Low voltage network capital requirements from gas-to-electricity and EV uptake

Low voltage network visibility, constraint risk, and capex assessment for Wellington Electricity Lines Limited

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Abstract

Electricity Distribution Businesses (EDBs) have limited visibility of low voltage (LV) networks, and significant uncertainty around the rate and location of uptake of new loads on each LV network. This makes it challenging to study the impacts of different future demand scenarios and the capital expenditure required to avoid network congestion. Developing an understanding of such impacts is becoming even more important as decarbonisation through electrification grows.

With rapid growth of EVs in the Wellington region, and the prospect of consumers transitioning from gas to electricity, Wellington Electricity needs to understand what investment is needed on their LV networks to accommodate these changes. Specifically, Wellington Electricity needs to know the overall cost of this future investment, where and when such investment may be required (which LV network and which LV assets), and how such investment might be reduced by using flexibility. Without the ability to forecast constraints and when new capacity is needed, Wellington Electricity and other EDBs will not be able to target their investments and meet their reliability, and quality obligations (including existing voltage quality targets and the expected future LV price-quality regulatory quality measures).

In 2023 Wellington Electricity commissioned ANSA to develop a model that assesses the risk of a constraint on each element of every residential LV network under future loading conditions and to produce a capex programme to resolve those constraints. ANSA did so by building on its constraint analysis tool, resulting in the ANSA Capex Model. ANSA's Capex Model applied a range of future load conditions including EV growth, demand transitions such as gas-to-electricity and urban infill, and PV export. Constraints considered for every LV asset included conductor loading, voltage excursions, and transformer loading. The ANSA capex model produced a constraint risk curve for each LV asset. The ANSA capex model then applied

standard asset costs to each constraint curve, the aggregate capex forming the capex programme.

This has allowed Wellington Electricity to forecast where and when LV investment is needed. They have now incorporated the capex programme into their Asset Management Plan. The constraint risk curves also highlight where flexibility might be used to reduce future investment, and the model provides the inputs to calculate the value those services can provide from deferring that investment.

This paper discusses the study that was carried out for Wellington Electricity's residential LV networks. Some of the key findings include aggregated constraints mapped across the network, which have provided key insights into investment patterns, reflecting historic network design standards, infill housing developments, and growth characteristics.

1. Introduction

Electricity Distribution Businesses (EDBs) have limited visibility of low voltage (LV) networks (230 Volt / 400 Volt networks), and significant uncertainty around the rate and location of uptake of new loads on each LV network. This makes it challenging to study the impacts of different future demand scenarios and the capital expenditure (capex) required to avoid network congestion, or the flexibility actions to take to defer or avoid capital expenditure. Developing an understanding of such impacts is becoming even more important as decarbonisation through electrification grows.

With rapid growth of electric vehicles (EVs) in the Wellington region, and the prospect of consumers transitioning from gas to electricity, Wellington Electricity needs to understand what investment is needed on its LV networks to accommodate these changes. Specifically, Wellington Electricity needs to know the overall cost of this future investment, where and when such investment may be required (which LV network and which LV assets), and how such investment might be reduced by using flexibility. Without the ability to forecast constraints and when new capacity is needed, Wellington Electricity and other EDBs will not be able to target their investments and meet their reliability, and quality obligations (including existing voltage quality targets and the expected future LV price-quality regulatory quality measures).

In 2023 Wellington Electricity commissioned ANSA to:

1. develop a model of their LV distribution networks that assesses the risk of a constraint on each element of every residential LV network under future loading conditions,
2. to produce a capex programme to resolve those constraints, and
3. to show how demand flexibility, specifically in the timing of EV charging, can reduce capex.

This paper outlines the methodology adopted by ANSA in its Caped Model, and the key inputs and data required to produce the capex programme. It then presents and discusses the results from the model, including capex programmes, geographical information, and how flexibility can help resolve some constraints. The paper ends with a conclusion and next steps.

2. Methodology

The approach taken to understanding capex requirements from the near term to many years, even decades, in the future was an element-wise analysis. Real LV network models and real load profiles were used in the analysis. This involved using ANSA's tools, in the process set out in Figure 1, to assess the risk of constraint of each element in every LV network. To achieve this, the ANSA tool applied a range of future load conditions including EV growth, demand transitions such as gas-to-electricity and urban infill, and PV export. Constraints considered for every LV asset included conductor loading, voltage excursions, and transformer loading. The ANSA model produced a constraint risk curve for each LV asset. The ANSA LV Capex Model then applied standard asset costs to each constraint curve, the aggregate capex forming the capex programme. This section begins by defining some key terms used throughout the paper, describes the modelling approach and challenges in more depth, sets out the assumptions and limitations of the model, and outlines the key scenario inputs to the model.

2.1 Definitions

The following terms are use through the paper or are important to understanding the analysis undertaken by ANSA.

PV future hosting capacity	The maximum export to the network (kW) that can be tolerated at one or more ICPs in the network, before it becomes likely that the network will be constrained, at a given penetration level and upper voltage level. The term "future" is used to emphasise the fact that the hosting capacity is determined based on future network configurations, rather than simply the present/past network state, as derived from monitoring data.
EV future hosting capacity	The maximum power rating of electric vehicle charger (kW) that can be installed at one or more ICPs in the network before it becomes likely that the network will be constrained at a given penetration level.
Network-level hosting capacity	The hosting capacity, as defined above, for all ICPs in an LV network. Also referred to as global hosting capacity.
Circuit-level hosting capacity	The hosting capacity, as defined above, for all ICPs on a circuit within an LV network. Also referred to as local hosting capacity.
Constraint risk	The probability or "risk" that an element in a low voltage network will become constrained or need to be upgraded to resolve a constraint. Constraint risk is determined by running element-level impact studies, in which the voltage and current is calculated at every point in a network for a range of different demand/export levels and configurations. The constraint risk is then equal to the proportion of cases in which an element becomes constrained due to loading or needs to be upgraded to resolve a downstream voltage constraint.
Constraint risk threshold	A defined level of constraint risk, above which an element is flagged as requiring an upgrade. All elements flagged for upgrade are subsequently used to determine the capex required to prevent unacceptable constraint levels. Setting a high constraint risk threshold flags fewer elements for upgrade, resulting in a lower capex forecast. As constraint risk threshold is lowered, more elements are flagged for upgrade, thereby increasing the capex forecast. Section 3.4 discusses constraint risk thresholds with reference to constraint risk, proportion of elements constrained, and capex results.

2.2 Modelling approach and challenges

There are numerous challenges to understanding LV network capex requirements from constraints due to future EV uptake and gas-to-electricity demand transition. The key challenges are:

1. Having sufficient network information to understand which elements are at risk of being constrained in the future.
2. Accommodating the uncertain future state of EV charger uptake and gas-to-electricity demand transition. This includes the location of EV chargers and gas-to-electricity demand transition, as well as the future uptake level.
3. Understanding consumer demand now and what it is likely to change to in the future with increased EV uptake and gas-to-electricity demand transition.
4. Handling the vast amounts of information produced and making it available to the user in a meaningful way.

The approach adopted by ANSA's LV Visibility and LV Capex Models addresses these challenges and is outlined in Figure 1, and explained in more detail below.

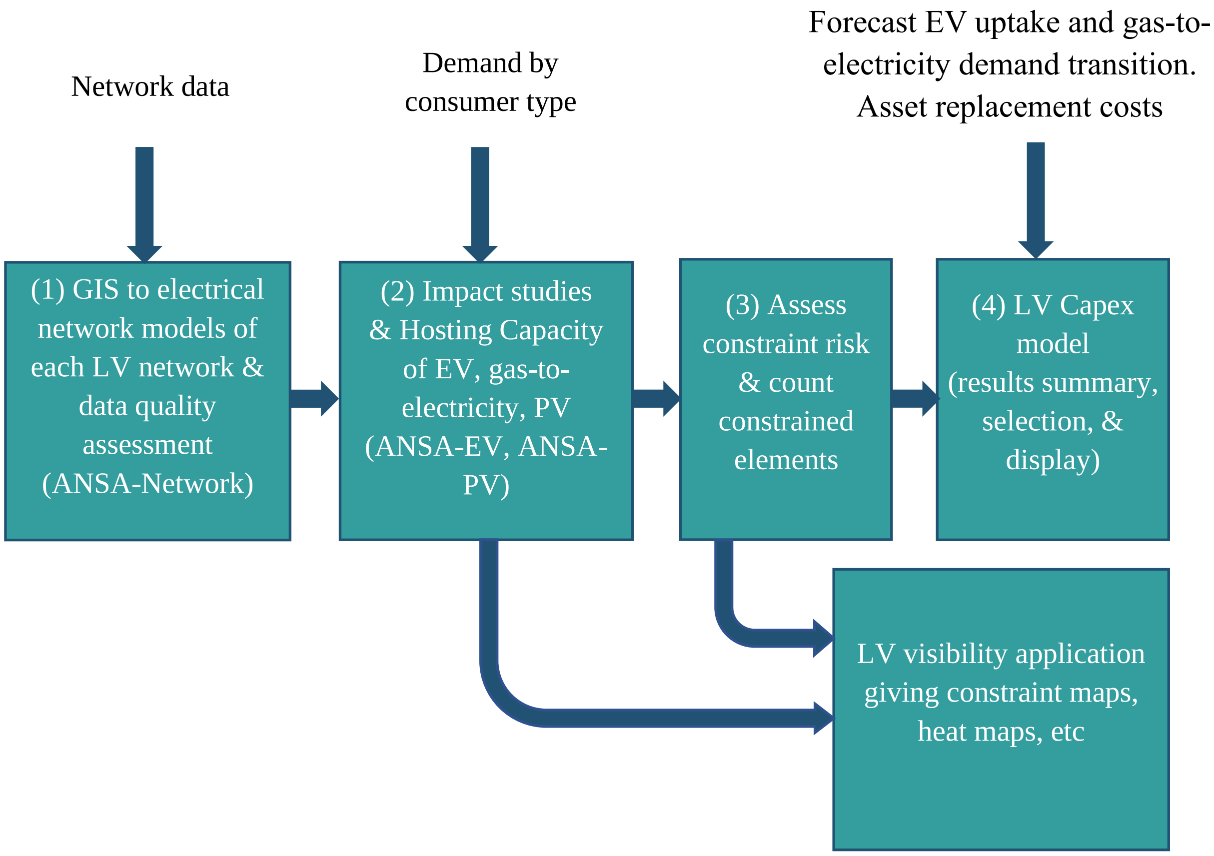


Figure 1: The process using ANSA's tools to assess the risk of constraint of each element in every LV network, resulting in LV capital expenditure plans to resolve thermal and/or voltage constraints.

2.2.1 Complete and accurate electrical models of each LV network

The first challenge of having sufficient network information is managed though use of ANSA's 'complete method', outlined in [1], to model every element and the complete topology of each LV network. This is shown at Step 1 in Figure 1. Elements include the distribution transformer (usually 11 kV/400 V), all segments of conductors (overhead and underground), busses and elements interconnecting busses, including point of supply busses. This method requires determination of network parameters, and resolution of any inconsistencies in network topology. This process also provides LV network data quality information and insights, useful for ongoing data quality improvement. Determination of network parameters and topology is outlined in [2].

2.2.2 Managing the uncertain future state of EV uptake and gas-to-electricity demand transition

The second challenge of the uncertain future state, such as locations and penetration level of EV chargers, and consumers who transition from gas to electricity many years in the future is managed through simulating possible future states. This is achieved through Monte Carlo simulations of several thousand iterations of power flows for each combination of inputs. In each iteration the location of EV chargers and gas-to-electricity demand transition is randomly assigned, at a given penetration level. Step 2 in Figure 1 represents this process.

An input to this process is the existing demand of each consumer at each time of day. This is assessed prior to and during the simulations with careful assignment of demand by customer type.

2.2.3 Determining the risk of constraint of each element in each LV network by year in the future

The process described earlier is an advanced network simulation and analysis (ANSA). As each set of iterations is repeated, the charger capacity (for EV chargers) is increased. Throughout, bus voltages and conductor loading are observed and recorded. The result is a set of constraint risks per element in the LV network, at each penetration level, EV charger size, and time of day of interest. Bus voltages are converted to conductor constraint risks by finding the least cost conductors to replace to relieve the voltage constraint.

A constraint risk threshold is set, with only elements with a constraint risk above that considered as needing replacement at a given penetration level. Since penetration level is specified as a function of time (year in the future), elements above the constraint risk threshold can be assessed in terms of when in the future they exceed that threshold and are therefore counted as needing to be upgraded. This is Step 3 in Figure 1.

2.2.4 Managing the large volumes of data to capex insights

Since the number of elements of each type that are constrained is known from the previous step, these can be converted to costs at Step 4 in Figure 1. The multiple inputs include:

- LV networks;
- elements per LV network;
- EV charger capacities;
- EV charger penetration and gas-to-electricity demand transition levels;
- time of day; and
- constraint risk threshold

The combinations of these inputs require a large number of power flow simulations which leads to an enormous number of outputs and data that must be stored and presented. For example, in this study, after reducing individual elements to five types of elements and constraint counts from over 1 billion power flow simulations, 65 million separate counts of conductors or transformers constrained by cause were yielded. The large number results from the combination of multiple inputs and constraint risk thresholds. Careful design of a database and method of handling, interacting with, summarising, and displaying these results was required. This is also achieved in Step 4 of Figure 1.

2.3 Assumptions and limitations

As with any modelling approach, it is necessary to make certain assumptions, and models have limitations. Some important assumptions and limitations are outlined below:

- There may be other factors that determine conductor and transformer replacement other than loading, such as age and condition.
- No mechanical constraints in upgrading conductors have been considered. These may be limited by wind and other structural loading.
- Quantifying consumers with gas, assessment of gas consumers' demand, and assignment of demand during modelling is limited due to imperfections in ascertaining which households are using gas , and the nature of their gas use (cooking, water heating, and space heating).
- Of the 1,777 LV networks, 1,100-1,200 had major topological issues (mainly due to ICP assignment issues). ANSA used a custom developed algorithm to resolve conflicts caused by ICP assignment and other topological issues. About 500 had no major topological issues.
- The capex forecasts presented in the results use a 100% constraint risk threshold. This means that every combination of inputs used to model each LV network resulted in constraints. This results in an optimistic forecast, reflecting only highly certain expenditure. There may be other lower probability constraints that have not been accounted for in the results.

- Equipment ratings used were their nameplate ratings at nominal ambient temperature – see Conclusion for further discussion.

2.4 Key model inputs – uptake forecasts, scenarios, and asset unit costs

Some key inputs required for ANSA's LV Capex Model are:

- Distributed energy resource uptakes – in this case EV penetration forecasts and gas-to-electricity transition forecasts. The model uses forecasts specified to the geographic levels of territory, statistical area 2, and individual LV networks. For this stage of the project the same EV and gas-to-electricity forecasts were used in all four of Wellington Electricity's territories and are shown in Figure 2 and Figure 3 respectively. In future investigations forecasts at a more granular geographic level will be made.
- Asset replacement unit costs were provided based on known unit costs of replacing overhead and underground conductors, as well as fixed costs per section requiring replacement. Costs used were for urban areas, with the model able to manage rural costs as well. Transformer replacement costs were provided for pole, pad-ground, pad-kiosk, and vault-indoor transformer types, as well as for capacity from 50 kVA up to 1.5 MVA. Where higher capacity transformers were required, the costs were determined from two transformers required to make up that capacity.

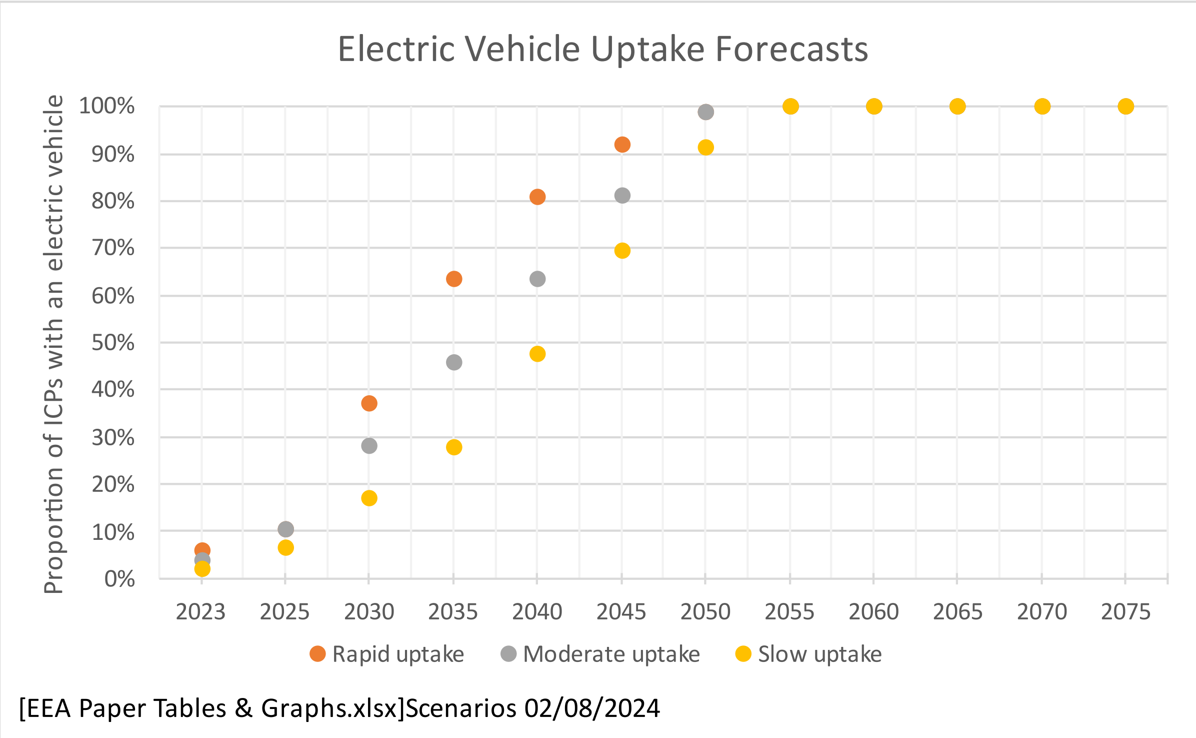


Figure 2: EV uptake forecasts applied to each territory. In the results presented in this paper the Moderate Uptake scenario is used, with an assumed 50% diversity of charging, meaning 50% of EVs were assumed to be plugged in and charging in the results.

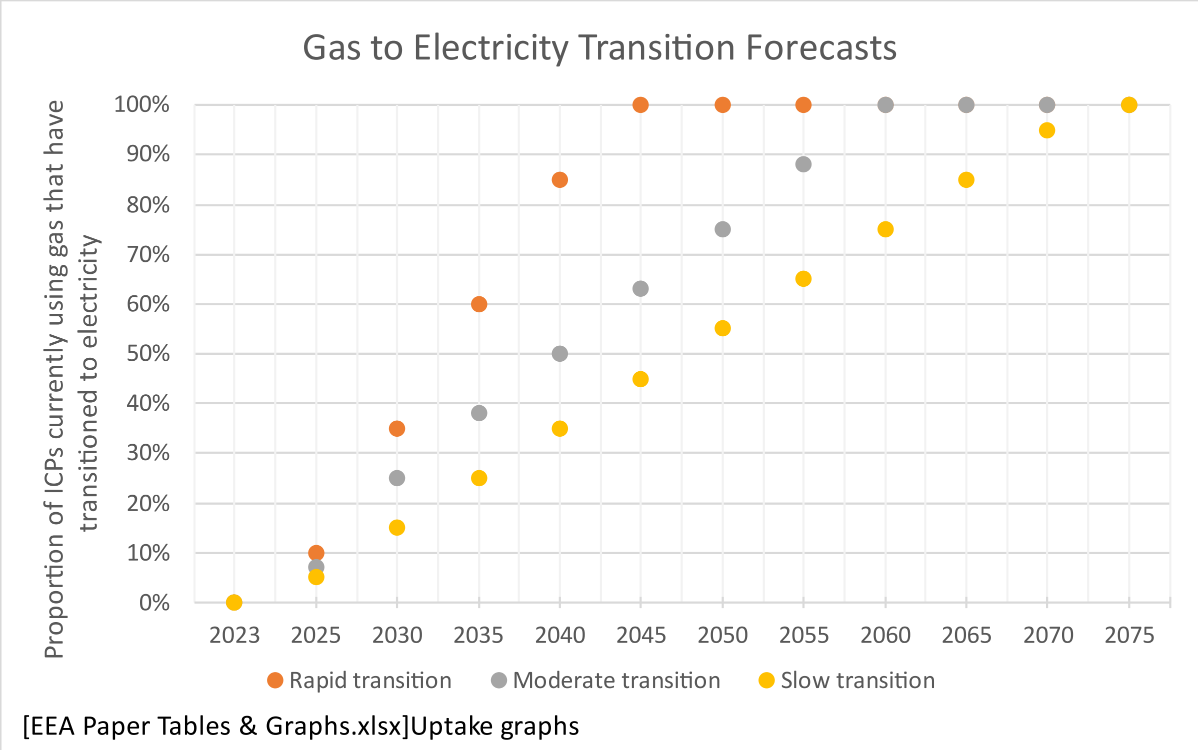


Figure 3: Gas-to-electricity demand transition forecasts. In the results presented in this paper the slow transition scenario is used.

The above forecasts were collectively expressed in the following decarbonisation scenarios:

Table 1: Decarbonisation scenarios.

Decarbonisation Scenario	EV Uptake Forecast (from Figure 2)	Gas-to-electricity transition forecast (from Figure 3)
Slow	Slow uptake	No gas transition (proportion of ICPs transition from gas to electricity set to zero in all years)
Expected	Moderate uptake	Slow transition
Rapid	Rapid uptake	Rapid transition

3. Results and discussion

A key result from the model is the number and cost of LV networks that need upgrading by year in each scenario. Further, how capex could be avoided in the future, and the location of assets by type constrained. Results for each of these are presented and discussed in the following sub-sections. The proportion of assets constrained, and the effect of lowering the constraint risk threshold from the 100% threshold used are then discussed in the final sub-section. Further information and results from the study can be found in Wellington Electricity's 2024 Asset Management Plan [3].

3.1 Networks constrained and network upgrade costs by decarbonisation scenario

The resulting number and cost of networks needing upgrading at each year by scenario, for a given selection of inputs, are provided in Table 2.

Table 2: (a) Number of LV networks out of the 1,777 studied requiring upgrading by scenario, (b) capex required to upgrade these networks by scenario. In these results 50% of 3.7 kW EV chargers are on at 6pm, with a 100% constraint risk threshold. See Section 3.4 for a discussion of constraint risk threshold.

(a) Number of LV networks requiring upgrading at each year

Decarbonisation scenario	2025	2030	2035	2040	2045	2050	Total
Slow	217	24	0	232	189	420	1,082
Expected	241	0	233	183	204	226	1,087
Rapid	241	220	184	144	349	0	1,138

[EEA Paper Tables & Graphs.xlsx]Results-cumulativeNWs 07/08/2024

(b) Cost of upgrading LV networks at each year ($m)

Decarbonisation scenario	2025	2030	2035	2040	2045	2050	Total present cost
Slow	$57	$6	$1	$61	$59	$156	$150
Expected	$64	$0	$60	$54	$68	$87	$172
Rapid	$67	$56	$55	$62	$127	$0	$207

[EEA Paper Tables & Graphs.xlsx]Results-cumulativeNWs 07/08/2024

From Table 2(a) it is evident that about 12% of LV networks are expected to be constrained relative to their nameplate ratings during winter peaks by 2025, even with the most optimistic constraint risk threshold of 100% (i.e. every one of the approximately 1000 power flow simulations of different EV and gas-to-electricity ICP locations resulted in a constraint somewhere in the LV networks shown in the table). A further 1.3% to 14% of LV networks are forecast to become constrained by 2030, depending on the decarbonisation scenario. By 2050 more than 50% of LV networks have become constrained.

The purpose of developing the decarbonisation scenarios, together with this capex investigation, are to give an envelope of expected costs in each period to 2050, as shown in

Table 2(b). The envelope starts out with little difference between years, as expected. The differences between scenarios in 2025 is explained by different strategies employed in the capex model to either leave or split LV networks into two, driven by slight differences in EV uptake to 2025. In the Slow scenario fewer LV networks are recommended by the capex model for splitting into two with a second transformer added compared to the Rapid scenario. By 2030 the differences in costs between scenarios becomes substantial, almost reaching the maximum difference between the scenarios.

3.2 Impact of charging behaviour on capex and capex reductions available through flexible charging

The results in Table 2 give Wellington Electricity important information to understand the investment in its network required to prepare for decarbonisation. Viewed in a different way, the results give Wellington Electricity information on how they might use flexibility to defer or avoid some network investment. The results in Figure 4 show the capex present cost required under a range of different inputs, for the Expected decarbonisation scenario. The Total present cost figure of $172 million from Table 2(b) is represented by the lefthand orange point in Figure 4.

Figure 4 shows how sensitive capex is to both charger capacity and time of day of charging. For example, employing flexible EV charging: by lowering charge rate and moving time of charging it may be possible to reduce the $182m at 6pm to $23m at 3am. If even higher capacity 7.4 kW chargers are predominantly installed even larger capex reductions are available, in the order of $200-$250m capex in present cost. Over the 123,300 ICPs on the 1,777 LV networks, the range of savings available are in the order of $1,300-$2,000 per ICP in present cost, or roughly $100-$150 per ICP per annum.

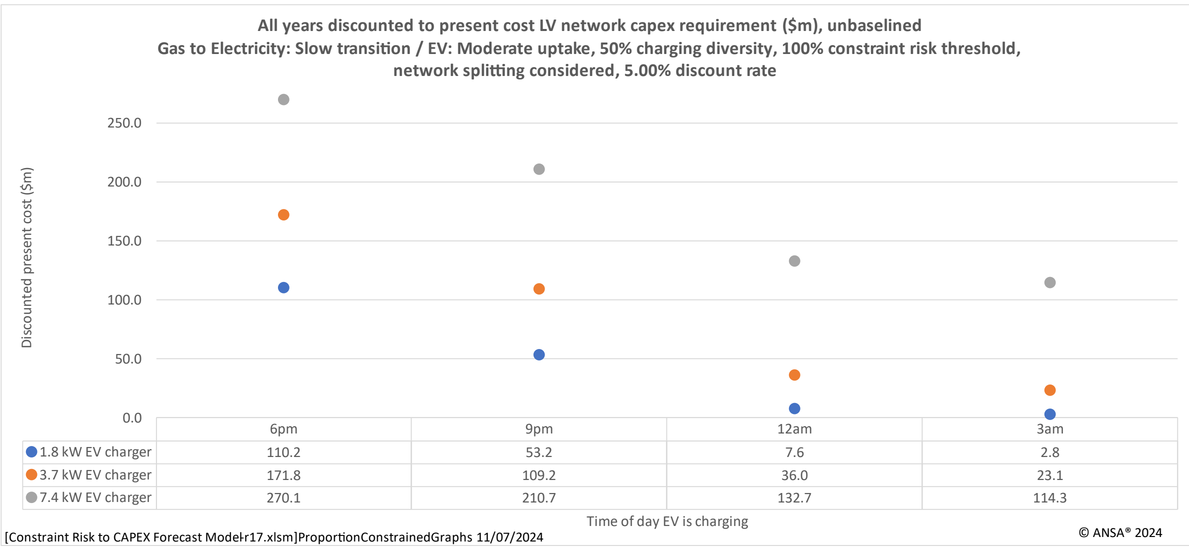
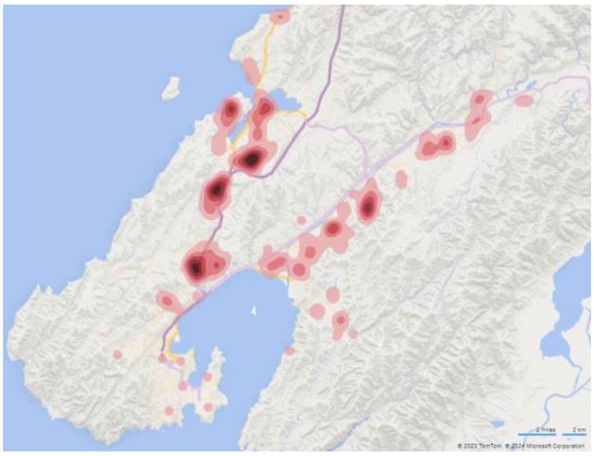


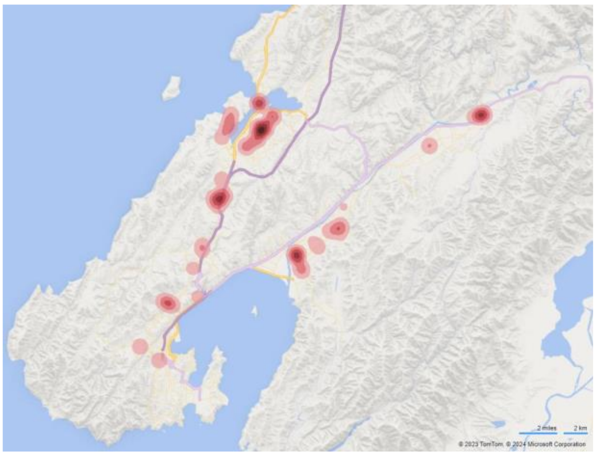
Figure 4: Impact of charging behaviour on LV network capex.

3.3 Location of assets forecast to be constrained

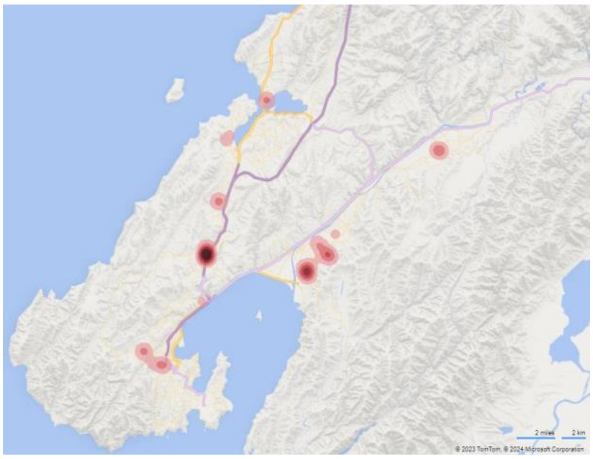
Because each element of each LV network is considered in ANSA's model, and because the location of each element is known, it is possible to show where LV network upgrades by asset type are expected to be required. Figure 5 illustrates the geographical location of asset replacements required. The geographical locations are typically older LV networks built using older network design standards, and/or areas where there has been large high-density infill housing.



(a) Distribution transformer constraints to 2030



(b) LV cable constraints to 2030



(c) LV line overhead constraints to 2030

Figure 5: Constraints to 2030 by asset type and location.

3.4 Constraint risk threshold and its impact on capex

Throughout the paper a constraint risk threshold of 100% has been used. A constraint risk threshold is set as a filter to decide whether an element should be counted as requiring an upgrade. This is necessary due the probabilistic nature of the modelling approach described in Section 2.2.

Figure 6 shows the constraint risk versus year for one of the 1,777 LV networks assessed, with the constraint map for the same network shown in Figure 7. At the 100% constraint risk threshold, indicated by the dotted horizontal line at 100%, only the transformer is flagged as requiring upgrade, and not until 2050. Reducing the constraint risk threshold to 80% shows that:

- the transformer is flagged for upgrade due to a thermal constraint in 2035,
- at least one conductor is flagged for upgrade due to a thermal constraint in 2040, and
- at least one conductor is flagged for upgrade to resolve a voltage constraint in 2045.

Lowering the constraint risk threshold even further to 60% shows that:

- the transformer and at least one conductor are flagged for upgrade in 2035 while
- at least one conductor is flagged for upgrade to resolve a voltage constraint in 2040.

As constraint risk threshold is lowered, more elements are flagged as requiring upgrade to avoid the risk of constraints occurring in the network. In particular, more conductors are considered as requiring upgrades to avoid downstream voltage constraints. This in turn results in higher total capex.

The effect of constraint risk threshold on the proportion of elements constrained across all LV networks can be seen in Figure 8. This chart relates to elements constrained in 2030, with the 100% constraint risk threshold used through this paper corresponding to the set of bars on the right-hand side.

The impact of constraint risk threshold on capex is illustrated in Figure 9, which shows total capex across a range of different EV scenarios for a constraint risk threshold of 100% and 80%. As the constraint risk threshold is decreased from 100% to 80%, the total capex (discounted to present cost) more than doubles, and in some cases triples. In the results presented in this paper, and used by Wellington Electricity, a 100% constraint risk threshold is used, giving the most optimistic (lowest) capex values.

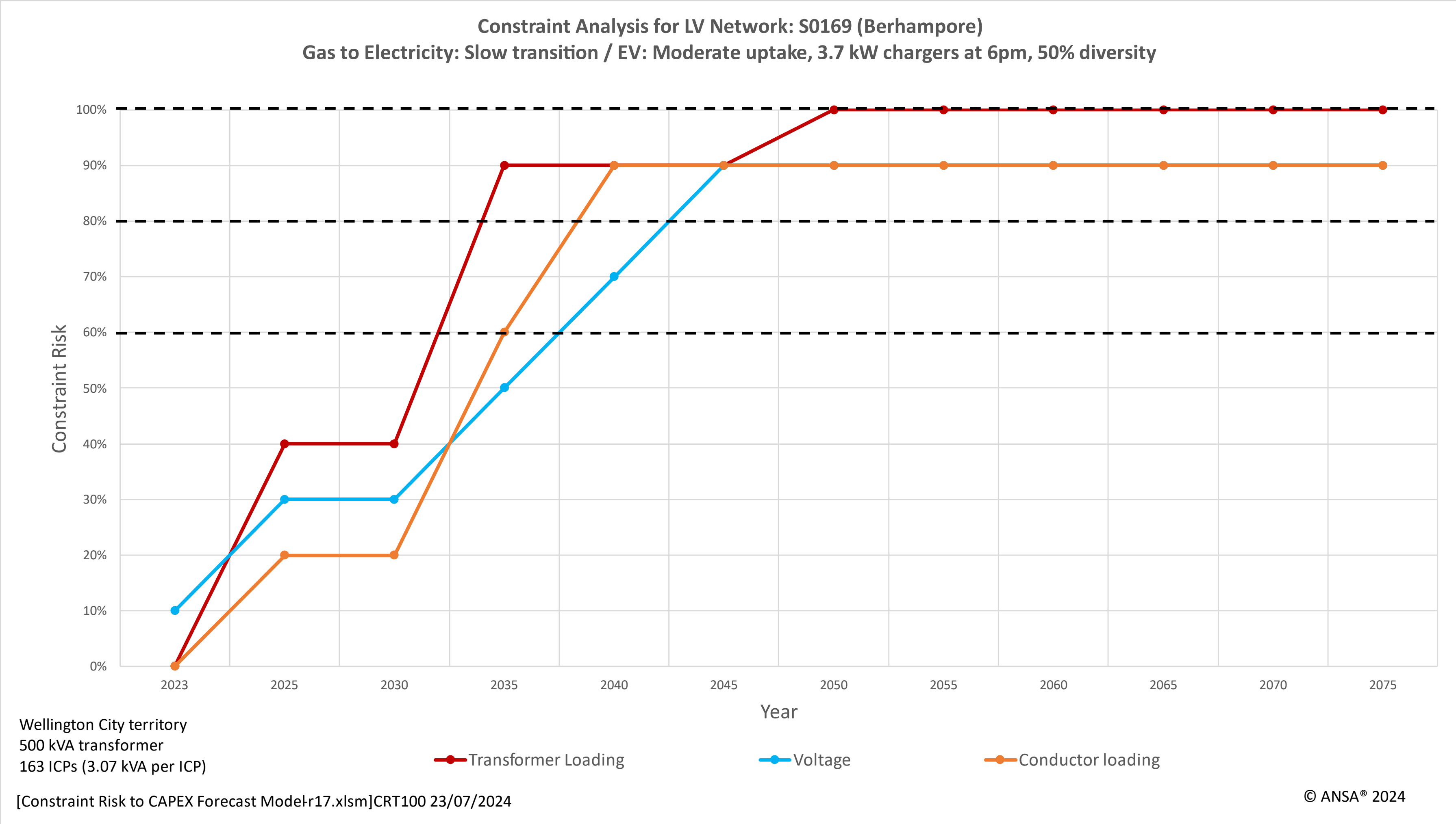


Figure 6: Constraint risk and constraint risk thresholds for one LV network.

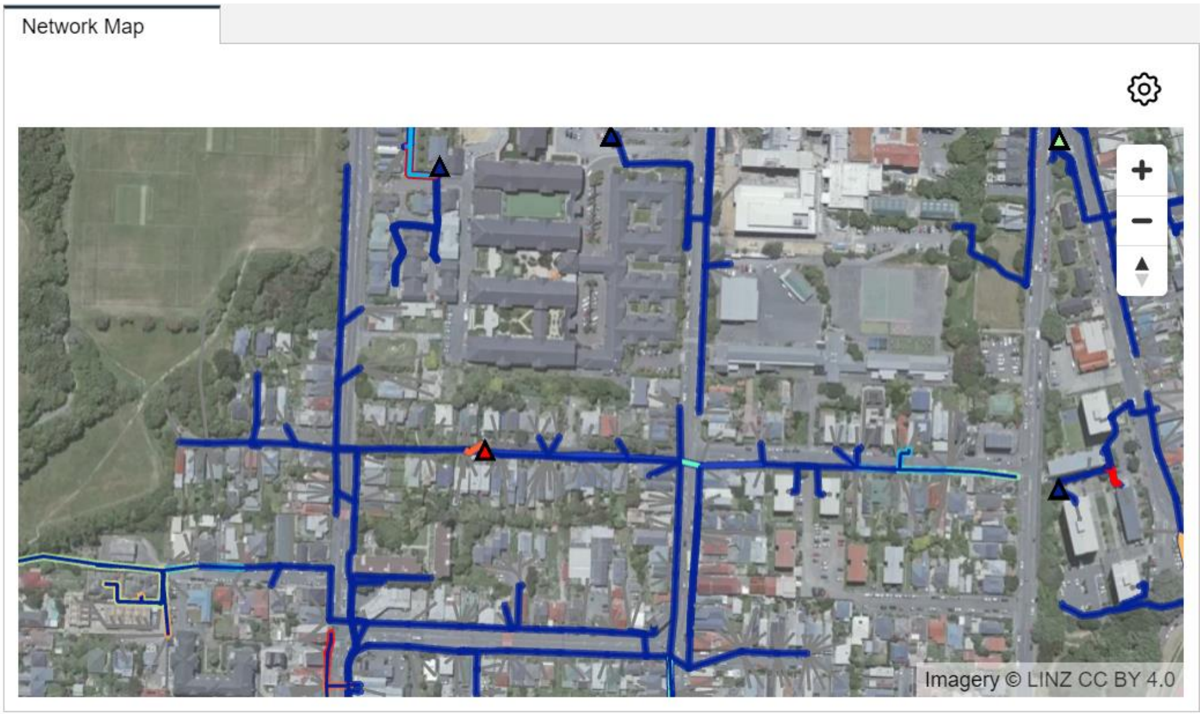
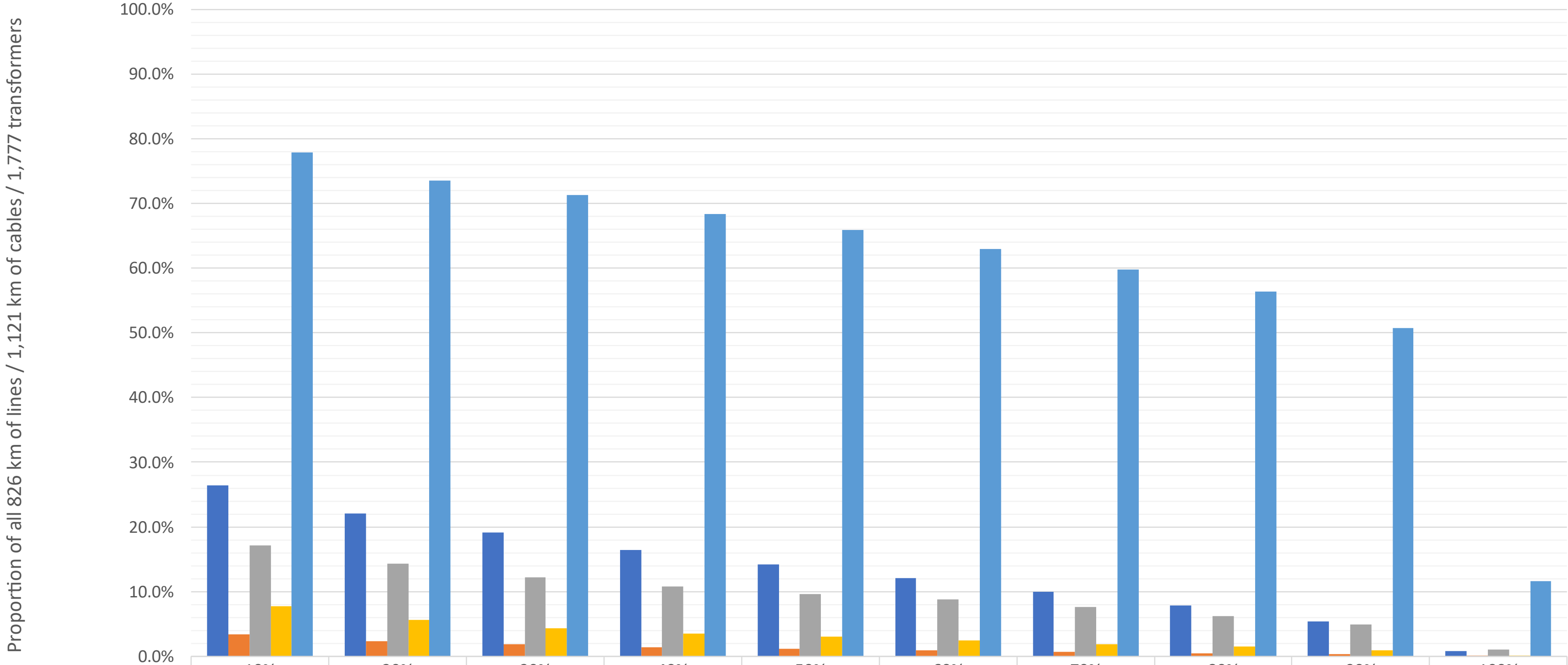
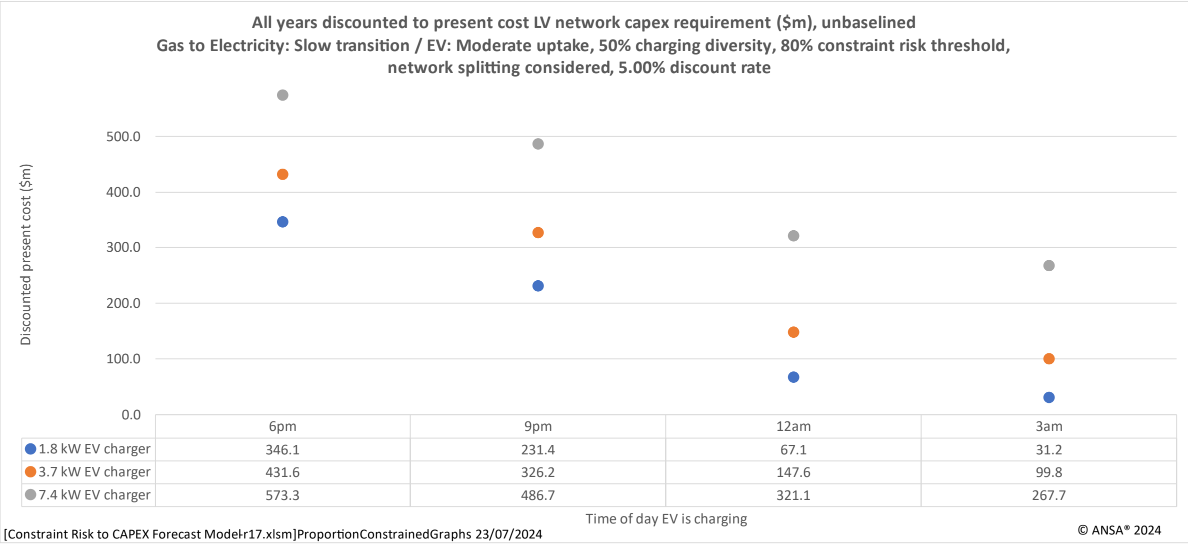


Figure 7: Constraint index for the network in Figure 6 with EV demand, from ANSA's LV Visibility Application. This shows the transformer constrained first, with some conductors nearing constraint, and voltage slightly constrained on the outer edge of the LV network (right-hand side).

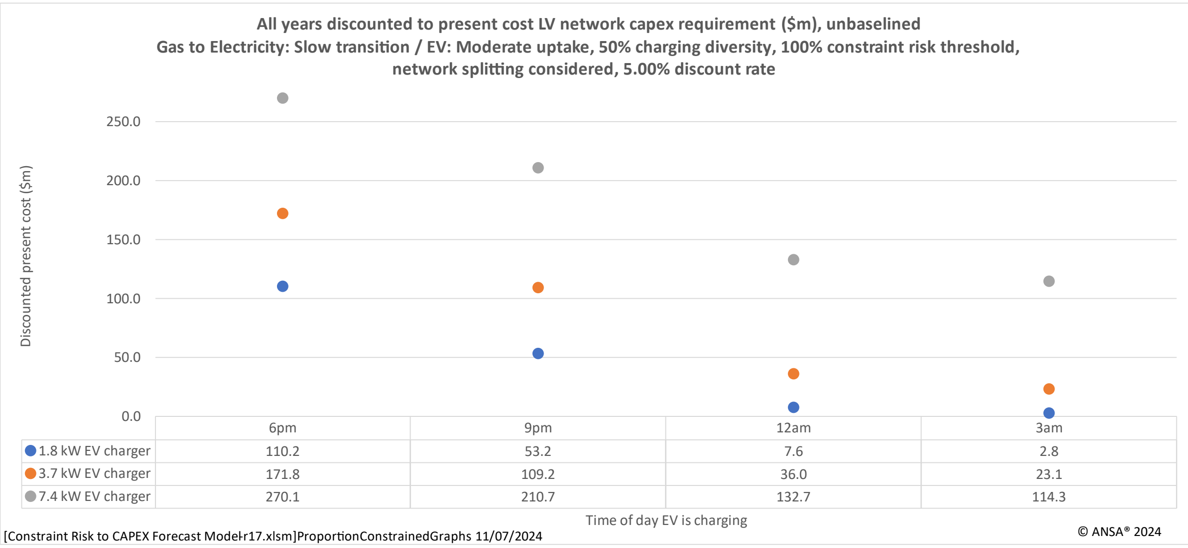


	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Lines on voltage	26.4%	22.1%	19.1%	16.4%	14.2%	12.1%	9.9%	7.9%	5.4%	0.8%
Lines on load	3.4%	2.4%	1.8%	1.4%	1.1%	0.9%	0.7%	0.5%	0.4%	0.0%
Cables on voltage	17.1%	14.3%	12.2%	10.8%	9.6%	8.8%	7.6%	6.2%	4.8%	1.0%
Cables on load	7.7%	5.6%	4.4%	3.5%	3.0%	2.4%	1.9%	1.5%	1.0%	0.1%
Transformers on load	77.9%	73.6%	71.3%	68.4%	65.9%	63.0%	59.8%	56.4%	50.7%	11.6%

Figure 8: The effect of lowering constraint risk threshold at a given year in the future on the proportion of elements constrained.



(a) Constraint risk threshold set to 80%



(b) Constraint risk threshold set to 100% (same as Figure 4)

Figure 9: Impact of EV charger sizes and charging times on LV network capex with (a) an 80% constraint risk threshold and (b) a 100% constraint risk threshold, the same as Figure 4.

4. Conclusions and next steps

From this study it has been possible to understand the LV network capex requirements many years in advance by analysing scenarios of EV uptake and demand transition from gas to electricity. In turn it is concluded that there is a substantial capex required immediately to relieve transformer constraints, and that these are mainly on older parts of the network. Further, from 2030 there will be another large capex requirement to upgrade both transformers and conductors. However, by careful use of flexibility, this cost can be avoided or deferred to a large extent.

Also evident from the results is how EV chargers drive the need for capex, and that gas-to-electricity transition increases demand further, which adds to the capex requirement. Because results are inherently related to geography, it is also possible to examine upgrade requirements by location. From this it is concluded that older networks with older design standards, and networks experiencing high density urban infill housing, are driving the need for immediate and future upgrades.

Planned work in the next stage includes:

1. Improving the GIS data quality input to the model (improvements have been underway since this study, in part using results from the ANSA-Network analysis) and load profile data quality by providing more specific load profiles by ICP, and more accurate identification of ICPs with gas.
2. Updating equipment ratings to use seasonal cyclic ratings.
3. More granular EV uptake forecasts, by location, will also be considered.
4. Further studies will then be undertaken, revising and improving results to date.
5. To enhance this, further functionality developed in ANSA’s LV Visibility Dashboard and Capex Model will be made available to view and interact with results.
6. In addition, the capex model will include capex implications from PV uptake.

References

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[3] Wellington Electricity Lines Limited, "2024 Asset Management Plan," Wellington Electricity Lines Limited, Wellington, 2024.

[4] Wellington Electricity Lines Limited, "2023 Asset Management Plan," Wellington Electricity Lines Limited, Wellington, 2023.