Project EDGE

Determining the Impact of Update Frequency on Operating Envelope Efficacy

A report prepared by the University of Melbourne, Department of Electrical and Electronic Engineering

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This report has been developed with the support of:

Important notice

PURPOSE

This *Determining the Impact of Update Frequency on Operating Envelope Efficacy* report has been prepared for Project Edge by the University of Melbourne, Department of Electrical and Electronic Engineering.

This report provides the results of the work conducted on the technical impacts of utilising forecasts with differing update frequencies when creating dynamic operating envelopes.

DISCLAIMER

The Project Edge participants (AEMO, Mondo Power Pty Ltd and AusNet Electricity Services Pty Ltd, each a **Project Participant**) have commissioned this *Determining the Impact of Update Frequency on Operating Envelope Efficacy* report by the University of Melbourne, Department of Electrical and Electronic Engineering, for the purposes of Project Edge. Each of the Project Participants has made reasonable efforts to ensure the quality of the information in this report but are not the author of this report and cannot guarantee that the information, forecasts and assumptions contained it are accurate, complete or appropriate for your circumstances. This report does not include all of the information that an investor, participant or potential participant in the national electricity market might require, and does not amount to a recommendation of any investment.

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The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

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Each Project Participant acknowledges:

- the work of the University of Melbourne, Department of Electrical and Electronic Engineering in preparing this report; and

- the support, co-operation and contribution of the other Project Edge participants and consultants in providing data and information used by the University of Melbourne, Department of Electrical and Electronic Engineering to prepare this report.

Executive summary

The rapid uptake of distributed energy resources (DER), and the opportunity for DER to actively participate in a DER marketplace have provided strong drivers for the implementation of dynamic operating envelopes (DOEs). The currently used static limits on DER exports are conservative by design but DOEs will allow distribution network service providers (DNSPs) to consider locational and temporal factors when assigning capacity to DER, increasing the capacity that can be allocated. However, to calculate DOEs, DNSPs rely on forecast values for head of feeder voltages and the power of customers. The error in these forecasts will impact the efficacy of the DOEs. This can either result in an under-allocation of aggregate capacity (compared to the perfect knowledge DOEs), potentially leading to unnecessary restrictions on customers, or an over-allocation of aggregate capacity (compared to the perfect knowledge DOEs), potentially leading to violation of network constraints. In general, the closer to real time that a forecast is generated, the more accurate it is likely to be. However, more frequent forecasts and updates to DOEs will come with associated technical and economic implications for the DNSP. To understand the potential benefits of making this investment this report looks at how DOE efficacy varies with day ahead, intra-day, and close-to-real-time (30-minute ahead) forecasts compared to the theoretical maximum available if the DNSP has perfect information.

Section 2 of this report describes the approach used to generate the three different forecasts that are being using in this work: the day ahead, intra-day and close-to-real-time (30-minute ahead persistence) forecasts. Additionally, some high-level analysis is provided of the forecasting data available from the Project EDGE field trials which showed there to be very limited difference between the day ahead and intra-day forecasts used in the trial. Therefore, the day ahead forecasts from the trial were used to train a machine learning tool used to generate the day ahead forecasts for the simulations. Analysis of day ahead and intra-day forecasts from 47 Mondo customer sites determines that it can be expected that intra-day forecasts improve upon the day ahead forecasts by 27.6% for PV generation and 13.1% for demand. For the voltage of intra-day forecasts, as there is no effective method of forecasting network voltages in the project, it is assumed that there is a 10% increase in accuracy compared to the day ahead forecast. This is because voltage forecasting at a specific node (in this case the head of feeder voltage) is less developed compared to demand or PV forecasting, and so the improvement of more frequent forecasts is likely to be less.

Section 3 describes the case studies that are conducted as part of this work. This includes modelling DOEs generated from perfect knowledge, persistence forecasts, intra-day forecasts, and day ahead forecasts for three representative networks – a *City*, *Suburban*, and *Regional* network. The objective functions were applied to the network over eight different DER penetration scenarios (from 20% to 100%) to determine the number of DER in the network. Each penetration scenario was further divided in four participation scenarios (Low, Mid, High, 100%), to determine the number of DER actively participating in the DER marketplace. For the *City* and *Suburban* networks, a higher and lower head of feeder voltage profile is modelled to test the impact of this upon the DOEs generated from the forecasts.

In Section 4 the results of the modelling are presented and analysed. It is seen that when the network is unconstrained, the difference between the perfect knowledge DOE and the uncertain forecast DOEs can be zero – that is to say that both will assign full capacity to the DER in the network (this may not

always be the case, as the network may be unconstrained in practice, but the inaccurate forecast may cause the DOE calculation to conclude there is a constraint, and so reduce capacity unnecessarily). Once either the perfect knowledge DOE or the uncertain forecast DOE calculate there to be a network constraint, differences between the perfect knowledge DOE and uncertain forecast DOE will occur. If the forecasts are fairly accurate, then the DOEs generated can mimic the general trajectory of the perfect DOE across the day but will often miss the detailed changes within that trajectory. However, if the forecast is inaccurate, then this can lead to large difference in the DOEs being generated.

For lower DER penetration scenarios, the higher DER participation levels result in larger deviations in aggregate DOE capacity allocation compared with the DOEs generated using perfect knowledge. However, as the DER penetration level grows the deviations in capacity allocation shift so that the lower DER participation levels have the greatest deviations in aggregate DOE capacity allocation compared with the DOEs generated using perfect knowledge. This is because, for lower DER penetrations, low participation often leads to unconstrained operation in practice. This means that while the errors in the forecasts may still be substantial, the likelihood of network constraints is significantly smaller. However, once the network is generally constrained even at lower DER participation levels, the greater uncertainty around the power of non-participating customers associated with the lower participation levels causes much larger deviations in aggregate capacity allocated in the network compared with the DOEs generated using perfect knowledge.

The results show that the over-allocation of aggregate export or import capacity can occur at times when it is more likely that the full capacity allocated will be utilised. For example, import capacity is over-allocated by the forecast DOEs during the morning and evening demand peaks, as well as overnight. For the higher voltage profile, the export capacity is over-allocated by the forecast dependent DOEs throughout daylight hours. The size of the constraint violation is dependent on the combination of the DER penetration level and the DER participation level. At lower DER penetration levels, lower DER participation levels cause the least and smallest constraint violations because there is significant network capacity available to be shared between a small number of participating DER. However, when DER penetration levels increase, having more of those DER receiving the DOEs reduces the overallocation of capacity, and subsequent potential network violations. This is because a high DER participation reduces the total power flow in the network from non-participating customers, which is a large source of forecast uncertainty. However, averaged across all DER penetration levels, the DER participation level does not seem to have a substantial impact on the average constraint violation. Instead, it appears to be beneficial to increase the DER participation rate in line with the DER penetration rate.

In general, as the number of DER in the network increases, the occurrence and severity of forecast DOEs over-allocating aggregate capacity (compared to the perfect knowledge DOEs) increases, and therefore so does the potential for voltage or thermal constraint violations from DOEs using forecasts. The 30-minute ahead persistence forecast will generally have a smaller number of constraint violations compared with the day ahead and intra-day forecasts. The difference in capacity allocation of the day ahead forecast and the intra-day forecast is minor, as they are both inaccurate forecasts and the incremental shift in accuracy with the intra-day forecasts doesn't have significant impact on the DOE allocation. If an intra-day forecast is able to provide a significant improvement on head of feeder voltages, then it is likely to substantially reduce the severity of network constraint violations or under-allocation of capacity.

Glossary

AEMO	Australian Energy Market Operator
DER	Distributed Energy Resources
DOE	Dynamic Operating Envelope
DNSP	Distribution Network Service Provider
EDGE	Energy Demand and Generation Exchange
LV	Low Voltage
NEM	National Electricity Market
PV	Photo-Voltaic
SWER	Single-Wire Earth-Return
UoM	The University of Melbourne

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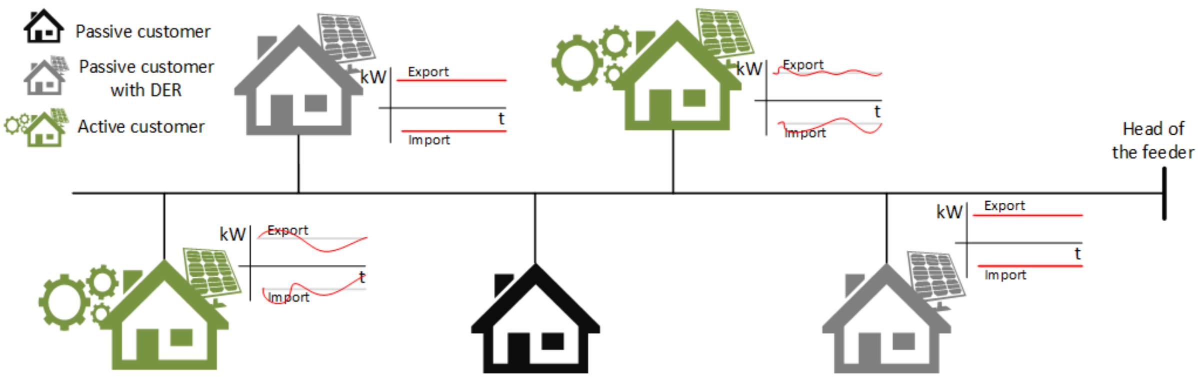
1 Introduction

As the rapid uptake of distributed energy resources (DER)[1] supported by the evolution of smart grid technologies increases, there are emerging opportunities for a distribution network service provider (DNSP)[2] to assume a more active role. This could enable DER to actively participate in a DER marketplace. However, a key challenge is how to manage many diverse devices while ensuring network reliability. Presently, this is managed through a static limit imposed on DER that does not consider the locational and temporal aspects of power injection and absorption and will become outdated with increasing DER penetration. To overcome this challenge Project EDGE (Energy Demand and Generation Exchange) is trialling an innovative approach called dynamic operating envelopes (DOEs).

A DOE is defined as dynamic power export/import limits at the customer's connection point. The DOEs are calculated by the DNSP, considering network limits. A simple illustrative example demonstrating the concept of the operating envelope is shown in Figure 1. The black, grey, and green houses represent customers with passive load, passive DER, and active DER respectively. The operating envelope (red) of passive customers are static throughout the day but, the operating envelopes (red) of active customers[3] are managed by the DNSP depending upon the network conditions.

Figure 1 Conceptual illustration of the operating envelope



In The University of Melbourne's (UoM's) previous reports on Fairness in Dynamic Operating Envelope Objectives and Testing Different DOE Approaches at DER Penetration levels in real-world networks, it was assumed that the DNSP had perfect knowledge of the network state when it was calculating the DOEs (customer active and reactive power, and head of feeder voltage levels). This allowed a level playing field when comparing the maximum efficacy of the DOEs. However, in reality the DOEs are calculated ahead of time with imperfect forecasts. The error in these forecasts will impact the

[1] Distributed Energy Resources include any flexible resources such as rooftop photovoltaics, household batteries, thermal loads, electric vehicles, etc.

[2] The company who manages the distribution network both at medium and low voltage levels.

[3] A customer who has provided control over their DER for participation in markets/services. In the context of Project EDGE, active customer provides market services through a trader.

efficacy of the DOEs. This can either result in an under-allocation of capacity, leading to unnecessary restrictions on customers, or over-allocation of capacity, leading to violation of network constraints.

In general, the closer to real time that a forecast is generated, the more accurate it is likely to be. However, more frequent forecasts and updates to DOEs will come with associated technical and economic implications for the DNSP. To understand the potential benefits of making this investment this report looks at how DOE efficacy varies with day-ahead, intra-day, and close-to-real-time forecasts compared to the theoretical maximum available if the DNSP has perfect information. So that the impact of the DOE update frequency can be assess, only a single DOE objective will be considered in this work, namely the Maximise NEM Export objective.

2 Forecast generation

In this section an overview will be provided on how the different forecasts used in this report are generated. There are three forecast update frequencies that are being modelled in this work: a day ahead forecast, an intra-day forecast, and a close to real time (persistence) forecast.

2.1 Day ahead forecast

One of the aims of this techno-economic modelling is linking the results of the Project EDGE field trial data across a range of network types and DER penetration scenarios. The field trial implemented day ahead forecasts in the creation of DOEs. The day ahead forecasts for power of customers in the network, as well as the head of feeder voltage are available. Additionally, the actual realisation of this data is also available. These forecasts (and their associated DOEs) are generated daily at 10:00 on day *T*, for implementation beginning at 04:00 on day *T+1*. Examples of the day ahead forecasts from the field trial are shown in Figure 2 – Figure 4. For Figure 2 the day ahead forecast is able to predict the generation shape of the PV generation profile, but often overestimates in this case, as it does not include weather forecasts as part of its forecasting algorithm. Additionally, it is not able to predict the sudden spikes of customer demand with great accuracy. Figure 3 highlights the difficulty in predicting the head of feeder voltage. In fact, from this figure the forecast for the Site A voltage remains fairly constant across the whole duration of the field trial data. This is not an accurate reflection of the head of feeder voltage. The forecast voltage in Figure 4 which predicts the Site C (single wire earth return (SWER) network) head of feeder voltage is more variable, but consistently under forecasts the head of feeder voltage.

Figure 2 Actual active power demand for customer A5 and AusNet day ahead forecast field trial data

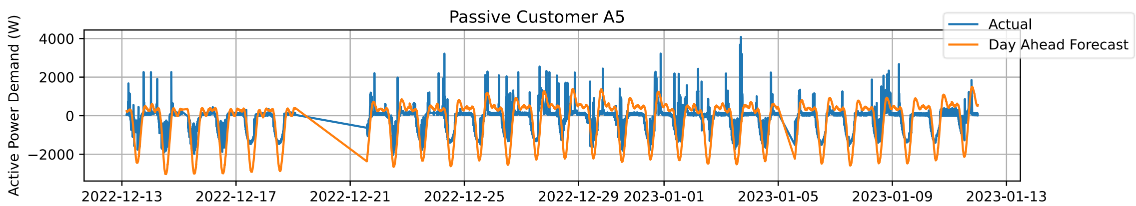


Figure 3 Actual head of feeder voltage for Phase R of Site A and AusNet day ahead forecast field trial data

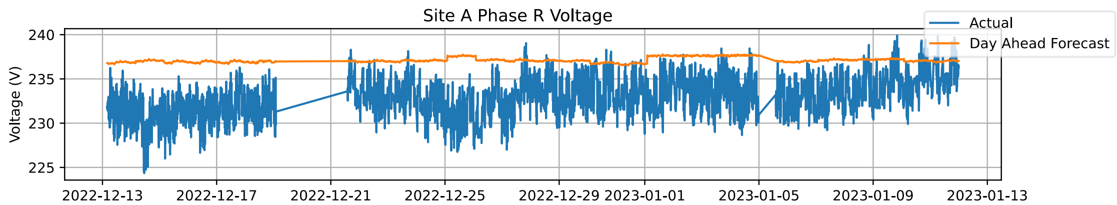
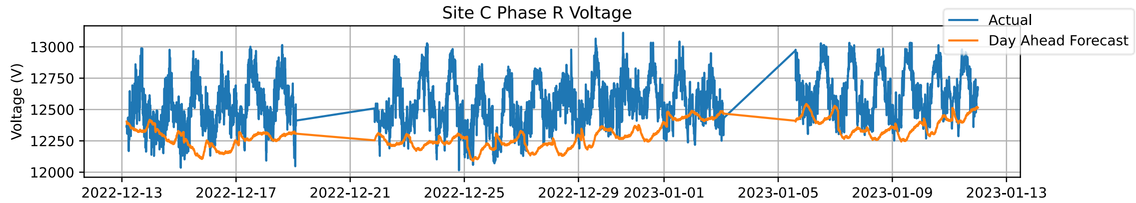


Figure 4 Actual head of feeder voltage for Phase R of Site C (SWER network) and AusNet day ahead forecast field trial data

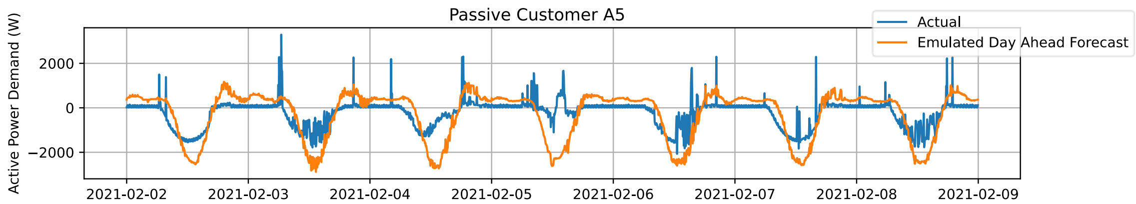


As the techno-economic modelling that is conducted in this work spans a number of network types and different DER penetration and participation levels, the forecasts from the field trials could not be directly used in the techno-economic modelling. Instead, a method was developed to create day ahead forecasts that emulate the forecasts used in the field trial. This is managed in the following way:

1. Pre-process data to align day-ahead forecast and actual realisations.
2. Train a tool with a random forest regression learning algorithm using both the forecast and actual data, as well as temporal information.
3. Input the perfect knowledge data for the different scenarios being run in the techno-economic modelling into the tool, which provides day-ahead forecasts.

The efficacy of this tool is highlighted in Figure 5, where the machine learning tool is used to emulate the AusNet forecast for demand data where no field trial forecast data is available. It is seen, similarly to Figure 2, that the general shape of the PV generation profile is capture, but consistently over-estimated and that the forecast is not able to predict the sudden spikes in customer demand.

Figure 5 Output of machine learning tool for data set that does not have an associated day head forecast from the field trial



2.2 Intra-day forecast

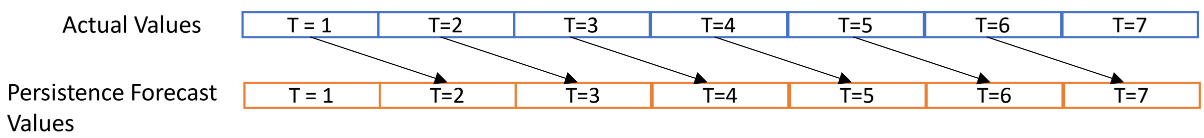
The intra-day forecasts (and their associated DOEs) in the Project EDGE field trial are conducted at 6 hour intervals and apply from 30 minutes after they have been generated. (I.e., a forecast is generated at 04:00 and the first DOE using this forecast is applied at 04:30). Initially, the intent was to emulate the intra-day forecasts from the field trials in a similar way to how the day ahead forecast is emulated and apply that to the techno-economic modelling scenarios. However, the problem arose in that the intra-day forecast used in the field trial is extremely similar to the day-ahead forecast. In fact, there is no appreciable increase in forecast accuracy in the intra-day forecast when compared to the day-ahead forecast. In general, it would be expected that an intra-day forecast would be more accurate. This is to be reflected in this work to provide insight into how increased forecast accuracy would impact DOE calculations. Therefore, a different approach to generating the intra-day forecast was taken.

As part of their operation in Project EDGE, Mondo have also been generating forecasts for their customers, both at the day ahead frequency and more regularly. This data will be leveraged in lieu of the AusNet forecast to assist in generating the intra-day forecast. A day ahead forecast model and an intra-day forecast model were both trained on 47 Mondo customer sites using a year of data. The accuracy of the forecasts then generated by these models was compared. The accuracy was modelled using the normalised root mean square error (nRMSE) statistic, as this allows customers of different sizes to be easily compared. The results showed that when forecasting demand, the intra-day forecast was 13.1% more accurate, and when forecasting PV generation, the intra-day was 27.6% more accurate compared with a day-ahead forecast. For the voltage of intra-day forecasts, as there is no standard method of forecasting network voltages it is assumed that there is a 10% increase in accuracy compared to the day-ahead. This is because voltage forecasting is less developed compared to demand or PV forecasting, and so the improvement of more frequent forecasts is likely to be less. The intra-day forecast for the techno-economic modelling would therefore apply these improvements to the day ahead forecast generated based on the field trial results to emulate an intra-day forecast. This was done by reducing the error between the day ahead forecast and the actual values by the specified percentage for each time step.

2.3 Close-to-real-time / persistence forecast

While this is not being trialled in Project EDGE, it is considered useful to understand how conducting DOE calculation close-to-real-time could impact the DOE efficacy. For this close-to-real-time forecast, a persistence forecast is used. As 30 minute time steps are used in the modelling, this is a 30-minute head persistence forecast. This assumes that the next time step will be the same as the previous time step. If there are not sudden changes in load, generation, or voltage this is usually a reasonable forecast for the next time step. This was created by taking the actual power and voltage values, and offsetting them by one time step, so that the actual values for time step 1 were used as the persistence forecast for time step 2. This is illustrated in Figure 6.

Figure 6 Diagram of the persistence forecast



3 Case studies

This section of the report provides details of the case studies that are used in the techno-economic modelling of the DOE using the Maximise NEM Export objective function using day ahead, intra-day, and close to real time forecasts. This section also includes realistic test networks, DER penetration levels, DER marketplace participation levels, use cases, and modelling assumptions.

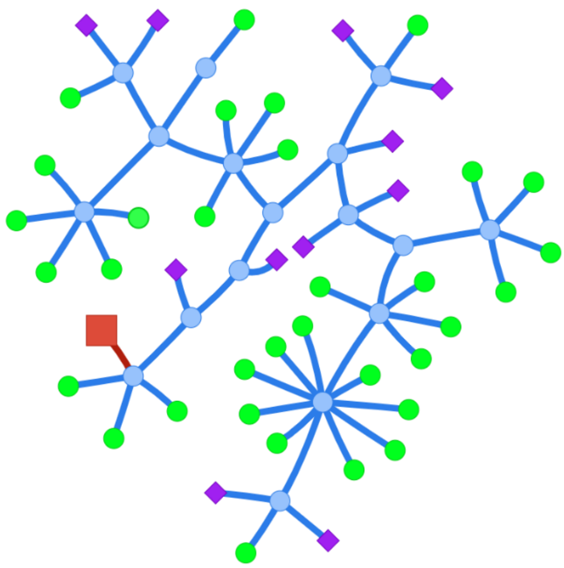
3.1 Networks

One of the major objectives of this work was to ascertain how these different DOE forecast frequencies would function on real-world networks. To try and understand how the forecasts may have different impacts in different LV networks in the NEM, different types of LV networks were chosen for the case studies. Informed by the CSIRO LV Network Taxonomy Report's[4] categorisation of LV networks in the NEM, and to align with the previous work on DOE objective functions, the same networks were chosen for this study – a *City* network, a *Suburban* network, and a *Regional* network.

3.1.1 City Network

"Network E" from the CSIRO LV Network Taxonomy Report is chosen as the representative *City* network. This representative network was chosen from the selection in the report as a good compromise between network size, number of customers, and number of networks in the cluster it represents. This network is shown in Figure 7, where the red node is the head of the feeder, the green nodes are residential customers, and the purple nodes are commercial customers. It should be noted that the split of residential and commercial customers is not from the CSIRO report but set by UoM so that there was a spread of residential and commercial customer splits across the three networks.

Figure 7 Diagram of the *City* network used in the techno-economic modelling

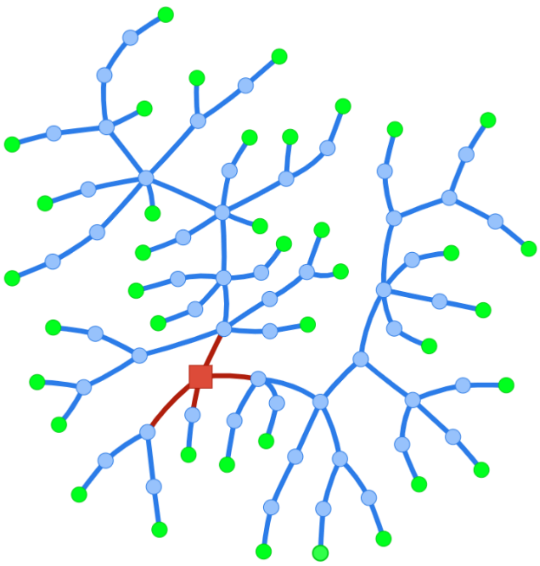


[4] https://arena.gov.au/assets/2022/08/national-low-voltage-feeder-taxonomy-study.pdf

3.1.2 Suburban Network

"Network L" from the CSIRO LV Network Taxonomy Report is chosen as the representative *Suburban* network. This representative network was chosen from the selection in the report as a good compromise between network size, number of customers, and number of networks in the cluster it represents. This is shown in Figure 8, where the red node is the head of the feeder, and the green nodes are residential customers.

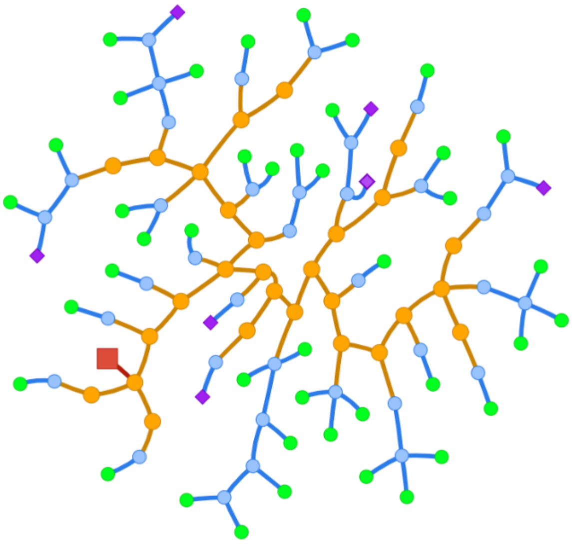
Figure 8 Diagram of the *Suburban* network used in the techno-economic modelling.



3.1.3 Regional Network

One of the networks that is being used in the field trials was deemed suitable to be the representative *Regional* network. This is a SWER network and is shown in Figure 9 where the red node is the head of the feeder, orange nodes are medium voltage (MV) nodes, blue nodes are low voltage nodes, the green nodes are residential customers, and the purple nodes are commercial customers. As this is a SWER network, the head of feeder is the isolation transformer and so the network contains both MV and LV network. This makes it distinct from the *City* and *Suburban* networks, which only contain LV network.

Figure 9 Diagram of the *Regional* network used in the techno-economic modelling



3.2 DER penetration levels and DER marketplace participation levels

Another major aim of this work is to investigate how the performance of the different forecast frequencies may differ as DER penetration in networks increases, and as participation in DER marketplaces increases. Through consultation with project stakeholders, it was determined that focusing on DER penetrations likely to materialise in the near future would be of high value. Therefore, in the eight DER penetration scenarios developed for this work, there are a number on the lower end of the DER penetration. The value for DER penetrations in Table 1 are the percentage of customers in the network who have DER.

Table 1 DER penetration levels and DER marketplace participation levels modelled

DER Penetration Scenario	1	2	3	4	5	6	7	8
PV Penetration	20%	25%	30%	35%	45%	60%	70%	100%
Storage Penetration	1%	5%	10%	20%	30%	40%	50%	100%
Participation Level - Low	5%	10%	15%	20%	25%	30%	35%	40%
Participation Level - Mid	20%	25%	30%	35%	40%	45%	50%	55%
Participation Level - High	35%	40%	45%	50%	55%	60%	65%	70%
Participation Level – 100%	100%	100%	100%	100%	100%	100%	100%	100%

In addition, DER participation rates may also impact the performance of the DOEs utilising different forecasts. Therefore, a Low, Mid, High, and 100% participation rate are proposed for each DER penetration scenario to align with previous studies. The participation levels in Table 1 are the percentage of customer with DER who are participating in the DER marketplace (and therefore receiving DOEs). In these scenarios, the percentage of DER participating in the marketplace increases as the DER penetration level increases.

3.3 Static limits

Another important aspect that was raised in consultation with project stakeholders was that static limits are likely not to / should not remain the same value that they are now with increasing DER penetration and that this phenomenon should be captured in the techno-economic modelling. In this model, customers with DER who are not participating in the DER marketplace are subject to static limits. In the previous techno-economic modelling work conducted by UoM an estimate the static limits of each representative network for each penetration was generated and is also used in this work. These static limits can be found in Table 2.

Table 2 Static limits applied for each network in each of the DER penetration scenarios. Values in brackets indicate solutions of static limit calculation that are greater than current static limit.

Scenario	1	2	3	4	5	6	7	8
Regional (kW)	3.5 (6.44)	3.5 (5.65)	3.5 (5.05)	3.5 (4.79)	1.52	1.38	1.16	0.88
City (kW)	5 (10.91)	5 (9.68)	5 (7.84)	5 (6.83)	5 (5.74)	4.01	3.74	2.59
Suburban (kW)	5 (7.72)	5 (7.19)	5 (5.61)	4.89	4.52	5 (7.87)	5 (6.53)	3.35

3.4 Use cases

In the previous study conducted on the DOE objective functions the focus of the modelling was on extreme demand and generation scenarios, as this would maximise the differences between the objective functions. However, as with the work on the Approximation Algorithm, it is of interest to compare the capacity allocated DOEs using different forecasts over different network load levels. This will help in understanding how much earlier the different forecasts start constraining the DER and how this capacity allocation changes with different network conditions. Therefore, a full day of DOEs (with 30 minute granularity to reduce computational burden of modelling) will also be generated to inform on the likely behaviour of the forecasts across a day. For the 3-phase networks (*City* and *Suburban*) a lower and higher head of feeder voltage forecasts are both modelled to help understand how this impacts the DOEs generated. A similar approach isn't conducted for the *Regional* network as this SWER network is highly sensitive to changes in head of feeder voltage and increasing the head of feeder voltages causes non-participating customers to be curtailed.

3.5 Forecasts

The forecasts for this day being modelled were generated as described in Section 2. The day ahead forecast is generated from the machine learning tool based on the EDGE field trial day ahead forecasts. The intra-day forecasts improve upon these forecasts by 27.6% for PV generation and 13.1% for demand. For the voltage of intra-day forecasts, it is assumed that there is a 10% increase in accuracy compared to the day-ahead. This is because voltage forecasting is less developed compared to demand or PV forecasting, and so the improvement of more frequent forecasts is likely to be less.

The close-to-real-time forecast takes the actual values of voltage and powers from the previous time step.

This section contains some examples of the different forecasts that are being used in the case study. Figure 10 shows the head of feeder voltage profile and forecasts for phase R of the *City* network. Comparing the day ahead and intra-day forecasts for the lower voltage profile Figure 10 (Left) and for the higher voltage profile Figure 10 (Right) are very similar. This is in line with the AusNet day ahead forecast of head of feeder voltages for three-phase LV networks shown in Figure 3. For the lower voltage profile this results in the day ahead and intra-day forecasts over-estimating the head of feeder voltage, and for the higher voltage profile the day ahead and intra-day forecasts understimate the head of feeder voltage. Generally, the persistence forecast performs well, although when there are sudden changes in the head of feeder voltage profile can lead to large errors in the forecast.

The head of feeder voltage profile and forecasts for the *Regional* network are shown in the actual values of the active power export two example customers, one without PV and one with PV as well as the day ahead, intra-day, and persistence forecasts of their active power. The day ahead and intra-day forecasts vary more than the *City* forecast, but consistently underestimate the voltage, as in the AusNet field trial data shown in Figure 4. Figure 12 shows an example of the actual active power export and forecasts for a customer without PV Figure 12 (Left) and for customers with PV Figure 12 (Right). Here we see that the forecasts are much better at estimating the actual active power setpoints of the customers compared to their ability to estimate head of feeder voltages, however in this example the day ahead and intra-day forecasts are overestimating the PV generation available to this specific customer. In Figure 10 – Figure 12 the intra-day forecast is closer to the actual realisation of the power / voltage by the percentages outlined in Section 2.2.

To show how the total network demand/export and their associated forecasts may change with increasing DER penetration, Figure 13 shows the total *City* network active power export for Scenario 1 – Figure 13 (Left) and Scenario 8 – Figure 13 (Right). With the increased DER penetration, the network export/demand profile becomes more homogenous during daylight hours. This allows the forecasts to provide more accurate estimates of the active power profiles during these hours.

Figure 10 The actual values of the phase R head of feeder voltage for the City network as well as the day ahead, intra-day, and persistence forecasts for (Left) the lower voltage profile and (Right) the higher voltage profile

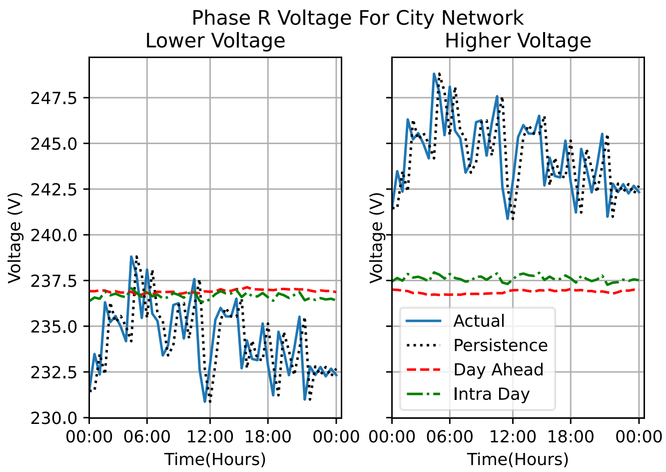


Figure 11 The actual values of the phase R head of feeder voltage for the *Regional* network as well as the day ahead, intra-day, and persistence forecasts

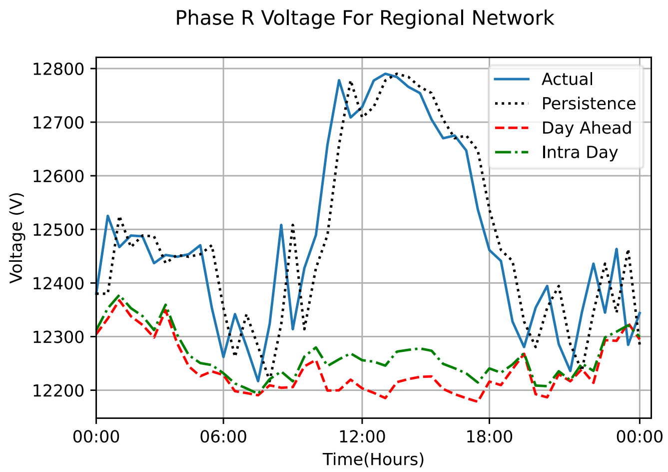


Figure 12 The actual values of the active power export two example customers, one without PV and one with PV as well as the day ahead, intra-day, and persistence forecasts of their active power

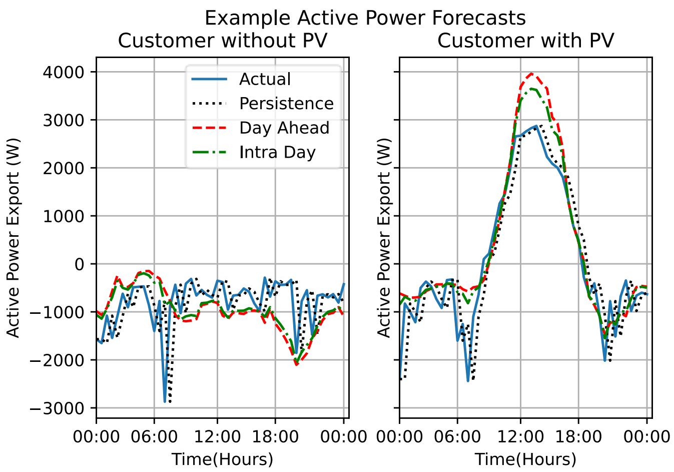
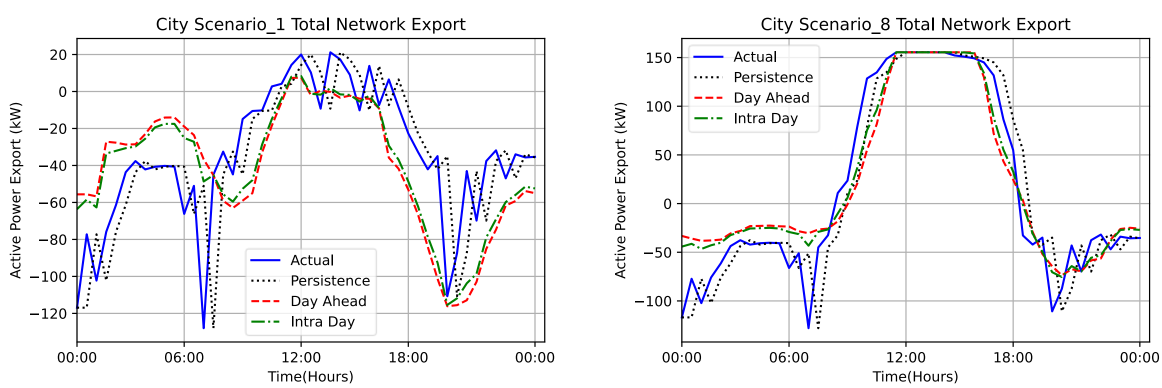


Figure 13 The actual values of total customer active power export in the network as well as the day ahead, intra-day, and persistence forecasts for (Left) Scenario 1 and (Right) Scenario 8.



3.6 Modelling assumptions

This section lists the assumptions that have been made as part of the modelling.

1. The head of feeder voltage for a specific use case and network does not vary across DER penetration or participation scenarios. Whilst the head of feeder voltage will have a material impact on the performance of a DOE, it is not plausible to obtain an accurate estimate of how the head of feeder voltage may change across these different scenarios, as this may also be impacted by DNSP network operation and installation / utilisation of network assets.
2. The initial static limit for 3-phase LV networks is set to be 5 kW and for SWER networks is set to be 3.5kW to align with current AusNet practices.
3. Upper and lower voltage limits of LV networks are set to -6% / +10% in line with *AS61000.3.100*.
4. Residential customers may not request capacity greater than 14kW per phase for C*ity* and *Suburban* networks due to fuse limits. Commercial customers may request greater capacity, up to 28kW for *City* and S*uburban*.
5. The location of new DER introduced into the networks for each penetration scenario is chosen at random.
6. The import DOE is being applied to flexible loads only. Therefore, the DOE import limit is being imposed on any imports above the base load of each customer. This is to ensure that the base loads of customers are satisfied.

4 Results

Figure 14 shows the aggregate operating envelopes for the whole network across the test day for perfect knowledge, 30-minute ahead persistence forecast, day ahead forecast, and intra-day forecast for the *City* network.

For the low DER penetration scenarios (such as Scenario 2) the network isn't highly constrained and so the operating envelopes are very similar (unconstrained).

As the DER penetration increases the DOEs start becoming constrained and so the DOEs based on the forecasts start to differ from each other and from the DOEs based on perfect knowledge. For instance, in the morning the day ahead and intra-day forecast DOEs over-allocate aggregate import capacity compares to the DOEs based on perfect knowledge. This is because in the morning the day ahead and intra-day do not capture the spike in demand around 6am. Additionally, in the evening the day ahead and intra-day under-allocated aggregate import capacity.

For Scenario 4 the export capacity is still unconstrained. For the higher DER penetration (Scenario 6 and Scenario 8) the export DOEs become constrained, and the day ahead and intra-day under-allocate export capacity in the morning (when the forecast voltage is greater than the actual) and slightly over-allocated export capacity during daylight hours (when the forecast voltage is less than the actual).

Over-allocation of export capacity during daylight hours may lead to increased instances of the network operating outside of its designated bounds. From the imports side it is seen that the day ahead and intra-day still fail to capture the drop in import capacity in the morning and, although they capture the general trend of reduced import capacity available in the evening, they do not manage to represent the final details of the DOEs. In general, the persistence forecast DOEs look very similar to the perfect knowledge. However, for time steps where there is a quick transition in voltage or power the persistence forecast may greatly over-allocate or under-allocate capacity.

Figure 15 shows a similar set of results for the high voltage profile scenarios in the *City* network. This difference in voltage has an impact on the export DOEs, even at low DER penetration levels (although only for very high participation scenarios).

In Scenario 2 for the 100% DOE participation, we see that the day ahead and intra-day forecasts do not identify that the network is constrained in the morning (due to underestimating the voltage), and so allocate full capacity. While some of these instances potentially occur before daylight hours, that are some that are certainly within daylight hours and so could result in network constraints being violated.

For Scenario 4 with 100% participation a similar trend is seen but on a much larger scale.

In Scenario 6 the day ahead and intra-day forecast DOEs have begun to restrict the export of DER, but they are still over-allocating the aggregate capacity (compared to the perfect knowledge DOEs) that will result in network violations if fully utilised. This is because for the higher voltage profile, the day ahead and intra-day forecasts are under-estimating the head of feeder voltage, which means they calculate that there is additional capacity that can be allocated, which in reality there is not.

Even though for the higher voltage profile the day ahead and intra-day are under-estimating the head of feeder voltage (which should mean that they would under-allocate import capacity) it is still seen for Scenarios 6 and 8 that the day ahead and intra-day over-allocate import capacity around the demand peaks that they were unable to predict. This is due to potential thermal constraints in the network rather than voltage constraints, which is why import capacity is being over-allocated, even with higher voltages.

The low voltage profile DOEs for the *Suburban* network for Scenarios 2,4,6 and 8 are shown in Figure 16.

These results highlight the fact that, while in a constrained system using inaccurate forecasts are likely to lead to network constraint violation, if there is a strong network that can operate unconstrained then the lack of accuracy of the forecasts will have limited impact. However, when the system is constrained is precisely the time that you need to have accurate DOEs.

In the *Suburban* network for Scenario 8 the exports are under-allocated and in general the imports are over-allocated. This can be largely derived from the fact that the day head and intra-day under-estimate the head of feeder voltage profile for the lower voltages profile scenario. For the higher voltage profile the *Suburban* network exhibits the same under-allocation of exports and over-allocation of imports as seen in the *City* network.

As is seen in the actual values of the active power export two example customers, one without PV and one with PV as well as the day ahead, intra-day, and persistence forecasts of their active power (Figure 11), the day ahead and intra-day forecasts for the *Regional* network underestimate the head of feeder voltage. Therefore, we see in Figure 17 that even from low DER penetration scenarios the day ahead and intra-day DOEs over-allocate export capacity.

However, for the higher DER penetration levels the day ahead and intra-day DOEs also over-allocate import capacity during the morning and evening demand peaks because these forecasts underestimate the customer demand peaks, and there are thermal constraints on the LV transformers.

From these results it is seen that export capacity allocation is driven predominately by the accuracy of the head of feeder voltage forecast as the voltage constraints are likely to be binding before the thermal constraints for exports. However, for imports the thermal constraints are more likely to be binding, so the customer power forecast can have more of an impact.

Figure 14 **Operating envelopes from *City* network Scenarios 2, 4, 6, and 8 with the lower voltage profile for perfect knowledge, persistence, day ahead, and intra-day forecasts**

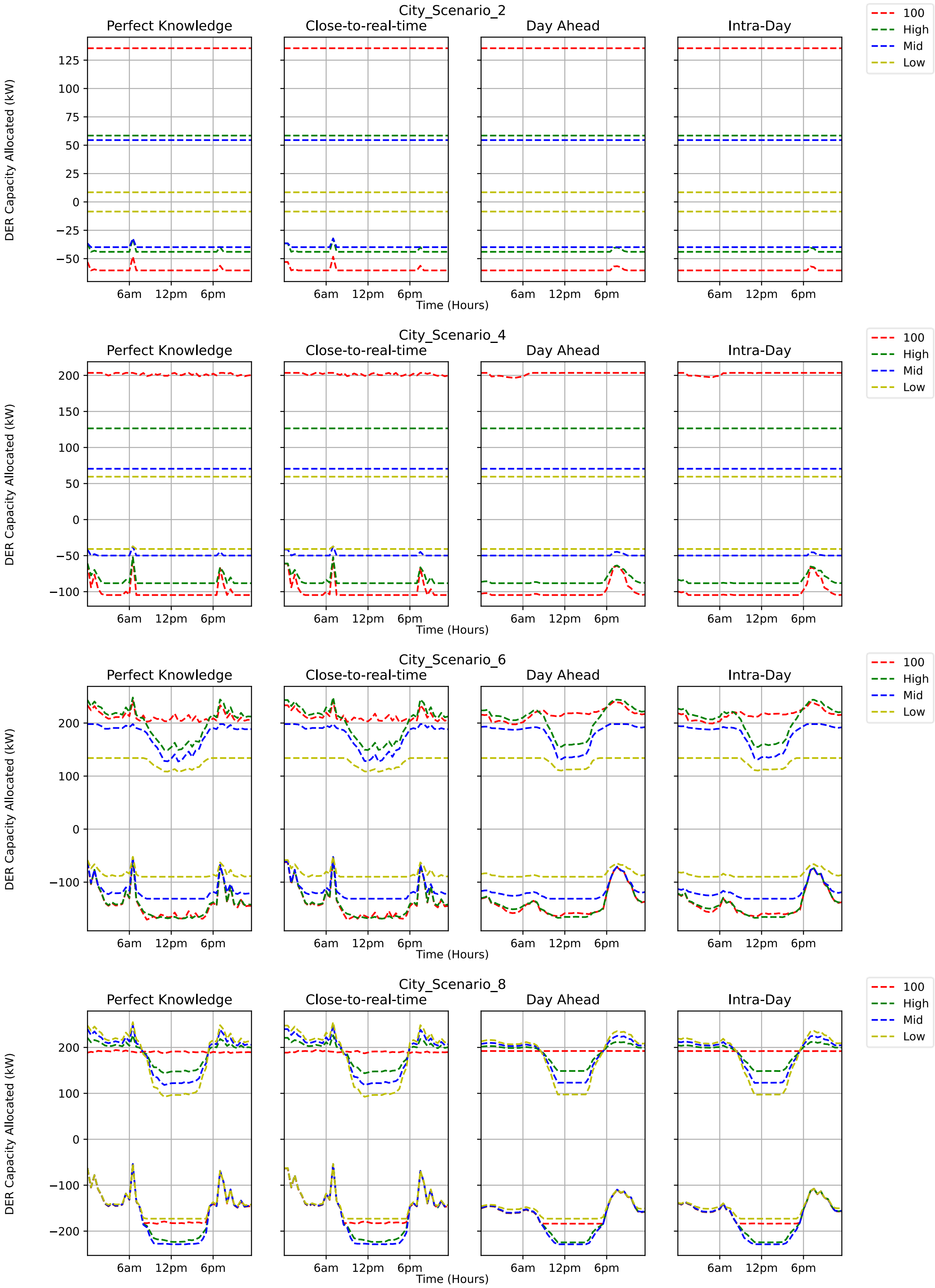


Figure 15 **Operating envelopes from *City* network Scenarios 2, 4, 6, and 8 with the higher voltage profile for perfect knowledge, persistence, day ahead, and intra-day forecasts**

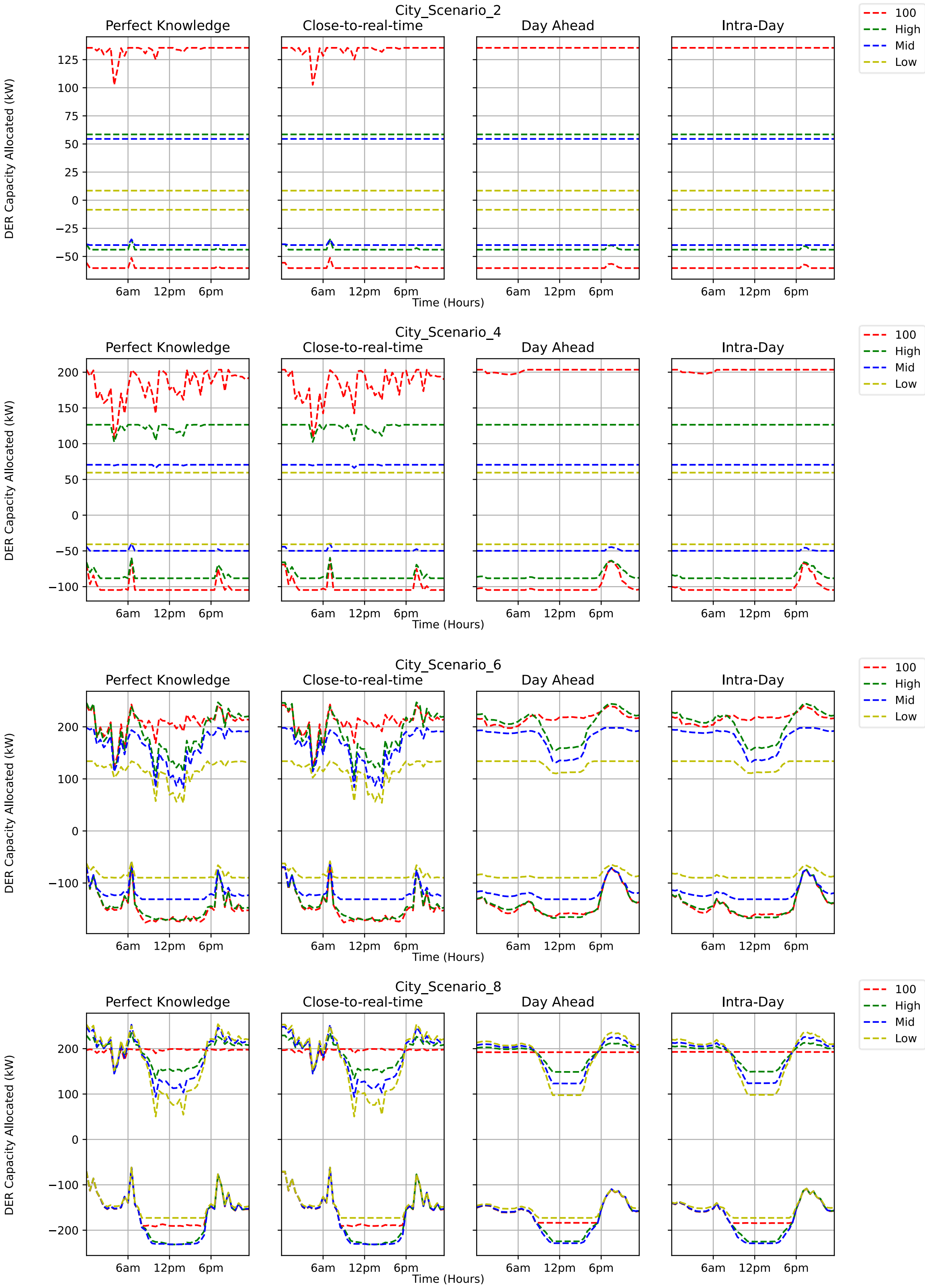


Figure 16 Operating envelopes from *Suburban* network Scenarios 2, 4, 6, and 8 with the lower voltage profile for perfect knowledge, persistence, day ahead, and intra-day forecasts

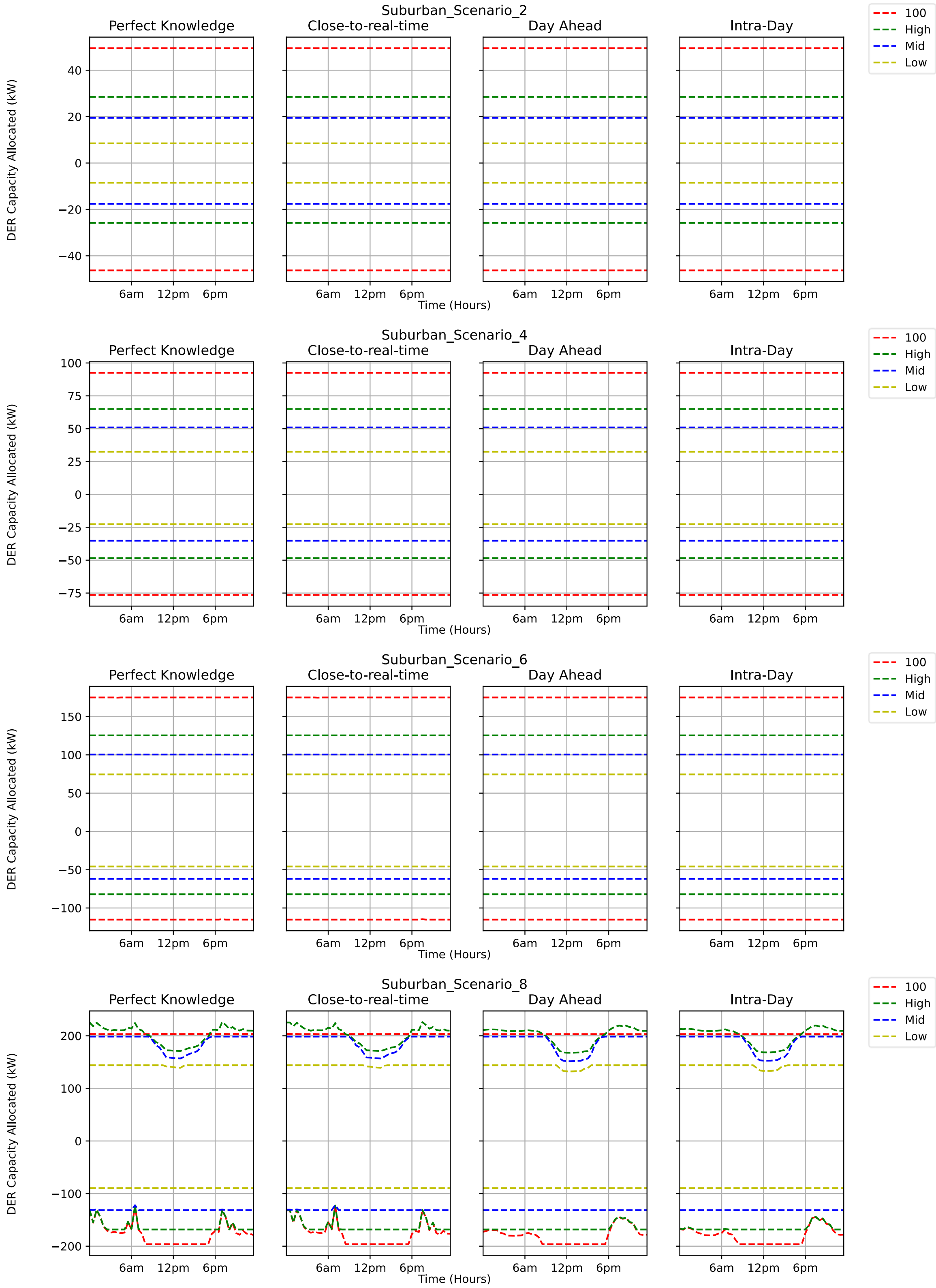
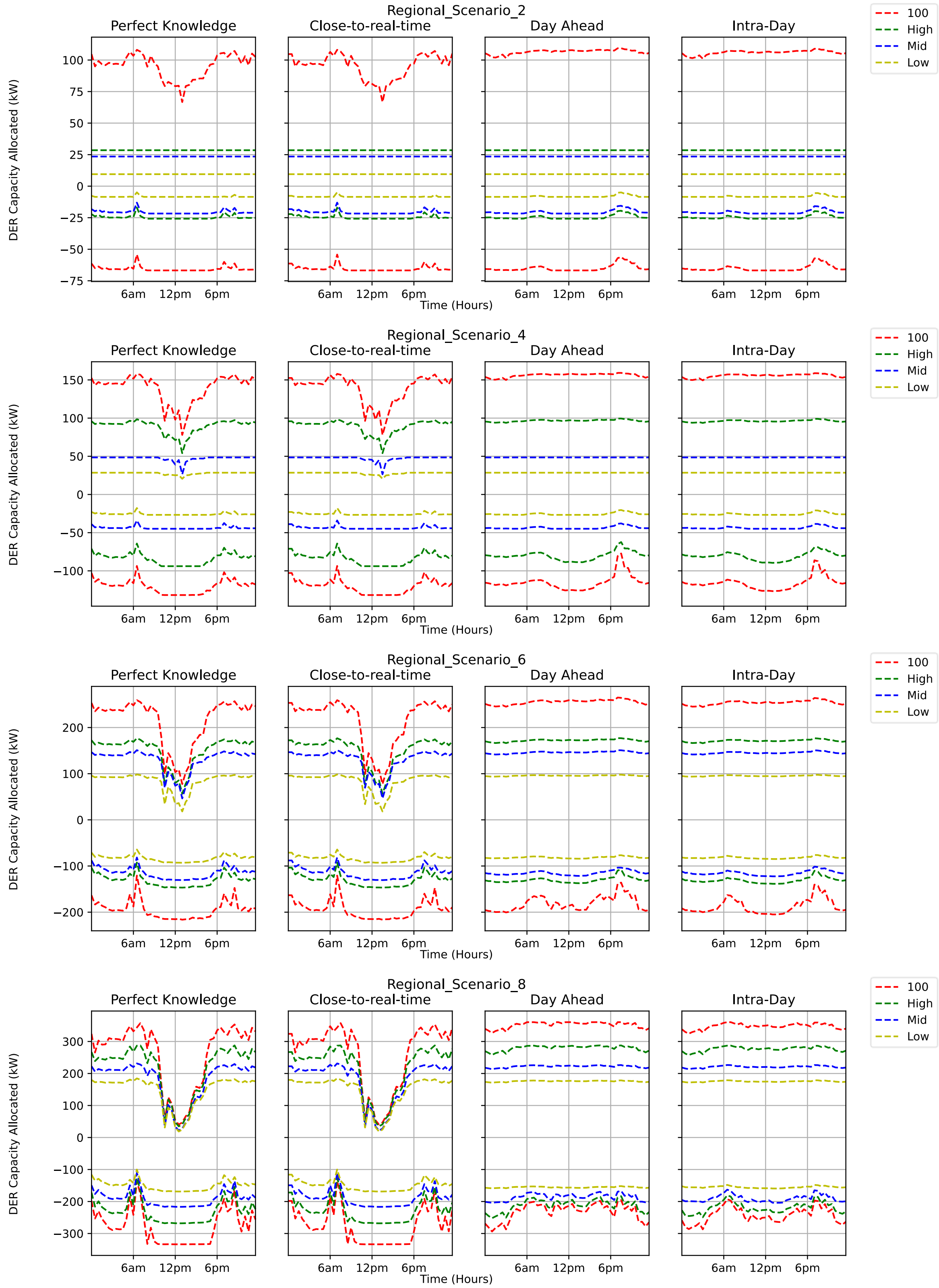


Figure 17 Operating envelopes from *Regional* network Scenarios 2, 4, 6, and 8 for perfect knowledge, persistence, day ahead, and intra-day forecasts



4.1 Difference in DOEs

At a fundamental level, the impacts that the forecasts have on the DOEs can be seen in the difference in the aggregate capacity that is allocated by the DOEs for each forecast approach. This is important to consider as any deviation from the optimal capacity allocation (that allocated by the DOEs using perfect knowledge) has negative implications. If the DOEs under-allocate capacity, this means that DER may be limited unnecessarily and so reduces the amount of DER power that can be imported/export. However, if the DOEs over-allocate capacity this means that if the capacity is fully utilised then the network will exceed its set limits and, depending on the severity and duration of this excursion, this could lead to serious implications on network operation. Therefore, the time at which this over-allocation occurs is important in determining if it may be problematic to the DNSP. This is due to the use of the rated capacity of the DER when calculating the DOEs. A PV system will not be able to export any active power overnight, let alone its full capacity. So, if the DOEs that use forecasts over-allocates export capacity overnight, it is unlikely to be a concern to the DNSP. If this over allocation of aggregate export capacity occurs at midday, then this would be a very real concern, as this is the likely time when PV would be able to utilise this additional capacity and likely cause network constraint violations. Similarly, for over-allocation of import capacity, the times of concern would be during the morning and evening demand peak. Additionally, the overnight period may be of concern, as this is a period where some large loads can be brought online to take advantage of an off-peak tariff.

Figure 18 shows the difference in the capacity allocated by DOEs using a day ahead forecasts vs perfect knowledge for the *City* network higher voltage profile, DER penetration Scenarios 5-7. This figure highlights an interesting inflection point in the results. Prior to Scenario 5 the 100% participation simulations had the largest deviations between the day ahead DOEs and the perfect DOEs. However, in Scenario 5 the High participation scenario overtakes the 100% participation. In Scenario 6 the error of the 100% and High participation simulation is reducing whilst for the Mid and Low participations the DOE error continues to grow. At this point the Low participation simulation has the most error. This trend continues in Scenario 7 where the error of the 100% participation simulation is significantly less than the Low participation simulation. For lower DER penetration levels, higher DER participation means a more constrained network and so more opportunity for errors in forecasts to impact the efficacy of the DOEs (if the network is unconstrained, small errors in voltage or power forecast will not change the DOE). However, once the network becomes constrained for all participation levels, the higher the DER participation, the less uncertainty there is in the total passive customer power which leads to DOEs having a reduced error.

In Figure 19 the performance of the different forecast frequencies can be compared. In this figure the error in DOE capacity allocation increases as the DER participation decreases, as described above. Looking at the day ahead forecast Figure 19 (Top) most of the DOE capacity error is over-allocating export capacity. This is because, for the higher voltage profile, the day ahead forecasts under-estimates the head of feeder voltage (as seen in Figure 10 (Right)). This means that the day ahead forecast DOE believes there is greater voltage headroom than in practice, and so over-allocates export capacity. For the reasons explained above, the over-allocation before 6am and after 6pm are not of great concern. However, there is also significant over-allocation of export capacity during the middle of the day using the day ahead forecast. For the intra-day forecast the DOE capacity allocation error is only marginally different from that of the day ahead forecast DOE. Due to the assumptions around the creation of the intra-day forecasts, the times at which these forecast error occur will generally match for the day ahead and intra-day forecast. The difference lies in the magnitude of that error, however by comparing the Top and Middle graphs in Figure 19 this difference does not seem to be significant. The DOE capacity allocation error varies quite significantly in the persistence forecast case. The persistence forecast is much more likely to under-allocate capacity compared with day ahead and intra-day. In general, the magnitude of the error is also less than for the day ahead and intra-day cases.

Figure 18 Percentage difference in network capacity allocation between DOEs using the day ahead (DA) forecast and the true values. A positive value indicates that the forecast DOE allocated additional capacity

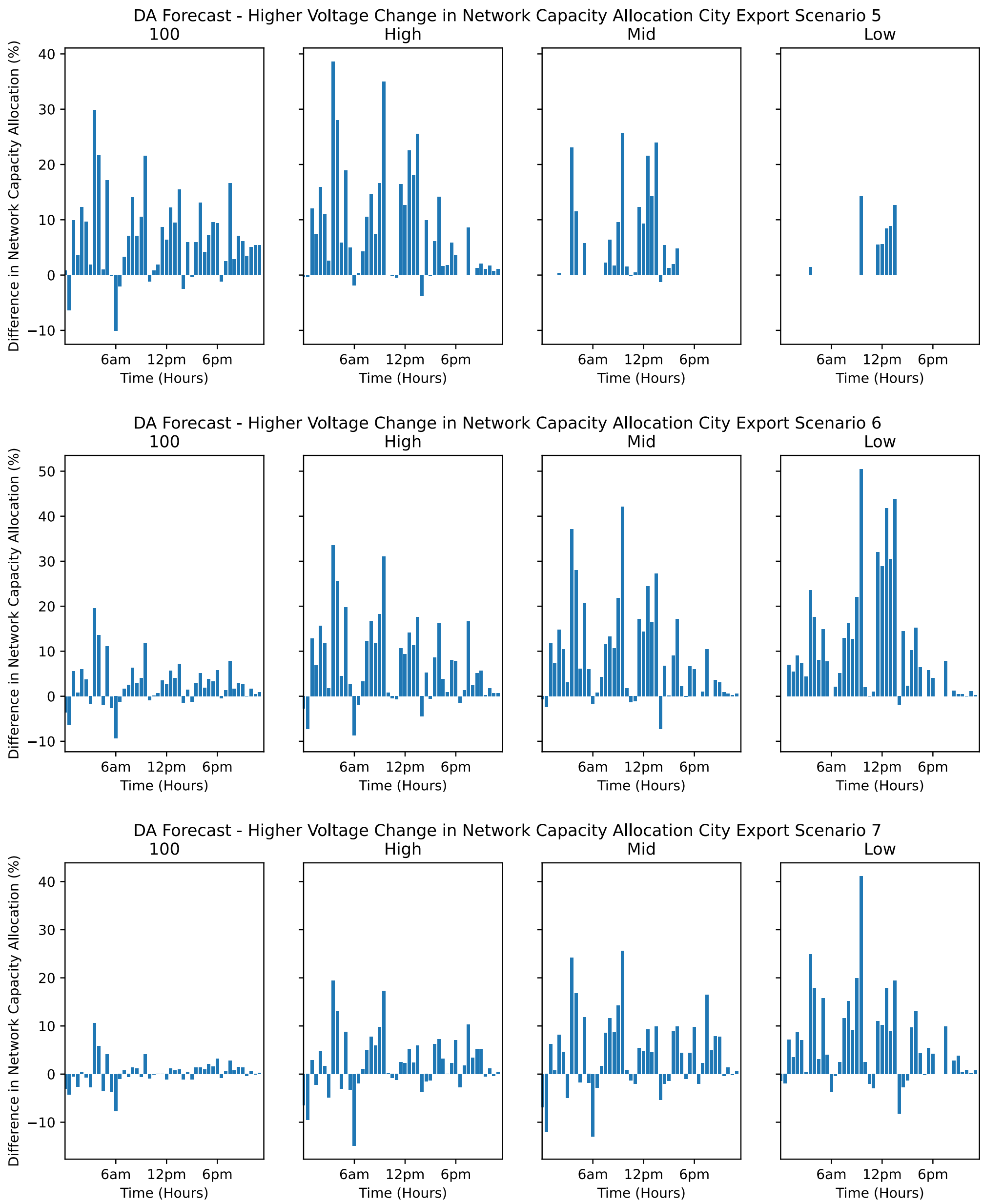
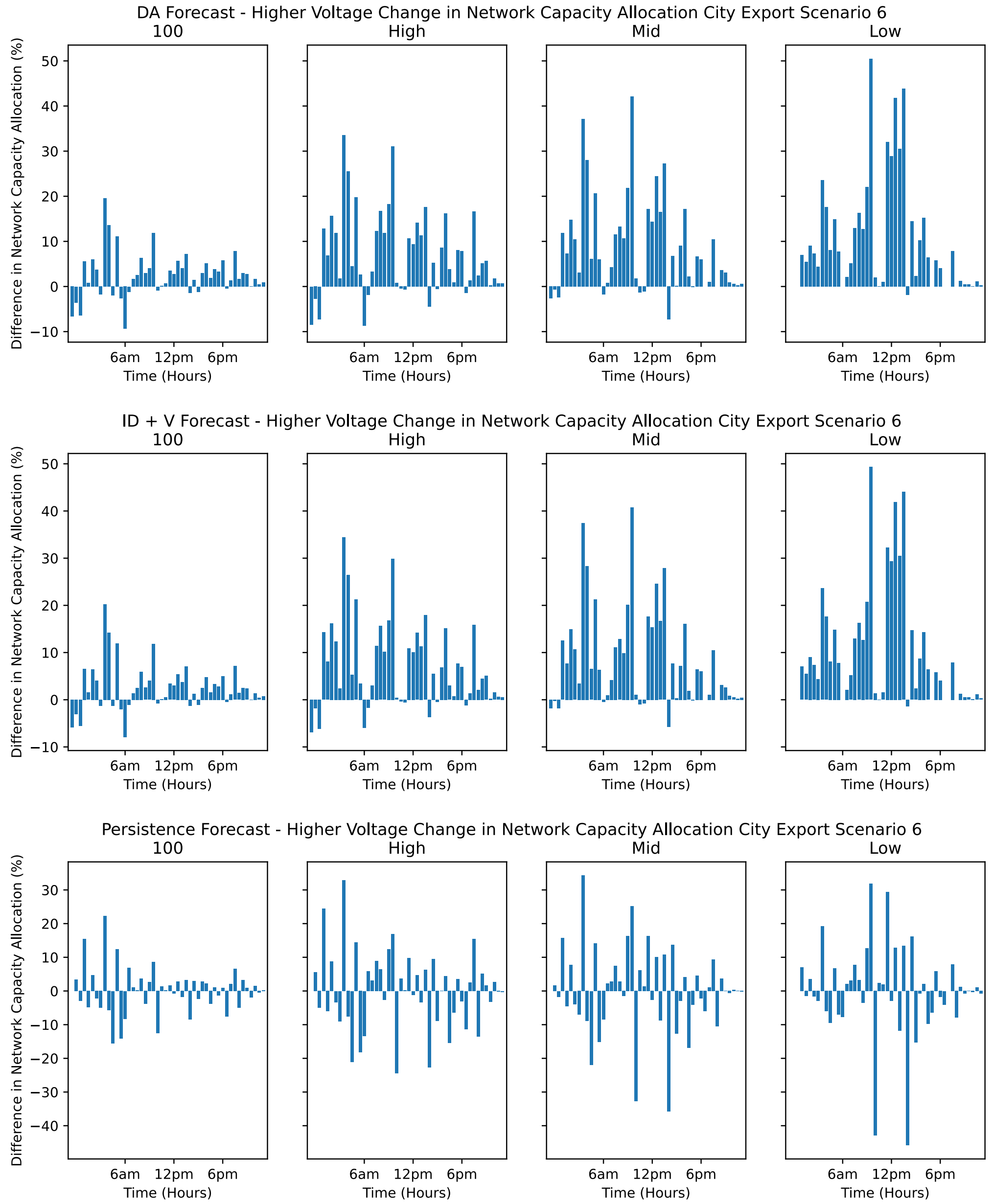


Figure 19 The difference in DOE export capacity allocation in the *City* network Scenario 6 with the higher voltage profile for (Top) the day ahead forecasts, (Middle) the intra-day forecast, (Bottom) the persistence (close to real time) forecast



4.2 Number of constraint violations

Comparing the DOEs of the different forecast frequencies and the perfect knowledge it is clear that if the capacity that is allocated is greater than that allocated by the perfect forecast, then a network violation must occur if the capacity is fully utilised. This could be a violation of a voltage constraint or a thermal constraint. The percentage of time that there is a voltage or thermal constraint in the network and the number of timesteps that are constrained for the day ahead forecast for each network is shown in Figure 20. For the *City* network, initially there are some thermal constraints on the imports and some minimal voltage constraint violations also occur for imports however this is far less than the thermal constraints. As the DER penetration increase, thermal constraint violations are also seen for exports across a large number of time steps. For the *Suburban* network there are very few constraint violations. Voltage constraints on exports happen in Scenario 5 due to the phase imbalances discussed in previous reports. However, during Scenario 6 these imbalances are reduced as DER are added to under-represented phases. For the *Regional* network the frequency of voltage and thermal constraints increase as the DER penetration increases. In general, the higher the DER participation, the more constraint violations. However, for voltage constraints, the number of time steps that violate constraints remains fairly constant. This indicates that for the *Regional* network, increasing the DER penetration doesn't make voltage constraint violation happen more regularly, but rather it just expands the number of nodes in the network that it impacts. This can be seen by further examination of Figure 17, where the day ahead and intra-day fail to capture the reduction in export capacity during the middle of the day, even at lower DER penetration scenarios. The number of time steps that are thermally constrained varies more for different DER penetration scenarios.

Figure 20 Graphs showing, for the day ahead forecast and lower voltage profile: a) the voltage violations for the *City* network; b) the thermal violations for the *City* network; c) the voltage violations for the *Suburban* network; d) the thermal violations for the *Suburban* network; e) the voltage violations for the *Regional* network; f) the thermal violations for the *Regional* network

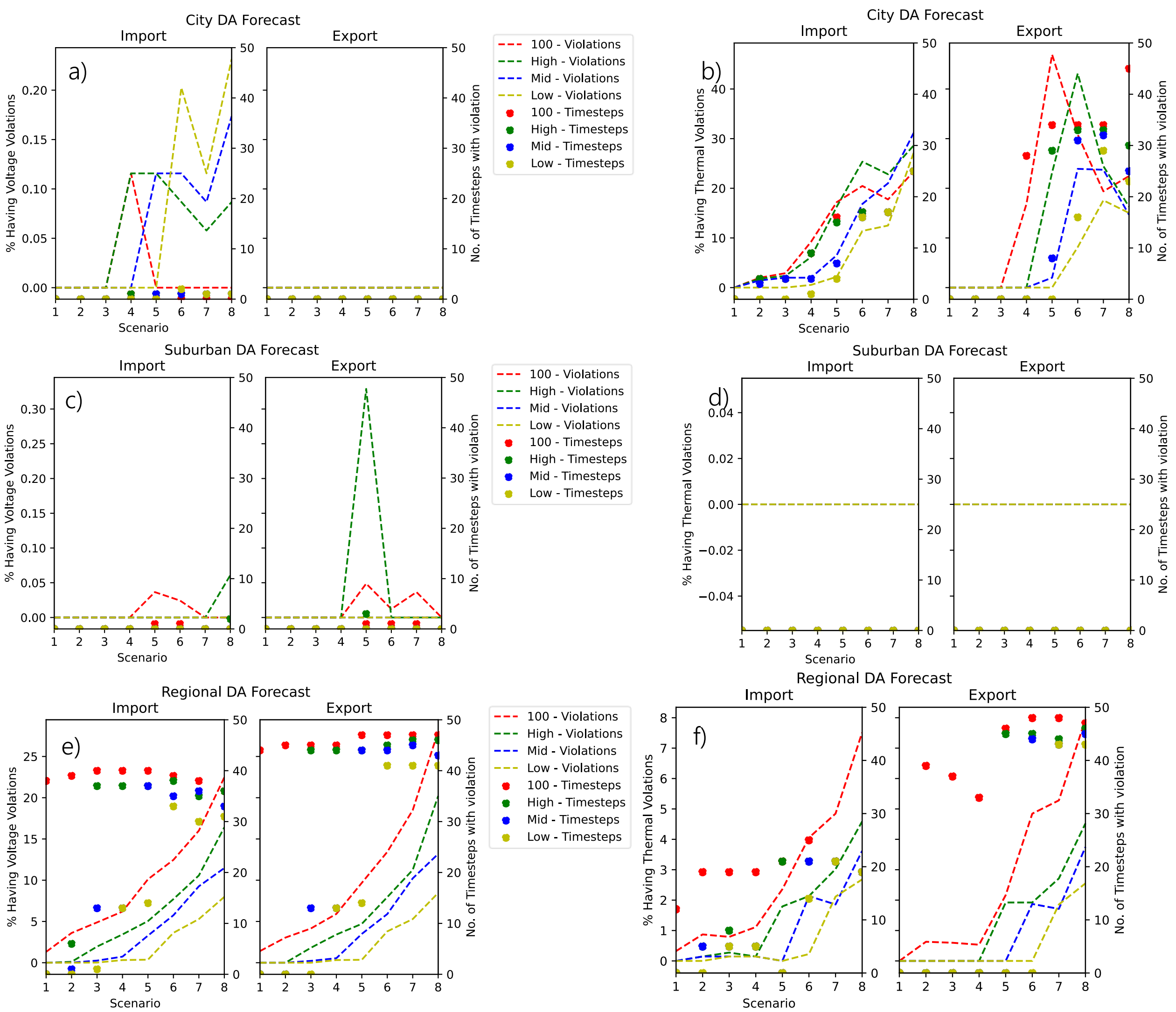


Figure 21 shows the number of voltage and thermal constraint violations for the intra-day forecast. These graphs are almost identical to the day ahead constraint violation graphs shown in Figure 20. This is not surprising, as due to the method of creating the intra-day forecast, if the day ahead forecast over-estimates or under-estimates a value, the intra-day will also over or underestimate the value, albeit with a lesser error. Therefore, it is likely that constraint violations will occur at the same time with the day ahead and intra-day forecasts, with the major difference being the size of the constraint violation.

Figure 21 Graphs showing, for the intra-day forecast and lower voltage profile: a) the voltage violations for the *City* network; b) the thermal violations for the *City* network; c) the voltage violations for the *Suburban* network; d) the thermal violations for the *Suburban* network; e) the voltage violations for the *Regional* network; f) the thermal violations for the *Regional* network

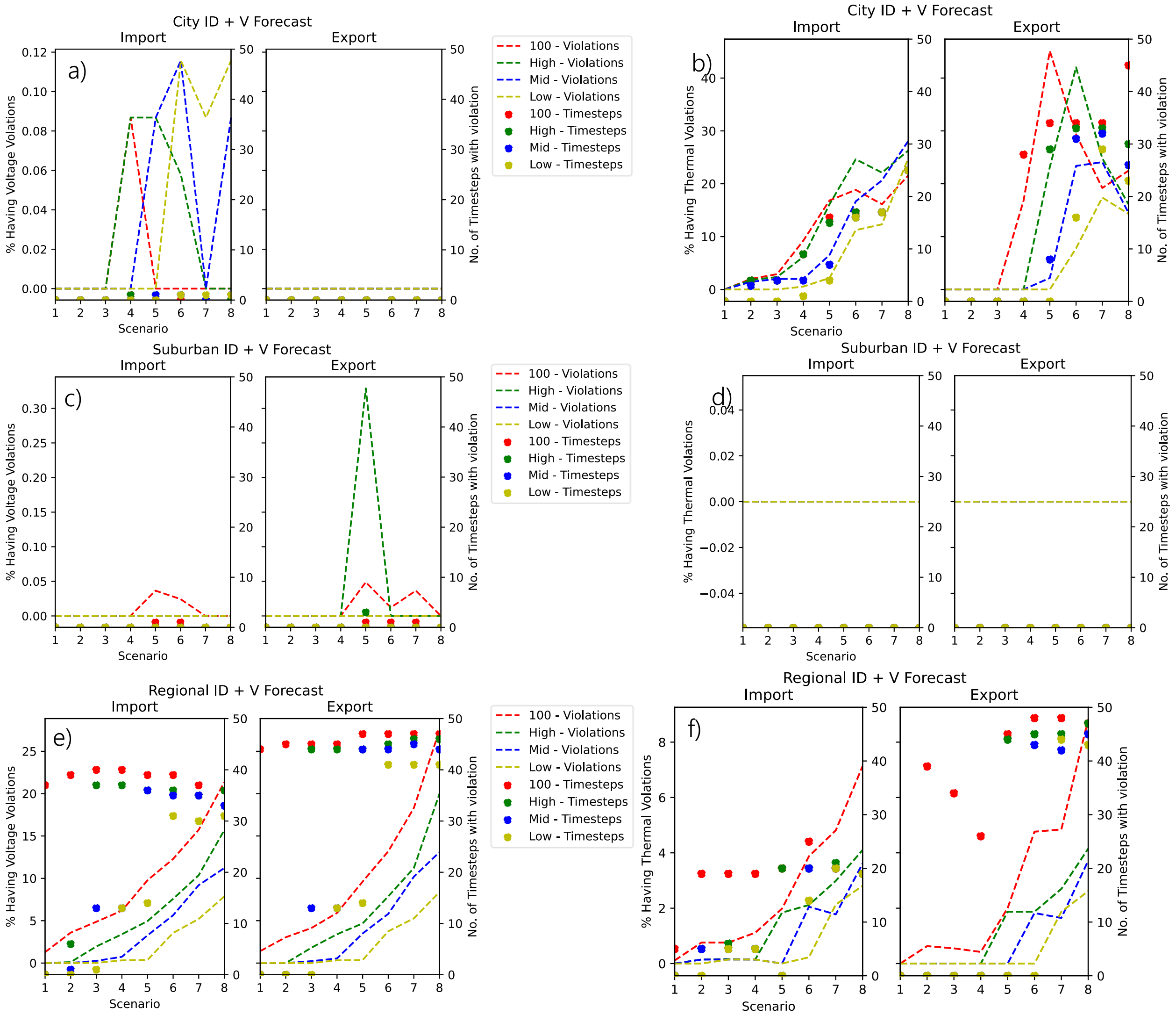
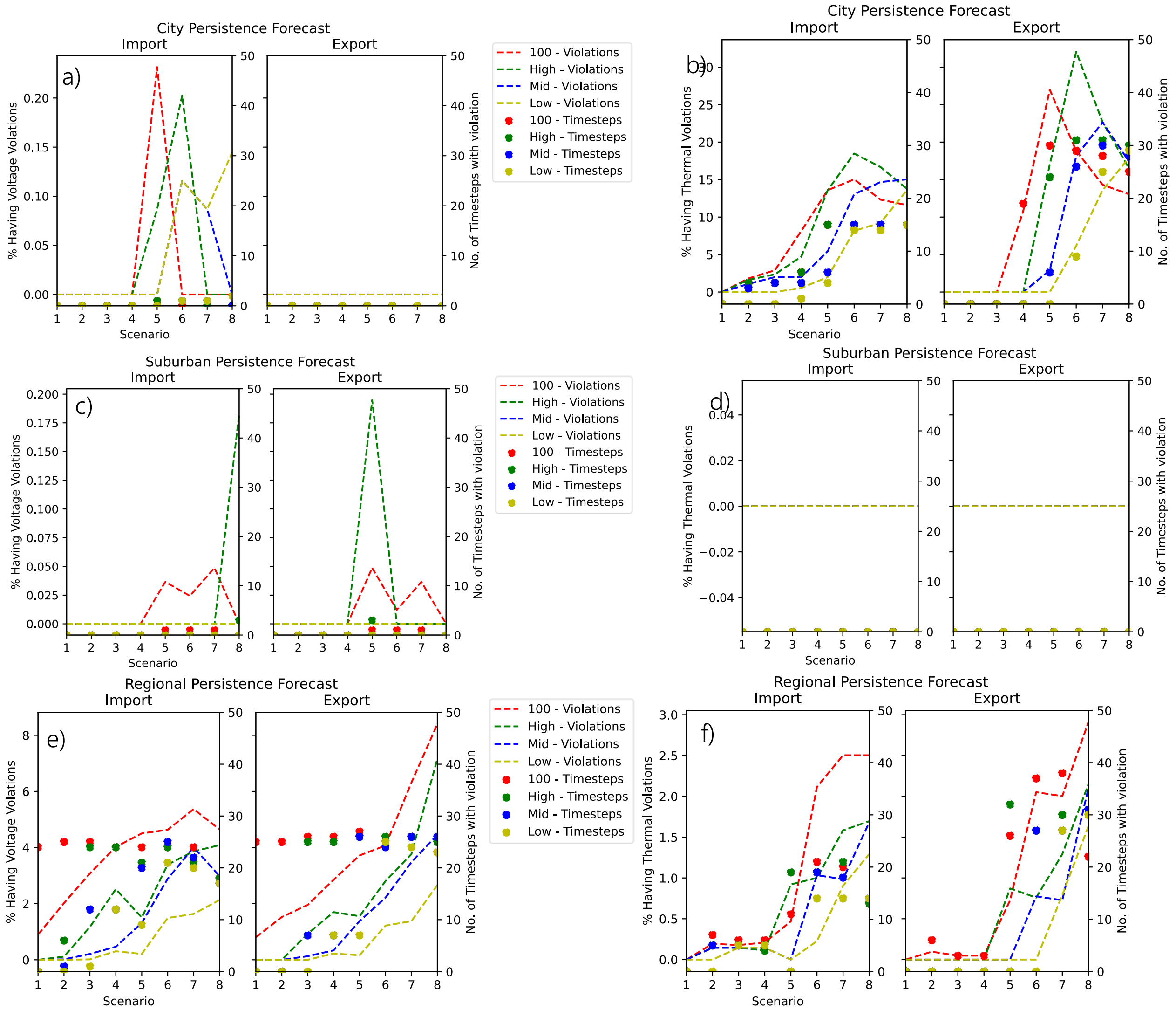


Figure 22 shows the number of voltage and thermal constraint violations for the close-to-real-time persistence forecast. It can be seen that the evolution of constraint violations at DER penetration and participation levels increase is very similar to the day ahead forecast, albeit on a slightly smaller scale.

Figure 22 **Graphs showing, for the persistence forecast and lower voltage profile: a) the voltage violations for the *City* network; b) the thermal violations for the *City* network; c) the voltage violations for the *Suburban* network; d) the thermal violations for the *Suburban* network; e) the voltage violations for the *Regional* network; f) the thermal violations for the *Regional* network**



4.2.1 Higher voltage profile

To see how the different DOE update frequencies perform on a more constrained system, the head of feeder voltage is increased in this section. Specifically of interest are the export constraints, as exports are more highly constrained due to the higher voltage. Note that there are no higher voltage profile results for the *Regional* network as that network is very voltage sensitive and the higher voltage profile resulted in many solutions where no export capacity could be allocated.

Looking at Figure 23 and Figure 24 it is again seen that the day ahead and intra-day forecasts result in a similar number of both voltage and thermal constraint violations in the *City* and *Suburban* networks. A spike in the number of voltage constraints is seen in Scenarios 4 - 6 for the *City* network which then subsides at higher DER penetration levels. This drop at higher DER penetrations is because when more DER in the network are participating, there is less error in the forecast of the total power from passive customers in the network.

The persistence forecast results in Figure 25 show a similar trajectory of constraint violations as the day ahead and intra-day, although only about half as many occurrences. Due to the method of creating the intra-day forecasts, if the day ahead forecast over-allocates capacity then the intra-day forecast will generally also do so. This is why there is very limited difference between the two in these graphs. The real difference between the intra-day and day ahead forecasts will be seen in the severity of the constraint violations, which will be discussed in the next section.

Figure 23 Graphs showing, for the day ahead forecast and high voltage profile: a) the voltage violations for the *City* network; b) the thermal violations for the *City* network; c) the voltage violations for the *Suburban* network; d) the thermal violations for the *Suburban* network

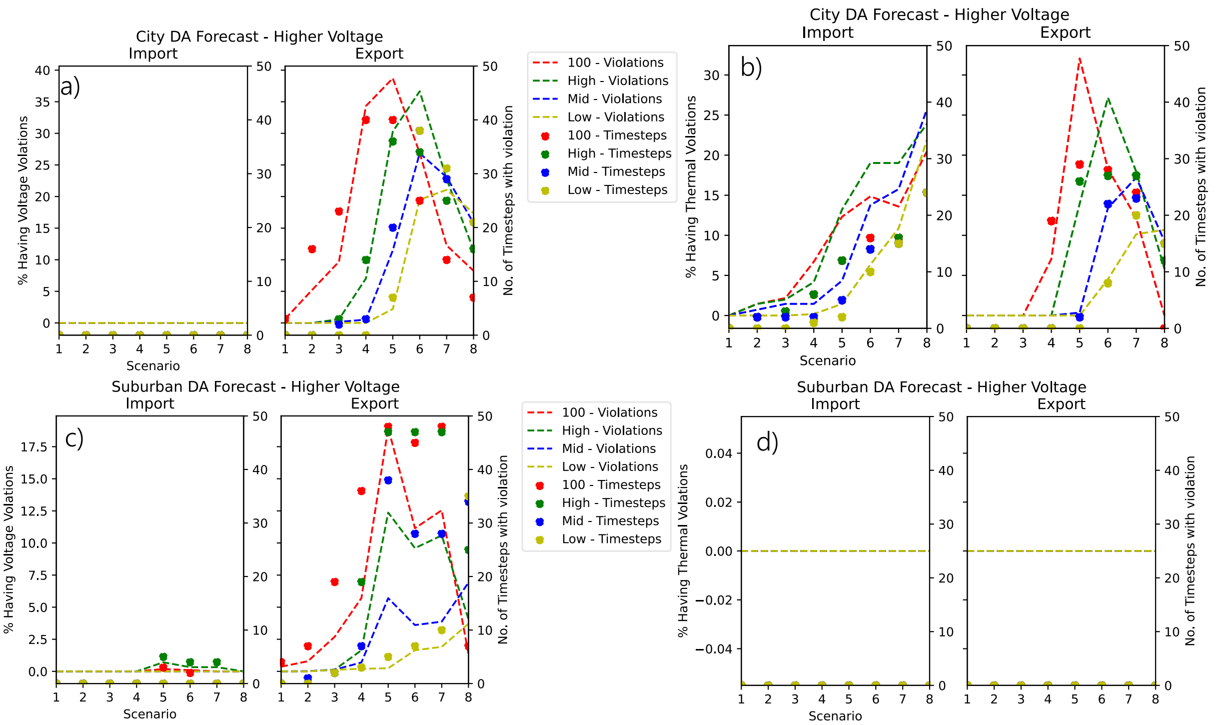


Figure 24 Graphs showing, for the intra-day forecast and high voltage profile: a) the voltage violations for the *City* network; b) the thermal violations for the *City* network; c) the voltage violations for the *Suburban* network; d) the thermal violations for the *Suburban* network

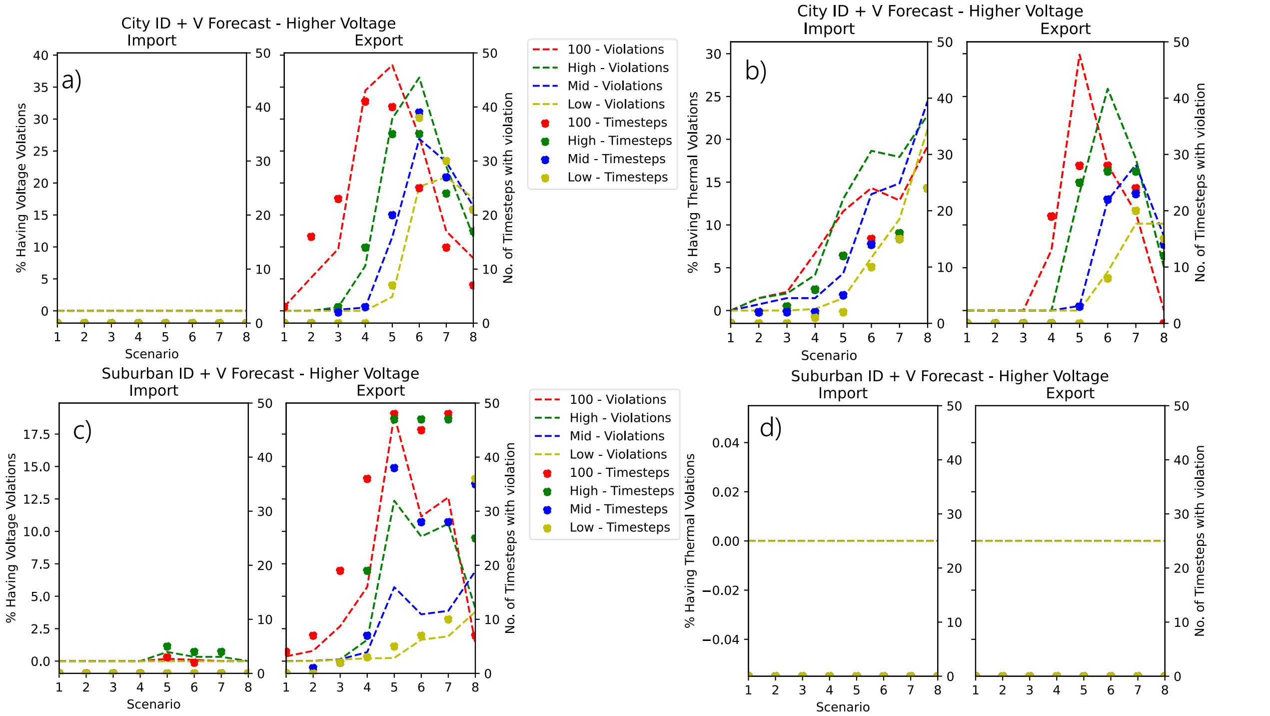
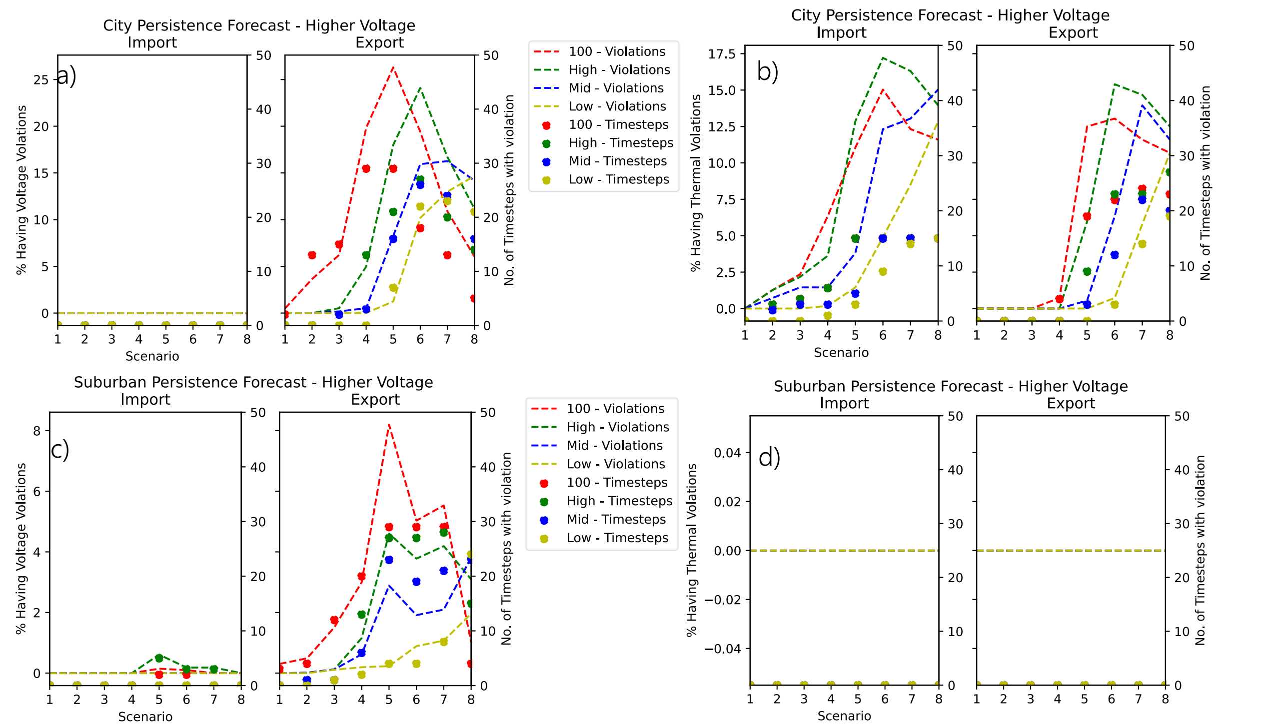


Figure 25 Graphs showing, for the persistence forecast and high voltage profile: a) the voltage violations for the *City* network; b) the thermal violations for the *City* network; c) the voltage violations for the *Suburban* network; d) the thermal violations for the *Suburban* network



4.3 Severity and time of constraint violations

Whilst it is of interest how widespread the constraint violations are in terms of total number of occurrences, and total number of timesteps that have a network violation, two other key features are the severity of those violations and when those violations occur. For example, if network constraint violations occur very frequently, but they only exceed the voltage limit by 0.1V, this may not be of great concern to a DNSP. However, if there is only a single time step where a voltage constraint is breached, but that voltage violation is 10V above the limit, then could lead to inverters tripping off the network and may have operational ramifications that extend past that single time step. Additionally, the time at which potential constraint violations may occur is also pertinent. For example, customers cannot fully utilise their export capability overnight as their PV will not be generating. Therefore, if an export constraint violation would occur overnight if the DOEs are fully utilised, this is unlikely to be of concern to a DNSP.

Figure 26 shows how the maximum thermal constraint violation in the network evolves throughout the day for different DER penetration and participation levels using the three forecasts.

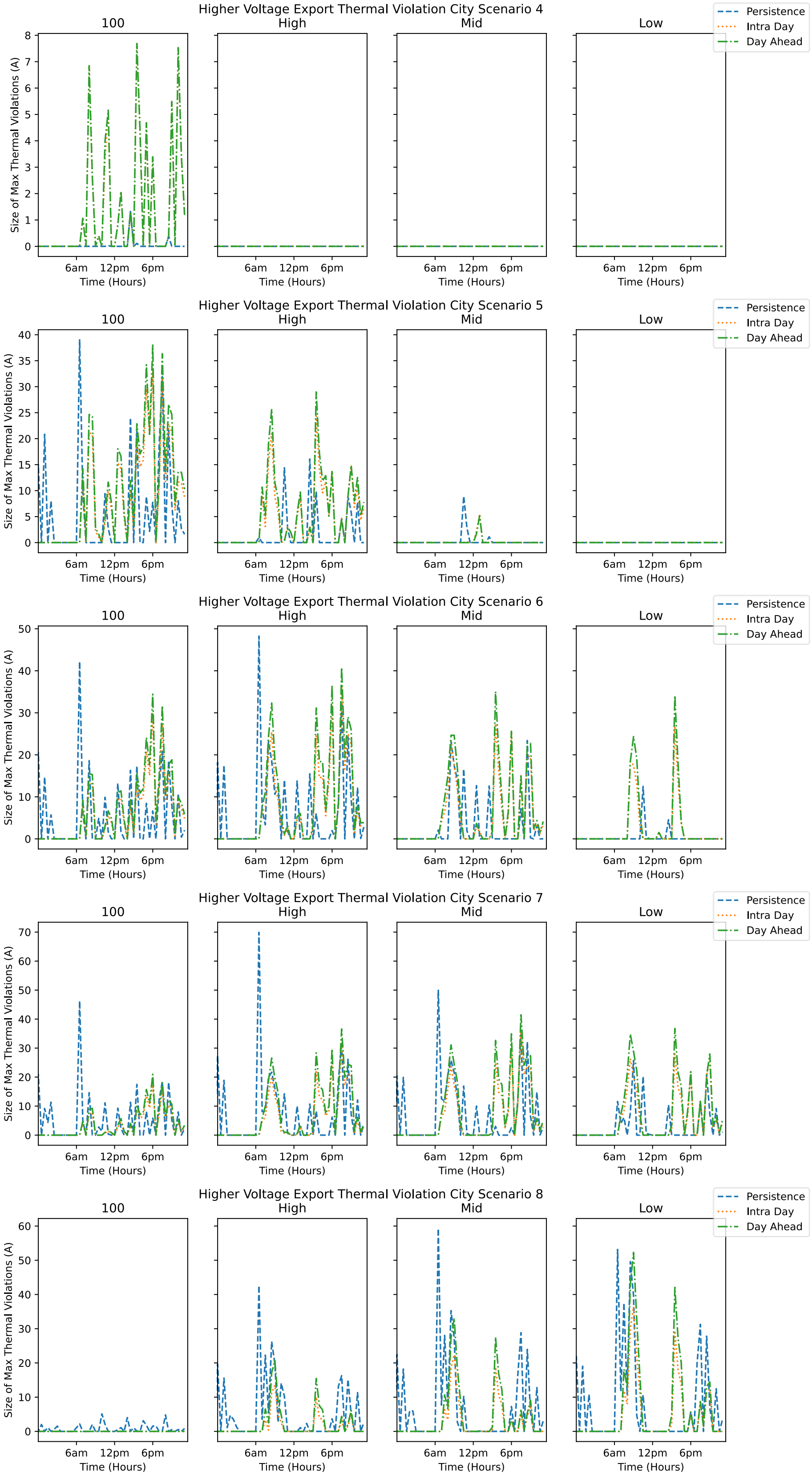
Looking at the top set of graphs in Figure 26, in Scenario 4 only the 100% participation level causes thermal constraint violations in the network, and these occur from 6am onwards to varying degrees. In Scenario 5 these maximum thermal violations increase in magnitude for the 100% participation and begin occurring in the High participation and Mid participation. In Scenario 6 the thermal constraint violations in the 100% participation level start to decrease, while for the lower participation levels it is still increasing.

By the time we get to Scenario 8, there are very limited thermal constraint violations for 100% participation, and the Low participation level has the largest thermal constraint violations.

This figure shows how, as more DER start participating in the DER marketplace the DOEs become more constrained and so small errors in the forecasts will result in constraint violations. As the DER penetration grows this begins happening even for low DER penetrations. However, once DER penetration reaches a certain level (for the *City* network this is somewhere between 45 – 60%) the 100% DER participation starts decreasing because the uncertainty in the forecast is becoming smaller when compared to the total capacity that is being allocated to participating DER. Therefore, as the penetration and participation increases from this point, the impact of the inaccuracies of the forecasts of customer power will continue to reduce.

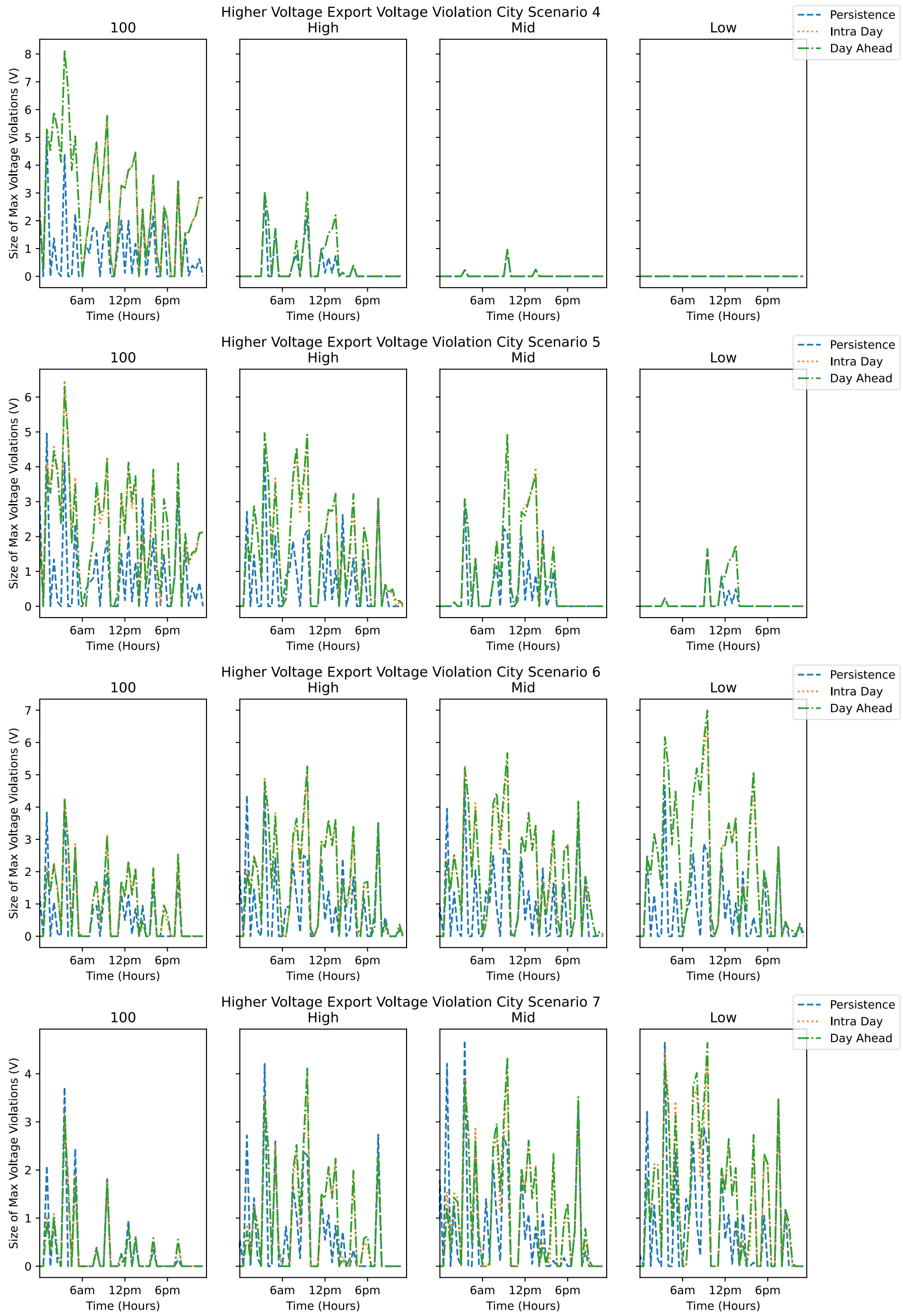
For Scenario 8, 100% participation there are only active customers in the network, and so the customer power forecast doesn't impact the DOEs and there are limit thermal constraint violations (due to the impact of voltage on the power throughput of lines). For Scenario 8 it can clearly be seen that these export thermal constraint violations are occurring at the beginning and end of daylight hours, most likely due to the forecast not accurately estimating the upwards and downward curves in the PV generation. The two spikes around these times may be of concern, as if the forecasting is estimating that the PV generation drops before it does in practice, PV that should be curtailed may be allowed to be exported. These thermal violations peak at around 70A, which could represent a significant violation.

Figure 26 The maximum thermal constraint violation for DOE exports for Scenarios 4 – 8 in the *City* network for the persistence, intra-day, and day ahead forecast and higher voltage profile



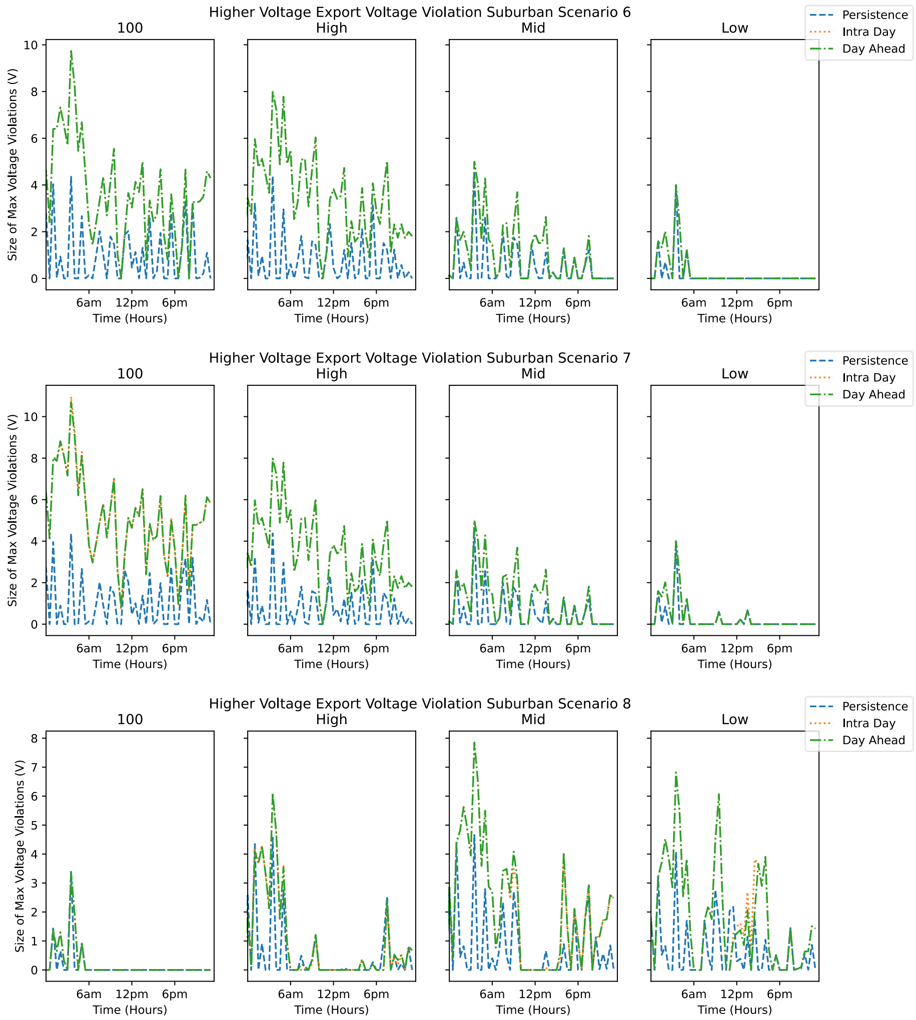
A similar development of constraint violations can be seen in Figure 27 which shows the maximum export voltage violation for the three forecast DOEs in the *City* network with a higher voltage profile. For Scenario 4, the 100% participation level causes significant voltage violation, whilst the High and Mid cause less violations. The peak voltage violation for Scenario 4 100% participation is around 8V in the day ahead and intra-day cases. This could be problematic as voltage violations of this magnitude would likely cause inverters to trip and disconnect from the network. However, this peak voltage violation occurs very early in the morning, when peak PV export will not be occurring. So, it is unlikely that the full 8V voltage violation will occur. Nevertheless, the over-voltage violations occur for most of the daylight hours up to 5V above the set limit. This is likely to be of concern to a DNSP. In Scenario 5 these large voltage violations in the middle of the day can also be seen in the High and Mid DER penetrations. For Scenario 6 the 100% participation constraint violations are about half the magnitude they were in Scenario 4. In fact, the Low participation now has the largest violations of up to 6V during the middle of the day. For Scenario 7 the voltage violations in the middle of the day for the 100% participation level are reduced greatly. This reflects observations made early about how initially the higher participation scenarios will cause more violations as the network will be more constrained, but once the network is constrained for the lower participation levels, then these are the once which will exhibit the worse constraint violations. By comparing the voltage violations for the different forecasts in Figure 27 it is seen that in general for day ahead and intra-day the constraint violations occur at the same time during the day and that the difference in magnitude is generally not significant.

Figure 27 The maximum voltage constraint violation for DOE exports for Scenarios 4 – 7 in the *City* network for the persistence, intra-day, and day ahead forecasts with a higher voltage profile



For comparison Figure 28 is provided which shows the maximum export voltage constraint violation for Scenario 6-8 of the *Suburban* network with the higher voltage profile for the day ahead, intra-day and persistence forecasts. This highlights that the maximum constraint violation differs only imperceptibly between the day ahead and intra-day forecasts. The persistence forecast has significantly less constraint violations. A large difference between Scenario 7 and 8 is also seen where there is a large drop in the maximum constraint violation for the higher DER penetration, and the jump in the constraint violation for the lower DER penetrations.

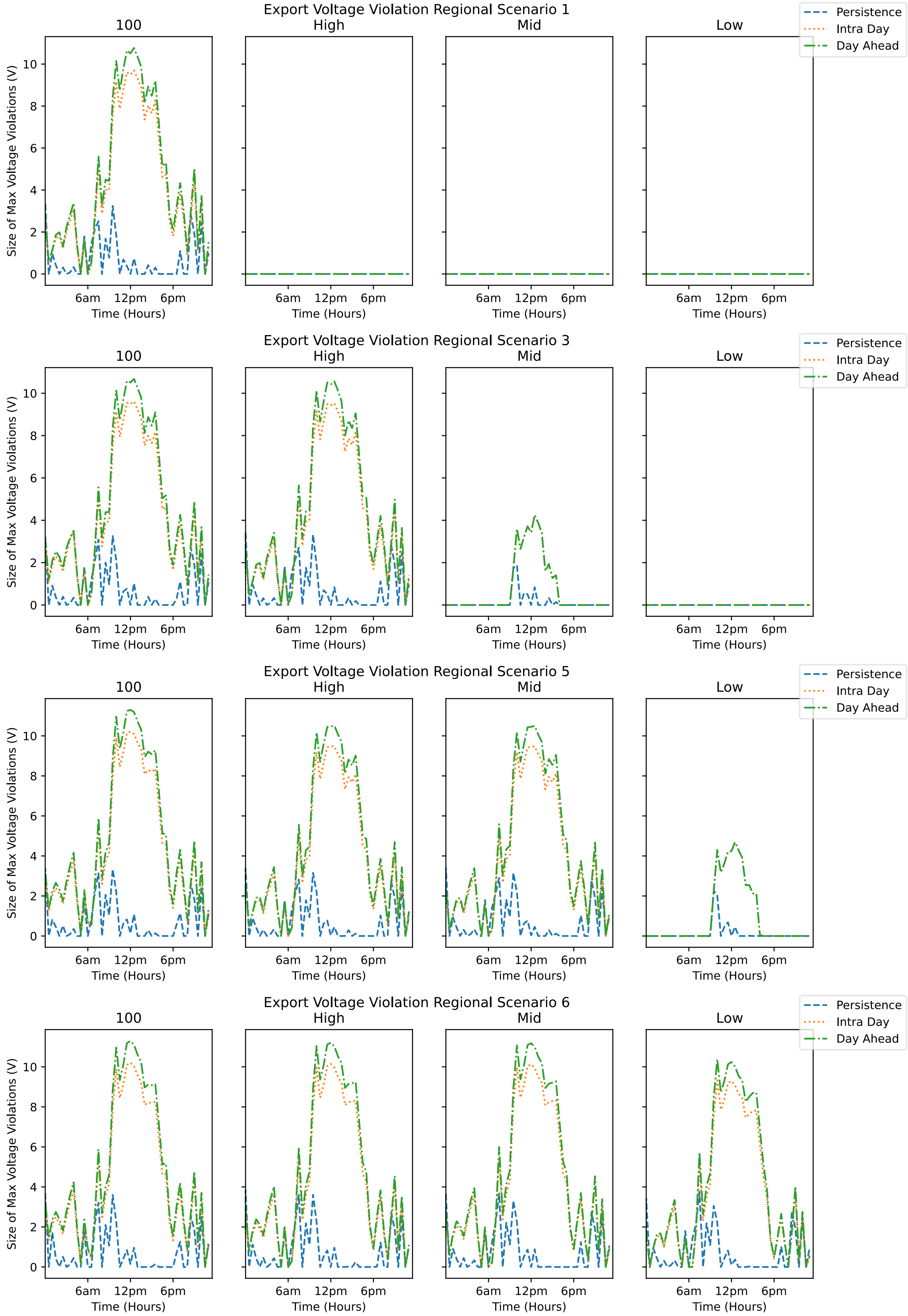
Figure 28 Comparison of the maximum export voltage constraint violation for Scenario 6-8 with the higher voltage profile for the *Suburban* network using day ahead forecast, intra-day forecast and persistence forecast



The *Regional* results for maximum constraint violations are somewhat different from the general pattern we have seen thus far in the *City* and *Suburban* networks.

This is seen in Figure 29 where the maximum constraint violation for the 100% participation remains very similar as the DER penetration scenario increases. Furthermore, once constraint violations begin occurring at lower participation levels, these also mirror the constraint violation curve of the 100% participation scenario. The cause of this is that, from the very first scenario, due to the error in the head of feeder voltage forecast, one of the customers participating in the 100% participation scenario has these voltage constraints. As the DER penetration increases more customers in the network become active customers. In Scenario 3 this customer with the high voltage constraint violation also begins participating in the High DER participation scenario. They would begin participating in the Mid DER participation at Scenario 5, and for Low DER participation at Scenario 6. There are slight difference in the shape of the constraint violation for different DER penetration and participation scenarios, but in general they all maintain the same shape. This is because the influence of the error in the head of feeder voltage for the *Regional* network far outweighs the influence of the error from the customer power forecast. The maximum voltage constraint violation peaks at around 10V above the maximum voltage limit of 253V. This would likely be enough to trip off DER inverters, and the extended during of the overvoltage may cause other operational issues and would impact a DNSPs reliability of service performance.

Figure 29 The maximum voltage constraint violation for DOE exports for Scenarios 1, 3, 5 and 6 in the *Regional* network for the persistence, intra-day, and day ahead forecasts



4.4 Average Constraint Violation across a day

Another way that the constraint violation can be visualised is by taking the average of all of the constraint violations in each time step and plotting them rather than the maximum as was done in the previous section.

From Figure 30 – Figure 32 show that the DER participation level has little impact on the average thermal import violation size, or its timing. It is also shown that these import thermal violations are focused around the morning and evening demand peak times, which are when DNSPs would be concerned about import constraints. The intra-day forecast does manage to slightly reduce the magnitude of the violations but not reduce the number of time periods in which they occur. The persistence forecast however manages to reduce the number of time steps with constraint violations. But notably it increases the average thermal import violations around the evening demand peak (the time of most concern). This would be caused by fast ramping demand increases, and variable head of feeder voltages during this time. Similarly, we see that overall, the DER participation level has little impact on the average voltage export violation size, or its timing. This reinforces the results that are shown in Section 4.4, that for the *City* network the performance of the DER participation level is directly dependent on the DER penetration level in the network. Each participation level performs well during some periods of DER penetration and poorly in others.

Figure 30 In the *City* network using the day ahead forecast and the higher voltage profile the: (Top) Average import thermal constraint violations over the test day. (Bottom) Average export voltage constraint violations over the test day

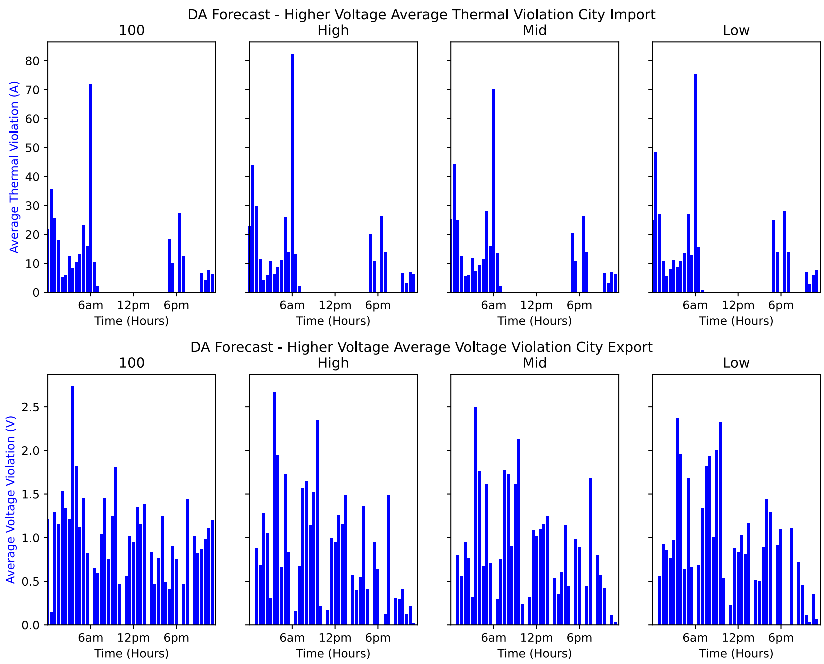
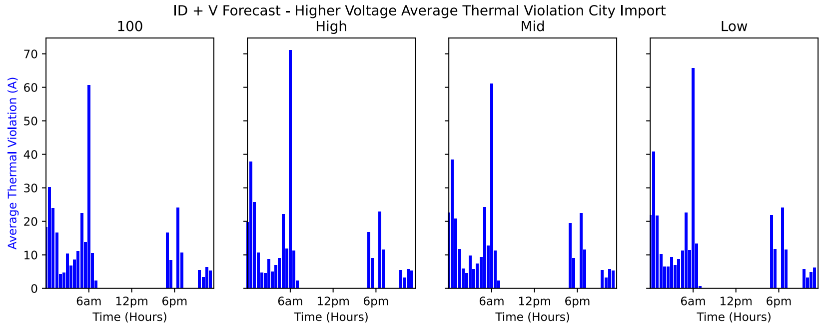


Figure 31 In the *City* network using the intra-day forecast and the higher voltage profile the: (Top) Average import thermal constraint violations over the test day. (Bottom) Average export voltage constraint violations over the test day



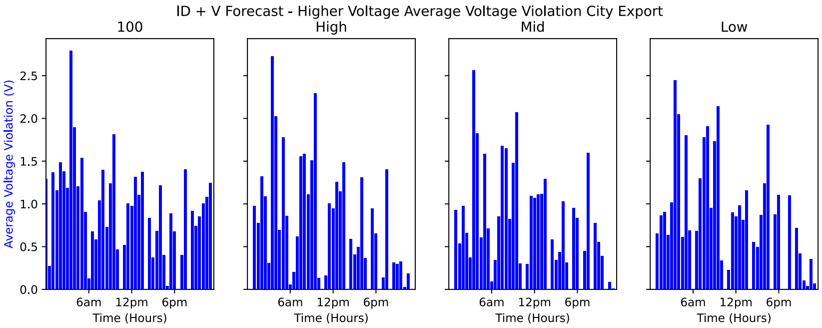
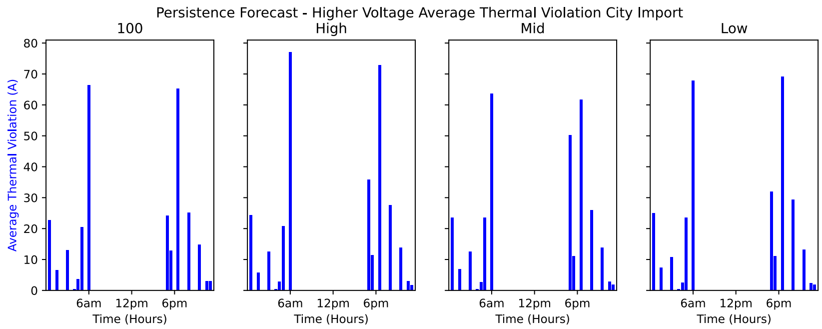
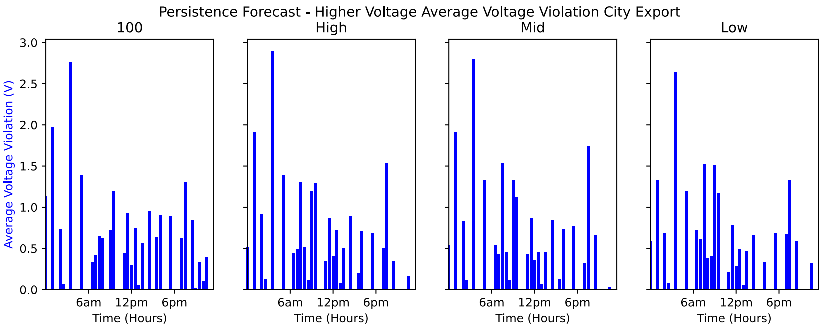


Figure 32 In the *City* network using the persistence forecast and the higher voltage profile the: (Top) Average import thermal constraint violations over the test day. (Bottom) Average export voltage constraint violations over the test day.





For the *Suburban* network, we see in Figure 33 that the DER participation level has more of an impact on the average voltage violation. This is because in the *Suburban* network the total size of the installed DER fleet grows less quickly than in the *City* network due to lack of commercial customers in the *Suburban* network. This means that in more of the DER penetration scenarios the higher DER participation levels cause network voltage issues while the lower DER participation levels can assign full capacity unhindered.

In Figure 34 are shown the average export voltage violations in the *Regional* network. It can be seen that once again, the DER participation level has little impact on these values.

In general, if a DNSP wants to control DER participation to limit constraint violation then they would minimise DER participation until the DER penetration reached a level such that static limits were beginning to cause network constraint violations. At this point the DNSP would want to rapidly increase the DER participation as quickly as possible. In this way the DNSP minimises the impact of the uncertainty associated with the forecasts used to create the DOEs. Of course, from the point of view of unlocking DER capacity, minimising DER participation is not advantageous and in reality a sudden shift of customers moving from non-participation to participation would be very difficult.

Figure 33 Average export voltage constraint violations over the test day in the *Suburban* network and the higher voltage profile using (Top) the day ahead forecast, (Middle) the intra-day forecast, (Bottom) the persistence forecast

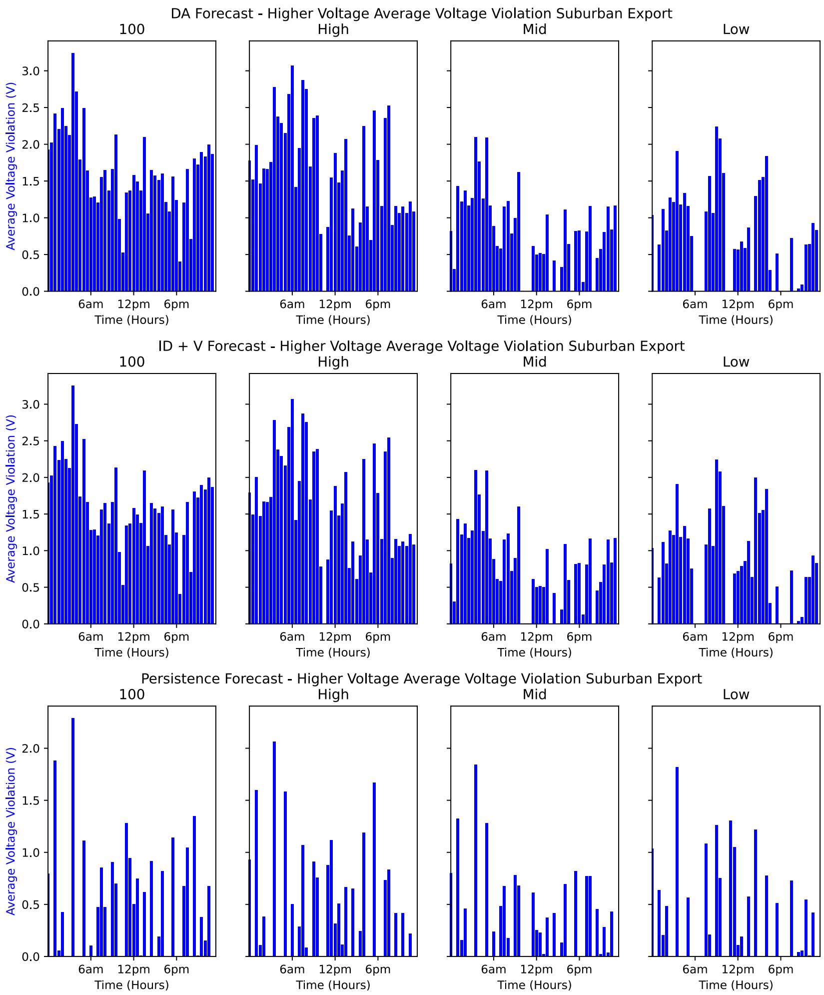
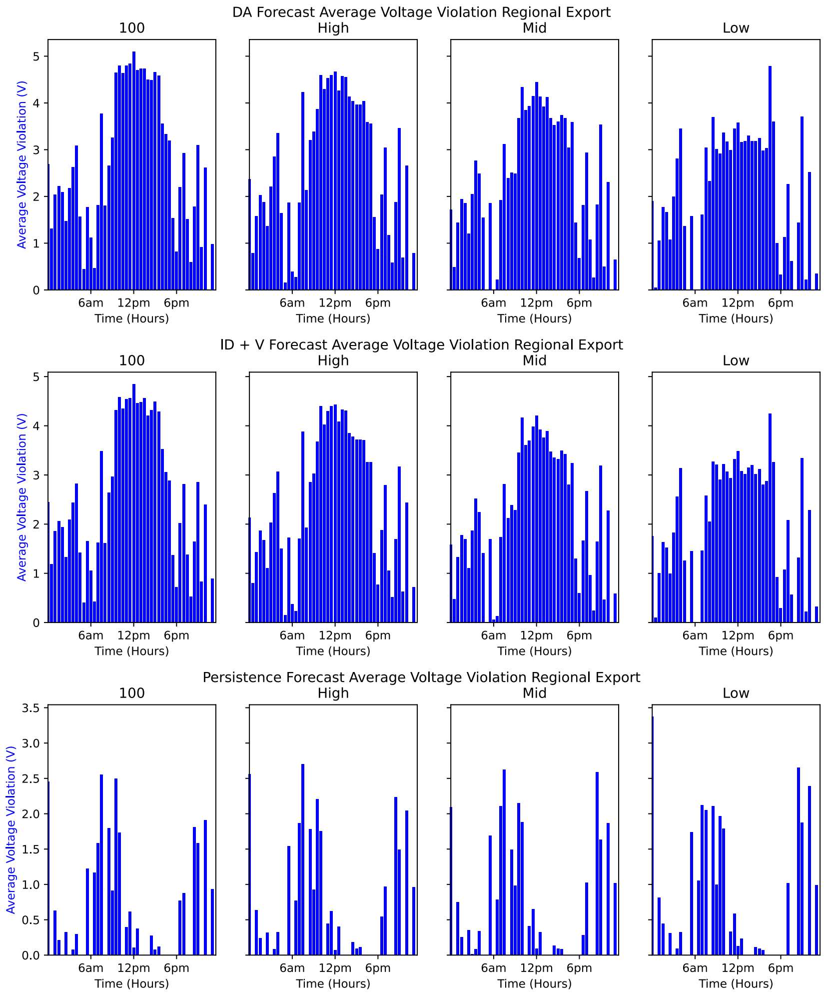


Figure 34 Average export voltage constraint violations over the test day in the *Regional* network using (Top) the day ahead forecast, (Middle) the intra-day forecast, (Bottom) the persistence forecast



Across all three networks, potential export voltage constraint violations occur during the middle of the day which is likely to be problematic for a DNSP. While the difference in average constraint violation size between day ahead and intra-day is minimal, the persistence forecast voltage violations are somewhat smaller and less frequent. However, there are still a significant number of these constraint violations and they do occur during the middle of the day when it is expected that the full export capacity allocation could be utilised.

5 Summary of results

From the results presented in this work it is seen that when the network is unconstrained, the difference between the perfect knowledge DOE and the uncertain forecast DOEs can be zero – that is to say that both will assign full capacity to the DER in the network (this may not always be the case, as the network may be unconstrained in practice, but the inaccurate forecast may cause the DOE calculation to conclude there is a constraint, and so reduce capacity unnecessarily). Once this is no longer the case then the difference between the perfect knowledge DOE and uncertain forecast DOE will occur. It is shown in Section 4.1 that if the forecast is fairly accurate, then the DOEs generated can mimic the general trajectory of the perfect DOE across the day but will often miss the detailed changes within that trajectory. However, if the forecast is inaccurate, then this can lead to large difference in the DOEs being generated.

Any deviations from the perfect DOEs is undesirable. If the uncertain forecast DOE under-allocates aggregate capacity compared to the DOEs generated using perfect knowledge, then the DER may be curtailed without reason. If the uncertain forecast DOE over-allocates aggregate capacity compared to the DOEs generated using perfect knowledge, then if the capacity is fully utilised there will be network constraint violations. For lower DER penetration scenarios, the higher DER participation levels result in larger deviations in DOE capacity allocation compared with the DOEs generated using perfect knowledge. However, as the DER penetration levels grow this shifts so that the lower DER participation levels have the greatest deviations in DOE capacity allocation compared with the DOEs generated using perfect knowledge. This is because, for lower DER penetrations, low participation often leads to unconstrained operation in practice. This means that while the errors in the forecasts may still be substantial, the likelihood of constraint violation is significantly smaller. However, once the network is generally constrained even at lower DER participation levels, the greater uncertainty around the power of non-participating customers associated with the lower participation levels causes much larger deviations in aggregate capacity allocated in the network compared with the DOEs generated using perfect knowledge.

The difference in capacity allocation of the day ahead forecast and the intra-day forecast is minor, as they are both inaccurate forecasts and the incremental shift in accuracy with the intra-day forecasts doesn't have significant impact on the DOE allocation. In general, whether the forecast DOE over-allocates or under-allocates aggregate capacity (compared to the aggregate capacity allocated by perfect knowledge DOEs) is largely determined by the accuracy of the voltage forecast. If the voltage forecast is lower than the actual voltage, in general the forecast DOE will over-allocate aggregate export capacity. If the voltage forecast is higher than the actual voltage, in general the forecast DOE will under-allocate aggregate export capacity. Of course, the customer power forecast also has an impact on this, but the inaccuracy of the power forecast needs to be significant to counter-act the impact of the voltage forecast inaccuracy. In general, the persistence (close to real time) forecast managed to best match the perfect knowledge DOEs, but there are some time steps where this is not the case due to large sudden changes in voltage or power.

In general, as the number of DER in the network increases, the occurrence and severity of forecast DOEs over-allocating aggregate capacity (compared to the perfect knowledge DOEs) increases, and therefore so does the potential for voltage or thermal constraint violations from DOEs using forecasts.

There are some occurrences at high DER penetration scenarios where the number occurrences of over-allocating aggregate capacity decreases. This is because, with these increased DER penetration scenarios, there is also higher DER participation which leads to the uncertainty about the power of non-participating customers being of a smaller magnitude compared to the controllable DER fleet and so the over-allocation of aggregate capacity from uncertain forecast DOEs are likely to be less severe. The 30-minute ahead persistence forecast will generally have a smaller number of constraint violations compared with the day ahead and intra-day forecasts. There is minimal different in the number of constraint violations by the day ahead and intra-day forecast DOEs. This is due to the method of generating the intra-day forecasts, where if the day ahead forecast underestimates the voltage or customer power then the intra-day forecast will also underestimate it (albeit by a smaller amount). Therefore, it is highly likely that if the day ahead forecast over-allocates capacity, then the intra-day will also over-allocate capacity.

The results show that the over-allocation of export or import capacity can occur at times when it is more likely that the full capacity allocated will be utilised. For example, import capacity is over-allocated by the forecast DOEs during the morning and evening demand peaks, as well as overnight. For the higher voltage profile, the export capacity is over-allocated by the forecast dependent DOEs throughout daylight hours. The size of the constraint violation is dependent on the combination of the DER penetration level and the DER participation level. At lower DER penetration levels, lower DER participation levels cause the least and smallest constraint violations because there is significant network capacity available to be shared between a small number of participating DER. However, when DER penetration levels increase, having more of those DER receiving the DOEs reduces the overallocation of capacity, and subsequent potential network violations. This is because a high DER participation reduces the total power flow in the network from non-participating customers, which is a large source of forecast uncertainty. However, averaged across all DER penetration levels, the DER participation level does not seem to have a substantial impact on the average constraint violation. It appears to be beneficial to increase the DER participation rate in line with the DER penetration rate.

The inaccuracies of the day ahead and intra-day forecasts DOEs are often dominated by the large inaccuracies in the head of feeder voltage forecast. As the intra-day forecast only has a marginal improvement on this value, which itself is still substantially different from the true value, there is very little benefit seen in these results from implementing intra-day forecasts. This aligns with other studies that have been conducted as part of Project EDGE that have shown that DOEs are much more sensitive to changes in the head of feeder voltage compared to the non-participating customer power. This is clearly illustrated for the *Regional* network in Figure 29 and Figure 34 where the trajectory of the constraint violation closely maps the error in head of feeder voltage forecast shown in Figure 11. Therefore, to be able to maximise the utility of DOEs, future focus on forecasting should be concentrated on forecasting the head of feeder voltages. If an intra-day forecast is able to provide a significant improvement on head of feeder voltages, then it is likely to substantially reduce the severity and frequency of network constraint violations or under-allocation of capacity.