Enhanced System Planning Project

C4NET | ESP Enhanced System Planning

C4NET Project Overview

Techno-economic Modelling (Existing & Future) of Demand-Side Flexibility

Work Package 2.7 & 2.8

April 2025

Table of Contents

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.*

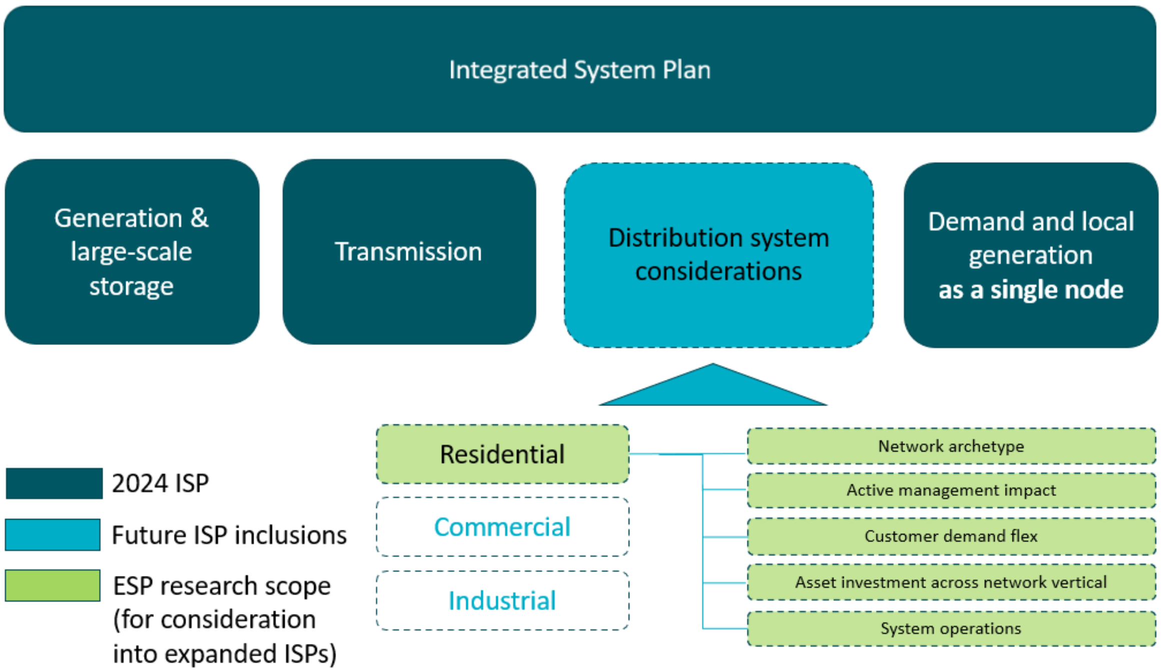


Figure 1 – Relationship between ISP and ESP

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.
- **Work package two**: Impact of flexibility options within distribution networks Techno-economic implications of future architectures.

[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 three:** Active distribution network considerations for whole-of-system planning implications: technical, economic and policy.

A key project of work package two, RMIT University and Monash University jointly undertook an independent research project: Techno-economic Modelling (Existing & Future) of Demand-Side Flexibility, with the goal of exploring the use of CER and DER flexibility as instruments to address demand-side management challenges within low-voltage (LV) distribution networks[3]. The network challenges examined were transformer overloading, voltage limit breaches, and hosting capacity constraints associated with high CER/DER penetration. Three key DER management solutions were evaluated: community batteries, EV charging through solar soaking, and Vehicle-to-Grid (V2G) technology. While economics of community batteries was examined, the primary focus of the project was on technical modelling of the DER flexibility instruments and their effect on LV network constraints, in a high CER/DER world, for urban and rural networks.

This report is designed to guide stakeholders in their understanding of how the research and tool developed can be used to assess the potential of these DER flexibility tools to resolve LV network issues and delay the need for network upgrades in the long-term interest of the consumers.

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 and 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.

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

2. Project Summary

The Techno-economic Modelling (Existing & Future) of Demand-Side Flexibility research project sought to develop a modelling framework and a user tool to evaluate the effectiveness of DER flexibility instruments in alleviating specific network issues caused by high penetration of CER/DER, with a primary focus on PV and EV. The project's relationship with other research projects in Work Packages 1 & 2 is illustrated in *Figure 2* below.

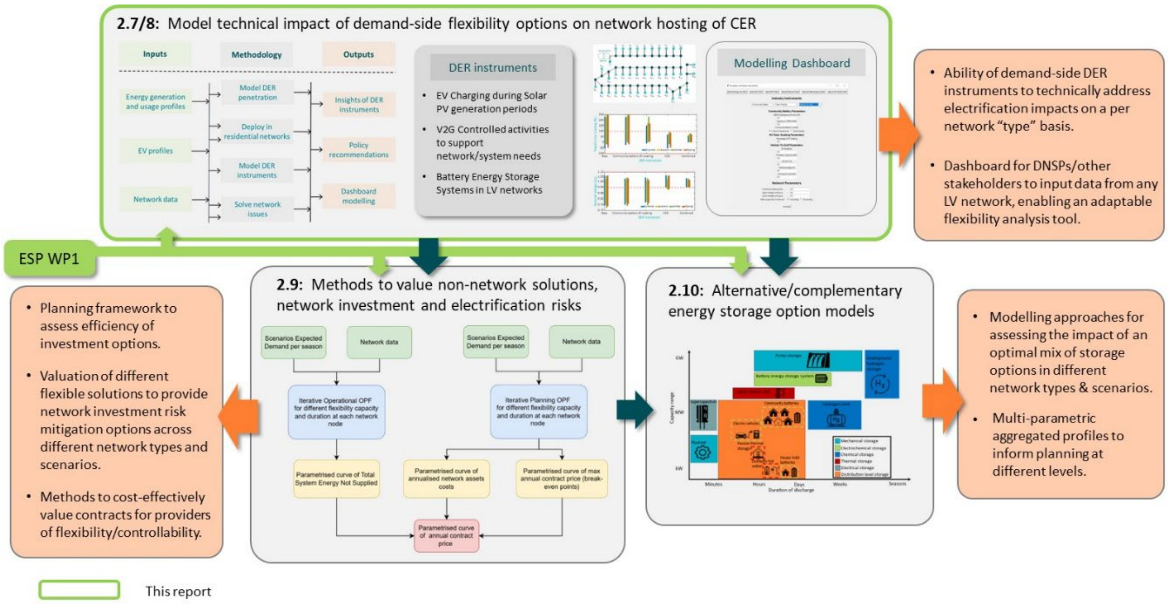


Figure 2 – Relationship between this research project and other projects in Work Packages 1 & 2

Under high DER/CER penetration scenarios, such as those involving 100% adoption of EVs and rooftop PV systems, LV networks are at risk of transformer overloading and voltage stability issues. the study's key findings delve into the extent to which DER instruments can be leveraged to avoid or mitigate such issues and defer the need for network investments. Due to the potential of these DER instruments, they should be considered for electricity network infrastructure planning.

To facilitate this analysis, the research project has developed a modelling tool. Through detailed modelling and case studies of illustrative rural and urban networks, the project demonstrated the potential for select DER flexibility instruments, specifically community batteries, EV charging through solar soaking, and Vehicle-to-Grid (V2G) technology, to resolve network issues.

The modelling tool includes a dashboard which allows DNSPs to input specific LV network data and simulate the application of DER management instruments under various operational scenarios. By populating the dashboard with real-world network data, DNSPs can evaluate the effectiveness of instruments such as community batteries, EV charging through solar soaking, and Vehicle-to-Grid (V2G) technology in alleviating specific network issues. The modelling tool provides an actionable framework for DNSPs to make data-driven decisions on deploying DER solutions within their unique contexts.

The sole focus of the project is on the use of DER flexibility instruments to resolve network issues. It should be noted that DER flexibility instruments can potentially also be used to respond to energy market signals which is outside the scope of this project.

3. Research methodology and approach

With Australia's commitment to achieve net zero emission by 2050, it is expected that future energy system scenarios will include high penetration of CER/DER at all voltage levels of the distribution networks, and in particular within the LV distribution networks where most CERs are connected. Each distribution circuit is designed to accommodate up to a maximum value of demand (i.e. electricity consumption) and local generation (i.e. reverse power flow). The high penetration of CER/DER (e.g. solar PV, EV), lack of diversity in their operation (e.g. solar PV all generating at the same time), and additional demand from electrification (e.g. gas substitution for space heating, cooking and domestic hot water) can cause these designed values to be exceeded, leading to network issues such as asset overloads, voltage limit violations (over or under voltages) and imbalances between the three supply phases. Mechanisms to encourage flexibility instruments in demand (consumption) and/or supply (generation) can reduce the network impact of CER/DER, which would otherwise require curtailment to the operation of CER/DER and/or investments to overcome the impact.

The project investigates three flexibility instruments:

- **Community Batteries.** Community batteries, also known as neighbourhood batteries, are devices which can consume electricity (by charging) and generate electricity (by discharging). They are sized to serve entire neighbourhoods and typically range up to power capacity of 5 MW and storage capacity from 100 kWh up to 5 MWh. The batteries are installed in front of the meter, typically on the LV grid and could be owned and operated by the DNSP or a third party. A typical use case for community batteries is to store excess energy generated by local solar panels during the day (reduce reverse power flow in a solar soak operation) and discharge it during peak demand periods (reduce maximum demand/consumption in a demand management operation), thereby improving energy efficiency and reliability within the local grid, and deferring network investment.
- **Vehicle-to-Grid (V2G).** The forecast in transport electrification will lead to many electric vehicles (EVs) being purchased by consumers. Charging of EVs and other electrification processes will drive up the maximum electricity demand, causing strains on the existing electricity supply infrastructure. Vehicle-to-Grid (V2G) technology represents an advancement in the integration of Electric Vehicles (EVs) into power grids. This technology allows for the bi-directional flow of electricity between EVs and the power grid, enabling EVs not only to draw power from the grid for charging but also to supply power back to the grid when needed. This capability transforms EVs into mobile energy storage units that can contribute to grid stability, thereby enhancing the overall efficiency and resilience of the power grid. A typical use case for V2G, not dissimilar to that of community batteries, is to charge up at other times and discharge during peak demand periods.
- **EV charging through solar soaking.** While uncontrolled EV charging leads to increase in maximum electricity demand (as most EV owners will charge their vehicles on arriving home from work, which coincides with other electricity usages), encouraging EV charging to occur

during periods of solar generation (in an operation called solar soaking) will effectively transform the impact of EV charging from negative into positive by preventing grid overloads, stabilising the overall electricity supply system while benefiting the EV and PV owners.

While these are not the only flexibility instruments for CER/DER, they are among the list of emerging applications that are being discussed and pursued in various trials and implementation projects across Australia and overseas.

3.1 Approach

The project methodology is depicted in Figure 3 and briefly described below:

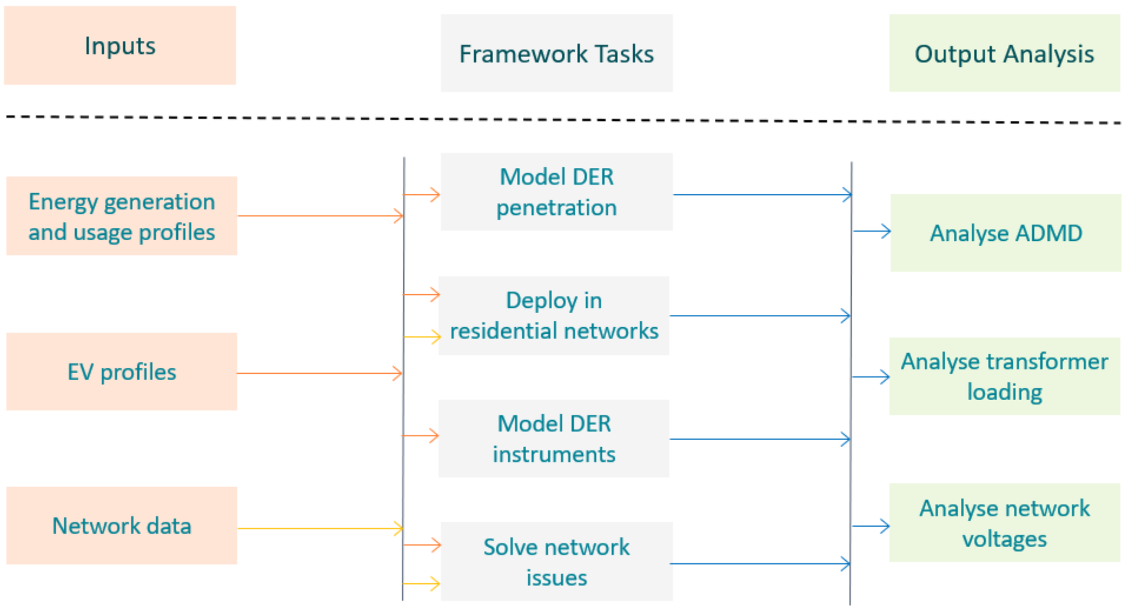


Figure 3 - Project methodology

3.1.1 Inputs

The three required inputs are:

- Energy generation and usage profiles,
- EV profiles, and
- Network models.

Energy generation profiles were essentially rooftop PV profiles of residential customers. Usage profiles referred to base load and Hot Water System (HWS) profiles. EV profiles were EV charging profiles. The network data represented the distribution transformer rating, feeder line data, and lengths between residential customers, and unbalanced structure. The initial models created in the ESP project *Development of illustrative distribution network models for Victoria research* (WP 1.4) were used as inputs for the modelling studies in this project consisting of a rural and an urban Low Voltage (LV) distribution network as shown in Figure 4 and Figure 5. The network models are for illustrative purpose only and are not meant to be exhaustive.

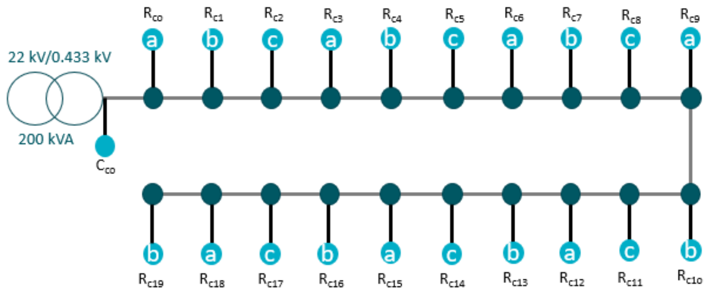


Figure 4 - Single-line diagram of a modelled LV rural network with 20 residential (R_{cx}) and 1 commercial (C_{co}) customers

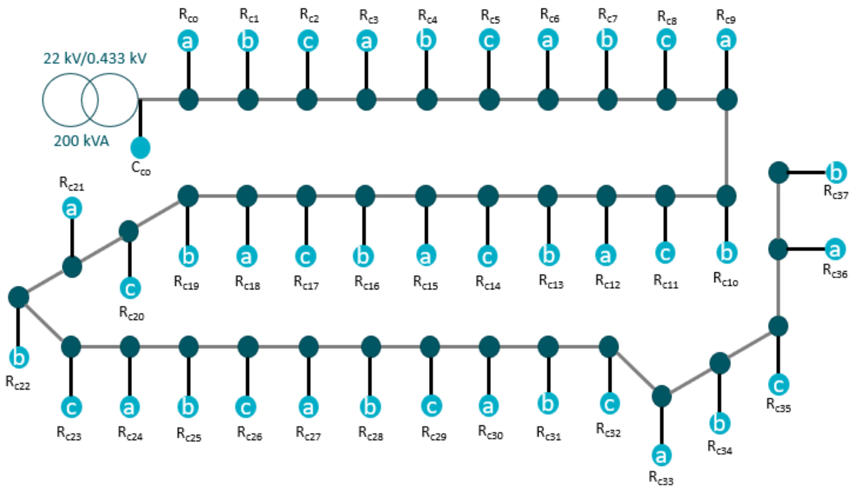


Figure 5 - Single-line diagram of a modelled LV urban network with 38 residential (R_{cx}) and 1 commercial (C_{co}) customers

3.1.2 Main Tasks

The project framework consisted of four main tasks:

- Modelled existing DER penetration (business as usual DER penetration scenario).
- Modelled future DER penetration,
- Deployed existing and future DER penetration in LV distribution network models to investigate the impacts on the network profiles (after diversity maximum demand, and transformer loading and voltage profiles) by running three-phase AC power flow,
- Modelled DER instruments (community battery, EV charging through solar soaking, and V2G) and deploying them in the LV distribution network models to investigate the impacts on the network profiles and compared the results with the base case (without DER instruments) to demonstrate the effect in resolving network issues. Two locations of community battery are modelled, one near the beginning of the distribution substation and one at the end of the LV distribution circuit.

3.1.3 Scenarios

Three scenarios of DER penetrations were considered to represent existing, near future, and potential future CER/DER penetration scenarios. Existing CER penetration scenario (Scenario A) consisted of customers with 30% PV and 10% EV, whereas near future CER penetration scenario (Scenario B) comprised customers with 50% PV and 50% EV. On the other hand, customers with 100% PV and 100% EV (1.6 EV per household) were considered in potential future CER penetration scenario (Scenario C). All CER customers were also assumed to have Hot Water Systems (HWS).

3.1.4 Coordination Mechanism

For the community battery modelling, it was assumed that the community battery was centrally coordinated by the DNSPs to charge during reverse power flow period to soak up local excess solar generation, and discharge during peak usage period to reduce transformer loading. The reactive power support from the community battery was activated by the central coordination mechanism to resolve voltage issues that arose.

For the EV charging through solar soaking modelling, a selected percentage of EV customers would shift their peak charging load to the excess PV hours (reverse power flow periods). The customer percentage varied from full behaviour shifting (assumed through mandatory central coordination) and partial behaviour shifting to reflect behavioural (not mandatory) change in charging by EV consumers.

For V2G modelling, a selected percentage of EV customers were modelled to discharge the energy stored in their EV and feed into the grid during peak usage period through central control. The V2G output power was limited by an export limit of 7kVA per customer and randomised to reflect the available battery state-of-charge (SOC) of their EV batteries.

After modelling the effect of individual flexibility instruments, the combined effect of the three flexibility instruments on the LV distribution networks was analysed for Scenario C (high CER penetration) by applying the instruments in the sequential order of EV charging through solar soaking, V2G and community battery.

3.2 Inclusions, exemptions and limitations

To simplify the modelling approach, some design characteristics were incorporated that have inherent limitations. These are:

- Two illustrative LV network models, one rural and one urban from WP1.4 work prior to its final outputs, were used to assess the impact of increased CER penetration and the effect of the three CER/DER flexibility instruments. They are by no means exhaustive.
- The profiles of net power (the difference between load and PV profiles) and HWS for the LV network customers were taken from smart meter data from another project, as the outputs of ESP WP1.4 were unavailable at the time this research was undertaken.
- The size of community battery modelled has a power rating of 400kW and an energy rating of 500kWh.

- The primary focus was on the impact of PV and EV and does not include other electrification initiatives.
- EV charging profiles were created through EV battery optimisation, considering existing EV charging plans and ensuring distributed charging patterns throughout different intervals of a sample day.
- Power flow simulations were conducted for a sample day on the LV network models and the potential influence of the upstream MV feeder powerflow has not been considered.
- The power quality response modes of PV Inverters (such as Volt-Var and Volt-Watt modes), which are now mandated by DNSPs to reduce the effect of voltage breaches during solar export, are not modelled.
- There was no economic assessment as originally intended for the project. The project has outlined community battery price trends but there is no assessment of the trade-offs of deploying such levers versus investment required or operational cost of doing so.

Apart from three CER/DER instruments considered in this report, there are other viable options that are being considered or implemented. These include

- Dynamic Operating Envelope (DOE) can be used to limit the maximum demand/import or maximum solar exports from CERs/DERs.
- Other consumer appliances, such as heating and cooling systems, hot water systems and home battery systems, can also provide flexibility service for demand management; and
- The policy setting to achieve customer acceptance for coordination of their CERs (e.g. tariffs) have not been modelled.

3.3 Researcher model

In addition to running case studies of power flows for the two illustrative LV networks over the three CER penetration scenarios, a specific dashboard[4] was developed which allows user inputs to mimic different choices of customers and DNSP networks. The table below summarises the user inputs and flexible variables in the dashboard:

Key features	Descriptions	Remarks
Inputs	• Net profiles from smart meters • EV profiles • HWS profiles • Space heating profiles • Customer IDs	• In this project case studies, space heating profiles are not used. • The 22kV side of the LV transformer is set to a voltage of 1 pu.

[4] WP 2.7 & 2.8 Techno-economic Modelling (Existing & Future) Final Report: 30 November 2024, Section 4, page 55

	• LV transformer voltage profiles • LV network model in OpenDSS format	
Flexible variables	• Upper and lower voltage limits • Size of the transformer • Size and location of the community battery • Average EV per customer • Percentage of EV charging through solar soaking and V2G • Available SOC for V2G and V2G export limit	• Two locations of the community battery are considered. For any other locations, OpenDSS[5] formatted circuit needs to be revised. • Consideration of high EV penetrations can allow more customers to participate in EV charging through solar soaking and V2G.
Outputs	• Impact on transformer loading • Impact on voltage profiles • Impact on after diversified maximum demand	• Impacts with CER/DER instruments are compared with the base case (without CER/DER instruments) to visualise the improvements.

Table 1 – Dashboard inputs, outputs and flexible variables

[5] OpenDSS is an electric power distribution system simulator (DSS) designed to support distributed energy resource (DER) grid integration and grid modernization. It was originally developed by EPRI in the US. It is now open sourced.

4. Observations, insights and key reflections for stakeholders

Through the evaluation of the work undertaken, 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.

4.1 DNSPs

The modelled outcomes show increases in distribution transformer loading, incidences of voltage non-compliance and three-phase voltage imbalances as the penetration of PV and EV increases from Scenario 1 to Scenario 3 under a business-as-usual environment, in line with the general understanding of DNSPs.

The outcomes of modelling (without CER/DER flexibility instruments) show more adverse effects on the urban network than the rural network as CER/DER penetration increases. This is due to the use of different customer counts in the two networks: 20 in rural network and 38 in urban network, which is not un-reasonable. However, with the assumptions of the same percentage of customers having PV and EV in the scenario assessment and identical distribution transformer size (200kVA), more extreme values of import and export are expected in the urban network. This may not be the situation in practice, for example, EV penetration is likely to be lower in rural areas due to the need for long distance travels, and the size of the distribution transformer is likely to be higher in the urban network.

The beneficial effects of the three flexibility instruments have been illustrated for the selected LV network models. Here are some insights:

- Community batteries.
    - The location of the community batteries in the LV network is important to assist with voltage compliance. Two locations of the community battery have been considered, close to the transformer (location 1) and towards the end of the feeder (location 2). Placing a community battery at location 2 has been found to improve voltage profiles better compared to location 1 due to reducing voltage drop across the network.
    - The size of the community battery is an important parameter to optimise. In the case studies the 400kW/500kWh community battery was fully charged fairly early and hence was not very effective in limiting the reverse power flow caused by PV export.
    - DNSPs will need to coordinate the operation of community batteries if they are to address network issues caused by the uptake of CERs. This will require collaboration with the battery owner (if not the DNSP), as the community battery

would also presumably be used within the wholesale energy market (in parallel with the provision of network services).

- EV charging through solar soaking.
    - This approach brings two benefits: reduced reverse power flow during PV generation period and reduced peak consumption as EVs are charged less during peak consumption period.
- V2G.
    - When compared with EV charging through solar soaking, V2G will further reduce the peak consumption by discharging energy back into the grid during peak consumption period.
- The modelling indicates that at very high CER penetration (Scenario C, 100% PV and 100% EV), all three flexibility instruments are required to bring network adverse impacts into compliance. There is no one silver bullet and hence DNSPs should consider deploying multiple DER instruments.

The dashboard developed allows DNSPs to investigate the impact of the three flexibility instruments on specific networks and parameters of their choice.

4.2 AEMO

AEMO's Integrated System Plan (ISP) includes forecast of highly orchestrated CERs (CERs that are centrally coordinated through arrangements such as VPP) primarily for the benefits of the energy market. The research project demonstrates that flexibility instruments for CER/DER can benefit the distribution networks in addition to their use for the energy market. Close collaboration between AEMO and DNSPs can more effectively unlock the network and market benefits of CER/DER flexibility.

4.3 Policy makers

The project illustrates that CER/DER flexibility instruments are effective in assisting the networks to accommodate increased penetration of CERs (such as PV and EV). While not demonstrated by the project, the same flexibility instruments can make significant contribution to the energy market.
As CERs are owned by consumers, the willingness of consumers to relinquish some control depends on government policy and incentive framework.

Policy makers can play a significant role in introducing a range of mechanisms or incentives that improve customer acceptance of flexibility provision noting that adaptation needs to balance the value for both the individual and communal system benefits, in a manner that avoids complexity for households:

(1) Standards – both EV solar soaking and V2G require standards to ensure EV charging equipment supports the benefits of flexibility instruments
(2) Incentives for consumers and DNSPs:
    a. provide ongoing incentives for the procurement of EV charging equipment that includes solar soaking and V2G functionalities
    b. consider linking existing incentives – e.g. an incentive for EV could include a requirement to be linked to on-site solar generation to minimise both solar export and EV contribution to peak demand
    c. consider the role of DNSPs in the provision of neighbourhood batteries to enable benefit sharing
(3) Tariffs – To a significant degree, consumer behaviour and choices will be influenced by the price they pay. If seeking to shift usage time to avoid network congestion, then tariff structures should be assessed as to how well aligned they are to achieve this. It is noted that:
    a. network tariff structures are only a component of the consumer bill; it is the retail tariff and price that is relevant to the consumer. Perhaps DNSPs and retailers could collaborate to find compelling products that send effective signals to consumers?
    b. the bulk of consumers prefer simplicity over complexity with utility products as few are deeply engaged in considering their purchase and usage of electricity. For any pricing incentive to work it would need to be easily understood and highly visible
    c. For community batteries, more customer participation could be realised if they could better capture the value of exchanging their generated energy with the community battery (storage and re-use at a later stage).
(4) Markets – While market for demand response exist in the National Energy Market (NEM), they are limited to peak demand management. Market framework is required for the extension to cover minimum demand management using EV for solar soaking and V2G.
(5) Awareness - raise awareness of consumers to the incentives/tariffs/automation opportunities that are designed to reduce the overall costs to support the move to the acquisition of EV.

4.4 Consumer

Existing and prospective EV owners should be made aware of the impact of EV on the network and energy market, and how being flexible in EV charging operation and having advanced V2G capability can assist in creating additional revenue stream by minimising the impact from transport electrification while opening up the opportunity for enhanced support to the energy system using their EVs.

4.5 Research

The modelling performed in the project is primarily technical and does not include economic modelling. Economic modelling is required to identify which CER/DER instruments are more effective in addressing the future scenario of increased PV and EV penetration. This would have to include quantification of the costs and benefits of the various flexibility instruments. WP2.9 and WP2.10, currently in progress, will explore the economic aspects of some of the flexibility instruments. While the project focuses on three CER/DER flexibility instruments, there are other flexibility instruments that have been demonstrated by research and limited trials both in Australia and overseas. A complete techno-economic modelling should include all known instruments to date.

Appendix One

Researcher profile

Conducted by: RMIT University & Monash University, Melbourne

	RMIT University	Monash University
Lead Researcher:	Prof Mahdi Jalili	Dr Reza Razzaghi
Research Team:	Dr Nameer Al Khafaf	Dr Imran Azim, Dr Mohsen Khorasany

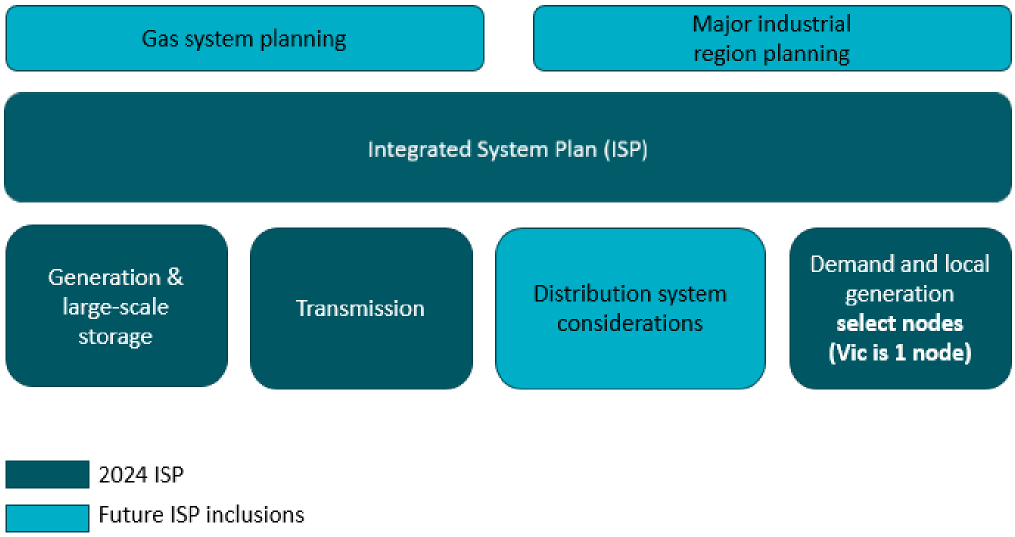
About C4NET

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.

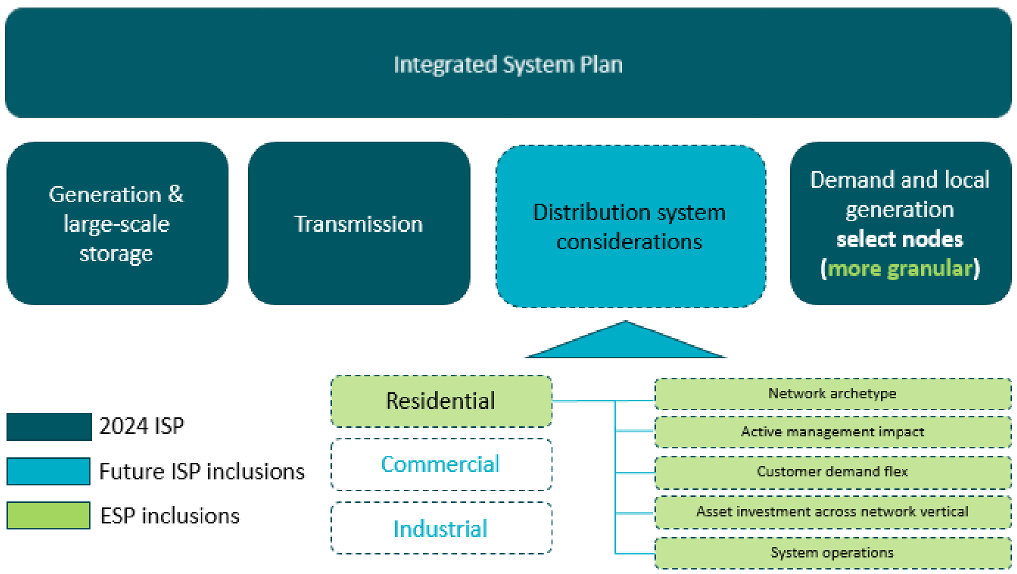
Appendix Two – Bigger picture integration with the ISP

Shift towards whole of system planning



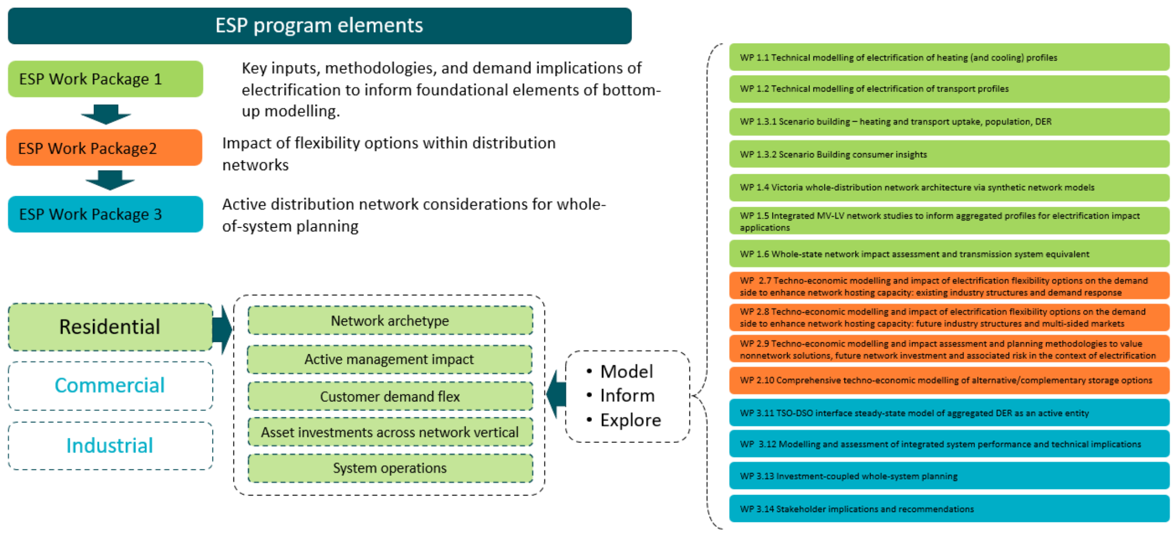
The Energy and Climate Change Ministerial Council (ECMC) accepted the recommendations of the review of the ISP which target transformation of the energy system as a whole, with particular reference to gas system planning, major industrial region planning and distribution systems.

Distribution system components of whole of system planning

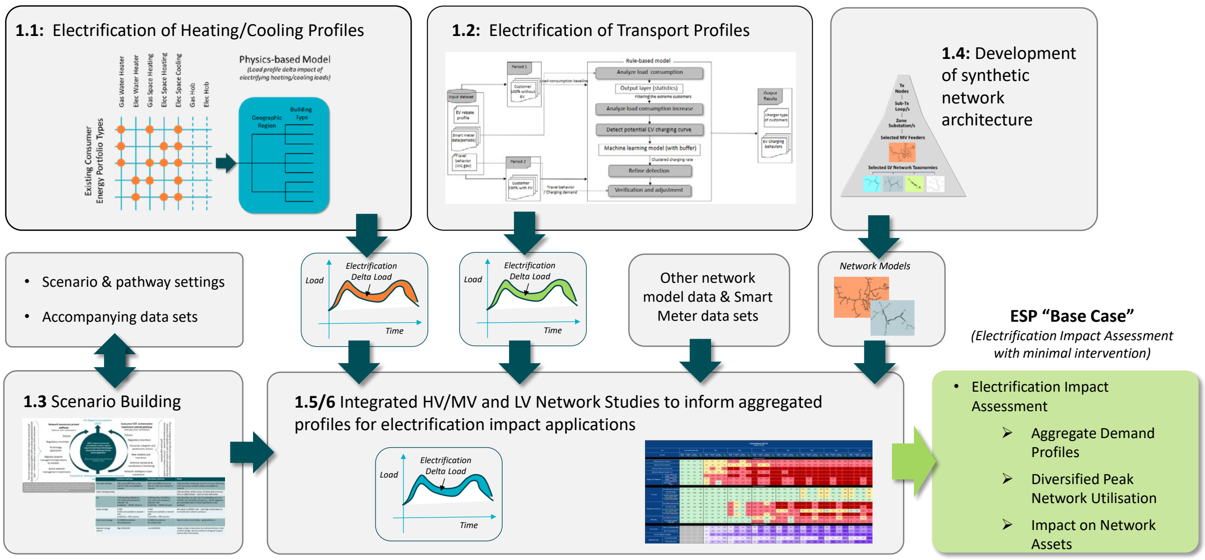


The ESP was scoped to be deliverable with the resources and time at hand to inform feasibility of broader application. It focussed on the more complex areas around residential and low voltage assets of the distribution system, with an application across Victorian networks with methodologies applicable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

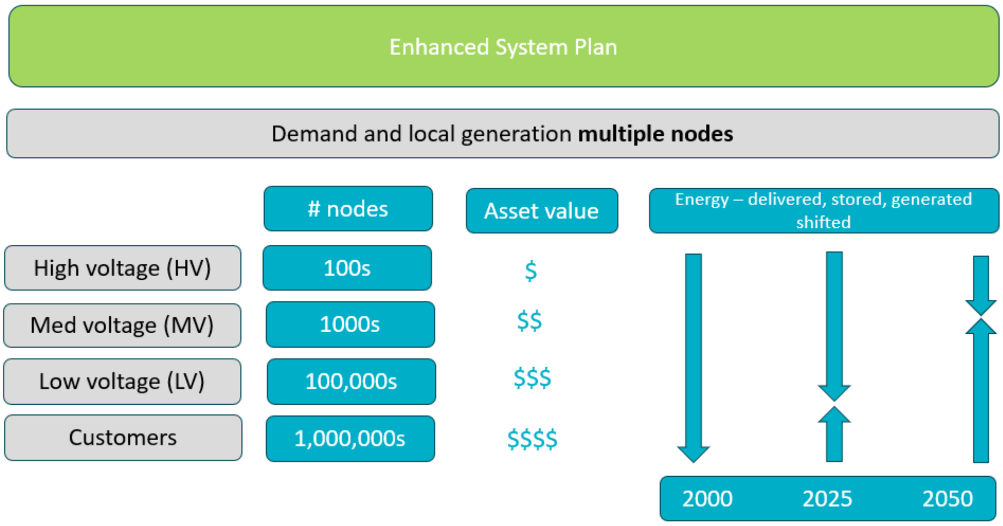
ESP alignment with distribution system components of whole of system planning



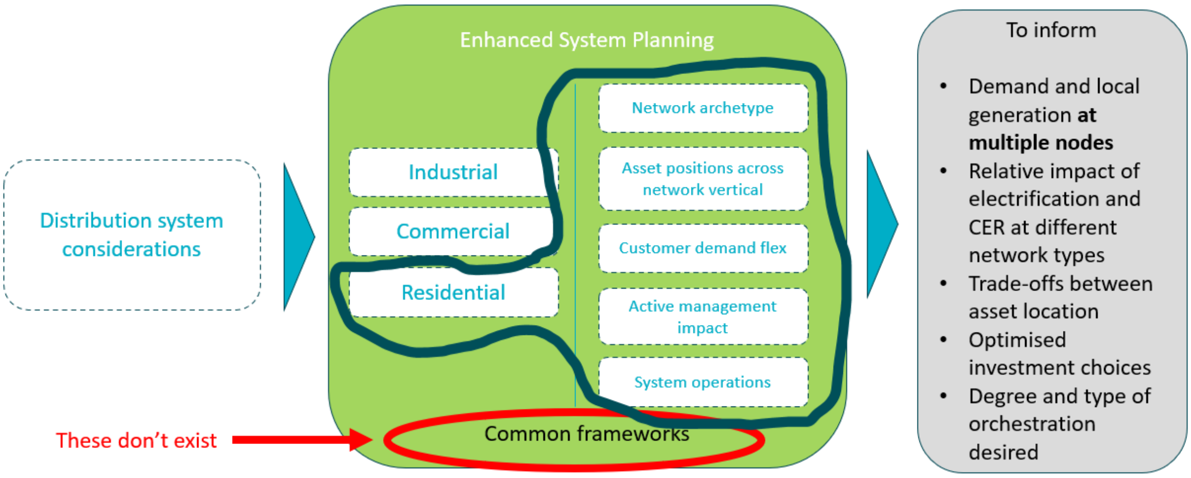
The 'base case' for residential electrification impact assessment, the flex options and relativity to other investment options



Elements needed to meaningfully inform distribution system aspects in whole of system planning



Methodological gaps in whole of system planning



Appendix Three – ESP project and research partners