Battery Storage and Grid Integration Program

ACT Government

Unplugged is inflexible

How drivers' plug in behaviour determines the flexibility of electric vehicle (dis)charging

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Acknowledgements

We acknowledge, respect and celebrate the Ngunnawal and Ngambri people, on whose land this research was conducted and pay our respects to Elders, past, present and emerging.

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Contents

Executive summary

The potential for electric vehicle (EV) charging to overload the electricity system is well known in policy and public discourses as electric vehicle sales boom. Similarly, it's well understood that EVs are parked most of the time so that their impacts can be reduced using "smart" or "managed" charging capabilities to fit this charging around existing electricity demand.

The oft overlooked link is that EVs must not only be parked for extended periods: they must be plugged in to a charger for extended periods. This is not a matter of technological systems but driver behaviour. If drivers only plug their EVs in when they require them to charge rapidly ahead of a trip, there is no flexibility.

This study focuses on this pivotal issue: how does the amount of time that EVs are plugged in to chargers impact the potential benefits of managed charging. We consider multiple objectives for managed charging and assess the impacts on the cost of charging, the stress on the distribution network and the potential to align charging with renewable energy generation.

We find that:

- **Vehicles being plugged in 25% of the day (6 hours), or 42 hours a week, is sufficient to realise most of the benefits of managed charging.**
- A modest plug-in-fraction of 25%
    - reduces charging costs from $1.28 to $0.72 per day in the absence of vehicle-to-grid,
    - enables vehicle-to-grid to greatly reduces costs further to $0.24 per day (plugged in at all times),
    - provides sufficient flexibility to ensure EV charging occurs at times of low zone substation load, facilitating a near optimal hosting capacity.
- The ACT contracted solar and wind farms provides a reliable output to power EV charging at any time. When EVs are plugged in most of the time charging can occur when renewable generation exceeds 2000MW.

We also consider scenarios where EVs can only connect to chargers during the daytime, or exclusively overnight. The impacts of these constraints are:

- The nighttime offers more opportunities to charge at simultaneously low prices and network demand.
- The financial value of vehicle-to-grid is similar when vehicles are plugged in during the daytime or overnight, but the grid impacts are far better overnight.

The central policy implication of these findings is that **encouraging EV drivers to plug their vehicles in as frequently as possible should be the primary behavioural message.** Plugging in around 25% of the time – 6hrs a day or most of the weekend – appears to be a good target. Encouraging charging overnight is a secondary priority.

Options should be explored for making **managed charging the default behaviour of EVs**, while discouraging, restricting, or prohibiting unmanaged Level 2 charging. Unmanaged Level 1 charging places five times less stress on the network.

Managed charging could be implemented via auto manufacturers, who have stable communication with their vehicles, irrespective of where they are and what charger/socket they're connected to.

Study outline

Motivation

The electrification of vehicles creates a tremendous new demand for electricity, which, theoretically, ought to be tremendously flexible in its delivery.

In the ACT, there are currently 320,000 vehicles[1]. If these were all to be electric vehicles (EVs) and to charge using a 7.4kW Level 2 charger, it would take less than a third of vehicles charging simultaneously to double the territory's 2023 peak demand[2].

The good news is that there is no need for so many vehicles to charge simultaneously. The average Australian vehicle drives 12,000km per year, which requires about 2,000kWh of electricity[3]. This could be delivered by a 7.4kW charger in 270 hours, in other words by charging 3% of the year. Given that private vehicles are parked spend a lot more time than this parked – over 95% of the year in some studies[4] – there ought to be ample opportunities to time the charging of electric vehicles to fit around other electricity demand (including other electric vehicle charging).

While this is all well known, it is oft overlooked that it is not sufficient for EVs to be parked for extended periods – the flexibility of EV charging also depends on EVs being plugged in to a charger for extended periods. If drivers only plug their vehicles in occasionally and then require them to charge rapidly ahead of a trip, then there is no flexibility.

Additionally, even where vehicles are plugged in for extended periods, realising the flexibility opportunity requires driver consent, technology capabilities, and contractual arrangements – which are outside of the scope of this work.

[1] https://www.abs.gov.au/statistics/industry/tourism-and-transport/motor-vehicle-census-australia/latest-release#states-and-territories

[2] https://www.evoenergy.com.au/-/media/Project/Evoenergy/EVO/Documents/About-us/APR/Annual-Planning-Report-2023.pdf

[3] https://electricvehiclecouncil.com.au/docs/how-much-electricity-does-charging-an-electric-vehicle-consume-compared-to-typical-household-usage/

[4] https://www.racfoundation.org/research/mobility/spaced-out-perspectives-on-parking

Conceptual approach

We distil EV driver behaviour down to the fraction of time that they plug their EV in to a charger, and then calculate how this constrains the opportunities for managed charging.

Our approach is shaped by carrot and stick forces. It is designed to circumvent the shortage of data available on how EVs are driven and charged. But beyond this, it is designed to focus policy and public conceptualisation and communication of EV charging behaviour on the simplest possible metric: **what portion of the week is an EV plugged in to a charger?**

From this simple metric it is highly intuitive that the more an EV is plugged in the more opportunities there are to manage its charging to achieve a desired goal(s). While it's possible to add further rules of thumb, such as electricity prices being low overnight and during sunny periods, these should be seen as secondary – and likely considered by only more engaged electricity customers.

To build on this simple metric – the fraction of time that EVs are plugged in to a charger – we use a Monte Carlo sampling approach. This essentially involves:

1. setting a desired *plug-in-fraction*,
2. calculating combinations of times during which an EV is connected, and is not connected, to a charger that meet the desired *plug-in-fraction* – each of which we call a *plug-in-profile*,
3. randomly selecting one of these *plug-in-profiles* and calculating the optimum charging behaviour to meet a specific objective (such as minimised cost),
4. repeating steps 1 & 2 thousands of times, across many different parts of the year, to build up a statistical sample of possible *plug-in-profiles* that meet the desired *plug-in-fraction* and the resultant optimised EV charging profiles.

We do this considering a multiday period, so that EVs do not need to be plugged in at all on any given day. We also consider additional constraints, such as what times of day vehicles can be plugged in. The method for composing *plug-in-profiles* and optimising within these is described in more detail in the following section.

Selected scenarios

Based on ACT Government input, we developed three temporal scenarios and applied these to two geographic regions. We considered four objectives that could be pursued through managed EV charging.

The ACT Government team are interested in understanding the features of EV charging in different contexts, such as in homes, in workplaces and in commuter carparks. We include these details by placing a constraint on when EVs could possibly plug in.

As there are no strict definitions or constraints of these contexts, we implemented **three temporal constraints**:

1. *Unconstrained* – EVs are equally likely to plug in to a charger at any time of day,
2. *Daytime only* – EVs are only able to plug in between 6am and 7pm,
3. *Nighttime only*– EVs are only able to plug in between 7pm and 6am.

We conducted studies with reference to the **zone substations in Belconnen and Gungahlin**. We found that these substations have very similar load profiles, in shape and proximity to substation capacity ratings, and therefore produced very similar results. In the interest of clarity we therefore present only one set of results, for Belconnen.

For each geographic and temporal scenario, we calculate the optimum charging behaviour with respect to **four objectives**:

1. *Minimise cost – no V2G* – minimise the cost of charging with reference to the National Electricity Market (NEM) price in NSW.
2. *Minimise cost – V2G* – minimise the cost of charging and maximise the revenue from discharging (using vehicle-to-grid) with reference to the NEM price in NSW.
3. *Minimise network demand* – charge at times when the zone substation is experiencing minimum demand.
4. *Maximise use of RE generators* – charge at times of maximum generation by a set of specified renewable energy generators.

For V2G we consider a roundtrip efficiency (charging and discharging) of 90% and impose a minimum threshold for the revenue that is to be made by a charge-discharge cycle of $500/MWh to cover the network costs of this energy, and some token of the degradation of the battery.

For the RE generator objective, we seek to match the output of the wind and solar farms included in the ACT Large-scale feed-in tariffs and reverse auctions. These are: Crookwell Wind Farm, Mugga Lane Solar Farm, Royalla Solar Farm, Sapphire Wind Farm, Hornsdale 1,2,3 Wind Farms, Ararat Wind Farm, Berrybank Wind Farm, Coonooer Bridge Wind Farm.

In total, these temporal combinations and objectives produce 12 distinct scenarios, listed in Table 1. We simulate these for 6000 samples across the year of 2022. This year was selected for data availability. It was a particularly volatile year for NEM prices, which must be kept in mind when assessing the results.

For all scenarios we consider EVs to require 14.8kWh of charge across the two-day period. This is slightly above the average demand of driving 12,000 km per year[5] (11kWh) but neatly matches 1 hour of Level 2 charging per day (at 7.4 kW).

[5] https://electricvehiclecouncil.com.au/docs/how-much-electricity-does-charging-an-electric-vehicle-consume-compared-to-typical-household-usage/

Table 1 – Scenarios and optimisation objectives considered in this study

Geographic region	Temporal constraints	Charging optimisation objective
Belconnen	Unconstrained	*Minimise cost – no V2G*
		Minimise cost – V2G
		Minimise network demand
		Maximise use of RE generators
	Daytime only	*Minimise cost – no V2G*
		Minimise cost – V2G
		Minimise network demand
		Maximise use of RE generators
	Nighttime only	*Minimise cost – no V2G*
		Minimise cost – V2G
		Minimise network demand
		Maximise use of RE generators

Results for Belconnen

This section presents the main results of the study: quantifying how the proportion of time that vehicles are plugged into chargers affects the possibilities of managed charging.

The aim of this section is to summarise the statistical results from our simulations in a way that highlights the effect of *plug-in-fractions*. This is done by distilling the results for each *plug-in-fraction* to a mean value, together with the 1st, 10th, 20th, 80th, 90th and 99th percentiles. This gives an indication of the spread of outcomes across the year and across the randomly selected *plug-in-profiles*.

We consider a range of *plug-in-fractions*. As the worst-case we take vehicles to plug in at 6pm each day and charge at full capacity for one hour (which is all the time that's required to meet their daily energy consumption) – this labelled as a *plug-in-fraction* of 0%. As the best-case we take vehicles to be plugged in 100% of the time, adhering to any scenario time constraints, such as only *Daytime only* or *Nighttime only*. Between these two extremes we consider plug-in-fractions of 8.3%, 16.6%, and – for *Unconstrained scenarios* – 25%, 33%, 50%, 66%. These correspond to vehicles being plugged in for an average of 6, 8, 16, 24, 32 hours across the 48 hour period.

EVs plug in at all hours

We begin by considering scenarios where EVs can connect to chargers at any time of the day. This likely represents private vehicles that aren't used for a strict commuting schedule.

Optimising charging to minimise cost – excluding V2G

Figure 1 presents the results under the *Minimise cost – no V2G* objective. The top graph shows the distribution of the cost of charging, in dollars per day. Note that this is only the energy component of electricity supply, at NEM wholesale rates. The blue and purple lines show the Confidence Intervals (C.I.) of the distributions. The middle graph shows the distribution of electrical load on the Belconnen zone substation at the times of EV charging. The bottom graph shows the EV hosting capacity of the region serviced by the Belconnen zone substation, in terms of the number of vehicles (black solid curve and left-hand side axis) and the percentage of residential customers within this region that could charge one EV at their premises (red dashed curve and right-hand side axis). The EV hosting capacity is set to the number of EVs that can charge before the zone substation is overloaded 1 in 10 days. This quantity is given by the top orange curve with square markers in the middle graph and has some variance across plug-in-fractions due to being at the edge of the statistically distribution.

These results exemplify the clear trend of all scenarios: that **charging EVs at full power in the evening – *as will happen with current defaults if drivers plug in upon arriving home after work* – is financially costly and places large additional load on the distribution network at the times when this network is already under maximum stress**.

The average daily cost of charging an EV reduces from $1.28 per day to $0.33 per day, when charging is shifted from 6pm to the lowest cost periods of each two-day period (noting again that this is only the wholesale energy component of costs; customers also need to pay network tariffs and most customers' energy costs are set by fixed retail offers). In Belconnen, only 4.7% of residential customers (852 households) would be able to charge their EV at 6pm before the substation is overloaded during the 6-7pm period on 1 in 10 days of the year.

In contrast, if vehicles are plugged in continuously and charging is optimised for cost, ignorant of substation loading, the number of customers that can charge one EV before pushing the substation above its limit increases dramatically. It takes 19.3% of residents (3494 households) charging their EVs with this charge management before the substation is overloaded during 1 in 10 days of the year. While almost four times the worst-case scenario, this is still a modest percentage because the Belconnen substation is heavily loaded by current demand[6].

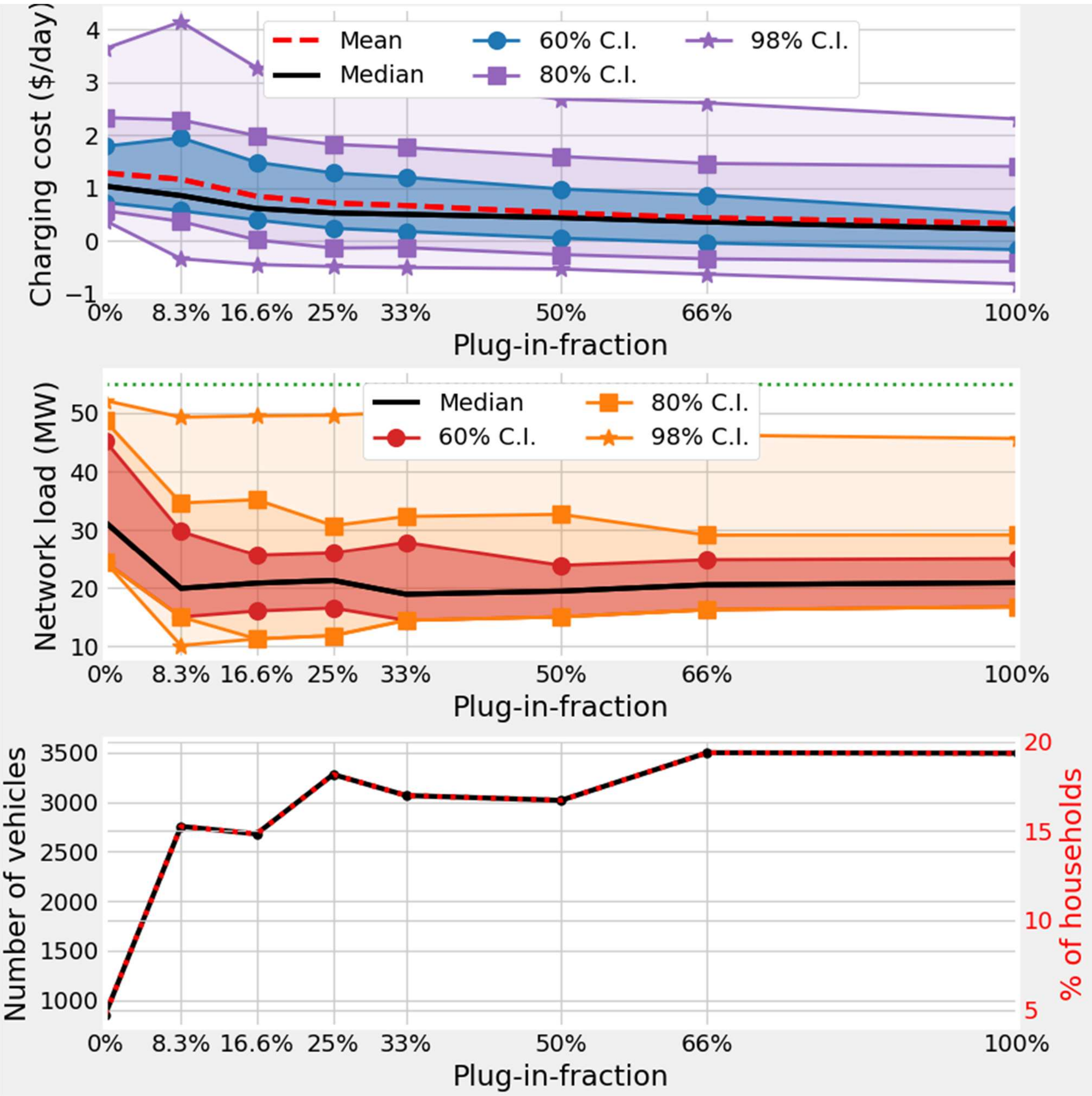
A modest *plug-in-fraction* of 25% – that's vehicles being plugged in for an average of 6 hours a day, which can be done within a workday or overnight – is sufficient to realise most of these benefits. The cost of charging reduces to $0.72 per day, and the substation can handle 18.2% (3280) of households charging an EV before becoming overloaded on 1 in 10 days.

Vehicles being plugged in for 6 hours a day, or 42 hours a week, is sufficient to realise most of the benefits of managed charging. That's compatible with plugging in overnight at home, or at work or a commuter carpark during the day, or plugging in only over the weekend.

Furthermore, these results demonstrate a general trend of our results: that NEM market prices and network load are general correlated (being low during solar hours and overnight) such that optimising for either one of these metrics has a positive impact on the outcome for the other.

[6] https://www.evoenergy.com.au/-/media/Project/Evoenergy/EVO/Documents/About-us/APR/Annual-Planning-Report-2023.pdf

Figure 1 Distribution of cost and network load outcomes as a function of plug-in-fraction when charging is optimised to minimise energy costs (excluding V2G)



Optimising charging to minimise cost – including V2G

The second scenario we consider is the enablement of vehicle-to-grid, that is the ability for EVs to discharge power to the grid, and the optimisation to minimising the energy cost of charging. These results are presented in Figure 2.

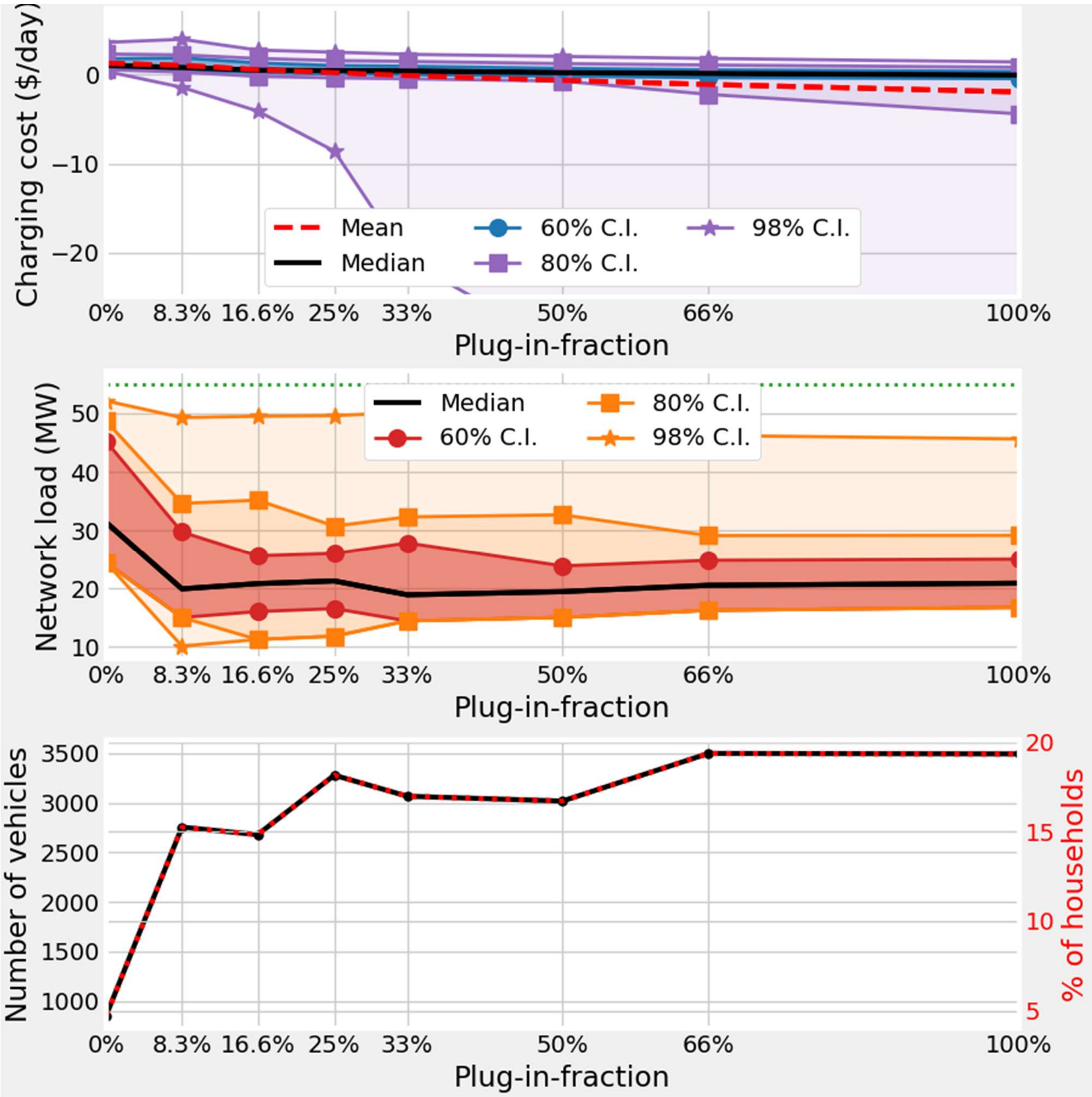
The results on the far left-hand end of the figure are the same as in Figure 1 because the worst-case scenario assumes vehicles are unplugged after their one hour of charging between 6-7pm each day. This simplification is necessary for computation reasons and creates a reference point between the V2G and non-V2G scenarios, but misses the scenario where vehicles stay plugged in overnight and perform V2G discharging-charging cycles after 7pm.

Turning now to the best-case scenario, when vehicles are continuously plugged in, the average cost of charging is found to drop to $-1.93 per day – that means an EV is earning almost a dollar a day. On rare occasions a daily charge cycle can earn a revenue of over $20.

The statistical impacts of these V2G discharging-charging cycles on the grid is minimal because they only occur occasionally with no strong correlation with time of day or network loading. The middle and bottom rows of Figure 2 are therefore very similar to Figure 1.

With vehicle-to-grid, the average daily cost of charging an EV is $0.24 when the vehicle is plugged in 25% of the time and $-1.93 when the vehicle is plugged in all the time.

Figure 2 Distribution of cost and network load outcomes as a function of plug-in-fraction when V2G is included and (dis)charging is optimised to minimise energy costs (maximise revenue)



Optimising charging to minimise grid impacts

The third scenario we consider is where vehicle charging is optimised to occur at times of minimum load on the local zone substation. This is the first and only scenario where the optimisation results are dependent on local grid conditions, and we here focus on the Belconnen zone substation. For this and the following fourth objective we exclude V2G.

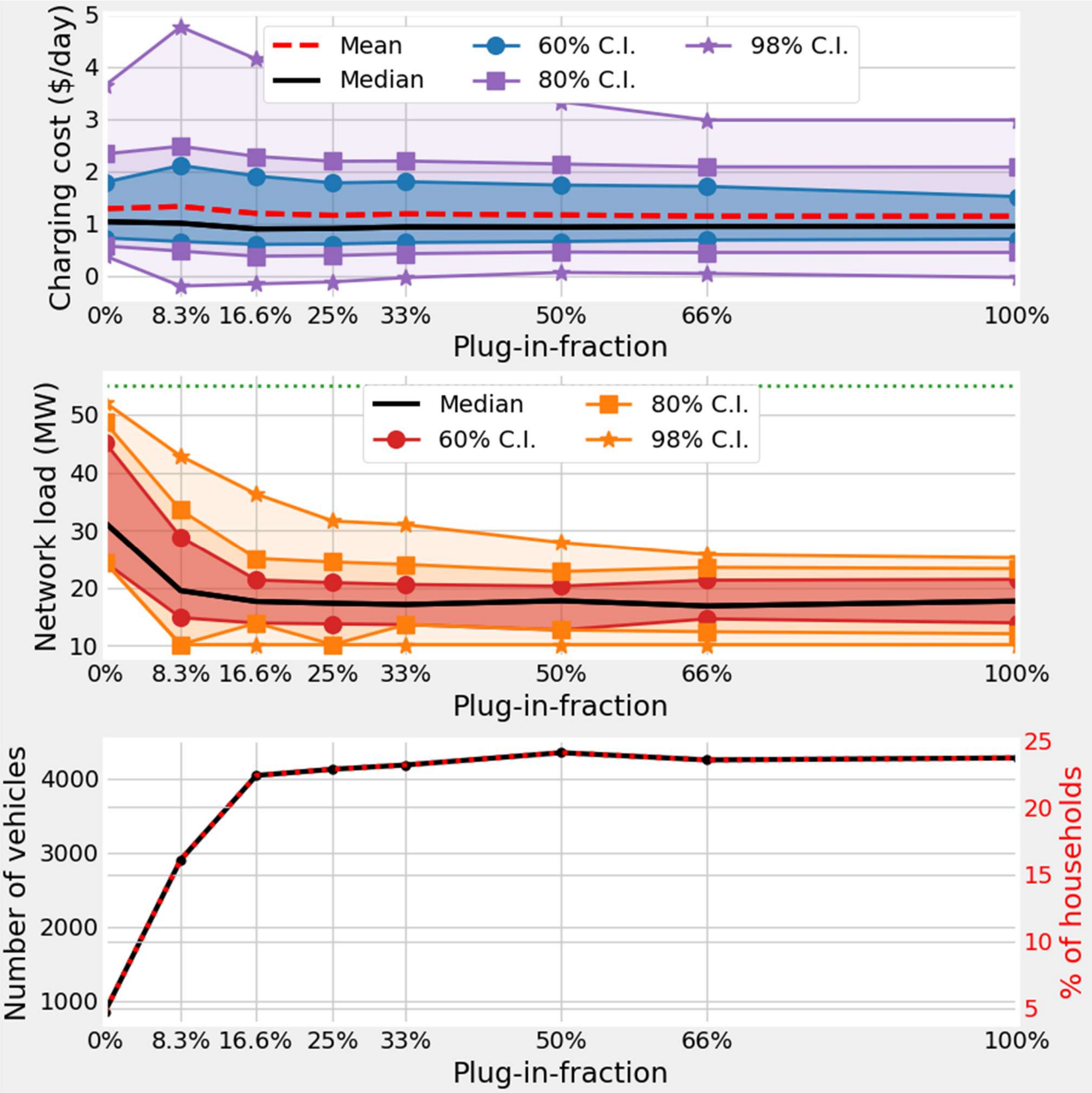
These results are presented in Figure 3, where the worst-case scenario is once again impervious to any optimisation and so the results are identical to previous figures.

The top row of Figure 3 indicates that this optimisation for minimised grid impacts has little impact on the cost of charging. The middle and bottom rows meanwhile demonstrate the major increases in network EV hosting capacity that occur under these operating conditions, and how these increase as a function of the *plug-in-fraction*.

For all *plug-in-fractions* of 25% and higher the substation can handle 22.9% of residential customers (4129) charging an EV before being overloaded 1 in 10 days. The effect of explicitly managing network load as the optimisation objective has an even more pronounced impact on reducing the occurrence of EV charging on peak network demand periods (see the 98% C.I. curve). The number of customers that can charge their EVs without exceeding the network limit on 1 in 100 days therefore increases from 2.1% (384 customers) to 22.3% (4028 customers).

A modest *plug-in-fraction* of 25% provides sufficient flexibility to ensure EV charging occurs at times of low zone substation load, facilitating a near optimal hosting capacity.

Figure 3 Distribution of cost and network load outcomes as a function of plug-in-fraction when charging is optimised to occur at times of minimum load on the zone substation



Optimising charging to maximise use of renewable energy generators

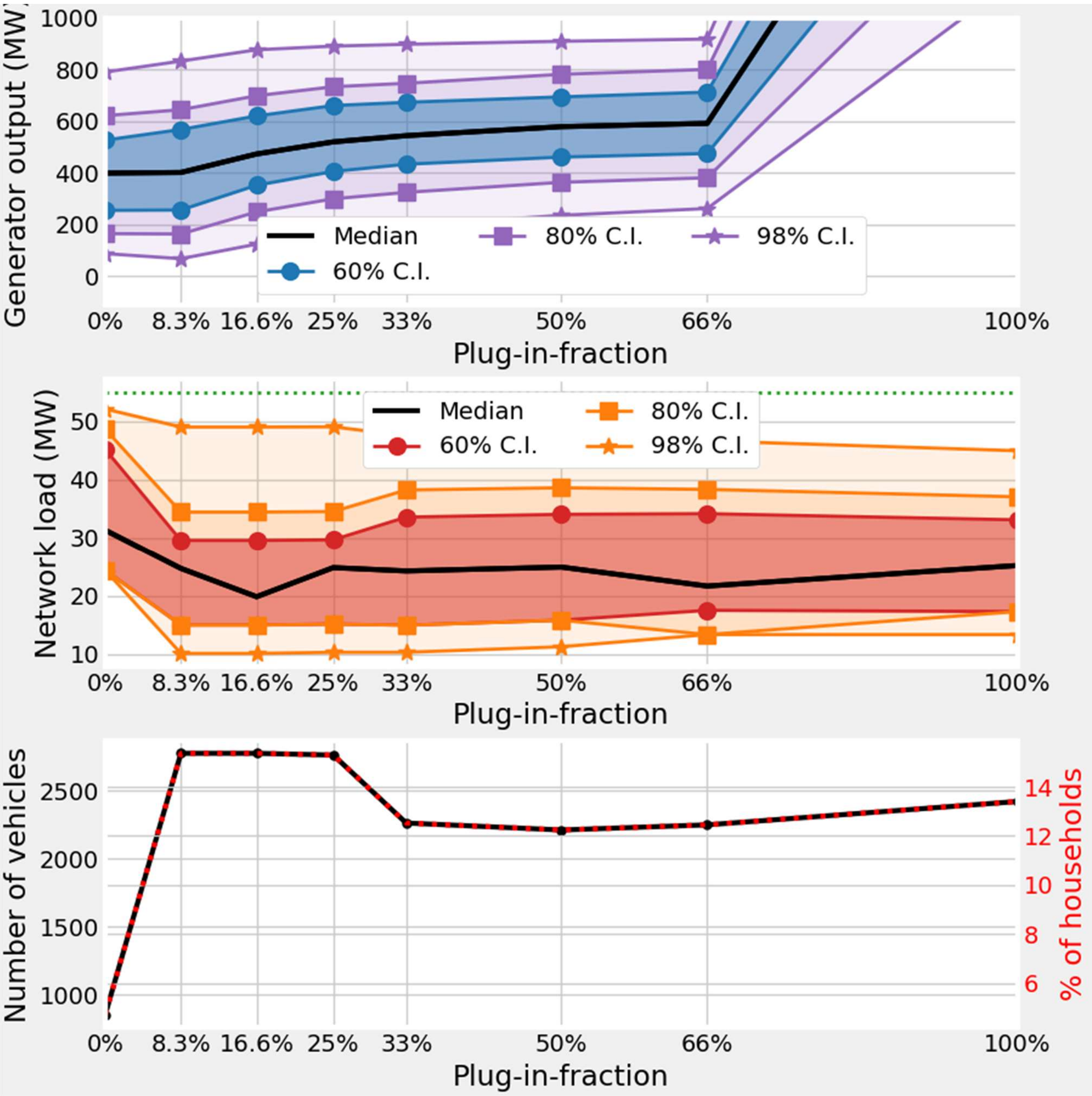
The fourth and final charging optimisation objective is to concentrate EV charging to times of maximum power production by a set of renewable energy generators. We choose to select the wind and solar farms contracted as part of the ACT's 100% renewable electricity program.

The top row of Figure 4 Distribution of cost and network load outcomes as a function of plug-in-fraction when charging is optimised to occur at times of maximum generation by the wind and solar farms contracted by the ACT governmentshows the cumulative power generation of these wind and solar farms at the times of optimised EV charging as a function of *plug-in-fraction*. In contrast to previous results for the other objectives, there is seen to be a significant advantage in EVs being plugged into chargers 33% or more of the time. When vehicles are plugged in at 6pm, the median renewable power generation at the time of EV charging is 400MW. This rises to 542MW for a plug-in-fraction of 33%, and 2386MW when vehicles are always plugged in. This reflects the hour-to-hour variability of these generators.

The middle and bottom rows of Figure 4 show that this type of optimised charging is less effective at shifting EV charging to times of low substation load. When vehicles are always plugged in and operating for this objective, only 13.4% of customers (2422) can charge an EV in this way before the substation is overloaded 1 in 10 days. This implies that the power generation of these wind and solar farms is less correlated to zone substation loads than NEM wholesale prices.

Combined, the ACT contracted solar and wind farms provides a reliable output, of around 400-500MW, to power inflexible EV charging. When EV charging is more flexible (higher *plug-in-fraction*) EV charging can mostly charge when renewable generation exceeds 2000MW.

Figure 4 Distribution of cost and network load outcomes as a function of plug-in-fraction when charging is optimised to occur at times of maximum generation by the wind and solar farms contracted by the ACT government



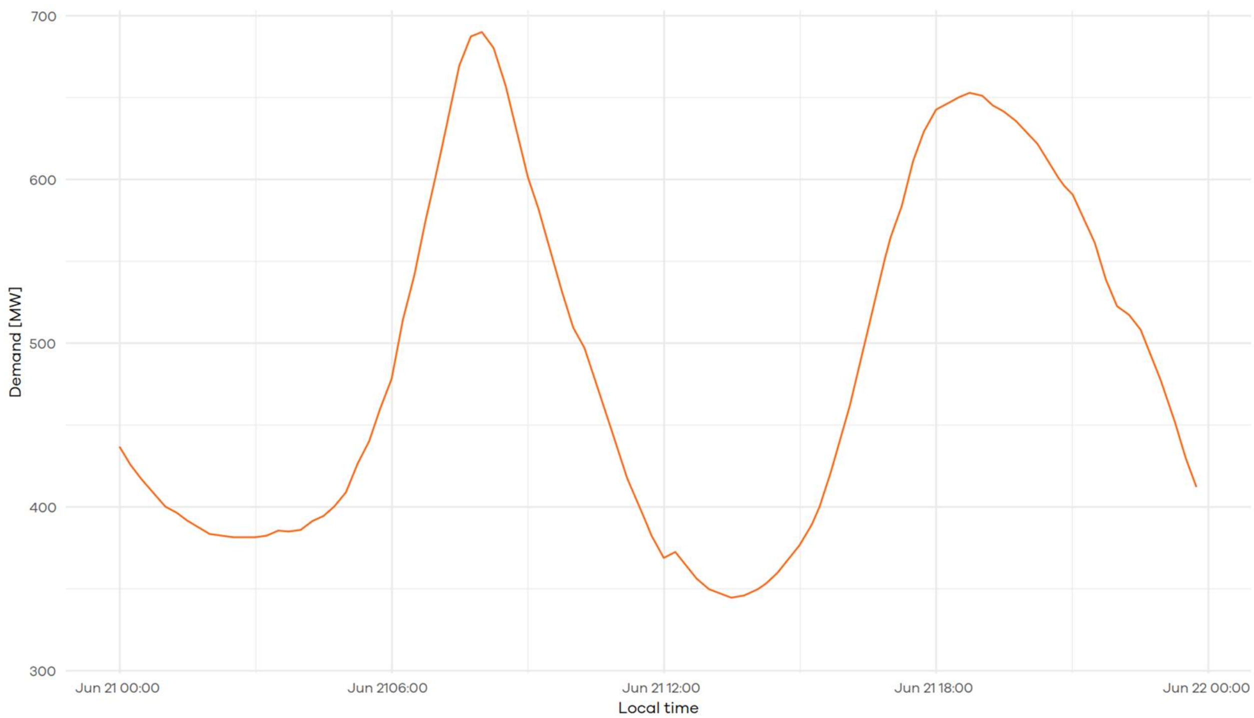
Plugged in only during the day or night

We now modify the scenarios by constraining the times during which EVs may plug in to either exclusively daytime hours, or exclusively nighttime hours. These are chosen to represent vehicle availability at commuter or workplace carparks, and at homes outside of work hours, respectively.

Restricting EV charging to occur exclusively between 6am and 7pm (daytimes) or between 7pm and 6am (overnight) are simplistic scenarios. However, both are instructive in highlighting certain trends in the interactions between EV charging demand and existing electricity system demands.

Electricity usage in the ACT (and across the NEM) peaks twice each day, once in the morning and once in the evening. This is illustrated in Figure 5 evoenergy maximum ACT electricity demand in winter 2023, which shows electricity usage in the ACT on the day of maximum demand in winter 2023[7] (the profile is similar in summer but with a reduced peak in the morning as there is no heating needs). Crucially for our study, electricity demand drops significantly during the daytime – between the two peaks – to levels similar to overnight demand. This trend is becoming more pronounced with the installation of more rooftop solar panels whose power production peaks during the middle of the day. Electricity prices are strongly influenced by demand and therefore follow a similar daily pattern.

Figure 5 evoenergy maximum ACT electricity demand in winter 2023



[7] https://www.evoenergy.com.au/-/media/Project/Evoenergy/EVO/Documents/About-us/APR/Annual-Planning-Report-2023.pdf

The consequence of these patterns in demand and prices is that there are opportunities to charge EVs at low prices and/or low demand solely during the daytime or solely during the night. With the way we've defined daytime and nighttime (to match human activity levels) most of the demand peaks fall within the daytime (for demand is driven by human activity).

Figure 6 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during daytime hours and charging is optimised to minimise energy costs (excluding V2G), Figure 7 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during nighttime hours and charging is optimised to minimise energy costs (excluding V2G) show the outcomes when optimising for NEM prices without V2G during the daytime and nighttime respectively. In these figures, 100% means vehicles are plugged into their charger 100% of constrained time window. These figures demonstrate how the higher average prices and network loads during the day limit the potential benefits of managed charging, while at nighttime the potential is comparable to when vehicles are plugged in across day and night.

The nighttime offers more opportunities to charge at simultaneously low prices and network demand.

This is supported by Figure 8, Figure 9 which show that the financial benefits of V2G are similar during the daytime and overnight (being plugged in throughout this daytime period the average cost of charging is $-1.34 per day, while overnight it is $-1.72), while the loading on the grid is as far an issue overnight that during the day (with twice the V2G EV hosting capacity overnight).

Figure 10, Figure 11 show that there are reliably periods of low demand on the Belconnen substation during the day and night, so EV charging that is optimised for minimal network impact can be equally effective irrespective of the day/night split.

Similarly, Figure 12, Figure 13 show that the correlation with wind and solar farm generation is comparable day and night – at least in the case of the ACT where the contracted generation is dominated by wind power over diurnal solar power.

The financial value of vehicle-to-grid is similar when vehicles are plugged in during the daytime or overnight, but the grid impacts are far better overnight.

Figure 6 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during daytime hours and charging is optimised to minimise energy costs (excluding V2G)

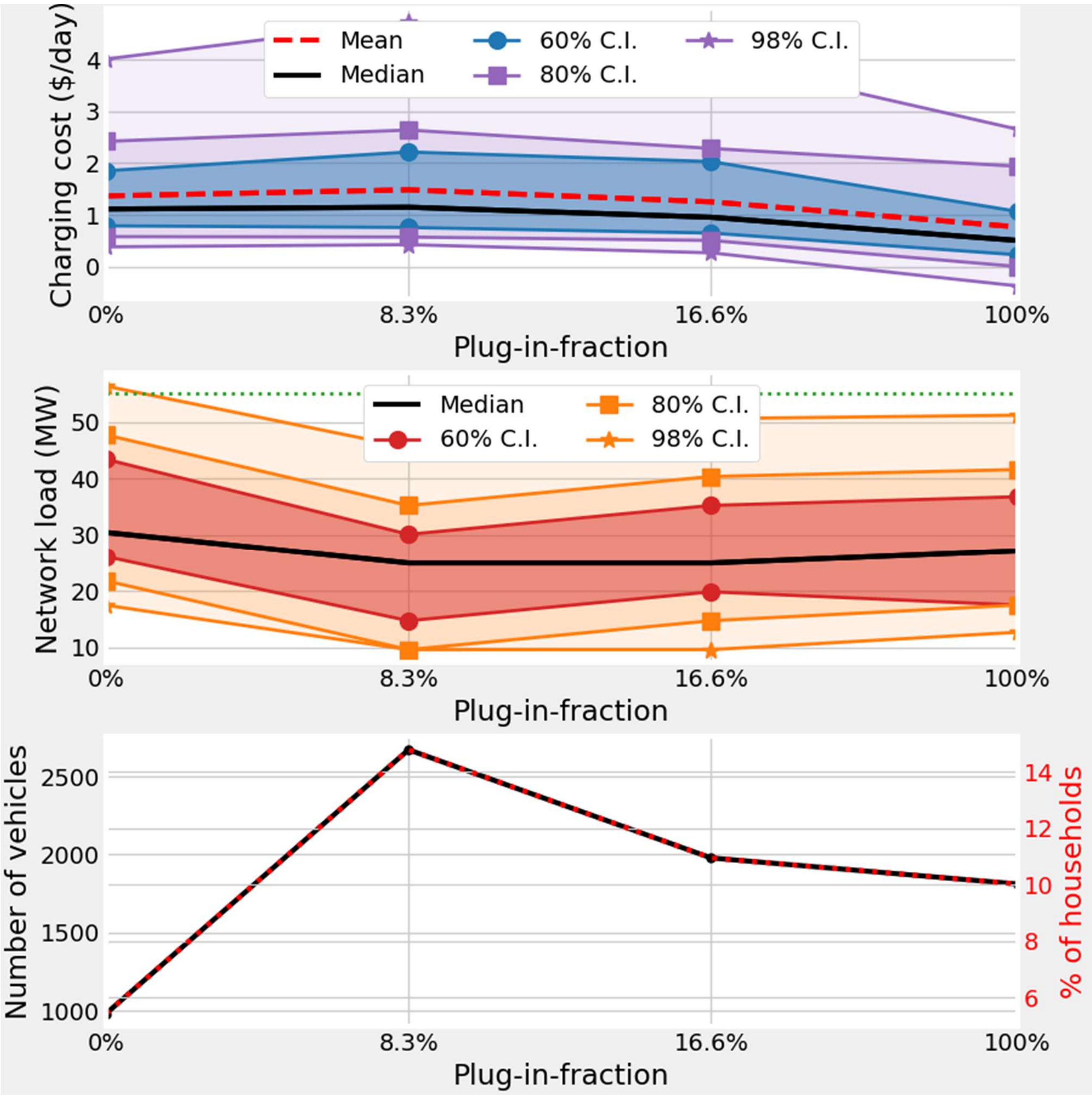


Figure 7 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during nighttime hours and charging is optimised to minimise energy costs (excluding V2G)

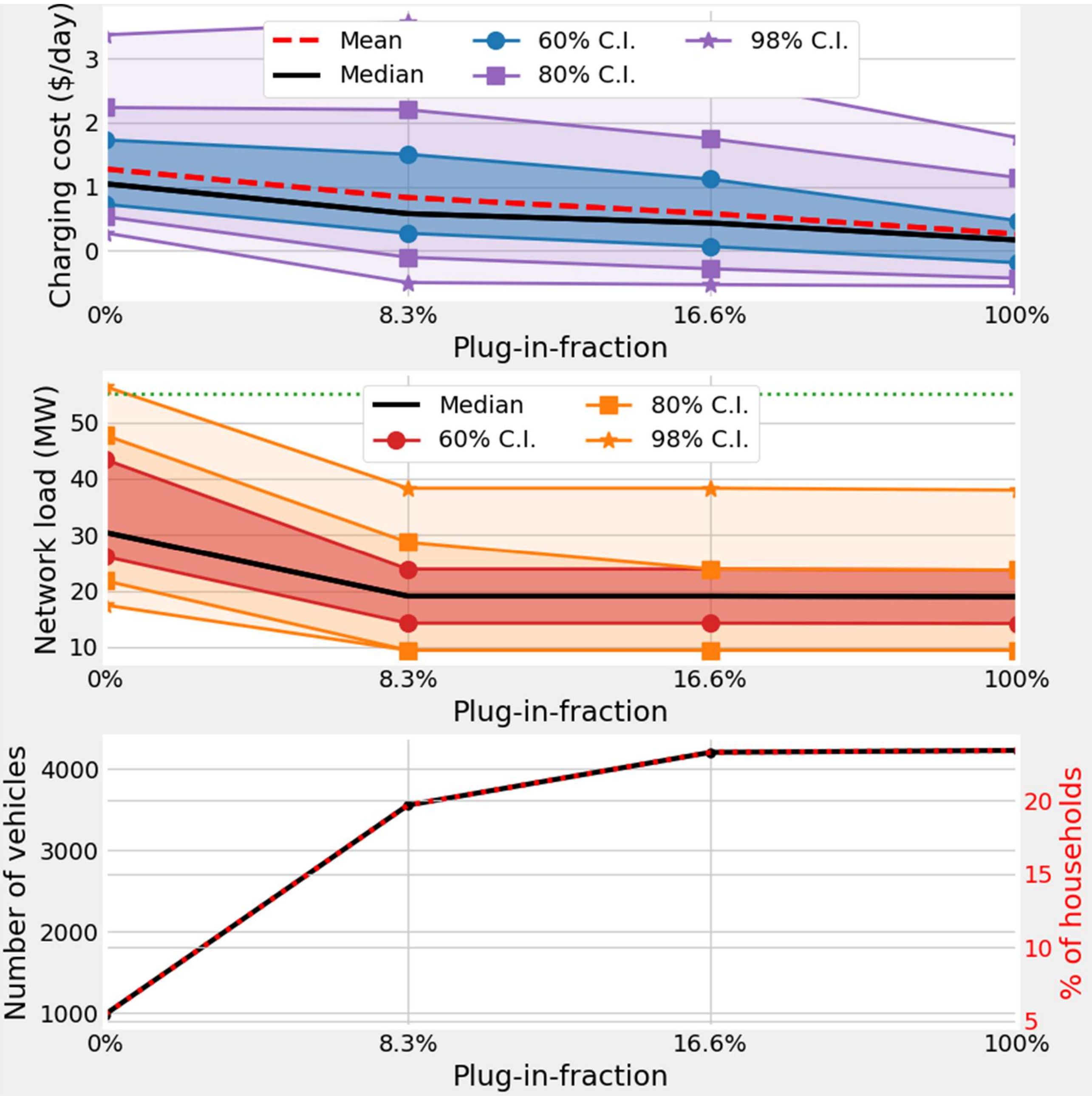


Figure 8 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during daytime hours and V2G is included so that (dis)charging is optimised to minimise energy costs (maximise revenue)

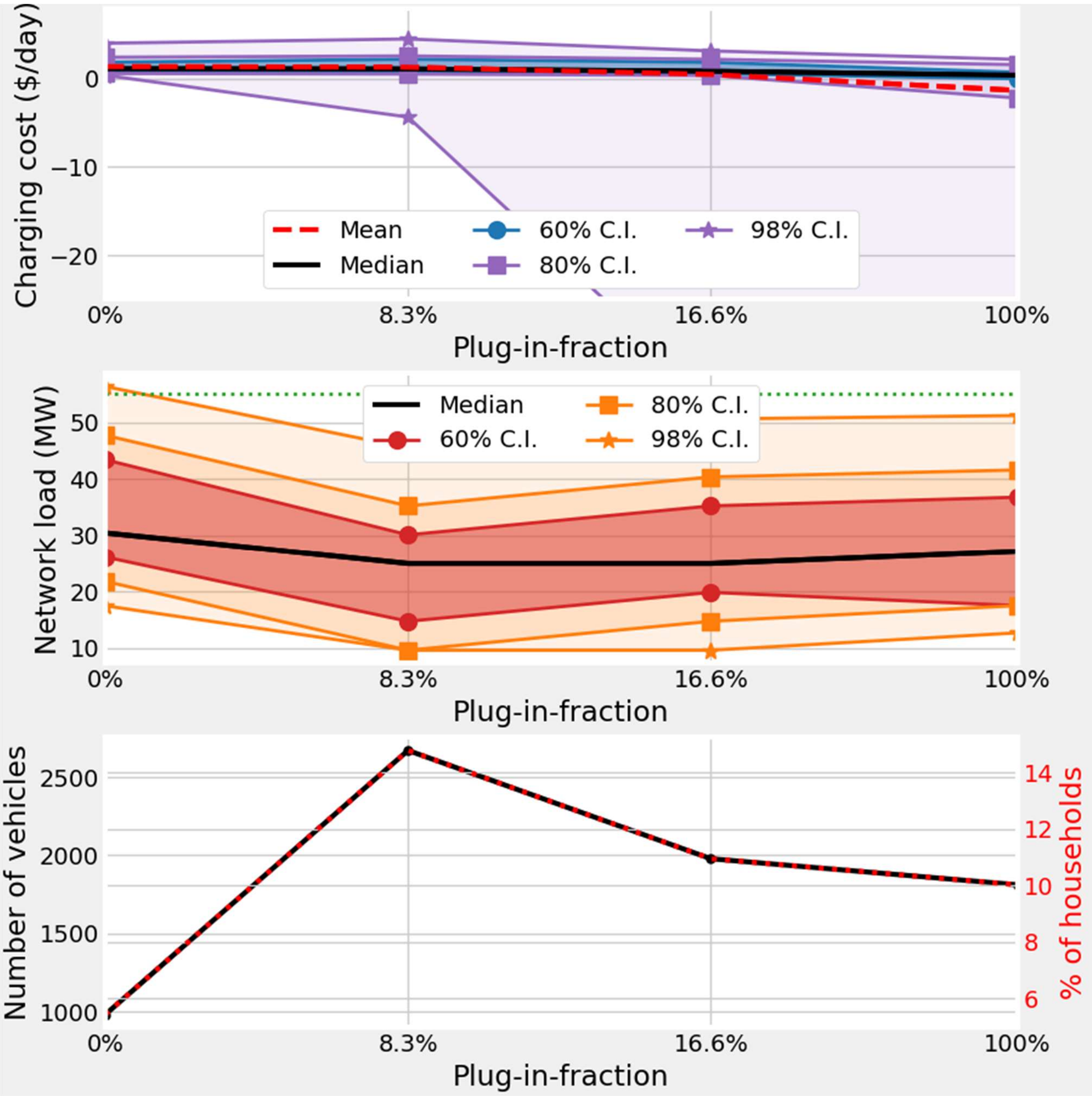


Figure 9 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during nighttime hours and V2G is included so that (dis)charging is optimised to minimise energy costs (maximise revenue)

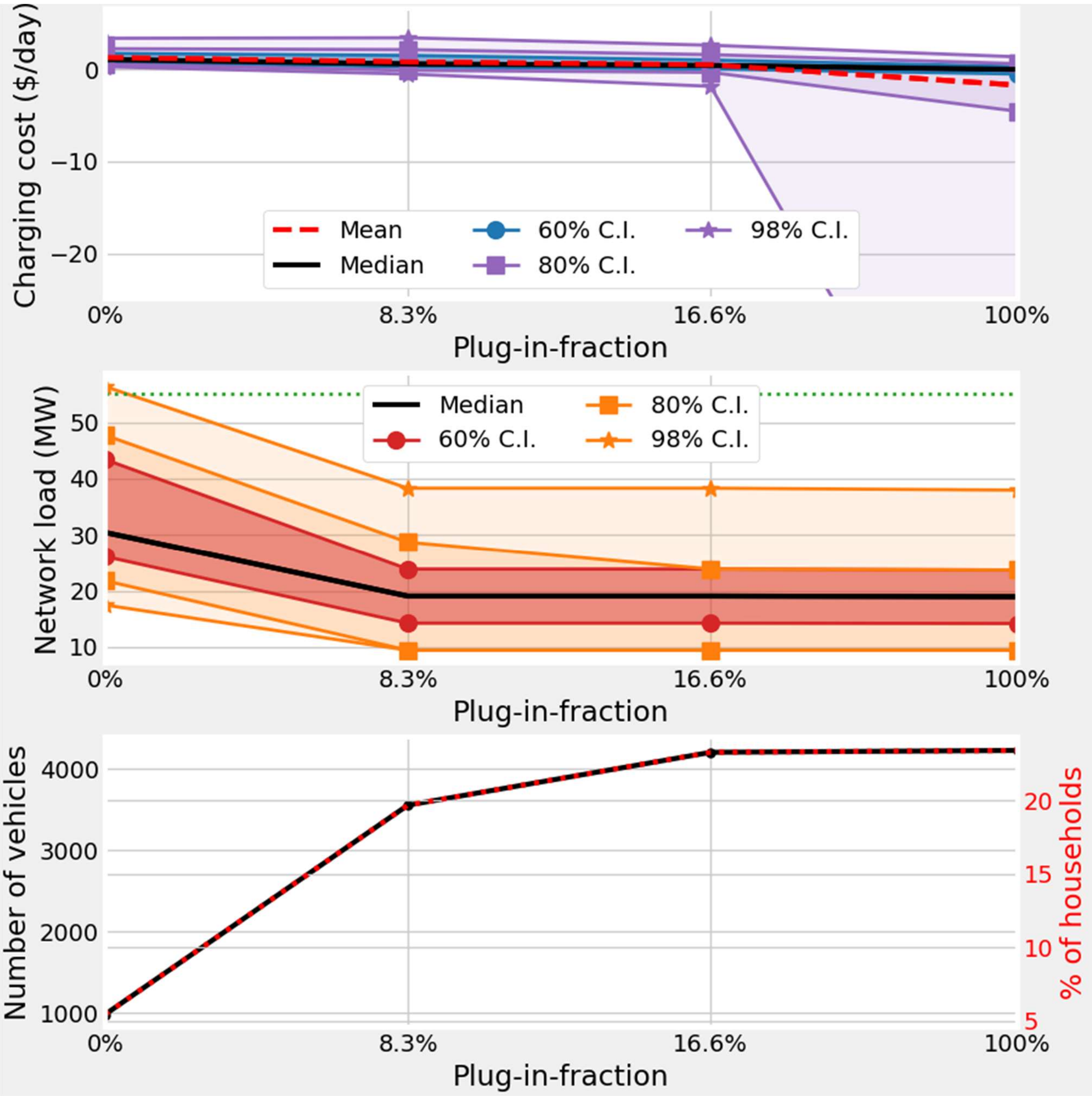


Figure 10 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during daytime hours and charging is optimised to occur at times of minimum load on the zone substation

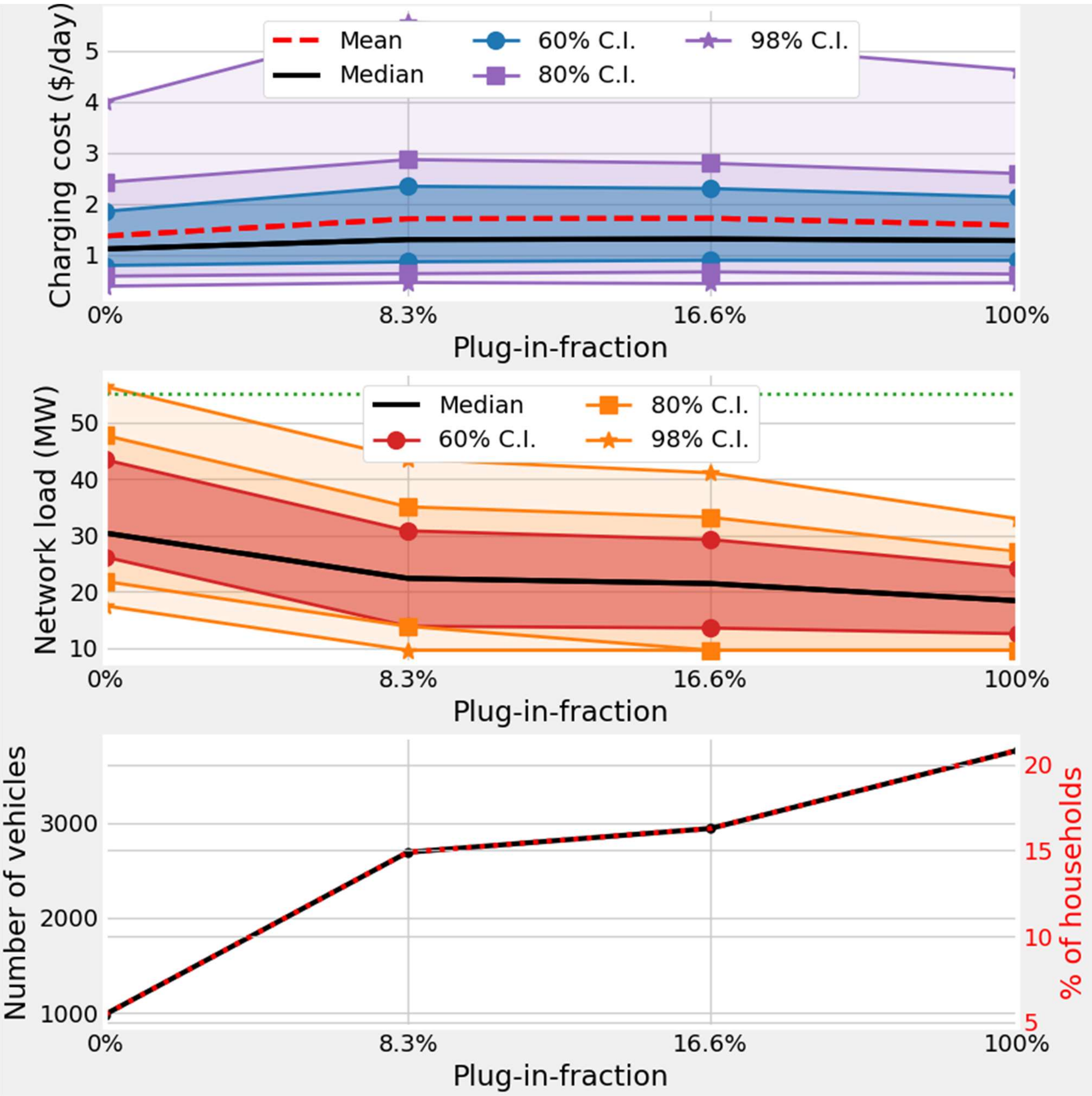


Figure 11 Distribution of cost and network load outcomes as a function of *plug-in-fraction* when vehicles are exclusively plugged in during nighttime hours and charging is optimised to occur at times of minimum load on the zone substation

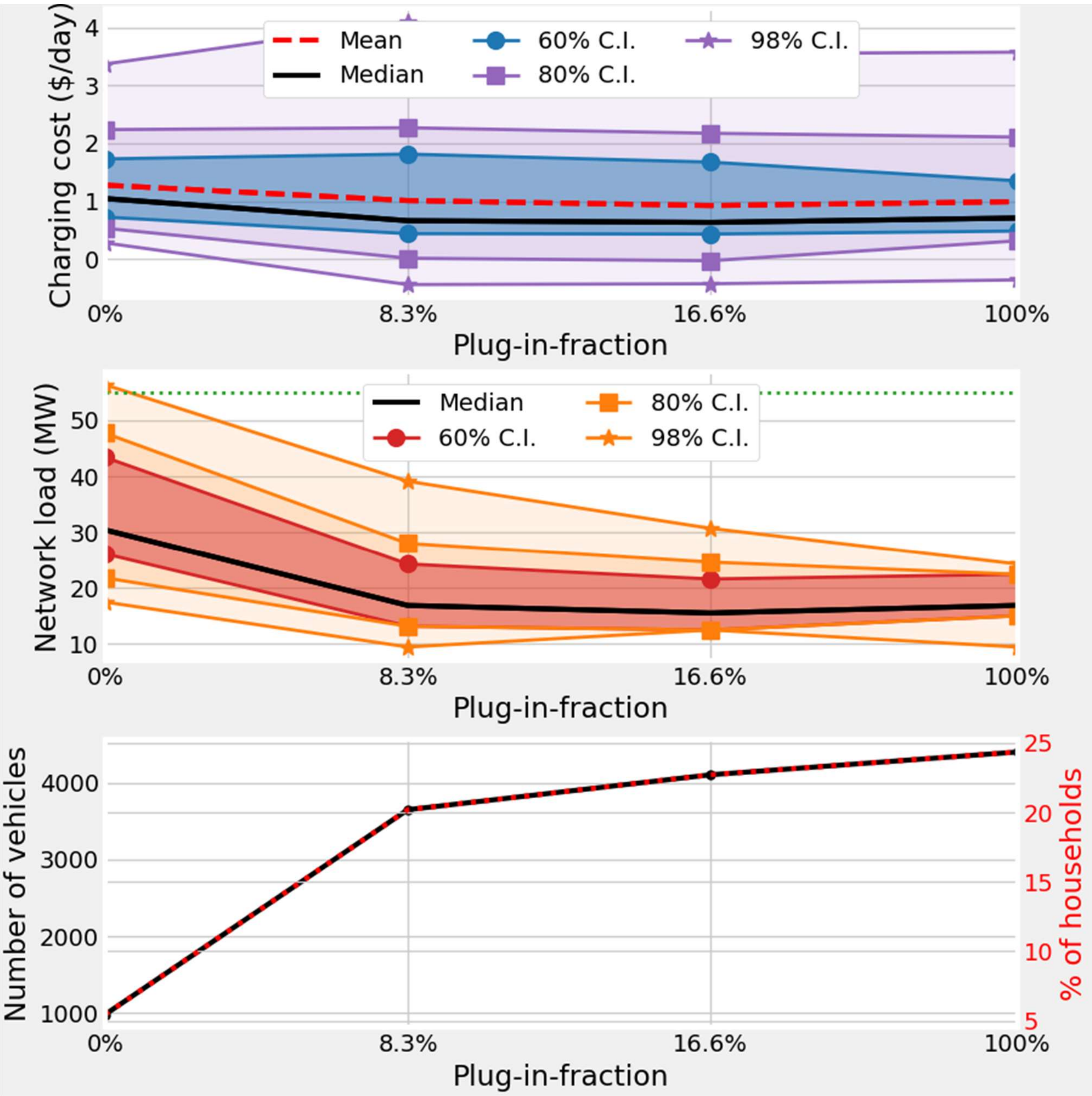


Figure 12 Distribution of power generated by the wind and solar farms contracted by the ACT government at the time of EV charging (top row), the network load at these times (middle row) and the number of EVs that can charge in this scenario before exceeding the zone substation limit (bottom row). All results are as a function of *plug-in-fraction* (x-axis) when vehicles are exclusively plugged in during daytime hours and charging is optimised to occur at times of maximum generation by the wind and solar farms contracted by the ACT government

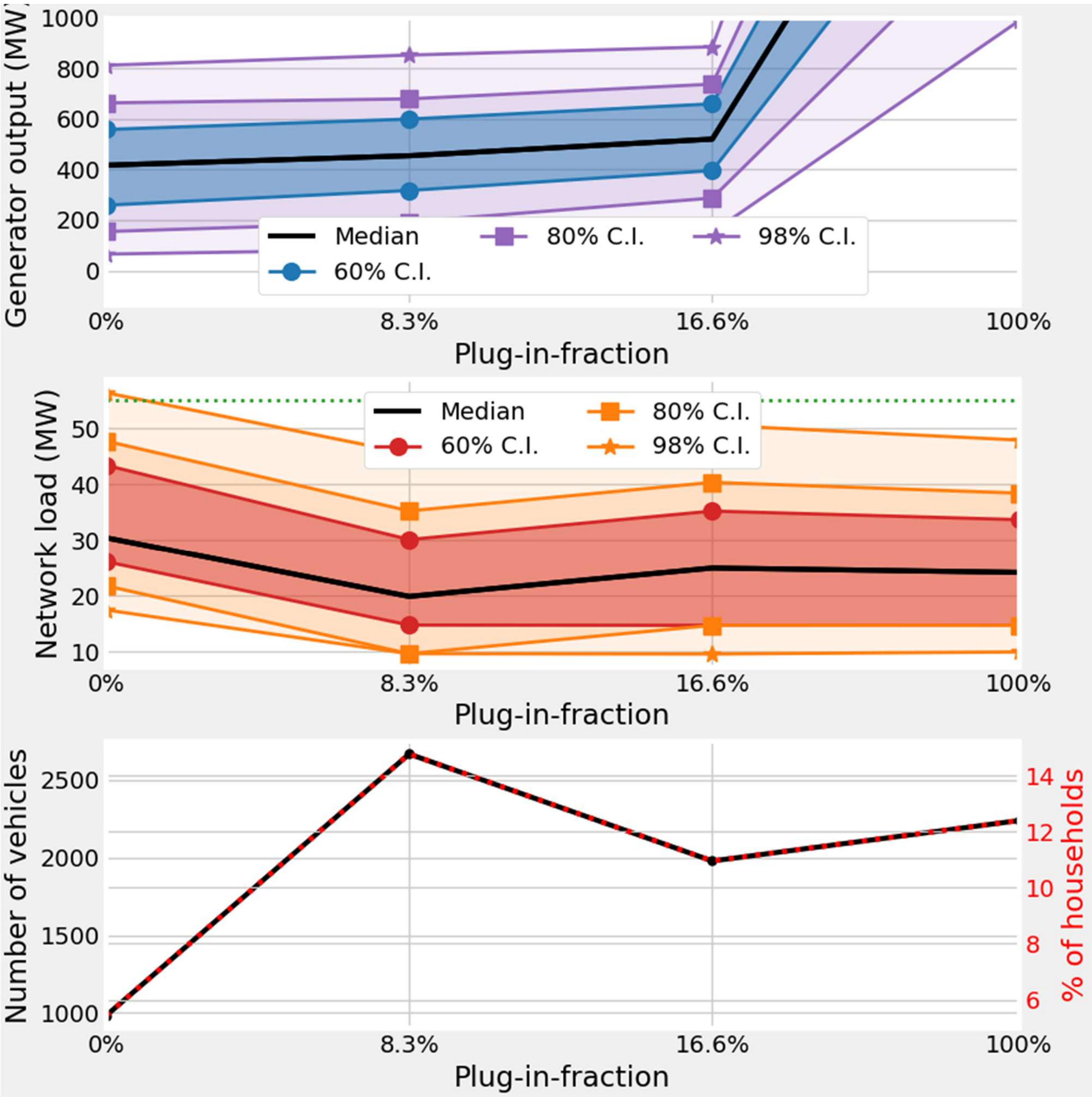
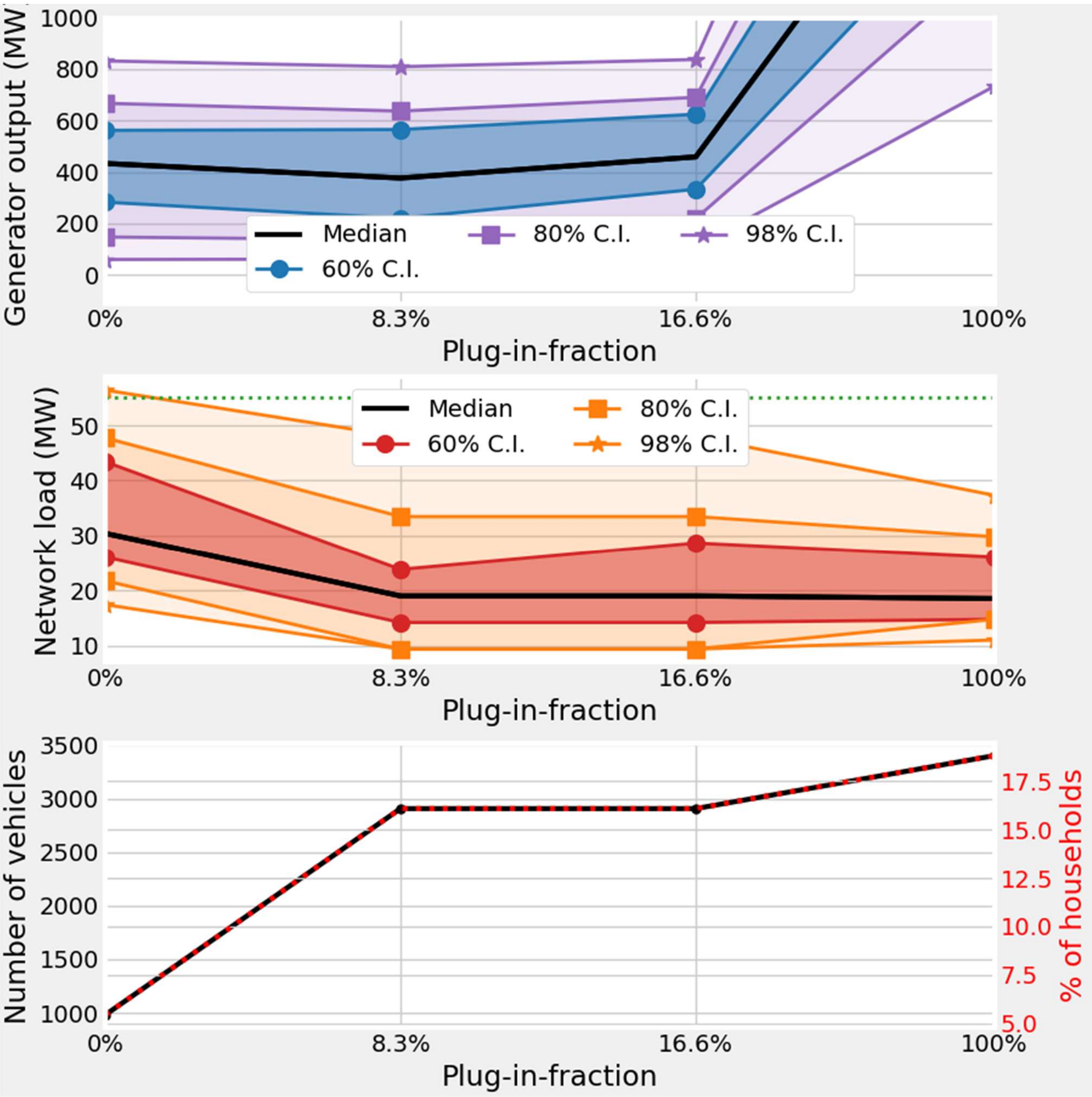


Figure 13 Distribution of power generated by the wind and solar farms contracted by the ACT government at the time of EV charging (top row), the network load at these times (middle row) and the number of EVs that can charge in this scenario before exceeding the zone substation limit (bottom row). All results are as a function of *plug-in-fraction* (x-axis) when vehicles are exclusively plugged in during nighttime hours and charging is optimised to occur at times of maximum generation by the wind and solar farms contracted by the ACT government



Method intuition

This section builds an intuition for the methodology by presenting results from the intermediate steps.

Having introduced the conceptual approach of using the Monte Carlo method to compile a statistical sample of possible *plug-in-profiles* we now focus on the internal method used in composing each of these *plug-in-profiles*, focusing on building intuition through visualisations.

Composing *plug-in-profiles* for a set *plug-in-fraction*

To aid with the tractability of the problem we assume that when an EV is plugged in, it remains plugged in for at least 4 hours. We can then use a python library to draw the appropriate number of (random) combinations of start times for plug in sessions across the multiday period that result in the desired *plug-in-fraction*. We consider a two-day period, for longer periods create an unmanageable number of possible permutations of start times.

Once a plug-in-profile is defined, we can select the NEM market price data, NEM generator output data and evoenergy zone substation data for these times – and only these times.

To illustrate this process, Figure 14 presents a *plug-in-profile* for a *plug-in-fraction* of 33% over the period of 28th and 29th of January. The two periods for which the NEM market price data is shown (red) indicate the periods during which the EV is plugged in for this *plug-in-profile*. The blue curves indicate the 5-minute intervals within this *plug-in-profile* during which the EV can be charged at lowest cost – adopting the cost minimisation objective.

Figure 15 presents a *plug-in-profile* (during the same day) that has a *plug-in-fraction* of 66%. This increased duration of being plugged in enables charging at cheaper times than the 33% *plug-in-fraction plug-in-profile* of Figure 14.

Finally, Figure 16 and Figure 17 show the worst- and best-case *plug-in-profiles*. For the worst case we assume that EVs are plugged in for one hour from 6pm each day, during which time they need to charge at full power capacity, irrespective of the NEM price. For the best case we assume the vehicle to be connected to its charger throughout the whole period, allowing charging to be distributed to the absolute lowest cost time periods. In this particular example, the *plug-in-profile* selected for a 66% *plug-in-fraction* covers the periods of lowest price, so leads to the same charging profile as the best-case scenario.

Figure 14 NEM price (red) during a 33% *plug-in-fraction plug-in-profile* on the 28th and 29th of January 2022. Also shown is the optimised EV charging profile (blue in % of charger power capacity), which selects the lowest cost times during this *plug-in-profile*

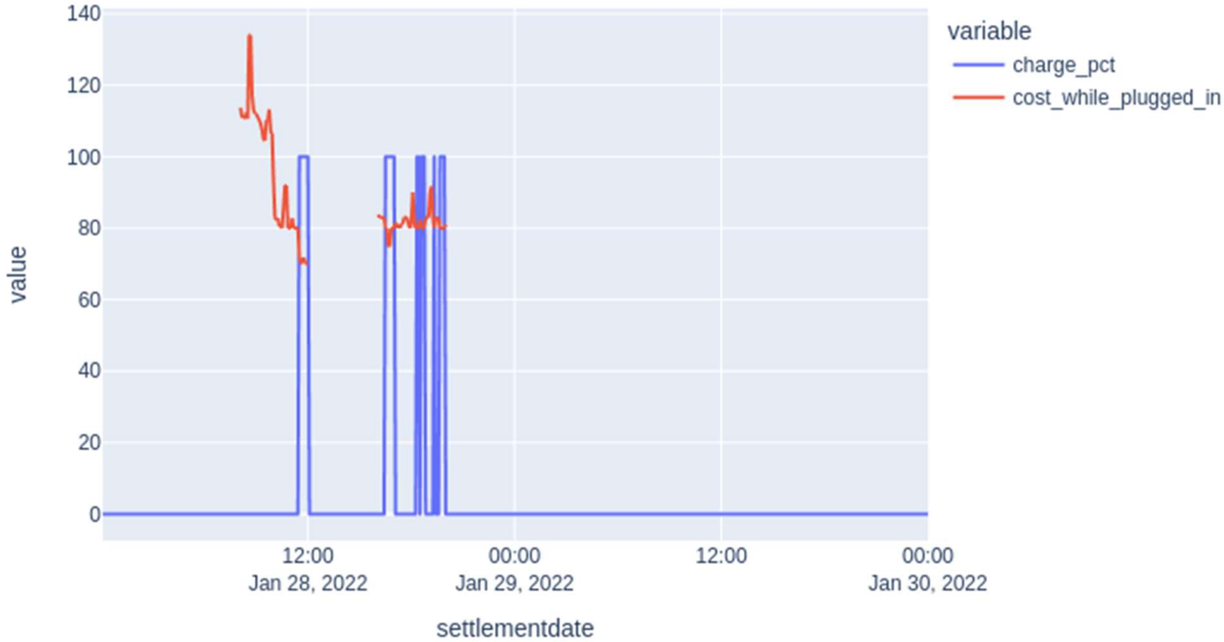


Figure 15 NEM price (red) during a 66% *plug-in-fraction plug-in-profile* on the 28th and 29th of January 2022. Also shown is the optimised EV charging profile (blue in % of charger power capacity), which selects the lowest cost times during this *plug-in-profile*

Figure 16 Profiles when EVs are plugged in for the minimum time required to charge. This scenario assumes EVs to be plugged in for one hour from 6pm each day, during which time they need to charge (shown in blue) at 100% power capacity, irrespective of the NEM price (red)

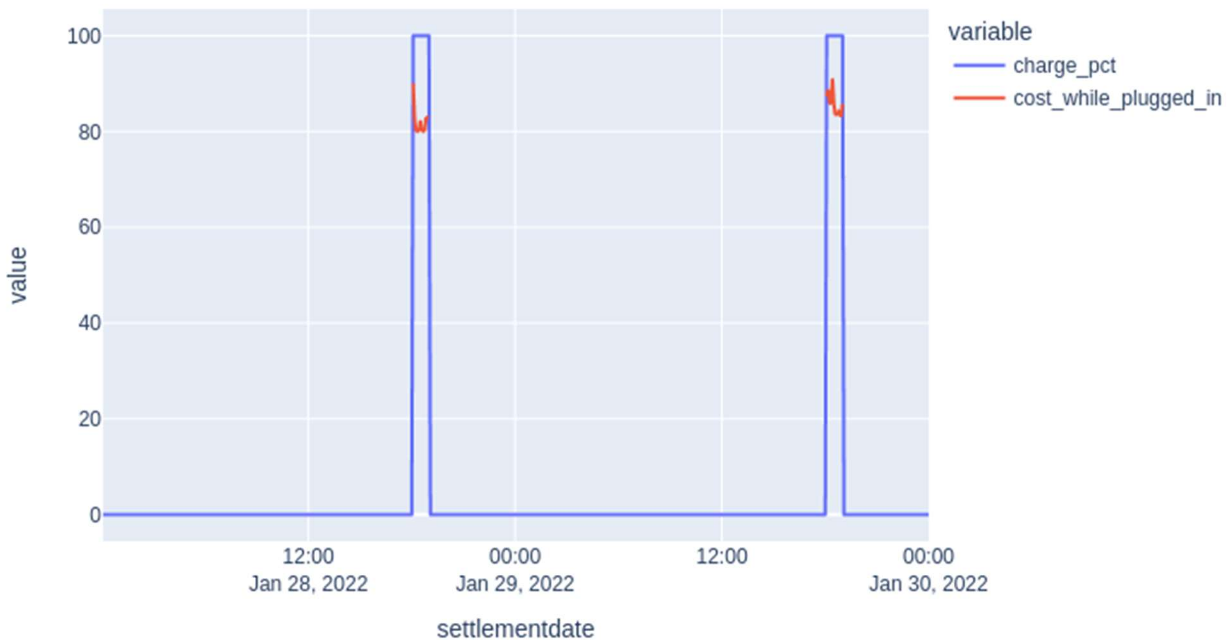
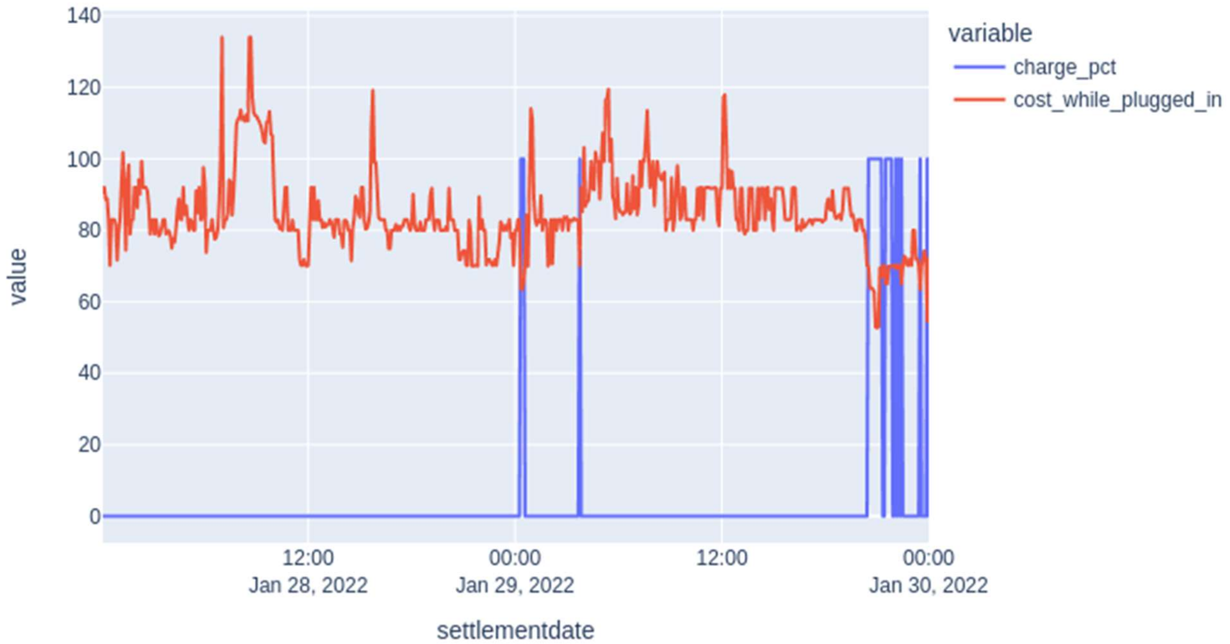


Figure 17 Best case charging scenario where EV is plugged in throughout the whole two-day period of 28th and 29th of January 2022. The EV can therefore charge at the absolute lowest cost moments - EV charging profile (in % of charger power capacity) shown in blue

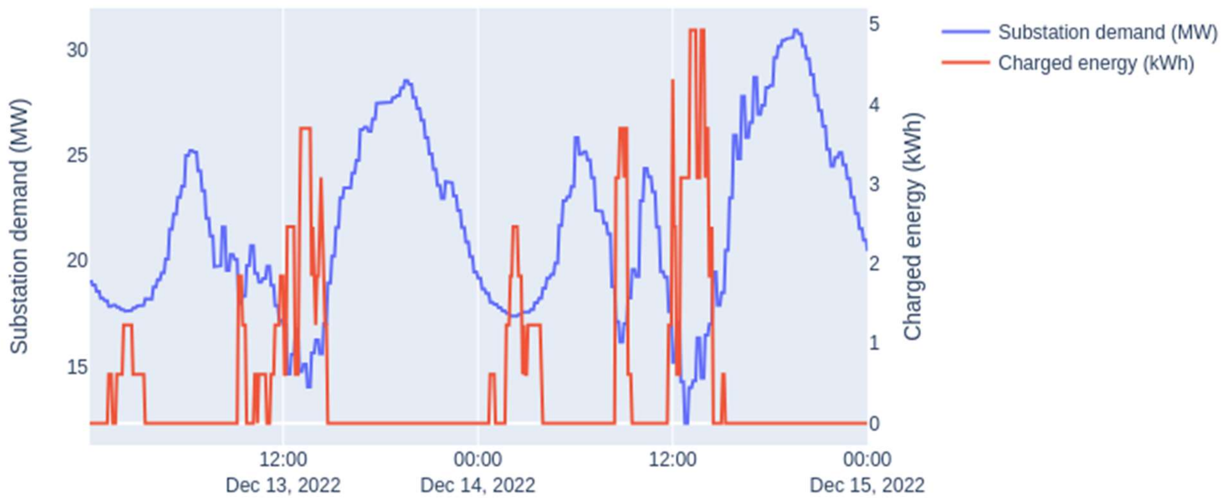


Distribution of outcomes for all *plug-in-profiles* for a set *plug-in-fraction*

Having developed our intuition about individual *plug-in-profiles* we now synthesise the results for all *plug-in-profiles* of a given *plug-in-fraction*.

Figure 18 firstly presents the cumulative charging profile from twenty *plug-in-profiles* applied to a two-day period in December – all of which have a *plug-in-fraction* of 33%. Also shown in blue is the Belconnen substation load during this period. The results show that all *plug-in-profiles* have allowed charging to occur outside of moments of peak substation load, with some facilitating charging at moments of absolute lowest load while others require some charging at relative minima.

Figure 18 Belconnen zone substation demand on 13,14 December 2022 (blue) and the cumulative EV charging load of 20 vehicles each plugged in 33% of the two-day period and optimised to minimise the stress on the substation (red).



Secondly, we can compose histograms that show the outcomes of *plug-in-fractions* (including all sampled dates and *plug-in-profiles)*. The cost outcomes are shown in Figure 19, while network loading outcomes are shown in Figure 20.

Figure 19 Distribution of costs per charging interval for low flexibility (*plug-in-fraction* of 8.3%, blue) and high flexibility (*plug-in-fraction* of 50%, red). The darker red area shows the overlap of the blue and red histograms.

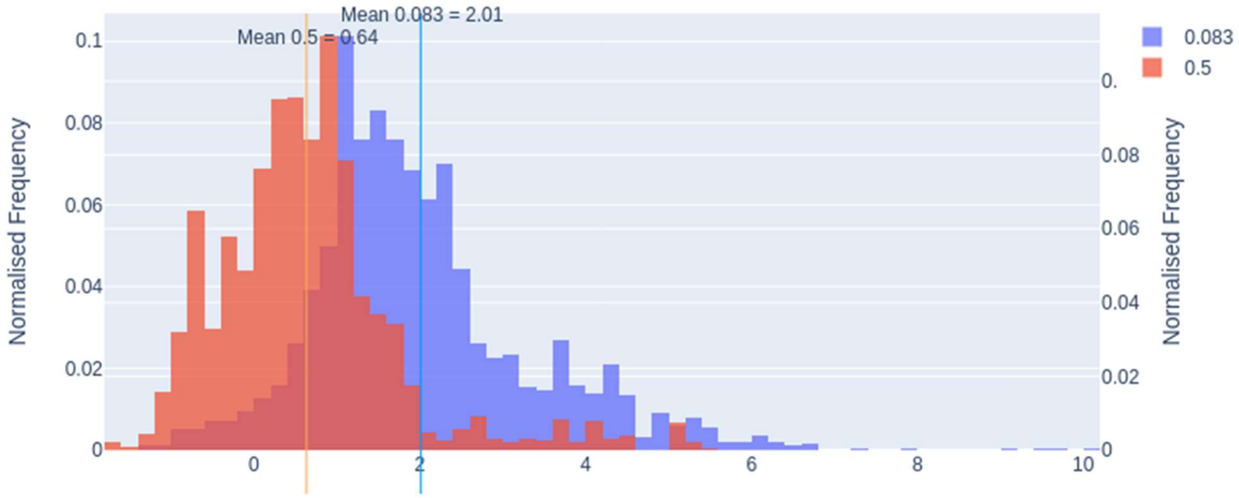
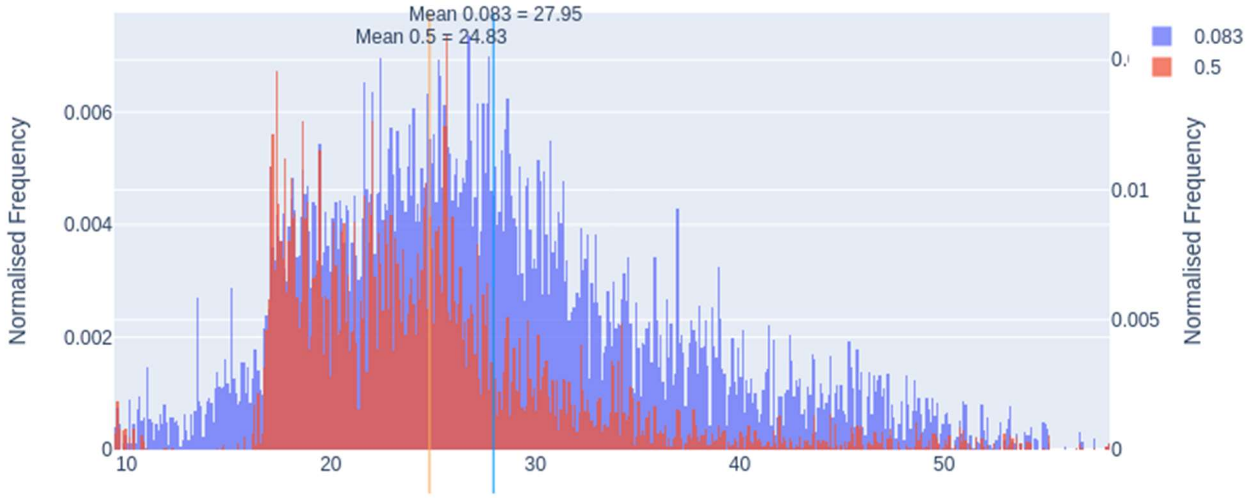


Figure 20 Distribution of zone substation loads during charging interval for low flexibility (*plug-in-fraction* of 8.3%, blue) and high flexibility (*plug-in-fraction* of 50%, red)



Summary & policy implications

In summary, our study reveals that:

- Having EVs plugged in to chargers for extended periods, much greater than the minimum required to meet their charging needs, is foundational to reducing the impact of EV charging on the electricity system.
- **Vehicles being plugged in 25% of the day (6 hours), or 42 hours a week, is sufficient to realise most of the benefits of managed charging.**
- A modest plug-in-fraction of 25%:
    - reduces charging costs from $1.28 to $0.72 per day in the absence of vehicle-to-grid,
    - enables vehicle-to-grid to greatly reduces costs further to $0.24 per day (plugged in at all times),
    - provides sufficient flexibility to ensure EV charging occurs at times of low zone substation load, facilitating a near optimal hosting capacity.
- Electricity market prices and distribution network loads appear to be sufficiently correlated to gain reasonably good network outcomes by optimising for market prices (though better results can be achieved when explicitly optimising for network objectives).
- The ACT contracted solar and wind farms provides a reliable output to power EV charging at any time. When EVs are plugged in most of the time charging can occur when renewable generation exceeds 2000MW.

We also consider scenarios where EVs can only connect to chargers during the daytime, or exclusively overnight. The impacts of these constraints are:

- The nighttime offers more opportunities to charge at simultaneously low prices and network demand.
- The financial value of vehicle-to-grid is similar when vehicles are plugged in during the daytime or overnight, but the grid impacts are far better overnight.

The central policy implication of these findings is that **encouraging EV drivers to plug their vehicles in as frequently as possible should be the primary behavioural message.** Plugging in around 25% of the time – 6hrs a day or most of the weekend – appears to be a good target. Encouraging charging overnight is a secondary priority.

Options should be explored for making **managed charging the default behaviour of EVs**, while discouraging, restricting, or prohibiting unmanaged Level 2 charging. Level 1 charging (1-2kW) places much less stress on the network than Level 2 charging (pulling 1-2kW of power compared to 7.4 - 22kW).

Managed charging could be implemented via auto manufacturers, who have stable communication with their vehicles, irrespective of where they are and what charger/socket they're connected to.

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