Modelling V2G

A study on the economic and technical value proposition for V2G

15/12/2022

Laura Jones, Kat Lucas-Healey, Bjorn Sturmberg, Johannes Hendriks

Australian National University

Battery Storage and Grid Integration Program

An initiative of The Australian National University

Contents

Contents ... 2

Executive Summary ... 3

1 Introduction ... 10

2 Questions and Scenarios ... 11

2.1 Framing ... 11

2.2 Scenarios ... 12

2.3 Data and limitations ... 15

3 Results ... 18

3.1 What is the value of V2G? ... 18

3.2 What is the environmental impact of V2G? ... 26

3.3 What is the trade-off between grid value and availability for transport? ... 29

3.4 What is the trade-off between emissions reduction, cost and availability for transport? ... 36

3.5 How could EV charging impact load growth? ... 38

3.6 What tools are effective at managing demand impacts of V2G? ... 45

3.7 Is V2G economic? ... 53

4 Conclusion ... 58

5 Bibliography ... 64

Appendix A Study framework ... 66

A.1 Collect input data ... 67

A.1.1 Vehicle data ... 67

A.1.2 Energy and generation data ... 71

A.2 Collate inputs ... 73

A.3 Define targets ... 76

A.3.1 Pricing ... 76

A.3.2 Constraints ... 79

A.4 Optimise ... 79

Appendix B Forecast constraints methodology ... 81

B.1 Scenario analysis ... 81

B.2 Forecast ... 82

B.3 Timeseries ... 84

This report has been created for knowledge sharing as part of the Realising Electric Vehicle to Grid Services project. This Project received funding from ARENA as part of ARENA's Advancing Renewables Program. The views expressed herein are not necessarily the views of the Australian Government.

Executive Summary

Vehicle-to-grid (V2G) technology enables electric vehicles (EVs) to discharge power from their batteries into the grid. This capability is seen as being tremendously beneficial due to:

- the economic and material efficiency of making better use of vehicles that are currently underutilised when parked (which is most of the time),
- the critical role of flexibility in 100% renewable energy power systems,
- the large energy storage capacity of individual EV batteries (and larger vehicles) and the large number of vehicles, and
- the significant power capacities with which EVs connect to the grid.

V2G is however still a relatively nascent technology. It presents numerous social, commercial, technical, and practical considerations that need to be addressed in order for the technology to evolve from niche trials to mainstream utilisation. Trials are an important mechanism to undertake this learning, and the Realizing Electric Vehicle to Grid Services (REVS) trial is no exception. We explore the role of trials further in our social science report [2] . The REVS trial is described further in Box 1.

This report follows the qualitative research undertaken in the REVS social research workstream [2] and the business models workstream [1]. It uses numerical modelling to add a quantitative dimension to many of the issues raised in the qualitative research, including how the benefits, risks, and impacts of V2G are influenced by user's prioritisation of various values and constraints. From these two reports, we defined seven themes that we have investigated in this report. These themes are based on questions that participants in the qualitative research asked, future scenarios they described, and clarity they sought. They are described in Table 1.

This study uses a scenario analysis method to investigate these themes. The data we based this study on is year-long scenarios of energy system and vehicle usage conditions for residential houses and commercial offices. We then examined scenarios consisting of combinations of:

- 4 types of charging behaviours: unidirectional convenience charging (V0G), unidirectional timed charging (V0G), unidirectional managed charging (V1G), and bidirectional charging (V2G),
- 3 optimisation targets: minimising costs under current pricing structures, minimising costs under prospective dynamic pricing structures, and minimising carbon emissions,
- 3 levels of conservatism: allowing V2G to make full use of the vehicle battery, disabling V2G disabled until the battery charges up to a minimum 50% state of charge, and disabling V2G disabled until the battery charges up to a minimum 90% state of charge.

Table 1 Themes and questions

Theme	Customer group	Questions
What is the value of V2G?	**EV Owners**	How will V2G impact energy costs? What is the energy cost of EV charging? What are the critical factors that drive value?
	Market Participants	How will V2G impact the cost of supplying customers? Which EV use cases are best suited to V2G?
What is the environmental impact of V2G?	**EV Owners**	What is the emissions impact of V2G? How does V2G impact self-consumption of photovoltaic (PV) power?
	Market Participants	What is the cost impact of minimising emissions from EV charging?
What is the trade-off between grid value and availability for transport?	**EV Owners**	How does V2G impact battery state of charge? What is the impact of reserving capacity for driving on the value of V2G?
What is the trade-off between emissions reduction, cost and availability for transport?	**EV Owners** **Market Participants**	How do EV owner preferences affect optimisation?
How could EV charging impact load growth?	**Grid Operators**	How will V2G impact load in the future? What tools are most effective at managing V2G's grid impact?
When is V2G economic?	**Market Participants**	When will it begin to be economic to offer V2G products to customers?

What is the value of V2G? (section 3.1)

The value that V2G can deliver depends critically on the amount of time EVs are plugged in to chargers. The "house" data set used in this study has low plug-in rates and therefore shows little opportunities for V2G to produce value. The "office" data set used in this study has high plug-in rates, which enable benefits from V2G services to outweigh the cost of charging vehicles, such that the net cost of adding additional EVs to the office is negative under both existing and dynamic prices. These findings are consistent with many V2G contracts stipulating minimum plug-in times.

This leads to Finding 1: the length of time vehicles are plugged into chargers is a critical determinant of V2G value. Initiatives that encourage uptake of V2G should also encourage high plug-in rates.

Finding 1: The length of time vehicles are plugged into chargers is a critical determinant of V2G value

EV owners	***The value that V2G services can produce is highly dependent on the length of time vehicles are plugged in to chargers. If plug-in times are sufficiently high, the impact of V2G can be so great as to make the cost of adding EVs to a site negative.***
Market Participants	

A particularly promising source of value for V2G is the provision of frequency services. This was corroborated in our modelling, where the revenue from FCAS accounted for half to two-thirds of the total value of V2G. This supports the REVS projects focus on commercialising V2G FCAS capabilities. It also means that the value of V2G is highly sensitive to value of the FCAS market, which is expected to decline as more flexible assets (batteries and demand response etc) connect to the market. The provision of FCAS also provided substantial value under V1G charging conditions, which may present competition to V2G charging.

Demand and energy price arbitrage are also significant drivers of V2G value, while utilising V2G to minimise marginal carbon emissions proved to be the most expensive of the considered charging methods.

This leads to Finding 2: FCAS revenue is the dominant component of the V2G value stack – under current market conditions.

Finding 2: FCAS revenue is the dominant component of the V2G value stack – under current market conditions

EV owners	***Demand and energy price arbitrage offer opportunities for significant benefit for V1G and V2G. Feed-in rebates or charges have minimal value.*** ***If the technical requirements can be met, FCAS is a valuable service that can significantly contribute to the overall value stack. This is even the case for V1G, which can stop/decrease charging to contribute to raising the frequency and can start/increase charging to lower the frequency.***
Market participants	

What is the environmental impact of V2G? (Section 3.2)

EVs are commonly marketed as a way for people to reduce their transport emissions. This means that some people may prefer that their vehicles are charged in a way that minimises their emissions impact.

We firstly considered the impact of operating V2G charging to minimise the carbon content of grid energy (considering the marginal emissions in the NSW1 region). This study showed that V2G can result in lower emissions at a site-wide level, particularly where vehicles are plugged in for extended periods, however this comes at a significant financial cost.

Secondly, we considered the impact of this optimisation strategy on the self-consumption of locally generated PV. Counterintuitively, the strategy of optimising to minimise marginal emissions reduces

PV self-consumption compared to optimising for price. This is because PV is commonly generating at a time when an emissions intensive coal generator is marginal, which makes it preferable (from an emissions perspective) to export PV into the grid and charge vehicles at another time when the marginal generator has a lower emissions intensity.

What is the trade-off between grid value and availability for transport? (Section 3.3)

Maximising grid or emissions value comes at the cost of the energy available in vehicles for driving.

As a baseline, our scenarios allowed the full capacity of vehicle batteries to be available for V2G uses, as long as there was sufficient energy available to meet known trips (with no guarantees about charge being available for unexpected trips).

Such an approach will likely not be palatable to EV drivers, and so we investigated the impacts on V2G value by reserving a minimum state of charge in the batteries. While doing so unsurprisingly reduces the value of V2G because it reduces the flexibility that can be used to extract grid value, the extent of this reduction was surprisingly low. Selecting a 50% conservatism level (with V2G disabled while the battery charges up to a minimum 50% state of charge) only reduced the value of V2G in offices by 20% under the dynamic pricing scenario. Increasing the conservatism to 90% had a much more marked impact, reducing the value of V2G by 80% for offices with dynamic pricing. This leads to Finding 3: conservatively operating vehicle batteries still allows significant value from V2G.

Finding 3: Conservatively operating vehicle batteries still allows significant value from V2G

EV owners	***While reserving capacity in EV batteries reduces value, the value available remains substantial, even with relatively high levels of conservatism.*** ***EV owners will need to consider what setting is appropriate for their use case and value drivers.***

What is the trade-off between emissions reduction, cost and availability for transport? (Section 3.4)

As found throughout the REVS project, the ability to operate V2G in pursuit of various objectives creates the potential for different values to be placed in tension with each other. The pursuit of reducing cost may, as detailed above, increase emissions and vice versa. Conserving energy for transport reduces V2G's ability to respond price signals or emissions profiles.

The key take away from this is that these tensions must be made explicit and then navigated carefully by all parties with a stake in the outcomes. This is summarised in Finding 4: V2G can serve multiple – at times conflicting – goals. All stakeholders need to be informed of this and have agency over defining their preferred trade-offs.

Finding 4: V2G can serve multiple – at times conflicting – goals. All stakeholders need to be informed of this and have agency over defining their preferred trade-offs.

EV owners Grid operators Market Participants	***Many values held by EV owners (such as emissions impact, PV self-consumption, and driving range) are in tension with economic returns. Furthermore, choices between objectives have consequences on the value available to other stakeholders. These tensions will need to be navigated carefully by all those with a stake in the outcomes of optimisation.***

How could EV charging impact load growth? (Section 3.5)

The impact of V2G on load growth is striking. The results of this study are a warning: If not managed carefully, V2G can increase peak demands and result in large power swings in the energy system. This illustrates how flexibility can be a challenge for the energy system if it is not managed carefully. This is summarised in Finding 5: flexible resources need to be managed carefully as their penetration increases.

Finding 5: Flexible resources need to be managed carefully as their penetration increases

Grid operators	***If poorly managed, flexible resources can dramatically impact the distribution network through peak loads or minimum demand caused by coincident price (or other) events. This can cause load extremes and rapid changes in demand. Grid operators will need to consider mechanisms that reduce variability of flexible assets.***

What tools are effective at managing demand impacts of V2G? (Section 3.6)

Demand pricing appears to be a useful tool that grid operators can use to manage the impact of flexibility on the energy system. Export pricing and export rebates did not elicit significant response in this study. This is summarised in Finding 6: demand pricing is an effective tool for moderating demand.

Finding 6: Demand pricing is an effective tool for moderating demand

Grid operators	***Demand pricing shows the most promise at modulating demand from flexible assets when compared with energy prices and feed in credits.***

Is V2G economic? (Section 3.7)

Today, V2G has challenging economics. But in some niche use cases, where vehicles are plugged in for extended periods, V2G could soon be economic. In most cases charger prices still need to drop before V2G is economic. This is particularly true when assumptions used in this study such as forecast accuracy are relaxed to more realistic conditions. This leads to Finding 7: V2G is not currently economic, but may shortly become so in some use cases.

Finding 7: V2G is not currently economic, but may shortly become so in some use cases

EV owners	***V2G currently has challenging economics.*** ***In ideally suited use cases – with high plug-in rates, high local demand to manage, and low capacity reservation needs – V2G may be economic soon.*** ***For many use cases significant price drops will be required before it is widely economic.***
Market Participants	

Future meaning and further work

This study provides a quantitative backing to the qualitative findings in the social science and business models reports. As shown in findings there are several tensions inherent in the flexibility offered by V2G, which will need to be managed and actively negotiated by stakeholders if V2G becomes a mainstream constituent of the energy and transport systems.

We see (at least) three threads to follow in future work. These are described in Table 18.

Table 2 Threads for further work

Thread	Description
Understand tension in optimisation	There is tension in the way EV owners and the energy system may want V2G to operate. Future work can understand the materiality of these tensions and how they might be navigated.
Managing energy systems with large amounts of flexiblity	Flexibility is likely to have a central role in the future energy system. It does however present risks, as well as many opportunities. Future work can help understand how multiple, overlaid signals can be managed in a way that reduces the likelihood of undesired, coincident behaviour negatively affecting the energy system.
Impact of less accurate forecasts on value	This study assumed perfect foresight of price and driving needs. Future work could understand the impact of less accurate forecasts on the overall value proposition of V2G.

Box 1 About the REVS trial

Introducing the Realising Electric Vehicle-to-grid Services (REVS) trial

This report has been developed as part of the REVS trial. In an Australian first, the Realising Electric Vehicles-to-grid Services (REVS) project demonstrates how commercially available electric vehicles (EVs) and chargers can contribute to energy stability by transferring power back and forth into the grid, as required.

EVs will inject power back into the grid during rare events (to avoid possibility of blackouts) and EV owners will be paid when their vehicles are used for this service.

Employing 51 Nissan LEAF EVs across the ACT as part of the ACT government and ActewAGL fleet, the REVS project seeks to support the reliability and resilience of the electricity grid, unlocking economic benefits making electric vehicles a more viable and appealing transport option for fleet operators.

The REVS consortium covers the whole electricity and transport supply chains including ActewAGL, Evoenergy, Nissan, SG Fleet, JET Charge, ACT Government and the Australian National University. Together the consortium will produce a roadmap with recommendations that will accelerate the deployment of V2G nationally.

The project has been endorsed by the Australian Renewable Energy Agency (ARENA) and has received funding as part of ARENA's Advancing Renewables Program.

REVS is underway and will publish a final report in late 2022.

https://secs.accenture.com/accenturems/revs/

1 Introduction

Vehicle-to-grid (V2G) is a technology that holds a lot of promise for the integration of electric vehicles (EVs) and the overall management of the grid. It promises to change EVs from being not only modes of transport, but also grid participants. However, realising the potential of V2G is not without challenge. How well can one device, an EV, deliver all these services? In the words of a participant in our qualitative research:

> *"The people want to have a car, the energy industry wants to have the battery… Maybe it's a bit hard to find out where these objectives meet?" – Adrienne (energy retailer) [1].*

This report analyses in quantitative terms how EVs can trade off transport and grid needs. It uses modelling and optimisation to understand the influence of different vehicle use cases and adds fidelity to the qualitative findings previously made in the business models [1] and social science [2] reports. These previous reports tell us *what*. This report adds *how much* to the discussion.

This report understands V2G from the point of view of three groups of customers, shown in Table 3. These customer groups have been sourced from the business models report, *Creating value from V2G* [1] which also describes the different needs that these types of customers have. The way customer needs have been translated into the optimisation model is described further in Appendix A.

Table 3 Customer groups [1]

Customer Group	Description
EV owners	People or organisations who own or drive EVs. Many of these people are also energy bill payers, although not necessarily.
Grid operators	Stakeholders who manage the technical performance of the power system.
Market participants	Stakeholders who are responsible for buying and selling energy and other grid services.

Chapter 2 will describe the research questions, the scenarios modelled in answering them, and the limitations of the modelling. The modelling inputs are also described in more detail in Appendix A. Next, chapter 3 presents the results in detail, set out by research question covering economic impact, environmental impact, end user preferences, grid impacts and implications for grid management. Throughout this chapter key findings are highlighted. Chapter 4 presents the conclusions of the study. It presents three threads for further work: Understanding tension in optimisation, Managing large amounts of flexibility, and the impact of forecasts on value.

2 Questions and Scenarios

2.1 Framing

This study aims to add quantitative context to the findings of the business models [1] and social science [2] reports that were also published as part of this project. These reports provide in-depth qualitative perspectives of the needs, desires, fears, and expectations of EV drivers and industry stakeholders. They present end user and stakeholder ideas and priorities about the future of V2G and what should be considered as the technology is developed.

Table 4 summarises the key themes raised in the earlier reports, adapted into questions. The table presents these in terms of the most interested customer group determined from our qualitative work. As a developing technology in a rapidly changing landscape, we expect however that our findings will be of broad interest.

Table 4 Themes and questions

Theme	Customer group	Questions
What is the value of V2G?	**EV Owners**	How will V2G impact energy costs? What is the energy cost of EV charging? What are the critical factors that drive value?
	Market Participants	How will V2G impact the cost of supplying customers? Which EV use cases are best suited to V2G?
What is the environmental impact of V2G?	**EV Owners**	What is the emissions impact of V2G? How does V2G impact self-consumption of photovoltaic (PV) power?
	Market Participants	What is the cost impact of minimising emissions from EV charging?
What is the trade-off between grid value and availability for transport?	**EV Owners**	How does V2G impact battery state of charge? What is the impact of reserving capacity for driving on the value of V2G?
What is the trade-off between emissions reduction, cost and availability for transport?	**EV Owners** **Market Participants**	How do EV owner preferences affect optimisation?
How could EV charging impact load growth?	**Grid Operators**	How will V2G impact load in the future? What tools are most effective at managing V2G's grid impact?
When is V2G economic?	**Market Participants**	When will it begin to be economic to offer V2G products to customers?

2.2 Scenarios

We address these questions using a scenario analysis approach considering a variety of bidirectional charging models, levels of EV owner conservatism, pricing structures, value streams, and optimisation targets.

The optimisation used four types of charging, shown in Table 5. These define how EVs will be charged and discharged, covering some but not all of the possible configurations as we have outlined in our previous report [3]. There were also three optimisation targets considered, shown in

Table 6. These define what the optimisation aims to achieve and are discussed further in Appendix A.3.1. The shorthand names that are used to refer to these target/charge method combinations are shown in Table 7.

Table 5 Charging types

Charge type	Description
V0G Convenience	EVs are charged at full power immediately on plugging in. No discharge.
V0G Timer	EVs are charged at full power but only during the "off peak" period (10PM-7AM in the Actewagl tariff used in the "current pricing" optimisation method). No discharge.
V1G	EV charging is optimised to best maximise the target and meet driving energy requirements. No discharge.
V2G	EVs charge and discharge to best maximise the target and meet driving energy requirements.

Table 6 Optimisation target types

Optimisation target	Description
Current pricing	Customers optimise for lowest cost against an existing retail price, assigned based on the customer class: • Houses are assigned the "ActewAGL Home Time of Use" tariff. • Offices are assigned the "ActewAGL LV TOU demand" tariff.
Dynamic pricing	Customers optimise for lowest cost against a dynamic retail price. Dynamic pricing builds a price signal that reveals the underlying nature of price drivers. It is split into two components: • A network price, based on the Evoenergy "smart battery" tariff. • A market price which is directly passed through for consumption, reduced by 10% for feed in.
Emissions	Customers optimise for lowest emissions. Marginal emissions for NSW1 region of the NEM is used as a dynamic price signal.

Table 7 Shorthand names for simulated charge types and optimisation targets

	Current	**Dynamic**	**Emissions**
V0G Convenience	V0G Convenience, Current,	V0G Convenience, Dynamic	V0G Convenience, Emissions
V0G Timer	V0G Timer, Current	V0G Timer, Dynamic	V0G Timer, Emissions
V1G	V1G, Current	V1G, Dynamic	V1G, Emissions
V2G	V2G, Current	V2G, Dynamic	V2G, Emissions

Additional to these scenarios, the impact of EV owners reserving capacity in their batteries is investigated using the conservatism parameter. Three levels of conservatism are investigated, described in Table 8. This optimisation maintains the battery capacity above this reserve reducing the capacity available for meeting the optimisation target. These values were selected to explore the impact of conservatism on the value of V2G. It does not necessarily reflect the expectations of any customer group.

Table 8 Conservatism levels

Conservatism level	**Description**
None	The optimiser charges vehicles for known trips or if it's needed to best meet the optimisation target. All results that do not specifically note a conservation level are for free battery use.
50%	50% of the battery's capacity is reserved for driving. This is around 135 km range in a 40 kWh Nissan Leaf.
90%	90% of the battery's capacity is reserved for driving. This is around 243 km range in a 40 kWh Nissan Leaf.

These three parameters are combined to create the study scenarios shown in Table 9.

Table 9 Study Scenarios

Scenario		**Charge method**	**Price**	**State of charge constraint**
V0G	V0G	Convenience	N/A	N/A
	V0G Timer	Convenience off/peak only	Current (used to schedule off-peak)	N/A

Scenario		Charge method	Price	State of charge constraint
V1G	V1G, Current, 0%	Managed	Current	None
	V1G, Current, 50%	Managed	Current	50%
	V1G, Current, 90%	Managed	Current	90%
	V1G, Dynamic, 0%	Managed	Dynamic	None
	V1G, Dynamic, 50%	Managed	Dynamic	50%
	V1G, Dynamic, 90%	Managed	Dynamic	90%
V2G	V2G, Current, 0%	Bidirectional	Current	None
	V2G, Current, 50%	Bidirectional	Current	50%
	V2G, Current, 90%	Bidirectional	Current	90%
	V2G, Dynamic, 0%	Bidirectional	Dynamic	None
	V2G, Dynamic, 50%	Bidirectional	Dynamic	50%
	V2G, Dynamic, 90%	Bidirectional	Dynamic	90%
	V2G, Emissions, 0%	Bidirectional	Emissions	None
	V2G, Emissions, 50%	Bidirectional	Emissions	50%
	V2G, Emissions, 90%	Bidirectional	Emissions	90%

All optimisations were performed on one scenario, built as per the process explained in Appendix A. This scenario included 298 EVs spread between 30 houses and 20 office buildings, shown in Table 10. The numbers of EVs are intended to reflect a future where all vehicles are electric, but with similar rates of vehicle ownership as present. The average daily energy consumption listed in the table does not include energy consumption from charging the EVs.

For simplicity, all results (except for those used to build the forecasts in section 3.5) assumed that all of the houses and office buildings have PV. Obviously, this is not necessarily realistic, but was done in order to simplify the presentation of results. Results for buildings without PV are available in the summary spreadsheet published with this report.

Data for this scenario was sourced and processed as per Appendix A.

Table 10 Scenario customers

id	Type	Average daily consumption (kWh)	Number of EVs	Size of PV array (kW)
resi01	house	13	2	8.1
resi02	house	18	2	7.6
resi03	house	35	1	8.8
resi04	house	10	2	4.9
resi05	house	28	1	8.0
resi06	house	27	1	8.8
resi07	house	15	2	4.0
resi08	house	25	2	7.7
resi09	house	16	1	6.8
resi10	house	50	2	3.0
resi11	house	17	2	5.7
resi12	house	22	1	5.6
resi13	house	53	1	3.1
resi14	house	36	1	9.0

id	Type	Average daily consumption (kWh)	Number of EVs	Size of PV array (kW)
resi15	house	36	2	4.5
resi16	house	16	1	7.6
resi17	house	32	2	9.0
resi18	house	30	2	8.4
resi19	house	13	2	7.1
resi20	house	21	2	9.6
resi21	house	29	2	2.6
resi22	house	35	2	2.4
resi23	house	33	2	9.6
resi24	house	35	2	7.6
resi25	house	18	1	2.8
resi26	house	24	1	4.0
resi27	house	29	2	8.3
resi28	house	26	2	9.9
resi29	house	35	1	5.6
resi30	house	14	1	6.0
office01	office	1625	7	56.9
office02	office	1101	14	20.9
office03	office	906	9	9.3
office04	office	2121	8	15.9
office05	office	1564	6	22.6
office06	office	1067	22	15.0
office07	office	2326	19	45.0
office08	office	271	4	16.9
office09	office	374	5	15.3
office10	office	372	8	7.8
office11	office	615	15	26.2
office12	office	1514	14	57.5
office13	office	829	7	34.1
office14	office	997	7	51.1
office15	office	1548	8	51.7
office16	office	1511	21	84.2
office17	office	809	13	52.7
office18	office	1734	25	66.2
office19	office	973	21	31.0
office20	office	455	17	37.4

2.3 Data and limitations

The results in this report must be taken in context of its source data and limitations. These are described in Table 11.

Table 11 Factors to consider in understanding results

Factor	Meaning
Source data	The "house" and "office" data was collected differently. The main impact of this is that house data reflects much shorter EV plug-in times than offices. This impacts the resulting value of each use case. Offices show a much greater benefit to V2G than houses. It is likely that if residential EV owners had V2G they would plug in more often, and indeed this may be a condition of a V2G contract, but there was no data available to reflect this difference. **Impact**: Differences in houses and offices are not necessarily representative of an inherent difference in value.
Price signals	Price signals used in this study are sourced from either 2019 market data or current and trial tariffs from Evoenergy and ActewAGL. FCAS data is taken for the NSW1 region in 2019. As the energy system evolves it is likely these will change. In particular, changes such as a capacity mechanism could dramatically alter market price outcomes. Similarly, some grid management issues revealed in this study may be resolved as networks evolve their pricing. This report forms part of the evidence base for future changes. **Impact**: Results and issues revealed in this study serve as indications of what might happen if current pricing and mechanisms continue. New studies may be required as the energy system evolves.
Foresight	This study used "perfect foresight" of future prices and vehicle usage, which is unrealistic in real world applications. It is hence likely the real world benefit of V2G is overestimated. Similarly the ability to co-optimise transport and energy system needs will reduce because not all trips can be forecast. **Impact**: The benefits shown in this study should be taken as an upper limit (taking into account all assumptions).
Conservatism	Conservatism is used as an indicator of how EV owners may require their batteries operated if they want to preference driving. This is not necessarily an indicator of a strategy that would preserve battery health. Battery health was not directly considered in this study. **Impact**: Optimising for battery health would give different (not necessarily of greater or lower benefit) results than optimising for conservatism.

Factor	Meaning
Emissions	The emissions intensity of grid electricity is simply determined from the power coming from each generator at a given moment and their overall emissions intensity. In contrast, the emissions impact of an additional flexibility resource on the grid (such as V2G charge/discharge) can be assessed using a variety of approaches. These include considering: • The **average emissions** of all generators currently generating at the time; or • The **marginal emissions** created by the price-setting generator that, in theory, will need to change its output in response to small changes in consumption. For this study, it was assumed that the actions of V2G would primarily impact the marginal generator. This assumption is correct while there is a relatively small amount of capacity and the overall generation mix and its economic signals have not changed. This choice represents the short-term impacts of charging based on current (2019) energy market. The average emissions approach may also have merit as it can be argued that bolstering demand at moments of high RE generation will positively effect confidence in developing further RE generation capacity. The purpose of including the emissions optimisation was to investigate how different the behaviour of EVs that aim to minimise emissions is to those that aim to minimise cost. **Impact**: Emissions optimisation results indicate how V2G can reduce emissions, but it is not the only way emissions can be measured.

3 Results

3.1 What is the value of V2G?

EV charging will impact total energy costs, and with the inclusion of V2G it is possible that the cost is negative because V2G has produced earnings. The average total energy costs per EV based on current pricing and dynamic pricing is shown in Figure 1 and Figure 2 respectively. These results clearly show a differing value proposition for houses and offices. For offices with V2G, the contribution of each EV to total energy costs is negative. This means that adding vehicles with V2G is an overall energy cost reduction. The same is not true for houses, where the charging of EVs always results in higher overall energy costs. While the tariffs and consumption profiles are different for houses and offices, the difference can mainly be explained by the different plug in patterns. As described in Appendix A, EVs at offices are plugged in for much longer times than EVs at houses, which gives V2G a much greater opportunity to deliver value.

This results in the first key finding for this study, shown in Finding 1.

Finding 1: The length of time vehicles are plugged into chargers is a critical determinant of V2G value

EV owners **Market Participants**	***The value that V2G services can produce is highly dependent on the length of time vehicles are plugged in to chargers. If plug-in times are sufficiently high, the impact of V2G can be so great as to make the cost of adding EVs to a site negative.***

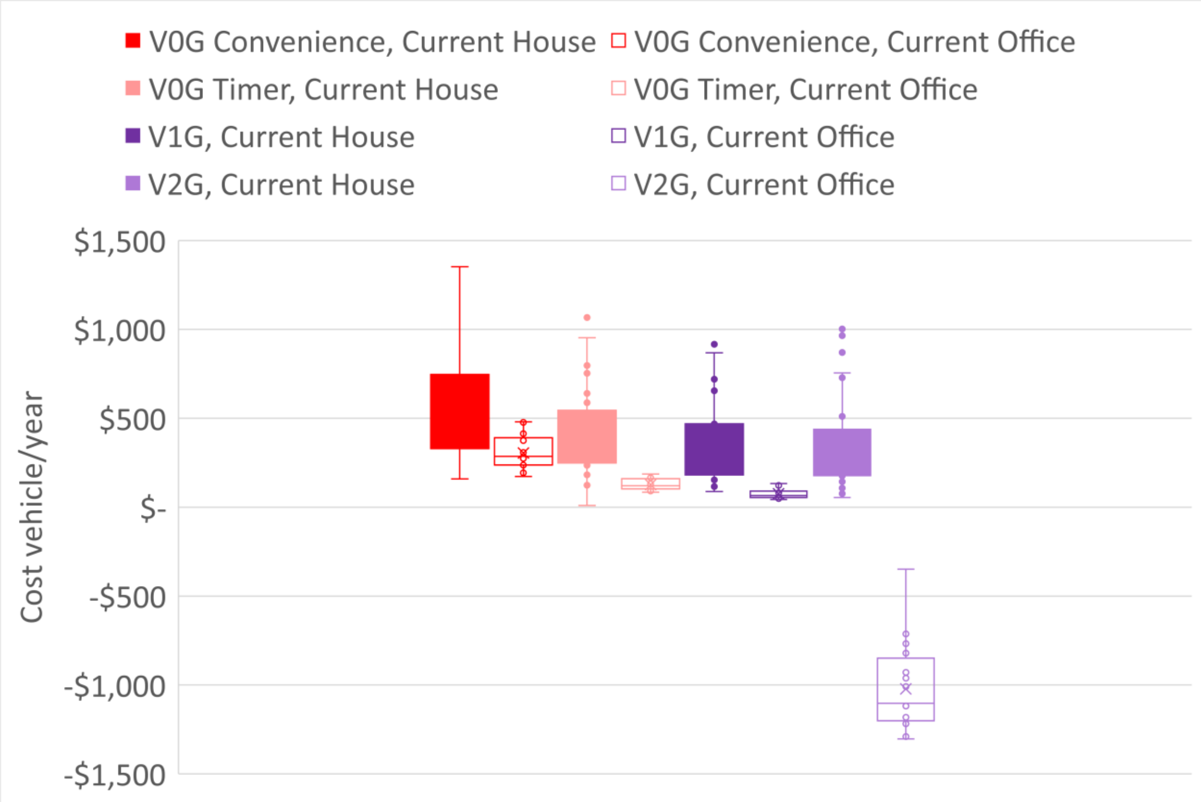


Figure 1 With current prices and without FCAS revenue, per EV charging cost varies between $1,353 (V0G, 'resi06' customer) and -$1,303 (V2G, 'office04' customer)

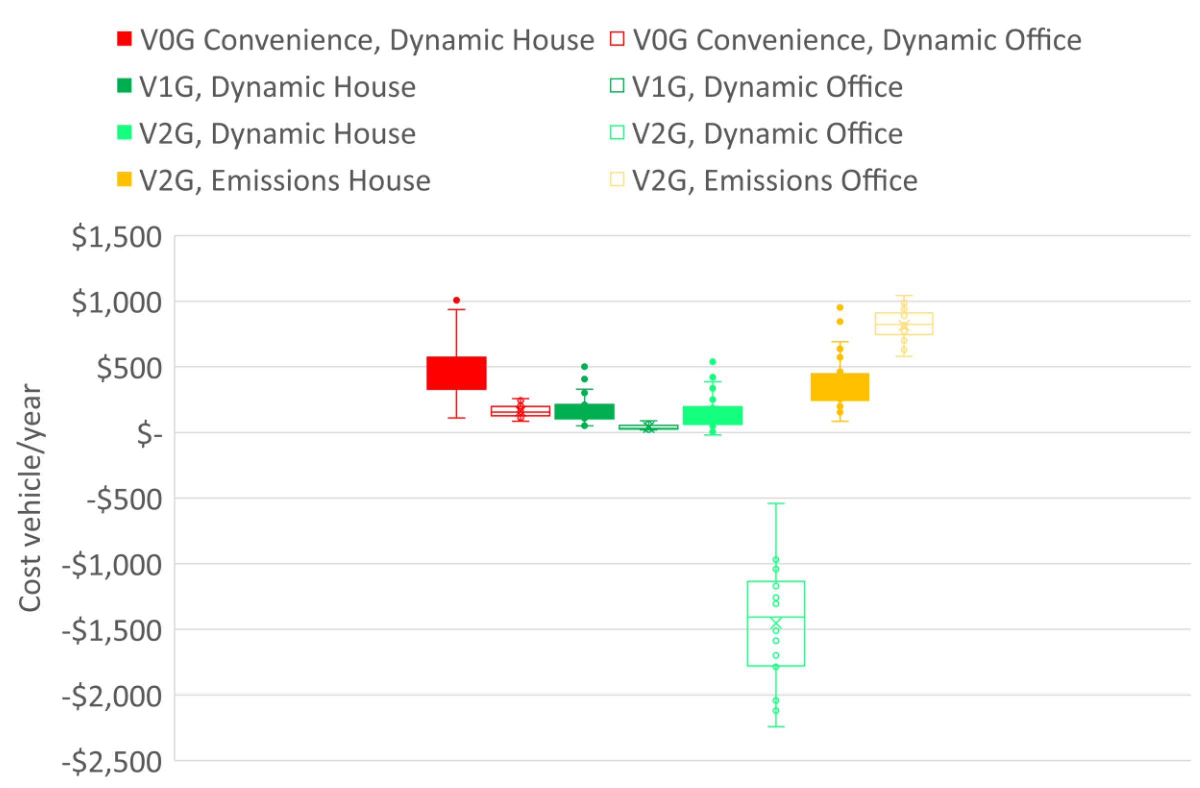


Figure 2 With dynamic prices and without FCAS revenue, per EV charging cost varies between $1,043 (V2G emissions, 'office05' customer) and -$2,241 (V2G dynamic, 'office04' customer)

Frequency control services (FCAS) increase the value proposition significantly. This can be seen in Figure 3, which compares V1G and V2G and current and dynamic pricing. The per-EV integration costs are negative for most V2G cases apart from some outliers in in the existing tariff/house case. In recent times FCAS has been highly valuable (as shown in Figure 4) which has led to strong returns for devices which can provide these services. V1G produces less benefit from V2G because the capability to provide services is much lower.

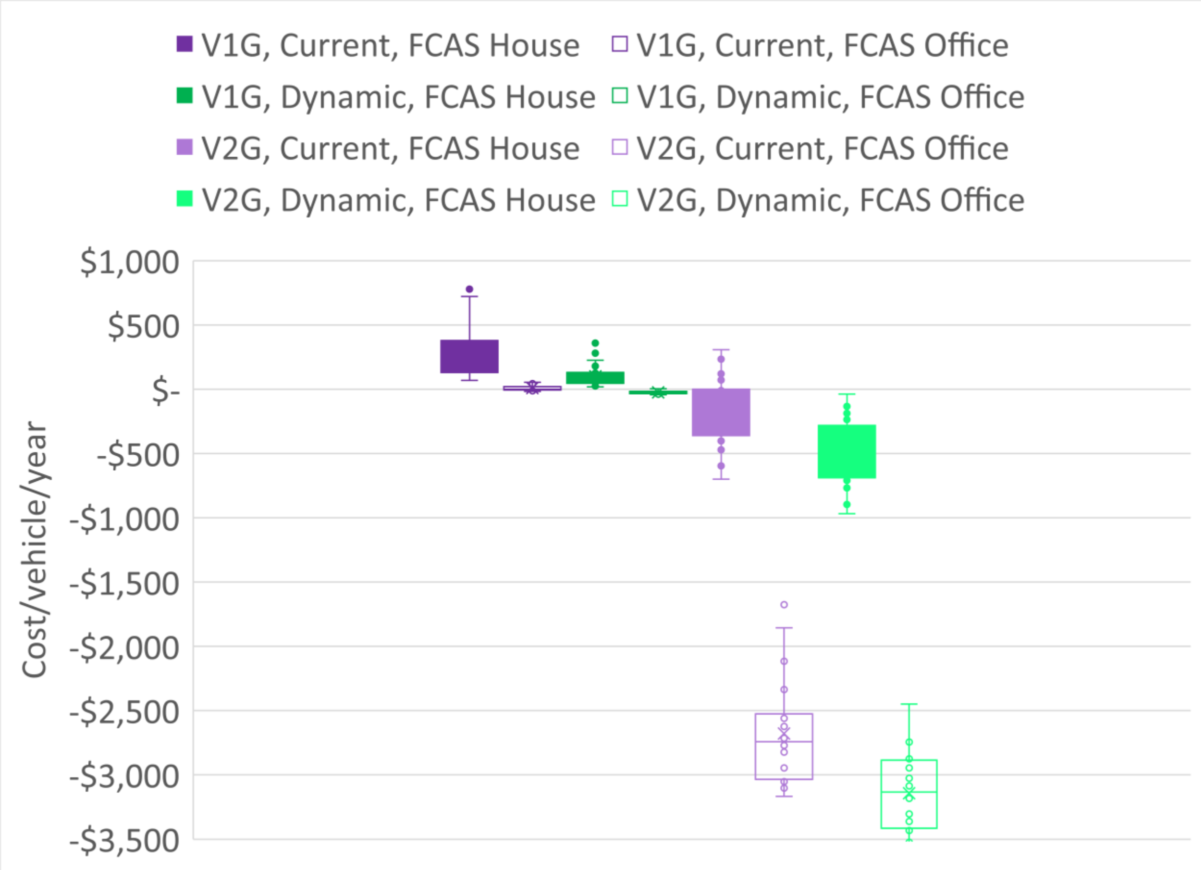


Figure 3 Per EV change in total energy costs (including FCAS) for V1G and V2G, current and dynamic prices. When FCAS is included, per EV charging cost reduces to between $779 (V1G current, 'resi07' customer) and -$3,744 (V2G dynamic, 'office04' customer)

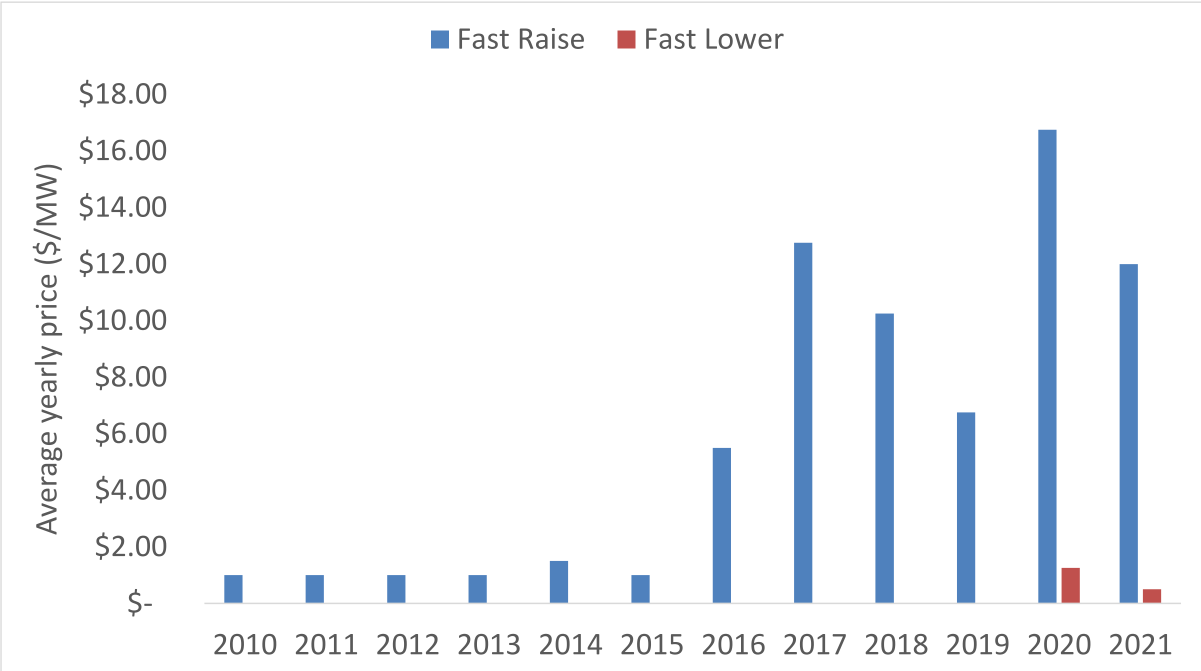


Figure 4 Average FCAS fast services prices in recent years. The average price of FCAS fast services (particularly raise) has increased in recent years from $1.00/MW in 2010, to $16.85.MW in 2020

The value results presented so far are obtained from different value components within the optimisation signal. There are seven components considered here, shown in Table 12. The contribution of these components to the overall price is shown in Figure 5 for V1G and Figure 6 for V2G. For V2G, FCAS is a very significant contributor to the overall value, contributing half to two-thirds of the total value. There is a relatively even split between most other streams: demand, network tariff arbitrage, and market value streams. Feed-in response has only a minor contribution to overall value. These findings are summarised in Finding 2.

Table 12 Components of value

Component	Description
Demand charges	Demand charges are based on the maximum energy consumption in any 30-minute interval during the period. These are part of the network tariff.
Peak energy	Energy consumed during the highest priced periods of the network tariff.
Non-peak energy	Energy consumed during periods other than peaks in the network tariff (off-peak, shoulder, and solar sponge).
Market price	Energy charges or revenue from feed-in for market price.
Network feed-in	Feed in charges and revenue as part of the network tariff.
FCAS raise	Revenue from FCAS raise services (fast, slow, and delayed).
FCAS lower	Revenue from FCAS lower services (fast, slow, and delayed).

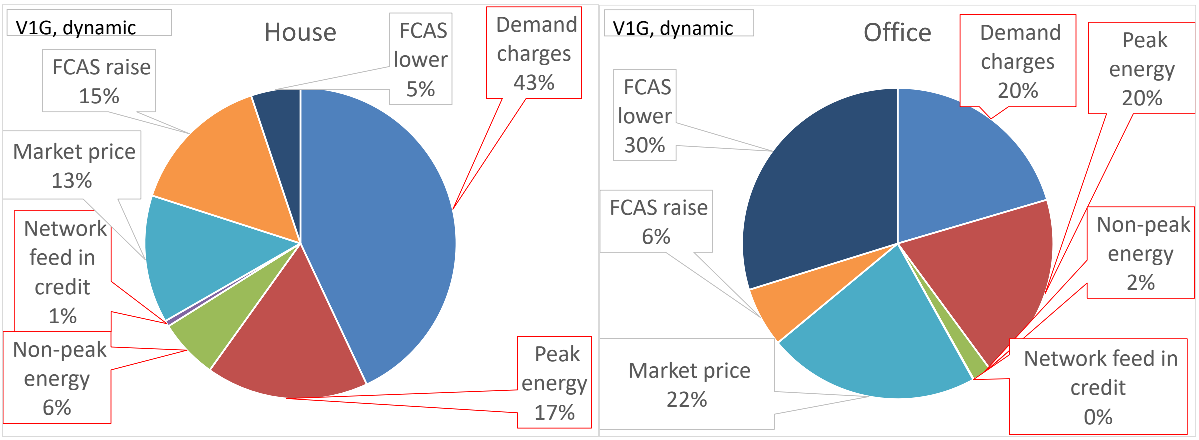


Figure 5 Contribution of components to total benefit (V1G, dynamic price). Demand charges make up a significant part of benefit for V1G, dynamic price scenario with FCAS and peak/market energy as significant contributors. Network tariff components are in red.

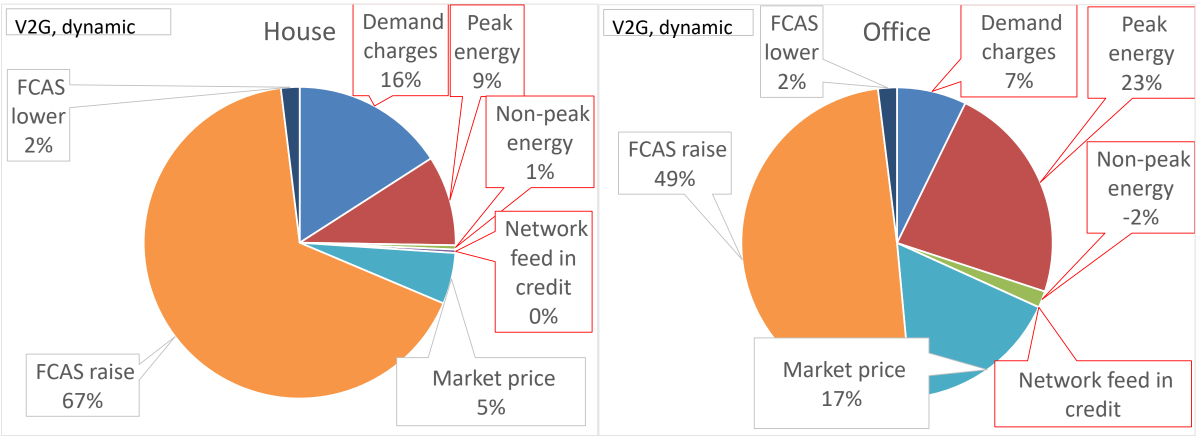


Figure 6 Contribution of elements to total benefit (V2G, dynamic price). FCAS makes up a significant part of benefit for V2G, dynamic price scenario with demand and peak/market energy are also significant contributors. Network tariff components are in red.

Finding 2: FCAS revenue is the dominant component of the V2G value stack – under current market conditions

EV owners	***Demand and energy price arbitrage offer opportunities for significant benefit for V1G and V2G. Feed-in rebates or charges have minimal value.*** ***If the technical requirements can be met, FCAS is a valuable service that can significantly contribute to the overall value stack. This is even the case for V1G, which can stop/decrease charging to contribute to raising the frequency and can start/increase charging to lower the frequency.***
Market participants	

The figures presented so far are in per vehicle terms. However, measuring costs and benefits in per unit of “fuel” (energy) may make more sense for some end users. The results for this are shown in Figure 7 (current price) and Figure 8 (dynamic price, including emissions target). The results align with those shown above for each vehicle. V2G can result in a negative fuel cost, as it can deliver overall cost reductions to the site. Even simple timers can reduce charge cost by around half.

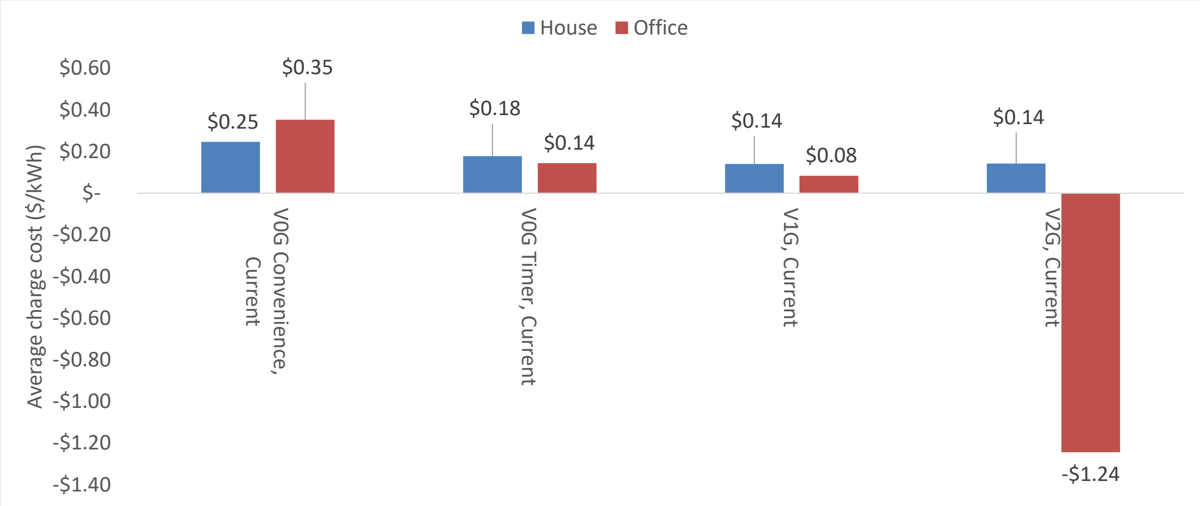


Figure 7 Equivalent energy cost for EV charging with current tariffs and no FCAS ($/kWh) is highest for convenience charging, particularly offices. Dynamic charging makes cost negative, particularly with the high plug-in rates of offices. V2G doesn't benefit houses

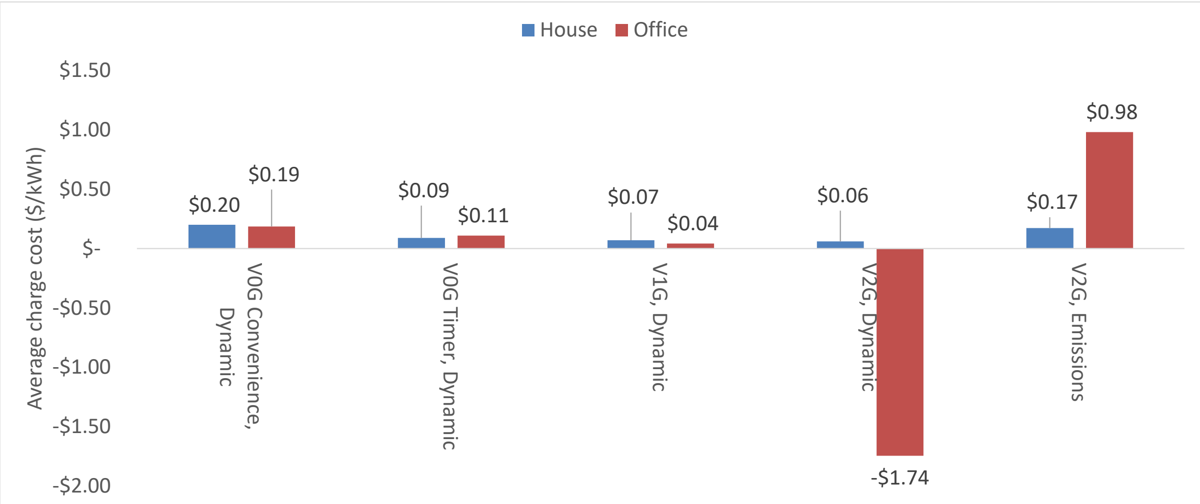


Figure 8 Equivalent energy cost for EV charging with dynamic tariffs and no FCAS ($/kWh) shows highest cost by far for emissions optimisation.

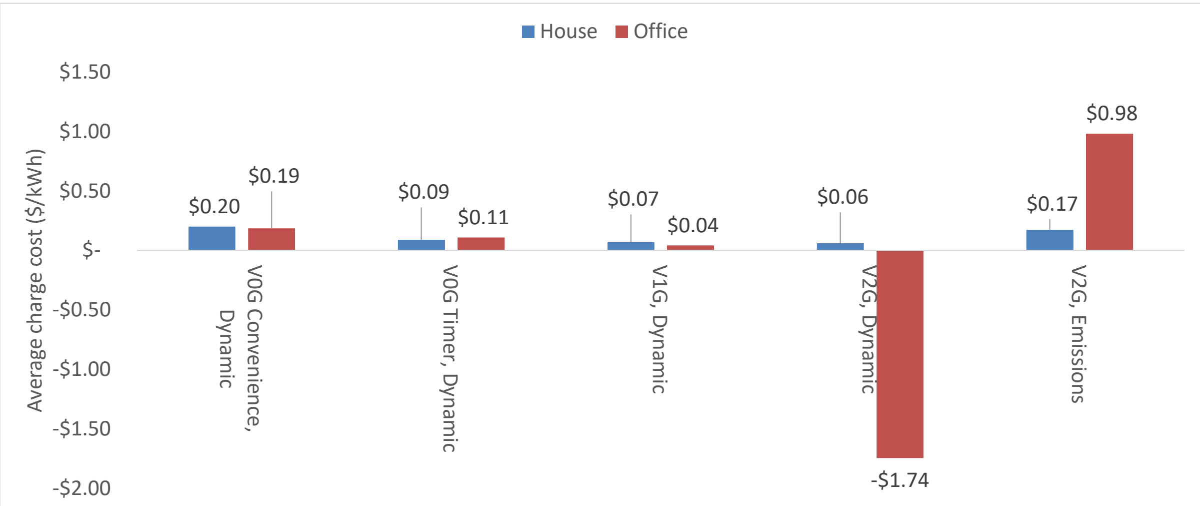


Figure 8 illustrates that emissions reduction is a different target to cost saving. In fact, the targets may incentivise conflicting behaviour, at least with the current generation mix in the electricity system and with our approach to estimating emissions. Optimising for lower emissions usually causes a cost increase compared to convenience charging. This is discussed in further detail in section 3.2; for now, we highlight how these results serve as note of caution to organisations intending to sell V2G or optimisation services.

In our earlier qualitative work, EV owners were concerned about the impact of V2G on battery state of charge and hence the availability of the vehicle for driving. This will be discussed further in 3.3, but this section shows the impact of conservatism on total vehicle charge costs in Figure 9 (No FCAS) and Figure 10 (Including FCAS). Particularly when FCAS is not included, high levels of conservatism dramatically reduce the value of V2G. This reflects the inherent tension between managing EV batteries for driving purposes and for grid participation purposes. However, there may be a common ground. With 50% conservatism there is still significant value to V2G. This shows that conservatism doesn't mean that V2G can't deliver value. It simply means that the tension between economic return and conservatism needs to me managed carefully.

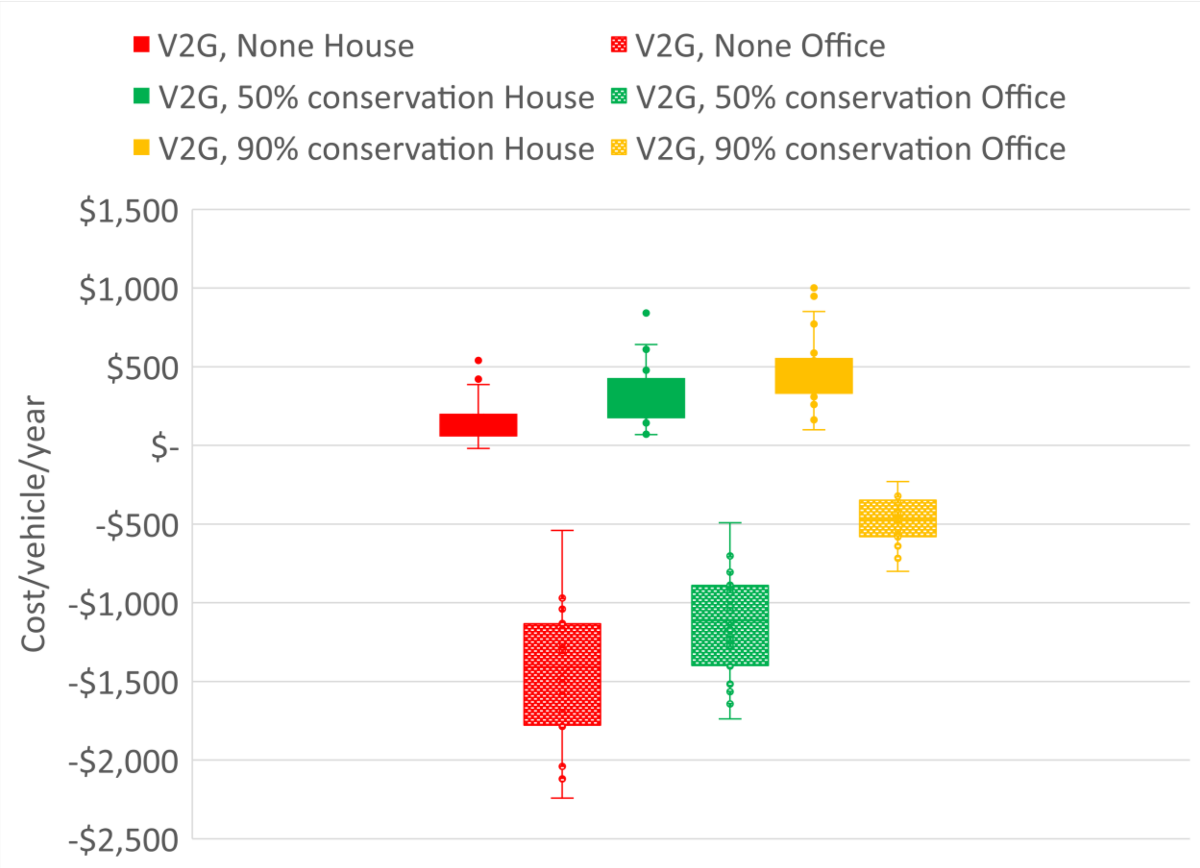


Figure 9 Impact of conservatism on value (dynamic price, no FCAS). Conservatism has a dramatic impact on cost with the office mean cost/vehicle/year increasing by $310/year for offices and 50% conservation and $665/year for 90% conservation

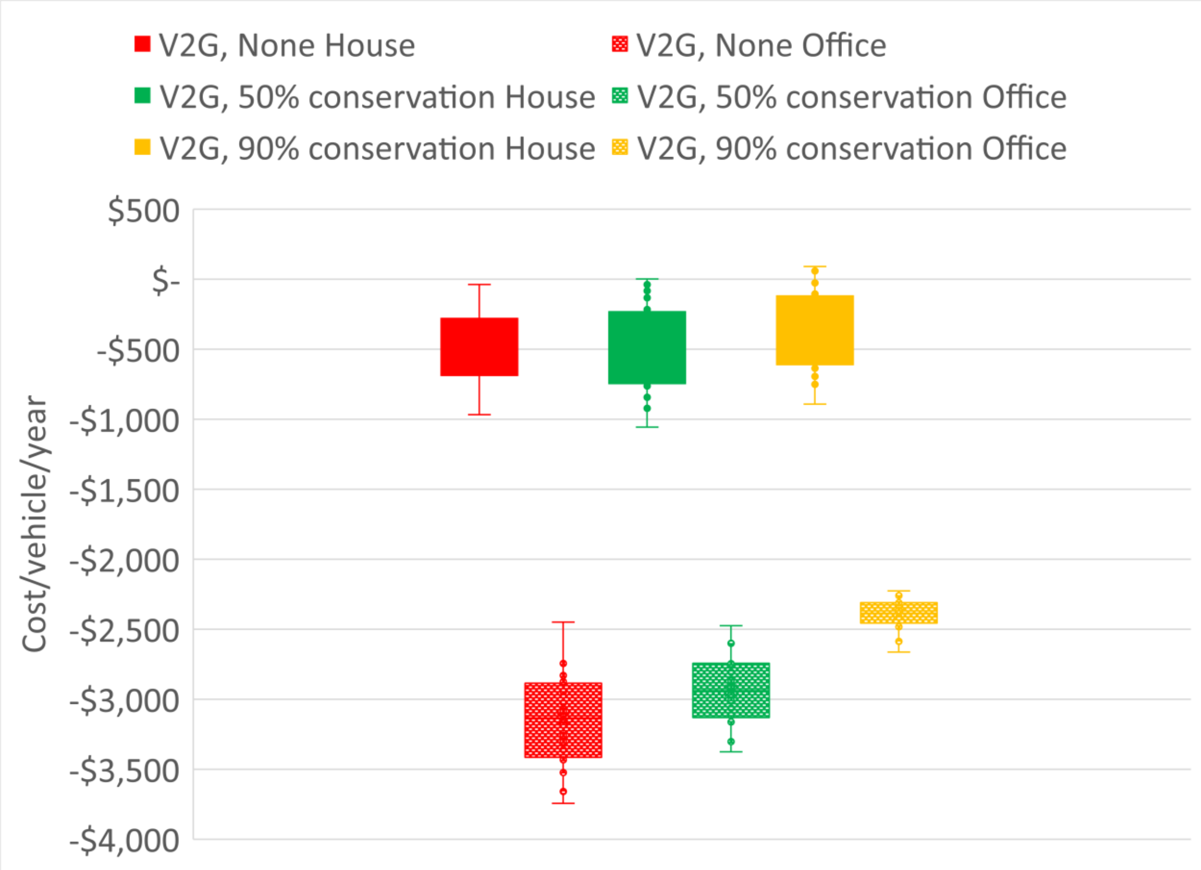


Figure 10 Impact of conservatism on value (dynamic price, including FCAS). FCAS reduces the impact of conservation as it increases the available capacity. The cost/vehicle/year increases by $204 for 50% and $548 for 90% conservation

3.2 What is the environmental impact of V2G?

Electric vehicles are widely marketed as an environmentally conscious choice that will reduce greenhouse gas emissions. The emissions intensity of driving an EV is determined by the emissions intensity of the electricity used to charge it. There are two common sources for electricity used for charging EVs:

- Grid electricity - the emissions intensity of which varies over time, depending on the current generator mix.
- Rooftop solar electricity – zero emissions intensity, but depends on EV charging being coincident with solar generation.

The emissions intensity of grid electricity is simply determined by the proportion of power coming from each generator at a given moment. In contrast, the emissions impact of an additional load on the grid can be assessed using a variety of approaches. These include considering:

- The **average emissions** of all generators currently generating at the time; or
- The **marginal emissions** created by the price setting generator that, in theory, will need to increase its output to provide the additional power for small changes in consumption.

For this study, it was assumed that the use of V2G would primarily impact the marginal generator. This assumption is correct while there is a relatively small amount of capacity and the overall generation mix and its economic signals have not changed. This choice represents the short-term impacts of charging based on the current energy market. The average emissions approach may also have merit as it can be argued that bolstering demand at moments of high renewable energy generation will positively affect confidence in developing further renewable energy generation capacity.

For this study, we use marginal emissions intensity for the NSW1 NEM region in 2019.

The per kWh and per vehicle emissions impact of the different charge optimisation targets are shown in Figure 11 and Figure 12 respectively. These figures clearly show that optimising for emissions can have significant environmental benefit compared to other optimisation targets. Similarly, they show that optimising for price can increase emissions. For houses, most scenarios show a reduction in emissions over the base case of V0G with convenience charging. Although the causes for this have not been investigated in detail, this result is due to the marginal emissions intensity being higher, or solar generation being lower, at the times when vehicles are assumed to be plugged in.

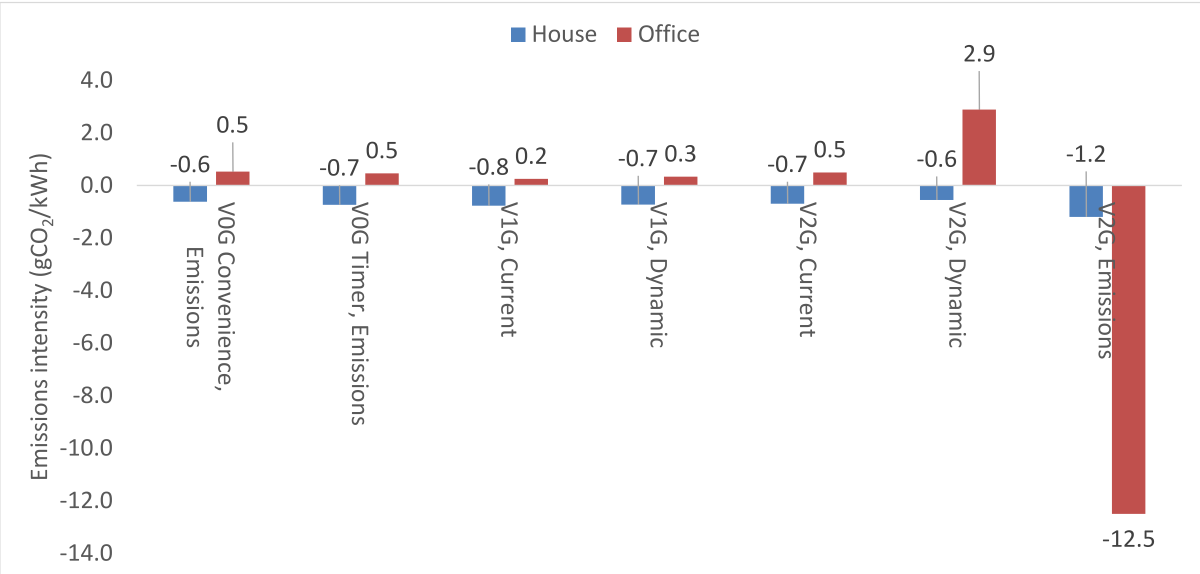


Figure 11 Per kWh emissions impact of EV charging. Emissions performance is the inverse of cost. The dynamic tariff incentivises increasing emissions while emissions pricing incentivises reduction.

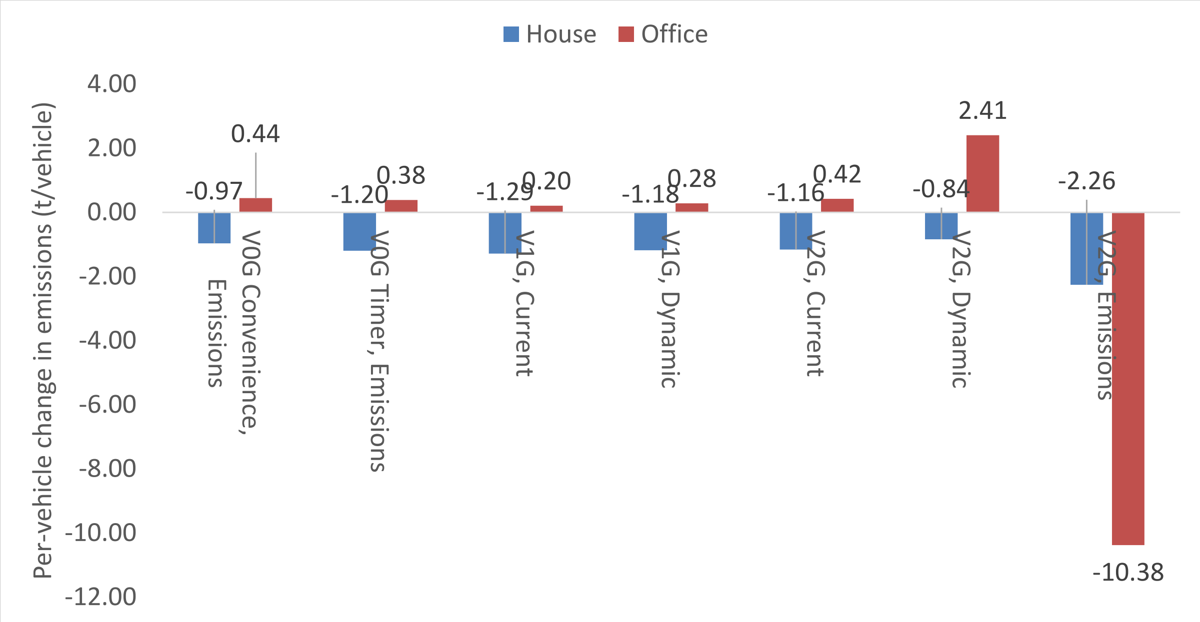


Figure 12 Per-vehicle emissions impact is similar to per kWh emissions shown in previous figure.

In the real world, many EV owners have solar PV. In interviews, participants described V2G as a tool to help EV owners self-consume their own generation, for financial, autonomy and/or environmental reasons. The extent to which this occurs depends on the charge method and what optimisation signal is used to govern charging. In this report we use the metric of self-consumption ratio – the percentage of PV generation that is consumed behind the meter.

The change in self-consumption for different charge methods is shown in Figure 13. From this graph we can see:

- The short, usually night time plug ins for houses using V0G convenience charging hampers self-consumption.
- Offices already self-consume most of their solar generation due to the energy load of running the building. This means that there is little scope for EVs to increase self-consumption.
- Dynamic prices are marginally more effective than the current tariff at encouraging self-consumption.
- Emissions reduction optimisation does not increase self-consumption greatly. This is because in the middle of the day when PV generation is highest, the marginal generator is often high-emissions coal. As a result, the optimal way to reduce emissions is to export PV to the grid rather than self-consume behind the meter.

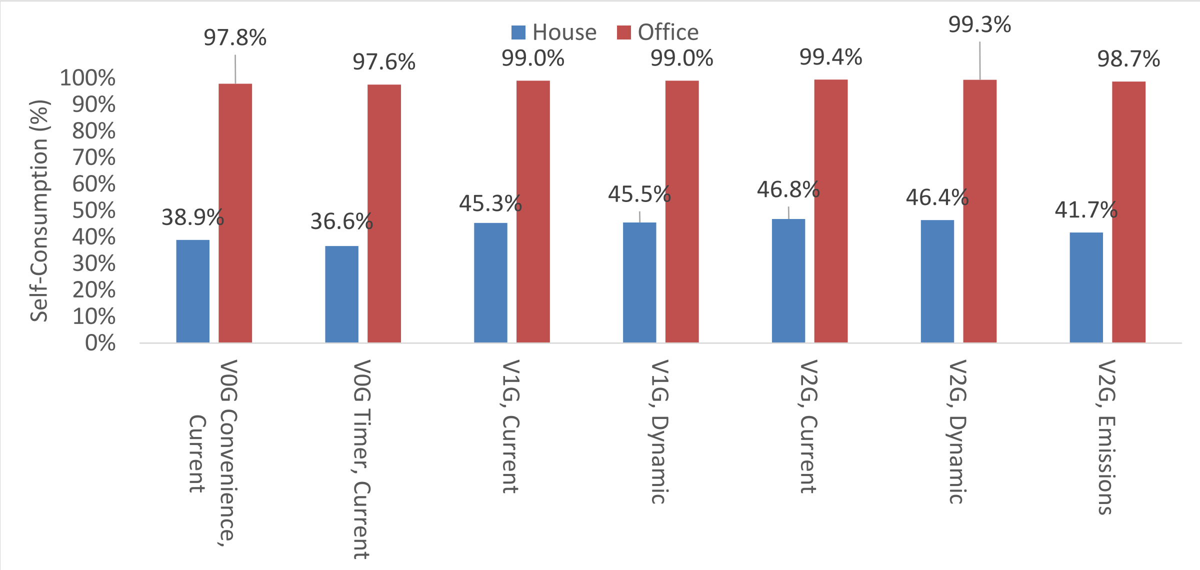


Figure 13 Self-consumption for charge methods

The results for environmental impact, self-consumption and cost are contextual and at times counterintuitive. For the scenarios tested here, reducing grid-wide emissions counterintuitively results in less PV self-consumption, at least when marginal emissions are used as the basis for optimisation. Optimising to minimise price increases self-consumption. Different model assumptions may also change the results. This highlights the need for clear, nuanced communication with respect to stakeholders' expectations and preferences. Offers may be confusing, and end users may be disappointed with unintended consequences of EV charging.

3.3 What is the trade-off between grid value and availability for transport?

EVs are primarily for driving. Although obvious, this point was raised many times in interviews both with drivers and industry representatives. V2G will reduce the average state of charge (and thus range) of EVs because it will at times discharge the vehicle's battery. V1G will similarly reduce the average state of charge by deferring charging. The impact of these can be seen in Figure 14 and Figure 15 for unidirectional charging and Figure 16 and Figure 17 for bidirectional charging (noting that these are only constrained by the model settings; in reality, drivers would be able to set a minimum state of charge).

On average, even V2G maintains state of charge above 30%, but there is no guarantee that this will be the case as can be seen in the 95% certainty traces. For V1G there is no guarantee of energy in an EV's battery. For V2G, a greater state of charge is maintained so that it is available for grid services. As expected, increasing the state of charge target increases average and 95% certainty state of charge as shown in Figure 18. Although for houses it is not possible to meet the charge target because vehicles are rarely plugged in.

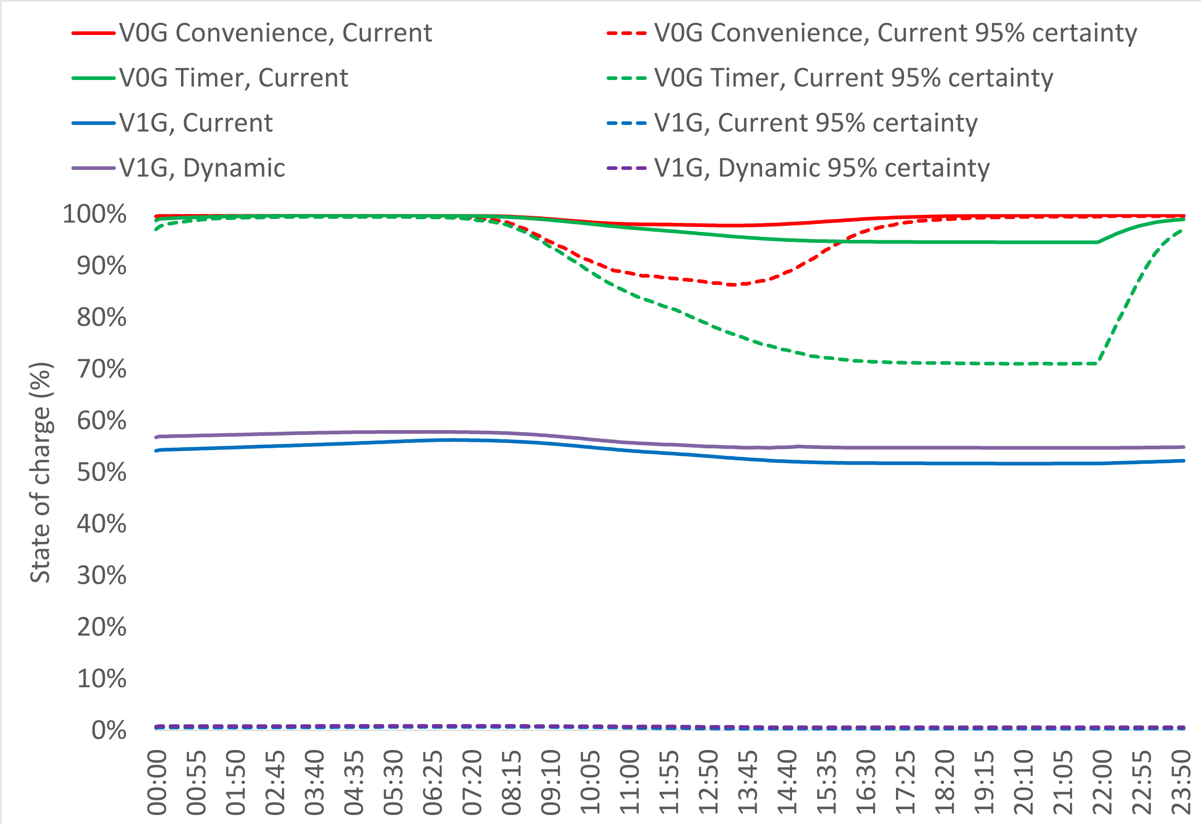


Figure 14 State of charge for unidirectional charging (office). Charge optimisation (V1G) has no guarantees of energy being available for driving

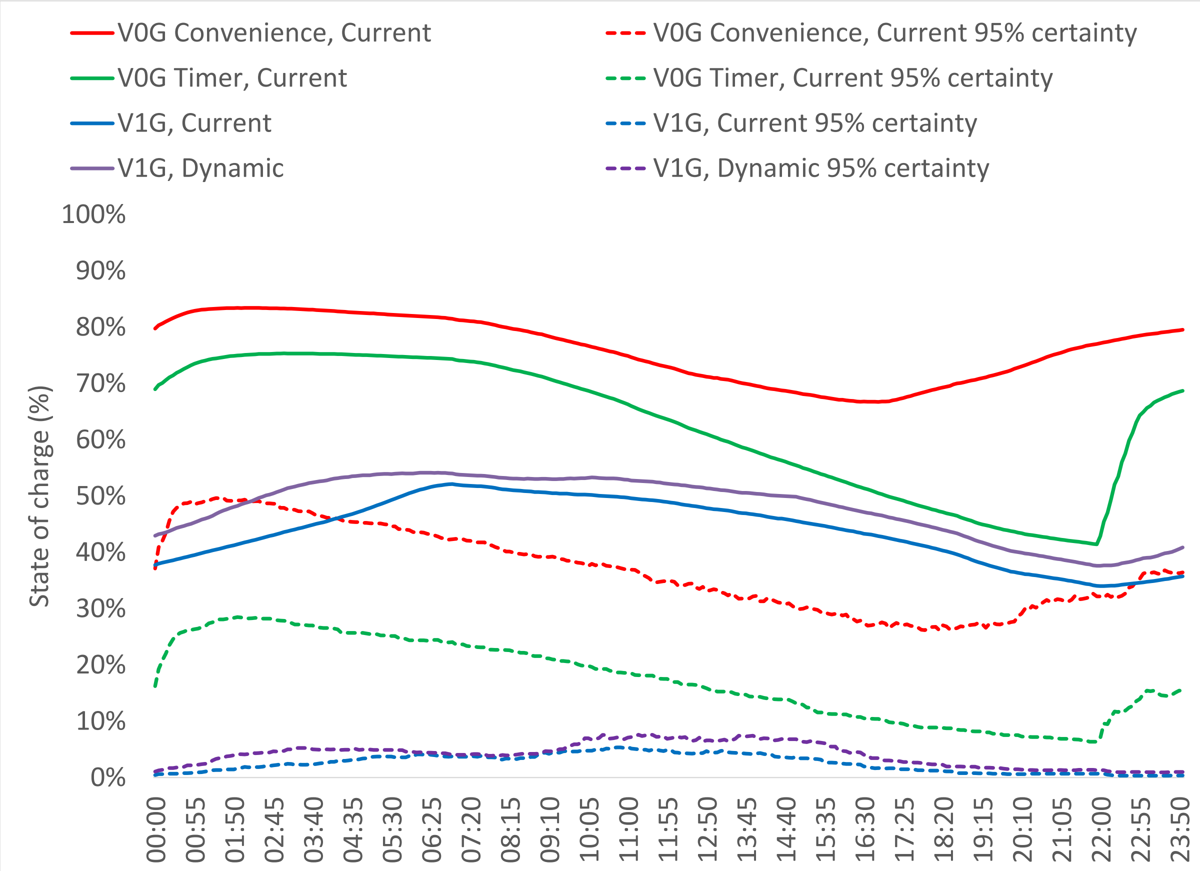


Figure 15 State of charge for unidirectional charging (house). Houses have a slightly higher 95% certain energy level, but it is still less than 10%

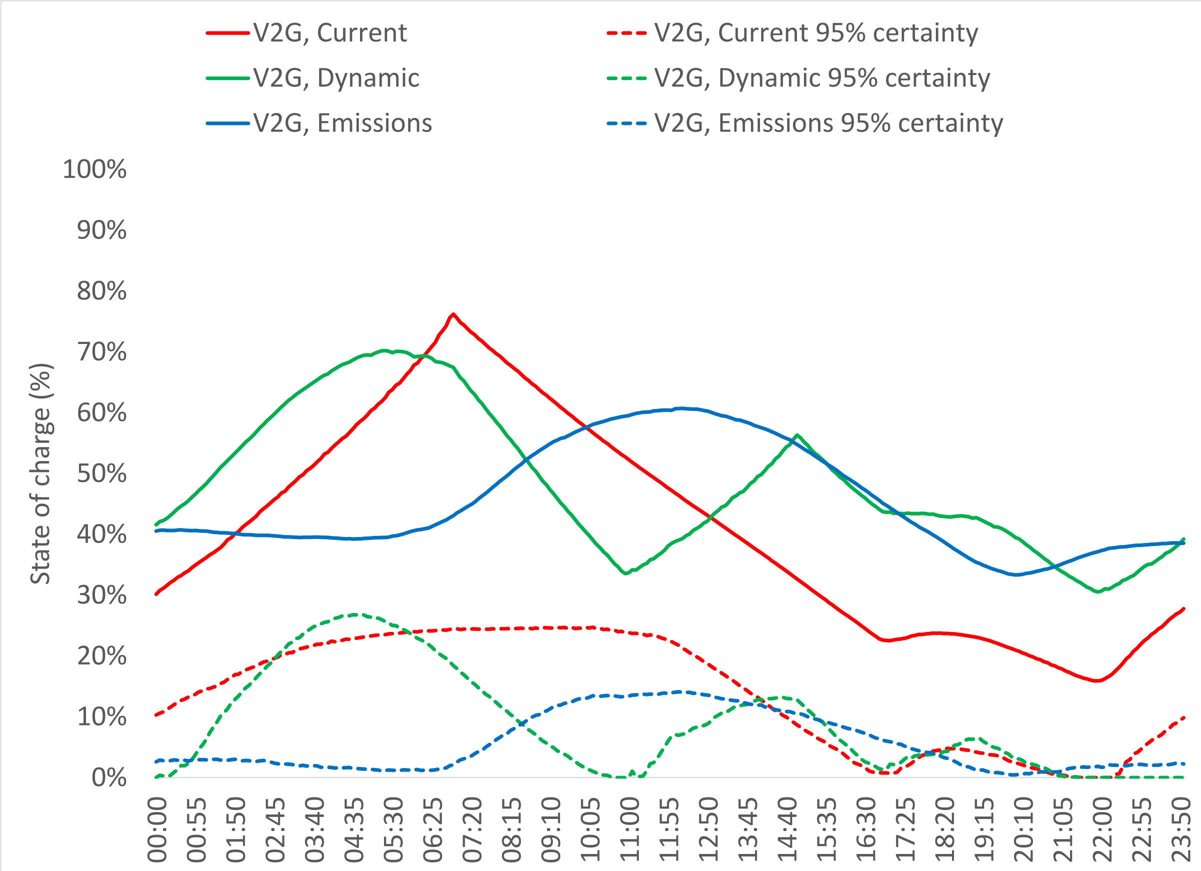


Figure 16 State of charge for bidirectional charging (office.)V2G increases 95% certain state of charge but only to the level needed for cost minimisation

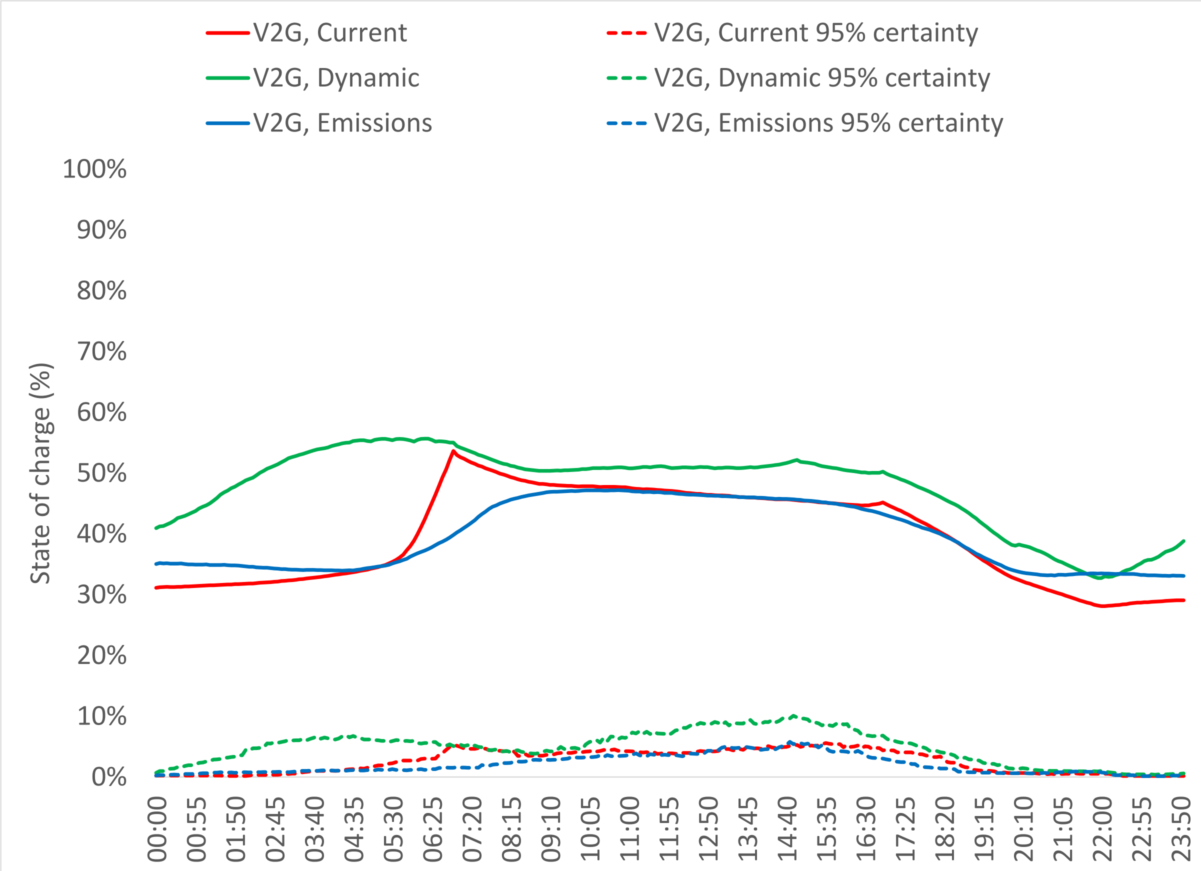


Figure 17 State of charge for bidirectional charging (house). For houses V2G does not appreciably increase 95% certain charge

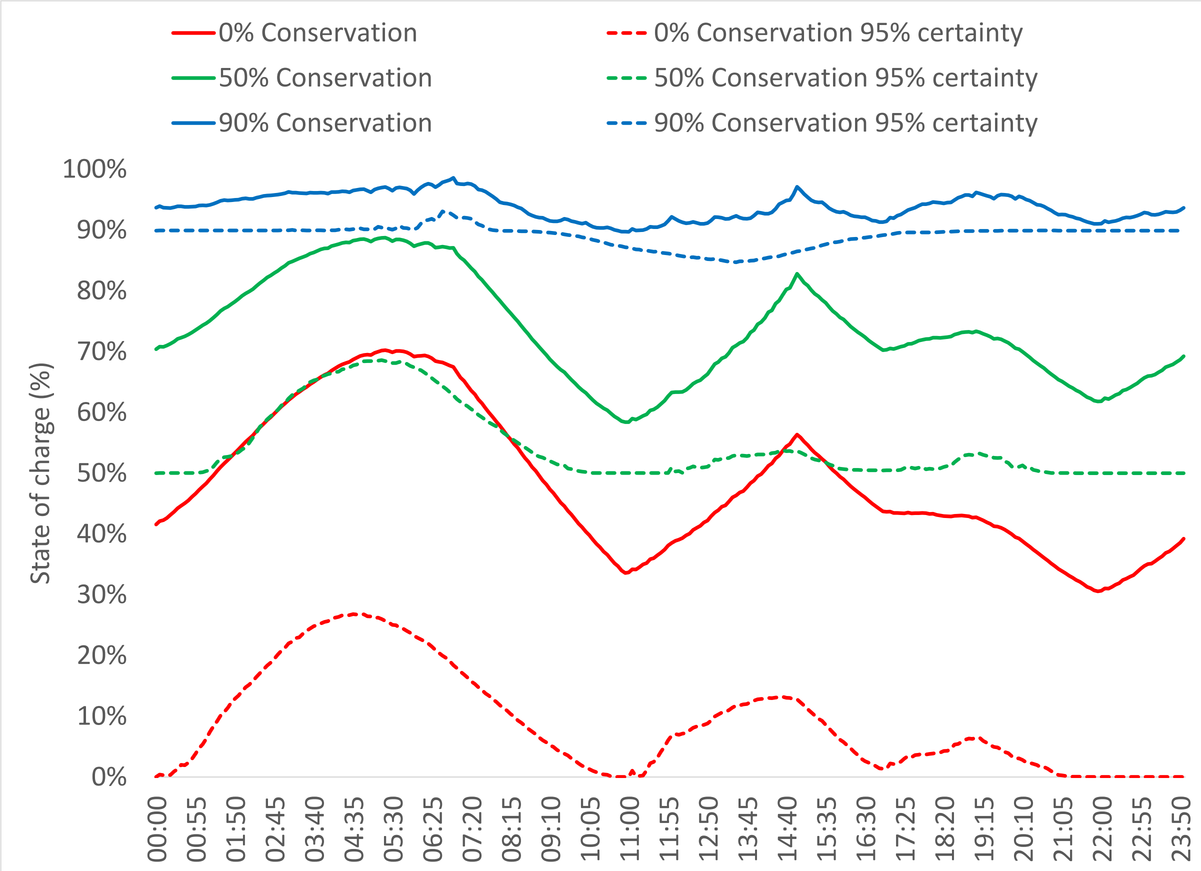


Figure 18 Impact of conservatism on state of charge (bidirectional charging, dynamic target, office). Operating vehicle batteries conservatively is effective at increasing charge levels for office

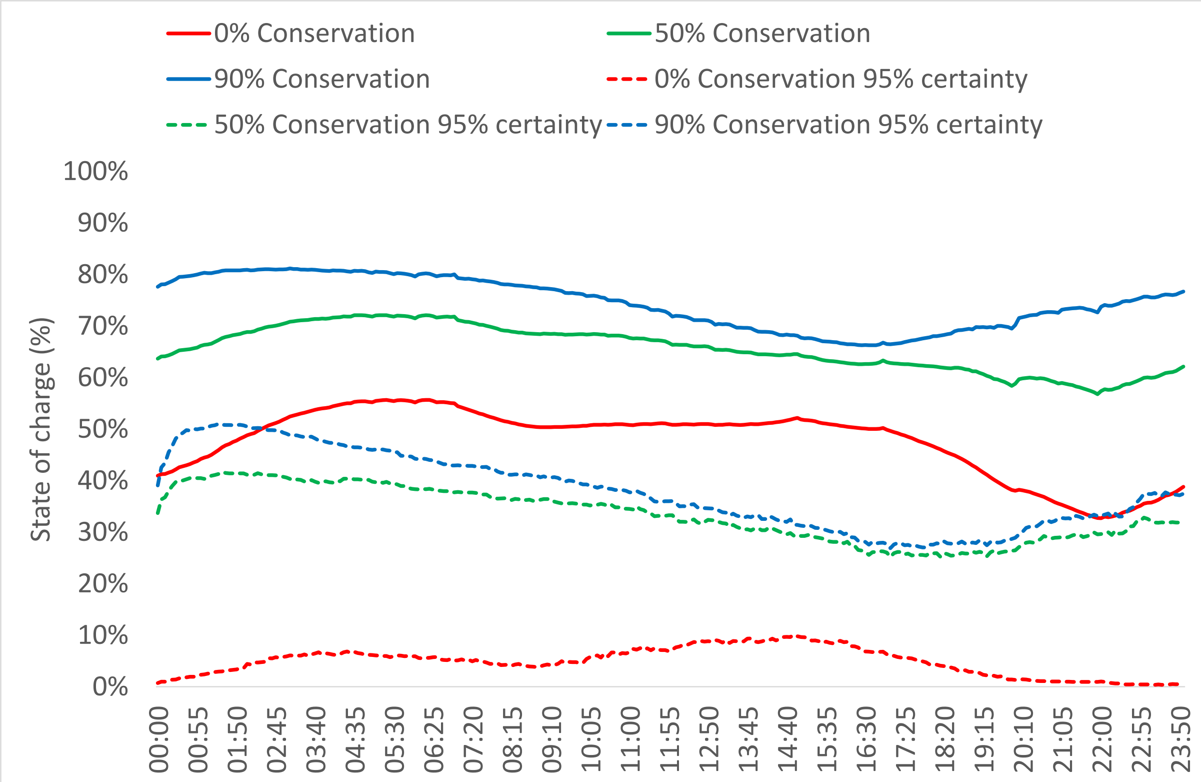


Figure 19 Impact of conservatism on state of charge (bidirectional charging, dynamic target, house). Due to low plug-in rates the desired level of conservation cannot be maintained as well for houses

The increase in average state of charge comes at a cost to other objectives V2G could meet. This is shown in Figure 20 (price) and Figure 21 (emissions). The impact of conservatism on price is by far the most pronounced with 90% conservation reducing value by 66%. In contrast, the same level of conservatism reduces emissions impact by 34%.

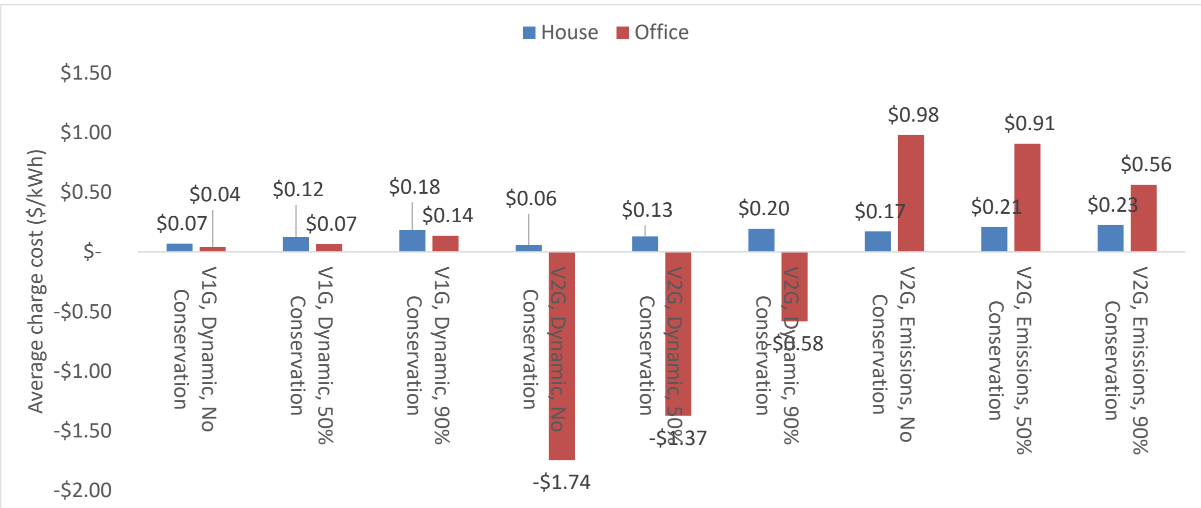


Figure 20 Equivalent energy cost comparison (Dynamic and emission pricing, varying conservation, no FCAS). Operating batteries conservatively brings price closer to convenience charging

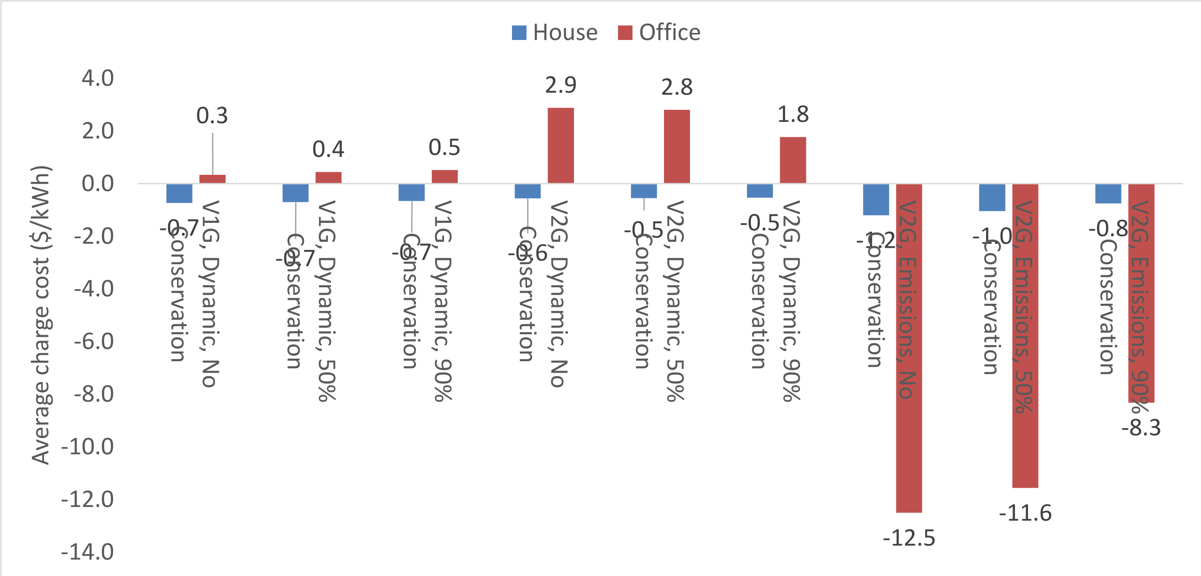


Figure 21 Equivalent emissions comparison (dynamic and emissions pricing, varying conservation, no FCAS). Operating batteries conservatively similarly brings emissions closer to convenience charging levels

Overall though these results are promising, as there is still significant value when drivers are highly conservative. 50% state of charge translates to around 135 km range in a 40 kWh Nissan Leaf and reduces value by 19% for offices and dynamic pricing. 90% conservatism translates to 243 km range. This has a significant impact on value though, reducing value by 80% for offices and dynamic pricing. This leads to Finding 3, described below.

Finding 3: Conservatively operating vehicle batteries still allows significant value from V2G

EV owners	***While reserving capacity in EV batteries reduces value, the value available remains substantial, even with relatively high levels of conservatism.*** ***EV owners will need to consider what setting is appropriate for their use case and value drivers.***

3.4 What is the trade-off between emissions reduction, cost and availability for transport?

As we have seen so far in these results, there are tensions implicit in the operation of V2G. For EV owners: financial return, emissions reduction, and certainty over available energy for driving are all factors that influence how V2G would operate. This means the decision around how to operate V2G needs to be made with an understanding of the EV driver's unique context. As an example, Figure 22 shows the trade-off between emissions and cost. Minimising emissions is costly, but minimising cost is emissions intensive. Similarly, convenience impacts both emissions and cost, but it should be noted that a 50% conservatism level has minimal impact when optimising for either emissions or cost.

The best way to operate a vehicle's battery with V2G is not necessarily to optimise to any of these extremes. There are points that may suit a particular driver. For example, reducing charging cost to zero could be achieved while still delivering some emissions reduction, even with some reserve capacity.

The other key result is that a V2G offer that meets the needs of EV drivers will need to go further than simply providing drivers with information. As described by Vargo and Lusch, organisations who focus on services need to be "more than just consumer oriented, it means collaborating with and learning from customers and being adaptive to their individual and dynamic needs" [4]. This is further described in the business models report published as part of this project [1]. Finding 4 summarises this.

Finding 4: V2G can serve multiple – at times conflicting – goals. All stakeholders need to be informed of this and have agency over defining their preferred trade-offs.

EV owners	***Many values held by EV owners (such as emissions impact, PV self-consumption, and driving range) are in tension with economic returns. Furthermore, choices between objectives have consequences on the value available to other stakeholders. These tensions will need to be navigated carefully by all those with a stake in the outcomes of optimisation.***
Grid operators	
Market Participants	

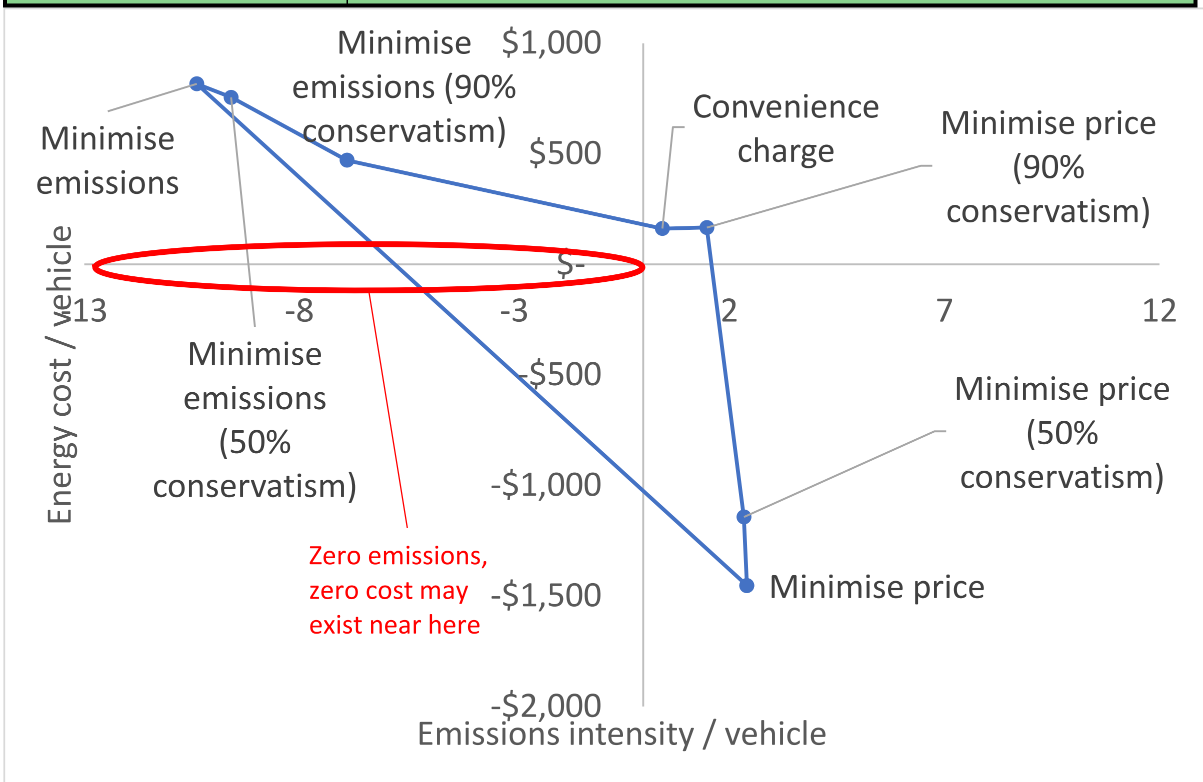


Figure 22 Optimal region: Emissions vs Energy cost (office, dynamic/emissions price, no FCAS)

3.5 How could EV charging impact load growth?

Optimisation signals can dramatically change when and where load/generation peaks occur, particularly when many EVs are exposed to the same signal. The cases presented so far in this report show how a single customer may react to a given set of conditions (charge method, optimisation target, and conservatism). This chapter investigates how these individual behaviours might aggregate up to system wide demand profiles through forecasts (shown in Appendix B).

We consider several charging scenarios with growing EV uptake:

- Unmanaged charging (V0G)
- Managed charging (V1G) with existing tariffs
- Managed charging with dynamic tariffs
- Managed charging that aims to reduce emissions
- V2G with existing tariffs
- V2G with dynamic tariffs
- V2G that aims to reduce emissions

The algorithm used to generate these results is as described in Appendix B. Note that in this study, dynamic tariffs have not been evolved to reflect changing grid circumstances as the penetration of EVs, V2G, and PV increases. However, as the results in Figure 23 through Figure 26 will show, even if tariffs do evolve, their co-incidence can cause significant issues to grid operators.

These plots indicate that managed charging using current prices minimises load growth from EVs the most. Most other charging methods increase peak demand over unmanaged charging, and emissions reduction causes the largest increase in peak demand for managed charging, while dynamic prices cause the largest increase for bidirectional charging.

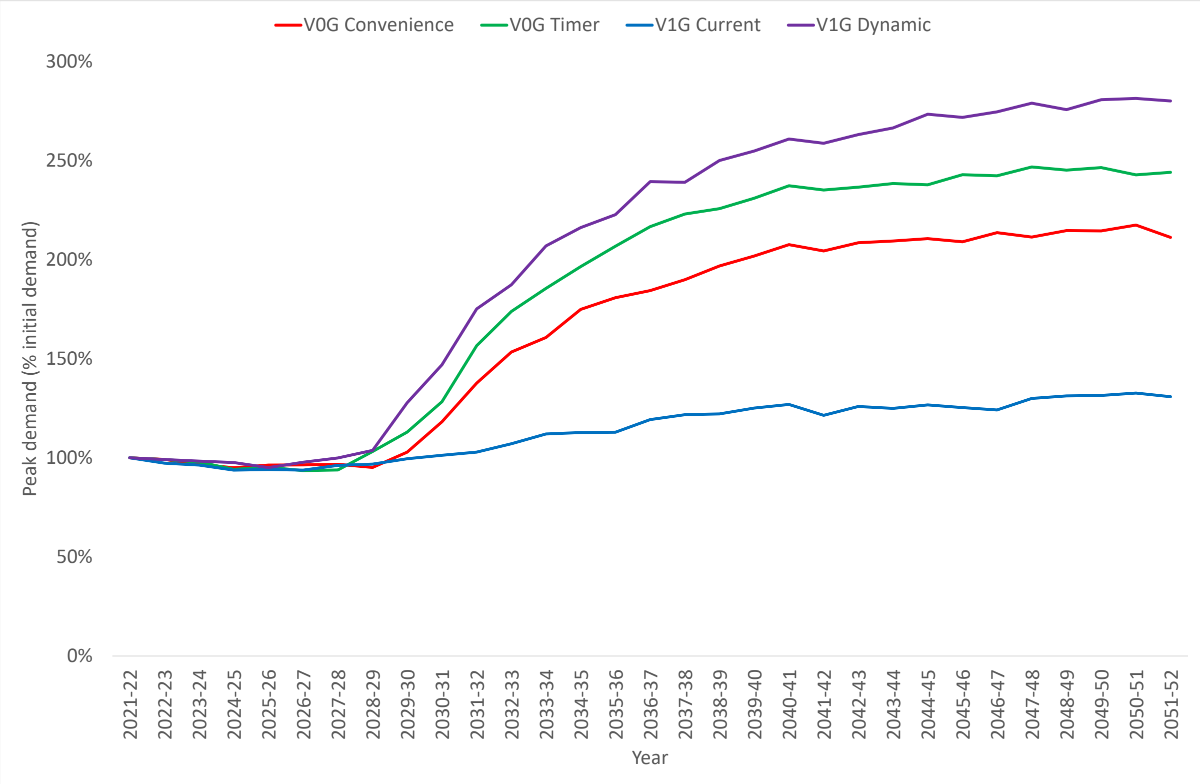


Figure 23 Peak demand forecast: unidirectional charging, houses. Timers and optimisation can dramatically increase coincidence of charging and thus peak demand for houses

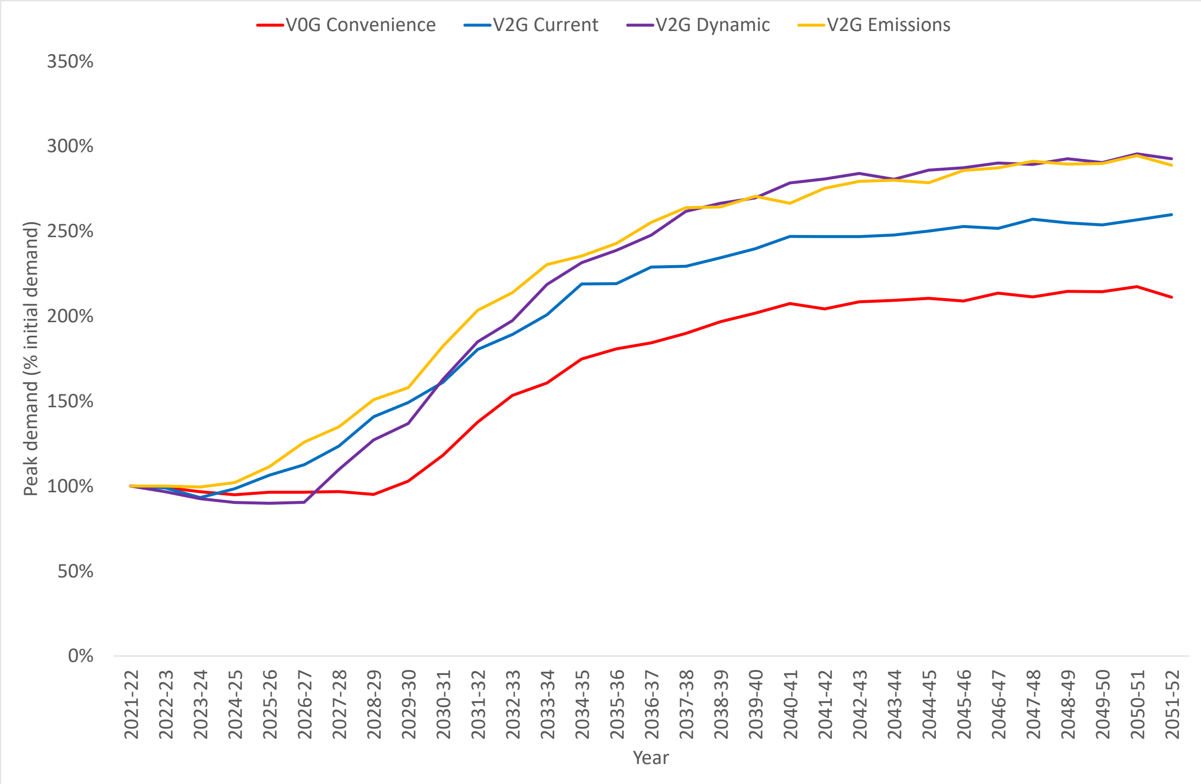


Figure 24 Peak demand forecast: bidirectional charging, houses. Bidirectional charging similarly increases peak demand for houses as EV uptake scales

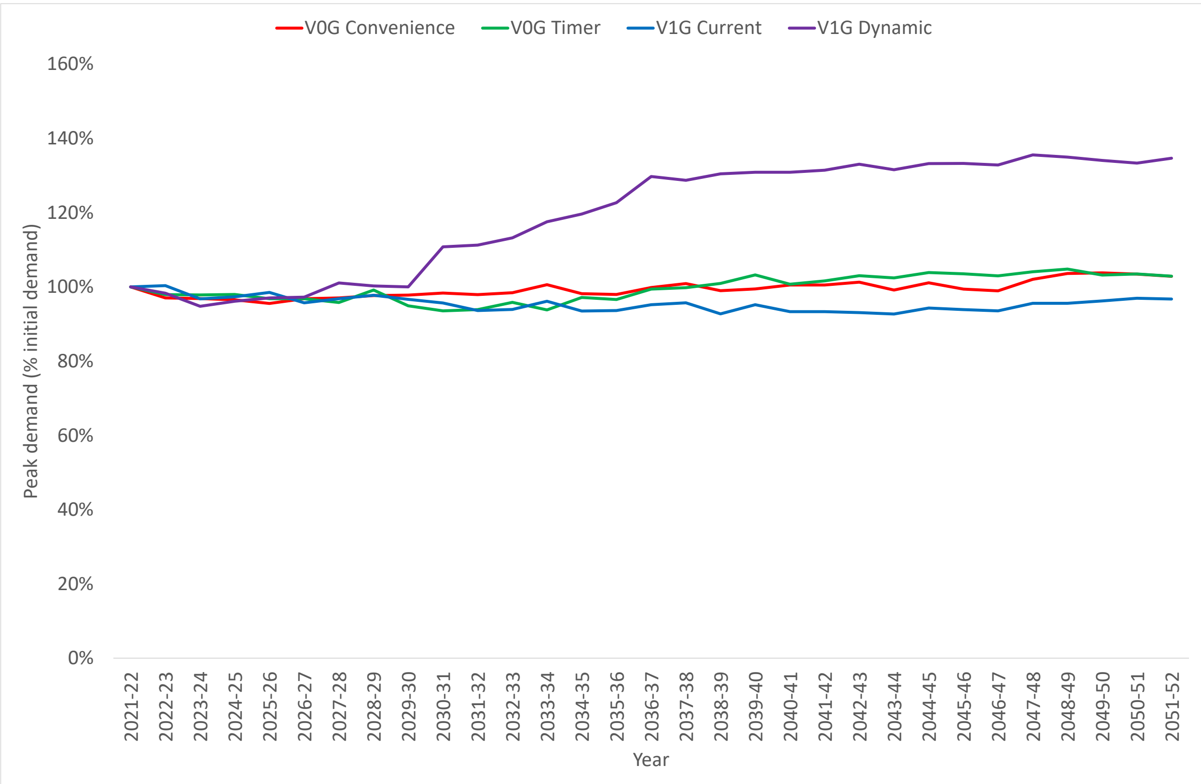


Figure 25 Peak demand forecast: unidirectional charging, office. Because of high plug-in rates and lower charging energy demand the impact on office peak demand is more muted. Dynamic prices still increases demand due to coincidence

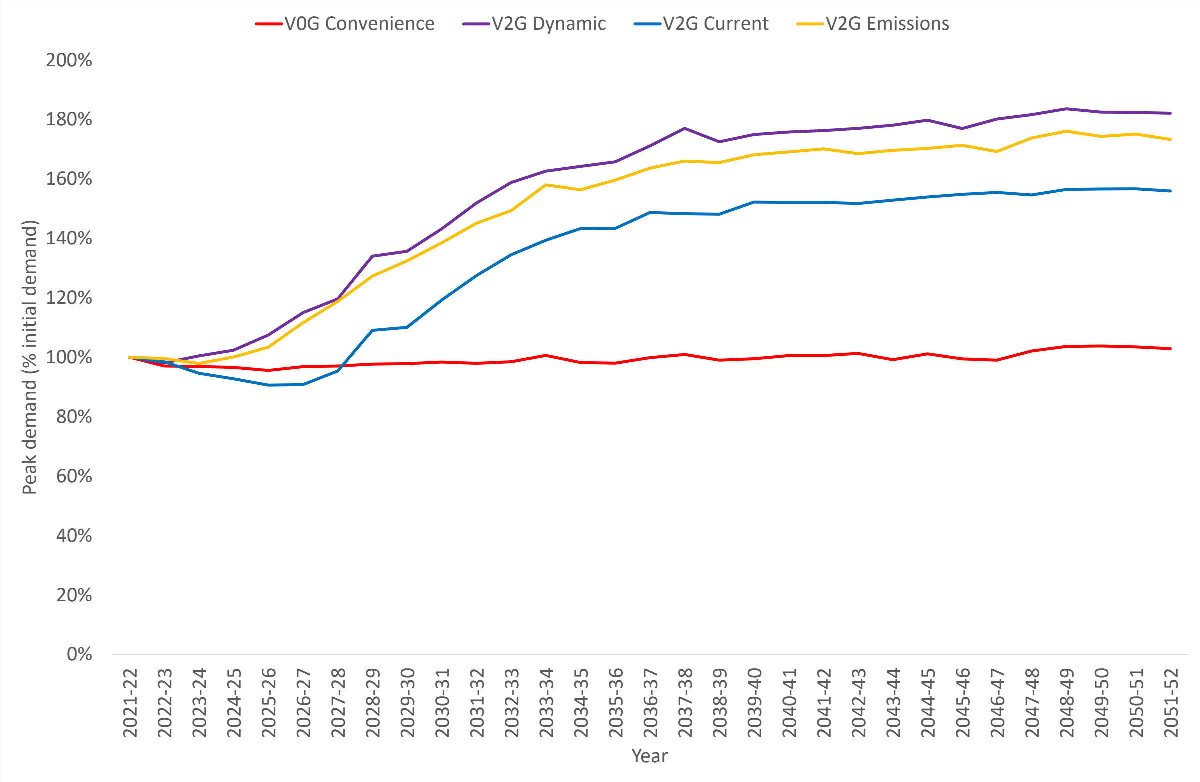


Figure 26 Peak demand forecast: bidirectional charging, office. V2G creates large coincident peaks for offices too, Particularly for emissions optimisation

These findings are counterintuitive. The aim of dynamic prices is to signal need and to **reduce** constraints, but evidently they can cause an increase in demand because of the large amount of flexibility in the network that can respond to signals. In this analysis all connections respond to the same signal which causes large co-incident responses when the price or emissions intensity is particularly high or low. An example of this is shown in Figure 27. In this figure, large swings in power can be seen in response to dynamic signals. Clearly this will be an issue to be managed as dynamic devices such as EVs penetrate the grid. Emissions optimisation in this study was based on marginal emissions, which changes every dispatch interval depending on which generator is marginal. In Figure 27 the emissions trace clearly shows rapid intensity changes between zero (likely where a renewable generator is marginal) and around 1 (likely where a coal generator is marginal). These impacts may be challenging to predict for grid operators. Even assuming the implementation of dynamic operating envelopes, rapid swings in network power can lead to voltage issues or wear on dynamic voltage control elements such as tap changers.

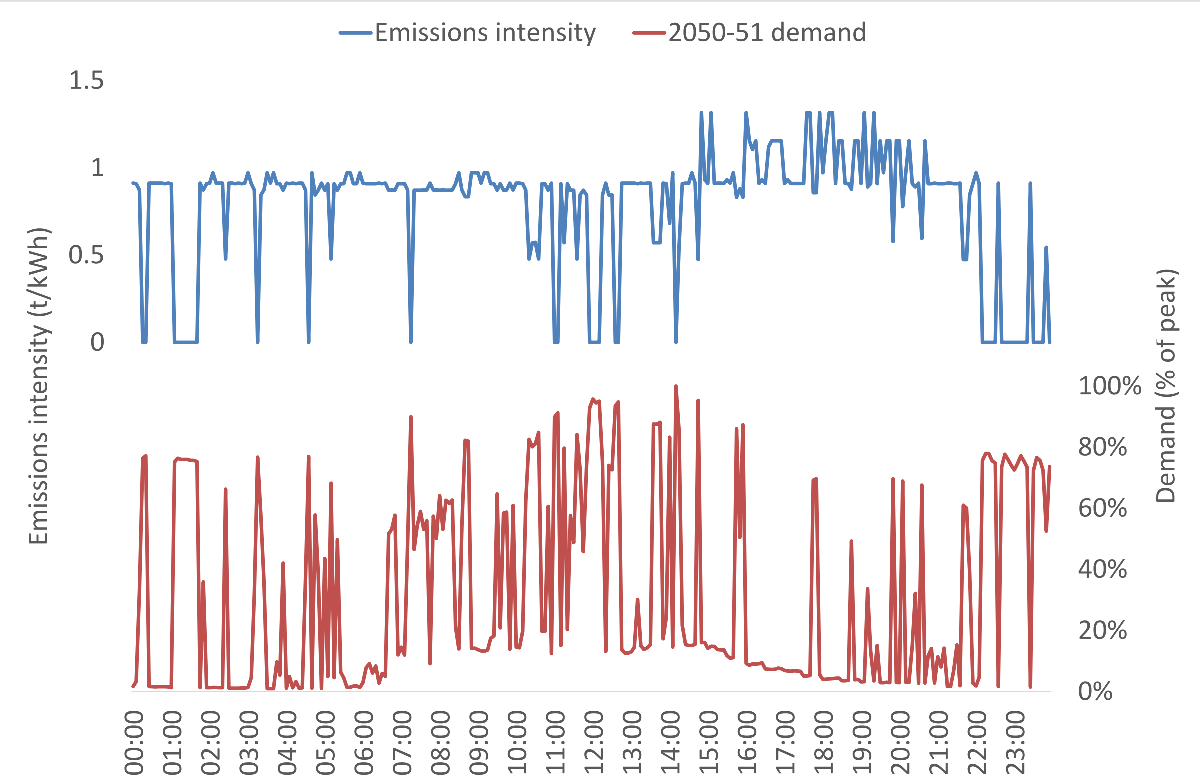


Figure 27 Emissions intensity and vehicle response (V2G, office)

Minimum demand sees similar variability, as shown in Figure 28 through Figure 31. Highly responsive devices such as V2G further reduce minimum demand. This means that the "dynamic range" of the network increases, as does its intra-day variability.

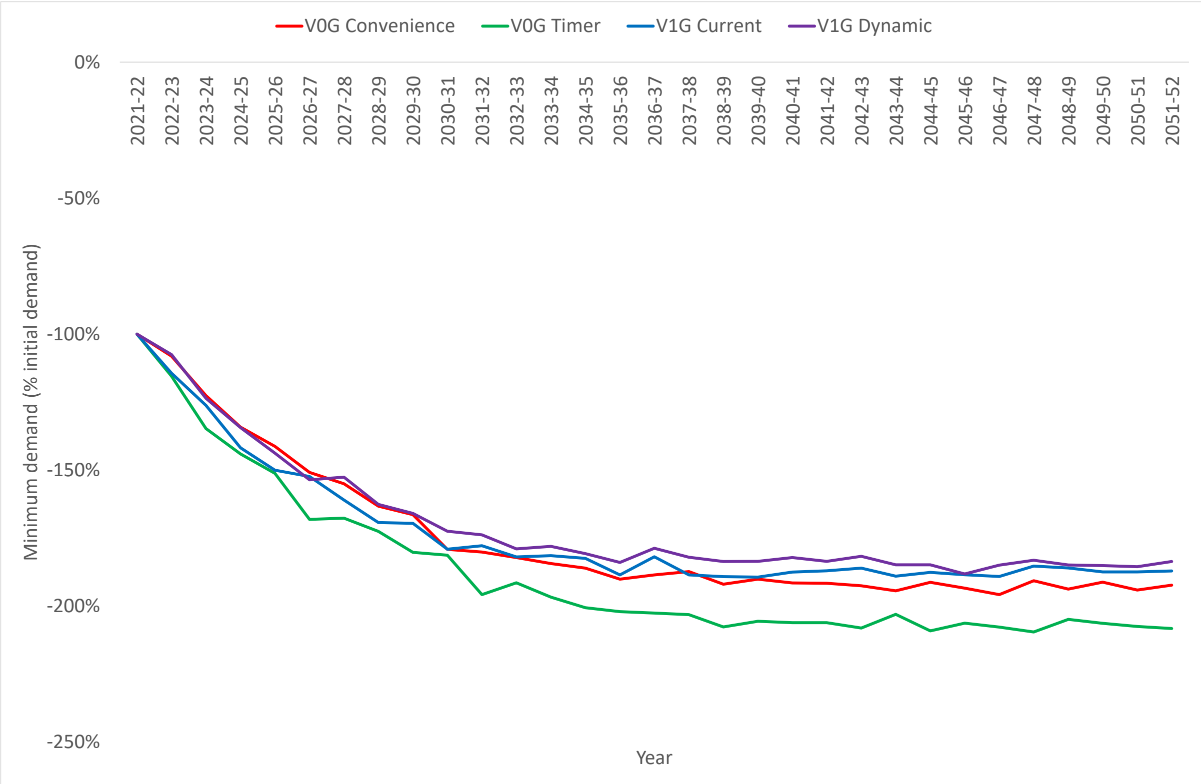


Figure 28 Minimum demand forecast: Unidirectional charging, house. Minimum demand declines in line with PV uptake for houses with managed charging

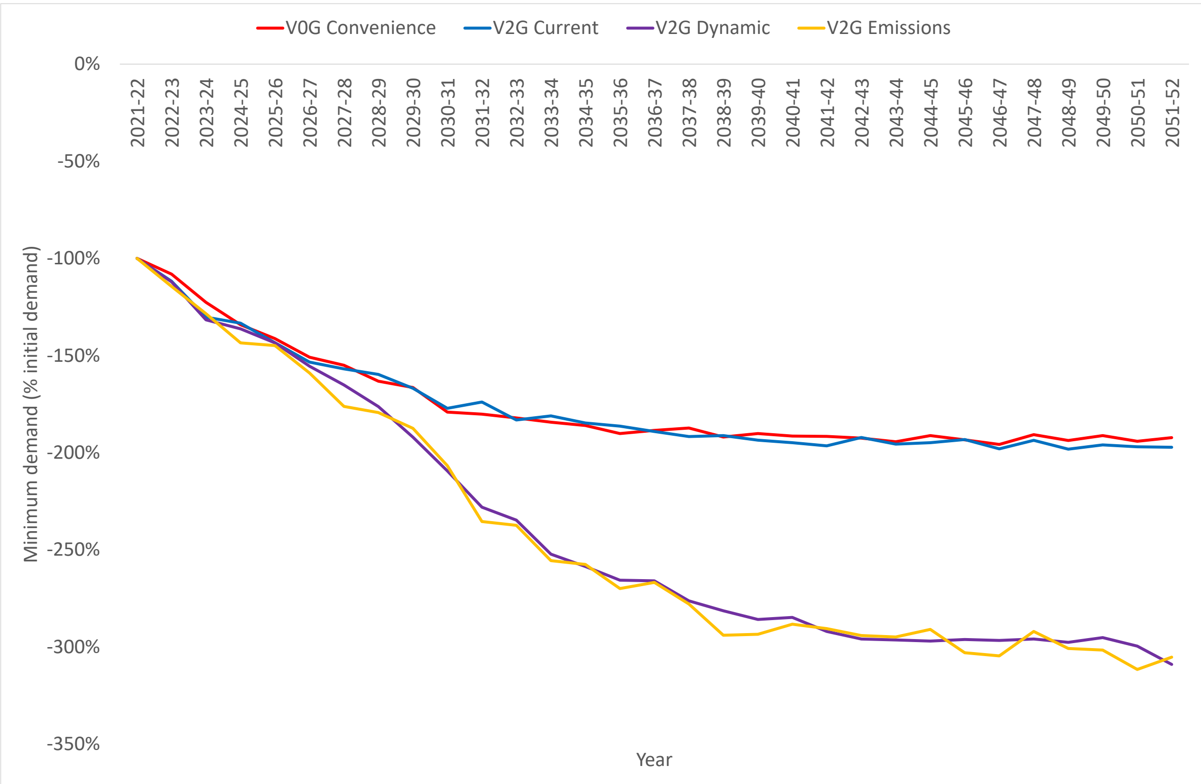


Figure 29 Minimum demand forecast: Bidirectional charging, house. Only dynamic and emissions tariffs provide an incentive to discharge EVs to the grid, but these events reduce minimum demand (houses)

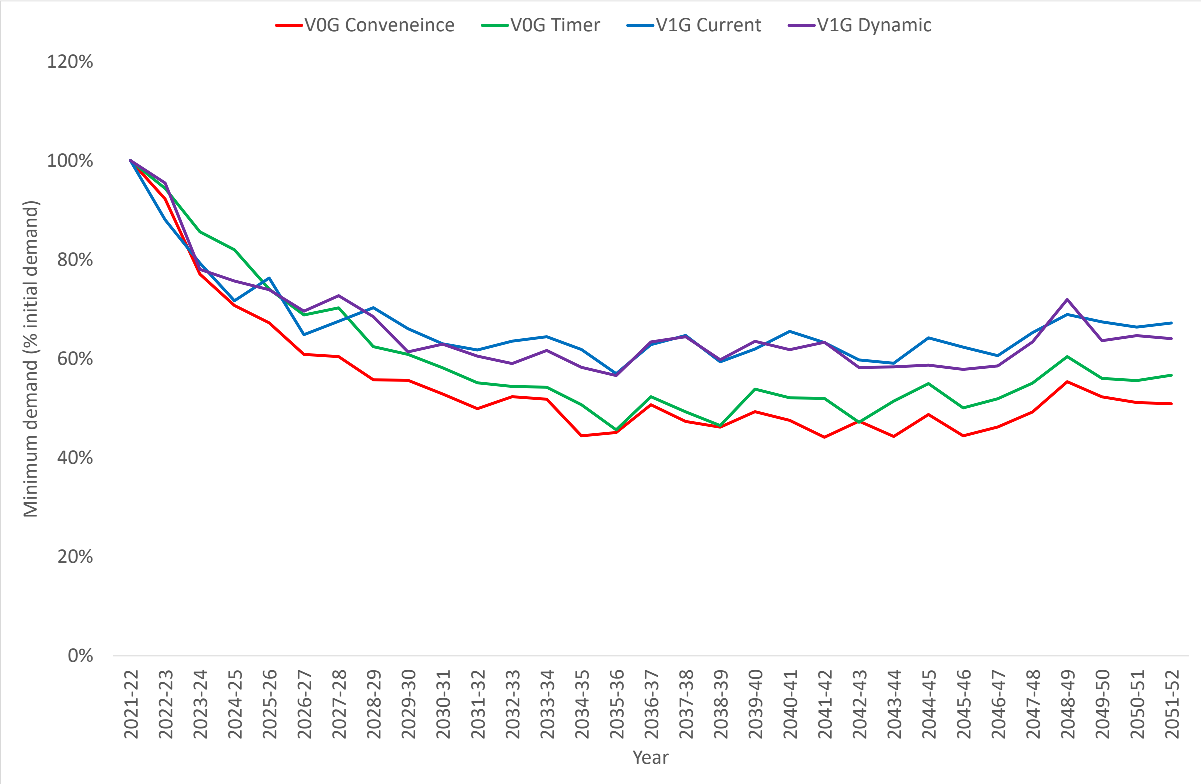


Figure 30 Minimum demand forecast: Unidirectional charging, office. Without discharge capability all minimum demand curves are similar for offices

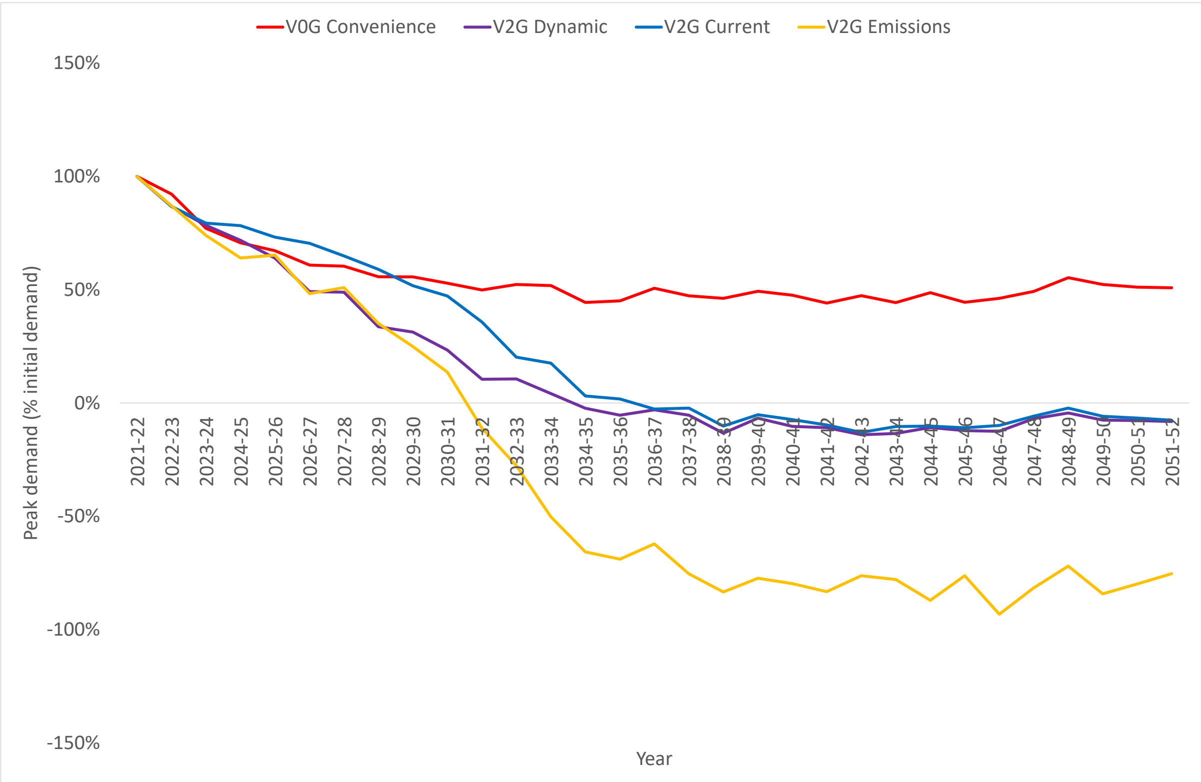


Figure 31 Minimum demand forecast: Bidirectional charging, office. The demand charge in the current tariffs incentivises office EVs with V2G to discharge with current tariffs.

Flexibility is undoubtably a valuable tool for energy system management. These results however show that, like any tool, it must be used with care. Grid operators need to ensure that their signals and standards ensure response is diversified. Undiversified signals such as energy market needs can easily lead to peak demand issues as described in this report. In the case of V2G this is exacerbated by their relatively high power capacity and energy storage compared to local consumption. This is summarised in Finding 5.

Finding 5: Flexible resources need to be managed carefully as their penetration increases

Grid operators	***If poorly managed, flexible resources can dramatically impact the distribution network through peak loads or minimum demand caused by coincident price (or other) events. This can cause load extremes and rapid changes in demand. Grid operators will need to consider mechanisms that reduce variability of flexible assets.***

3.6 What tools are effective at managing demand impacts of V2G?

In our interviews with grid operators (conducted as part of the business models research), they described dynamic prices as the future "end point" for network pricing. They envisioned that the need for traditional network response would become minimal as uptake of these dynamic prices coupled with dynamic operating envelopes increased [1]. The results in section 3.5 show that this may not be the case. Large amounts of flexibility could mean that peak demand increases as they all respond to co-incident signals. Dynamic operating envelopes may go some way to resolving the absolute peak demand issues as described by the *evolve* project [5], however Intra-day variability and unexpected demand patterns may remain an issue. Rapid swings in active power can reduce power quality or wear active voltage control elements (such as on-load tap changers). Similarly large and unexpected swings in demand profiles make planning networks and outages challenging. This section will explore how the components of the optimisation signal interrelate to generate the outcomes seen in 3.5.

The impact of the optimisation signals on average daily demand can be seen in Figure 32 and Figure 33. From these graphs we can take away several things:

- Current pricing supresses demand throughout the day but increases it in the evening and morning. This is particularly apparent in the morning where charging demand is very high. The optimiser used in this study tends to delay action until the end of long periods of similar prices such as occurs in current time-of-use tariffs.
- Dynamic pricing introduces a period of charge in the middle of the day and reduces demand in the lead up to the morning peak. The more variable nature of price signals reduces the co-incidence of charging on average, although there is a very strong charging peak in the middle of the day to coincide with the "solar sponge" component of the network tariff.
- Emissions optimisation encourages behaviour counter to that indicated by market price and network tariffs. Charging occurs coincident with morning and evening peaks. This is because (at least in 2019 in NSW) these times were when marginal emissions were lowest.

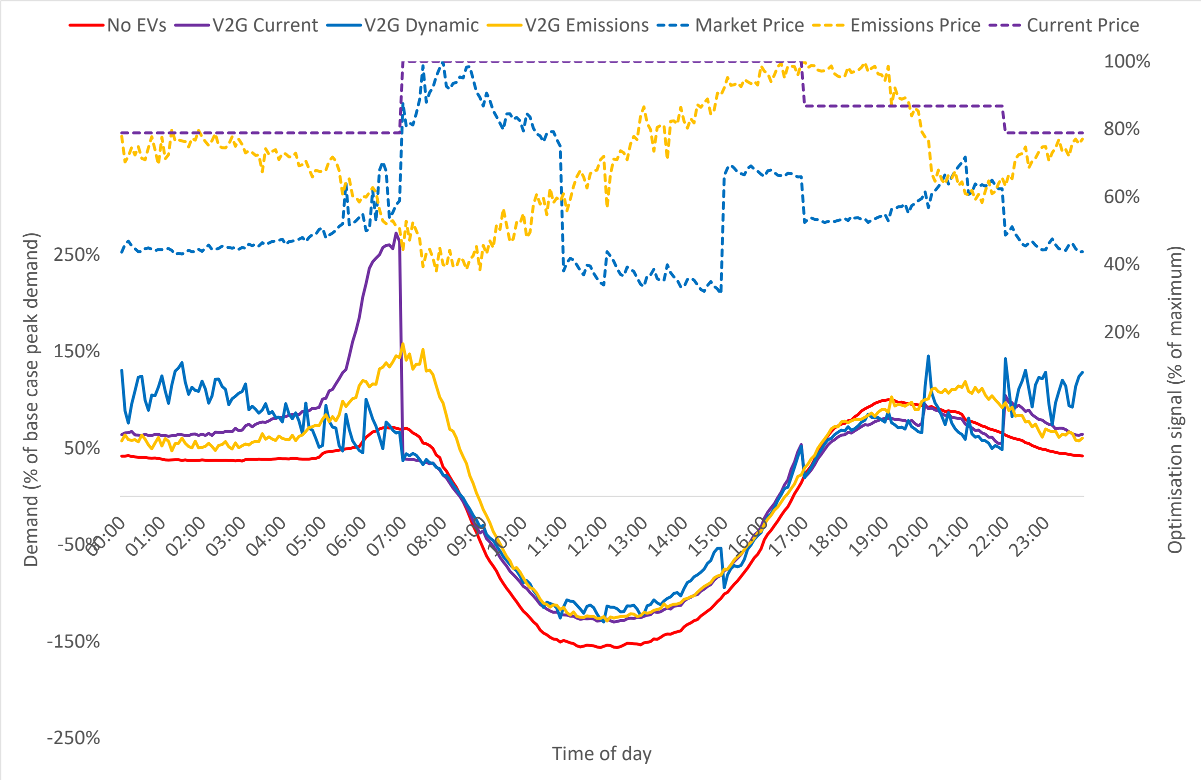


Figure 32 Impact of price signal on V2G EV charge behaviour (office). Different price signals elicit dramatically different EV behaviour

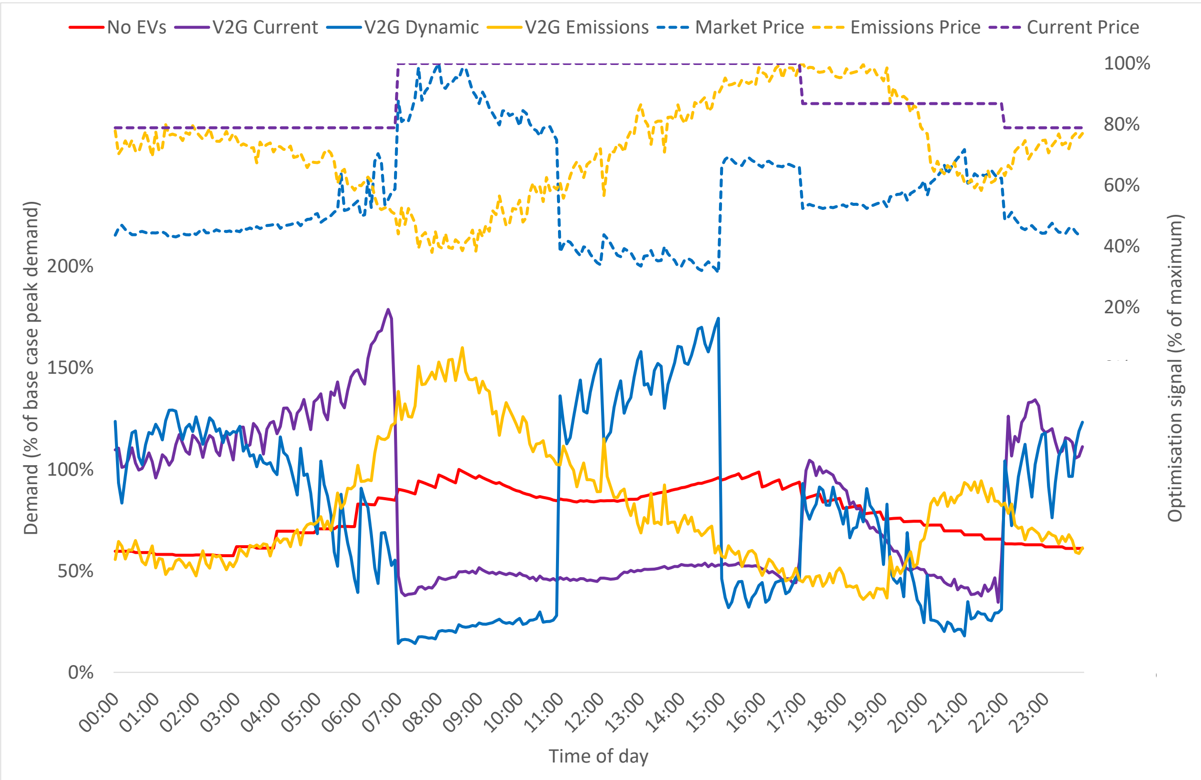


Figure 33 Impact of price signal on V2G EV charge behaviour (houses). Similarly for houses with less V2G capability due to lower plug-in rates

The results shown in Figure 32 and Figure 33 are averages. This hides many of the events that cause the peaks discussed in 3.5 which are less common. The averaging effect is shown in the example duration curve in Figure 34: there are relatively few very large peaks. This is common in electricity networks, however the proliferation of active elements, particularly relatively large ones like V2G, makes peak events more extreme.

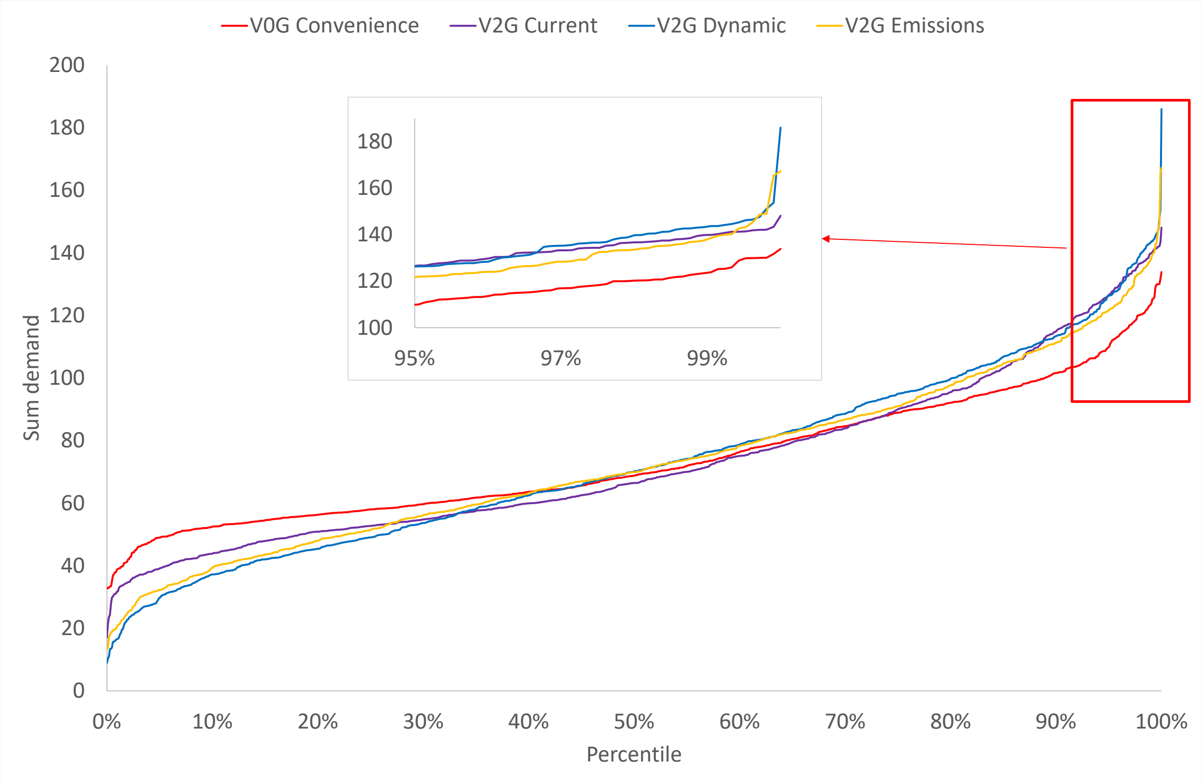


Figure 34 Demand duration curve (office, V2G). Dynamic price signals create rare, extreme peaks in demand

The network tariff used in the dynamic signal contains several components including:

- Time of use energy
- A feed in charge
- A demand charge
- A feed in credit

This section aims to understand the impact of these components, particularly demand pricing and the feed in credit. It shows how EV charge power changes in response to the price signals in the dynamic optimisation signal.

Demand pricing aims to reduce customers' peak demand by implementing a price proportional to their *maximum* demand over a particular time period (often monthly). The aim is to incentivise customers to reduce maximum demand but not necessarily their overall energy use. The impact of demand pricing under the different optimisation targets can be seen in the change in consumption during periods when the pricing is active. Figure 35 shows the reduction in average charger power during periods where demand pricing is active relative to that observed when vehicles are convenience charged. Clearly V2G responds strongly to demand signals, at least for offices where grid infeed is lower. During peak periods V2G discharges strongly with dynamic and current optimisation signals. Under emissions reduction and self-consumption there is little reduction in charge power. For houses (Figure 36), charge power commonly increases although less than it does for emissions and self-consumption targets.

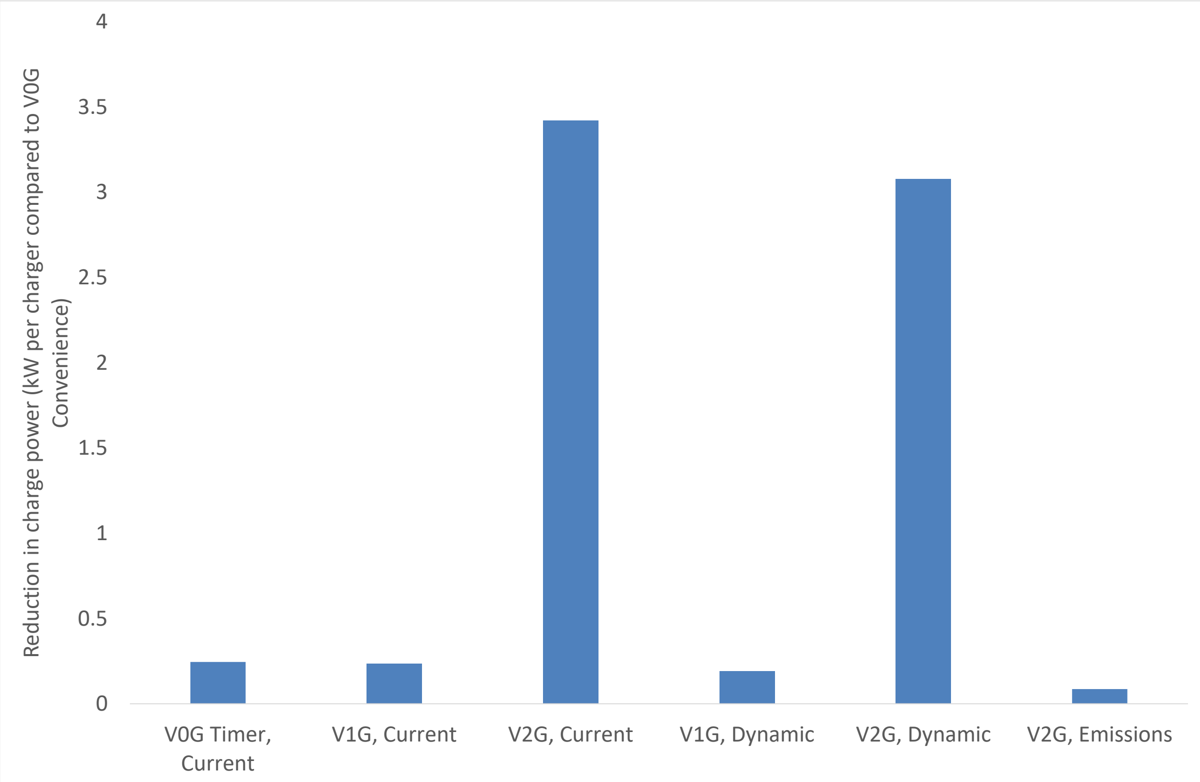


Figure 35 Influence of demand pricing (Office, EV power). For offices, V2G and demand prices can reduce peak demand

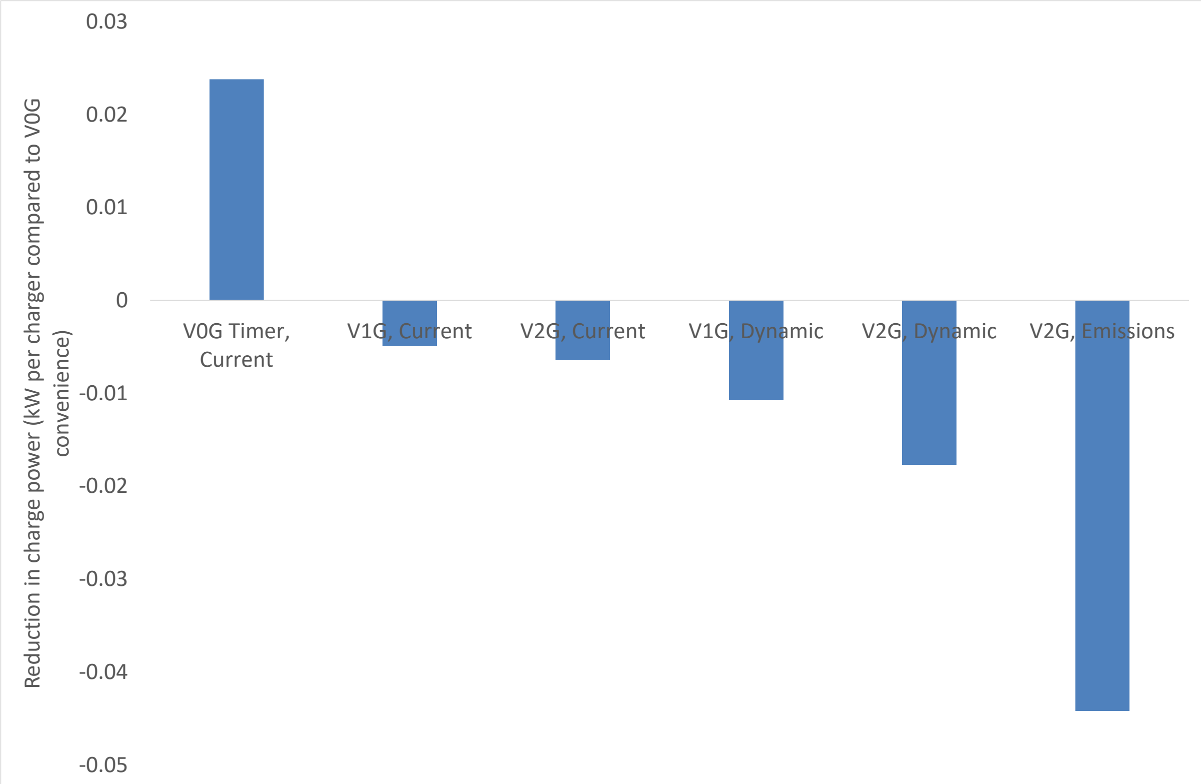


Figure 36 Influence of demand pricing (House, EV power). For houses the impact of demand price on demand is less

Evoenergy's smart battery tariff also includes a peak demand feed in credit. This pays customers $1.95/kWh for grid infeed during specified peak events. This credit has a more variable effect on charger power, as seen in Figure 37. On average there is a small net response from offices, but very little from houses. This response is measured by averaging the power at the same time on the same day of the week for the surrounding 6 weeks. Events are as per A.3.1.

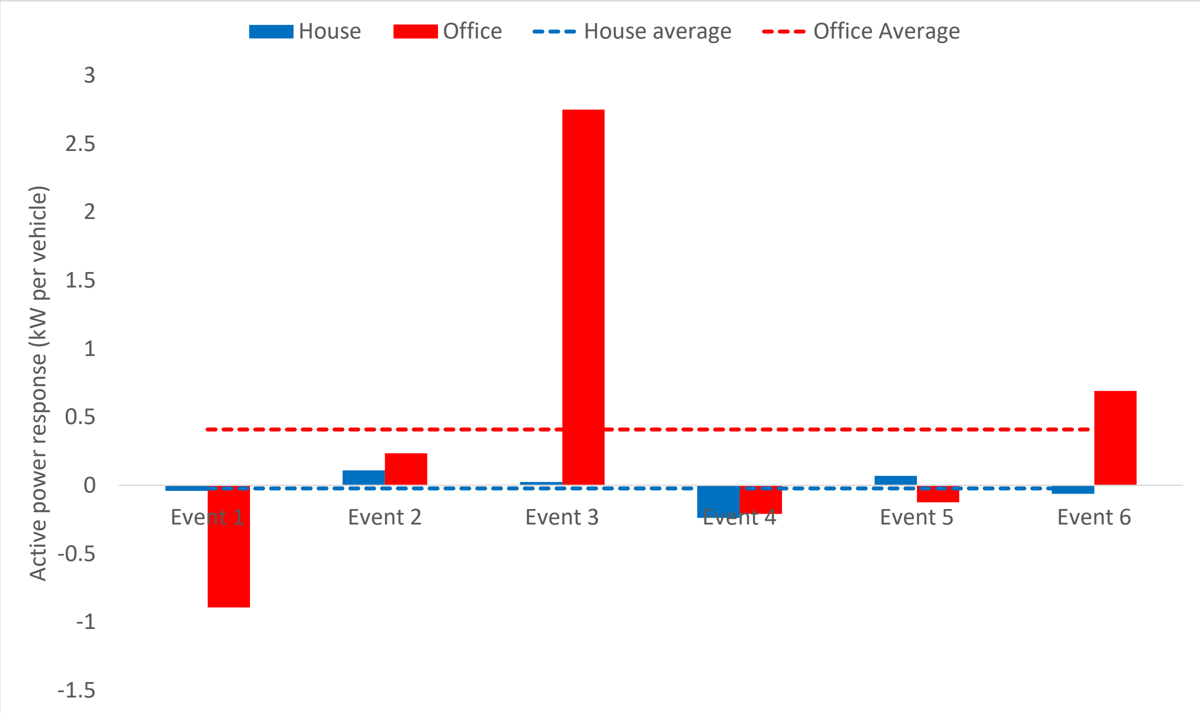


Figure 37 Average power response to feed in credit events

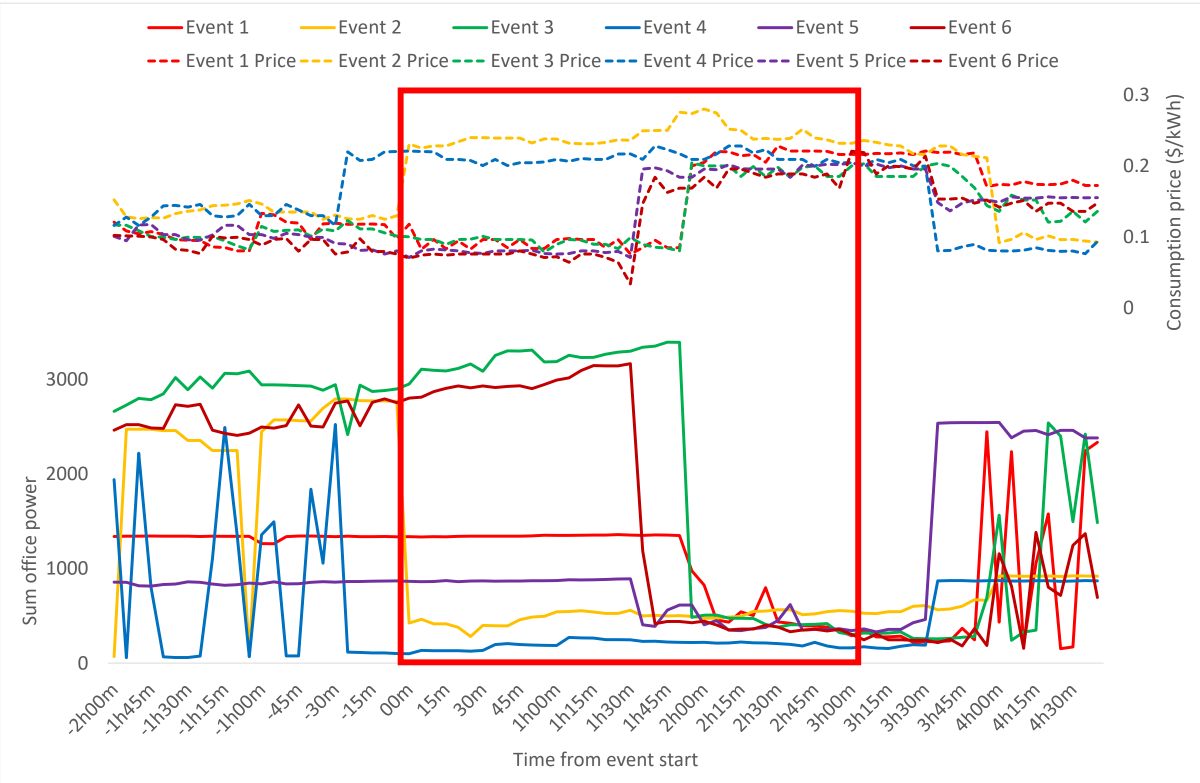


Figure 38 Office grid power during events shows that response to feed in credit is coincidental response to consumption price. Event period denoted by red box

From this analysis we can see that demand tariffs are a better tool to signal customer behaviour than energy prices. Feed in credits don’t strongly influence behaviour therefore may not be an effective tool.

As discussed in 3.3, vehicle owners may prefer that their batteries are operated conservatively. This could mean that they will reserve capacity for unexpected events, thus reducing the capacity available for response to energy price. This can clearly be seen in the office response to demand pricing, shown in Figure 39. For homes (Figure 40), many are exporting at high price times therefore EVs are charging with excess PV energy, but even those see a reduction in power levels as conservatism increases.

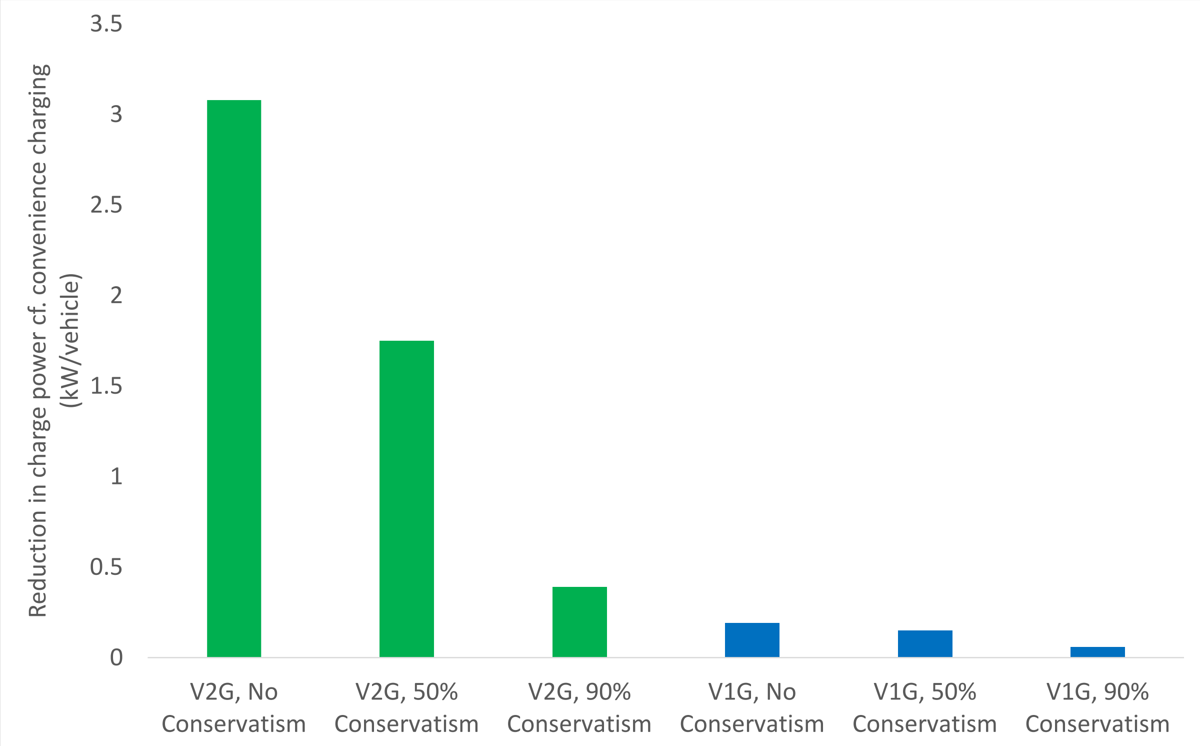


Figure 39 Impact of conservatism on demand pricing effectiveness (office)

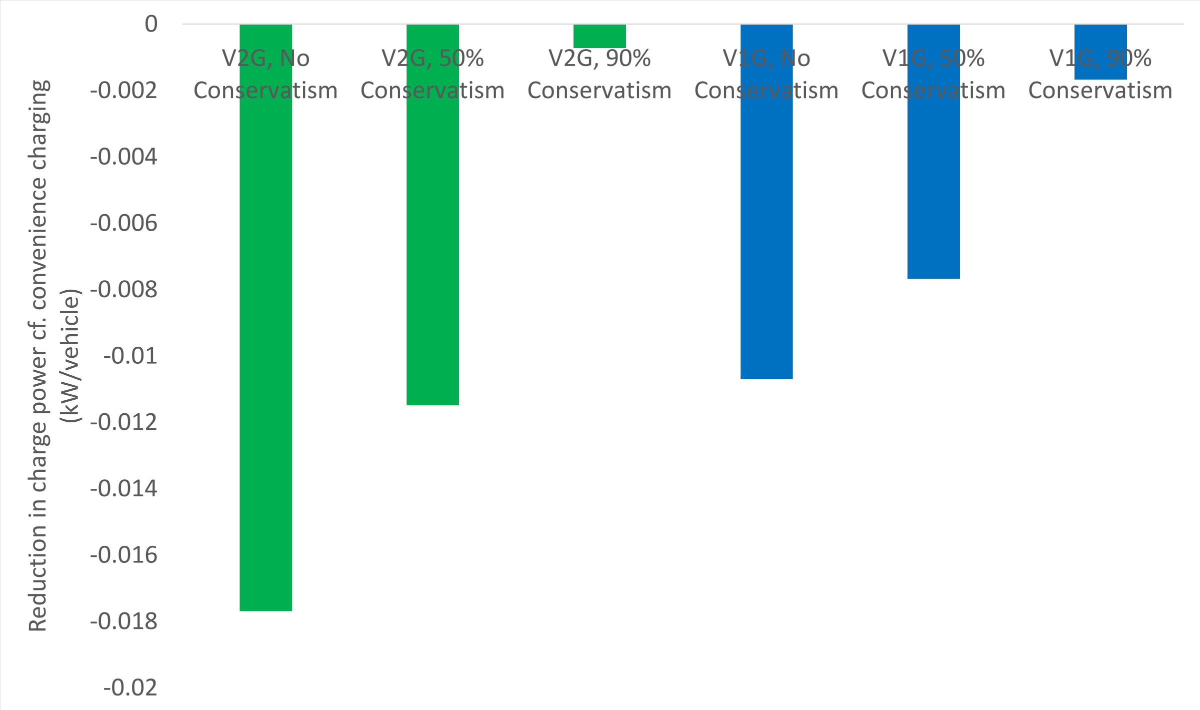


Figure 40 Impact of conservatism on demand pricing effectiveness (house)

Conservatism has the largest effect in the middle price bands. Figure 41 shows how average charger power changes with price for different levels of conservatism. In particular, 90% conservatism alters the average charge power the most, bringing it closer to zero.

Figure 41 Impact of conservatism on charger power (office, V2G, Dynamic price)

From this analysis, we can see demand tariffs are a promising tool for grid operators to reduce the impact of flexible assets on the network. Energy prices have trouble competing with the large swings in price in the energy market during periods of scarcity. Similarly, in this study the feed in credit was not effective at reducing demand.

Finding 6: Demand pricing is an effective tool for moderating demand

Grid operators	***Demand pricing shows the most promise at modulating demand from flexible assets when compared with energy prices and feed in credits.***

3.7 Is V2G economic?

For V2G to be economic, the benefits must compare favourably with the costs. A comparison of expected total installed costs for V2G and V1G chargers is shown in Table 13, sourced from [6].

Table 13 Cost of charge hardware (costs sourced from [6] scaled by current $USD/AUD exchange rate ($1.45) except for V2G charger from [7])

Item	House (V0G)	House (V1G)	House (V2G)	Office (V0G)	Office (V1G)	Office (V2G)
Wiring	$1,514	$1,410	$1,410	$6,444	$8,497	$8,497
Direct installation	$353	$653	$653	$4,129	$4,761	$4,761
Charger	$767	$1,581	$10,000	$3,275	$8,885	$25,000
Ports/charger	1	1	1	2.4	2.5	2.5
Total (per charger)	$2,634	$3,643	$12,062	$5,770	$8,857	$15,303
Incremental cost		$1,009	$9,428		$3,087	$9,533

From these costs, payback periods for the different scenarios are shown in Table 14. For most scenarios, charger payback periods exceed 5 years. Only 3 scenarios have a payback period that is within 5 years for current commercial rates. The scenarios with the shortest payback period are:

- For houses, V1G has the fastest payback period
- For offices, V2G has the fastest payback period

Table 14 Payback periods for charge scenarios

	Current commercial interest rates (9.99% pa) [8]		No Interest	
	House	**Office**	**House**	**Office**
V1G, Dynamic, 0% Conservation	5	>10	4	>10
V1G, Dynamic, 50% Conservation	7	>10	6	>10
V1G, Dynamic, 90% Conservation	>10	>10	>10	>10
V2G, Dynamic, 0% Conservation	>10	5	>10	4
V2G, Dynamic, 50% Conservation	>10	5	>10	5
V2G, Dynamic, 90% Conservation	>10	6	>10	5
V2G, Emissions, 0% Conservation	>10	>10	>10	8
V2G, Emissions, 50% Conservation	>10	9	>10	7
V2G, Emissions, 90% Conservation	>10	8	>10	7

In light of the longer payback period, a more constructive question may be the inverse: what would the installed cost of a charger need to be for the benefits to exceed the costs of a standard loan on a 5 year term? This is shown in Table 15, including the cost reductions required to make the scenario economic.

Table 15 Required charger cost for 5-year payback

	Current commercial interest rates (9.99% pa) [8]		No Interest	
	House	**Office**	**House**	**Office**
V1G, Dynamic, 0% Conservation	**$1,242 (Economic)**	$620 (80% reduction)	**$1,425 (Economic)**	$711 (77% reduction)
V1G, Dynamic, 50% Conservation	$817 (19% reduction)	$548 (82% reduction)	$937 (7% reduction)	$629 (80% reduction)
V1G, Dynamic, 90% Conservation	$384 (62% reduction)	$346 (89% reduction)	$441 (56% reduction)	$397 (87% reduction)
V2G, Dynamic, 0% Conservation	$3,375 (65% reduction)	**$11,264 (Economic)**	$3,871 (59% reduction)	**$12,920 (Economic)**
V2G, Dynamic, 50% Conservation	$3,362 (65% reduction)	**$10,630 (Economic)**	$3,856 (60% reduction)	**$12,193 (Economic)**
V2G, Dynamic, 90% Conservation	$2,902 (70% reduction)	$8,831 (7% reduction)	$3,329 (65% reduction)	**$10,130 (Economic)**
V2G, Emissions, 0% Conservation	$2,293 (76% reduction)	$5,236 (45% reduction)	$2,630 (72% reduction)	$6,006 (37% reduction)
V2G, Emissions, 50% Conservation	$2,899 (70% reduction)	$5,746 (40% reduction)	$3,326 (65% reduction)	$6,591 (31% reduction)
V2G, Emissions, 90% Conservation	$2,707 (72% reduction)	$6,259 (34% reduction)	$3,105 (67% reduction)	$7,179 (25% reduction)

Forecasting hardware costs is error prone. Costs are likely to reduce in the future as hardware costs drop, but the rate will depend strongly on how technology develops. One recent study forecasted annual hardware cost declines of 3% [9]. Installation costs though may not experience the same rate of decline. Some forecast that overall installed costs will increase as easy installation sites become exhausted [10].

Costs can also be forecasted by observing the cost development of other parallel industries. NREL has published annual "bottom up" price indexes of solar PV costs since 2010 [11]. They have observed cost declines from \$2.50/W to \$1.00/W in this period, although that is largely driven by PV module cost reduction and efficiency increases [12]. The progression of inverter costs is shown in Figure 42. These costs show a 10-20% annual reduction in costs over the period.

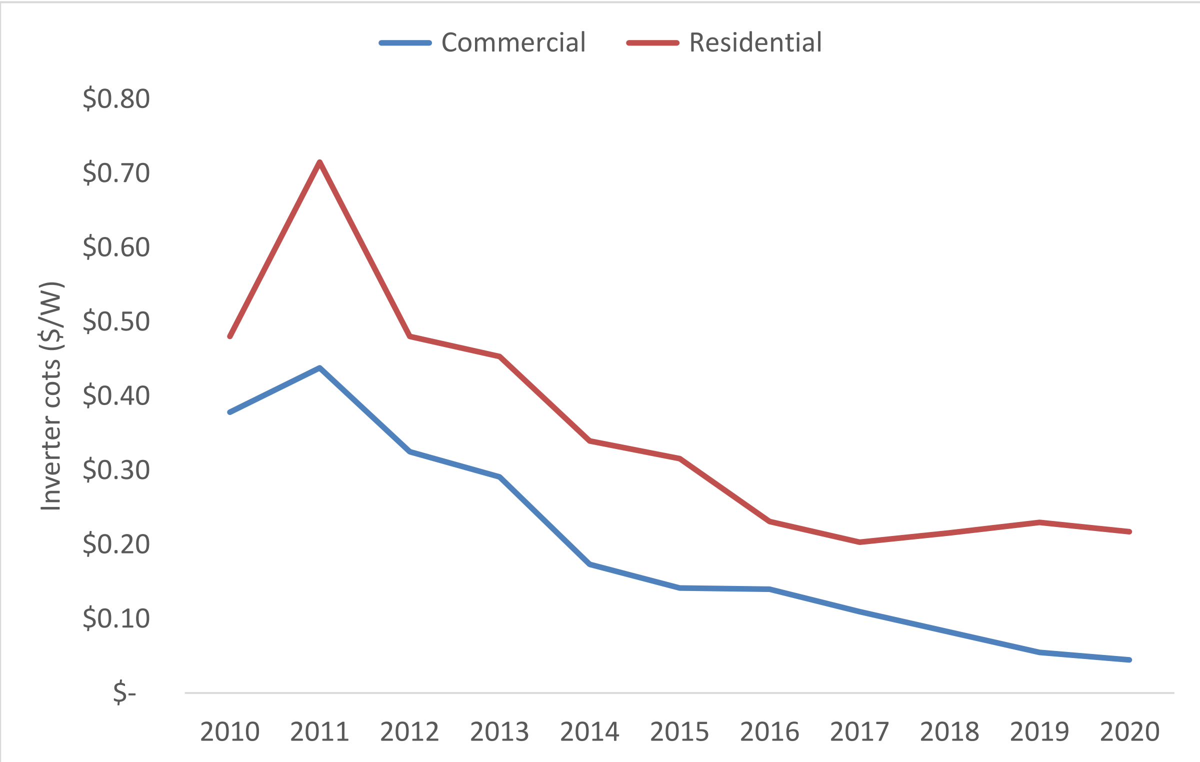


Figure 42 PV Inverter cost progression [11]

For this analysis, two scenarios are considered:

- Low estimate: hardware annual cost reduction rate of 3%
- High estimate: hardware annual cost reduction rate of 20%

The forecast incremental cost of V2G for both these cases is shown in Figure 43.

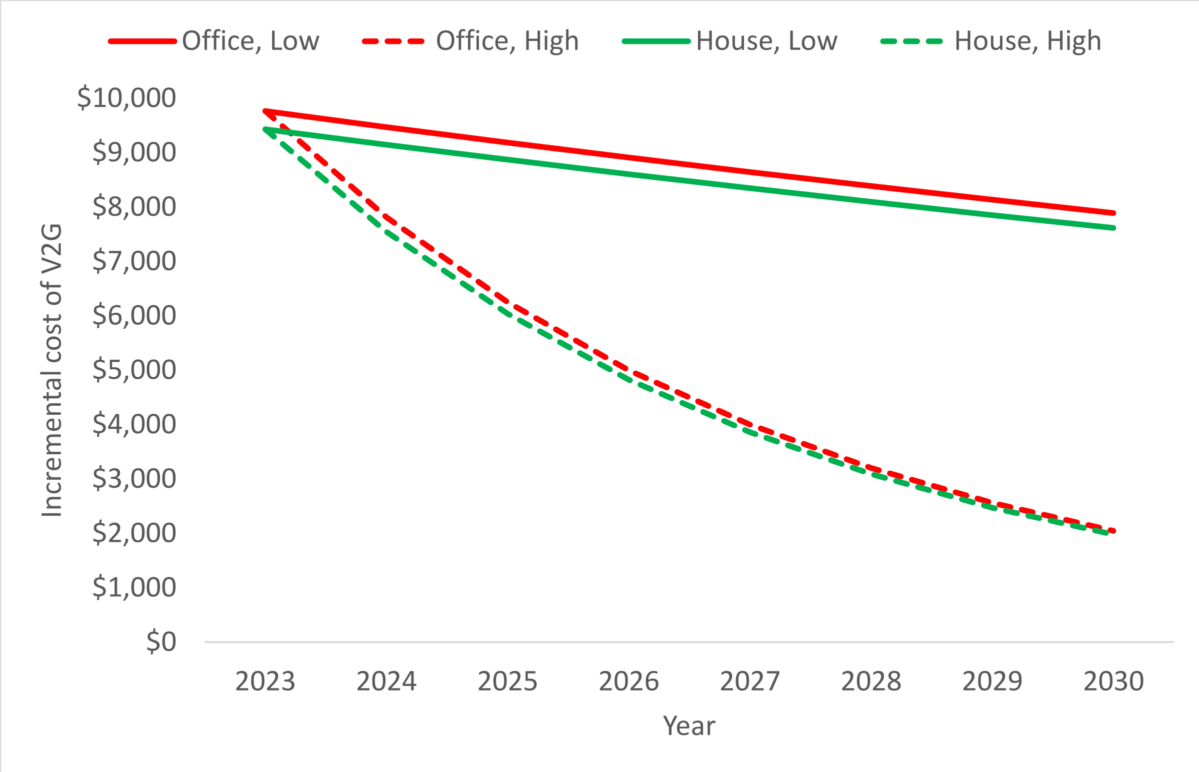


Figure 43 Incremental cost of V2G forecast for low (3%/year price reductions) and high (10%/year price reductions) scenarios

Based on these forecasts, the year where the scenarios become economic is shown in Table 16. With a high learning rate, office (high availability) V2G use cases become economic mostly before 2025. Houses, with lower plug-in rates, are not economic until much later.

Table 16 Year scenarios become economic

	House		Office	
	Low learning rate	High learning rate	Low learning rate	High learning rate
V1G, Dynamic, 0% Conservation	**2022**	**2022**	2030+	2030+
V1G, Dynamic, 50% Conservation	2030	2024	2030+	2030+
V1G, Dynamic, 90% Conservation	2030+	2028	2030+	2030+
V2G, Dynamic, 0% Conservation	2030+	2028	**2022**	**2022**
V2G, Dynamic, 50% Conservation	2030+	2028	**2022**	**2022**
V2G, Dynamic, 90% Conservation	2030+	2029	2027	2024
V2G, Emissions, 0% Conservation	2030+	2030	2030+	2026
V2G, Emissions, 50% Conservation	2030+	2029	2030+	2026
V2G, Emissions, 90% Conservation	2030+	2029	2030+	2025

The main points are summarised in Finding 7. These findings confirm what was discussed in 3.1: high plug-in rates are critical for V2G's economics. While these results show that V2G is economic today in some cases, this may not be the case outside of simulations. This study assumed perfect foresight of both vehicle usage and market price. Neither of these are true in a real implementation of V2G. Understanding this is left to a future study.

Finding 7: V2G is not currently economic, but may shortly become so in some use cases

EV owners **Market Participants**	***V2G currently has challenging economics.*** ***In ideally suited use cases – with high plug-in rates, high local demand to manage, and low capacity reservation needs – V2G may be economic soon.*** ***For many use cases significant price drops will be required before it is widely economic.***

4 Conclusion

This report explores quantitatively the benefits, risks, and impacts of V2G. It used a set of models, optimisation targets, and constraints to understand what a future with V2G might look like and to probe the variables that will influence viability. It is grounded in the findings from the qualitative part of the REVS research. It aims to investigate the propositions, constraints, and values that interviewees described in this research.

There were four charging types, three optimisation targets, and three levels of conservatism studied. These are described in Table 17.

Table 17 Parameters Studied

Charging type	Optimisation target	Conservatism level
V0G Convenience EVs are charged at full power immediately on plugging in. EVs do not discharge power.	**Current Pricing** Charging is optimised for lowest cost against an existing retail price, assigned based on the customer class: • Houses are assigned the “ActewAGL Home Time of Use” tariff. • Offices are assigned the “ActewAGL LV TOU demand” tariff.	**None** The only constraint on the utilisation of V2G is that vehicles must have sufficient charge to cover upcoming trips, which the optimiser is aware of with perfect foresight. All results in this report that do not specifically note a conservation level use this approach.
V0G Timer EVs are charged at full power but only during the “off peak” period (10PM-7AM). EVs do not discharge power.	**Dynamic Pricing** Charging is optimised for lowest cost against a dynamic retail price. Dynamic pricing builds a price signal that reveals the underlying nature of two cost drivers: • A network price, based on the Evoenergy “smart battery” tariff. • A market price which is directly passed through for consumption, scaled to 90% for feed in.	**50%** The use of V2G is constrained by 50% of the battery’s capacity being reserved for driving. This is equivalent to roughly 135 km range in a 40 kWh Nissan Leaf battery.
V1G EV charging is optimised to maximise the specified target and meet driving energy requirements. EVs do not discharge power.	**Emissions** Charging is optimised for lowest emissions. The optimisation considers marginal emissions for NSW1 region of the NEM.	**90%** The use of V2G is constrained by 90% of the battery’s capacity being reserved for driving. This is equivalent to roughly 243 km range in a 40 kWh Nissan Leaf battery.

Charging type	Optimisation target	Conservatism level
V2G EVs charge and discharge to maximise the specified target and meet driving energy requirements.		

This report investigated seven themes, described below:

What is the value of V2G? (section 3.1)

The value that V2G can deliver depends critically on the amount of time EVs are plugged in to chargers. The “house” data set used in this study has low plug-in rates and therefore shows little opportunities for V2G to produce value. The “office” data set used in this study has high plug-in rates, which enable benefits from V2G services to outweigh the cost of charging vehicles, such that the net cost of adding additional EVs to the office is negative under both existing and dynamic prices. These findings are consistent with many V2G contracts stipulating minimum plug-in times.

This leads to Finding 1: the length of time vehicles are plugged into chargers is a critical determinant of V2G value. Initiatives that encourage uptake of V2G should also encourage high plug-in rates.

Finding 1: The length of time vehicles are plugged into chargers is a critical determinant of V2G value

EV owners Market Participants	***The value that V2G services can produce is highly dependent on the length of time vehicles are plugged in to chargers. If plug-in times are sufficiently high, the impact of V2G can be so great as to make the cost of adding EVs to a site negative.***

A particularly promising source of value for V2G is the provision of frequency services. This was corroborated in our modelling, where the revenue from FCAS accounted for half to two-thirds of the total value of V2G. This supports the REVS projects focus on commercialising V2G FCAS capabilities. It also means that the value of V2G is highly sensitive to value of the FCAS market, which is expected to decline as more flexible assets (batteries and demand response etc) connect to the market. The provision of FCAS also provided substantial value under V1G charging conditions, which may present competition to V2G charging.

Demand and energy price arbitrage are also significant drivers of V2G value, while utilising V2G to minimise marginal carbon emissions proved to be the most expensive of the considered charging methods.

This leads to Finding 2: FCAS revenue is the dominant component of the V2G value stack – under current market conditions.

Finding 2: FCAS revenue is the dominant component of the V2G value stack – under current market conditions

EV owners	***Demand and energy price arbitrage offer opportunities for significant benefit for V1G and V2G. Feed-in rebates or charges have minimal value.***
Market participants	***If the technical requirements can be met, FCAS is a valuable service that can significantly contribute to the overall value stack. This is even the case for V1G, which can stop/decrease charging to contribute to raising the frequency and can start/increase charging to lower the frequency.***

What is the environmental impact of V2G? (Section 3.2)

EVs are commonly marketed as a way for people to reduce their transport emissions. This means that some people may prefer that their vehicles are charged in a way that minimises their emissions impact.

We firstly considered the impact of operating V2G charging to minimise the carbon content of grid energy (considering the marginal emissions in the NSW1 region). This study showed that V2G can result in lower emissions at a site-wide level, particularly where vehicles are plugged in for extended periods, however this comes at a significant financial cost.

Secondly, we considered the impact of this optimisation strategy on the self-consumption of locally generated PV. Counterintuitively, the strategy of optimising to minimise marginal emissions reduces PV self-consumption compared to optimising for price. This is because PV is commonly generating at a time when an emissions intensive coal generator is marginal, which makes it preferable (from an emissions perspective) to export PV into the grid and charge vehicles at another time when the marginal generator has a lower emissions intensity.

What is the trade-off between grid value and availability for transport? (Section 3.3)

Maximising grid or emissions value comes at the cost of the energy available in vehicles for driving.

As a baseline, our scenarios allowed the full capacity of vehicle batteries to be available for V2G uses, as long as there was sufficient energy available to meet known trips (with no guarantees about charge being available for unexpected trips).

Such an approach will likely not be palatable to EV drivers, and so we investigated the impacts on V2G value by reserving a minimum state of charge in the batteries. While doing so unsurprisingly reduces the value of V2G because it reduces the flexibility that can be used to extract grid value, the extent of this reduction was surprisingly low. Selecting a 50% conservatism level (with V2G disabled while the battery charges up to a minimum 50% state of charge) only reduced the value of V2G in offices by 20% under the dynamic pricing scenario. Increasing the conservatism to 90% had a much more marked impact, reducing the value of V2G by 80% for offices with dynamic pricing. This leads to Finding 3: conservatively operating vehicle batteries still allows significant value from V2G.

Finding 3: Conservatively operating vehicle batteries still allows significant value from V2G

EV owners	***While reserving capacity in EV batteries reduces value, the value available remains substantial, even with relatively high levels of conservatism.*** ***EV owners will need to consider what setting is appropriate for their use case and value drivers.***

What is the trade-off between emissions reduction, cost and availability for transport? (Section 3.4)

As found throughout the REVS project, the ability to operate V2G in pursuit of various objectives creates the potential for different values to be placed in tension with each other. The pursuit of reducing cost may, as detailed above, increase emissions and vice versa. Conserving energy for transport reduces V2G's ability to respond price signals or emissions profiles.

The key take away from this is that these tensions must be made explicit and then navigated carefully by all parties with a stake in the outcomes. This is summarised in Finding 4: V2G can serve multiple – at times conflicting – goals. All stakeholders need to be informed of this and have agency over defining their preferred trade-offs.

Finding 4: V2G can serve multiple – at times conflicting – goals. All stakeholders need to be informed of this and have agency over defining their preferred trade-offs.

<table>
<tr><td>EV owners</td><td rowspan="3">Many values held by EV owners (such as emissions impact, PV self-consumption, and driving range) are in tension with economic returns. Furthermore, choices between objectives have consequences on the value available to other stakeholders. These tensions will need to be navigated carefully by all those with a stake in the outcomes of optimisation.</td></tr>
<tr><td>Grid operators</td></tr>
<tr><td>Market Participants</td></tr>
</table>

How could EV charging impact load growth? (Section 3.5)

The impact of V2G on load growth is striking. The results of this study are a warning: If not managed carefully, V2G can increase peak demands and result in large power swings in the energy system. This illustrates how flexibility can be a challenge for the energy system if it is not managed carefully. This is summarised in Finding 5: flexible resources need to be managed carefully as their penetration increases.

Finding 5: Flexible resources need to be managed carefully as their penetration increases

Grid operators	***If poorly managed, flexible resources can dramatically impact the distribution network through peak loads or minimum demand caused by coincident price (or other) events. This can cause load extremes and rapid changes in demand. Grid operators will need to consider mechanisms that reduce variability of flexible assets.***

What tools are effective at managing demand impacts of V2G? (Section 3.6)

Demand pricing appears to be a useful tool that grid operators can use to manage the impact of flexibility on the energy system. Export pricing and export rebates did not elicit significant response in this study. This is summarised in Finding 6: demand pricing is an effective tool for moderating demand.

Finding 6: Demand pricing is an effective tool for moderating demand

Grid operators	***Demand pricing shows the most promise at modulating demand from flexible assets when compared with energy prices and feed in credits.***

Is V2G economic? (Section 3.7)

Today, V2G has challenging economics. But in some niche use cases, where vehicles are plugged in for extended periods, V2G could soon be economic. In most cases charger prices still need to drop before V2G is economic. This is particularly true when assumptions used in this study such as forecast accuracy are relaxed to more realistic conditions. This leads to Finding 7: V2G is not currently economic, but may shortly become so in some use cases.

Finding 7: V2G is not currently economic, but may shortly become so in some use cases

EV owners Market Participants	***V2G currently has challenging economics.*** ***In ideally suited use cases – with high plug-in rates, high local demand to manage, and low capacity reservation needs – V2G may be economic soon.*** ***For many use cases significant price drops will be required before it is widely economic.***

Future meaning and further work

This study provides a quantitative backing to the qualitative findings in the social science and business models reports. As shown in findings there are several tensions inherent in the flexibility offered by V2G, which will need to be managed and actively negotiated by stakeholders if V2G becomes a mainstream constituent of the energy and transport systems.

We see (at least) three threads to follow in future work. These are described in Table 18.

Table 18 Threads for further work

Thread	Description
Understand tension in optimisation	There is tension in the way EV owners and the energy system may want V2G to operate. Future work can understand the materiality of these tensions and how they might be navigated.
Managing energy systems with large amounts of flexiblity	Flexibility is likely to have a central role in the future energy system. It does however present risks, as well as many opportunities. Future work can help understand how multiple, overlaid signals can be managed in a way that reduces the likelihood of undesired, coincident behaviour negatively affecting the energy system.
Impact of less accurate forecasts on value	This study assumed perfect foresight of price and driving needs. Future work could understand the impact of less accurate forecasts on the overall value proposition of V2G.

5 Bibliography

[1] L. Jones, K. Lucas-Healey, and B. Sturmberg, “Creating value from V2G: A report on business models,” Battery Storage and Grid Integration Program, Sep. 2022.

[2] K. Lucas-Healey, L. Jones, and B. Sturmberg, “Final Social Report,” Battery Storage and Grid Integration Program, Jun. 2022.

[3] L. Jones, K. Lucas-Healey, B. Sturmberg, H. Temby, and M. Islam, “The A to Z of V2G,” The Australian National University, Jan. 2021.

[4] S. L. Vargo and R. F. Lusch, “Evolving to a New Dominant Logic for Marketing,” *J. Mark.*, vol. 68, no. 1, pp. 1–17, 2004.

[5] The Australian National University and ZepBen, “Evolve Project Knowledge Sharing Report Milestone 5 DER Impacts on Operational Technology,” Mar. 2021. Accessed: Nov. 04, 2022. [Online]. Available: https://arena.gov.au/assets/2021/04/evolve-project-der-Impacts-on-operational-technology.pdf

[6] R. Farley, M. Vervair, and J. Czerniak, “Electric Vehicle Supply Equipment Pilot Final Report,” Avista Corporation, Oct. 2019. Accessed: Nov. 14, 2022. [Online]. Available: https://myavista.com/-/media/myavista/content-documents/energy-savings/electricvehiclesupplyequipmentpilotfinalreport.pdf

[7] C. Hunter, “World-first bi-directional EV chargers almost here - carsales.com.au,” Feb. 14, 2022. https://www.carsales.com.au/editorial/details/world-first-bi-directional-ev-chargers-almost-here-134220/ (accessed Nov. 14, 2022).

[8] Brighte, “Personal Loan – fixed interest rate for home improvements,” *Brighte*. https://brighte.com.au/homeowners/personal-loan (accessed Nov. 14, 2022).

[9] M. Nicholas, “Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas,” International Council of Clean Transportation, 2019. Accessed: Oct. 06, 2020. [Online]. Available: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf

[10] G. Bauer, C.-W. Hsu, M. Nicholas, and N. Lutsey, “CHARGING UP AMERICA: ASSESSING THE GROWING NEED FOR U.S. CHARGING INFRASTRUCTURE THROUGH 2030,” The International Council on Clean Transportaton, 2021. Accessed: Nov. 16, 2022. [Online]. Available: https://theicct.org/wp-content/uploads/2021/12/charging-up-america-jul2021.pdf

[11] D. Feldman, V. Ramasamy, and R. Margolis, “U.S. Solar Photovoltaic BESS System Cost Benchmark Q1 2020 Report.” National Renewable Energy Laboratory - Data (NREL-DATA), Golden, CO (United States); National Renewable Energy Laboratory (NREL), Golden, CO (United States), p. 1 files, 2021. doi: 10.7799/1762492.

[12] National Renewable Energy Laboratory, “Documenting a Decade of Cost Declines for PV Systems,” Feb. 10, 2021. https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html (accessed Nov. 16, 2022).

[13] E. Dudek, K. Platt, and N. Storer, “Electric Nation: Customer Trial Final Report,” Western Power Distribution, Bristol, 2019. Accessed: Jul. 06, 2020. [Online]. Available: https://www.westernpower.co.uk/downloads-view-reciteme/64378

[14] Western Power Distribution, “Western Power Distribution - Electric Nation Data,” *Western Power Distribution*. https://www.westernpower.co.uk/electric-nation-data (accessed Nov. 19, 2021).

[15] IBM, “IBM ILOG CPLEX Optimization Studio CPLEX User’s Manual,” IBM, 2017. Accessed: Nov. 29, 2022. [Online]. Available: https://www.ibm.com/docs/en/SSSA5P_12.8.0/ilog.odms.studio.help/pdf/usrcplex.pdf

[16] Australian Energy Market Operator, “2022 Integrated System Plan For the National Electricity Market,” Australian Energy Market Operator, Jun. 2022. Accessed: Aug. 22, 2022. [Online].

Available: https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf?la=en

[17] Australian Bureau of Statistics, “2016 New South Wales, Census All persons QuickStats | Australian Bureau of Statistics,” 2016. https://www.abs.gov.au/census/find-census-data/quickstats/2016/1 (accessed Oct. 31, 2022).

[18] P. Graham and L. Havas, “Electric vehicle projections 2021,” CSIRO, Australia, 2021. Accessed: Oct. 31, 2022. [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/csiro-ev-forecast-report.pdf?la=en

Appendix A Study framework

The aim of this work is to quantify the benefits and risks of V2G. This work does this by understanding how V2G would be used given a variety of conditions, assumptions, and optimisation targets. Essentially, it aims to answer the question: "How could customers change their energy usage when they have an EV and V2G?".

There are four steps to building this model, shown in Figure 44. They are described further in sections A.1 to A.4.

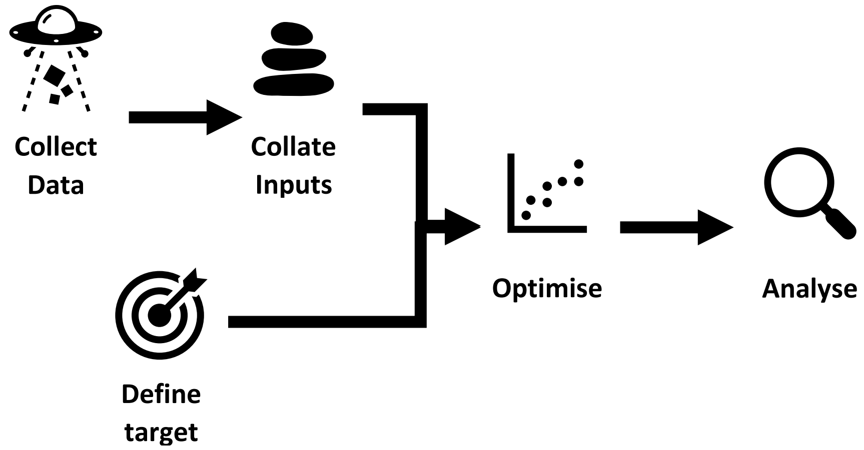


Figure 44 Analysis steps

The aim of this study is to understand customer behaviour and how this relates to the value customers and energy system bodies achieve form V2G. This means this study needs to begin with and understanding of the customer and their energy and transport landscape. Customers have four key factors that flow through to optimisation and thus value in different ways, shown in Table 19.

Table 19 Key customer factors for optimisation

Factor	Optimisation parameter	Type
Customer	Needs and aims	Optimisation target (
	Constraints on EV usage	Optimisation constraint
Site	Consumption profile	Input data
Generation	Generation profile	Input data
Vehicle(s)	Vehicle usage and energy needs	Optimisation constraint
	Charger type	Optimisation parameter

There are two different types of customer studied, described in Table 20.

Table 20 Customer types

Customer type	Details
Office	Offices are commercial buildings. Commonly have larger fleets and larger PV arrays.
House	Houses are private residences. Have small numbers of vehicles and moderate size PV arrays.

A.1 Collect input data

This step creates consistent input data. This input data is the basis for the rest of the studies therefore it is important that this data is high quality. There was four input data sources used, described in Table 21

Table 21 Input data

Data	Detail	# items	Use
ACT government vehicle data	Data on how the ACT government uses their vehicles. Telematics and booking data	142	Office vehicle usage and energy needs
ACT government site energy consumption	Data on consumption patterns of ACT government sites	10	Office energy consumption
Electric Nation vehicle usage	Vehicle charge energy data from Electric Nation trial in the UK	601	House vehicle usage data
NextGen house consumption	House consumption and PV generation data from NextGen project in the ACT	473	Solar generation for all customers. House consumption

These data sets were used to generate consistent datasets. There were two types of these: vehicle and consumption data. Both of these datasets are timeseries in 5-minute intervals.

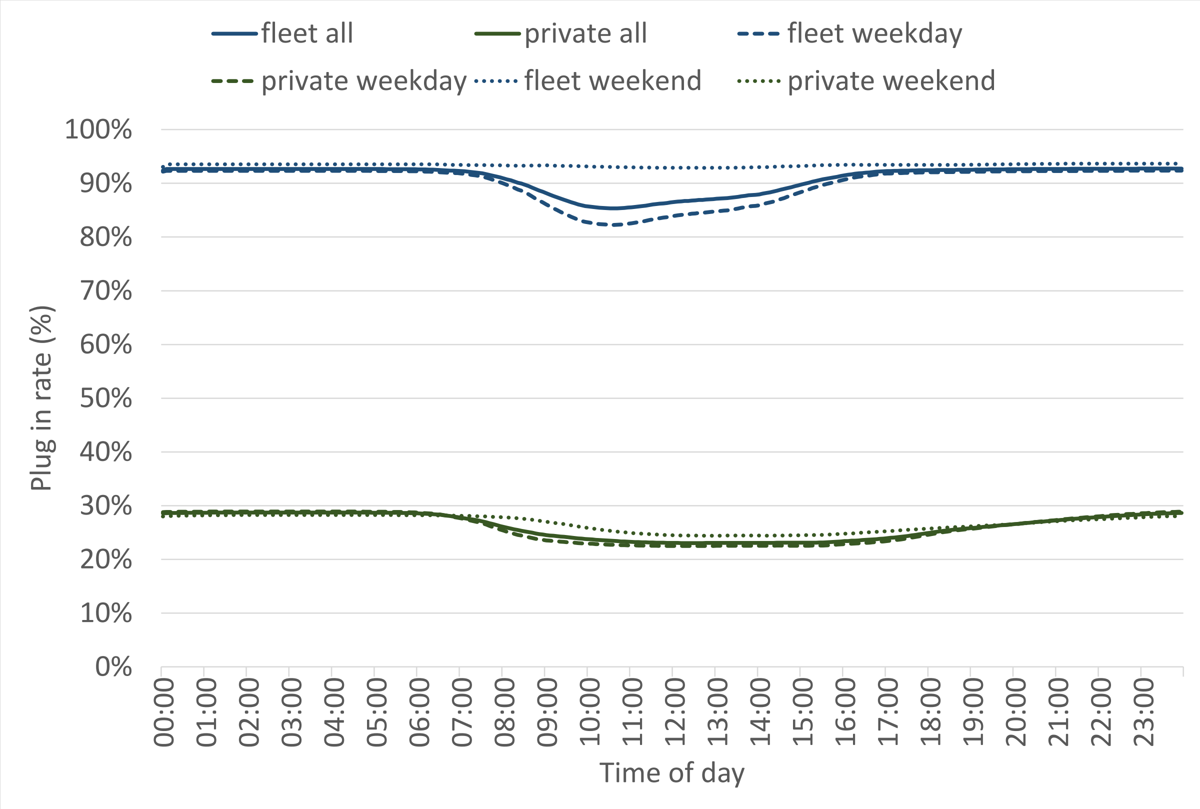
A.1.1 Vehicle data

Vehicle data indicates when vehicles are used and how much energy they use. It is built from ACT government vehicle data (sourced from vehicle usage data) and the Electric Nation project (charge session data). Although both datasets have been converted to the same format, due to their different source data they indicate different usage of the vehicle, shown in Table 22.

Table 22 Vehicle usage data sources

ACT government fleet data	Vehicle usage data assumes the vehicle is plugged in and could be used for V2G when it is at its home location
Electric nation charge data	Charger energy data assumes vehicle can be used for V2G only when it was plugged in in the Electric Nation trial. This is generally only every few days [13].

The difference in use can be seen in the data. Average vehicle availability for the two vehicle classes is shown in Figure 44.



REVS data also intersects with COVID. This means that usage may be lower than would occur had this not been the case. This can be seen in fleet vehicle usage data, shown in Figure 45

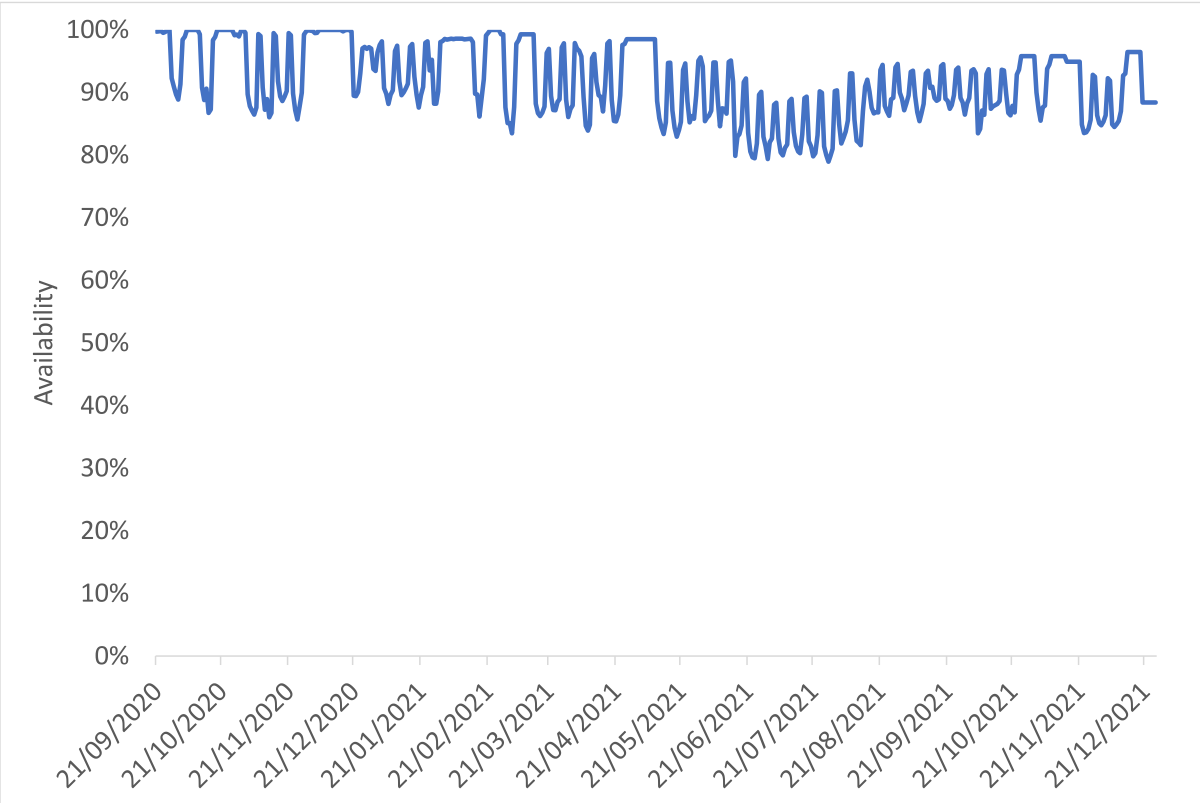


Figure 45 Daily fleet vehicle availability

Private vehicle data was collected prior to COVID, as shown in Figure 46. Similarly, as charger data it exhibits a much lower availability rate. Private vehicles, unlike fleet vehicles, appear to have a seasonal variation. Plug in rates are higher in winter (in December to February in the northern hemisphere).

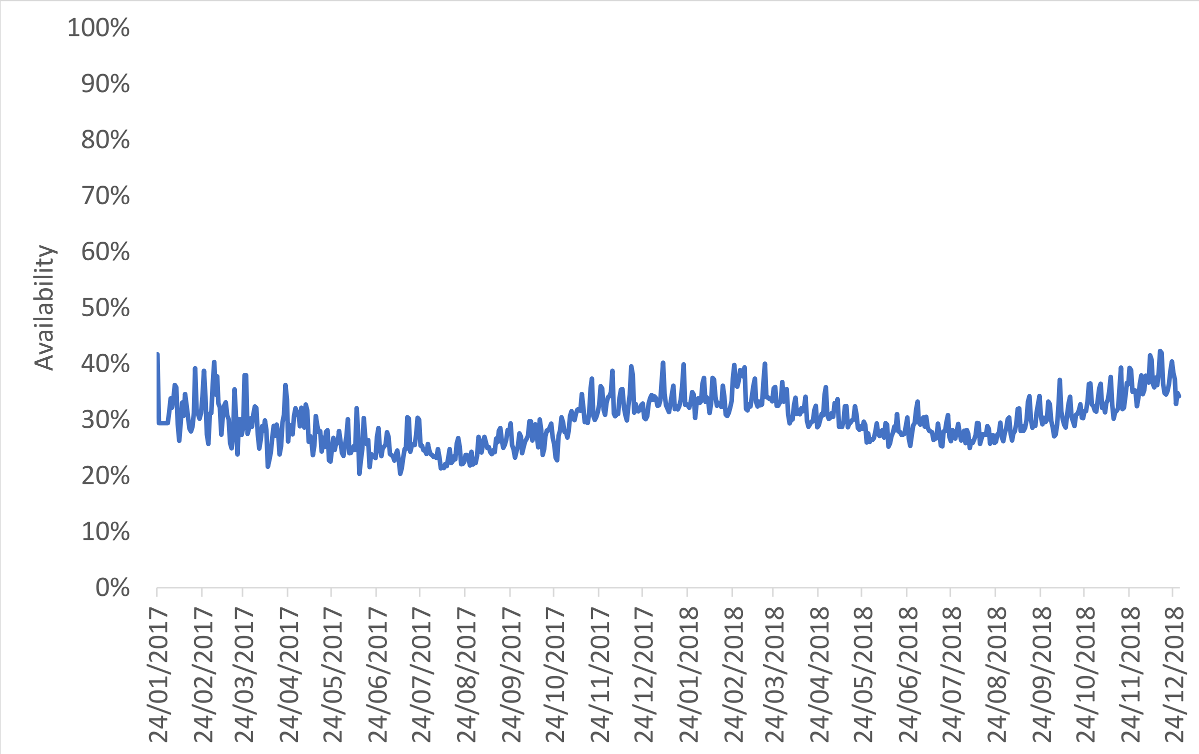


Figure 46 Daily private vehicle availability

ACT Government vehicle data

Office vehicle usage is based on data sourced from the ACT government. This data details vehicle usage for all ACT government vehicles between early 2021 and early 2022.

There were two datasets, shown in Table 23.

Table 23 ACT Government fleet data sets

Booking data	Indicates when vehicles are booked for use by drivers. Does not indicate when vehicles are used or how far they went.
Telematics data	Indicates events that have occurred in vehicles (e.g. when and where vehicles were started and stopped and how far they drove between these events).

For the purposes of this project it was assumed that all vehicles were 40 kWh Nissan Leafs.

These datasets were combined to create the final dataset. The data cleaning steps are described in Table 24.

Table 24 REVS vehicle data processing steps

Step 1: Read in booking data

Booking data is a series of events that describe:

- Which vehicle it relates to
- When the booking starts and ends

The first step is to convert this to timeseries availability data. This involves:

1. Create a standard timeseries for each vehicle – assuming vehicle is always available
2. Assign vehicle as unavailable during booking periods

Step 2: Read in telematics data

Telematics data is a series of events that describe:

- Which vehicle it relates to
- What kind of event it is
- When it occurs
- Where relevant: How far it went

Relevant types of events are:

- Start events denote the vehicle started driving ("Ignition On", and "Power Up")
- Stop events denote the vehicle stopped driving ("Ignition Off")

This step creates an entry that indicates when the vehicle is driving

3. Create a standard timeseries for each vehicle – assuming vehicle is never driving
4. Assign vehicle as unavailable during periods between start and stop events
5. Assign the distance the vehicle drove between these events to the first row the vehicle was driving
6. Assign the vehicle's location based on location of events

Step 3: Convert drive events to trips

Step 2 created a series of driving events. A trip will be made of multiple of these. For example, driving to and from a site are separate driving events but form one trip. This step does two things:

- Determines when vehicles were at their home base
- Determines how far they drove each event they weren't at their home base

This is done by the following steps:

7. Determine where vehicle's home is
    a. Group similar locations together by dividing into 100m x 100m boxes
    b. Set "home" as all locations where the vehicle spends more than 5% of its overnight (7PM-7AM) time when it isn't driving
    c. Set "home" flag based on the vehicle's presence at home locations
8. Determine lengths of trips away from home
    a. Between events where vehicle was not home, add all drive lengths together
9. Add missing booking data
    a. Where vehicles have no booking data or it is missing, substitute telematics "home" data
10. Add booking trip energy
    a. Summate all trip lengths between the start of each booking and the start of then next
    b. Convert length to energy by multiplying by 0.15 (40kWh leaf battery capacity divided by 270km advertised range)

Electric nation vehicle usage

Electric Nation was a trial in the UK between 2016 and 2018 by Western Power Distribution [13]. As part of their knowledge sharing for this project they made charging transaction data publicly available [14].

This data is converted to timeseries availability and energy use data for use in this project using the process described in Table 25.

Table 25 Electric nation processing steps

Step 1: Combine events
The Electric Nation data is made of a series of charging events. Charging transaction data is sourced from the chargers of trial participants. It specifies: • When the car was plugged in and unplugged • How much energy was transferred to the car in that time • Metadata on the vehicle (make, model, battery capacity) Several events are very short or close together. The first step involves combining these events: 1. Flag short events (less than one minute long) 2. Flag close events (less than 1 minute separating events) 3. Combine close and short events by extending start and stop times and consumed energy
Step 2: Generate data
This step converts processed transaction data to timeseries data. It involves: 4. Create a standard timeseries for each vehicle – assuming vehicle is always unavailable 5. Assign vehicle as available during periods when charging

A.1.2 Energy and generation data

Energy and generation data is used to determine how customers consume and generate energy. There were two different types of energy and generation data used in this project, shown in Table 22

Table 26 Energy data sources

ACT government consumption data	Metering data from ACT government sites that are participating in REVS. This is 30-minute timeseries connection point energy transfer data. There is no solar PV data in the provided dataset
NetGen energy data	De-identified behind the meter consumption data for houses participating in the NextGen trial. Includes consumption, generation, and battery power.

Average daily consumption is shown in Figure 47 and average generation is shown in Figure 48.

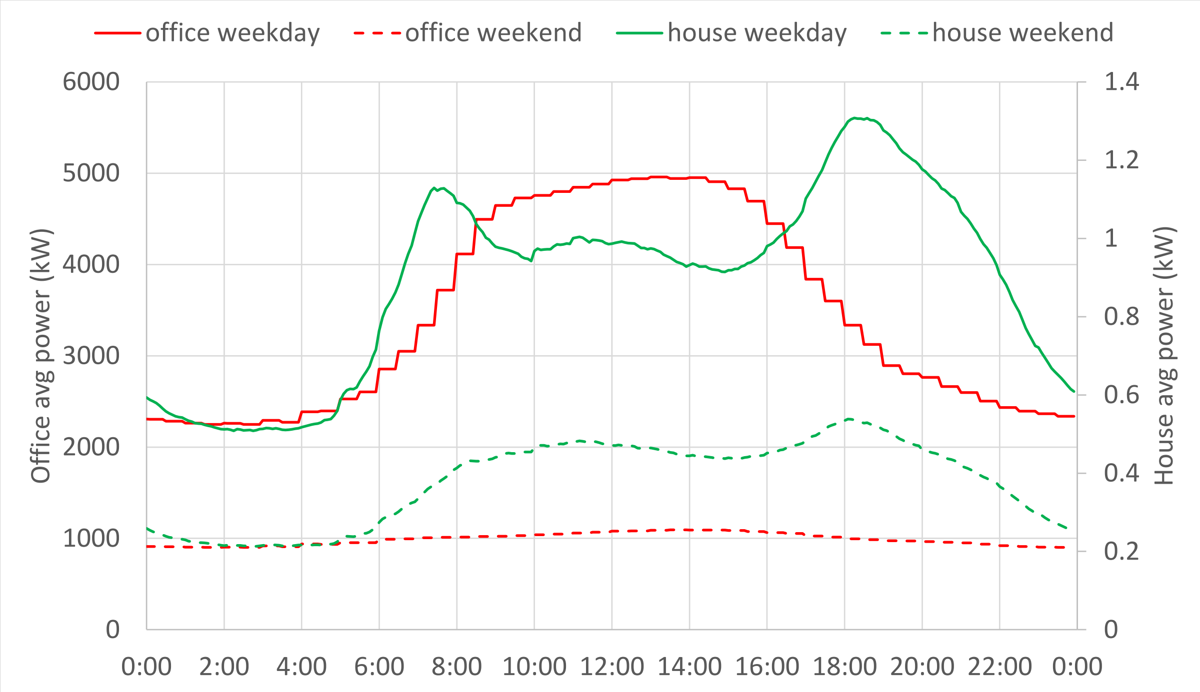


Figure 47 Average consumption over a day

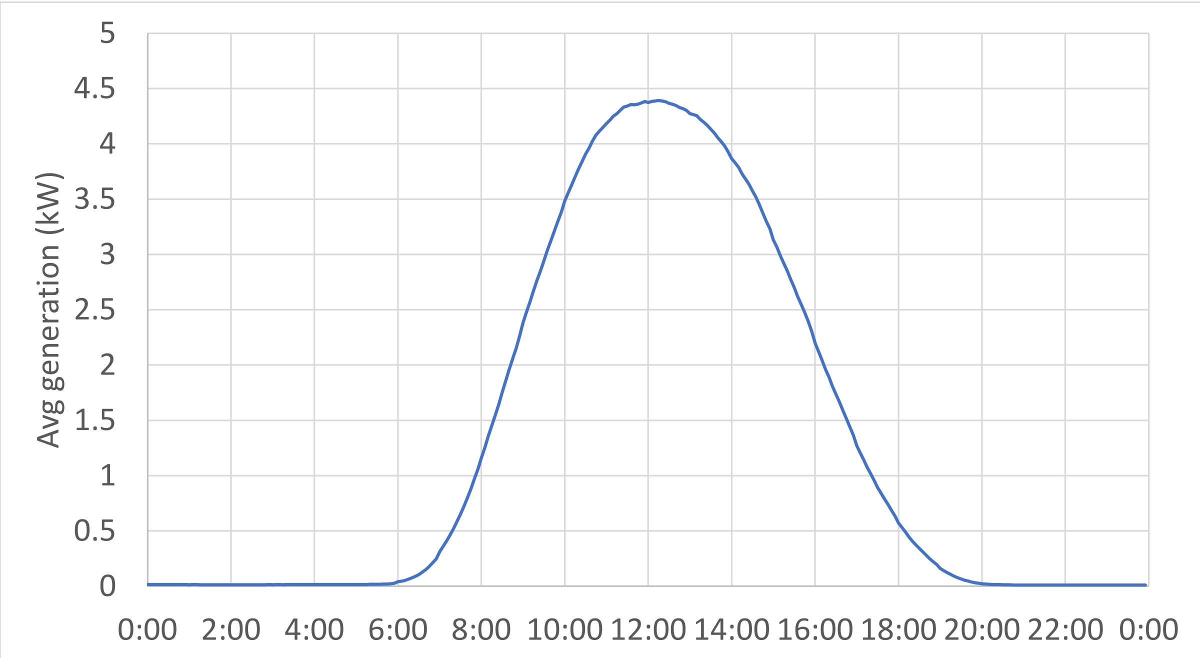


Figure 48 Average generation over a day

ACT government consumption data

ACT government consumption data covers connection point consumption for all 11 participating sites in the REVS trial. Average consumption for these sites varied between 94 and 2,400kWh/day. This data was presented as 30-minutely connection point consumption. For this project the data was resampled to 5-minute consumption by dividing the 30-minute consumption evenly between the 5-minute periods. Data was between mid-2020 and mid-2021.

NextGen consumption and generation data

NextGen data contains de-identified behind the meter consumption, generation, and battery data for households participating in the ACT Government Next Gen energy storage program. This data includes:

- House load consumption
- Solar generation
- Battery state of charge and power

Data was between mid 2017 and early 2019. The data cleaning process is shown in

Table 27 NextGen data cleaning process

Step 1: Clean input data
The first step was to remove battery data. Home batteries were not considered in this project. The data processing steps were: 1. Input data and remove errors (such as duplicate values) 2. Calculate load power by removing battery and PV influence from measured meter power 3. Calculate meter power by removing battery influence from measured meter power 4. Convert power to energy to be compatible with other consumption data
Step 2: Find and fix errors
The resultant data from step 1 had significant areas of missing data. This step: • Substitutes missing data less than 2 weeks long • Removes sites with more than 2 weeks of missing data Data is substituted for equivalent data from the previous week

A.2 Collate inputs

Source data provides the basis for the studies in this report, but before it can be used it must be converted. All data is from different times and places. Data is collated to be consistent in time and place. This takes the form of a "scenario".

Scenarios are a group of customers. Customers are people who connect to the energy system, and own energy related assets such as EVs. Customers have properties as described in Table 28.

Table 28 Customer properties

Property	Description
Customer type and consumption	Can be "house" (residential customer) or "office". Other types of customers (such as shops, factories, parking garages) were out of scope because we didn't have source consumption data for these types of customers.
Electric vehicles	How many EVs the customer has and how they use them.
Solar	How large PV array does the customer have and what is its generation profile.

Scenario generation involves building consistent collections of customers with appropriate metadata. The process to do this is described below.

Scenario building starts with the desired average daily consumption of the customer. This enable scenarios to be easily build based on load flow models if desired, although this was not done in this study.

Customer type and consumption

The first task is to determine what sort of customer is connected at the connection point and their consumption profile. For this study, customers were either houses (residential customers) or offices (non-residential customer). No input data for other customer types was available.

The process to assign this data is shown in Table 29.

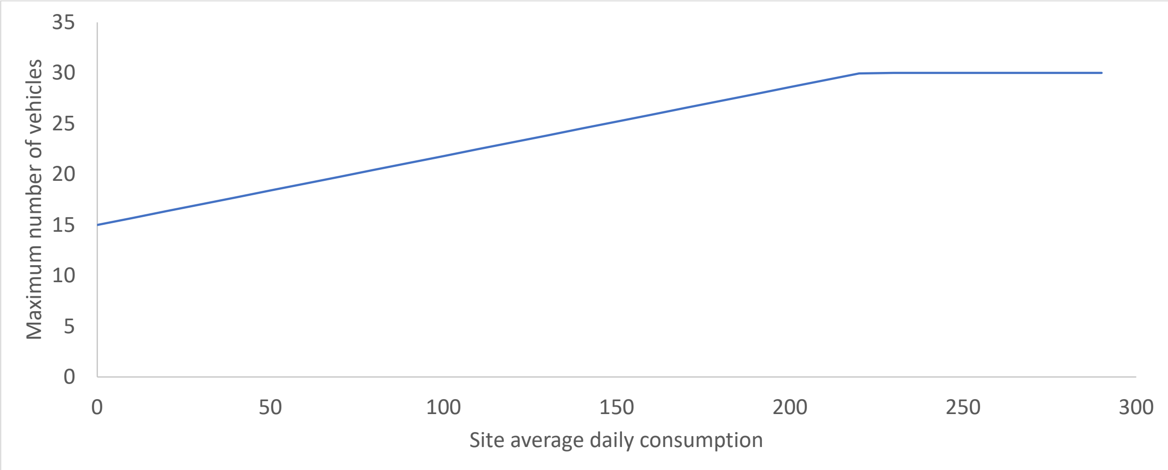
Table 29 Customer type and consumption process

Step 1: Assign customer type
The first step is to determine what type of customer is at each connection point. Customer type is assigned based on average daily consumption. In this study, customers with less than 80kWh/day consumption are assumed to be houses, and over 80kWh/day are offices.
Step 2: Assign source data
This step assigns an appropriate source data to the connection point. Source data is selected based on: • Being the same type (e.g. house or office) • Having average daily consumption close to the requested consumption
Step 3: Add timeseries data
This step assigns the timeseries source data. This involves two translations: • Translating data in time • Translating data in place Both functions are performed based on temperature. The process for this is: 1. Collect daily maximum temperatures for source data 2. Collect daily maximum temperatures for destination dates and place 3. Fill destination data week by week by finding the source date week with the minimum RMS error in maximum temperatures over the week

Electric Vehicle data

The main purpose of the REVS trial was to understand the value of V2G. This means vehicle data is very important. The process to assign vehicle data is shown in Table 30.

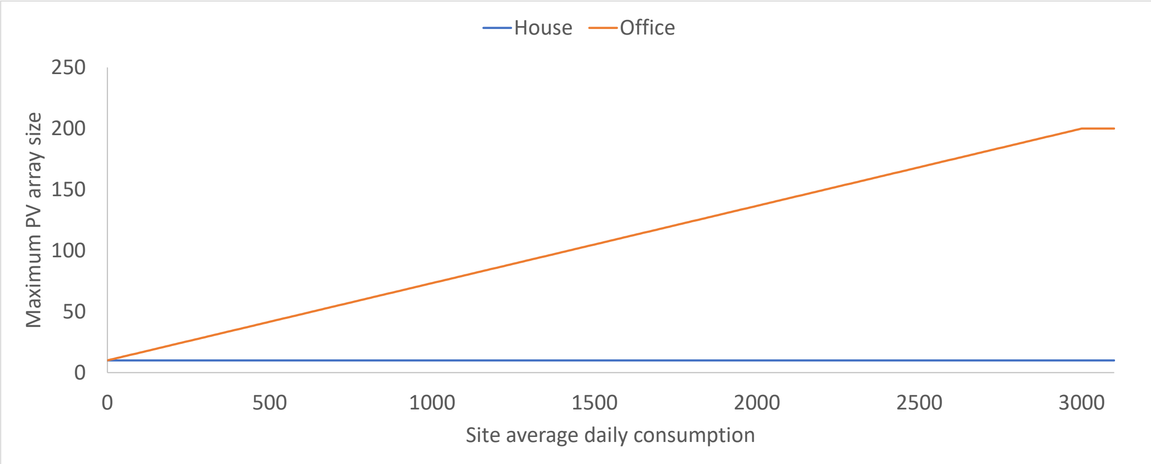
Table 30 EV data process

Step 1: Determine how many EVs each customer has
Customers can have multiple EVs. Each customer was assigned a number of vehicles randomly, with a maximum number based on their consumption. • Houses had 1 or 2 EVs based on typical vehicle ownership (of any type of vehicle) • Offices had EVs assigned based on the function in Figure 49.  *Figure 49 Maximum office EV related to consumption*
Step 2: Assign source data
Each EV has source data assigned to it. Where possible (for REVS data) vehicles were assigned from the same site. This preserves common use patterns over sites. Similarly, vehicles were assigned from the same class. E.g., Electric Nation data was used to assign private vehicles, and REVS data for offices.
Step 3: Add timeseries data
Timeseries data was assigned using a similar methodology to consumption data. The key difference was where vehicles were away at the end of the week, multiple consecutive weeks were added until the vehicle was available at the end of the week.

Solar data

PV data was sourced from NextGen for both houses and offices because no REVS sites have PV installed. The methodology for assigning data is shown in Table 31.

Table 31 PV data process

Step 1: Determine size of customer's PV array
Customers were connected with a PV array based on their average daily consumption. A random PV array size was selected up to the value given in the function in  *Figure 50 Maximum PV array size based on consumption*
Step 2: Assign source data
Timeseries PV data was randomly assigned and scaled from NextGen trial data.
Step 3: Add timeseries data
Timeseries data was assigned using a similar methodology to consumption data.

A.3 Define targets

The scenario builder described in A.2 contains a set of base data. This step builds a set of targets for the optimiser to develop EV charge profiles.

Targets are two factors:

- Pricing communicates measures of good
- Constraints communicate how flexible parameters are.

A.3.1 Pricing

The optimiser aims to reduce the overall price of supplying energy at the customer's connection point. In most cases for REVS this is an energy (network and retail) price, however in the emissions case, emissions intensity was used as a proxy.

There were three pricing methods used, described in Table 32 and in more detail below.

Table 32 Pricing types

Price	Description
Current pricing	Customers are optimised against an existing retail price, assigned based on the customer class: • Houses are assigned the "ActewAGL Home Time of Use" tariff • Offices are assigned the "ActewAGL LV TOU demand" tariff
Dynamic pricing	Dynamic pricing builds a price signal that reveals the underlying nature of price drivers. It is split into two components: • A network price, based on the EVO energy "smart battery" tariff • A market price which is directly passed through for consumption, scaled to 90% for feed in
Emissions	Marginal emissions for NSW1 region of the NEM is used as a dynamic price signal

Current pricing

This is two existing tariffs:

- Houses are assigned the "ActewAGL Home Time of Use" tariff
- Offices are assigned the "ActewAGL LV TOU demand" tariff

The pricing components and their values is shown in Table 33

Table 33 Current pricing components

ActewAGL Home Time of Use	ActewAGL LV TOU demand
Peak energy: • $0.37433/kWh • 7AM - 9AM and 5PM – 8PM daily **Shoulder energy:** • $0.25982/kWh • 9AM - 5PM and 8PM – 10PM daily **Off-Peak energy:** • $0.21945/kWh • 10PM – 7AM daily **Feed in:** • $0.08/kWh	**Demand:** • $0.46057/kVA/day • Maximum half-hourly demand each month **Peak energy:** • $0.22/kWh • 7AM-5PM weekdays **Shoulder energy:** • $0.1825/kWh • 5PM - 10PM weekdays **Off-Peak energy:** • $0.16/kWh • All other times **Feed in:** • $0.08/kWh

Dynamic pricing

The dynamic price is made of two components:

- A dynamic distribution component based on evoenergy's "smart battery tariff" trial tariff. For residential customers this is applied directly, for offices it has been modified to reflect commercial pricing
- A market price passthrough, scaled to 90% for feed in

The commercial version of the smart battery tariff was created by:

- Changing the pricing periods of time of use elements to reflect the ActewAGL LV TOU demand. This involved:
    - Extending peak demand time to cover all workday except for solar sponge period
    - Making all weekend off-peak
    - No export charge was modelled
- Rebalancing prices so overall cost was like the existing ActewAGL LV TOU demand price

The pricing components and their values is shown in Table 34

Table 34 Dynamic pricing components

House	Office
Market price passthrough • 100% of NSW1 market price **Max energy:** • $0.10529/kWh • 7AM - 9AM and 5PM – 8PM daily **Mid energy:** • $0.06816/kWh • 9AM – 11AM, 3PM - 5PM, and 8PM – 10PM daily **Economy energy:** • $0.03354/kWh • 10PM – 7AM daily **Solar Sponge energy:** • $0.01676/kWh • 11AM – 3PM daily **Export charge:** • $0.01552/kWh for export over 3.75kWh/day • 11AM – 3PM daily **Critical peak price:** • $1.95647/kWh export rebate • During critical peaks only **Feed in:** • 90% of NSW1 market price **Demand:** • $0.15353/kW/day in summer and winter • $0.10246/kW/day in autumn and spring • Maximum half-hourly demand between 5PM - 8PM each month	**Market price passthrough** • 100% of NSW1 market price **Peak energy:** • $0.13645584/kWh • 7AM - 11AM and 3PM – 5PM weekdays **Evening energy:** • $0.08833536/kWh • 5PM – 10PM weekdays **Off-peak energy:** • $0.0434674/kWh • All other times **Solar Sponge energy:** • $0.01676/kWh • 11AM – 3PM daily **Critical peak price:** • $1.95647/kWh export rebate • During critical peaks only **Feed in:** • 90% of NSW1 market price **Demand:** • $0.19874/kW/day in summer and winter • $0.13279/kW/day in autumn and spring • Maximum half-hourly demand between 5PM - 8PM each month

The peak events for the "critical peak" elements are shown in Table 35. These events were selected by the dates and times of maximum summated power for the "no EV" case in the scenario used in this study.

Table 35 Critical peak events

Event	House	Office
Event 1	16/06/2019 17:15	23/01/2019 13:05
Event 2	24/06/2019 17:25	21/02/2019 7:00
Event 3	27/06/2019 17:10	1/03/2019 13:05

Event	House	Office
Event 4	14/07/2019 19:25	1/07/2019 7:25
Event 5	26/07/2019 17:55	1/08/2019 13:25
Event 6	13/08/2019 16:30	1/11/2019 13:25

Emissions price

The emissions price does not reflect any real energy pricing methodology. It is designed to understand how V2G would operate if the aim was to reduce emissions.

This signal is the marginal tons/CO_2/kWh of the NSW1 region of the NEM.

A.3.2 Constraints

There were two constraints modelled in this study, both of which were related to drive energy:

- Ensure there is enough energy at the start of every trip for driving needs
- Attempt to maintain a minimum state of charge (conservation value)

The first constraint aims to minimise public charging requirements. Charging at base is more convenient and cheaper than public charging therefore it is preferable to public charging. This is modelled the same way in all cases.

The second constraint reflects the desire of fleet managers to have energy in vehicles for unexpected travel. There are three different levels studied: 0%, 50%, and 90% state of charge.

A.4 Optimise

The optimisation aims to minimise the cost of supplying energy to a customer while ensuring that EVs are sufficiently charged to meet upcoming trip requirements and subject to constraints. Here, we show an example optimisation formulation for a customer with a single EV and solar considering import and export tariffs that vary as a function of the day: the extension from this to multiple EVs and more complicated block and peak demand tariffs is straight-forward. The objective function is expressed as

$$\min \quad \sum I_t \; p_{imp,t}^{+} E_t p_{exp,t}$$

Where t specifies a time period for which I_t is the cost of importing energy from the grid, $P_{imp,t}$ is the amount of power imported, E_t is the amount paid for exporting energy to the grid, and $P_{exp,t}$ is the amount of power exported to the grid. The costs and amount paid will vary depending on the specific tariffs used. All p variables are considered to have units of kWh.

The power balance for the customer is enforced with the constraint

$$P_{imp,t} + P_{exp,t} + P_{sol,t} + P_{ch,t} + P_{dis,t} = 0,$$

Where $P_{sol,t}$ is the solar generation, $P_{ch,t}$ is the EV charging energy and $P_{dis,t}$ is energy discharged from the EV.

To ensure that the EV cannot simultaneously charge and discharge, and that power cannot be simultaneously exported and imported from the grid, the following constraints are used:

$-Ma_t b_{1,t} \leq P_{dis,t} \leq 0,\ \ 0 \geq P_{ch,t} \geq (1 - b_{1,t})Ma_t,$

$-Mb_{2,t} \leq P_{exp,t} \leq 0, \quad 0 \geq P_{imp,t} \geq (1 - b_{2,t})M,$

Where $b_{1,t}$ and $b_{2,t}$ are binary decision variables, M is a large value and a_t is a binary value representing whether the EV is plugged in and available to charge. This is commonly referred to as the Big-M method for splitting a single variable into its positive and negative values.

The state of charge of the EV battery is determined according to

$SOC_{t+1} = SOC_t + \eta_{ch} p_{ch,t} + \eta_{dis} p_{dis,t} - u_t,$

Where u_t is energy used on a trip, $\eta_{ch}$is the charging efficiency and $\eta_{dis}$is the discharging efficiency.

The state of charge is constrained within by its capacity

$SOC_t \geq 0 \qquad SOC_t \leq F,$

Where F is the maximum capacity. An additional constraint is then placed on the state of charge to represent customer conservativeness

$SOC_t \geq C_t - s_t,$

where C_t specifies the level of conservativeness and $s_t \geq 0$ is a slack variable allowing state of charge to go less than C_t if it is required for a trip, or there is no other feasible solution. A high cost on s is added to the optimisation objective.

The final optimisation has the decision variables $\{p_{ch,t}, p_{dis,t}, b_{1,t} b_{2,t}, s_t : \forall t\}$ and optimising these variables is a mixed integer linear problem. The optimisation is solved using CPLEX [15].

Appendix B Forecast constraints methodology

In this study, constraints are forecast using existing optimisation results. The process to generate these scenarios is shown in Figure 51. There are three key steps: scenario, forecast, and timeseries.

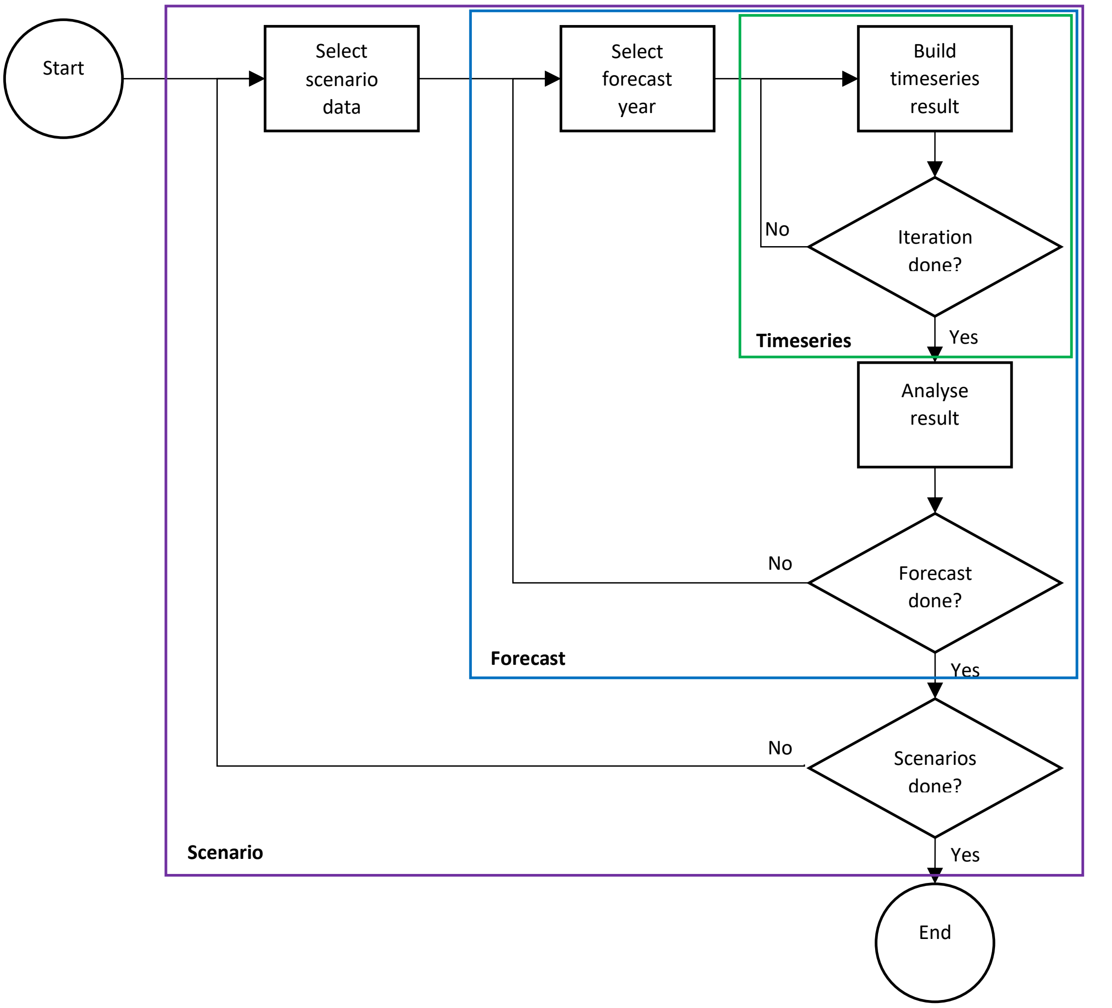


Figure 51 Forecast constraint analysis flowchart

B.1 Scenario analysis

This step selects the source data. For each scenario there are four data sources used in the analysis of each scenario, shown in Table 36.

Table 36 Scenario data sources

	With PV	**Without PV**
With EV	Scenario optimisation with PV	Scenario optimisation without PV
Without EV	Base case with PV	Base case without PV

Each scenario defines an optimisation target and charge method. The scenarios considered are described in 3.5.

B.2 Forecast

Forecasts in this report were based off the ISP 2022 forecasts [16]. There are three forecasts used: Demand, PV penetration, EV penetration

Demand forecasts

Demand forecasts are based on the 50% POE maximum demand forecasts for the "Step change" scenario for the "NSW1" region. Both are assumed to grow at the same rate. The forecast (in ratio of base demand) is shown in Figure 52. To generate the demand curve, the original demand is multiplied by this ratio.

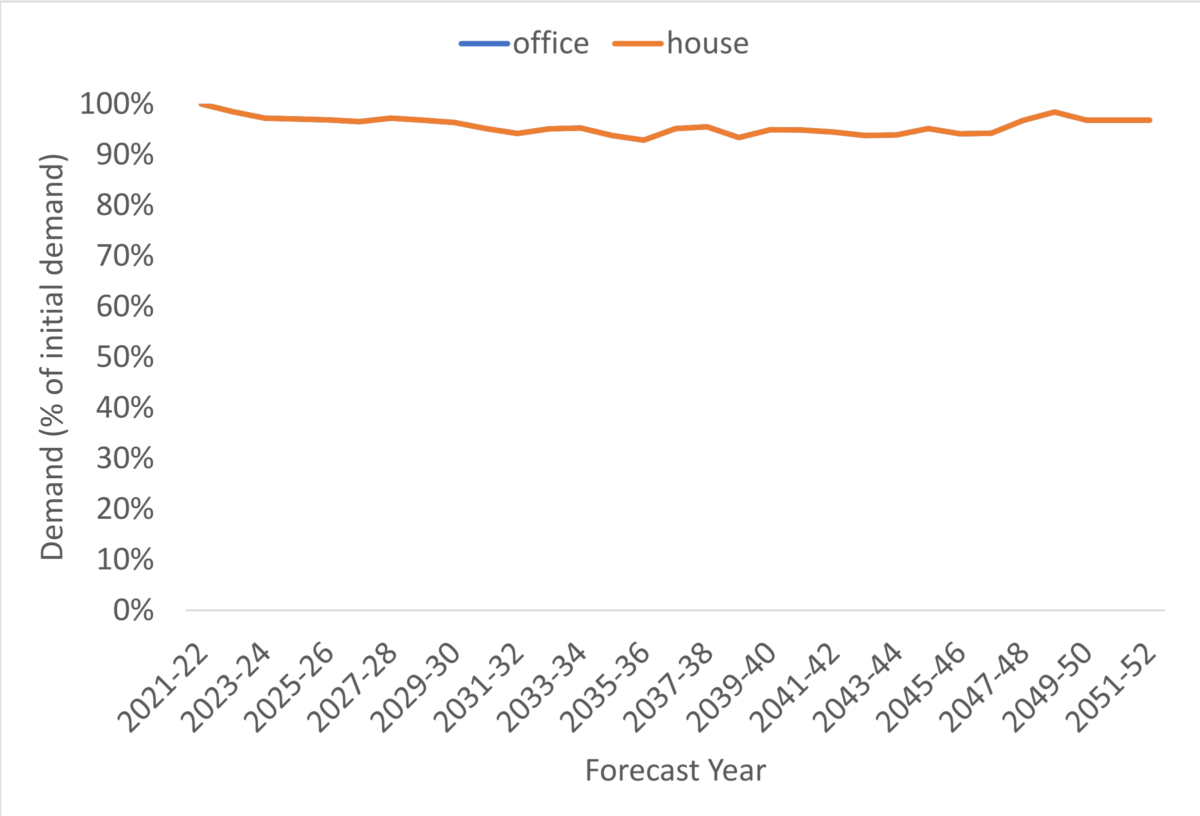


Figure 52 Demand forecast

PV penetration

PV penetration forecasts in the ISP are presented in terms of installed capacity (MW). For use in this study, this needed to be converted to penetration (%). To convert between the two, Equation 1 was used, where:

- $PV_{\%}$ is the forecast percent penetration of PV for the year
- PV_{MW} is the forecast total MW of PV for the year for the "step change" scenario, sourced from the ISP [16]
- *AvgSize* is the average size of PV systems for the year. 8 kW was used in this study
- *NumConnections* is the number of private dwellings in NSW. This is 3,059,599 as per [17]

$$PV_{\%} = \frac{PV_{MW}/_{AvgSize}}{NumConnections} \text{ (1)}$$

The forecast for both houses and offices is the same. The forecast penetration is shown in Figure 53.

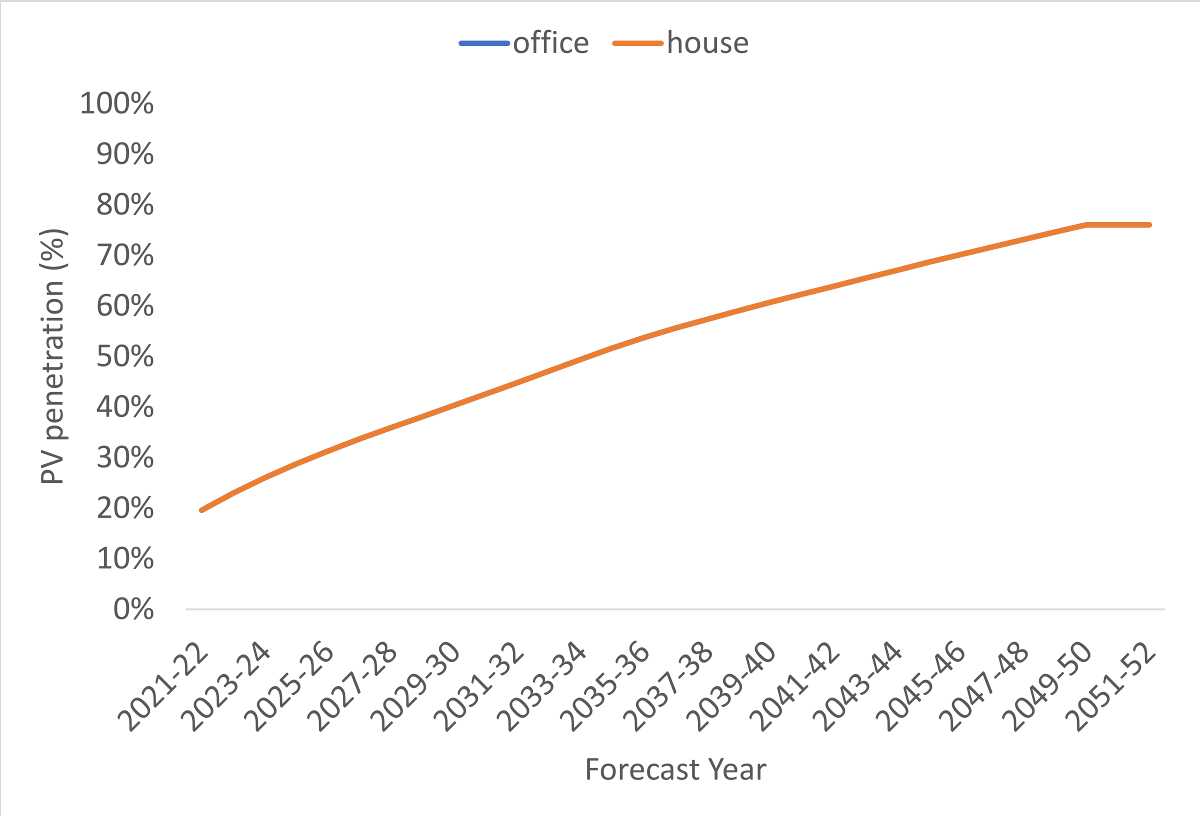


Figure 53 PV penetration forecast

EV penetration

EV forecasts were as per CSIRO forecasts [18] for “car”. Both office and house used the same forecasts. For simplicity all vehicles at a location were assumed to transition to electric simultaneously. The forecast is shown in Figure 54.

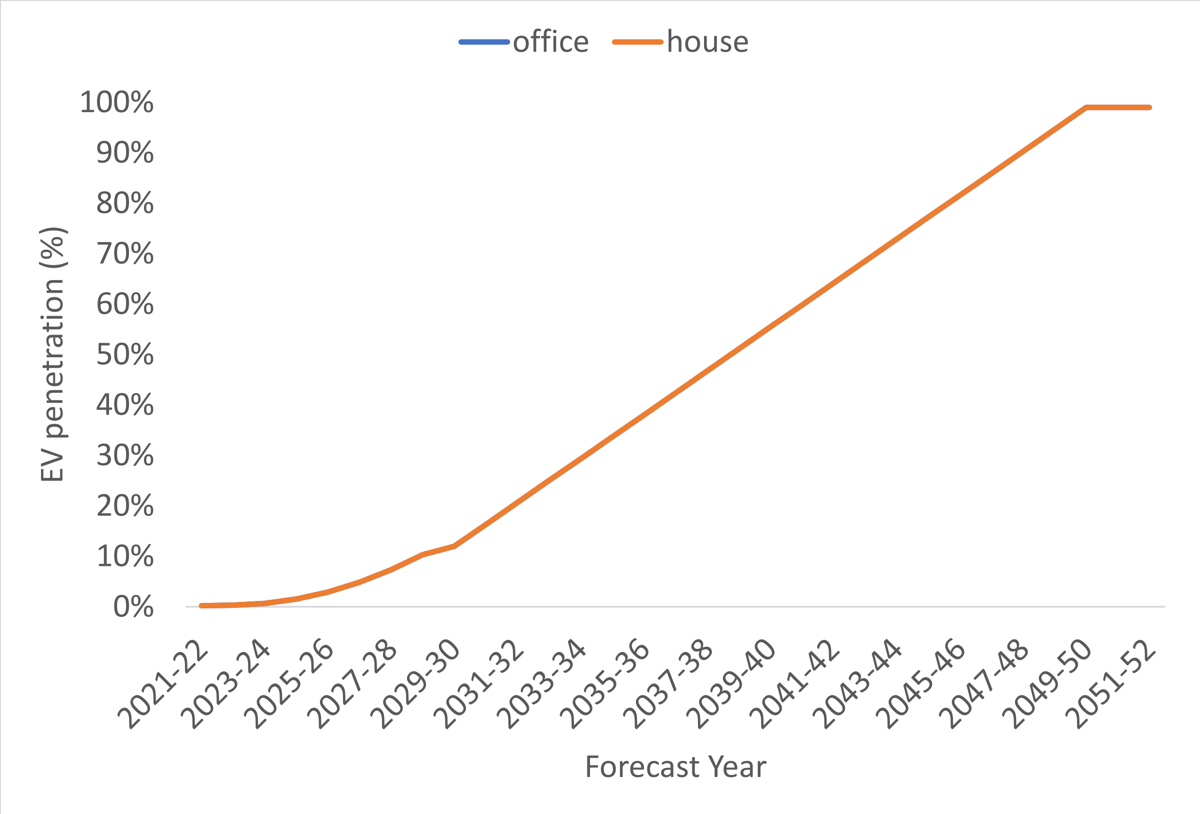


Figure 54 EV penetration forecast

B.3 Timeseries

Timeseries data is generated using combinations of existing results from optimisation. Each scenario/forecast combination is studied 10 times to control for variance in the randomly generated source data. The flow chart for timeseries studies is shown in Figure 55.

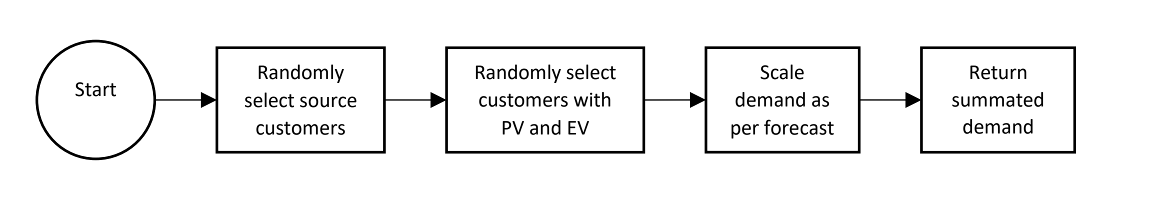


Figure 55 Timeseries generation flowchart