Enhanced System Planning Project

C4NET | ESP Enhanced System Planning

C4NET Project Overview

Technical modelling of electrification of transport profiles

Work Package 1.2

January 2025

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1. Purpose of the report

The Enhanced System Planning (ESP) project is a significant and collaborative research project aimed at informing electricity planning below transmission level in Australia beyond 2030. Its focus is on building methodologies and approaches for bottom-up modelling and to highlight the opportunities presented through the distribution system and by integrating Consumer Energy Resources (CER) and Distributed Energy Resources (DER), with the goal of informing whole of system planning. The ESP seeks to inform gaps that would emerge if the Australian Energy Market Operator's (AEMO) current Integrated System Plan (ISP)[1] is expanded beyond its current scope to take a more whole-of-system approach in alignment with the energy and Climate Change Ministerial Council's (ECMC) recommendations for enhancing energy demand forecasting in the ISP[2]. The ESP Project is targeted at addressing the distribution system considerations aspect of this expanded scope, with particular focus on bottom-up modelling approaches from the low voltage distribution system upwards, as outlined in *Figure 1*. For the bigger picture of integration with the ISP see *Appendix Two.*

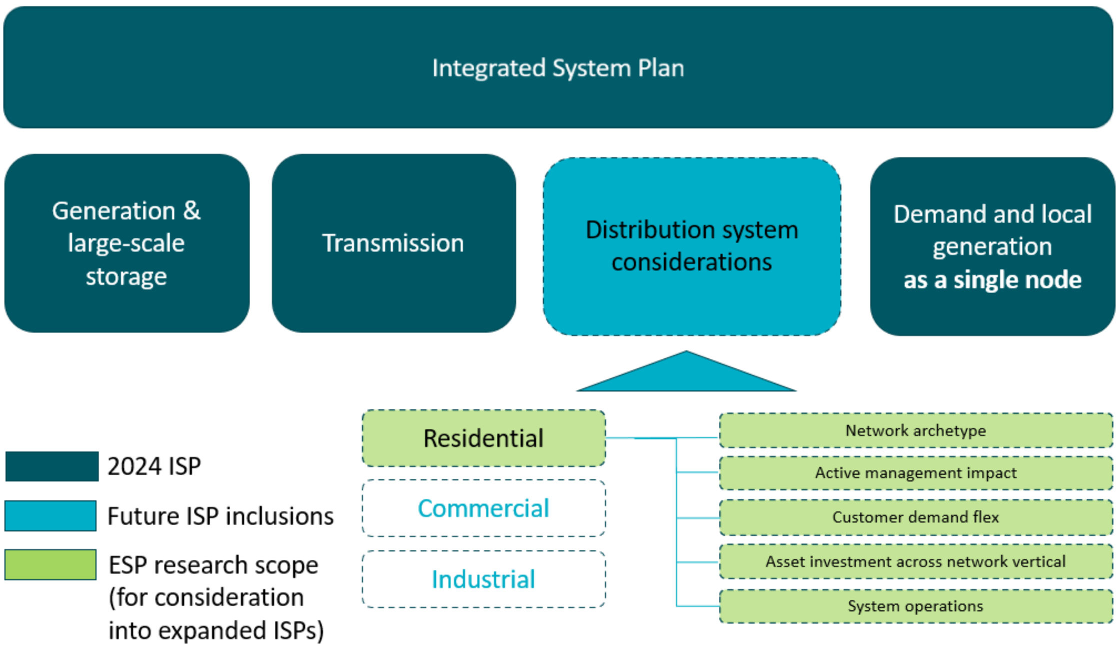


Figure 1 Distribution system components of whole of system planning

This has been addressed through fifteen projects across three distinct work packages:

- **Work package one:** Key inputs, methodologies, and demand network implications of electrification to inform foundational elements of bottom-up modelling.

[1] 2024 Integrated System Plan (ISP), Australian Energy Market Operator, June 2024
[2] Review of the Integrated System Plan: ECMC Response, ECMC, April 2024

- **Work package two**: Impact of flexibility options within distribution networks Techno-economic implications of future architectures.
- **Work package three:** Active distribution network considerations for whole-of-system planning implications: technical, economic and policy.

Providing a foundation of inputs into the ESP for work package one, Monash University undertook an independent research project: *Technical modelling of electrification of transport profiles*, with the goal of understanding the impacts of the electrification of residential transport.

This report is designed to frame the outcomes of the research to guide stakeholders in their understanding of how the research can inform bottom-up modelling. In addition, C4NET has sought through this report to summarise and evaluate the research, identify any opportunities or limitations with the approach taken, and highlight any observations or insights for distribution network service providers (DNSPs), regulators and policy makers, market operators, and for future research. This has also been done taking into consideration broader consultation and a range of stakeholder views and seeks to maintain a focus on consumers as the beneficiaries of an integrated energy system.

2. Project Summary

The *Technical modelling of electrification of transport profiles*[3]*.* sought to inform the electricity demand profiles for residential EV charging and the impact of Vehicle-to-Grid technology on the demand profiles. The key inputs, methodologies, and demand implications of electrification to inform foundational elements of bottom-up modelling are provided in *Figure 2* below.

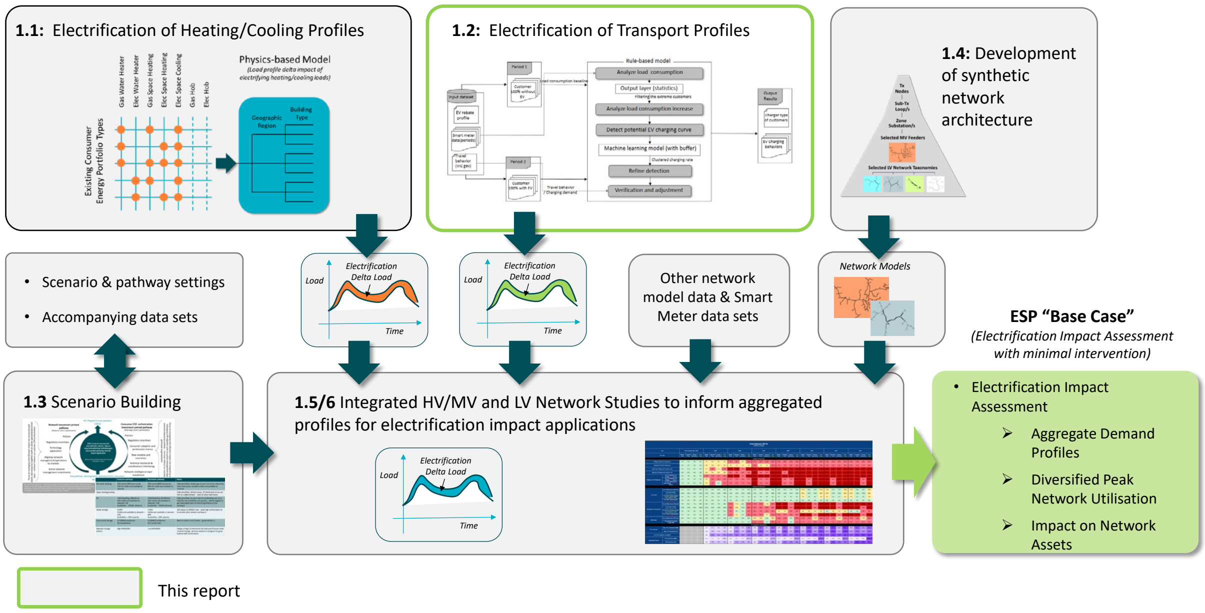


Figure 2 The base case for transport electrification impact assessment, highlighting the role of electrification of transport profiles.

The transport sector is one of the biggest (and growing) sources of greenhouse gas emissions. To reach Australia's target of net zero emission by 2050, conversion of transport to run on zero emission fuel is a priority for state and federal governments. Electric vehicles (EVs) are the most common form of zero emission vehicles (ZEVs) found today, in particular battery electric vehicles (BEV) which are charged from the electricity networks.

EVs present both challenges and opportunities for the electricity networks. The primary challenge is to provide adequate network capacity to cater for the increased electricity demand that comes from EV charging. The opportunities are improved utilisation of electricity assets and renewable generation (roof-top solar PV in particular) if EV charging can be encouraged and/or controlled to occur during off-peak times or when there is an excess supply of renewable generation. Future Vehicle-to-Grid (V2G) technology presents further opportunity for EV to feed energy back to support the electricity grids.

[3] The research reports can be found here: www.c4net.com.au/projects/enhanced-system-planning-project/

3. Research methodology, approach and findings

A top-down approach can rapidly inform the annualised and seasonal energy impact of electrification of domestic premises at an aggregated level, but it is hypothesised that a bottom-up approach is needed to inform the impact on network infrastructure deeply integrating D**istributed Energy Resources (D**ER**)** and **Consumer Energy Resources (**CER**)**[4] where each level of distribution network asset from transmission connection through to customer meter is informed.

Further consideration of broader concurrent changes on the system such as decentralisation of generation (solar PV in particular), energy storage, population and housing changes, consumer activity and electrification of transport necessitate a means of granular assessment in temporal and locational aspects. In doing so, the network planning can be considered from a whole-of-system impact, including network operation, consumer, regulatory and market structure considerations.

3.1 Approach

To arrive at the uplift to residential electricity demand profile due to electric vehicle (EV) charging, the following factors were considered:

- Different charging levels (kW)
- Length/duration of charging
- When charging occurs (variation by season, days of the week and then time within that day)
- Frequency of charging events (across same dimensions as above)
- How the individual charging demand aggregates to represent a localised diversified load

In addition, to assess the impact of V2G technology, vehicle connection time – the time when vehicle is connected to the grid, not just the time when there is active charging - was considered.

The research project adopted an evidence-based approach whereby residential smart meter data from 2020 to 2022 was disaggregated to try and extract the underlying electric vehicle (EV) charging patterns to inform bottom-up modelling. The patterns detected include the rating of the EV charger, the charging time (days of the week, start time and duration), frequency of charging and the energy consumption from EV charging. The data analysis was conducted firstly on non-PV customers as they are not affected by PV generation which add complexity to the analysis, especially during the daytime. The framework was then applied to the analysis of smart meter data of PV customers by assuming consistent solar PV generation capacity over 2020-2022.

[4] For the purpose of clarification, in this context, DER refers to resources in front of the meter, CER refers to resources behind the meter.

The smart meter data used was time series data in the form of energy consumption (kWh) of the site over each 30-minute time interval from the grid. In the case of PV customers, the smart meter data was the net energy consumption/generation (kWh) over each 30-minute time interval. The energy consumption represents the aggregate consumption of all the appliances at the premise. An approach was developed by the research project to disaggregate the smart meter data into energy that is consumed by EV charging.

For PV customers, there is an additional variable to be considered – that of the PV generation. When EV charging occurs during daytime and PV is generating, the EV could be charged by the PV generation and not detected in the smart meter data. The project has adopted an approach to account for this situation.

3.2 Inclusions, exemptions and limitations

The process for the disaggregation of smart meter data to extract the underlying EV charging patterns began with a dataset of 493 non-PV customers after initial data cleansing (removal of incomplete, inconsistent, and erroneous data) and merging with data from Vic Government's EV rebate program (which proxied the start date when EV charging could have occurred). The dataset reduced to 403 after removing customers with inconsistent energy consumption profiles using 3-sigma statistical principle. Travel distance filter (5,000 kilometres per year) was then applied to further reduce the dataset to 394. Finally, after applying the charging frequency filter (specifically, the threshold for the number of active charging – the number of charging hours as 200), the number of customers dropped to 265. The rule-based approach used to select EV customers for EV charging data extraction improves the reliability of the extracted data but possibly means that not all EV charging operations are captured.

A similar data processing was conducted for 705 PV customers and ended with 447 customers used for EV extraction analysis.

The research report's insight is therefore based on the analysis of a limited cohort of 265 non-PV and 447 PV customers who own EVs.

There are, however, doubts about the accuracy of the analysis outcome as:

- There is no charger data which can be used to validate the accuracy of the detection algorithm.
- The research report's insight is based on the analysis of a limited cohort of 265 non-PV and 447 PV customers who own EVs and may not be representative of the broader population of EV owners. While already a limitingly small number, the sample needed to be further broken down to inform various cohorts (such as the three charge levels) making them prohibitively small to draw representative conclusions from.

- The same cohort of EV customers is used in formulating probability distribution functions (PDF, more details in 3.4) to account for diversity in the aggregate effect of EV charging. Due to the geographical diversity of the EV customers in the dataset, this diversity may not be observed on local electricity infrastructure.
- From a network impact perspective, DNSPs are concerned with all levels of EV charging. The higher the charging power the greater the concern as this could lead to significant overloading of their distribution assets. The project has identified three different EV charging levels from the smart meter data: 2.3kW, 3.7kW and 7.4kW. The small sample size of 7.4kW chargers in the analysis (7.2% of non-PV customers, 10.5% of PV customers) means that the increase in electricity demand may not be accurately determined.
- The energy consumption data in 2020-2022 are likely to be affected by COVID lockdowns, in particular, EV usage may be less than "normal" time resulting in less EV charging consumption.
- As illustrated in the research report, the analysis may not fully capture EV charging profiles for PV customers during the daytime due to the absence of solar PV generation data. This lack of visibility will become more prominent when more customers decide to install PV systems.
- The EV customer cohort analysed represent the early adopters of EV. As more customers purchase EV, the rating of their EV charger and their charging behaviours could vary from what is revealed in the research.

The limitations were sufficiently material that the modelled results were not carried forward into further parts of the ESP project. Instead, the stylised CSIRO modelled charging predictions incorporated in the 2024 ISP were carried forward to minimise difference to the ISP. In future, these could be better informed through empirical data analysis as sufficient representative data becomes available. It is further noted that what charge rates consumers will adopt in future will be a major variable in informing demand impact and it remains a key unknown so any future modelling should include a range of scenarios.

3.3 Base assumptions

The smart meter data cover the period from 2020 to 2022. EV ownership start dates come from Victorian Government's EV rebate program. The disaggregation of smart meter data to extract EV charging pattern is based on the comparison of the smart meter data before and after the EV purchase. This assumes that there is no significant change in household consumption (appliance usage, new appliances) and EV usage, and for PV customers, additional assumptions that there is no upgrade of the PV system nor the installation of residential batteries.

For V2G synthesis, the analysis does not consider shifting EV charging into the peak solar generation hours, where there may be wider system benefits compared to overnight charging, which could be future research directions.

The analysis discovered predominantly 2.3kW charging level. Due to the small sample sizes of other residential charger types (3.7kW and 7.4kW), the analysis and representative conclusions cannot be drawn. Only a proportion of the overall energy consumption uplift observed by the sites after acquiring an EV was explained by the charging detected by the algorithm. While it is possible other factors are at play, C4NET's experience is the bulk of the uplift is explained by EV charging meaning the algorithm may have under-detected some charging behaviour.

3.4 Researcher findings

Readers should note that limitations outlined in 3.2 on use of any of these results given the concerns raised around accuracy of findings to date given the shallow pool of data and other factors.

3.4.1 Non-PV Customers

Presented below are the disaggregated data provided by the research for 265 non-PV residential customers. The data shows that 2.3kW charger is predominantly used (Fig. 1), charging events are detected in the meter load (Fig. 2) and charging loads are quite evenly spread out over weekdays but less over the weekend, in particular on Sunday (Table 1).

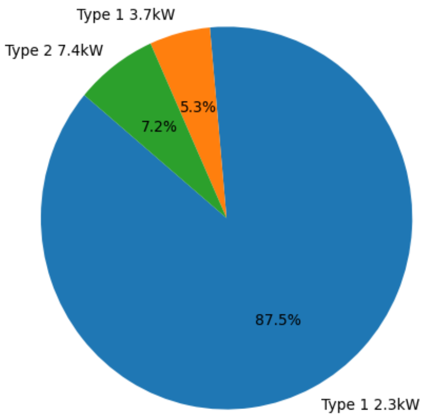


Figure 1. Distribution of EV customers by types of chargers in the process dataset[1]

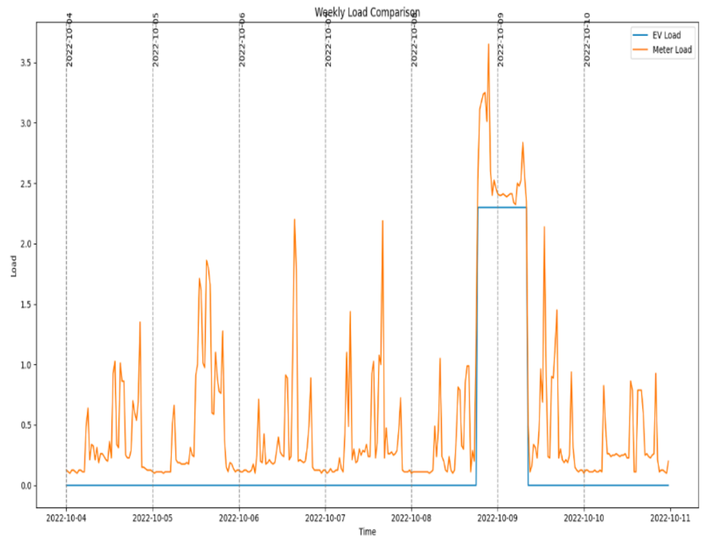


Figure 2. Weekly meter load and EV charging for customer using 2.3kW charger 1exxxxad9 from 2022-10-04 to 2022-10-11[1]

Table 1. Average EV charging energy consumption for each day of week showing relatively equal spread of charging over weekdays and less charging occurring over weekends, in particular Sunday [5]

Day of Week	Average EV Energy Consumption
Monday	10.25 kWh

[5] WP1.2 Technical modelling of electrification of transport profiles Milestone Report: EV charging profile extraction methodology and results, Page 32, Table 2

Tuesday	10.53kWh
Wednesday	10.56kWh
Thursday	10.33kWh
Friday	10.67kWh
Saturday	9.73kWh
Sunday	8.88kWh

The disaggregated EV charging data are then aggregated to form the collective EV charging consumption of non-PV customers using a probability distribution function (PDF) approach that accounts for key factors such as charger types, charging segments, and the temporal distribution of charging events. The PDF is expressed as the probability of charging events over the 24 hours of a day. The probability is determined by counting the number of charging events at each hour and then divided it by the total number over 24 hours. Figures 3 to 6 below show empirical PDF for 7.4kW EV charger over four different time segmentation: 'morning segment' for charging events that occur between 12am and 8am, 'daytime segment' for charging events that occur between 8 am and 4 pm, 'evening segment' for charging events that occur between 4pm and 12am, and 'morning & evening segment' for charging events that occur between 12 am and 8 am and between 4 pm and 12 am. The X-axis in the figures denote the hours of a day while the Y-axis is the calculated probability.

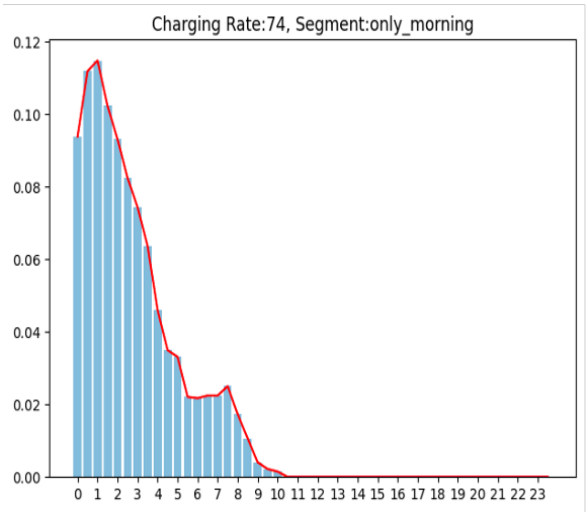


Figure 3. PDF for morning charging segmentation for 7.4kW charger[1]

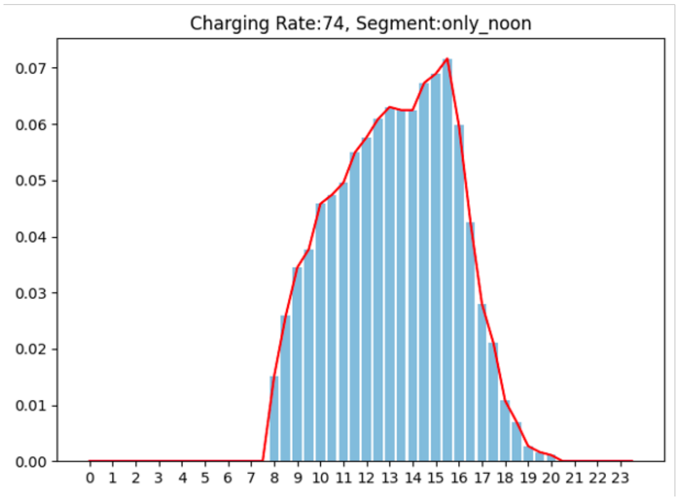


Figure 4. PDF for daytime charging segmentation for 7.4kW charger[1]

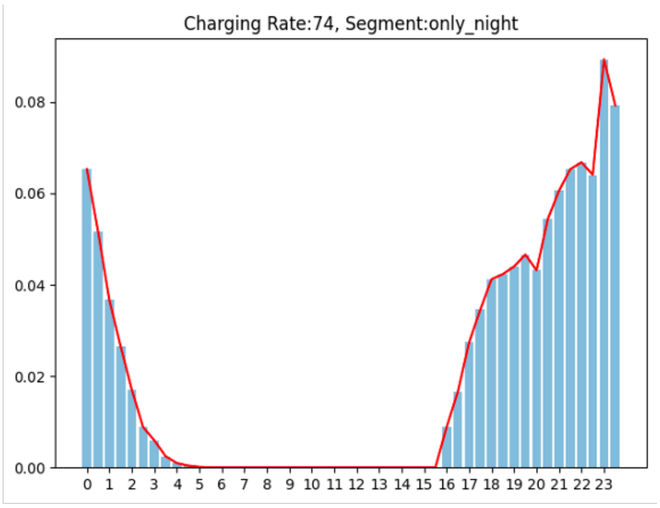


Figure 5. PDF for evening charging segmentation for 7.4kW charger[1]

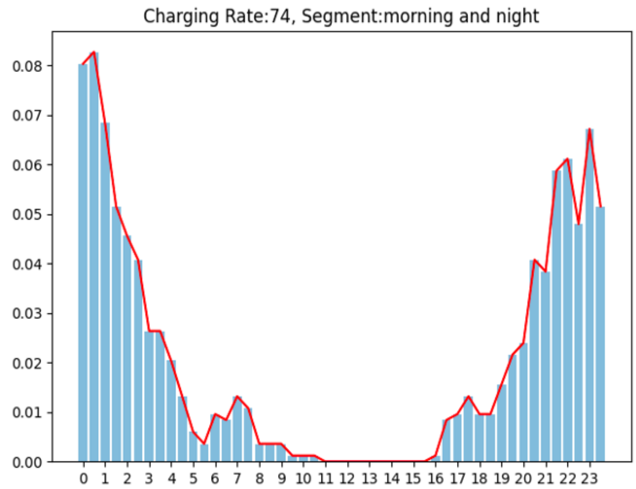


Figure 6. PDF for morning-evening charging segmentation for 7.4kW charger[1]

3.4.2 PV Customers

Presented below are the disaggregated data for 447 PV residential customers. The data shows that 2.3kW charger is predominantly used (Fig. 7), charging events are detected in the meter load (Fig. 8) and charging loads are higher on Tuesday and lower on Thursday and Sunday (Table 2).

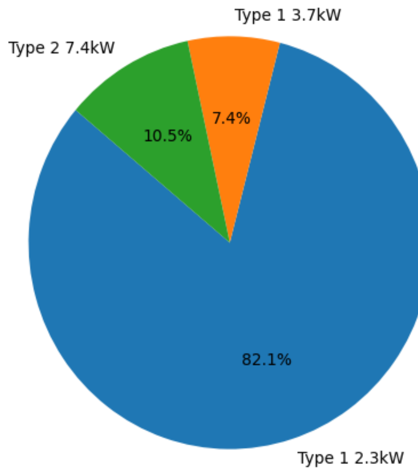


Figure 7. Distribution of EV customers with PV by types of chargers[1]

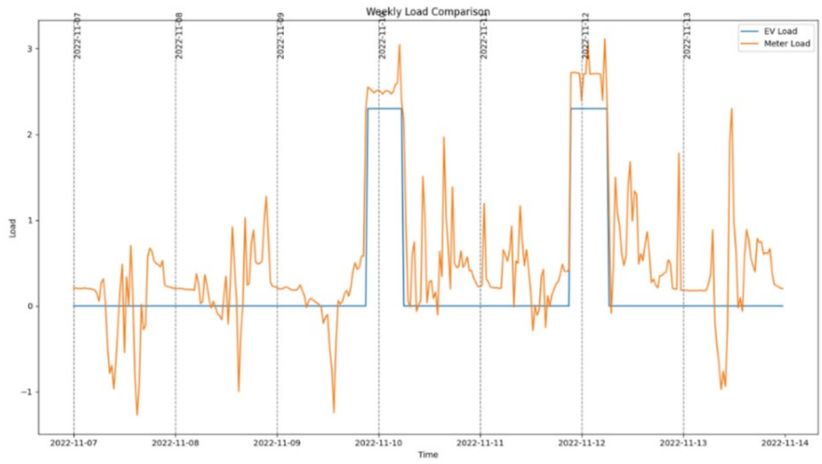


Figure 8. Weekly meter load and EV charging for customer using 2.3kW charger showing that….[1]

Table 2. Average EV charging energy consumption for each day of week showcasing [6]

Day of Week	Average EV Energy Consumption
Monday	9.78 kWh
Tuesday	10.58 kWh
Wednesday	9.50 kWh
Thursday	9.07 kWh
Friday	9.42 kWh
Saturday	9.37 kWh
Sunday	9.07 kWh

The disaggregated EV charging data are then aggregated to form the collective EV charging consumption of PV customers using a probability distribution function (PDF) approach that accounts for key factors such as charger types, charging segments, and the temporal distribution of charging events. The PDF is expressed as the probability of charging events over the 24 hours of a day. The

[6] WP1.2 Technical modelling of electrification of transport profiles Milestone Report: EV charging profile extraction and aggregation for PV customers, Page 20, Table 1

probability is determined by counting the number of charging events at each hour and then divided it by the total number over 24 hours. Figures 9 to 12 below show empirical PDF for 7.4kW EV charger over four different time segmentation: 'morning segment' for charging events that occur between 12am and 8am, 'daytime segment' for charging events that occur between 8 am and 4 pm, 'evening segment' for charging events that occur between 4pm and 12am, and 'morning & evening segment' for charging events that occur between 12 am and 8 am and between 4 pm and 12 am. The X-axis in the figures denote the hours of a day while the Y-axis is the calculated probability.

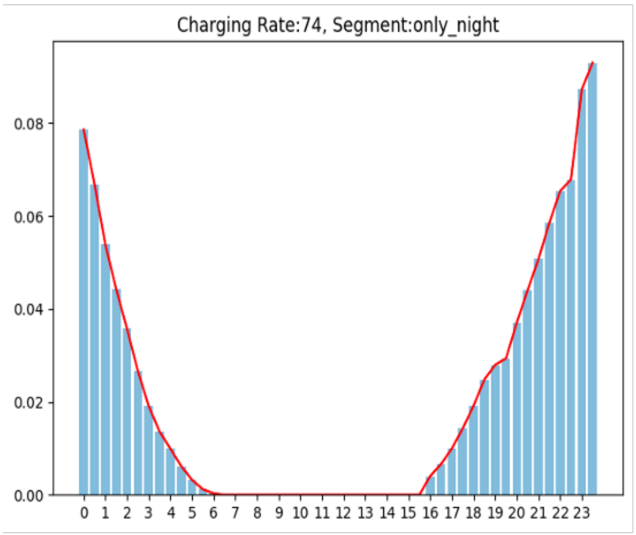


Figure 9. Probability Distribution Function (PDF) for morning charging segmentation[1]

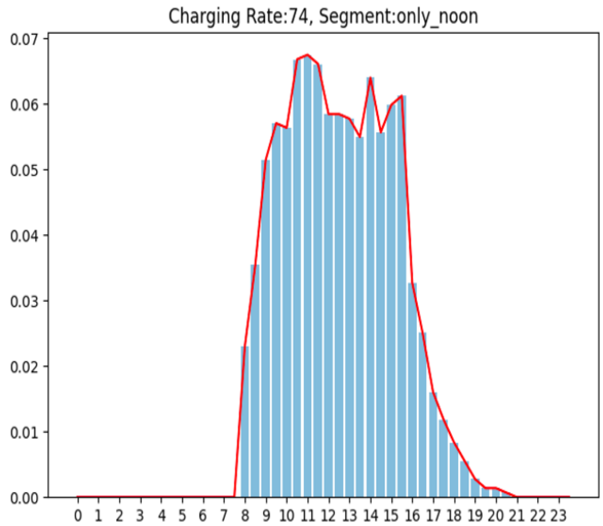


Figure 10. PDF for daytime charging segmentation[1]

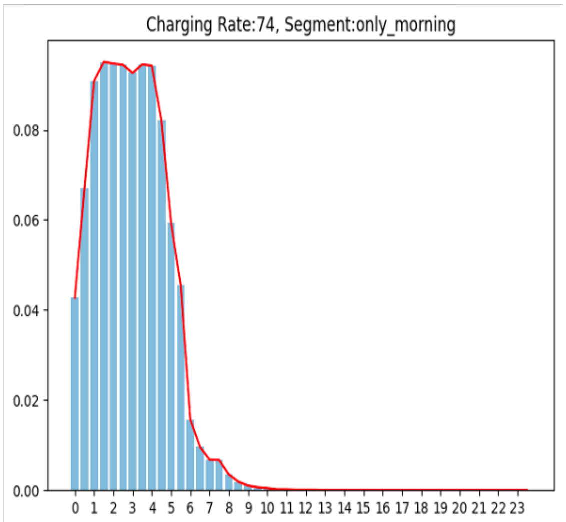


Figure 11. PDF for evening charging segmentation[1]

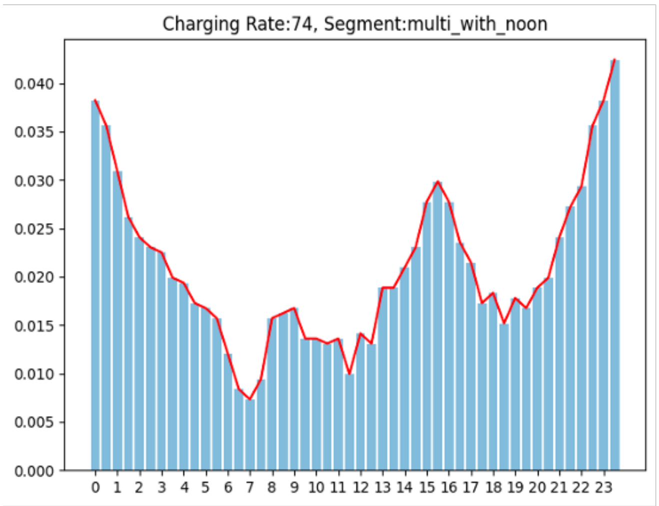


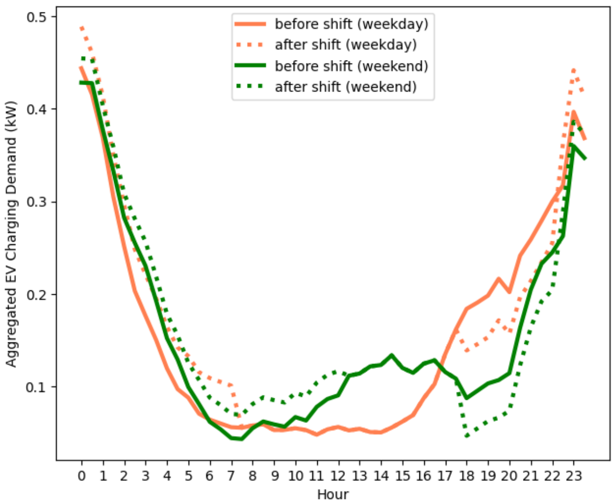
Figure 12. PDF for multi-charging with daytime charging

Compared with non-PV customers, the researchers observed that PV customers prefer daytime charging with a higher number of active charging and more charging sessions starting from daytime. From this observation it is inferred that installing solar PV systems may to some extent alter the residential energy consumption patterns. This is because EV customers with solar PV systems may tend to take advantage of the solar PV generation during daytime to charge their EVs. Their EV charging consumption at night times (especially during night peak hours) is therefore partially shifted toward the daytime periods.

It is recognised that the analysis may not fully capture EV charging profiles for PV customers during the daytime due to the absence of solar PV generation data. The method used relies on smart meter data, but the specific solar PV generation occurring behind the meter, which could contribute to EV charging, is unknown.

3.4.3 Vehicle-to-Grid (V2G)

Based on the researcher's analysis of non-PV EV customers, synthetic scenarios of V2G in shifting load and mitigating peak demand are simulated to demonstrate its effectiveness. The methodology outlines a systematic approach for implementing V2G technology, with the goal of reducing peak load demand on the grid by strategically discharging stored EV energy during peak hours (6pm to 10pm) and shifting EV charging to off-peak periods (10:30pm to 7am for weekdays, and 10:30pm to 12 noon on weekends). Three load shift scenarios are synthesised – 10%, 15%, and 20% load shifts. Note the scenarios are synthesised and not based on data when the EVs are connected to their respective chargers that allow V2G to occur.



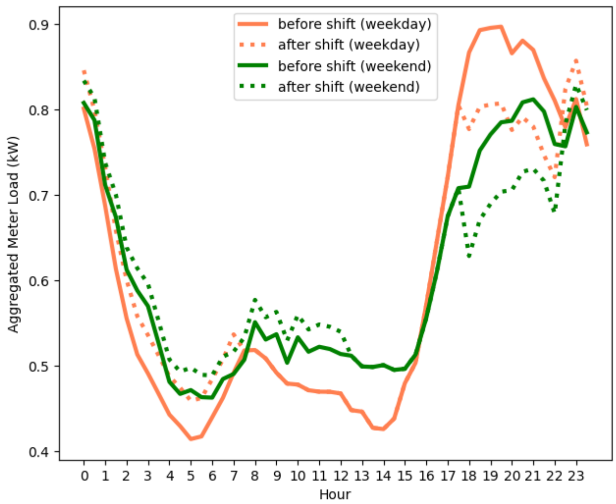


Figure 13. Aggregate demand profiles before and after 10% peak load shift via EV discharging[7]

[7] WP1.2 Technical modelling of electrification of transport profiles Milestone Report: Vehicle-to-Building/Vehicle-to-Home analytical methodology and results, Page 20, Figure 7

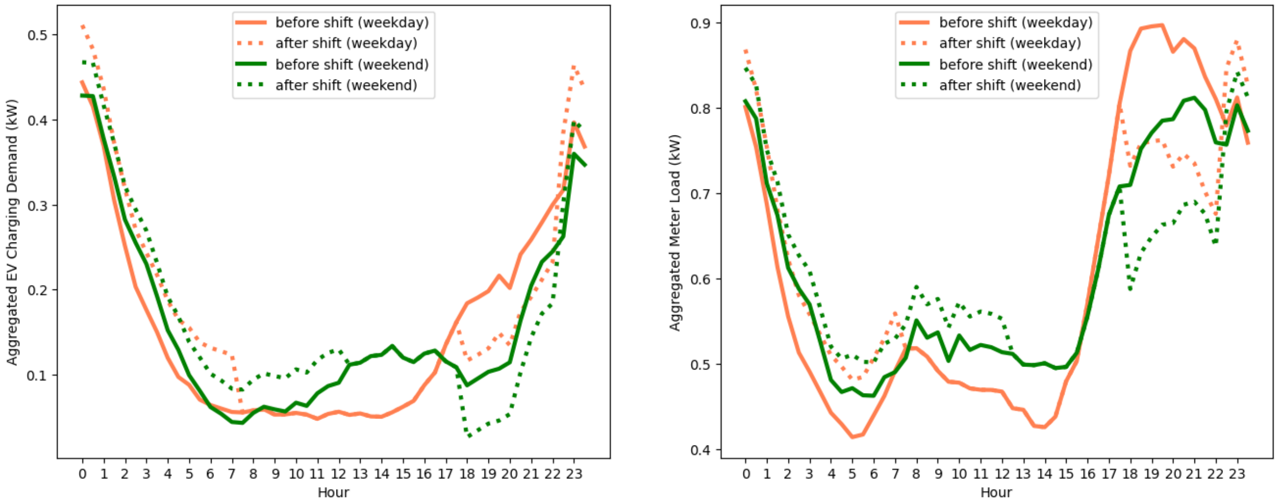


Figure 14. Aggregate demand profiles before and after 15% peak load shift via EV discharging[8]

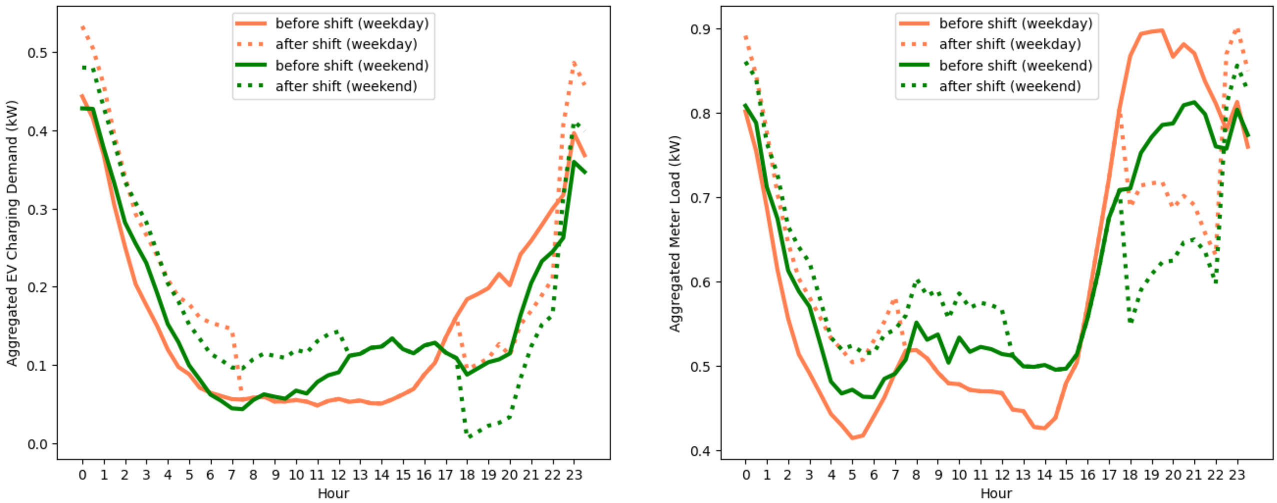


Figure 15. Aggregate demand profiles before and after 20% peak load shift via EV discharging[9]

This analysis illustrates that V2G technology can play a critical role in shaping future energy systems, where EVs are not just consumers but active participants in promoting and maintaining grid balance.

[8] WP1.2 Technical modelling of electrification of transport profiles Milestone Report: Vehicle-to-Building/Vehicle-to-Home analytical methodology and results, Page 21, Figure 8
[9] WP1.2 Technical modelling of electrification of transport profiles Milestone Report: Vehicle-to-Building/Vehicle-to-Home analytical methodology and results, Page 21, Figure 9

4. Observations, insights and key reflections for stakeholders

In reviewing the project's research reports and findings, C4NET has identified some observations, insights and key reflections for stakeholders. Outlined below we have summarised these for DNSPs, AEMO, policy makers and researchers, with a section highlighting observations in relation to consumer outcomes. While these are summarised for stakeholder type, this section should be read as a whole to ensure cross-sectoral awareness.

The research reports and findings are published on the C4NET website[10].

4.1 DNSPs

It is noted that many DNSPs already use their own ongoing estimation modelling to inform the impact of EV demand based on their network data. The research offers valuable insights into EV customers' charging equipment rating and charging behaviour e.g. weekday versus weekend, charging start time and charging duration. The aforementioned limitations means that it is difficult to draw strong conclusions likely across the entire population but instead provides insights of cases-in-point to help design future analysis and validation testing.

To provide a stronger foundation of insights related to EV customer's, there is an opportunity for DNSPs to repeat the analysis on a regular basis using their own data, so changes in customer demographics and preferences can be tracked. This will require modification to the research methodology to enhance outcomes, including:

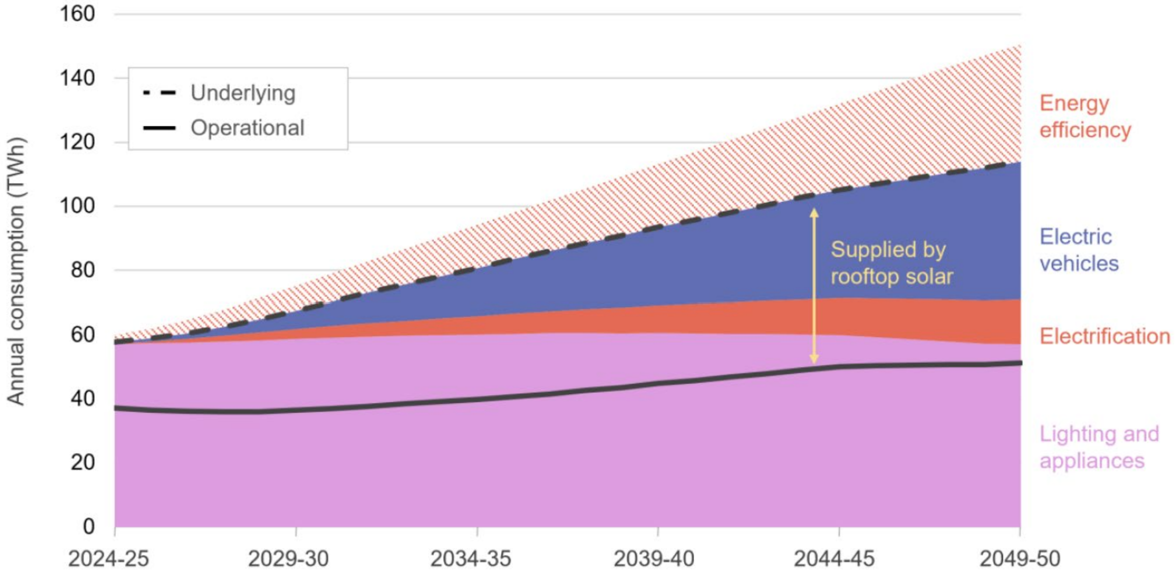
- Understanding household consumption at the granular level to identify the impact of different appliances. This will address the current assumption that there is no significant change in household appliance consumption after EV purchase in particular when longer time horizon is used. Moreover, the increasing electrification of gas appliances (driven by government policy) will add to household appliance consumption. Data additional to smart meter 30-minute consumption data, such as charger device data, could be useful in identifying EV charging.
- Gaining increased visibility of behind-the-meter EV consumption for PV customers.
- Drawing on a larger data pool. The research relied on Vic Government EV rebate program to match anonymised site behaviour to EV ownership. There are other sources of EV ownership data (e.g. VicRoads, major EV charger installers) that could support the identification of EV locations and potentially the types of chargers.
- Apart from 30-minute smart meter energy data, additional smart meter data (e.g. instantaneous voltage and current measurements) could be deployed to better differentiate EV charging from other appliance operations particularly for low level charging (2.3kW).

[10] www.c4net.com.au/projects/enhanced-system-planning-project/

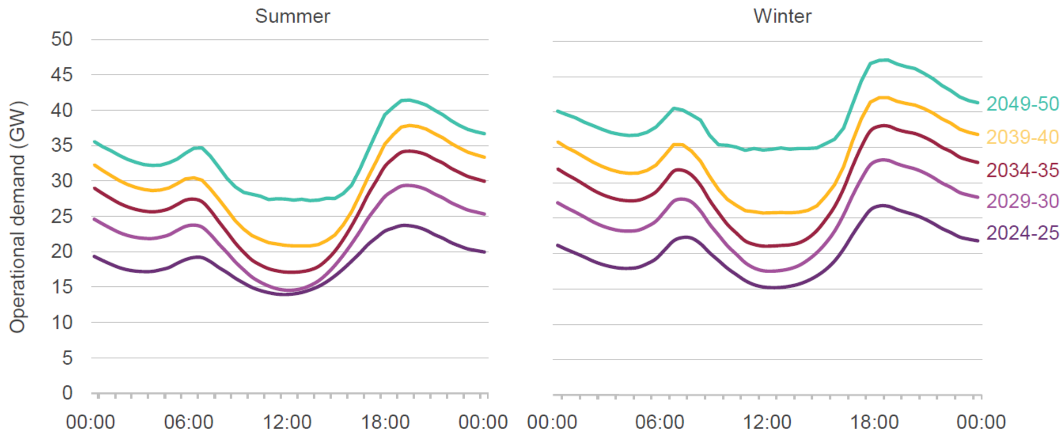
To encourage EV customers to charge when there is either excess network capacity or excess renewable energy production, DNSPs could consider providing incentives through either tariffs or real-time dynamic signals. Looking further out, V2G could see the challenges posed by EV turn into opportunities.

4.2 AEMO

AEMO's Integrated System Plan (ISP)[11] investigates a number of possible future energy scenarios for Australia. The "Step Change" scenario, considered by energy industry stakeholders to be the most likely scenario to play out, forecasts significant increases in both energy consumption (MWh) and demand (MW) from EV charging.



[11] AEMO, https://aemo.com.au/-/media/files/major-publications/isp/2024/2024-integrated-system-plan-isp.pdf?la=en



The research project's approach and methodology for the development of aggregated PDF for EV charging, based on empirical evidence, could be useful for AEMO to determine the average operational demand by time of day and season. However, as stated above in ***4.1 DNSPs***, the accuracy of the PDF would need to be improved by incorporating a larger dataset of EV owners and detection algorithm.

4.3 Policy makers

Not all EV locations can be identified using the current rebate program. There are other useful datasets (e.g. VicRoads, major EV charger installers) but there are barriers to the sharing of these datasets primarily to do with privacy provisions. Policy makers can facilitate the sharing of these datasets for specific purposes. The new EV loads are likely to be comparable to current household grid consumption and therefore advisable to inform as best as possible for market operators (AEMO), infrastructure planners. investors and policy makers/regulators. At present, there is no mandatory recording of EV charger installation and DNSPs are individually building algorithms to detect EV charging behaviour. This could be greatly simplified through the addition of EV registration data in a similar manner to the AEMO's DER register. As the sector transitions to high penetration of EV ownership and supports V2G charging, some basic registration details would make planning and supporting more efficient.

4.4 Consumer

EV customers can reduce the burden on the electricity infrastructure by charging at the time when there is network spare capacity or excess renewable generation or accepting limitation on charging behaviour. Policymakers and regulators can work to enable EV customers to seamlessly participate in V2G to generate revenue for their EV / enhance distribution system needs, through the development of standards, regulations and market-based incentives.

4.5 Research

Monash University has developed an innovative methodology of using 30-minute energy consumption data to discover EV charging. To ensure accuracy the methodology discards data that could still be related to EV charging. In other words, the methodology probably under-estimates the demand caused by EV charging. With electrification of other household appliances, the methodology will need to be enhanced if it is used to determine EV consumption beyond the early adopters. In this regard, it is noteworthy that Vic DNSPs are trialling the use of other smart meter data (5-minute snapshots of voltage and current) and pattern recognition techniques to discover household energy intensive appliances.

Appendix One

Researcher profile

Conducted by: Monash University

Lead Researcher: Hao Wang

Research Team: Jinhao Li, Leo Li, Chenghao Huang,
Department of Data Science and AI

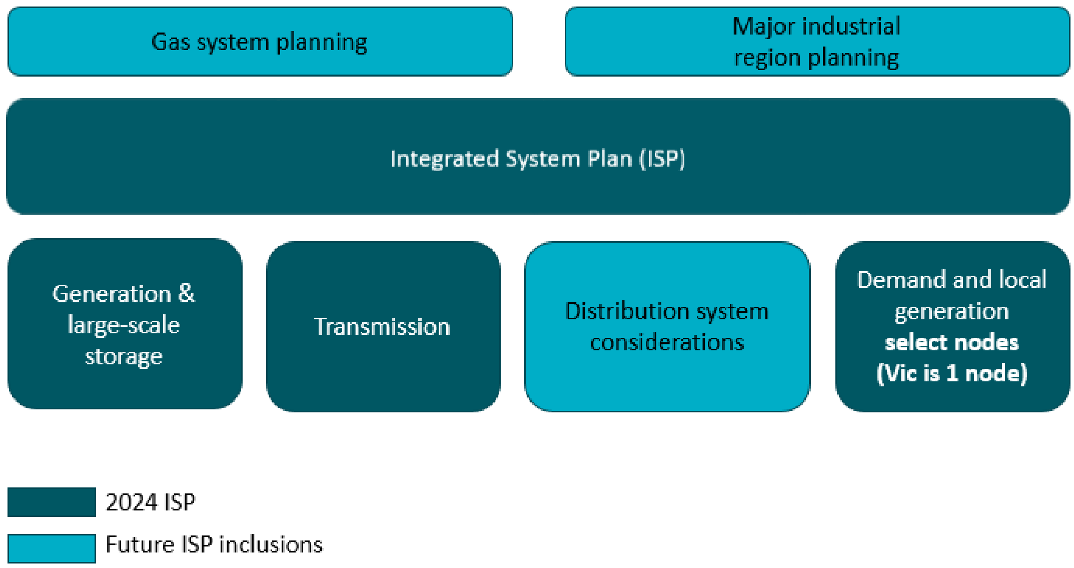
About C4NET

C4NET delivers multi-disciplinary solutions to the challenges the energy industry is facing. Working with complexity requires diverse skills, reliable data and new approaches, which C4NET facilitates by bringing together governments, industry and universities, creating new links across the sector.

Central to C4NET's program of work is the Enhanced System Planning (ESP) project, a significant and collaborative research project aimed at informing sub transmission level electricity planning beyond 2030, with a focus on building methodologies and approaches for bottom-up modelling and to highlight the opportunities presented through the distribution system and integrating Consumer Energy Resources (CER), to inform whole of system planning.

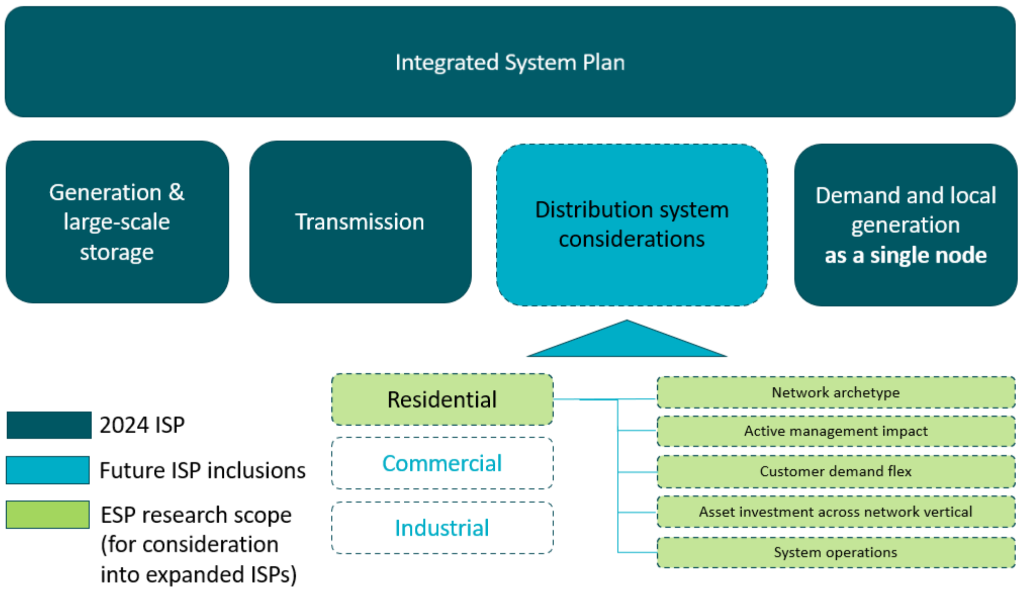
Appendix Two – Bigger picture integration with the ISP

Shift towards whole of system planning



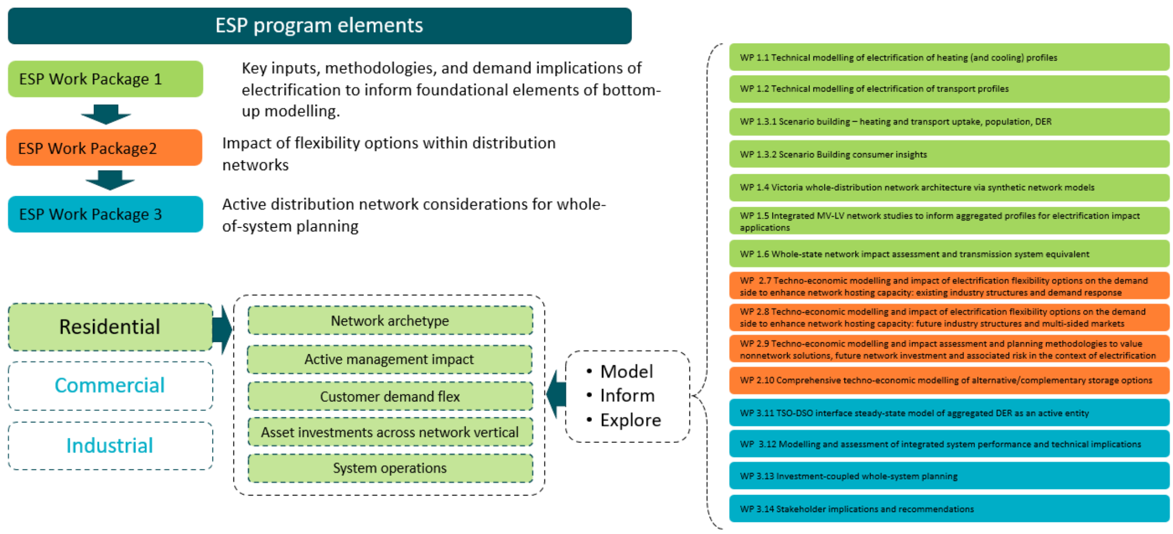
The Energy and Climate Change Ministerial Council (ECMC) accepted the recommendations of the review of the ISP which target transformation of the energy system as a whole, with particular reference to gas system planning, major industrial region planning and distribution systems.

Distribution system components of whole of system planning

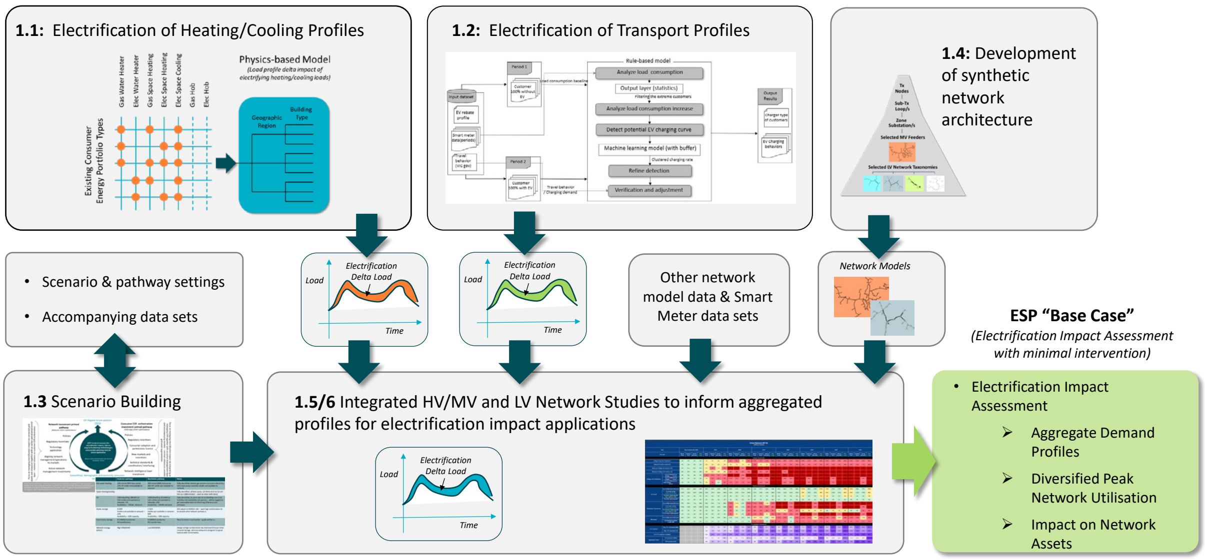


The ESP was scoped to be deliverable with the resources and time at hand to inform feasibility of broader application. It focussed on the more complex areas around residential and low voltage assets of the distribution system, with an application across Victorian networks with methodologies applicable to any region in the NEM.

ESP alignment with distribution system components of whole of system planning



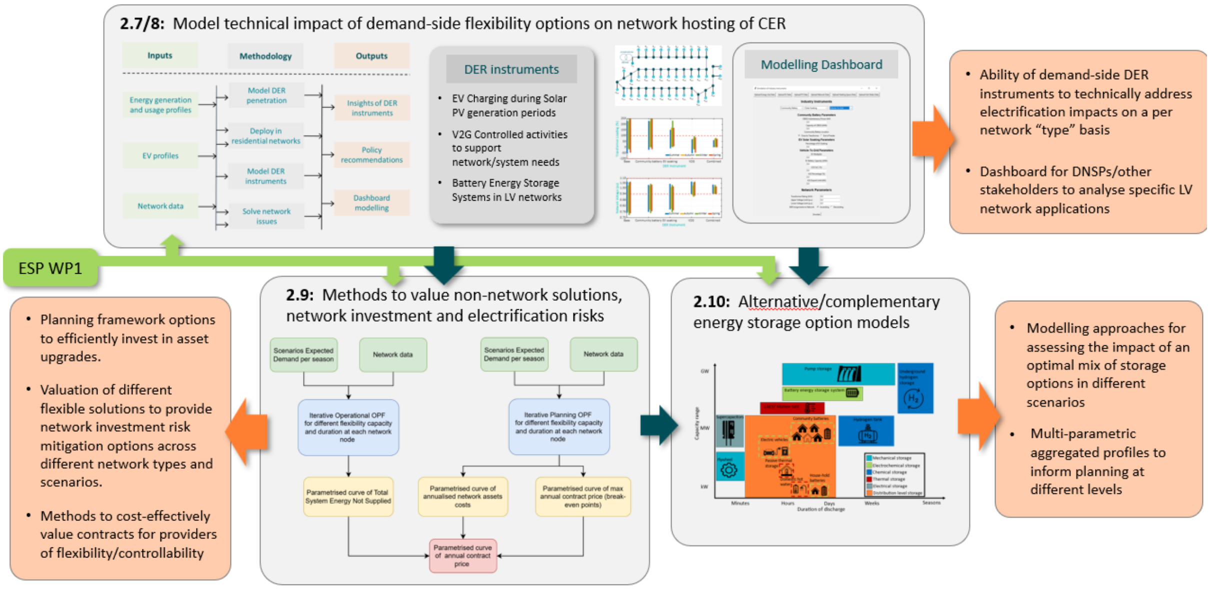
The 'base case' for residential electrification impact assessment, the flex options and relativity to other investment options



C4NET

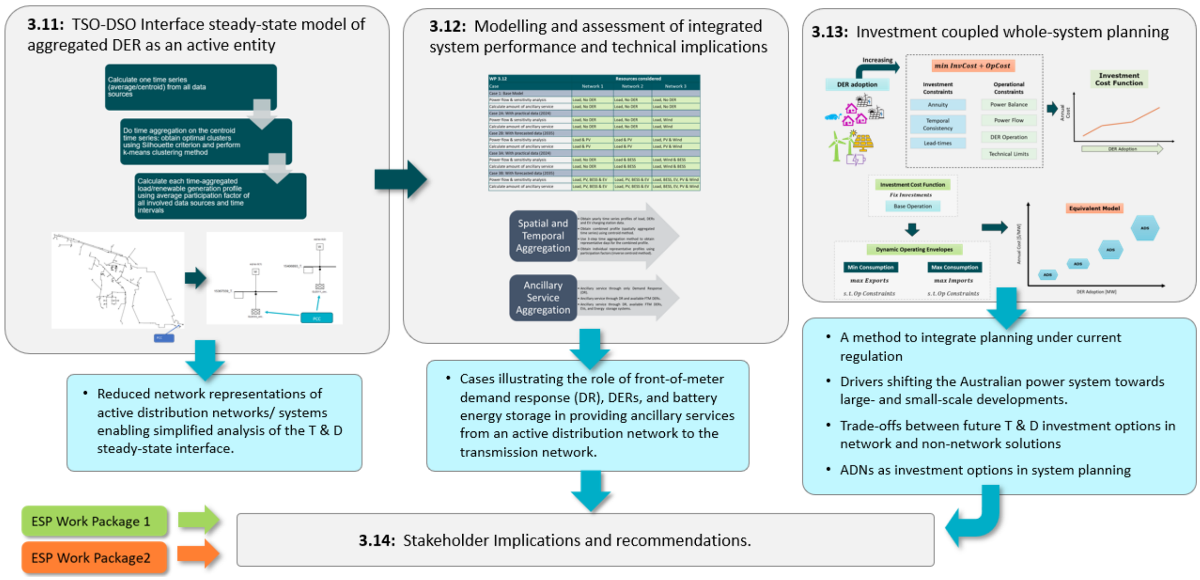
Impact of flexibility options within distribution networks

(ESP Work Package 2)



Active distribution network considerations for whole-of-system planning

(ESP Work Package 3)



Appendix Three – ESP project and research partners