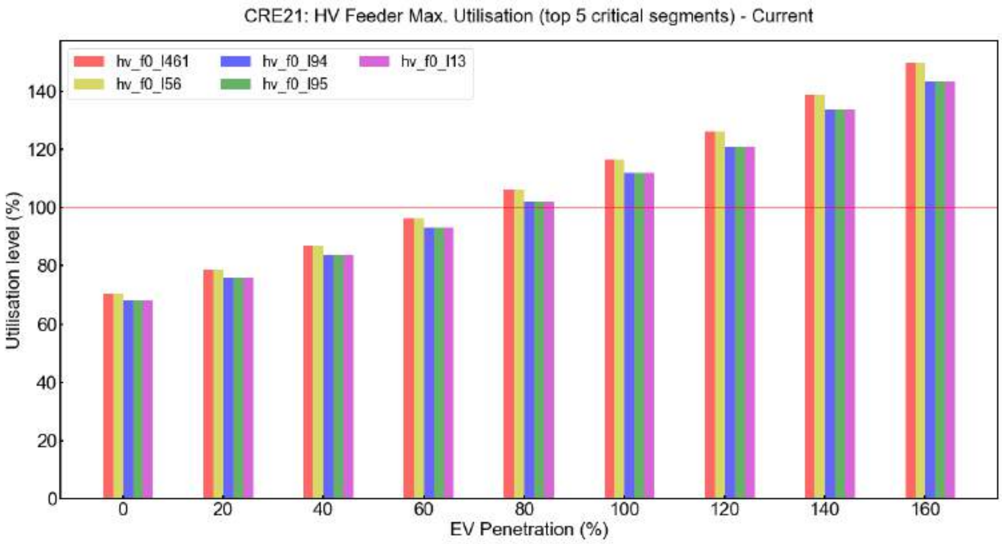
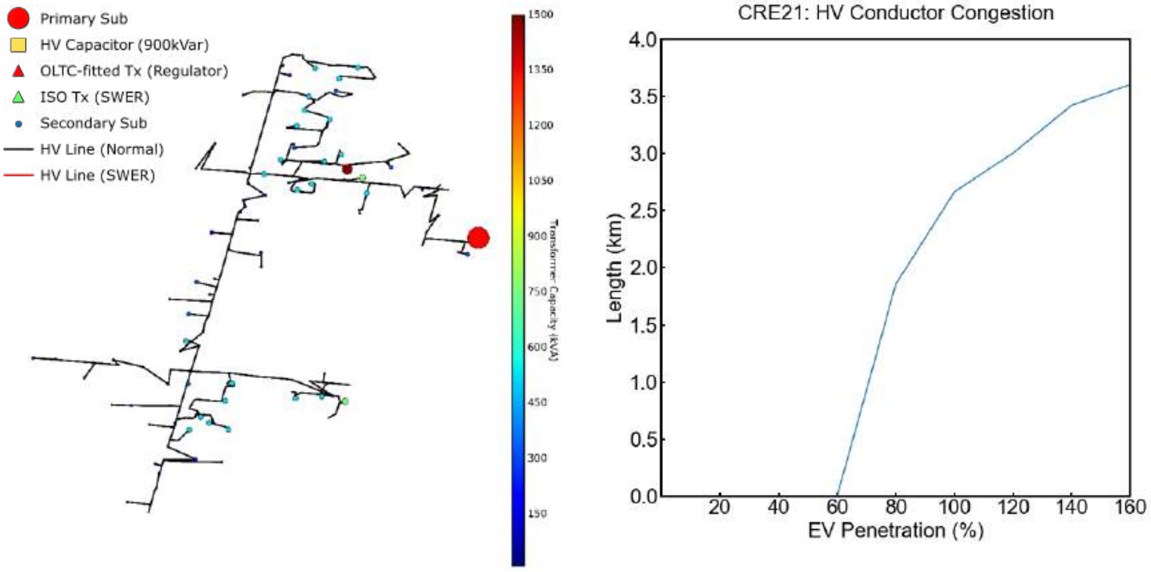


Figure 10-5. Urban VIC Base Case. EV Impact on the Top Five Utilised HV Line Segments

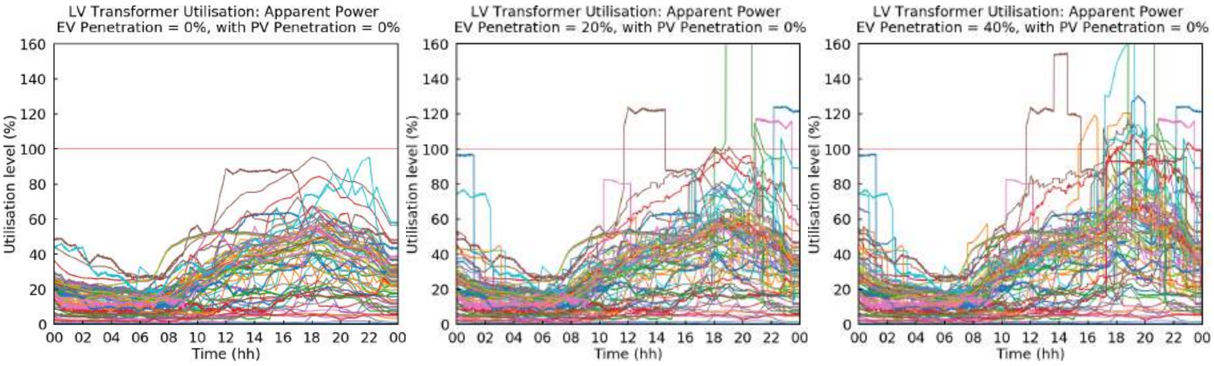


(a) (b)

Figure 10-6. Urban VIC Base Case (a) Network Topology and (b) Total length of HV Conductor Congestion

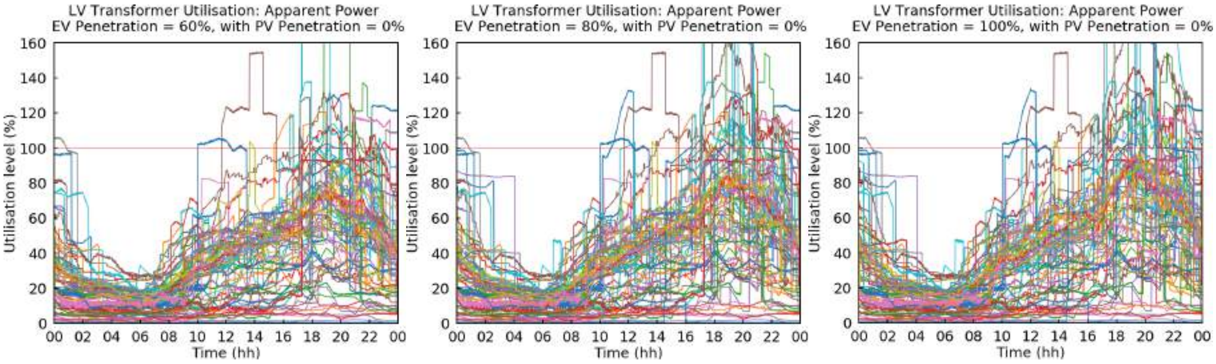
10.2.2 LV Distribution Transformer Utilisation

Figure 10-7 to Figure 10-9 presents the impacts of EVs on the utilisation of LV Distribution Transformers (Tx) for Urban VIC, considering the increase of EV penetrations up to 160%.



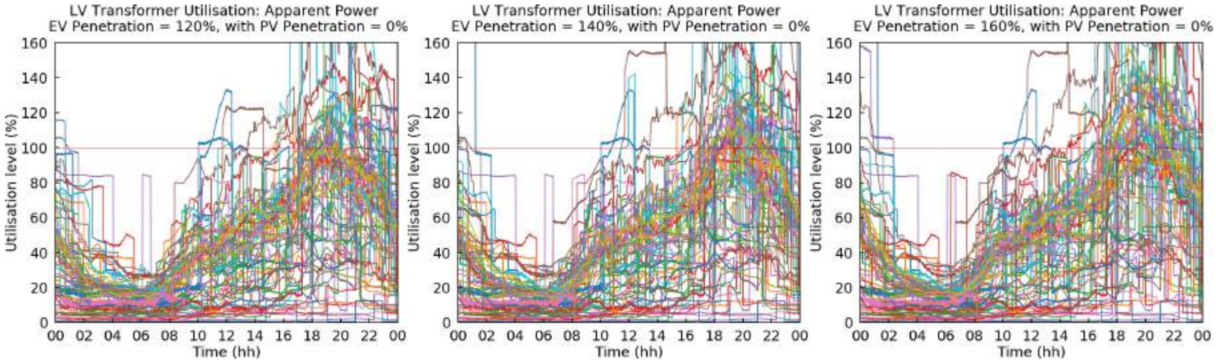
(a) (b) (c)

Figure 10-7. Urban VIC Base Case LV Tx Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 10-8. Urban VIC Base Case LV Tx Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



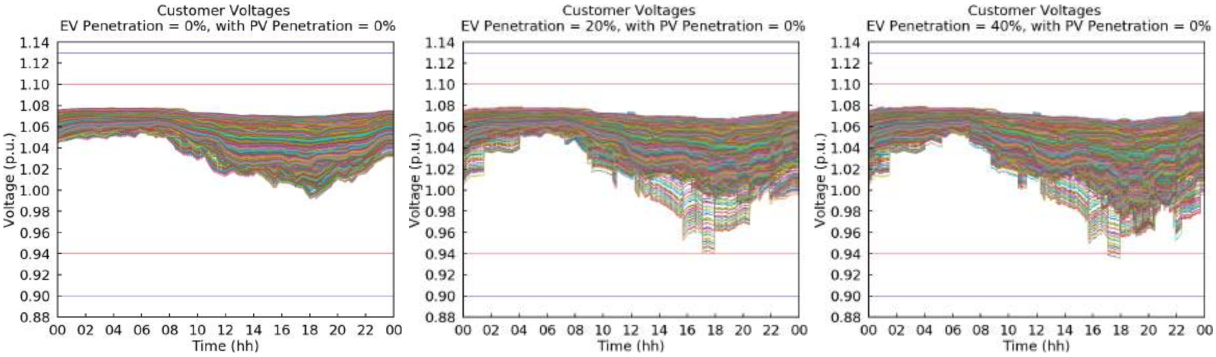
(a) (b) (c)

Figure 10-9. Urban VIC Base Case LV Tx Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen in the results that for the base case all LV distribution transformers are within limits, and that EV causes asset utilisation problems at 20% EV penetration and beyond. As the EV penetration increase, both the severity and number of LV distribution transformers increase. By the 120%, approximately half of the LV distribution transformers are overloaded.

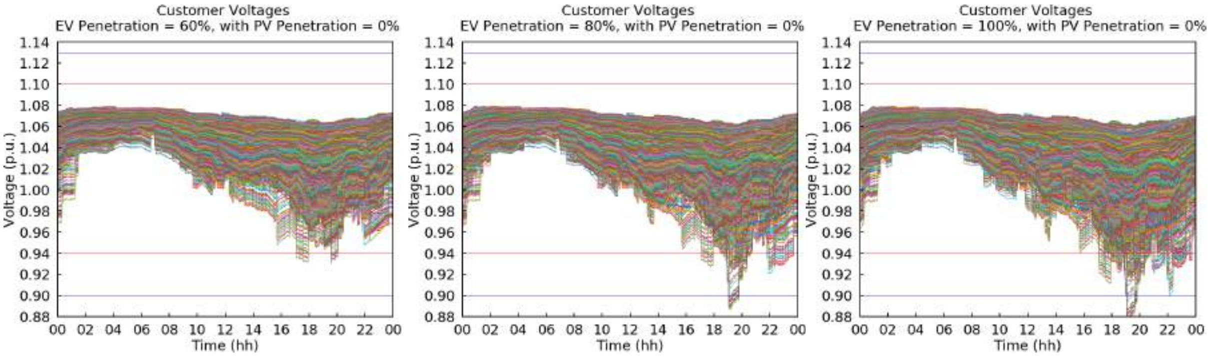
10.2.3 Residential Customer Voltages

Figure 10-10 to Figure 10-12 presents the impacts of EVs on the residential customer voltages for Urban VIC, considering the increase of EV penetrations up to 160%.



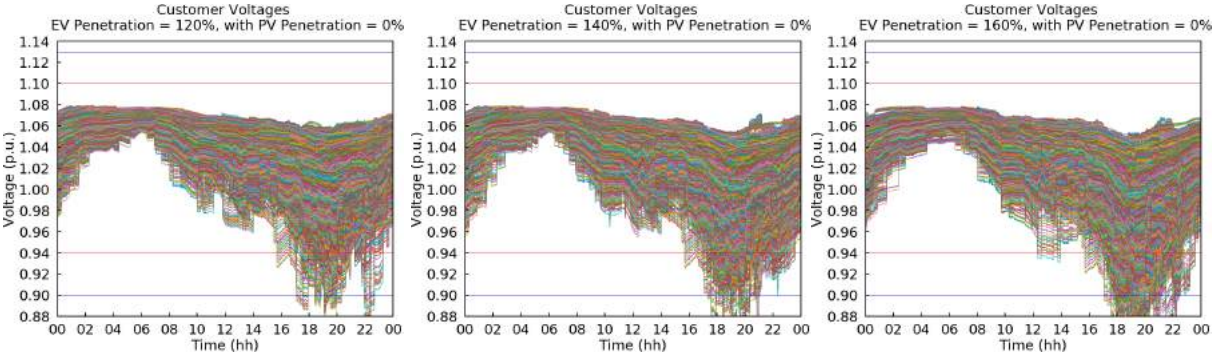
(a) **(b)** **(c)**

Figure 10-10. Urban VIC Base Case Customer Voltages with EVs: (a) 0%, (b) 20% and (c) 40%



(a) **(b)** **(c)**

Figure 10-11. Urban VIC Base Case Customer Voltages with EVs: (a) 60%, (b) 80% and (c) 100%



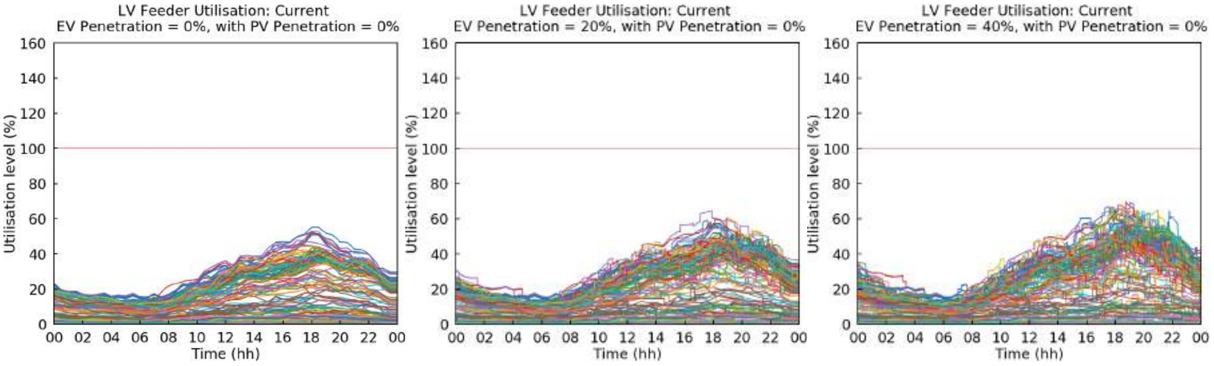
(a) **(b)** **(c)**

Figure 10-12. Urban VIC Base Case Customer Voltages with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen that voltage problems, shown by the blue line that reflects the updated (as of April 2020) Victorian LV voltage limits as defined in the Electricity Distribution Code [31], occur at 80% EV penetration and beyond. As EV penetration increase, so does the severity of the voltage violations. However, relative to the total number of customers within the feeder, only approximately 2% of customers are breaching the voltage standard.

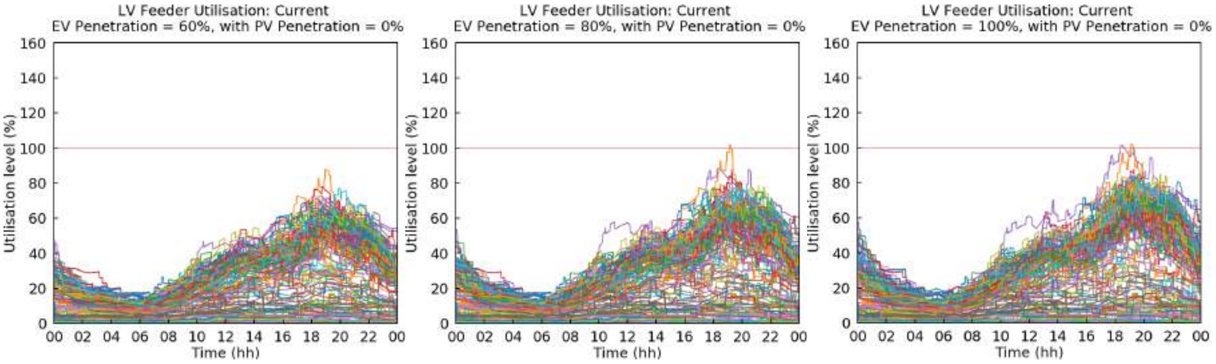
10.2.4 LV Feeder Utilisation

Figure 10-13 to Figure 10-15 presents the impacts of EVs on the utilisation of LV conductors for Urban VIC, considering the increase of EV penetrations up to 160%.



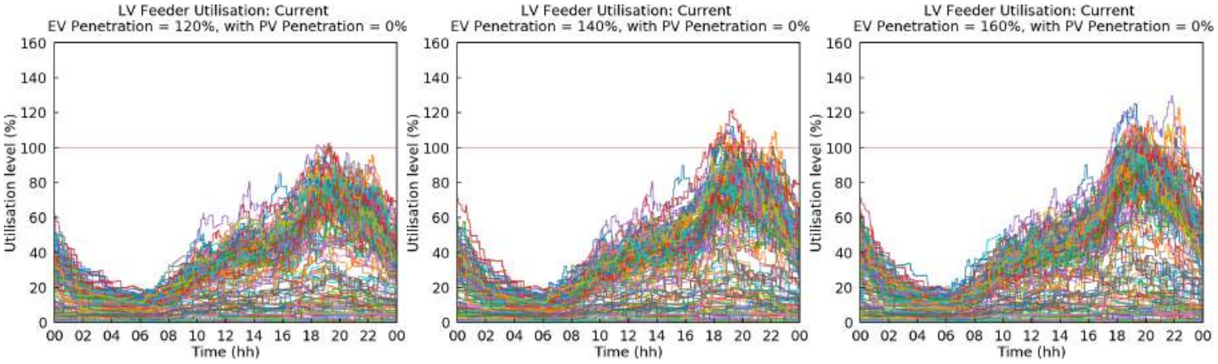
(a) (b) (c)

Figure 10-13. Urban VIC Base Case LV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 10-14. Urban VIC Base Case LV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



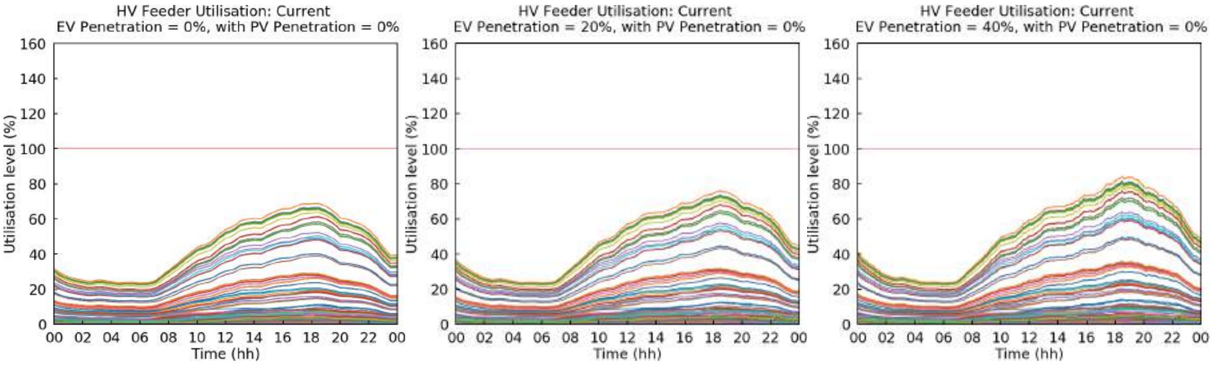
(a) (b) (c)

Figure 10-15. Urban VIC Base Case LV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

As shown in Figure 10-14, LV feeders for Urban VIC have LV conductors within them that exceed their rated capacities at 80% EV penetration and beyond. At the maximum EV penetration (160%), the peak LV conductor utilisation for all the feeders was approximately 130%.

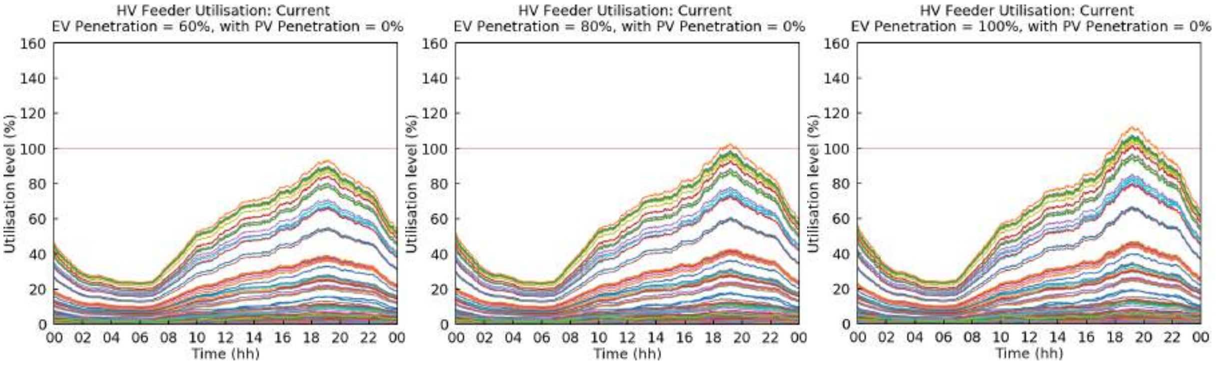
10.2.5 HV Feeder Utilisation

Figure 10-16 to Figure 10-18 presents the impacts of EVs on the utilisation of HV conductors for Urban VIC, considering the increase of EV penetrations up to 160%.



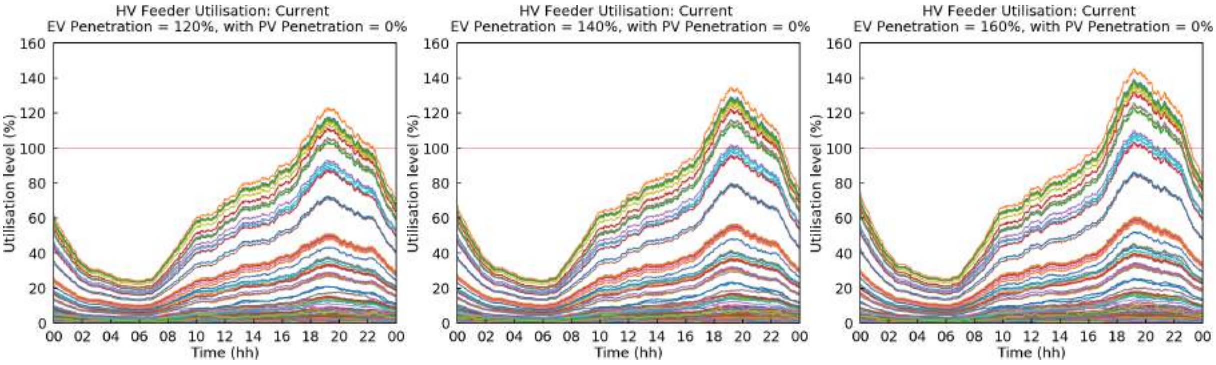
(a) (b) (c)

Figure 10-16. Urban VIC Base Case HV Feeder Utilisation with EVs: (a) 0%, (b) 20% and (c) 40%



(a) (b) (c)

Figure 10-17. Urban VIC Base Case HV Feeder Utilisation with EVs: (a) 60%, (b) 80% and (c) 100%



(a) (b) (c)

Figure 10-18. Urban VIC Base Case HV Feeder Utilisation with EVs: (a) 120%, (b) 140% and (c) 160%

It can be seen in Figure 10-17 that the HV feeder exceeds 100% of its rated capacity at 80% EV penetration and beyond. The severity and number of segments that are overloaded increases as EV penetration increase. By the maximum EV penetration, the maximum utilisation for an HV conductor is approximately 140%.

10.2.6 Key Remarks

- LV distribution transformers start to overload at 20% EV penetration and beyond. By 60% EV penetration, approximately a quarter of LV distribution transformers are overloaded. By 120% EV penetration, this reaches half of LV distribution transformers.
- Customer voltages start to exceed the new Victorian limits (as defined in the Electricity Distribution Code [31]) at 80% EV penetration and beyond. If the Australian standard AS 61000.3.100 would be considered instead (with stricter limits), then issues would occur with 40% EV penetration. By 160% EV penetration, approximately 1 in 50 customers would exceed the Victorian voltage limits.
- LV feeders begin to have asset utilisation problems within the LV conductors at 80% EV penetration and beyond. At maximum EV penetration, approximately a quarter of LV feeders have an LV conductor utilisation problem within them.
- The HV feeder has as asset utilisation problems for conductors within the HV feeder at 80% EV penetration and beyond. At 100% EV penetration, over 2.5km of HV conductor is congested whilst reaching just over 3.5km (out of 30km, just over 10% of total length of HV conductors) at maximum EV penetration (160%).
- The increase in peak apparent power for Urban VIC increases by approximately 110% by the maximum 160% EV penetration. For feeders with lower non-residential demand and more residential customers, this figure would be expected to increase. This could have serious implications for the zone substation and further upstream in the network when considering other HV-LV feeders also connected to the same network assets.
- Considering the above, the **EV hosting capacity of the Urban VIC feeder is less than 20% of residential customers with an EV**, with the LV distribution transformers being the first issue. At 80% EV penetration and beyond, customer voltages, HV feeder and LV feeders all become problematic and are the next limiting factors.

11 Conclusions

The report at hand corresponds to Milestone 6 “Network Modelling and EV Impact Assessment”, part of the 2-year collaborative project on “EV Integration” between Energy Networks Australia (ENA), the Australian Power Institute (API), the Centre for New Energy Technologies (C4NET), and The University of Melbourne, as part of the ENA and API’s Australian Strategic Technology Program.

The report first presented in Chapter 2 the processes adopted by The University of Melbourne to validate and produce detailed three-phase models for six HV (e.g., 22kV, 11kV) feeders selected by the DNSPs TasNetworks, Endeavour Energy and AusNet Services as part of this project. This included an overview of the parameters used to model the pseudo-LV (400V) feeders, a key feature to fully capture the effects of EVs on end customers. Chapter 3 then presented the different modelling aspects and considerations to produce realistic time-series demand profiles for light-duty EVs (primarily used for the transport of passengers). Chapter 4 presented data associated with demand and PV generations as well as corresponding considerations used for the case studies. Chapter 5-10 presented the impacts related to residential EV charging for the selected HV feeders modelled as HV-LV integrated networks.

The following summarise the key points and findings of this report.

<u>HV-LV Feeder Modelling</u>

The table below some of the characteristics of the HV-LV feeders modelled within OpenDSS and used in this project.

Feeder	Voltage Level (Total HV length)	No. Customers (HV Peak Demand)	No. LV Dist. Tx	Avg Residential Peak Size (kW)	Residential Data Used	ADMD (kW)	PV Penetration for Base Case (%)	Avg PV Size (kW)
Rural NSW (Hazelbrook)	11kV (20km)	1,401 (3.14MW)	39	2.0	VIC Smart Meter	6.5	24	3.8
Urban NSW (Preston)	11kV (6km)	616 (1.62MW)	17	2.0	VIC Smart Meter	6.5	30	5.8
Rural TAS (Norwood)	22kV (11km)	1,506 (6.15MW)	33	3.0	Avg Profile	5.0	0	-
Urban TAS (West Hobart)	11kV (6km)	620 (5.41MW)	12	3.5	Avg Profile	5.0	0	-
Rural VIC (SMR8)	22kV (486km)	3,669 (14.7MW)	765	2.0	VIC Smart Meter	4.0	0	-
Urban VIC (CRE21)	22kV (30km)	3,383 (7.80MW)	80	2.0	VIC Smart Meter	4.0	0	-

- <u>Selected HV Feeders</u>. The six HV feeders were identified and selected by the DNSPs using their know-how and expert views and considering several characteristics (rural, urban, length, number of customers, etc.) to capture an adequate spectrum across Australia within the timeframe available. There is an inherent trade-off between the quality and availability of data (conductor information, SCADA measurements, GIS coordinates, customer information, etc.) as well as the corresponding data extraction complexity and associated time restrictions, both in finding and extracting this data as well as converting it into HV-LV network models.
- <u>Integrated HV-LV Feeders</u>. These feeders were modelled using the software OpenDSS (developed by the Electric Power Research Institute - EPRI, USA). Since LV feeder information is not readily available from most DNSPs (unlike the HV feeder models which are available), LV networks are modelled based on the number of customers per distribution transformer, planning residential after diversity maximum demand (ADMD) values used by DNSPs and design principles (e.g., length, conductor, distribution of customers, etc.). By modelling the LV networks, even if not exactly as in reality, it is possible to have a better quantification of the impacts closer to LV customers, in particular, voltages at the customer connection points. These form so-called pseudo-LV feeder models.
- <u>Validation of HV-LV Feeders</u>. Validation of the modelled integrated HV-LV feeders is required. The objective is to ensure that the demand and generation (where applicable) profiles of

residential and non-residential customers connected to the pseudo LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements. This ensures that the integrated HV-LV models mimic the real behaviour to the extent that is possible (given the limited data availability). The validated integrated HV-LV models will therefore represent the base case from which the impacts of different EV penetrations will be assessed.

EV Modelling

- EV Data. Realistic EV profiles are derived from the UK EV trial "Electric Nation" [13-15] with nearly 700 EV owners taking part, with data found to be applicable for Australia. Four pools of time-series 1-min resolution EV demand profiles have been created by type of day (weekday/weekend) and charger size (Level 1/Level 2), each with 1,200 profiles.
- Weekdays. From the perspective of EV impact analyses, the EV demand of interest corresponds to weekdays. Therefore, in this project, weekday profiles (from both level 1 and level 2 pools) are used to assess the effects of EVs on the integrated HV-LV feeders.
- Charger Size. 80% of EVs are assumed to be equipped with Level 2 chargers (7.36kW), 20% of EVs are assumed to be equipped with Level 1 chargers (3.68kW).
- EV Penetration. EV penetration is defined in this project as the percentage of houses with a single EV. Since it is expected that eventually around 60% of houses will have two EVs (similar to regular cars), the maximum EV penetration to be considered in this project is 160%, i.e., every house has one EV, and 60% of them have a second EV.
- Multiple EVs per House. To create profiles for multiple EVs per household, the charging setup for each house must be considered. Two Level 1 chargers or a single Level 1 charger and a single Level 2 charger will not cause an issue for a typical residential single-phase connection and, therefore, can be directly assigned demand profiles. For two Level 2 chargers, a dual-headed Level 2 charger is considered which results in an adapted profile in which the excess demand (above 7.36kW) is deferred, thus extending the total charging duration.
- Diversified EV Demand. Based on the individual EV profiles created, no matter the type of day, the diversified peak demand of Level 2 charging (around 2kW during weekdays and 1.5kW during weekends) is approximately twice that of Level 1. For houses with two EVs, the largest diversified peak corresponds to the use of dual-headed Level 2 charges (around 4kW during weekdays and 3kW during weekends) and is nearly twice the values of a single Level 2 charger. It should be noted that EVs are modelled individually using the corresponding pool of profiles, but this information is presented for completeness.
- Daily Charging Coincidence Factor. Not all the EVs in a given area will have a charging event every day. Assuming that EVs will charge up to 4 days in a week, it is estimated that 70% or less of the existing EVs will have a charging event on the same day.
- Power Factor. A power factor of 0.99 (lagging) is used for all EV demand profiles.

Demand and PV Modelling

- Demand Profiles. For the feeders located in New South Wales (Endeavour Energy) and Victoria (AusNet Services), Victorian smart meter data is used to model residential customer demand. For the feeders located in Tasmania (TasNetworks), an aggregated residential profile from in inner Hobart in 2020 was provided by the DNSP and used for those feeders. Non-residential demand (or commercial and industrial load) is modelled at the secondary busbar of the LV transformers within the HV-LV feeder. After residential demand is modelled in time-series (either with smart meter data or an average residential profile), the profile for non-residential demand is tuned following the steps in section 2.5 per HV feeder.
- PV Systems. PV penetration is defined as the number of residential customers with a solar PV system. The penetrations and average installed capacity per customer for each HV feeder (which forms part of the net demand for the base case, before EVs are considered) was defined from information per feeder from the DNSPs. Datasets of clear sky PV irradiance based on Melbourne are used to model the solar PV generation. The clear-sky irradiance is used for simplicity but also to capture the highest PV generation. The resulting voltage rise issues can trigger the need for changes in voltage regulation devices (such as the tap position of off-load tap changers [3]) which in turn can exacerbate voltage drop issues due to EVs.

EV Impact Assessment

To assess the impacts for different EV penetrations, each of the six integrated HV-LV feeders considers nine EV penetrations: from the base case (0%) up to a maximum of 160% in 20% steps. Houses with a second EV are only considered after all houses have one EV (i.e., 100% of EV penetration). The maximum EV penetration of 160% assumes that 60% of houses have a second EV. EV location is randomly assigned across and within the LV feeders up to the EV penetration being investigated.

Voltage compliance and asset utilization are used as performance metrics to quantify the technical impacts caused by different penetrations of EVs.

It is important to note that no EV management techniques or time-of-use tariffs that alter EV charging behaviour are considered in this report. This report focuses on the impacts of unmanaged EVs, e.g., following a standard tariff. These aspects will be investigated in the next stage of the project.

A summary of the residential EV charging impacts on integrated HV-LV feeders modelled as part of this project is presented below, split into rural/ urban and then compared by region.

Rural Feeders

- Overall, **rural feeders were found to have an EV hosting capacity of up to 40% of residential customers with an EV**. LV transformer utilisation issues can appear with as little as 20% EV penetration for Rural VIC and become wider at 40% for Rural NSW and TAS, including significant customer voltage drops and LV conductor issues.
- The larger number and smaller size of LV transformers typically used in rural feeders results in many congested transformers with relatively low EV penetrations. Furthermore, the length of the rural feeders and resulting higher impedances lead to lower voltages with relatively low EV penetrations.
- LV distribution transformers can have problems as early as 20% of residential customers with an EV. By 80-100% of residential customers with an EV, approximately a quarter of LV distribution transformers within the rural feeders investigated can have asset utilisation problems.
- Residential EV charging for rural feeders can be problematic for customer voltages decreasing below the statutory standards. These issues can first occur from 20 to 60% EV penetration. By maximum EV penetration (160%), between 1 in 10 and 1 in 5 of residential customers may have a lower voltage standard violation
- LV feeders can contain LV conductors that are congested as EV penetration increases. This can occur from 100% EV penetration and can vary in severity depending on the region and the ADMD used for the LV feeder design when they were built. Overall, because rural feeders are more spread out with more LV transformers/feeders per customer, the impact on LV conductors is generally lower than it was for urban feeder
- HV conductor issues very significantly between regions for rural feeders. Issues can occur at very low EV penetrations, 120% EV penetration or not at all for any EV penetration. At maximum EV penetration, the length of overloaded conductors in rural feeders ranges from a few km to approximately 35km depending on the feeder and the feeder size. Although HV conductor impacts will vary on feeder-by-feeder basis, these impacts affect less than 10% of the total HV conductor length.

Urban Feeders

- Overall, **urban feeders were found to have an EV hosting capacity of up to 80% of residential customers with an EV**. The first limiting factor was asset congestion (LV conductors, HV conductors or LV distribution transformers).
- While voltage issues are not significant for urban feeders until high EV penetrations, the high density of residential customers inevitably leads to a much larger peak demand even with modest EV penetrations, resulting in asset congestion.
- LV distribution transformers can become congested from 20% EV penetration and beyond for the urban feeders investigated. The severity will depend on the region and the HV feeders individually.

- Voltage problems occur at 80% EV penetration and beyond for one urban feeder, whilst the other two urban feeders have no lower voltage lower standard violation problems.
- LV conductors within LV feeders can be problematic from 20%-100% EV penetration, depending on existing loading, the region and the corresponding ADMD when the LV feeders were constructed.
- HV conductor asset utilisation can vary between region, with either no congestion at all, or over 2.5km of congested HV feeder possible at maximum EV penetration.

New South Wales (NSW) Feeders

- Overall NSW feeders were found to have an EV hosting capacity of 0-80% before problems are encountered. The rural feeder was unable to host a 20% EV penetration and is first limited by LV distribution transformers becoming congested followed by voltage problems at 60%. For the urban feeder, the hosting capacity reached 80% before LV conductors become a problem and limit hosting capacity and is followed by LV distribution transformers limiting hosting capacity at 140%.
- No customer voltage standard violations for the urban feeder, whilst the rural feeder does have lower voltage standard violation issues from 60% EV penetration. Voltage problems for the rural feeder increases significantly after 100% EV penetration, with just over 1 in 5 residential customers with a lower voltage standard violation at maximum EV penetration (160%). Despite the urban feeder despite having no voltage issues, both feeders were close to and constrained by the upper voltage limit (due to PV) as well as close to or exceeding the lower voltage limits. In the case of the urban NSW feeder, it exports power during the peak daylight hours. Whilst there may be some advantages from an increase of PV penetration alongside EV penetration (which mitigate some impacts from EVs), it is expected that PV penetration will increase alongside EV penetration. Therefore, DNSPs may be constrained by both voltage limits (e.g., DNSPs will be unable to adjust off-load tap positions due being constrained in both directions).
- In both rural and urban feeders, LV feeders can have congested conductors within them at 100% EV penetration and beyond for both feeders. For the urban feeder, this was the limiting factor for hosting capacity. This impact of EVs on the LV feeders is relatively lower than other regions due to the higher ADMD employed by the DNSP for this region in combination with a slightly lower (compared to TAS) residential peak from the Victorian smart meter data.
- LV distribution transformer asset utilisation problems occur in both the rural and urban feeders investigated. The rural feeder has significant asset utilisation problems as early as 20% EV penetration, with nearly a quarter of LV transformers congested by 80% EV penetration and half congested at 160%. On the other hand, the urban feeder only has one LV distribution transformer congested for 140% and the maximum EV penetration (160%). For the rural feeder this was a limiting factor in hosting capacity.
- 1km of HV congested conductors for the rural feeder at the maximum EV penetration, whilst the urban feeder did not have any HV conductor problems.
- By the maximum EV penetration there is an increase in peak apparent power for both feeders between 90-110% when compared with the base case. When considering other HV-LV feeders also connected to the same network assets upstream, this could have serious implications for the zone substation and beyond.

Tasmanian (TAS) Feeders

- Overall, it was found TAS feeders have an EV hosting capacity of 0-40% before problems are encountered. The urban feeder is unable to host 20% of customers with an EV with LV conductors being the first limiting factor. The next limiting factor for the urban feeder was the congestion of HV conductors which begin to overload at 40% EV penetration, followed by LV distribution transformers at 80%. The rural feeder on the other hand has a hosting capacity limit of 40% EV penetration, LV conductor problems and a small number of customers with a voltage problem being the limiting factor. The next limiting factor for the rural feeder is the LV transformer utilisation at 60% EV penetration.
- LV feeder utilisation becomes a problem for the rural feeder by 40% EV penetration and just 20% for the urban feeder. This is partly because of the higher residential demand for the urban feeder (3.5kW versus 3.0kW) and a higher morning peak for the rural feeder. At 100% EV penetration, the urban feeder with the higher residential demand sees over half of LV

feeders with LV conductor problems, whilst it is approximately a quarter at the same EV penetration for the rural feeder. Overall, the higher average residential demand, combined with the middle sized ADMD used for all the regions, leads to the TAS feeders investigated being constrained by the LV conductors. It should be noted that, TAS feeders may use conductors with a higher ampacity rating to that used in this project.

- Peak apparent power at the head of the HV feeder increases between 20-40% for rural and urban respectively when considering the maximum EV penetration. This will likely change slightly between feeders depending on the proportion of residential customers. However, the higher residential demand on average seen in Tasmania reduces the percentage increase relative to other regions. When considering other HV-LV feeders also connected to the same network assets upstream, this could have serious implications for the zone substation and beyond.
- The urban feeder has no residential customer voltage standard problems. However, the rural feeder encounters a couple of customers exceeding lower voltage standard violations by 40%. However, problems only become more widespread at 120% EV penetration, with over 1 in 10 residential customers with a lower voltage standard violation at maximum EV penetration. Whilst there may be some advantages from an increase of PV penetration alongside EV penetration (which mitigate some impacts from EVs), it is expected that PV penetration will increase alongside EV penetration. Therefore, DNSPs may be constrained by both voltage limits.
- LV distribution transformers have asset utilisation issues at 60% for the rural feeder and 80% for the urban feeder. At 100% EV penetration approximately a quarter of LV transformers are congested for both feeders. For the rural feeder, by max EV penetration it increases to nearly half of all LV distribution transformers. Furthermore, for a rural feeder with a high evening demand instead of the morning LV distribution transformer congestion could occur at 20-40%, like that seen in rural NSW, instead of 60% currently seen for rural TAS. Finally at over 100% EV penetration, the rural feeder also saw asset utilisation problems in the LV distribution transformers occurring in the morning as well as the evening.
- HV feeder utilisation is problematic for the urban feeder by 40% EV penetration with just over 0.6km of HV congested conductors and over 1.2km of HV congested conductors for 140 and 160%. Meanwhile the rural feeder has no issues within the HV conductors. This may be partly due to the urban feeder being 11kV versus the 22kV of the rural feeder, or simply variations between feeders.

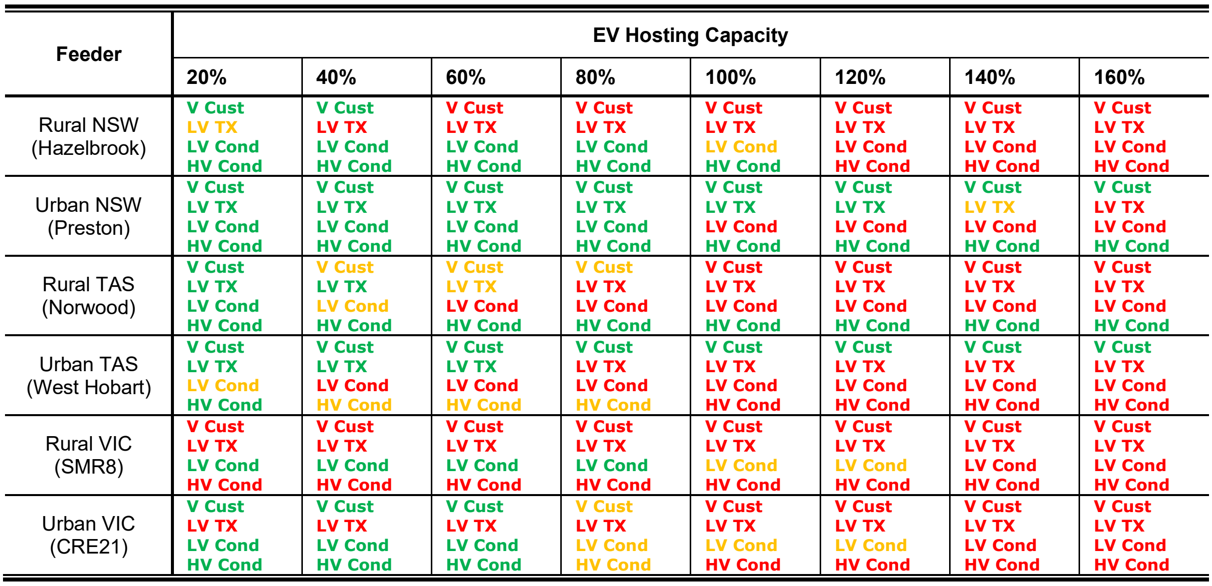
<u>Victorian (VIC) Feeders</u>

- Overall, it is found that the EV hosting capacity of VIC feeders is 0%, with problems occurring at 20% EV penetration for both the rural and urban feeder. For the urban feeder, the limiting factor is LV distribution transformers with some overloading at 20% EV penetration. Beyond this, the next limiting factors are the HV, LV and customer voltages all becoming problematic at 80% EV penetration and beyond. For the rural feeder, the limiting factor is customer voltages and HV conductor overloads that first occur in the base case when considering the peak demand day. This rural feeder is much larger than other feeders considered and contains a significant number of single wire earth return networks that are much more sensitive to voltages. The next limiting factor is LV distribution transformers that begin to overload at 20% EV penetration.
- The HV-LV integrated feeders were modelled in OpenDSS from a previous project Advanced planning of PV-Rich Distribution Networks [1-6] and originally considered minimum demand from each season. The base case from these networks is used and data corresponding to the peak demand day is applied, with everything else remaining unchanged (except for the addition of EVs for impact analysis). When considering the base case (peak demand day and no EVs) for the rural feeder, there was a very small percentage of customers (less than 1%) with a voltage problem and a few segments of HV conductors overloaded. Further analysis will be carried out to determine more adequate off-load tap positions and potentially a more adequate voltage at the head of the HV feeder. Nonetheless, voltage issues are known to exist in rural areas. It should be noted, no issues occur in the base case for the urban feeder.
- The Victorian feeders investigated are much larger than the other feeders. This means in terms of the number of congested assets and length of HV conductor that is overloaded, is much higher than the other feeders. Furthermore, it partly explains voltage issues for the

Victorian feeders despite the larger Victorian voltage limits defined in the Electricity Distribution Code [31]. Whilst the rural feeder has some voltage issues in the base case, this is a very small percentage (less than 1%) of customers. However, at the maximum EV penetration, for the rural feeder, approximately 1 in 5 customers will have a voltage issue despite the wider voltage limits. Meanwhile for the urban feeder, it is the only urban feeder to experience customer voltage problems despite the wider voltage limits. However, this affects a very small percentage of customers (around 2%) at the maximum EV penetration (160%).

- For both the rural and urban feeder, LV distribution transformers start to overload at 20% EV penetration. For the urban feeder, by 60% EV penetration, approximately a quarter of LV distribution transformers are overloaded and by 120% EV penetration, this reaches half of LV distribution transformers. For the rural feeder by 100% EV penetration, approximately a quarter of LV distribution transformers are overloaded.
- For the rural feeder, the HV feeder is already having overload issues when considering the base case of a peak demand day. However, as EV penetration increases the severity and number of overloaded HV conductors increases. By 100% EV penetration close to 25km of HV conductor could be overloaded, and at maximum penetration this is approximately just under 35km (out of 486km). For the urban feeder, HV conductors become overloaded at 80% EV penetration and beyond. At 100% EV penetration, over 2.5km of HV conductor is congested whilst reaching just over 3.5km (out of 30km) at 160% EV penetration.
- For the urban feeder, LV feeders begin to have asset utilisation problems within the LV conductors at 80% EV penetration and beyond. At maximum EV penetration, approximately a quarter of LV feeders have an LV conductor utilisation problem within them. Whilst for the rural feeder, LV feeders were found to have asset utilisation problems within the LV conductors at 100% EV penetration and beyond. However, this only affects a small portion of LV feeders.
- By maximum EV penetration, the peak increase in apparent power increases between approximately to 55-110% for the rural and urban feeder respectively. This figure will change depending on the proportion of non-residential to residential demand seen in the feeder, as well as the average residential demand. When considering other HV-LV feeders also connected to the same network assets upstream, this could have serious implications for the zone substation and beyond.

The table below summarises the network impacts from unmanaged residential EV charging. Green indicates the parameter (e.g., customer voltages, LV transformer utilisation, etc.) is within limits, yellow indicates marginally exceeding limits whilst red indicates the limit was significantly exceeded.



Feeder	EV Hosting Capacity							
	20%	**40%**	**60%**	**80%**	**100%**	**120%**	**140%**	**160%**
Rural NSW (Hazelbrook)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Urban NSW (Preston)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Rural TAS (Norwood)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Urban TAS (West Hobart)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Rural VIC (SMR8)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**
Urban VIC (CRE21)	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**	**V Cust** **LV TX** **LV Cond** **HV Cond**

Limitations of the Study

- Fast charging stations. Fast charging stations were not considered. However, depending on their location, their demand in addition to that of residential EV charging could exacerbate problems, particularly for the HV feeder.
- Peak demand day. This study considers a peak demand day (modelled with 1-min resolution profiles) as it represents the worst-case scenario to quantify the EV impacts on the networks. While this is useful to capture the EV hosting capacity of a HV feeder, seasonal or annual-related aspects such as energy losses, cannot be quantified.
- Assignment of EVs to residential customers. EVs were randomly assigned to residential customers. There would be variations in impacts depending on the distribution of EVs. For instance, EV clusters could lead to voltage issues faster for those residential customers as well as congestion for the corresponding assets.
- LV feeders. In practice, LV conductors will use different specifications to those adopted in this project. As a consequence, the exact impacts on LV feeders versus those seen in the pseudo-LV feeders will vary. Depending on the age of the LV feeder and the ADMD used at the time of it being built (e.g., older feeders typically were designed with a lower ADMD and LV conductor specification, etc.), impacts could be slightly higher or lower.
- Uptake of Level 1 and Level 2 chargers. Factors such as subsidies that promote the use of Level 2 chargers may decrease EV hosting capacity (if more than 80% of EV users end up with a Level 2 charger). Conversely, a lack of Level 2 charger uptake may increase EV hosting capacity (higher percentage of Level 1 chargers).
- Cyclic ratings of transformers and conductors. This study did not consider cyclic ratings for transformers and conductors, only seasonal ratings. The consideration of cyclic ratings could increase EV hosting capacity. However, the peak hours might last longer.
- PV systems uptake in combination with EV uptake. The presence of residential PV systems was limited to the existing/available information when modelling the HV feeders. However, PV uptake is likely to increase with EV uptake. Whilst there is some small mitigation of EV impacts during daylight hours, the majority of EV demand will occur after daylight hours. Therefore, DNSPs may find a situation of voltage rise issues during the day and voltage drop issues once the sun has set.
- Residential Batteries. This study did not consider residential batteries. This technology could be used by customers to charge their EVs at night using energy captured from PV generation, thus reducing imports from the grid and the corresponding impacts.

12 References

[1] A. Procopiou and L. Ochoa, "Deliverable 1 "HV-LV modelling of selected HV feeders"," in "Advanced Planning of PV-Rich Distribution Networks " The University of Melbourne and AusNet Services, Australia, 2019. Accessed: September 2020. [Online]. Available: https://www.researchgate.net/publication/334458042_Deliverable_1_HV-LV_modelling_of_selected_HV_feeders

[2] A. Procopiou and L. Ochoa, "Deliverable 2 "Innovative Analytical Techniques"," in "Advanced Planning of PV-Rich Distribution Networks " The University of Melbourne and AusNet Services, Australia, 2019. Accessed: September 2020. [Online]. Available: https://www.researchgate.net/publication/337853057_Deliverable_2_Innovative_Analytical_Techniques

[3] A. Procopiou, K. Petrou, and L. Ochoa, "Deliverable 3 "Traditional Solutions"," in "Advanced Planning of PV-Rich Distribution Networks " The University of Melbourne and AusNet Services, Australia, 2020. Accessed: September 2020. [Online]. Available: https://www.researchgate.net/publication/339472314_Deliverable_3_Traditional_Solutions

[4] A. Procopiou, M. Liu, W. Nacmanson, and L. Ochoa, "Deliverable 4 "Non-Traditional Solutions"," in "Advanced Planning of PV-Rich Distribution Networks " The University of Melbourne and AusNet Services, Australia, 2020. Accessed: September 2020. [Online]. Available: https://www.researchgate.net/publication/344038943_Deliverable_4_Non-Traditional_Solutions

[5] W. Nacmanson and L. Ochoa, "Deliverable 5 "Cost Comparison Among Potential Solutions"," in "Advanced Planning of PV-Rich Distribution Networks " The University of Melbourne and AusNet Services, Australia, 2020. Accessed: December 2020. [Online]. Available: https://www.researchgate.net/publication/346853363_Deliverable_5_Cost_Comparison_Among_Potential_Solutions

[6] W. Nacmanson and L. Ochoa, "Deliverable 6 "Consolidation of Findings (Final Report)"," in "Advanced Planning of PV-Rich Distribution Networks " The University of Melbourne and AusNet Services, Australia, 2021. Accessed: Februrary 2021. [Online]. Available: https://www.researchgate.net/publication/349312771_Deliverable_6_Consolidation_of_Findings_Final_Report

[7] K. Petrou and L. F. Ochoa, *AusNet Mini Grid Clusters - Deliverable 1 “HV and LV Network Modelling”*, Australia: The University of Melbourne and AusNet Services, 2017.

[8] A. Jehad, *Electrical Design Standard for Underground Distribution Cable Networks, Technical Standard - TS-100*, Australia: SA Power Networks, 2012. [Online]. Available: https://goo.gl/gqiKuY. Accessed on: January 2018.

[9] A. Seneviratne and J. Murphy, *Electrical Design Information for Distribution Networks: After Diversity Maximum Demand*, Australia: Horizon Power, 2013. [Online]. Available: https://goo.gl/HLWjwT. Accessed on: January 2018.

[10] J. Bridge, *Distribution Annual Planning Report 2017 -2021*: AusNet Services, 2017. [Online]. Available: https://goo.gl/RXtnEu. Accessed on: January 2018.

[11] A. Seneviratne and J. Murphy, *Distribution Design Manual – Underground Cable Distribution*: Horizon Power, 2014. [Online]. Available: https://goo.gl/KQB9go. Accessed on: January 2018.

[12] *Distribution Substation Manual (DSM) Section 1 - Customer Supply Arrangements*, Australia: Western Power, 2009. [Online]. Available: https://goo.gl/7qrdcn. Accessed on: January 2018.

[13] Electric Nation. "Electric Nation Smart Charging Project." https://electricnation.org.uk/resources/smart-charging-project/ (accessed April, 2021).

[14] Western Power Distribution. "Electric Nation Data." https://www.westernpower.co.uk/electric-nation-data (accessed April, 2021).

[15] E. Dudek, K. Platt, and N. Storer, "Electric Nation Customer Trial Final Report," Western Power Distribution, 2019. Accessed: April 2021. [Online]. Available: https://eatechnology.com/media/girhcnsc/electric-nation-customer-trial-report.pdf

[16] *IEC 61851-1:2017 Electric vehicle conductive charging system - Part 1: General requirements*, International Electrotechnical Commission, 2017.

[17] P. Lavieri, "Literature Review Report: A Consumer-Focused Review, Large-Scale Network and System Integration of Electric Vehicles: A Techno-Economic Perspective," 2021.

Accessed: October 2021. [Online]. Available: https://www.researchgate.net/project/EV-Integration
[18] Australia Bureau of Statistics, "Survey of Motor Vehicle Use, 2019.6-2020.6," Australia.
[19] Ausgrid, "New South Wales Electric Vehicle Owners Survey - Summary Report," 2020. Accessed: June 2021. [Online]. Available: https://www.ausgrid.com.au/-/media/Documents/Demand-Mgmt/DMIA-research/EV-Owners-Survey-Summary-Report.pdf?la=en&hash=0C623383DFD414A006C05C1FE685D1C1B213FAD3
[20] Victorian Department of Transport, "Typical Hourly Traffic Volume, 2015-2021," Australia.
[21] ENERGEIA, "Australian Electric Vehicle Market Study," 2018. Accessed: June 2021. [Online]. Available: https://arena.gov.au/assets/2018/06/australian-ev-market-study-report.pdf
[22] Y. B. Khoo, C.-H. Wang, P. Paevere, and A. Higgins, "Statistical modeling of Electric Vehicle electricity consumption in the Victorian EV Trial, Australia," *Transportation Research Part D: Transport and Environment,* vol. 32, pp. 263–277, 2014 2014.
[23] CSIRO, "Projections for small-scale embedded technologies," 2020. Accessed: April 2021. [Online]. Available: https://aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Inputs-Assumptions-Methodologies/2020/CSIRO-DER-Forecast-Report
[24] P. S. Lavieri and G. J. M. Oliveira, "Electric Vehicle Charging Consumer Survey, Insights Report," 2021. Accessed: October 2021. [Online]. Available: https://www.researchgate.net/project/EV-Integration
[25] Idaho National Laboratory. "Advanced Vehicle Testing Activity." https://avt.inl.gov/ (accessed June, 2021).
[26] A. T. Procopiou and L. F. Ochoa, "Deliverable 1 Literature review and initial modelling," *Solar PV Penetration and HV-LV Network Impacts* Australia: The University of Melbourne and AusNet Services, 2018, p. 24.
[27] A. T. Procopiou and L. F. Ochoa, "Deliverable 2 Progress Report on the analysis of network impacts due to solar PV," *Solar PV Penetration and HV-LV Network Impacts* Australia: The University of Melbourne and AusNet Services, 2018, p. 9.
[28] A. T. Procopiou and L. F. Ochoa, "Deliverable 3 Analysis of Network Impacts due to Solar PV," *Solar PV Penetration and HV-LV Network Impacts* Australia: The University of Melbourne and AusNet Services, 2018, p. 28.
[29] I. Richardson and M. Thomson. "Integrated domestic electricity demand and PV micro-generation model." Loughborough University. https://dspace.lboro.ac.uk/2134/7773 (accessed March, 2018).
[30] I. Richardson and M. Thomson, *Integrated simulation of Photovoltaic Micro-Generation and Domestic Electricity Demand: A one minute resolution open source model*, United Kingdom: Loughborough University, 2011. [Online]. Available: https://goo.gl/igXxrd. Accessed on: March 2018.
[31] "Electricity Distribution Code," 11 ed. Melbourne, Victoria, Australia: Essential Services Commission, 2020, p. 72. [Online]. Available: https://www.esc.vic.gov.au/sites/default/files/documents/Electricity%20Distribution%20Code%20version%2011.pdf