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Authors' Disclaimer:

The authors tried their best to make reliable uptake projections. However, they cannot guarantee that the projections will be close to the actual uptake in the future, and under no circumstances will they be liable for any omissions, incorrectness, or consequences of using the outcomes of this publication in any projects or applications.

Abbreviations and Acronyms

ABS	Australian Bureau of Statistics
AEMO	Australian Energy Market Operator
AEC	Advanced Energy Centre
ASHP	Air Source Heat Pumps
AusTIMES	Australian version of the TIMES model
BITRE	Bureau of Infrastructure and Transport Research Economics
DER	Distributed Energy Resources
DNSP	Distributed Network Service Provider
ETSAP	Energy Technology Systems Analysis Project
EV	Electric vehicles
GHG	GreenHouse Gas
HEV	Hybrid electric vehicles
IASR	Inputs, Assumptions and Scenarios Reports
IEA	International Energy Agency
ISP	Integrated System Plan
MVC	Motor Vehicle Census
PHEV	Plug-in hybrid electric vehicles
TIMES	The Integrated MARKAL-EFOM System
V2H	Vehicle to Home
V2G	Vehicle to Grid

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Executive summary

One of the biggest challenges worldwide is achieving net zero carbon emissions. Australia has pledged to reduce emissions by 43% by 2030 and reach net-zero emissions by 2050. Renewable energy use is the only way to achieve these goals as electricity using natural resources (solar, wind, hydropower and geothermal) produces a very small amount of carbon. The adoption of rooftop solar and battery storage is accelerating the use of renewable energy. One of the effective solutions to achieve net zero emissions is the electrification of transportation and buildings. However, consumer led DERs, EV charging at home (V2G), and electrification of household appliances, including heating and cooling systems will create a huge impact on MV/LV distribution networks, demanding informed planning of future electricity infrastructure. The aim of this project is to build scenarios using a bottom-up approach that will give valuable insights to planners and DNSPs to design and implement future electricity transmission and distribution networks more accurately. This review covers the literature associated with EV and heating & cooling uptake, consumer led DER projection, and the reconciliation of the bottom-up approach to be adopted in this project with the top-down approach (such as AEMO's IASR scenarios).

AEMO produces scenario-based long-term projections of annual energy consumption and generation by small non-scheduled generators. AGL analysed the AEMO's scenarios for the annual temporal projection of decarbonisation from 2020 to 2050, demonstrating the potential for achieving 90%+ reduction by 2050 and the remaining emission can be removed using currently available CO_2 capture technologies. AEMO's IASR scenarios are developed based on a top-down approach, and thus, they do not consider regional aspects that can impact regional energy demand and generation.

We also review the literature on the techniques of modelling EV uptake and the outlook of national and international EV uptake. Notably, the scenarios at a more granular level such as urban, semi-urban, and rural regions are absent. Besides, the impact of local climate change, especially the regional temperature and solar radiation variations over the seasons, on the load profiles of EVs is yet to be estimated.

There exist many studies that consider the impact of climatic and socioeconomic factors (such as per capita GDP) on per capita electricity demand for heating and cooling. Along with different building representative archetypes used in bottom-up approach, these studies explore different heating and cooling technologies such as space heating, domestic hot water (DHW), and split and packaged air conditioning systems. This literature review on heating and cooling uptake reveals that apart from AEMO's IASR scenarios, no other studies specifically focus on the long-term projection of energy demand and energy efficiency for heating and cooling uptake for residential and business buildings. As mentioned earlier, AEMO's IASR scenarios are developed using a top-down approach and, as a result, do not account for regional factors that influence local energy demand. To achieve accurate long-term projections for heating and cooling uptake, including their regional variations, it is crucial to accurately estimate energy efficiency and its sensitivity to outdoor temperatures and desired indoor temperatures for comfortable living.

In our investigation of the future energy landscape for heating, cooling, and transport, this literature review offers insights from both domestic and international perspectives, shedding light on the path ahead for energy generation. CSIRO's latest projections show modified growth trajectories for solar PV and batteries until 2050, assisting AEMO in its planning efforts. The GenCost 2022-23 report highlights fluctuating technology costs, influenced by global climate change initiatives and the COVID-19 pandemic's supply chain disruptions. The FES report presents four pathways for Great Britain's energy landscape towards 2050, emphasising consumer roles and technology adoption. Multiple studies from around the world address the global transition towards renewable energy, emphasising strategic planning, carbon neutrality goals, and sustainable development. Data sources, such as GenCost, AEMO, and FES, lend a precise lens, enriching our understanding. Central to these studies lie the underpinning assumptions and dynamics driving projections. Moving forward, the many uncertainties and risks, from tech changes to policy shifts, cannot be ignored. As we think about the future of power generation, dealing with these factors is crucial for creating a lasting and flexible scenario building.

We also noted that reconciliation has been applied in many disciplines such as social inclusion, education, health, environment and so on. However, to our knowledge, there is no technique that reconciles long-term energy demand and supply projection.

On completion of this literature review, we have identified several research issues pertinent to scenario building. Building upon these findings, we present the methodology of our proposed scenario-building framework, which is grounded in a bottom-up approach.

1 Background

The AEMO is instrumental in navigating the evolving landscape of energy and its interplay with broader socio-economic trajectories. Its inputs, assumptions, and scenarios are pivotal tools that shed light on the multifaceted challenges and opportunities presented by the imperatives of climate change. By facilitating a comprehensive understanding of these dynamics, AEMO aids governments and industries in devising strategies for infrastructure and development, as well as in sculpting informed policy decisions. In this context, there arises an imperative need to critically examine the AEMO's Inputs, Assumptions and Scenarios Report (IASR). Such an examination is key to fostering a robust environment where competitive scenario modelling can thrive, allowing for a more resilient and sustainable energy future.

1.1 AEMO's Inputs, Assumptions and Scenarios Report

AEMO's IASR scenarios and their input assumptions are developed and updated through the consultations of industry, government and consumer stakeholders and experts every two years. IASR are developed in a particular year and used the next year's Integrated System Plan (ISP). For example, IASR scenarios developed in 2021 have been used in ISP 2022. Table 1 shows the following four scenarios that were developed in 2021 IASR [6]:

Table 1: Comparison between four scenarios – (i) Slow Change, (ii) Progressive Change, (iii) Step Change and (iv) Hydrogen Superpower developed in 2021 IASR.

Criteria	Slow Change	Progressive Change	Step Change	Hydrogen Superpower
Reflects	The impact of COVID-19 pandemic on economic, load closures and net zero emission action	Meeting net zero emissions by 2050 target	Faster than progressive transition from fossil fuel to renewable energy and step increases in Australia's commitments to keep global temperature rise below 2°C.	Strong global action and breakthrough technologies usage in transport and domestic manufacturing, enabling Australia to export huge amount of renewable energy..
Assumes	Challenging economic environment, higher risk for load closures, and decarbonisation objectives cannot be achieved as per Australia's target. Scenario benefit weighting: 4%	Building up momentum progressively to provide deep cut in emissions after 2040s and making the NEM capacity almost double. Widespread adoption of EVs and residential and business consumers gradually switch to electricity for heating. Scenario benefit weighting: 29%	Rapid increase in consumer-led energy generation, adoption of digital energy and higher energy efficiency. Making the NEM capacity nearly double. Domestic hydrogen production supports transport and industry sectors after 2040s. Scenario benefit weighting: 50%	Making NEM energy nearly quadruples to export hydrogen energy. Household gas connections gradually move to hydrogen-gas blend. Scenario benefit weighting: 17%
Climate effect	RCP 7.0 (~4oC)	RCP 4.5 (~2.6oC)	RCP 2.6 (~ 1.8°C)	RCP 1.9 (<1.5 oC)

The differences between the four 2021 IASR scenarios in terms of reflections, assumptions and RCP climate change pathways are summarised in Table 1. For example, Slow Change considers the impact of COVID-19 pandemic on economic, load closures and net zero emission action; Progressive Change aims to achieve net zero emission by 2050 progressively; Step Change will be faster than Progressive Change and uses step changes to meet Australian carbon emission commitments limiting global temperature below 2°C; and Hydrogen Superpower enables Australia to export renewable energy export.

The long-term expected changes in economic growth and technologies and the investments in consumer energy resources (CER) and other renewable DER sectors have made 2021 IASR Slow Change scenario invalid. These changes were the main reasons behind the updated 2021 IASR. Additionally, the pressing need and rapid ongoing policy development for decarbonisation have reduced the uncertainties of the previous IASR scenarios and increased the possibility to achieve net zero faster than previously thought. Consequently, IASR scenarios 2021 need to be updated to reflect current and future associated factors for energy forecasting and infrastructure planning paving the way to refining four 2021 IASR scenarios to the following three 2023 IASR scenarios – (i) Progressive Change, (ii) Step Change and (iii) Green Energy Exports that are shown in Figure 1 (source reference [7]):

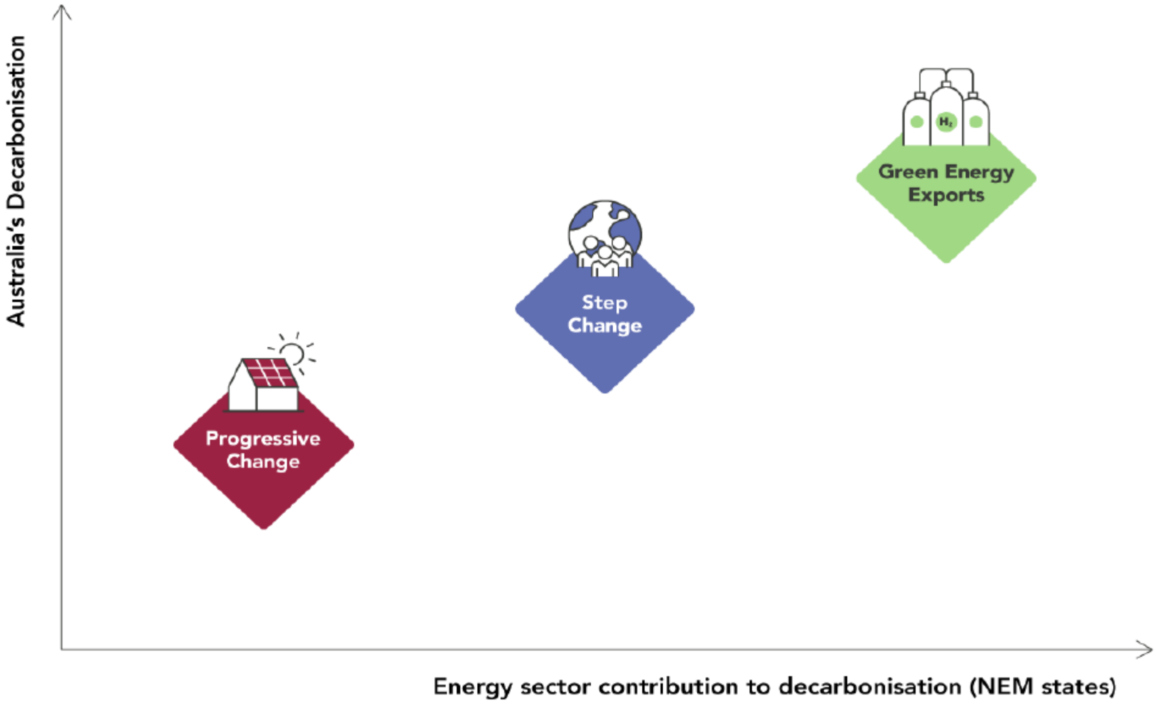


Figure 1: 2023 IASR Scenarios

The differences between the three 2023 IASR scenarios in terms of reflections, assumptions and RCP climate change pathway are summarised in Table 2.

Table 2: Comparison between three scenarios – (i) Progressive Change, (ii) Step Change and (iii) Green Energy Export developed in 2023 IASR.

Criteria	Progressive	Step	Green Energy Exports
Reflects	Australia's commitment of 43% emissions reduction by 2030 and net zero emissions by 2050	larger scale of energy transformation that supports Australia's contribution to limiting global temperature rise to below 2°C compared to pre-industrial levels	very strong, rapid decarbonisation activities domestically and globally
Assumes	transformational investments continue, but economic and international factors place industrial loads at greater risk	very strong, rapid and significant contribution from consumers in CER, strong transport electrification, and/or exploit hydrogen production opportunities	Consumer investments are very high, and global demand for green energy contributes to a new and very strong green energy export economy
Climate effect	limiting temperature rise to below 2°C by 2100 (RCP 4.5)	may be compatible with 1.8°C pathways (RCP 2.6)	limiting temperature increase to 1.5°C (RCP 1.9)

If we compare the scenarios presented in Table 1 with those given in Table 2, 2023 IASR Progressive Change covers both 2021 IASR Slower Change (slower economic growth and load risks) and Progressive Change (only modest technology cost change). Decarbonisation investment decisions included in this scenario reflect national and state-based policy yielding faster transition that 2021 IASR Slow Change scenario. 2023 IASR Step Change scenario is almost similar to the 2021 IASR Step Change scenario. In 2023 IASR Step Change scenario. the relative faster commitments from industry and consumers for reducing carbon emissions scale electrification in other sectors high.

A comparison between common scenario parameters for 2021 and 2023 IASR presented in Table 3. There have been some adjustments in the scenarios presented in the 2021 IASR compared to those in the 2023 IASR. In the 2021 IASR, the Hydrogen Superpower scenario was replaced with the Green Energy Exports scenario, and biomethane (identified as another alternative green energy source). This is due to the transformation of Australia's energy sectors, which involves a robust adoption of electrification, green hydrogen, and biomethane. Furthermore, hydrogen and biomethane are considered as one of the parameters for all three 2023 IASR scenarios. On the other hand, the Slow Change scenario was not included in the 2023 IASR. In line with the 2022 ISP's assessment of its extremely low relative likelihood, a significant number of stakeholders backed the decision to remove the Slow Change scenario. Another reason was the increased ambition and commitment of governments to accelerate decarbonisation efforts have rendered the 2021 IASR's Slow Change scenario obsolete. As a result, AEMO has removed this scenario from the collection, as it is no longer aligned with Australia's commitment to transitioning to net zero emissions.

In 2023 IASR, decarbonisation target renamed as national decarbonisation targets since the pathway for Australia's energy sector transformation is important as the country moves towards net zero emissions.

A number of additions have been made in the IASR 2023, including global economic growth and policy coordination as demand driver parameters. Furthermore, virtual power plant (VPP) has also been added alongside DSP growth. The involvement of consumers in promoting decarbonisation by continuously adopting consumer energy resources (CER), and the possibility of coordinating these resources through VPPs.

The shared socioeconomic pathway (SSP) has been removed from the revised IASR scenario parameters. While generator retirements have been removed from the revised IASR scenario parameter summary, they are still considered in the analysis.

Table 3: Comparison between 2021 IASR and 2023 IASR common scenario parameters summary (Note that the Table 2 considers all 2023 IASR scenario parameters which resulted some of the 2021 IASR parameters have not been considered in this table and some of the 2023 IASR parameters are not considered in 2021 IASR parameters)

Scenario	IASR	Slow Change	Progressive Change	Step Change	Hydrogen Superpower / Green Energy Export
Input assumptions					
Green Energy	2021 [10]				Hydrogen Superpower
	2023 [11, 13]	N/A			Green Energy (Hydrogen and Biomethane) Exports
National decarbonisation target					
National decarbonisation target	2023	N/A	43% emission reduction by 2030, Net zero by 2050		
	2021	26% - 28% emission reduction by 2030 (No explicit target beyond 2030)	26% - 28% emission reduction by 2030 (Economy-wide net zero target by 2050)	Exceeding 26% - 28% emission reduction by 2030 (Economy-wide net zero target before 2050) Consistent with 2 Degree temp. rise	Exceeding 26% - 28% emission reduction by 2030 (Economy-wide net zero target before 2050) Consistent with 2 Degree temp. rise
Demand Drivers					
Global economic growth and policy coordination	2023	N/A	Slower economic growth Lesser coordination	Moderate economic growth Stronger coordination	High economic growth Stronger coordination
	2021	Not considered			
Australian economic and demographic drivers	2023	N/A	Lower	Moderate	Higher (Partially driven by green energy)
	2021	Low	Moderate	Moderate	High
Energy efficiency	2023	N/A	Lower	Moderate	Higher
	2021	Low	Moderate	High	High
VPP and DSP Uptake	2023	N/A	Lower	High (VPP) and Moderate (DSP)	Higher
	2021	Low (VPP only)	Moderate (VPP only)	High (VPP only)	High (VPP only)
CER Uptake					
Batteries, PV and EVs	2023	N/A	Lower	High	Higher
	2021	Low	Moderate	High	Moderate/High
Hydrogen and Biomethane					
Hydrogen Use	2023	N/A	Low production for domestic use and no export	Medium-low production for domestic use and minimal export	Cost reduction, high production for domestic use and export
	2021	Domestic use and export with no specific target			
Hydrogen blending to gas distribution network	2023	N/A	Up to 10% vol		
	2021		Not Considered		
Biomethane / Synthetic methane	2023	N/A	Allowed, but no specific target to introduce it		
	2021	Not Considered			

Table 3 (Cont.): Comparison between 2021 IASR and 2023 IASR common scenario parameters summary

Scenario	IASR	Slow Change	Progressive Change	Step Change	Hydrogen Superpower / Green Energy Export
Scenario alignment					
Global/domestic temperature settings and outcomes	2023	N/A	Applies RCP 4.5 where relevant (~ 2.6°C)	Applies RCP 2.6 where relevant (~ 1.8°C)	Applies RCP 1.9 where relevant (~ 1.5°C)
	2021 IASR	RCP 7.0 (~4oC)	RCP 4.5 (~2.6oC)	RCP 2.6 (~ 1.8°C)	RCP 1.9 (<1.5 oC)
IEA 2021 World Energy Outlook scenario	2023	N/A	Stated Policy Scenario (STEPS)	Sustainable Development Scenario (SDS)	NZE2050
	2021	DRS	STEPS	SDS	NZE2050
Build cost trajectories					
Generation and storage build costs	2023	N/A	CSIRO GenCost Current Policies	CSIRO GenCost NZE post 2050	CSIRO GenCost NZE by 2050
	2021	CSIRO GenCost Current Policies	CSIRO GenCost Current Policies	CSIRO GenCost NZE post 2050	CSIRO GenCost NZE by 2050
Fuel price settings					
Gas prices	2023	N/A	ACIL Allen (2023), Progressive change	ACIL Allen (2023), Step Change	ACIL Allen (2023), Green Energy Exports
	2021	Lewis Grey Advisory (2021), Slow Change	Lewis Grey Advisory (2021), Net Zero	Lewis Grey Advisory (2021), Step Change	Lewis Grey Advisory (2021), Hydrogen Superpower
Coal prices	2023	N/A	Wood Mackenzie (2021) & Oxford Economics Australia (2022): High price	Wood Mackenzie (2021) & Oxford Economics Australia (2022): Central	Wood Mackenzie (2021) & Oxford Economics Australia (2022): Low price
	2021	Wood Mackenzie, Slow Change	Wood Mackenzie, Central	Wood Mackenzie, Step Change	Wood Mackenzie, Step Change
Gas Market Settings					
New Gas Supplies	2023	N/A	As forecast AEMO's 2023 GSOO		
	2021	As forecast AEMO's 2022 GSOO			
All other Gas market settings	2023	N/A	Consistent with AEMO's 2023 GSOO Progressive Change scenario	Consistent with AEMO's 2023 GSOO Orchestrated Step Change scenario	Consistent with AEMO's 2023 GSOO Green Energy Exports scenario
	2021	Consistent with AEMO's 2022 GSOO Low gas price scenario	Consistent with AEMO's 2022 GSOO Progressive Change scenario	Consistent with AEMO's 2022 GSOO Step Change scenario	Consistent with AEMO's 2022 GSOO Hydrogen Superpower scenario

Demographic trends, socioeconomic shift, EV uptake transformation and climate change impact on uptake have been considered in 2023 IASR scenarios. However, AEMO's scenarios are at the national and state/territory level. The scenarios at more granular level such as urban, semiurban, and rural regions are absent. Our aim is to develop scenarios at urban, semiurban, and rural regions of Victoria using the assumptions and levers consistent with those adopted by IASR and additional ones. As a case study, we will use

Horsham (rural and agro-industries), Ballarat (regional urban and agro-food industries), Melbourne City Council (urban CBD), Dandenong (urban) and Epping or nearest suburb. Different regions have different EV uptake transformation that represents vehicle travelling patterns. Therefore, the consideration of EV uptake transformation in the scenarios will indicate the vehicle uses in a particular region and thus help in the planning to develop public and office EV charging infrastructures.
Sensitivity analysis on the key assumptions and levers (refer to Table 1) that impact the scenario outcomes. We will develop relevant hypotheses to perform sensitivity analysis. For example: Higher the population growth, the higher the EV uptake in a particular regions/suburb?

1.2 AEMO's IASR Scenario Analysis

In the existing literature, there have been some studies conducted by industry and research institutes that implement and analyse AEMO's IASR scenarios to assess how the Australian industrial and government commitments to meet targeted carbon emission reductions and cost for decarbonisation, and limit global temperature. These studies are briefly presented below:

1.2.1 Scenario Analysis and Task Force on Climate-related Financial Disclosure (TCFD) Reporting

TCFD reporting [2] assesses the impact of a scenario on decarbonisation over time. Four scenarios developed based on RCP (Representative Concentration Pathway) and SSP (Shared Socioeconomic Pathways) are used – (i) National Targets, (ii) Response 2020, (iii) Response 2030 and (iv) 1.5 Degree Limit Apart from RCPs and SSPs defined by IPCC (Intergovernmental Panel on Climate Change), the bedrock of these scenarios is the scenarios presented in ISP2020 developed by AEMO such as Central, Fast Change and Step Change. Scenario (i) assumes current industry commitments and government policies are to be continued over time, while Scenario iv targets very fast decarbonisation which is collaborative and cooperative approach. Scenario ii and Scenario iii are in between of them. For the progressive electricity adoption, the annual temporal projection of decarbonisation from 2020 to 2050, demonstrating the potential for achieving 90%+ reduction by 2050 and the remaining emission can be removed using currently available CO_2 capture technologies. In this scenario analysis, how to achieve net zero emissions by 2050 or earlier by AGL through the progressive closure of its coal power stations is also shown. For achieving net zero emissions by 2050, all four scenarios show NEM needs to increase 80% of renewable energy generated in 2020. This project also analyses the opportunities for investment in renewable energy sectors considering the customer demand using Scenario i and Scenario iv. The different factors (e.g., RCP, SSP, temperature increase range, AEMO's ISP scenarios) usage associated with carbon emission reduction in the four scenarios is responsible for the variation of carbon emissions reduction among them. Note that risks arising if other countries do not reduce emissions as per AEMO assumptions or not considering the role of other Australian sectors in carbon emissions reduction have not been considered in the model.

1.2.2 Multi-sector energy modelling 2022: Methodology and results: Final report

CSIRO and Climateworks Centre performed multi-sector energy modelling (MSEM) in 2022 utilising four scenarios – (i) Progressive Change, (ii) Exploring Alternatives, (iii) Step Change, and (iv) Hydrogen Export applying the AusTIMES model [14]. AusTIMES is an Australian version of TIMES as it was developed by CSIRO in collaboration with Climateworks on the bedrock of The Integrated MARKAL-EFOM System (TIMES) model. TIMES is an optimisation model based on linear programming that minimizes total discounted system costs over time. The International Energy Agency (IEA) and the Energy Technology Systems Analysis Project (ETSAP) jointly developed TIMES. AEMO defined these four scenarios and appointed CSIRO and Climateworks Centre for the MSEM task. Under these four scenarios. MSEM analyses the projection of electric demand, decarbonisation cost for the climate change effect and land sequestration cost to meet the carbon emission reductions targeted from 2021-2022 to 2053-2054.

The results exhibiting the decarbonisation role show the following things:

- Decarbonisation in terms of faster coal-fired generation reduction (44% by 2030 compared with 22% reflected in their previous model developed in 2021) and growth in electrification is vital to fulfill Australia's new 2030 carbon emission target. Slower coal-fired retirement rate can limit the efficacy of electrification to meet net zero carbon emissions by 2050.
- Electrification plays the central role and appears to be a cost-effective pathway for all scenarios in decarbonisations because of its consistently high take-up in energy efficiency and renewable energy) which is mainly driven by transport and industry.
- The projected energy distributions of natural gas, hydrogen and biomethane, alternative fuels to electrification show alternative fuels can contribute to decarbonisations, but they have some technical issues that needs to be addressed. It is noteworthy to mention that biomethane does play any role in Step Change.
- Decarbonizing electricity and green hydrogen production will increase industrial growth in green energy sector and put Australia as a pioneer to export renewable energy.

The main features of the AusTIMES model are:

- Yearly early projections based on financial years from 2022 to 2054 for all Australian states and mainland territories (ACT, NSW, NT, QLD, SA, TAS, VIC, WA)
- Eight end-use sectors – (i) agriculture, (ii) mining, (iii) manufacturing, (iv) other industry, (v) commercial and services, (vi) residential, (vii) road transport and (viii) non-road transport.
- Fuel types, electricity sector and five hydrogen production pathways

Table 4: Datasets and key assumptions used in different end-user sectors.

End-user sectors	Datasets	Key Assumptions
Transport	• ABS data on vehicle stock (ABS, 2021-MVC) • Average kilometres travelled (ABS, 2020b), BITRE (2019) • Australian Energy Statistics data (DISER, 2021-AES) on fuel use • NGA emission factors for fuel (DISER, 2021-NGAF) • population/Gross State Product (GSP) projections • Oil price projections (Lewis Grey Advisory, 2022) • Production costs on biofuels (Butler et al., 2001)	• Future vehicle costs & efficiency improvements (Graham and Havas, CSIRO 2021)
Residential Buildings	• 2016 ABS census on number of dwellings (driven by ABS Series II household projections) scaled to BIS Oxford Economics Macroeconomics Forecasts on population growth	• Upper limits of electrification uptake are derived assuming all residential users are fully electrified by 2050 • The limits of energy efficiency uptake are estimated by leveraging the potential for savings (ClimateWorks Australia, 2016) • Fixed compound annual growth rates in dwellings from 2021 to 2054/2055 for each scenario • Annual autonomous energy efficiency within [0.45 %, 1.41%], which is the same for all scenarios • Multiplier on maximum electrification uptake limits for each scenario. For example, pre-2025: 0.72x & post-2025: 0.94x for step change • The same maximum hydrogen uptake potential (10% by volume blended in pipelines by 2030) for all scenarios
Commercial Buildings	• The floorspace projections for commercial building archetypes from the Commercial Buildings Baseline Study (Pitt and Sherry, 2012).	• Upper limits of electrification uptake change based on commercial users use by 2050 (ClimateWorks Australia, 2016) • The limits of energy efficiency uptake are estimated by leveraging the potential for savings (ClimateWorks Australia, 2016) • The same commercial activity projection (millions m2 of floorspace) at compound annual growth rate of 2.09% from 2020 to 2050 for all scenarios.

		• Annual autonomous energy efficiency within [0.11 %, 0.95%], which is the same for all scenarios • Other assumptions are almost the same as residential buildings.

Table 4 shows vehicle cost and efficiency improvement are the influential factors for the electrification uptake in transportation sectors. The household and commercial activity projections (number of dwellings and area of floorspace) and energy efficiency play a vital role in the residential and commercial buildings electrification forecast.

1.3 Assumptions and Parameters

Electricity System Operator (ESO) delineates the primary domains for Future Energy Scenarios (FES) where Carbon Capture and Storage (CCC) data has been employed and the accompanying assumptions. For both System and Consumer Transformations, the research predominantly adheres to the CCC's Balanced Pathway. Notable deviations from these assumptions are explicitly highlighted in Table 5. Moreover, it's imperative to highlight the distinct approach to non-energy sectors. Specifically, the study adopts a unique stance on interconnectors in the FES, emphasising net zero considerations. As per international carbon accounting norms, emissions are attributed to the country of origin. Consequently, electricity imported to the UK via these interconnectors is perceived as having zero carbon footprint from the UK's standpoint.

Table 5: FES assumptions summary (Taken from CCC (Climate Change Committee) [15].

	Aviation	Shipping	Agriculture	Land use	Waste
System Transformation and Consumer Transformation (based on CCC Balanced Pathway)	• 42% emissions reduction (compared to 2018) due to slower demand growth (only 25% increase compared to forecast 65%), improvements in aircraft efficiency and a modest share of sustainable aviation fuels at 25%	• Emissions reduce to close to zero by 2050 using zero carbon fuels • 87% of the emissions savings come from using ammonia • Remaining reductions come from electrification	• 38% reduction in emissions from agriculture by 2050 (compared to 2018) • By 2050, reduction by a third for weekly meat consumption and 20% reduction for dairy	• 50,000 hectares of trees planted annually by 2035 • 79% of peatland restored • 700,000 of perennial energy crops by 2050	• All net zero scenarios follow the Widespread Innovation pathway • 51% fall in edible food waste by 2030 and 61% by 2050 (compared to 2007)
Leading the Way (based on CCC Widespread Innovation)	• 64% reduction in emissions despite 50% increase in demand (both compared to 2018) • Achieved through 25% carbon neutral synthetic jet fuel, 25% biofuels and efficiency improvements for planes	• Widespread adoption flow carbon fuels over the 2030s, so that by 2040 shipping is at practically zero emissions • System Transformation followed the Widespread Innovation pathway for shipping	• 57% reduction in emissions from agriculture by 2050 (compared to 2018) • By 2050, 50% less meat and dairy, with 30% of meat coming from lab-grown sources	• 70,000 hectares of trees planted annually by 2035 • All peatland restored by 2045 • 1.4m hectares of energy crops by 2050	• 50% fall in inedible food waste by 2050 and more widespread wastewater treatment improvement • Emissions fall just over 75% from today's levels by 2050

2 Transport Update

There are two types of transports – (i) road and (ii) non-road transports. Road transport includes motorcycles; passenger, commercial and articulated vehicles; rigid trucks and buses. Rail, aviation, and shipping are non-road transport. Since road transport is in a better position in terms of their technology and transportation infrastructure for the electrification than non-road transport, electric vehicle (EV) covers mainly road transport.

2.1 Modelling electric vehicle uptake using regression analysis

Still now the percentage of EV of all registered vehicles across Australia is less. However, the EV adoption rate will increase over the time because of electrification of transport and government policies to encourage EV adoption. The following key issues identified in electric vehicle uptake [31]:

- High vehicle price and operating cost
- Consumer concerns for EV driving range
- Availability of charging infrastructure
- Socioeconomic factors that impact EV uptake
- A broader range of EV makes and models availability.

Techniques used in EV uptake are mainly based on a statistical modelling called regression analysis:

- Multinomial logit (MNL) model. an extension of logistic regression is used to calculate the likelihood of HEV uptake for a particular zone of Windsor, Ontario, Canada [32]
- Spatial regression is used to analyse whether the EV adoption of a region is influenced by the availability of EV charging infrastructure (number of charging points), including the infrastructure of its neighbouring regions.in UK [33]

Mitchell and Monterosso [31] introduced an approach to model spatial EV updates at a local level across Australia by leveraging the correlation (elasticities) between the EV uptake of a region (spatial EV uptake at a postal area level) and a factor of interest using the MNL model. This approach considers the following demographic, socioeconomic and other (e.g., EV charging capacity, solar generation capacity, median commute distance) factors:

- median household income
- dwelling type in proportion of detached houses
- average household size in number of persons
- job density in number of jobs per person
- education level in proportion of persons having a tertiary education
- median commute distance
- population density
- household solar generation capacity
- EV charging capacity (installed power capacity of EV charging sites)

The elasticity estimates the percentage change of EV uptake of i^{th} region (u_i) with respect to percentage change of j^{th} factor (f_j), which is defined as:

$$\frac{\delta u_i}{\delta f_j} \times \frac{f_j}{u_i} = c_j f_j (1 - u_i) -(1)$$

where, c_j is the coefficient of the MNL model and the MNL model (u_i) is defined as:

$$u_i = \frac{1}{1 + e^{-\sum_j c_j f_{ji}}} - (2)$$

The datasets used in this project are provided in Table 6.

Table 6: Dataset used in EV uptakes.

Source/year	Description
Australian Bureau of Statistics- https://www.abs.gov.au/ausstats/abs@.nsf/mf/9309.0, 2020	Motor Vehicle Census (MVC), 2020 provides statistics on the number of registered EVs and HEVs.
BITRE - https://www.bitre.gov.au/, 2021	BITRE, 2021 received MVC makes and models wise data in 2020, noted that elective vehicle category includes non-PHEV and provided the number of registered EVs for known makes and models.
ABS Census of Population and Housing- https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/2071.0main+features22016. 2016	Socioeconomic factors were obtained from the 2016 Census of Population and Housing data available from ABS Census TableBuilder.
Household solar generation capacity - https://www.cleanenergyregulator.gov.au/RET/Forms-and-resources/Postcode-data-for-small-scale-installations#Postcode-data-files, 2020	Solar generation capacity were estimated using the Clean Energy Regulator's (CER) postcode-level data.
EV charging site locations and installed power capacity - https://github.com/openchargemap/ocm-data, 2020 and https://www.plugshare.com/, 2020	Data for EV charging site locations and installed power capacity were collected from OpenChargeMap and PlugShare's online site.

The results reported in [31] show that EV uptakes are strongly positively correlated with income, education level and job density, but less impacted by commute distance, household size and population density. There is a small impact of EV charging and household solar generating capacity on EV uptakes. EV Uptakes are negatively correlated with commute distance.

In this study, the EV uptake projection in 2030 at postal area level is conducted by exploiting the weights of population and socioeconomic profile of each postal area. It is estimated that overall EV uptake will increase up to 25%, having less than 5% of EV ownership in 75% of the postal areas.

The two key limiting factors of this study are - (i) the datasets used are not sufficient (e.g., MVC data for only 2020) to draw conclusive decisions, especially for the early stage of EV uptakes and (ii) the R^2 value for the EV uptake prediction produced by the MNL model is low (e.g., 0.54), representing the limitation of this study for predication efficacy.

2.2 Electric vehicle projections

The Australian Energy Market Operator (AEMO) annually commissions the CSIRO to provide projections on electric vehicle (EV) adoption and their operational patterns. CSIRO EV projection report [17] focus is on various types of electric vehicles like battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). While the scope encompasses on-road vehicles, including light vehicles and heavy-duty vehicles like trucks and buses, off-road vehicles, particularly those used in sectors like mining, are not considered. Significant changes observed include a stronger EV uptake anticipated before 2030, variations in household charging patterns with decreased demand during peak hours, and increased charging during weekends. Additionally, there have been updates regarding time-of-use charging behaviours and public fast charging behaviours.

Post the 2021 projections, the most notable shift has been the introduction of robust state and commonwealth EV policies. The initiation started with New South Wales in June 2021, outlining targets like achieving about 50% EV sales by 2030, backed by state subsidies ranging from $3000-$3500 and Commonwealth subsidies between $8000-$12000. These policies, along with Australia's commitment to reduce emissions by 43% by 2030, have given a boost to the EV market, especially as Australia witnessed growth in EV sales while the global vehicle market shrunk.

Earlier data on EV charging was derived from trials conducted more than five years ago or adapted from overseas data. However, recent publications from entities like Origin Energy, Energex, Ergon networks, University of Queensland, and the Electric Vehicle Council have revealed new insights. Key revelations include that most users rely on standard power points with a charge capacity of around 2.3 to 3.6kW, weekend charging has been more prevalent than previously thought, and new time-of-use profiles have emerged showing more consistent charging patterns. Additionally, public fast charging data reveals a prolonged peak during daylight hours.

Adoption projections are provided for various timelines, ranging from months to decades. While long-term projections are anchored in comprehensive models that evaluate human and market behaviour, short-term models leverage extrapolation techniques based on recent activities. The blend of both approaches ensures accurate projections that are in tune with current market dynamics and long-term trends.

The Market Retirement Model considers the implications of EV adoption on the entire vehicle fleet, including the retirement of internal combustion engine (ICE) vehicles. As commercial support for ICE vehicles wanes due to increased EV adoption, consumers will face choices regarding the sale, scrapping, or limited use of their ICE vehicles. This dynamic will potentially expedite the transition to an electric and hydrogen-fuelled fleet.

Various factors influence transport demand projections. Economic growth impacts a minority of vehicle sales, especially freight vehicles, hence its direct effect on EV projections is marginal. Meanwhile, cost of travel, mainly driven by fuel prices, influences transport demand; if the cost decreases, demand rises, and vice versa. Innovations like vehicle electrification and autonomous vehicles might lead to reduced travel costs in the future. Additionally, the model also considers the effects of autonomous vehicles and ridesharing on transport demand.

CSIRO EV projection [17] considered ten different assumptions, ranging from the price dynamics of electric vehicles, government policies and the complex landscape of sustainable transportation. They have discussed ten important assumptions for EV projections. Here we discussed all those assumptions with an analysis to understand the correlation among the assumptions.

(1) Technology Costs: The technology cost for electric vehicles, assumes that short-range electric vehicles (SREVs) will achieve cost parity with internal combustion engine vehicles by 2030, with this parity being reached by heavy SREVs in 2040. These projections are based on the Exploring Alternatives scenario. Moreover, while long-range electric vehicles (LREVs) won't reach upfront cost parity due to increased battery costs, their overall driving cost will be competitive by 2030. These assumptions might be too conservative, especially considering rapid advancements in battery technology. If such advancements outpace predictions, the costs for both SREVs and LREVs could drop even sooner. As production scales up and technology becomes more advanced, economies of scale are expected to drive down costs. This trend mirrors the early adoption curve of many technological innovations.

(2) Electricity Tariffs: Assumptions has been made about the future of retail electricity prices based on recent trends, including the impact of fossil fuel prices. It is expected that retail prices will stabilize in the future, as non-fossil fuel sources play a bigger role. The assumption also suggests that electricity refuelling costs won't have a significant impact on vehicle adoption rates. While this is an informed projection, it would be important to frequently reassess it against real-world data. International politics, technological innovations, and policy shifts could all affect the trajectory of electricity prices. Infrastructure will play a pivotal role in the EV revolution. The assumption here rests on the symbiotic relationship between EV adoption rates and the availability of charging stations. It's not just about quantity, but also about the quality and speed of these charging points.

(3) Income and Population Growth: The projection methodology uses Gross State Product (GSP) and population growth assumptions provided by AEMO and BIS Oxford Economics. These variables serve as the basis for projecting vehicle numbers and determining passenger transport demand growth. However, the methodology assumes that factors other than economic growth primarily drive the adoption curve. Given the complexities of economic behaviours, relying on static assumptions may not capture the full picture. It would be prudent to include other socio-economic variables or explore more dynamic modelling methods.

(4) Separate Dwellings and Home Ownership: Assumptions in this category revolve around housing types and ownership rates. There's an expectation that separate dwellings (e.g., detached houses) will decline over time due to increasing land costs. Homeownership trends also seem to be declining, especially among younger demographics. These assumptions are significant because homeownership typically offers more flexibility to adopt technologies like EV chargers. It would be beneficial to also consider alternative infrastructure or charging solutions that cater to non-homeowners or those living in apartments.

(5) Vehicle Market Segmentation: The market segmentation looks at non-financial factors that could limit vehicle adoption in different market segments, primarily focusing on household data. While this is a logical approach, businesses might have different considerations, and equating their needs with households might be an oversimplification. It would be beneficial to look deeper into the specifics of business requirements, especially given their potential for bulk vehicle purchases.

(6) Vehicle to Home or Grid: Starting with the notion of "Vehicle to Home or Grid", EVs, once they gain traction in the market, aren't just seen as modes of transport but as potential large-scale battery storage units. Particularly, long-range EVs present an exciting prospect as they offer more storage capacity than many stationary batteries currently in the market. Their potential is magnified when one considers that the batteries in many EVs might be underutilised based on average usage. This suggests there's room for these batteries to serve additional purposes, such as providing household power. The economic viability of such a model further strengthens when vehicles are charged during low-cost solar energy periods.

(7) Shares of Electric Vehicle Charging Behaviour: Considering the shares of electric vehicle charging behaviour, it becomes evident that convenience, accessibility, and economic incentives are driving forces. The majority of EV owners will likely gravitate towards charging at home or in private spaces, making public charging infrastructure secondary, yet still crucial. The way EV owners choose to charge their vehicles is shaped by various factors, ranging from the availability of home charging equipment to incentives and solar charging opportunities. Charging behaviour is driven by convenience, accessibility, and economic incentives. Most EV owners will prefer charging at home, and public charging infrastructure plays a secondary, though important, role.

(8) Transport Demand: Transport demand throws light on a broader perspective, tying the growth of EVs to overarching transport trends. While the demand for vehicles, in general, is bifurcated between passenger and freight transport, it's also subject to global events, like the COVID-19 pandemic, which has disrupted historical growth patterns like aviation's rise in popularity. However, this sector is resilient and adaptable, with scenarios forecasting different growth trajectories based on policy decisions and market forces.

(9) Non-road Transport Electrification: Moving beyond road transport, non-road transport electrification underscores the potential of electrification in rail and aviation sectors. Passenger rail already consumes a significant chunk of electricity, but the electrification of freight rail is hampered by infrastructure and cost challenges. On the aviation front, technological advancements have made electrification more plausible. Still, for the foreseeable future, it might be limited to specific use-cases or short-haul trips.

(10) Vehicle Charging Profiles: Surprisingly, a significant number of EV owners prefer standard power sockets for charging, which may lead to a lower-than-anticipated peak demand. Data on public or fast chargers also paints a distinct picture, and when one factors in heavy vehicles, the charging profile becomes even more nuanced, influenced by time-of-use incentives and other factors.

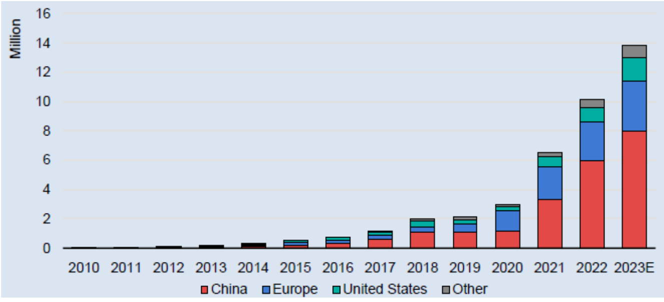
In conclusion, while these assumptions provide a foundational understanding of the projected uptake of electric vehicles, it's imperative to continually revisit and refine these assumptions. Periodic assessments, taking into account real-world data, technological advancements, and changing socio-economic dynamics, will ensure a more accurate and informed projection.

2.3 Global EV Outlook 2023

The international Energy Agency (IEA- www.iea.org) has released its recent annual publication The Global EV Outlook that identifies and discusses recent developments in electric mobility across the globe. It is developed with the support of the members of the Electric Vehicles Initiative (EVI). Combining historical analysis with projections to 2030, the report examines key areas of interest such as electric vehicle and charging infrastructure deployment, battery demand, electricity consumption, oil displacement, greenhouse gas emissions and related policy developments. It also represents in-depth analyse of the government policies, financial performance of companies involved in the electric vehicle (EV) sector, investments made by venture capital firms in EV-related technologies, material supply chain and the global trade of electric vehicles [20].

The key findings of this report, published in 2023, are summarised below in Table 7:

Table 7: Key findings for global EV outlook 2023.

Key findings	Description
The electric vehicle (EV) market demonstrated exponential growth	With 10 million units sold in 2022, and a projected 14 million sales by the end of 2023, EV market representing a 35% year-on-year increase. National policies and incentives, along with potential high oil prices, are expected to sustain this growth. China still dominates the EV sales market and the EU and the US are catching up. While major markets dominate, emerging EV markets like India, Thailand, and Indonesia exhibited promising growth in 2022. Notably, Thailand and Indonesia are refining policy support, offering potential insights for other emerging economies seeking to promote EV adoption. The following figure (Figure 2) shows the trend of EV sales over the years.  Figure 2: The growing trend and projection of EV
Landmark EV policies are bringing the EV industry closer to meeting climate objectives	Both the EU and US have introduced legislation to align with their electrification goals. The EU has implemented new CO_2 standards for cars and vans, in line with its 2030 targets. In the US, the Inflation Reduction Act (IRA), coupled with the adoption of California's Advanced Clean Cars II rule by multiple states, is poised to achieve a 50% electric car market share by 2030, in line with the national target. Furthermore, the emissions standards adopted by the US Environmental Protection Agency is expected to strengthen the existing policy and targets. Notably, the announced plans for battery manufacturing capacity by 2030 exceed the demand implied by government commitments, potentially even accommodating the requirements for electric vehicles in a Net Zero Emissions by 2050 scenario.
Affordable models are being available in the markets	As spending and competition in the electric car market intensify, more affordable models are in the markets. In 2022, global spending on electric cars exceeded USD 425 billion, up 50% from 2021, and venture capital investments in EV and battery tech startups increased by 30%. SUVs and large cars dominated the market, providing consumers with an increasing variety of choices. Furthermore, an increasing number of new makers, primarily from China but also from emerging markets, are introducing more cost-friendly models. Established car manufacturers are also heightening their ambitions, particularly in Europe, and the years 2022-2023 witnessed a series of significant EV-related announcements, including plans for fully electric fleets, more affordable vehicles, increased investments, and vertical integration involving battery production and critical minerals.
The focus on electrification extends beyond cars to encompass a wider range of vehicle segments.	Commercial vehicles are increasingly electrified, with global electric light commercial vehicle (LCV) sales surging by over 90% in 2022. There's a growing ambition to electrify heavy-duty vehicles, with roughly 220 new electric heavy-duty vehicle models introduced in 2022, bringing the total to over 800 models from 100+ manufacturers. Notably, 27 governments have committed to achieving 100% zero-emission bus and truck sales by 2040, and both the United States and European Union have proposed stricter emissions standards for heavy-duty vehicles. Figure 3 show how electric bus and truck sales are increasing in developed countries over the years.

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In emerging markets and developing economies, two or three-wheelers stand out as the most electrified segment, surpassing cars in numbers. In 2022, over half of India's three-wheeler registrations were electric, driven by government incentives and lower lifecycle costs, particularly in the face of rising fuel prices.

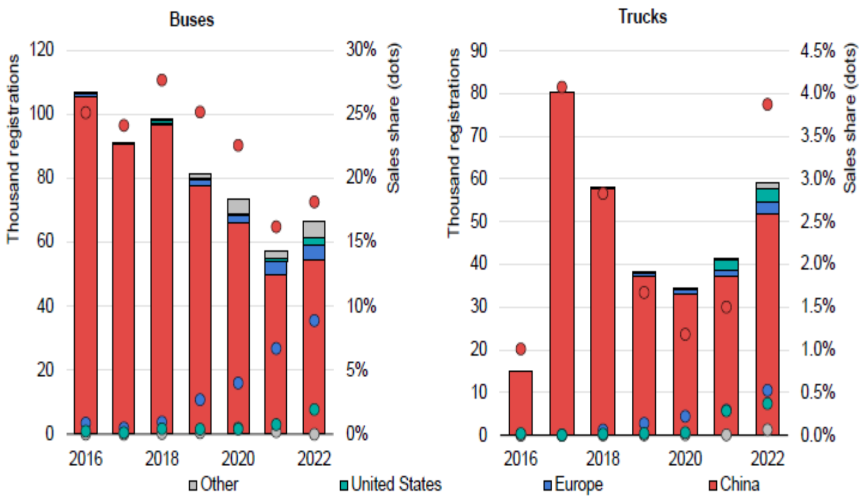

Figure 3: Increasing trend of bus and truck sales in EU, US, China and other countries
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<td>EV supply chains and battery production are gaining increased attention in policy formulation</td>
<td>Emerging alternatives to the traditional lithium-ion technology are gaining traction, and supply networks for sodium-ion batteries are also in development. Although the EV supply chain is expanding, it remains largely concentrated, with China playing a pivotal role in battery and EV component trade. Policymakers are now prioritizing EV supply chain resilience through diversification. For instance, the European Union introduced the Net Zero Industry Act in March 2023, targeting nearly 90% of the EU's annual battery demand to be met by EU battery manufacturers. Meanwhile, in the United States, the Inflation Reduction Act emphasizes booting domestic supply chains for EVs, EV batteries, and battery minerals, outlined as criteria for qualifying for clean vehicle tax credits. Consequently, from August 2022 to March 2023, major EV and battery manufacturers announced a cumulative investment of at least USD 52 billion in North American EV supply chains post-IRA.</td>
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<td>Public charging points are increasingly necessary to enable wider EV uptake</td>
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While home charging currently satisfies most demand, publicly accessible chargers are crucial to match the convenience of refuelling conventional vehicles. In densely populated urban areas, public charging infrastructure is vital, especially where home charging options are limited. Public fast chargers, particularly along highways, facilitate longer trips and alleviate range anxiety, encouraging EV adoption among a broader population as maximum range autonomy is a priority for customers. Figure 4 shows in 2022, the global count of fast chargers rose by 330,000, with over 70,000 in Europe, a 55% increase from 2021. The European Union is committed to expanding this infrastructure through the Alternative Fuels Infrastructure Regulation (AFIR) and significant funding. In the US, the fast charger stock reached 28,000 by 2022, with accelerated deployment expected due to the National Electric Vehicle Infrastructure Formula Program (NEVI).

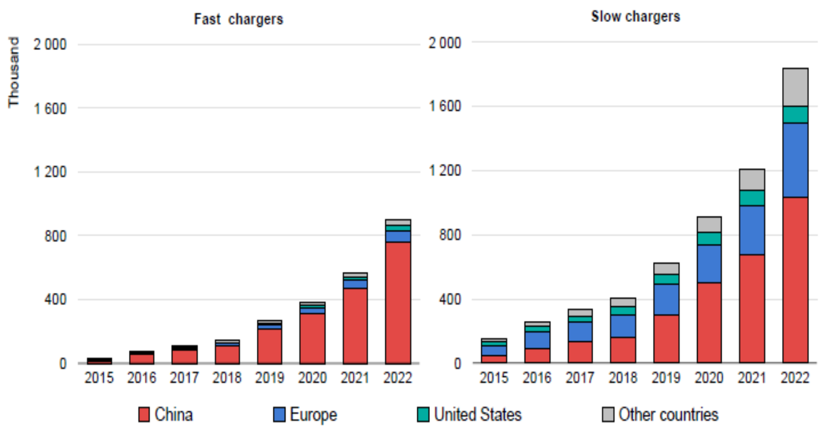

Figure 4: The increasing trend public charging stations
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3 Heating and Cooling Uptake

Heating and cooling uptake refers to adopting heating and cooling appliances for the energy required to raise temperatures for heating during cold days and lower temperatures for cooling during hot days. It is noted that climate change can significantly impact heating and cooling energy demand. Accurately forecasting future electricity demands requires a critical analysis of how climate change affects these energy demands. This analysis plays a major role in both power system planning and the strategic development of the power market. Many research studies have investigated the effects of climate change on heating and cooling in current and future residential buildings and appliances.

In the next section, we will conduct a comprehensive analysis of the data sources used in these studies and delve into the underlying assumptions and parameters employed. We will also summarise and highlights any uncertainties and risks mentioned in their findings.

3.1 Recent Studies on Heating and Cooling Uptake

Recent reports from Cold Hard Facts 2021 [42] and 2022 [43] by the Australian Government Department of Agriculture, Water, and the Environment highlight significant trends by analysing data related to the scale and impact of Australia's cooling economy. Between 2016 and 2020, there was a noticeable slowdown in the regulated refrigerant bank's growth; in 2020, there was no significant growth despite robust equipment sales. This slowdown suggests the Australian refrigerant bank's global warming potential (GWP) value peaked in 2019-20. However, the latest data from 2021 indicates a potential reversal of this trend, with an unexpected increase in the size of the refrigerant bank. This change is attributed to the rapid deployment of more heat pumps, driven by government policies promoting eco-friendly appliances. However, even with these shifts, challenges related to adopting modern technologies and the ongoing impact of COVID-19 may impede the decline in the carbon dioxide equivalent (CO_2e) value of the refrigerant bank in the future.

Tony Issacs Consulting's (TIC) [44] study evaluated the impact of implementing maximum heating and cooling load intensity limits and minimum star ratings for Class 1 and 2 dwellings. The assessment considered the implications of these load limits on housing design and construction across various climate zones within the Nationwide House Energy Rating Scheme (NatHERS). The NatHERS methodology determines star ratings by combining the intensity of heating and cooling loads. However, in areas where heating and cooling are necessary, this method can lead to designs that prioritize minimizing one type of load, such as heating, while not adequately considering the other, like cooling. In the state of New South Wales (NSW), the Building Sustainability Index (BASIX) has addressed this limitation by introducing heating and cooling caps, which establish maximum load levels for each season. The development of heating and cooling load intensity limits ("load limits") aims to balance energy efficiency and flexibility. To assess heating and cooling load limits, two methods were employed. Method 1 involved statistical analysis of a dataset when sufficient data was available, while Method 2 correlated average heating fractions with load limits for regions with limited data. Separate heating and cooling load limits were deemed unnecessary in climates where one type of load dominated others in one season. Furthermore, this study identified specific climatic regions based on whether the heating load accounted for less than 5% or more than 95% of the total heating and cooling loads. This classification streamlined the need for load limits.

The recent annual energy budget promotes energy-efficient household appliances, covering air conditioners, water heaters, rooftop solar installations, and various energy-consuming aspects like heating, cooling, hot water, lighting, and pool pumps. Apartment budgets are set around 40% higher to account for challenges related to rooftop solar installation on apartment buildings. This initiative strongly aligns with Australia's objective of reducing emissions by 43% by 2030 and achieving net-zero emissions by 2050. In addition to offering an average annual energy bill savings of approximately $185 for houses, average benefits-cost ratios for new houses are 1.4 for and 1.3 for apartments.

3.2 Heating and cooling uptake- International Perspectives

The "Future of Home Heating- Ontario, Canada " study [26], conducted by the Advanced Energy Centre (AEC) in partnership with Enbridge Gas Distribution Incorporation, addresses the challenge of reducing greenhouse gas (GHG) emissions in Ontario's buildings, which account for a huge portion of the province's emissions. This study evaluates various electrification options using air source heat pumps (ASHP) for both retrofit and new homes. These options include full-electric systems, ASHP/Gas Hybrid systems, and CC-ASHP/Gas Hybrid systems. The study finds that hybrid scenarios offer lower lifetime energy costs than full-electric systems, although they have higher initial capital costs. However, operating costs for all scenarios are higher than those of high-efficiency gas appliances. This study also emphasizes the need for innovative rate designs and smart controls to encourage the adoption of hybrid systems. An essential advantage of the hybrid approach is its flexibility, allowing for seamless fuel switching between electricity and gas in response to grid conditions and demand fluctuations. This can help optimize electrification efforts and reduce grid stress. Additionally, ongoing research in gas innovation, like renewable natural gas and hydrogen, promises further benefits and cost savings for GHG reduction.

The Heating and Cooling Installer Study (HaCIS) [41] aimed to gain a comprehensive understanding of the current heating and cooling installer workforce in England, focusing on their characteristics, activities, and attitudes and also provides an overview of the research methodology and its various stages, presented in the order of their execution. The research covered multiple dimensions: installer demographics, backgrounds, skills, qualifications, and diversity. It also examined their activities, particularly their involvement with heat pumps and other heating technologies, as well as their expectations for the future in this regard. This knowledge was intended to shape future government policies concerning training, diversity, quality assurance, and support for installers in the context of transitioning to low-carbon heating, in line with the Government's "leveling up" agenda. It also involved categorizing installers into archetypes, an examination of attitudes toward standards and accreditation, and exploring the challenges that installation businesses face as they navigate this transition.

The study [27], conducted in partnership with the Sustainable Energy Authority of Ireland (SEAI), aims to establish a comprehensive evidence base to address reducing greenhouse gas emissions in Ireland's heating and cooling sector. Given the sector's substantial contribution to emissions, urgent decarbonisation efforts are crucial to meet Ireland's commitment to reducing emissions by 51% by 2030 and achieving carbon neutrality by 2050. The study evaluates various pathways to achieve net-zero emissions by 2050, focusing on heating and cooling technologies and strategies. The study's objectives encompass quantifying energy consumption in Ireland's heating and cooling sectors, creating archetype models representing diverse building and consumer types, mapping thermal demand across the country, and assessing opportunities for energy efficiency improvements. These objectives aim to comprehensively understand heating and cooling demand, support assessing low-carbon technologies and fuels, explore pathways towards net-zero emissions by 2050, consider diverse stakeholder perspectives, and offer detailed insights for policymakers and the public. The archetype modelling approach simplifies the representation of Ireland's complex heating and cooling systems while maintaining a practical balance between detail and feasibility, facilitating informed decision-making to advance emissions reduction goals. The chosen archetype modelling process simplifies Ireland's heating and cooling demand into a manageable set of archetypes. These archetypes, tailored to each sector, balance detail and practicality, considering factors like existing heating systems. This modelling approach reduces time and effort, aligning data calibration with official national energy statistics.

Several studies [28], [29], and [30] have conducted in-depth investigations into the implications of climate change on electricity consumption, each with a unique focus. Fan et al. meticulously examined the regional effects of climate change on electricity consumption within Guangzhou, China, utilizing statistical methods like the Mann-Kendall test and regression analysis. Expanding their scope, Zheng et al. developed a comprehensive climate change feedback model for China's electricity demand at the national level, emphasizing critical climatic factors and predicting future electricity demand trends under various climate scenarios. In contrast, Liu et al. delved into data-driven approaches to assess the intricate interplay between climatic and socioeconomic variables, with a specific focus on electricity demand in Hong Kong, considering factors such as temperature, solar radiation, GDP, and population size. These studies provide valuable insights into the complex challenges posed by climate change on electricity consumption, offering valuable insights for policymakers and decision-makers. Table 8 shows comparative analysis of studies on heating and cooling uptake in international perspectives, while data sources used by the studies on heating and cooling uptake are shown in Table 9.

Table 8: Comparative analysis of studies on heating and cooling uptake- international perspectives

Authors/Organisations	Challenge Addressed	Models/Methods	Data/Variables	Country
The Advanced Energy Centre (AEC) in partnership with Enbridge Gas Distribution Inc. [26]	Reducing GHG emissions in Ontario's buildings	Assessment of electrification options utilizing Air Source Heat Pumps (ASHP) for existing and new residential buildings	Various electrification options, including ASHP/Gas Hybrid systems, CC-ASHP/Gas Hybrid systems and full-electric systems	Ontario, Canada
Partnership with the Sustainable Energy Authority of Ireland (SEAI) [27]	Reducing GHG emissions in Ireland's heating and cooling sector	Evaluation of pathways to achieve net-zero emissions by 2050, focusing on heating and cooling technologies and strategies	Various climatic and socioeconomic variables, including GDP, population, heating and cooling demand, energy efficiency measures	Ireland
Fan et al. [28]	Assessing the regional impact of climate change on electricity consumption in Guangzhou	Statistical methodologies, including the Mann-Kendall test and regression analysis	Various climatic variables such as rainfall, duration of sunlight and temperature	Guangzhou, China
Zheng et al. [29]	Developing a climate change feedback model for electricity demand	Emphasis on climatic factors like temperature, rainfall, and sunshine duration; Predictions under future climate scenarios	Climatic variables, including rainfall, duration of sunlight and temperature, as well as control factors such as urbanisation rate, industrial value added, electricity price, per capita GDP and more	China
Liu et al. [30]	Measuring the effects of climatic and socioeconomic changes on monthly electricity demand over the long term, focusing on Hong Kong	Data-driven methods; Utilisation of climatic and socioeconomic variables, including temperature, solar radiation, enthalpy, GDP, population size, and more	Climatic variables (temperature, solar radiation), socioeconomic variables (GDP, population), electricity consumption data, etc.	Hong Kong, China

Federation University

Table 9: Data sources used by the studies on heating and cooling uptake.

Technical Report/ Title	Data	Sources
Predicting long-term monthly electricity demand under future climatic and socioeconomic changes using data-driven methods: A case study of Hong Kong [19]	Energy electricity consumption National income and balance of payments	Census and Statistics Department of Hong Kong. [17][18]
Principles and methodology for setting ncc heating and cooling load intensity limits & draft heating and cooling load intensity limits for all NatHERS climates	Ratings for a variety of dwelling types, including volume builder houses, apartments, semidetached residences, specialized passive solar homes in cooler climates, and well-ventilated houses in warmer climates	NatHERS
Heating and Cooling Installer Study (HaCIS) [41]	Market Location, a provider of B2B wholesale business data, conducted a sample survey of all heating and cooling companies in their database categorized under the SIC code 43220.	
Heating and cooling in Ireland today: Archetype Profiles, Spatial Analysis, and Energy Efficiency Potential [27]	1) surveyed the commercial building stock in Ireland 2) the total count of residential homes and significantly impacted the choice of renewable heating systems for potential home upgrades. 3) Total building count for each building activity. 4) Number of residences categorized by building type and primary heating system.	1) Commercial and public sectors [22] 2) Residential sector, CSO Census data [23] 3) Commercial and public sectors, additional GeoDirectory data [24] 4) Residential home CSO Census data [25]
Cold Hard Facts 2021 [42]	Field data has been collected on charge sizes, leakage rates, and refrigerant loss during the recovery process from 1,152 split systems at the end of their operational life.	Refrigerant Reclaim Australia in 2021
Cold Hard Facts 2022 [43]	The Department of Climate Change, Energy, the Environment and Water (DCCEEW) data on pre-charged equipment imports for 2005 and 2006.	Department of Environment Water Heritage and the Arts (DEWHA)
Cold Hard Facts 2022 [43]	The sales values of residential and small commercial split and packaged air conditioning systems in the years just before 2006.	Commercial market research
Cold Hard Facts 2022 [43]	The original stock model has undergone enhancements and refinements through the incorporation of new data sources and market insights. This includes data on bulk and pre-charged import statistics, including quantities, mass, species, license holders, and product categories from 2006 to 2021.	DCCEEW

3.3 Assumptions and parameters used in heating and cooling uptake studies

In this section, we provide an overview of the key assumptions and parameters related to heating and cooling uptake, which are summarized in Table 10.

Table 10: Fundamental assumptions and parameters for heating and cooling uptake

Variables/DataPoints	Assumption/Parameter
Archetype Representation [27]	Each archetype is assumed to represent of the building or use-case stock assigned to it.
Variations Around Archetypes [27]	Variations may exist in the underlying stock around the defined archetype.
Consolidation of Buildings [27]	Buildings with slightly differing characteristics are consolidated into singular archetypes.
BER Data as Primary Source [27]	BER data is the primary data source for residential and services sectors, covering approximately 50% of the relevant building stock.
Appliance Demand [27]	Appliance demand is separately included in non-heating electricity demand.
Negligible Cooling Demand [27]	Cooling demand in the residential sector is assumed to be negligible.
Uniform Appliance Energy Consumption [27]	Appliance energy consumption is assumed to be uniform across all homes.
Calibration for Energy Consumption [27]	Calibration assumes alignment between actual and predicted consumption up to a threshold, with a fixed reduction for demands exceeding the threshold.
Similarity in Electric Heating [27]	Less efficient homes relying on electric heating are assumed to be like those using gas or oil for heating.
Possible Underestimation of Appliance Energy Use [27]	Bottom-up methods may underestimate appliance electricity consumption, potentially due to growth in appliance energy usage.
Possible Underestimation of Heating Electricity Use [27]	Chance of underestimating electricity use for heating, leading to a higher allocation to appliances.
Exclusion of Information and Communication Category [27]	Total final energy use attributed to electricity in the commercial sector excludes energy consumption from the Information and Communication category.
Electric Heating Similarity [27]	The approach assumes that electric heating shares similarities with gas or oil heating.
Constant Cooling Demand [27]	Cooling demand at the archetype level for commercial and public sectors is assumed to remain constant until 2050.
Correlation of HDD and CDD with Electricity Demand [28]	A positive correlation exists between Heating Degree Days (HDD) and Cooling Degree Days (CDD) with per capita electricity demand.
GDP Relationship with Electricity Demand [28]	Per capita GDP positively correlates with per capita electricity demand, measured at constant 1995 prices.
Monthly Dummy Variables [29]	Utilized to capture seasonal patterns in time series data.
Deterministic Seasonality [29]	Assumes that seasonal patterns are deterministic in nature.
Limited Data Points [29]	Certain dwelling types may have a limited range of data points.
Inferred Data Points [29]	Additional data points are inferred to enhance curve fitting functions.
Inferred Data Points for Heating [29]	Inferred data points are incorporated for cases with 0% and 100% heating proportion.

3.4 Uncertainty and Risks

In this section, Table 11 provides a comprehensive summary of key uncertainties and risks in cooling and heating uptake related to climate change models, site-specific data, socioeconomic factors, as well as technical and environmental aspects.

Table 11: Key summary of uncertainty and risks

Uncertainty	Risks and effects	Reported in
Climate Change models	The inherent uncertainty in climate models can result in inaccurate predictions of future climate conditions, impacting multiple sectors.	[29]
	Inaccurate climate models can lead to suboptimal policy decisions related to climate change mitigation and adaptation.	
Site-specific data	The absence of site-specific data for estimating fuel usage and heating demand may lead to inefficient energy planning and increased expenses.	[27]
	Errors in estimations might result in industries failing to meet emissions reduction targets.	
Socioeconomic uncertainties	Socioeconomic uncertainties, such as changes in population growth and gross domestic product (GDP), can introduce inaccuracies in long-term energy demand predictions	[19]
	Inaccurate long-term energy demand predictions driven by socioeconomic uncertainties can lead to costly mistakes in energy infrastructure investments	
Technical	Technical uncertainties can cause project delays, cost overruns, and potential equipment failures.	[42]
	Inadequate handling of retrofitting challenges can lead to system performance.	
	Concerns about assuming responsibility for historical issues that may exist with retrofitting systems could result in legal liabilities for contractors.	
Environmental	Premature compressor failures due to elevated discharge temperatures may lead to additional costs and projects.	[42]
	The surge in HFC410A charged heat pumps might have environmental and economic consequences if not managed effectively.	

The literature review also shows except for AEMO's IASR scenarios for residential and business buildings, there exist no studies in the literature that specifically focus on the long-term projection of energy demand and energy efficiency for heating and cooling uptake. As alluded to before, AEMO's IASR scenarios are developed based on a top-down approach, and thus, they do not consider regional aspects that can impact regional energy demand. For long-term projection of heating and cooling uptake and capturing their regional variations, accurate estimation of energy efficiency and their sensitivity to outdoor temperature and set indoor temperature are of paramount importance.

4 Long Term Power Generation Outlook

A long term power generation outlook is important for anticipating and accommodating the future energy demands driven by the electrification of sectors like heating, cooling and transport. By understanding and preparing for socioeconomic shifts and technological advancements, such a comprehensive forecast ensures that regions can sustainably meet their future energy needs while supporting environmental, economic, and societal goals. Several recent studies and reports have investigated into both local and international facets of energy generation. In this section, we explore these recent studies on power generation outlook in depth. We provide an analysis on the assumptions and parameters employed by these studies. Furthermore, we have explored data sources and analysed the uncertainty and risks in different studies.

4.1 Recent Studies on Power Generation Outlook

CSIRO's updated projections report concerning small-scale solar PV and battery adoption offers a comprehensive overview [12]. The key information of the projection summarised in

Table 12. The projection presents short term and long-term projections. Short term projection utilises data from 2014 to 2022 and provided region-based projection for 2022 to 2023. Long term projection utilises data from 2020 to 2023 and provided projection until 2050 for different scenarios. These projections have been formulated as inputs for AEMO's planning and forecasting tasks, with the update occurring over an 18-month period. The primary modifications in these projections entail a slightly subdued growth trajectory for both batteries and solar PV until 2030, coupled with the anticipation of reduced long-term costs for solar PV. While this adjusted deployment rate will still signify robust expansion in solar PV installations, it does not identify in the previous year forecasts. Up to approximately 2030, the revised solar PV projections generally align below the figures of the 2021 projections. However, between 2030 and 2050, uptake projections tend to be more optimistic.

The long-term prospects for batteries exhibit a marginal enhancement owing to the augmented growth in solar PV installations. The central rationale behind installing batteries is to facilitate the temporal shift of solar power for later consumption, coinciding with the period of higher demand. Consequently, the expansion of the solar PV market proportionally enlarges the market for batteries. This is particularly true for locations with substantial solar PV installations, where the export prices for surplus solar generation tend to be lower, and instances of curtailment may be more frequent due to grid voltage fluctuations or system security concerns. These evolving dynamics, coupled with diminishing battery costs, jointly foster a higher rate of battery adoption during the 2030 to 2050 timeframe.

The geographical scope of the study encompasses the National Electricity Market (NEM) states: New South Wales, Victoria, Queensland, South Australia, and Tasmania. However, this range excludes certain postcodes in these states that are not linked to the NEM, while parts of Western Australia integrated into the South West Interconnected System (SWIS) are incorporated. The projections for small-scale solar cover residential and commercial systems below 100kW, with separate estimates provided for larger solar PV systems across distinct ranges. As for batteries, the projections encompass residential systems and categorise commercial systems into small and large scales. Four scenarios are employed for the projections: Progressive Change, Exploring Alternatives, Step Change, and Hydrogen Export.

Table 12 shows a summary of small-scale solar PV and battery projections.

Table 12: CSIRO small-scale solar PV and battery projections (Dec 2022)

Scope	**NSW, VIC, QLD, SA, TAS and Part of WA (Postcode excluded not connected to NEM, part of the WA SWIS are included)**
Scale of Solar PV projection	1) Small-scale solar residential and commercial systems (> 100kW) 2) Larger solar PV systems (< 100kW to 1MW) 3) Larger solar PV systems (< 1MW to 5MW) 4) Larger solar PV systems (< 5MW to 10MW) 5) Larger solar PV systems (< 10MW to 30MW)
Scale of batteries projection	Residential and commercial systems (Small and large scale)
Scenarios	(1) Progressive Change (2) Exploring Alternatives (3) Step Change (4) Hydrogen Export
Scale factors for regression analysis	Progressive Change - 1.5% Exploring Alternatives - 0.75% Step Change 1.5% Hydrogen Export 3%
Key inputs	For Payback Period – Existing and new electricity load, technology cost and electricity terrif For Non-price factors – Ownership of building, type of dwelling, income
Strongest Drivers	1) Solar generation costs 2) Electricity prices and 3) Any additional available renewable energy credits

The influence of the report extends to various assumptions that constitute key elements in the formulation of these projections. Reliable data for battery storage sales is absent, leading to the application of the same weights as rooftop solar. Technological costs are subject to fluctuation, with a greater reliance on lower observed prices for solar PVs over time. Small-scale technology certificates (STCs) are assumed to persist across all scenarios, while the costs of batteries and their installation are sourced from GenCost 2021-22.
An updated report for GenCost is available for the year 2022 -23 [15]. The updated report indicated technology cost as one of the key puzzles. Furthermore, global inflation due to COVID-19 pandemic is another significant factor. Due to this uncertain event, electricity generation cost projection deemed highly varied compared with the report in the previous year. The GenCost is a joint effort between CSIRO and AEMO, annually reviews the costs associated with electricity generation, energy storage, and hydrogen production. Now in its fifth edition since its 2018 launch, GenCost offers detailed projections on electricity generation costs, constantly adjusting based on yearly changes. These updates rely on stakeholder input and feature the latest capital cost estimates, supplied by Aurecon, as well as levelised costs of electricity (LCOEs) that showcase the competitiveness of different generation technologies.

According to GenCost 2022-23 report, technological advances in electricity generation are intrinsically tied to global climate change initiatives. After COP27 in Sharm el-Sheikh, leaders emphasised the goal of limiting the global temperature rise to 1.5°C. In Australia, the goal of reaching net zero emissions by 2050 is either an aspiration or a legislated target across all states and territories. Globally, renewables, predominantly wind and solar, are the most rapidly expanding energy sources. Over the next three decades, electricity's role is forecasted to grow significantly due to its cost-efficient carbon reduction potential. All major global scenarios underscore the need for a more diversified energy system, with a greater reliance on renewables, continued use of fossil fuels (though diminishing), and evolving transportation concepts. Australia's energy landscape is marked by both its energy exports and domestic consumption patterns. In the report, it was identified that the COVID-19 pandemic has caused global supply chain disruptions, affecting raw material prices and freight costs. This has led to increased capital costs for technologies under consideration for construction. Aurecon has provided updates on these cost adjustments, and it's anticipated that undeployed technologies would also see cost increases if deployed.

The Future Energy Scenarios (FES) report outlines four possible pathways for Great Britain's energy landscape until 2050 [16]. These pathways are designed to highlight the potential methods of sourcing and consuming energy in an attempt to reach the net-zero emissions target. Beyond providing a roadmap for energy consumption, these scenarios play a pivotal role in directing energy network investments, shaping policy, steering academic research, and informing financial decisions linked to net zero technologies.
FES outlined that the Consumer Transformation scenario envisions a 2050 where consumers take a proactive role, making their homes more energy-efficient and integrating technologies like electric heat pumps and

vehicles. In contrast, the System Transformation scenario sees net zero achieved by 2050 but requires fewer adjustments from consumers, relying more on large-scale changes such as hydrogen production from natural gas. The ambitious Leading the Way scenario achieves net zero by 2046, propelled by rapid decarbonisation, consumer involvement, and energy-efficient homes utilising renewable hydrogen. The last, Falling Short, doesn't meet the 2050 target, making some progress but maintaining a significant reliance on natural gas and witnessing a slower EV adoption rate.

To transition towards a sustainable energy future, several key recommendations are highlighted by FES. These include reducing investment uncertainty surrounding net-zero critical technologies and advancing the adoption and clarity around heat sources like heat pumps and hydrogen. Emphasis is also placed on the implementation of negative emissions technology, promoting energy savings through smart digital solutions, and fostering consumer trust in the energy transition. Furthermore, recommendations underline the importance of enhancing home energy efficiency, streamlining connections to the GB electricity system, and strategically positioning significant electricity demands to serve the broader energy system most efficiently.
Reedman et al. [14] from CSIRO provided an overview of the historic dominance of coal-fired generation in the NEM and its anticipated transition to renewable sources. It underlines the rapid growth of distributed rooftop solar PV systems and the surge in renewables due to favourable factors such as falling technology costs and decarbonisation objectives. The work provided analysis on four prospective scenarios (e. g. Net Zero 2050, Step Change, Hydrogen Superpower and Strong Electrification), emphasizing their consequences and drawing attention to the indispensable role of storage technologies in the future energy framework.

In addition to this transition, the work mentioned about 31 new electricity generation and storage technologies. These range from traditional sources like black and brown coal with and without CO_2 capture and sequestration (CCS) to more modern solutions like onshore and offshore wind generation, large-scale solar PV, and a variety of pumped storage hydro and battery storage. There is also mention of niche energy sources like wave, tidal, and geothermal, ensuring a holistic view of potential future energy mixes. Yet, with such a breadth of technologies mentioned, a more in-depth exploration of these technologies is required for get insight of their potential impact and feasibility.

In a continual effort to anticipate future energy trends, the U.S. Energy Information Administration (EIA) publishes the Annual Energy Outlook (AEO), employing the National Energy Modelling System (NEMS) to formulate long-term projections of energy dynamics within the United States [37]. The 2022 iteration of AEO delves into prospective scenarios up to 2050, taking into account various pre-defined assumptions and methodologies. They offer an in-depth exploration into the prospective investments required for augmenting electric generation capacity, relying on intricate modelling systems to evaluate the future competitive worth of diverse generation technologies. Key measures such as Levelized Cost of Electricity (LCOE), Levelized Cost of Storage (LCOS), and Levelized Avoided Cost of Electricity (LACE) are harnessed to streamline investment evaluations within NEMS. Despite not encapsulating every variable in NEMS, these metrics, when configured into a value-cost ratio, furnish a viable framework for assessing the economic viability of an array of technologies. The discourse provides a comprehensive exposition of LCOE, LCOS, and LACE averages for technologies anticipated to be operational in 2024, 2027, and 2040, in alignment with the AEO2022 Reference case, thereby elucidating the regional cost variability across the diverse U.S. supply sectors delineated in the NEMS Electricity Market Module (EMM).

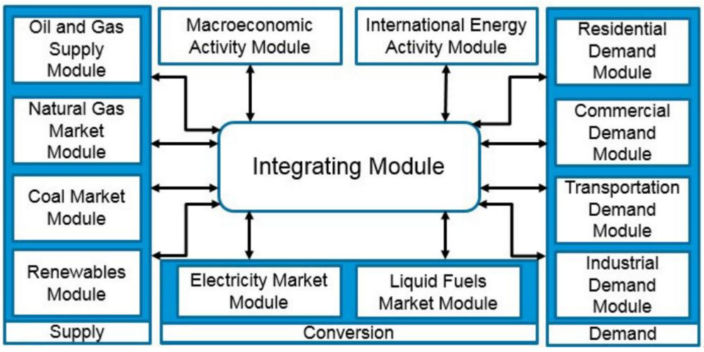

Figure 5: National Energy Modelling System (US) [37]
Source: U.S. Energy Information Administration, Office of Energy Analysis

The constituent modules of NEMS, as illustrated in Figure 5, depict the discrete supply, demand, and conversion segments within domestic energy markets, while also encompassing international and macroeconomic modules. Typically, these modules engage with one another through values indicative of prices or expenditures attributed to the energy supplied to consumer sectors, as well as the volumes of end-use energy consumption.

Amidst escalating climate challenges, Solar Power Europe's recent forecast reveals a promising surge in solar capacity, indicating a pivotal balance between evolving policies, infrastructural preparedness, and localised action [38]. Solar Power Europe predicts a robust growth in solar capacity, forecasting installations of 54 GW to 68 GW in 2023, representing a 30-65% increase from 2022’s record 41 GW. The trajectory of growth is anticipated to escalate, with projections of annual capacity additions reaching up to 120 GW by 2026. The European Commission, under its REPowerEU initiative aiming to hasten the deployment of renewables and supplant fossil fuels, has set ambitious targets of 400 GW and 740 GW solar capacity by 2025 and 2030, respectively. However, Solar Power Europe's scenarios suggest that these goals may be surpassed, with potential capacities reaching 591 GW by 2026 and 1184 GW by 2030 under the high scenario. Notably, the growth of solar power has continually surpassed anticipations, with evolving policies facilitating the enhancement of targets. The prevailing aspirations from REPowerEU and Solar Power Europe are not only in alignment with but are also exceeding the necessities for maintaining a 1.5C temperature increase. The imperative now is the translation of these EU objectives into tangible local actions, with Member States tasked with ensuring the adequacy of regulations and infrastructure to accommodate the swift deployment of renewables, a transition seen as both essential and inevitable.

Facing an unparalleled energy crisis in 2022, precipitated by Russia’s invasion of Ukraine, the EU is hastening its shift away from dependence on Russian fossil fuel imports, reinforcing its commitment to a clean energy transition. Despite a brief increase in coal power, largely viewed as a short-term measure, the focus remains on the expansion of renewable energy sources, particularly wind and solar, which experienced record generation and capacity additions in 2022. As the transition gathers momentum, there is a pressing need for the EU to implement effective policies, secure investments, and develop the requisite infrastructure to sustain this inevitable shift towards renewable energy.

In a rapidly expanding energy market, Türkiye emerges as a notable player, featuring among the top 20 energy-consuming nations globally. In [39] Türkiye’s ambitious trajectory, focusing on long-term electricity generation portfolio optimisation amidst prevailing uncertainties. Pioneering in its approach, the study integrates a multi-objective genetic algorithm with the Pareto Uncertainty Index, providing a nuanced exploration of multiple scenarios and their policy implications – a first in Turkish-centric research. Three distinct scenarios are scrutinised: Business-as-usual (BAU), which includes planned nuclear and solar investments sans specific renewable legislations; an unrestricted scenario devoid of mandated investments; and a government scenario adhering to the Renewable Energy National Action Plan and aimed at curtailing natural gas usage below 30%. The research reveals that minimising emissions is a less risky and more sustainable strategy compared to purely cost minimisation, and it critically assesses the feasibility of government’s aspirational plans in nuclear and renewable sectors. Through comprehensive comparisons with other studies and government projections, the work presented a valuable insight into the interplay of nuclear, renewable, natural gas, and hydro resources in Türkiye's evolving energy landscape, underscoring the vital role of strategic planning for sustainable development and economic growth.

An innovative multi-layered dynamic carbon emission quantification model is developed to analyse the carbon emission trends and mitigation strategies in China's building sector in [40]. This sector plays an important role in China's quest to achieve carbon peak and neutrality goals. The model considers various influencing factors such as climate area, building type, end-use services, and technique renovation through building metabolism, providing a more detailed and nuanced analysis compared to existing models. The study unveils that significant carbon emission mitigation—up to 64.51% by 2060—is feasible through the collective societal efforts, decarbonisation of electricity generation, building stock regulation, and fostering residential green behaviours. However, it also highlights the necessity of employing carbon capture, utilisation, and storage techniques to realize complete carbon neutrality. A notable aspect of this study is the identification of varying strategies needed for different building types and climate zones, reflecting the diverse needs of the northern, transition, and southern areas of China. The emphasis is placed on the importance of technology improvements and the shift towards building electrification to enhance emission reductions. Furthermore, the study concludes that the model and the findings offer valuable insights and tools for setting realistic emission mitigation goals and formulating effective policies, addressing the distinct requirements of different building types and regions in China.

4.2 Data Sources

In the context of our scenario modelling, domestic datasets more important while international data sources might ensure relevancy and precision. Within Australia, we have outlined and relied on several reputable datasets. Specifically, data from GenCost provides valuable insights into the costs associated with various generation technologies. Simultaneously, the AEMO offers datasets that capture the nuances of the nation's energy market operations. Lastly, the Future Energy Scenarios (FES) contributes projections and possible trajectories for Australia's energy sector. Table 13 presents a comprehensive compilation of long term power generation data sources available from the aforementioned three sources: GenCost, AEMO, and FES.

Table 13: Long term power generation data sources

Technical Report	Data	Sources
CSIRO PV and Battery Projection [12]	Cost of installed rooftop solar	GenCost 2021-22
GenCost 2022-23 [15]	Existing and selected new electricity generation, storage and hydrogen production technologies Current cost and performance data; Capital costs for generation technologies, storage technologies capital costs	AEMO commissioned Aurecon (2023) for this
Future Energy Scenarios [16]	Energy consumer (Energy demand for residential, transport, industrial and commercial places), hydrogen and electrification, Energy Systems (Electricity supply, hydrogen supply, natural gas, bioenergy)	FES 2023 Data Workbook

4.3 Assumptions and Parameters

CSIRO's projections report [12] on small-scale solar PV and battery adoption navigates through diverse facets like electricity tariffs, battery management, virtual power plants, and socio-economic indicators, offering a multi-dimensional perspective on the projections' underlying assumptions. All the reported assumptions are summarised in

Table 14. Furthermore, Table 15 presents a summary of the scenarios and assumptions from GenCost [15].

Table 14: Data Assumptions for CSIRO's small-scale solar PV and battery adoption projections

	Assumption
Reliable battery storage sales data is not available	The same weights apply to battery storage as for rooftop solar
Technology costs	
Discounting and remote subsidies	Greater prevalence of the lower observed prices over time for solar PVs
Small-scale technology certificates (STCs)	STC subsidies are assumed to prevail across all scenarios.
Batteries and installation	Cost sourced from GenCost 2021-22; Upfront battery capital costs are considered, not degradation or end-of-life disposal costs; No assumptions are made about disposal costs due to the lack of maturity of the Australian lithium-ion battery recycling industry.
New solar system sizes (less than 100kW)	
Inverter capacity	Residential rooftop solar systems commonly have panel to inverter capacity ratios greater than 1. Installers require inverters to be at least 75% of panel capacity.
Residential system	Trend of increasing residential system sizes in the short term. Government subsidies per watt of solar power capacity are declining. Expected decline in revenue for exported solar power. Assumption of a continued increasing trend in system size for several years, then a saturation in the long run in the residential sector
Electricity tariffs, battery management and virtual power plants	
Assumed trends in retail and generation prices	Higher generation costs are expected to ease in the next few years due to improving international circumstances and increased non-fossil fuel capacity. Commercial retail prices assumed to follow residential retail price trends for all scenarios. Daytime generation prices important as an anchor point for feed-in tariffs. Feed-in tariffs may not reflect daytime generation prices due to retailers' pricing strategies.
Reduction in rooftop solar production	Progressive Change 50% Exploring Alternatives 43% Step Change 40% Hydrogen Export 33%
Current electricity terrif	Increasing proportion of residential customers have time-of-use (TOU) retail tariffs. Around a quarter of registered battery owners participated in virtual power plant (VPP) trials. Battery ownership facilitates customer adoption of more complex tariffs.
Battery owner incentives	Changes to customer connections and network charges are main policy arrangements for changing tariff structures for battery owners. Simulation assumes residential customers receive around $250 per year incentive for VPP participation.
Community batteries	Community batteries reduce the need to import electricity from large coal generators. Community batteries can support the operation of the local distribution grid.
Income and customer growth	
State product and customer connection	Gross state product (GSP) assumptions are provided by AEMO and BIS Oxford Economics. GSP assumptions are used to project income growth.
Separate dwellings and home ownership	
Ownership	Share of separate dwellings (detached houses) will fall over time in all scenarios. Exploring Alternatives and Step Change scenarios assume separate dwellings to occupy a 45% share by 2050. Exploring Alternatives and Step Change scenarios assume the declining trend in home ownership to continue. Progressive Change scenario assumes a slightly faster reduction in home ownership rates. Hydrogen Export scenario assumes a slower rate of decline in home ownership consistent with higher solar and battery installation.
Rooftop solar and battery storage market segmentation	
Battery storage market	Battery storage market assumed to be a subset of rooftop solar market due to motivation to enhance solar returns. Payback period for solar with integrated batteries lags behind solar alone, impacting the adoption fraction of batteries

Table 15: GenCost scenarios and assumptions summary [15].

Key drivers	Global NZE by 2050	Global NZE post 2050	Current policies
IEA WEO scenario alignment	Net zero emission by 2050	Announced pledges scenario	Stated policies scenario
CO_2 pricing / climate policy	Consistent with 1.5 degrees world	Consistent with 1.7 degrees world	Consistent with 2.5 degrees world
Renewable energy targets and forced builds / accelerated retirement	High reflecting confidence in renewable energy	Renewable energy policies extended as needed	Current renewable energy Policies
Demand / Electrification	High	Medium-high	Medium
Learning rates	Stronger	Normal maturity path	Weaker
Renewable resource & other renewable constraints	Less constrained	Existing constraint assumptions	More constrained than existing assumptions
Decentralisation	Less constrained rooftop solar photovoltaics (PV)	Existing rooftop solar PV constraints	More constrained rooftop solar PV constraints

The UK’s EFS report [16] provides a detailed overview of key assumptions related to electricity generation, considering various factors such as technological advancements, policy implications, market dynamics, and environmental considerations. For scenario modelling in the Victorian context, the UK's EFS report can serve as a foundational guide. While direct implementation of all assumptions might not be feasible due to regional and market differences, the overarching themes and strategies can be adapted and fine-tuned to suit Australia's unique landscape. The key assumptions related to electricity generation from the UK’s EFS report is summarised below:

- Hydrogen and gas Carbon Capture, Usage and Storage (CCUS) power generation capacity reaches 12.3 GW by 2035 in System Transformation.
- High levels of renewable generation with low hydrogen production led to high electricity curtailment and export in the Consumer Transformation scenario.

- Two-thirds of hydrogen produced in Consumer Transformation is used in aviation, while another 20% is used for electricity generation to support security of supply.
- A strong focus exists on improving how offshore generation connects to the onshore network to support the 2030 government offshore wind targets.
- The UK has moved significantly away from coal-powered generation to gas power and renewables.
- The UK's electricity grid will need to continue decarbonizing to accommodate increasing electricity demand during the transition to net zero.
- The power sector must achieve negative emissions. By 2030, wind and solar generation will account for at least 66% of electricity generation in the Falling Short scenario, rising to between 71% and 84% by 2050.
- Total generation capacity is expected to grow rapidly in the 2020s, with an increase of between 42% and 85% by 2030.
- Offshore wind is anticipated to be the predominant growth area in electricity supply in the 2020s and will become the primary generation source by 2035 in all scenarios.
- In scenarios like Consumer Transformation, there is rapid electrification with a focus on renewable generation, particularly offshore wind and solar. Gas generation's role will diminish but remain important for security of supply.
- By 2050, total electricity generation capacity in Consumer Transformation will be 301 GW, and electricity generation output will be over three times current levels. This scenario will heavily rely on renewable energy, with a significant portion coming from offshore wind.
- Despite high levels of electrification, hydrogen will play a role in decarbonizing hard-to-abate sectors.
- Growth in offshore wind will continue, with 31 GW expected by 2030. Gas with CCUS and large-scale nuclear are projected to play roles post-2035.
- In the Falling Short scenario, by 2050, total electricity generation capacity will be 243 GW, dominated by renewables, particularly offshore wind, but with a role for fossil fuels.
- Electricity supply in Consumer Transformation shows a significant rise by 2050, with the majority coming from offshore wind. Fossil fuel generation will decrease by two-thirds by 2030.
- Across all scenarios, the primary driver of short-term capacity growth through the 2020s is new renewable generation. The most substantial increase is seen in the Leading the Way scenario.
- Barriers like grid connection availability, supply chain growth, and project financing could influence the growth in new capacity.

4.4 Uncertainty and Risks

In this section, we summarise key uncertainties and risks associated with power generation. These uncertainties can stem from a myriad of factors, such as technological advancements, policy changes, market dynamics, and environmental variables. Recognising and understanding these uncertainties is crucial for long-term power generation planning. Table 16 summarise risk and uncertainty in various studies.

Table 16: Key summary of uncertainty and risks

Uncertainty	Risks and effects	Reported in
Economic Factors	Economic fluctuations, such as recessions, booms, or inflation that can Influence power demand and raw materials cost	Raw material cost [12]
Global Pandemic	Impact energy demand due to reduced industrial activities, changes in work patterns (e.g., work-from-home scenarios), and disruptions in global supply chains.	Inflation due to COVID-19 [12] Global supply chain disruption due to COVID-19 [15]
Integration of Renewables	Uncertainties related to grid stability, energy storage, and the intermittent nature of sources like solar and wind	Robust expansion in solar PV installations [12]
Technological Advancements	The pace and nature of technological advancements in energy generation and storage can be unpredictable.	Battery cost reduction [12] Net-zero critical technologies [16]
Policy and Regulatory Changes	Governments can introduce or alter policies that either promote or restrict certain types of energy sources. For instance, changes in subsidies for renewable energies.	Global climate change initiatives [15]
Innovation in Energy Efficiency	Rapid advancements in energy efficiency can reduce the demand for power, introducing uncertainty in future energy requirements.	Home energy efficiency [16]

The electrification of important sectors, such as heating, cooling, and transport, underscores the significance of a forward-looking power generation strategy. By grounding our insights in domestic and international energy generation perspectives, we are better positioned to anticipate evolving energy demands and uphold vital environmental, economic, and societal standards. Drawing upon important data sources, like GenCost, AEMO, and FES, has enriched our analysis. It is evident that understanding the underlying forces and assumptions behind energy projections is a cornerstone of effective scenario modelling. Furthermore, addressing uncertainties and risks, from technological advancements to policy shifts, will be important. Recognising and incorporating uncertainties and risks related to technological and policy changes is crucial for resilient scenario building.

5 Reconciliation with existing scenarios and parameters

For studying the relationship and the implication of management and policy, reconciliation has been applied in numerous disciplines such as social inclusion, education, health, environment and so on. Some of the studies on reconciliation are as follows:

- Explaining the importance of reconciliation in children's education [34]. This study also analyses the impact of discrimination experienced by the Aboriginal and Torres Strait Islander children on their education outcomes using the least squares regression analysis.
- Reservoir-based hydropower is leveraged in two different systems having different priorities and constraints – (i) renewable energy generation and storage, and (ii) water allocation. Because of these priorities and constraints, the two systems are not adequately represented, resulting in different planning outcomes. Rheinheimer et al. [35] presented the differences in hydropower utilisation in energy and water systems and emphasized that better representation would reconcile these differences in the planning and management.
- Acute care units involve inter-professional healthcare activities between nurses, doctors, pharmacists and other care providers [36]. The lack of proper clinical guidelines for practices and adequate training limits the efficacy of the nurses, especially for hospital discharge. The guidelines and training for medication reconciliation will help nurses improve patient safety and reduce discharge delays.

We will analyse the differences between the projections of annual electricity energy consumption and generation estimated by 2023 IASR scenarios and their relevant scenarios aimed in this project. 2023 IASR scenarios generate long term temporal projection at NEM and state/territory level. In contrast, spatial granularity will be considered to generate the projections in urban, semi-urban and rural level.

Rehfeldt et al. [3] adopted a bottom-up approach to disaggregate the Eurostat's industrial energy balance at the subsector level, leveraging the temperature profile of an industrial process (activity) and end-use. They matched the energy use distribution for an industrial subsector of each country between the aggregated energy derived from the bottom-up approach with that for Eurostat. The results show a similar amount of energy use by temperature level. However, individual European Union countries have a different distribution of energy use at the process level than that for the Eurostat subsector level.

We will adopt the similar bottom-up approach presented in [3]. As shown in Figure 6, for a region (council, urban, semi-urban, rural) or postcode, scenarios will be developed by disaggregating the AEMO's long-term projections considering the weight/influence (correlation) of demographic trends, socioeconomic shift and both global and local climate change for that region or area indicated by that postcode.

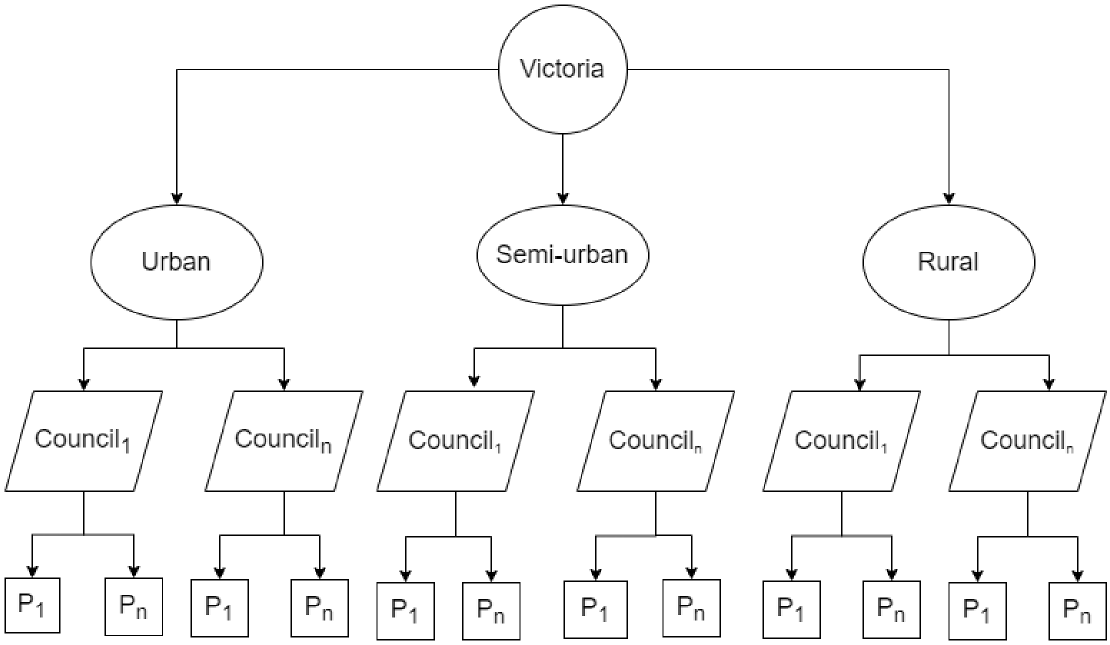

Figure 6: Hierarchical structure of the bottom-up approach. Here, $council_1$= First council; counciln= n^{th} council; P_1= First postal area; and P_n= n^{th} postal area.

For reconciliation, we will aggregate the projections for all regions or postcodes across Victoria using the bottom-up approach. The aggregated bottom-up projections will be contrasted against the AEMO's (top-down) projections for Victoria. We will also perform a sensitivity analysis on how local change or government strategies increase the gap between bottom-up and top-down projections, presenting the implication of differences in the context of energy demand, supply, and distribution.

We will also contrast the input parameters and assumptions used in the progressive and step change scenarios of 2023 IASR against those for the relevant scenarios that will be utilised in this project. Note that we will conduct reconciliation for both energy demand and generation projections.

6 Research Issues and Proposed Methodology

Research issues have been identified after a comprehensive literature review. The proposed methodology has been designed considering the research issues that need to be addressed for a smooth transition to electrification and achieving net zero by 2050. The following sections present the research issues and proposed methodology for scenario building:

6.1 Research Issues

We survey the literature on scenario analysis, EV and heating and cooling uptakes, renewable energy generation and reconciliation. After literature review, we identify the following research issues that are relevant to scenario building:

- For long-term energy demand and generation projections, demographic trends, socioeconomic shift, EV uptake transformation and climate change impact on uptake have been considered in 2023 IASR scenarios. However, AEMO's scenarios are developed considering the top-down approach assuming values of top-level levers (input and parameters). They are at the national and state/territory level. The scenarios at a more granular level such as urban, semiurban, and rural regions are absent.
- Besides demographic trends, socioeconomic shifts and climate change, long-term energy demand and generation projections are sensitive to unpredictable things, such as natural disasters/events (COVID-19), global political situations, government strategies and technological development (energy efficiency). These things make long-term energy projections a challenging and daunting task and demand the consideration of special events and their sensitivity analysis for it. For this reason, even though a vast number of studies on short and medium-term energy projections are available, there exist a very few works on long-term energy projections in the literature.
- Local climate change, especially the regional temperature variations during a particular session, changes the load profiles of EV and buildings. Local climes change in long-term projection is yet to be considered.
- Vehicle to Home (V2H) EV charging and electrification of home heating and cooling appliances create a more building energy demand, and consumer-led DERs such as PV (rooftop solar), battery storage and Vehicle to Grid (V2G) are turning homes into energy-generating sources. This type of in-home energy demand and generation vary among houses and regions. The bottom-up approach is suitable for estimating this type of energy demand and generation projections as it focuses on the characteristics (e.g., demographic trends, socioeconomic shifts, local climate change) of individual regions and their EV and building load profiles and seasonal variations. However, the bottom-up approach has not been well investigated for the long-term energy projections.

6.2 Proposed Methodology

Using the bottom-up approach, our aim is to develop scenarios at urban, semiurban, and rural regions of Victoria using the assumptions and levers consistent with those adopted by IASR and additional ones. As a case study, we will use Horsham (rural and aggro-industries), Ballarat (regional urban and agro-food industries), Melbourne City Council (urban CBD), Dandenong (urban), Epping or nearest suburb and Mildura (edge of the grids).

We will conduct sensitivity analysis on the key assumptions and levers (refer to

Table 17) that impact the scenario outcomes. We will develop relevant hypotheses to perform sensitivity analysis. For example: the higher the population growth, the higher the EV uptake in a particular regions/suburb.

Table 17: Key inputs and Assumptions that will be used in scenario building

Inputs and Assumptions	Relationship	Scenario Report	Data Source	Observation/Rationale
Energy consumption, generation and population growth	Correlation between energy consumption & generation and population growth	Energy demand, EV and heating & cooling uptake and PV & battery adoption rate in regions/suburbs in interest as population changes.	ABS/Local Council/Informed ID population forecast data. Victorian PV and battery adoption data	EV uptake is concentrated in more populated areas in Australian major cities [8]. Population growth can affect PV and battery uptake by influencing home ownership rates, average income levels, housing types, sensitivity to system costs, and various non-price demographic factors [12].
Energy consumption, generation and socioeconomic shift	Correlation between energy consumption & generation and socioeconomic shift	EV and heating & cooling uptake, and PV & battery adoption rate [12] in regions/suburbs in interest as socioeconomic condition changes	ABS/Local Council/Informed ID socioeconomic forecast data Note that income level [8] forecast data are not currently available. Victorian PV and battery adoption data	EV uptake is concentrated in higher -income areas in Australian major cities [8]. An EU study shows economic structures (e.g., income distribution, sectoral composition) create differences in heating and cooling demand [3].
EV uptake forecast & historical/current EV adoption rate	Correlation between EV uptake and inputs	EV uptake	VicRoads Vehicle including EV registration data [8]. CSIRO EV uptake projection data [21].	Registration data will show the distribution of EV use across regions/suburbs
Government policies affecting uptake and generation	Correlation between uptake & generation projection, and inputs	EV and heating & cooling uptake, and generation projection	Australian Energy Regulator, Vic Government, Federal Chamber of Automotive Industries (FCAI)	AEMO 2023 IASR suggests investment decisions such as CER are significantly impacted by Government policy. AEMO's change to three scenarios from four scenarios also reflects policy change by government [9].
Climate effect	RCP pathways in Australian context	EV and heating & cooling uptake	Bureau of Meteorology and IPCC Data Distribution Centre	developed RCP pathways to analyse the global temperature rise. AGL TCFD report mentions that for their scenarios. RCP pathways were converted in Australian context discounted registration rate [2]

For scenario building, we will consider the inputs and assumptions presented in Table 17. We welcome opinions and feedback from C4NET researchers and practitioners. Based on their feedback, the above table will be updated.

The over of techniques that will be used in the proposed methodology is as follows:

- To build regional/suburban scenarios, we will leverage recent IASR forecast data on annual energy consumption, maximum and minimum demand, EV uptake, heating & cooling uptake and small non-scheduled generator for Victoria at the top level and then distribute (i.e., disaggregate) them in the regional levels as per demographic or socioeconomic shifts, climate change including local climate change and other relevant factors (e.g., EV registration rate).

- The disaggregation at each regional/suburban level will be decided considering the influence of projected trends (such as correlation between energy consumption and population growth; correlation between energy consumptions and socioeconomic shift, e.g., income level shift).
- We will identify the key parameters that influence renewable energy generation and adoption of PV and battery storage based on demographic or socioeconomic shifts and other relevant factors (e.g., climate change).
- The model will use any selected IASR scenario data and can be integrated with AMEO's ISP.
- We will reconcile the scenarios generated by bottom-up approach with those for top-down approach (2023 IASR scenarios).

Every two years AEMO changes their ISP model and forecast data up to 2054 for EV and heating cooling uptake and small non-scheduled generator of each scenario for each state/territory. We use these 2023 IASR forecast data for Victoria at the top level and then distribute them in the regional levels as per demographic and socioeconomic shifts and climate change. We need to estimate the factors for both generation and demand (e.g., correlation between energy consumption and population growth and EV uptake and socioeconomic shift i.e., income level shift) that will impact disaggregation. Our proposed model will be developed based on open architecture and therefore, it will use any selected IASR scenario forecast data at the state/territory level and can be easily integrated with AMEO's ISP. The overview of the methodology for the proposed scenario building framework is illustrated in Figure 6.

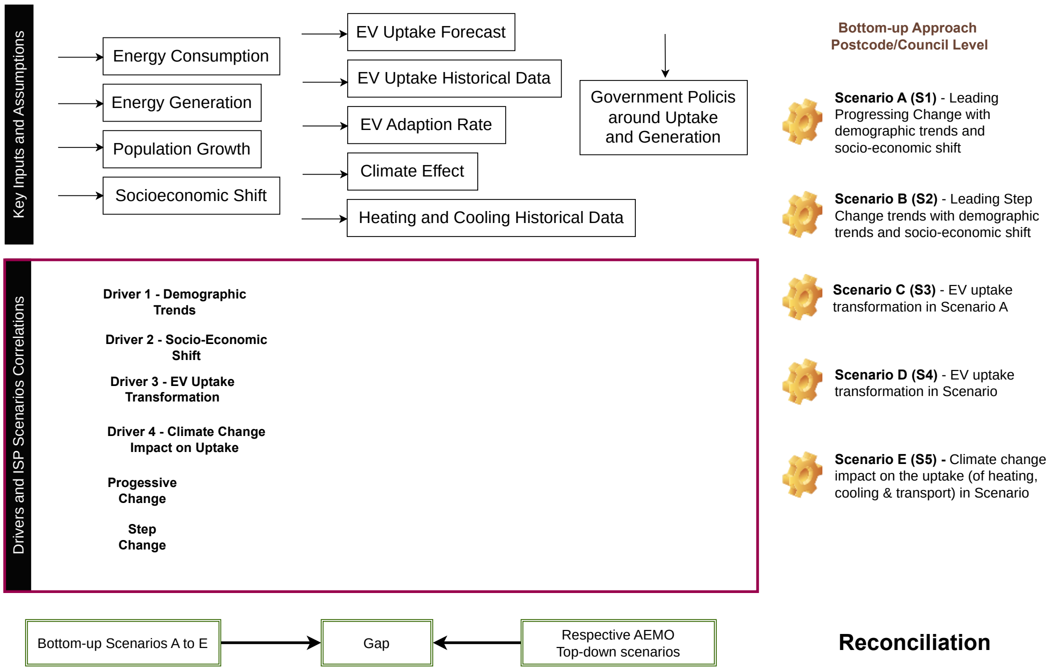

Figure 7: Overview of the methodology for the proposed scenario building framework.

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