Project EDGE

Testing Different DOE Approaches at DER Penetration levels in real-world networks

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

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Important notice

PURPOSE

This *Testing Different DOE Approaches at DER Penetration levels in real-world networks* report has been prepared for Project EDGE by the University of Melbourne, Department of Electrical and Electronic Engineering.

This report provides the approaches taken and results of the work conducted on the technical efficacy of the Approximation Algorithm compared to the Basic DOE for a range of DER Penetration and Participation levels in real-world networks.

DISCLAIMER

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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

As the rapid uptake of distributed energy resources (DER) supported by the evolution of smart grid technologies increases, there are emerging opportunities for a distribution network service provider (DNSP) 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 a large number of 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on DER that does not consider the locational and temporal aspects of power injection and absorption and will become outdated with increasing DER penetration.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). An issue dynamic operating envelopes has is that it requires a complete and verified model of the LV network impedances and topology. It can often be the case that a DNSP may not have access to such a model. Obtaining and verifying an LV network model may be time consuming and costly, so an alternative approach is also proposed which doesn't require an LV network model.

Section 2 of this report provides an overview of the three different DOE algorithms that are examined in this work. These are:

- *Basic DOE:* which will be utilising the *Maximise NEM Export* objective function. In this algorithm the DNSP provides as input the forecast of the active and reactive power set points of non-participating customers as well as forecasts of the head of feeder (secondary side of the LV transformer). The algorithm then uses a verified model of the LV network with network topology and impedances to calculate the optimal capacity allocation while ensuring that network constraints are not violated. This method requires a detailed model of the LV network that has been validated to ensure its accuracy.
- *Approximation Algorithm:* has been developed by AusNet Services to be able to generate DOEs for networks where they do not have a validated LV network model. This algorithm also does not require forecasts of the network state (active power, reactive power, voltage) in order to operate. Instead, the previous 4 weeks of historical LV transformer data are used to determine the available hosting capacity per phase at a 98% confidence interval. Historical customer voltage data from the previous 4 week are then used to estimate the 99th percentile voltage profile of each customer.
- *Grouped DOE:* is a concept aiming to leverage any ability to calculate DOEs in an aggregate fashion rather than for individual NMIs. The aim of this is to allow DOE capacity to be exchanged between local resources, for example if one resource is allocated more capacity than it can utilise, and there is another resource close by who could use more capacity that additional capacity could automatically be re-allocated. Due to the highly locationally sensitive nature of network voltages, this approach can only be used to reallocate capacity for networks under thermal constraints.

This report focuses on the comparing the technical performance of the Basic DOE and the Approximation Algorithm. Additionally, high level analysis of the Grouped DOEs is provided to explore how they may be implemented, and the cases in which they would provide benefits.

In Section 3 the case studies that are used for the techno-economic modelling in this work are presented. The representative networks that are used, a *City* network and a *Suburban* network, align with previous techno-economic modelling work conducted on DOEs in this project. The techno-economic modelling is focused on the Basic DOE and Approximation Algorithm. These two approaches 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. Due to the nature of the Approximation Algorithm's reliance on substantial amounts of historical data, it could not directly be modelled for this future DER scenarios. Therefore, in consultation with AusNet Services an approach was agreed as a proxy that would provide results that would capture the general operation of the Approximation Algorithm. This proxy is described in Section 3, along with modelling assumptions used in this work.

The results of the techno-economic modelling are presented in Section 4. The results show that for a 3-phase LV network that is voltage constrained, the lost DER capacity associated with using the Approximation Algorithm rather than the Basic DOE can be divided into 5 stages. In general, for a single time step the lost DER capacity measured in kW can be thought to be in one of these 5 stages:

- Stage 1: Basic DOE and Approximation Algorithm allocate the same capacity, because the system is unconstrained in both cases. So expected loss in capacity allocation is 0.
- Stage 2: The Approximation Algorithm becomes voltage constrained but not the Basic DOE. During this stage the loss in capacity allocation will increase as DER penetration increases. This is because Approximation Algorithm will reduce the amount of capacity it can allocate, while Basic DOE still allocates full capacity.
- Stage 3: Basic DOE now begins to be voltage constrained. However, the network is less heavily constrained in the DOE case as it has only just become constrained, so it has more options to allocated additional capacity. This means that lost DER capacity will continue to increase, but more slowly.
- Stage 4: Once Basic DOE hits thermal limits then the expected loss in capacity allocation will reduce, as the Basic DOE is now unable to increase the absolute capacity it is allocating, whilst the Approximation Algorithm is still able to.
- Stage 5: It is possible, if the DER fleet in the network is sufficiently large (oversized) that the Approximation Algorithm could also reach the thermal capacity of the transformer. Then at this point, there is again no difference between Basic DOE and Approximation Algorithm. This means the lost DER capacity will remain constant.

For a system with significant phase imbalance the five stages of operation remain the same, but the DER capacity during which the network is in each stage may vary greatly when compared to a balanced network. This will cause some changes in the shape of the overall lost DER capacity curve.

For a network which is not voltage constrained, but rather thermally constrained, there is a simple 3 stage process for the lost DER capacity measured in kW is:

- Stage 1: Basic DOE and Approximation Algorithm allocate the same capacity, because the system is unconstrained in both cases. So expected loss in capacity allocation is 0.
- Stage 2: Due to the conservative assumption on network demand/generation the Approximation Algorithm will hit the network thermal constraint before the Basic DOE. During the period where the Approximation Algorithm is constrained but the Basic DOE isn't the lost DER capacity allocation increases almost as fast as the DER fleet size increases.

- Stage 3: The Basic DOE now also becomes thermally constrained. At this point, the lost DER capacity allocation (in kW) will remain fairly constant, and this gap will be governed by the gap between the conservative network demand estimate of the Approximation Algorithm and the network demand forecast of the Basic DOE.

In very high demand or generation time steps it appears that the Approximation Algorithm may fail to allocate any capacity, even when the Basic DOE is still able to assign full capacity. This is due Approximation Algorithm determining that there is no additional hosting available to the transformer due to its conservative assumptions.

The Approximation Algorithm is most effective when the network is sufficiently unconstrained that, even with the conservative assumptions, it can still allocate full capacity. It can also be somewhat effective when the DER fleet in the network is sufficiently oversized so that the capacity allocation is thermally constrained rather than voltage constrained. Although, the lost DER capacity at this point will be dependent on how conservative the assumption of network demand is compared to the Basic DOE forecast. For voltage constrained networks, the Approximation Algorithm performs most poorly for export capacity when the Basic DOE is heavily voltage constrained. The more time periods where the Basic DOE is voltage constrained, the worse the Approximation Algorithm will perform over the day. The lost DER capacity allocation in these voltage constrained time steps is worse for lower DER participation scenarios.

For networks that are not voltage constrained, the largest loss in DER capacity allocation occurs at the point just before the Basic DOE becomes thermally constrained, and the Approximation Algorithm is already thermally constrained. Therefore, the more time periods that occur in a day when the Approximation Algorithm is thermally constrained and the Basic DOE is not, the worse the Approximation Algorithm will perform over the day.

Section 5 provides a high level analysis of the Grouped DOE approach. In a simple network it is illustrated how, when a network is thermally constrained, the Grouped DOE can act to simultaneously reduce the cost of the aggregators bid curves in the network, and also unlock additional capacity that would have remained unused under the Basic DOE approach. The results from Section 4 are then analysed for their influence on the potential usefulness of the Grouped DOE. It was determined that currently Grouped DOEs are likely to only be of significant use in capacity allocation of imports due to their ability to help combat the inability of the Basic DOE to utilise flexible load diversity in allocating import capacity. This will remain true unless and until DNSPs implement more advanced voltage regulation schemes to limit the voltage rise in distribution networks. This would lead to more occurrences of export capacity allocation being thermally constrained, and so being suitable for Grouped DOEs.

For DNSPs to make a decision around when to transition from the Approximation Algorithm approach to the Basic DOE approach would require a full cost benefit analysis for a given network. When the Approximation Algorithm starts losing DER capacity allocation, and the speed at which this lost DER capacity allocation increases will be dependent on the physical network, the DER within the network, and the conservatism of the estimates of network state used by the Approximation Algorithm. However, the general shape of the lost DER capacity curve seems similar across networks. From these results it is recommended that while the Approximation Algorithm allocates capacity in a largely unconstrained way, there is little benefit in making the investment required to transition to the Basic DOE. Once the Approximation Algorithm begins becoming constrained, the lost DER capacity increases quickly as new DER are added to the network. The controllable DER fleet capacity will likely need to be significantly oversized for the lost DER capacity stops increasing, so it is not recommended that DNSPs wait on their transition to the Basic DOE for this to occur, as this will result in near constant network constraint events. An increase in the severity or frequency of Approximation Algorithm capacity allocation being constraint should be a warning to DNSPs that they are potentially losing significant amounts of DER capacity by not transitioning to the Basic DOE, and the problem will only keep getting worse.

As mentioned previously, lost DER capacity allocation does not necessarily translate to lost DER capacity in practice. Export capacity between the late evening and early morning is unlikely to be fully utilised, and so the lost DER export capacity allocation will likely have a limit impact during these periods. However, the time steps where the network is most constrained are also the time steps where there will be the largest difference between the Approximation Algorithm and the Basic DOE and will be the time steps where the capacity is most likely to be fully utilised. DNSPs should therefore consider how the capacity is being used in each time step as well as the lost DER capacity allocation when making their decision.

With increasing amounts of flexible loads (including batteries and electric vehicles), the Approximation Algorithm will be the approach that will first have to constrain import capacity allocation in light of thermal constraints. As load diversity cannot be assumed when assigning import capacity, thermal constraints on DOEs for imports may soon become an issue in distribution networks. Moving from Approximation Algorithm to Basic DOE will assist in unlocking additional import capacity allocation, but it is estimated that transitioning to Grouped DOEs will likely have the largest impact in this respect noting detailed implementation analysis was not in scope of this study. The ability for import capacity to be re-allocated based on the aggregator bids re-introduces a level of load diversity into the import capacity allocation that could be key in delaying network reinforcement.

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
HoF	Head of Feeder
LV	Low Voltage
NEM	National Electricity Market
NMI	National Meter Identifier
PV	Photo-Voltaic
SCED	Security Constrained Economic Dispatch
SWER	Single-Wire Earth-Return
UoM	The University of Melbourne

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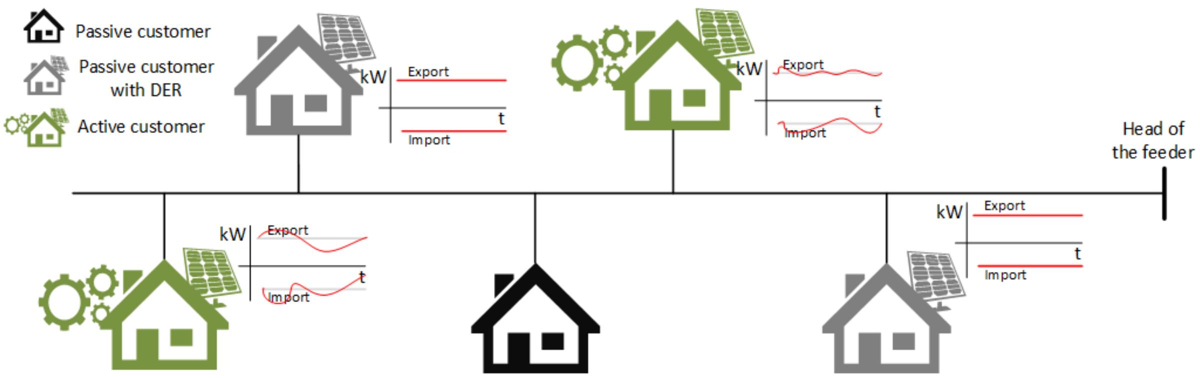
1 Introduction

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 a large number of 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 report on [Fairness in Dynamic Operating Envelope Objectives](), it was assumed that the DOE operated in such a way that the DNSP received a forecast of the network state (customer active and reactive power, and head of feeder voltage levels), and then employed an algorithm utilising a model of the LV network to determine the optimal allocation of capacity to fulfil the chosen objective whilst maintaining the network within allowable thermal and voltage limits. However, this is not the only method by which the DNSP could generate DOEs.

An issue with the approach proposed above is that is requires a complete and verified model of the LV network impedances and topology. It can often be the case that a DNSP may not have access to

[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.

such a model. Obtaining and verifying an LV network model may be time consuming and costly, so an alternative approach is proposed in Project EDGE which doesn't require an LV network model.

Another potential drawback with the above proposed DOE algorithm is that it does not directly consider the bids of the aggregators when assigning capacity. This means that capacity could be assigned to expensive resources that will not be cleared in the wholesale energy market. This would lead to capacity going to waste that could otherwise have been used by cheaper resources. Therefore, an alternative approach is also proposed in which both technical and economic considerations are included in the assignment of DOEs. Section 2 will provide more detail on these three possible approaches to DOEs.

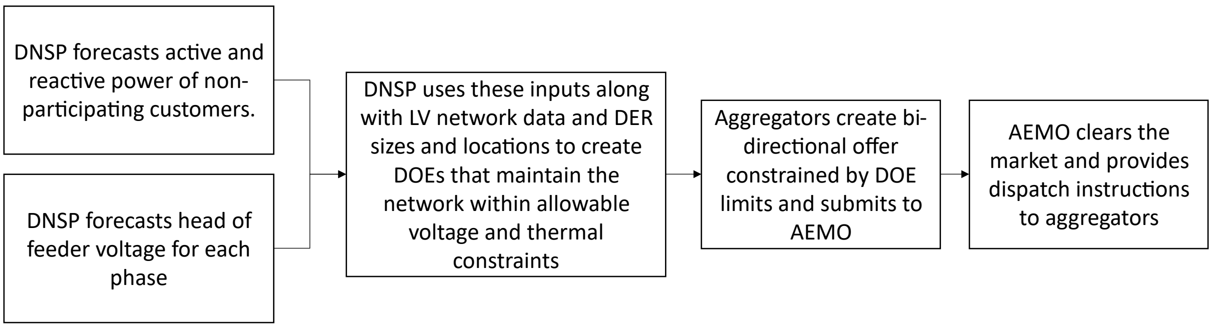
2 DOE Approaches

In this section an overview will be provided of the three different DOE algorithms analysed in this work: Basic DOEs, Approximation Algorithm, and Grouped DOEs. The Basic DOE and Approximation Algorithm will be compared via techno-economic modelling in Section 4, while Section 5 will provide high level commentary on the Grouped DOE.

2.1 Basic DOEs

The Basic DOE approach is the approach that was assumed in the previous UoM report on Fairness in DOE Objective Functions. Based on the recommendations of that work, it is assumed in this report that the Basic DOE will be utilising the *Maximise NEM Export* objective function. An indicative flowchart of the algorithm for the Basic DOE can be seen in Figure 2. In this algorithm the DNSP provides as input the forecast of the active and reactive power set points of non-participating customers as well as forecasts of the head of feeder (HoF) voltage (secondary side of the LV transformer). The algorithm then uses a verified model of the LV network with network topology and impedances to calculate the optimal capacity allocation while ensuring that network constraints are not violated. This method requires a detailed model of the LV network that has been validated to ensure its accuracy. An incomplete or inaccurate network model will either result in overly conservative DOEs, or DOEs that do not maintain the network within the prescribed set limits. In networks for which the DNSP does not have a complete network model, the Approximation Algorithm can be used.

Figure 2 Flowchart to illustrate the operation of the Basic DOEs

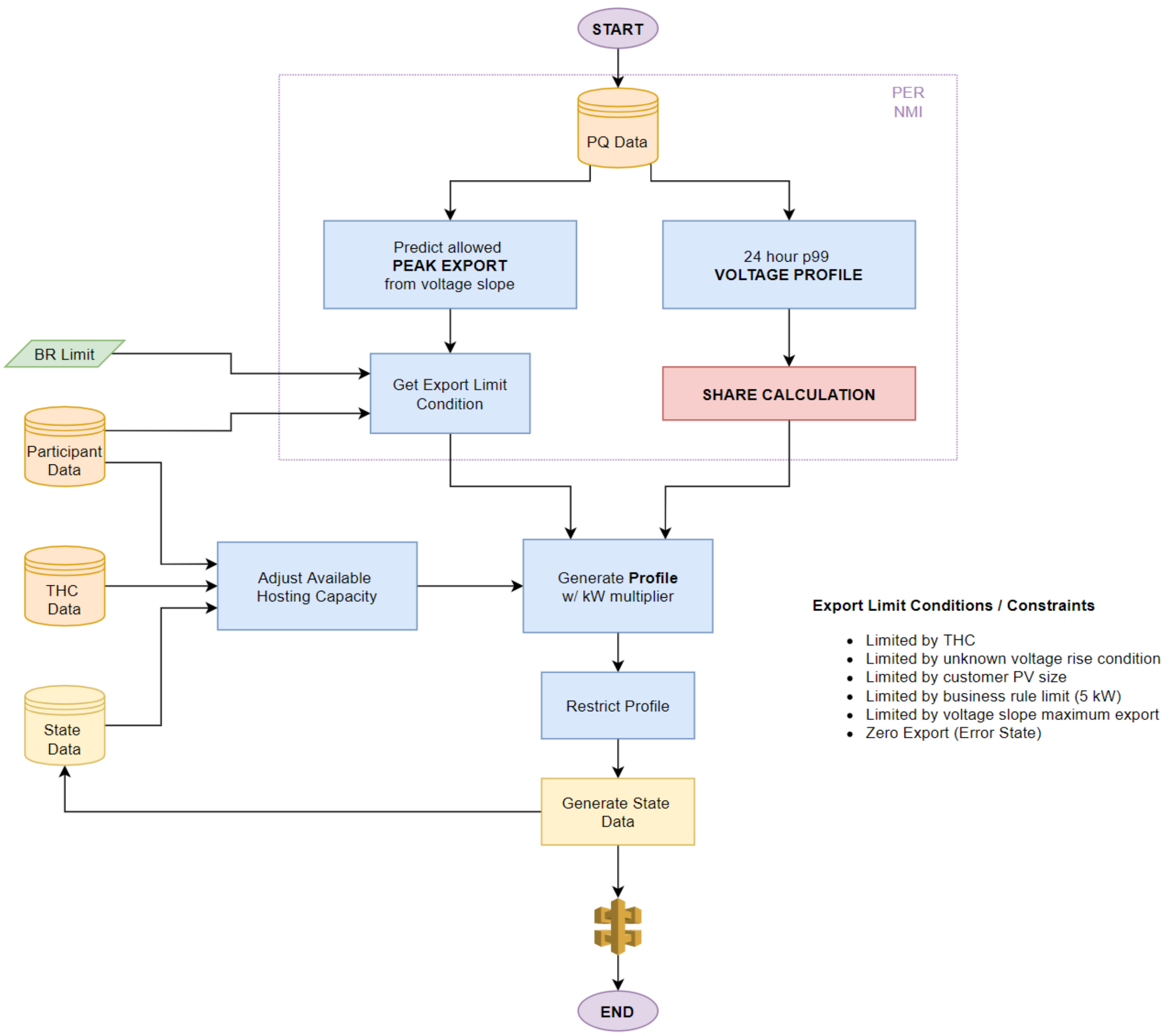


2.2 Approximation Algorithm

The Approximation Algorithm has been developed by AusNet Services to be able to generate DOEs for networks where they do not have a validated LV network model. This algorithm does not require forecasts of the network state (active power, reactive power, voltage) in order to operate. Instead, the previous 4 weeks of historical LV transformer data are used to determine the available hosting capacity per phase at a 99th percentile. Historical customer voltage data from the previous 4 weeks are then used to estimate the 99th percentile voltage profile of each customer. Each customer's available voltage headroom is then determined, and they are issued a share of their phase's hosting capacity based on the amount of voltage headroom they have available as a percentage of the total available customer voltage headroom on that phase. Historical customer active power and voltage data is then used to predict if the capacity allocated to each customer would cause that customer to exceed the upper voltage threshold (253V).

This process is visualised in the flowchart shown in Figure 3. As is apparent from the description of this approach, the trade-off for not requiring a detailed network model is that conservative estimates need to be made for the available capacity and the likelihood of constraint violation. In general, this would lead to a more conservative capacity allocation than the Basic DOE if both were applied to the same network.

Figure 3 AusNet Services Approximation Algorithm operational flowchart

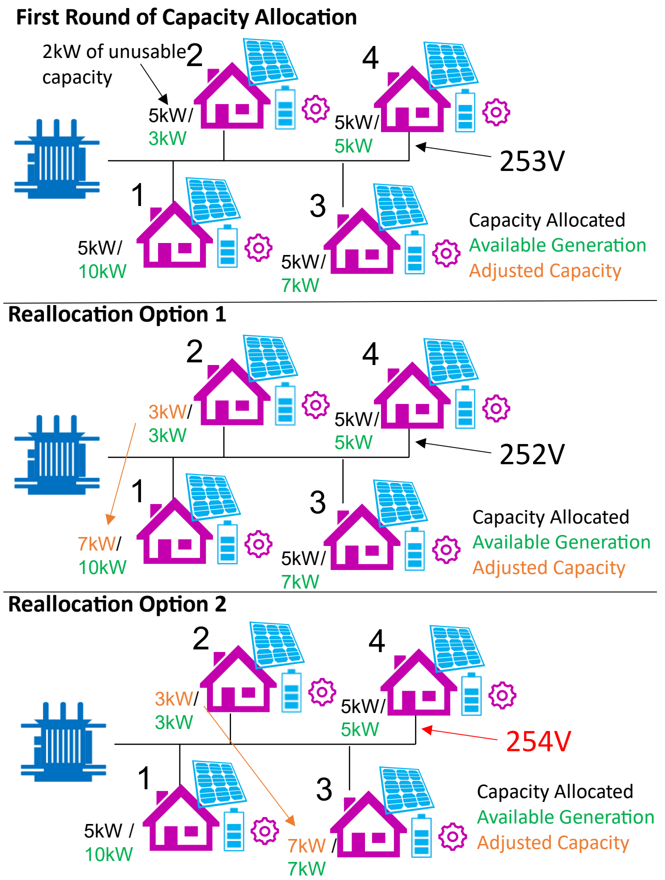


2.3 Grouped DOE

The Grouped DOE is a concept aiming to leverage any ability to calculate DOEs in an aggregate fashion rather than for individual NMIs. The aim of this is to allow DOE capacity to be exchanged between local resources. For example, if one resource is allocated more capacity than it can utilise and there is another resource close by that could use more capacity, then that additional capacity could be re-allocated. Due to the highly locational impact of power injection of network voltages it is very difficult to determine the allowable transfer of DOE capacity that could occur between two resources at different locations in a voltage constrained network (even if they are relatively close) without completely re-calculating all of the DOEs in the network. However, if an element is thermally constrained it is much less sensitive to where the power is being injected/absorbed, as long as it is downstream of the constraint.

In Figure 4 there is a simple illustrative example of this re-allocation of capacity.

Figure 4 Simple example to illustrate the potential issues with of trying to reallocate capacity under a voltage constraint



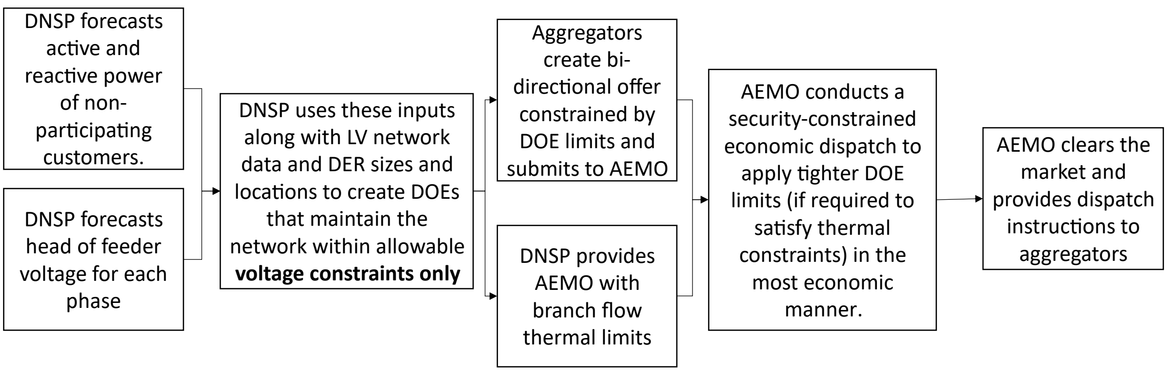
In the top network, the first round of DOEs has been calculated, and all customers have been allocated 5kW of capacity. However, customer 2 will only have 3kW of export capacity at this time, while customers 1 and 3 both have spare export capability that they could use if they were allocated extra capacity. In the middle network, it is seen that the 2kW of additional capacity is reallocated from customer 2 to customer 1. As customer 1 is closer to the head of the feeder, this reduces the voltage rise in the network. This is shown by the voltage at the end of the feeder dropping from 253V (maximum limit) to 252V. In this case, this reallocation of capacity wouldn't cause voltage issues in the network, and in fact additional capacity could be allocated if the thermal limits allowed. However, if reallocation option 2 was taken and the spare capacity was reallocated to customer 3, the end of feeder voltage now exceeds the 253V limit. Therefore, this reallocation would not be viable.

Voltage rise in the network is also influenced by phase imbalances and therefore for each reallocation another power flow would need to be run to ensure the network was in an acceptable state. Additionally, if the *Maximise NEM Export* DOE objective function is being used for DOE calculation (as recommended in the previous report on DOE objective functions and fairness), then capacity will generally be allocated to customers at the head of the feeder first. This means that if a customer in the network has excess capacity, it is highly unlikely that any customer closer to the head of the feeder will have use for the spare capacity (as they will likely have already been assigned significant capacity). It will therefore be customers closer to the end of the feeder who have use for the additional capacity. This means that a simple heuristic rule of only allowing capacity to be reallocated upstream would not be suitable in this case.

If, instead of being voltage constrained, the network in Figure 4 was thermally constrained by a 20kW transformer limit, then it would not matter how the capacity was reallocated within the network, as the power flow in the transformer would still be the same (except for a small difference in losses). This means that to reallocate capacity in this network if it is subject to a thermal constraint only a simple linear constraint is required ($P_1 + P_2 + P_3 + P_4 \leq P^{TX}$) rather than a full three phase power flow. As well as being simpler, it means that the entity conducting the re-allocation does not require a full network model, just a set of branch flow constraints. For simplicity of explaining this analysis, it is assumed AEMO conduct the re-allocation via a SCED however it is important to note that this responsibility is not meant to prescriptive.

With all of this in mind, an indicative flowchart of how a Grouped DOE algorithm may operate is shown Figure 5. In this algorithm, the DNSP still calculates DOEs, but does so only considering the voltage constraints in the network. Then these DOEs are communicated to the aggregators, whilst simple branch flow limits are communicated to AEMO. The aggregator then submits their partially constrained bi-directional offers to AEMO. AEMO uses these bi-directional offers and the branch flow constraints provided by the DNSP to conduct security-constrained economic dispatch (SCED). The results of the SCED are then used to clear the market, and AEMO provides aggregators with their dispatch instructions.

Figure 5 Indicative flowchart for Grouped DOE algorithm



If the network is only voltage constrained then the SCED will not be beneficial, as all of the branch flow constraints will automatically be satisfied, because the maximum bids of the aggregators will be such that the voltage constraints are maintained. However, if the network is also thermally constrained, or only thermally constrained, then the Grouped DOEs have the opportunity to arrive at a more economical solution than Basic DOEs. A Grouped DOEs arrangement would require alignment between DER aggregations and the location of the binding thermal constraints. Depending on the topographic prominence of this alignment it may be more appropriate for DNSPs to operate a SCED.

3 Case Studies

This section of the report provides details of the case studies that are used in the techno-economic modelling of the Basic DOE and Approximation Algorithm, including realistic test networks, DER penetration levels, DER marketplace participation levels, use cases, and modelling assumptions.

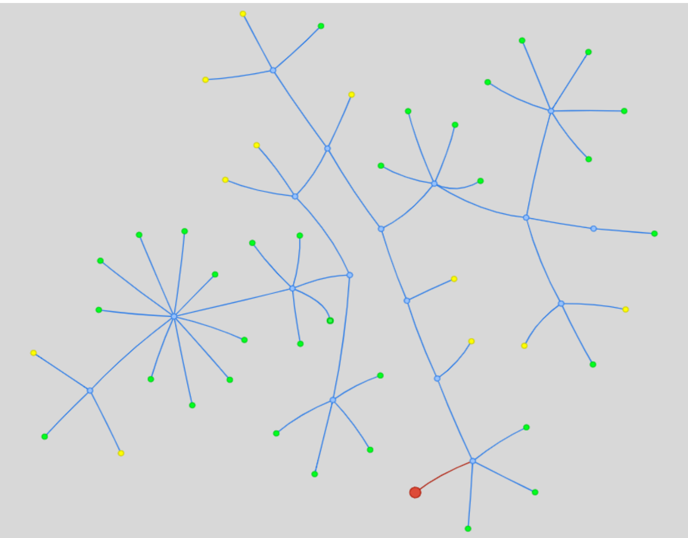
3.1 Networks

One of the major objectives of this work was to ascertain how these different DOE algorithms would function on real-world networks. To try and understand how the algorithms 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. However, the Approximation Algorithm in its current state is not suitable to be implemented in single-wire earth return (SWER) networks. Therefore, the *Regional* network (which is a SWER network) has been omitted from these studies. Therefore, the *Suburban* and *City* networks will be modelled in these case studies.

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 6, where the red node is the head of the feeder, the green nodes are residential customers, and the yellow 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 6 Diagram of the *City* network used in the techno-economic modelling

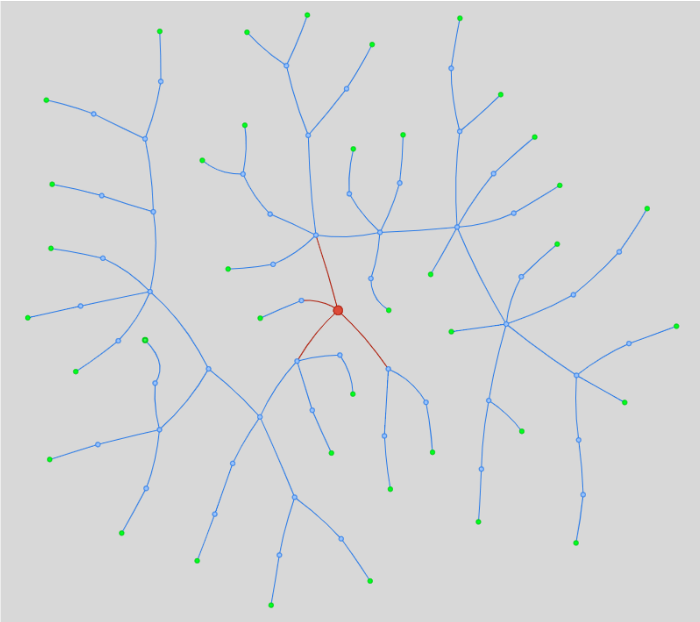


[4] https://arena.gov.au/assets/2022/08/national-low-voltage-feeder-taxonomy-study.pdf

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 7, where the red node is the head of the feeder, and the green nodes are residential customers.

Figure 7 Diagram of the *Suburban* 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 Basic DOEs and Approximation Algorithm 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.

In addition, DER participation rates may also impact the performance of the DOE algorithms. 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.

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%

3.3 DOEs being modelled

The bulk of this work will be the comparison between the Basic DOEs and the Approximation Algorithm. In addition, some commentary will be provided in Section 5 around the network states under which the Grouped DOEs would provide additional value to the DER marketplace, as well as when these network states may occur.

The Basic DOE that will be modelled in this work is the DOE with *Maximise NEM Export* objective function. As shown in previous work, this is the most technically effective DOE objective and the one recommended as default for DNSPs. Due to the Approximation Algorithm's reliance on historical data to generate its DOEs, it is not suitable to be used directly in the techno-economic modelling to analyse its efficacy over future DER penetration and participation scenarios, as this would require a significant amount of "historical" data to be generated for each penetration and participation scenario. Instead, through consultation with AusNet Services, a suitable proxy for the Approximation Algorithm was developed and is outlined in the following section.

3.3.1 Proxy to the Approximation Algorithm

The main features of the Approximation Algorithm that are aimed to be replicated in the proposed proxy are:

1. The 99th percentile hosting capacity of each phase of the LV transformer to determine the total capacity available for allocation.
2. The 99th percentile customer voltage profile being used to determine the available voltage headroom for each customer.
3. The method of allocating capacity to customers is based on their individual voltage headroom. This is likely to lead to customers closer to the head of the feeder being allocated more capacity.

The hosting capacity of each phase on the LV transformer is primarily governed by the voltage on the secondary side of the LV transformer. In fact, if there is no voltage constraint, or other thermal constraint downstream, the hosting capacity of the LV transformer would be exactly the rated capacity of the transformer. Therefore, in this proxy the 99th percentile hosting capacity is equated to the 99th percentile voltage profile for each phase.

The customer voltage profile would be largely influenced by the head of feeder (HoF) voltage, and the power demand or injection of the customer. As the HoF voltage has already been set to replicate feature 1 of the Approximation Algorithm, the 99^{th} percentile customer voltage profile in this proxy is equated to the 1^{st} percentile customer demand profile. That is, the customer's voltage profile will be close to its highest level when the customer's demand profile is close to its lowest (here we are considering net demand, so a high power injection from a customer is viewed as a low demand).

As the method of dividing the total capacity between customers should be such that customers near the head of the feeder receive greater capacity than those at the end of the feeder, the DOE objective function of *Maximise NEM Export* is chosen. This objective function prioritises customers near the head of the feeder and so should act similarly to the Approximation Algorithm.

In summary, the proxy for the Approximation Algorithm for exports is a *Maximise NEM Export* DOE that takes as input the 99^{th} percentile head of feeder voltage profile, and 1^{st} percentile customer demand profile. Conversely, when using the Approximation Algorithm for inputs, the proxy is a *Maximise NEM Import* DOE that takes as input the 1^{st} percentile head of feeder voltage profile and the 99^{th} percentile customer demand profile.

3.4 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 the following approach was proposed to estimate the static limits of each representative network for each penetration.

Firstly, it was assumed that 100% of DER in the network were participating in the DER marketplace. Next the DOE calculation was conducted for the peak generation use case with the *Absolute Equal Individual Allocation* objective. This provides the maximum export limit during the peak generation period that can be applied equally to each customer with DER whilst maintaining the network within allowable limits. *Absolute Equal Individual Allocation* does not take into account the size of the installed DER, only the number and location. This then means that if this export limit were applied to all installed DER at this set level, the network thermal and voltage limits would not be breached due to DER exports. This is assumed to be the static limit that the DNSP would enforce on customers not participating in the DER marketplace for all subsequent modelling of that network & penetration combination. The results of this approach for the *City* and *Suburban* networks for the penetration levels studied in this report are shown 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
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

3.5 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. The same extreme use cases will also be run to compare how the Approximation Algorithm and the Basic DOE perform under high demand and generation scenarios. However, as the Approximation Algorithm makes some conservative assumptions for its operation, it is also of interest to compare the capacity allocated by the two approaches over different network load levels. This will help in understanding how much earlier the Approximation Algorithm starts constraining the DER and how this "lost capacity" (the difference in capacity allocated by the Basic DOE and the Approximation Algorithm) changes with different network conditions. Therefore, in addition to the extreme demand and generation use cases, 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 two approaches across a day.

Four weeks' worth of customer demand data (including generation data for customers with PV) and head of feeder voltage data for one the Project EDGE trial sites was used as historical data to generate the 99th percentile and 1st percentile network demand and head of feeder voltage profiles to be used by the Approximation Algorithm. One of the daily network demand and head of feeder voltage profiles was then taken as the forecast values that would be used the Basic DOE. The network demand is divided amongst customers randomly. For customers with PV, a generation profile is taken from the 1st percentile, 99th percentile, and forecast demand data and scaled according to the size of the customers' systems. To be able to assess how the Approximation Algorithm and Basic DOE perform with differing head of feeder voltage levels, voltage offsets were applied to the forecast voltage, 99th percentile voltage and 1st percentile voltage so that low and high HoF voltage profiles could be assessed. As an example, the 1st percentile, 99th percentile, and forecast voltage for the *Low HoF Voltage* use case can be seen in Figure 8.

Figure 8 The 99th percentile, 1st percentile, and forecasts the head of feeder (HoF) voltages for Phase A in the "Low HoF Voltage Use Case"

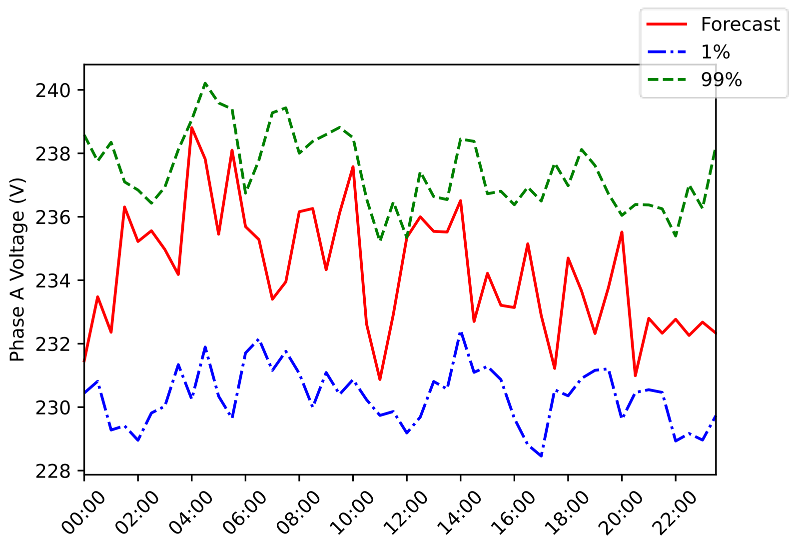
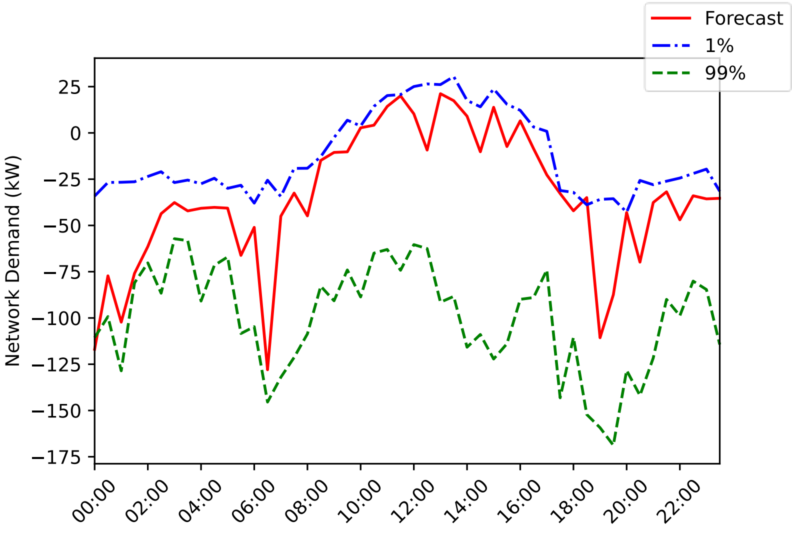


Figure 9 The 99th percentile, 1st percentile, and forecast network demand profiles for *City* network Scenario 1



For each combination of DER penetration level and participation level (for example *Scenario 1 – Low)*, a *High HoF Voltage* and *Low HoF Voltage* day are be modelled. Additionally, for each DER penetration level and participation level combination a high generation and high demand time step will also be modelled.

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 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 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 *Suburban*.
5. The location of new DER introduced into the networks for each penetration scenario is chosen at random.
6. The assumptions around the proxy for the Approximation Algorithm have been outlined in Section 3.3.1.
7. 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

This section of the report presents the results of the realistic techno-economic modelling. The focus of these results will be on the comparison between the capacity allocated by the Approximation Algorithm, and the capacity allocated by the Basic DOE utilising the *Maximise NEM Export/Import* objective function. The difference between the capacity allocated by these two approaches is termed the “list DER capacity”. It is noted there that the results for the Approximation Algorithm are generated using the proxy approach described in Section 3.3.1. However, when analysing results this is just referred to as the “Approximation Algorithm”.

4.1 Impact of DER Capacity in the network – Single Time Step

To try and gain an in-depth understanding of how the amount of capacity allocated is reduced when using the Approximation Algorithm, initially a single time step is examined. For this single time step, the DER capacity in the network is increased sequentially and the Basic DOE and Approximation Algorithm modelled. The DER capacity lost from using the Approximation Algorithm compared with the Basic DOE was then plotted.

4.1.1 City Network

4.1.1.1 Exports - Voltage Constrained

For the *City* network, we sequentially run the Basic DOE and Approximation Algorithm for increasing DER sizes. This is repeated for a single time step, which in this case is a high demand time step. This is why in Figure 10, the Approximation Algorithm doesn’t become constrained until 138kW of capacity has been allocated. The section with black markers up to 138kW is a section where neither the Basic DOE nor Approximation Algorithm is constrained. The next section with orange markers is where one phase of the Approximation Algorithm are voltage constrained. The third section with grey markets is when all three phases of the Approximation Algorithm are voltage constrained. In both the orange and grey sections, the Approximation Algorithm is unable to allocate the full DER capacity, whilst the Basic DOE can. This is why we see an increase in the lost DER capacity. The green section is the first time that one of the phases of the Basic DOE becomes voltage constrained. However, the Basic DOE is only constrained in one phase, whereas the Approximation Algorithm is constrained in all three, so the lost DER capacity keeps increasing in a similar fashion. The purple section is when all three phases of the Basic DOE are voltage constrained. Here we see that lost DER capacity starts increasing more slowly. Then as the size of the DER in the system increases, the Basic DOE phases start becoming thermally constrained. In the yellow section, at least one of the phases is still voltage constrained, and the lost DER capacity grows even more slowly. The blue section at the end is when all three phases of the Basic DOE are thermally constrained. During this section the lost DER capacity reduces, as the Basic DOE can no longer allocate additional DER capacity because the network is thermally constrained, but the Approximation Algorithm can still allocate more capacity as the DER fleet size increases because it is voltage constrained.

The same breakdown of sections can be seen in Figure 11 which shows the capacity allocation lost by using the Approximation Algorithm as a percentage of the total controllable DER fleet capacity.

Comparing Figure 10 and Figure 11, the shapes of the curves are very similar, however for the absolute value of lost capacity the curve peaks at the transition between when the Basic DOE is voltage constrained and thermally constrained (the yellow and blue sections). For the lost capacity expressed as a percentage of the DER fleet the peak occurs at the transition between the Basic DOE being voltage constrained in all three phases, and being voltage constrained in only one phase. This highlights that in this section the lost DER capacity is not growing as quickly as the controllable DER fleet capacity.

Figure 10 The capacity allocation (in kW) that is lost when using Approximation Algorithm rather than Basic DOE for a single time step and increasing DER size for the City network

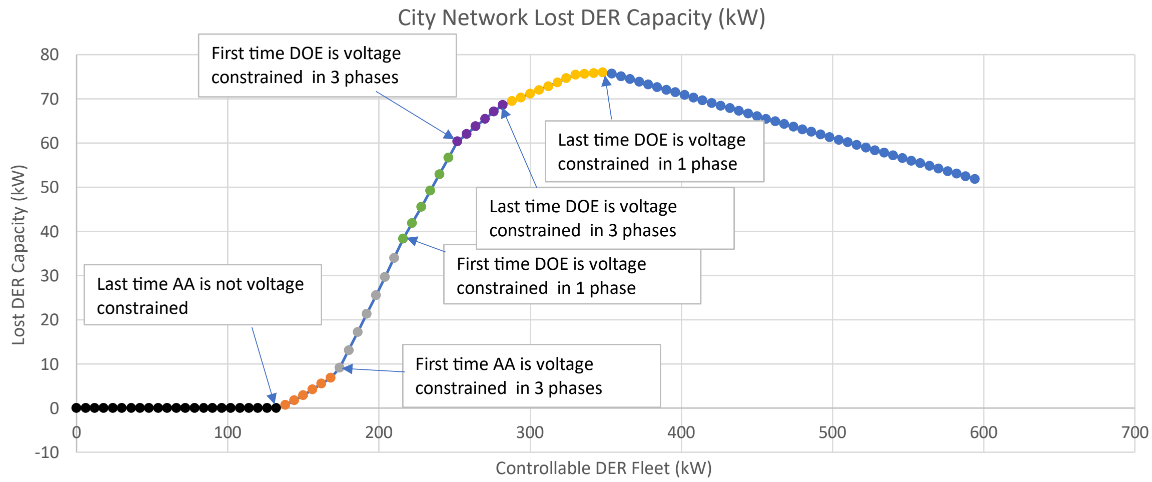
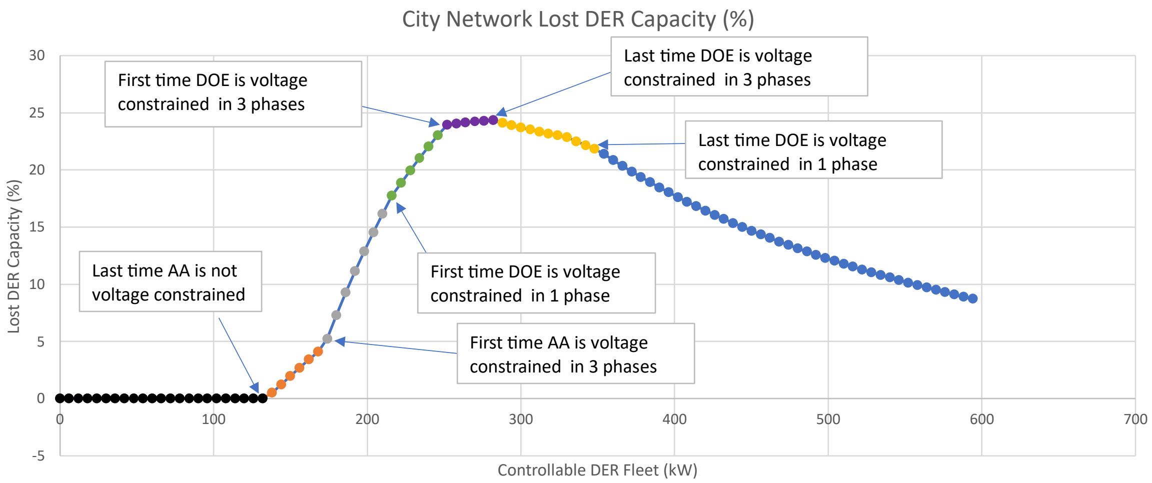


Figure 11 The capacity allocation (as a percentage of the controllable DER in the network) that is lost when using Approximation Algorithm rather than Basic DOE for a single time step and increasing DER size for the City network

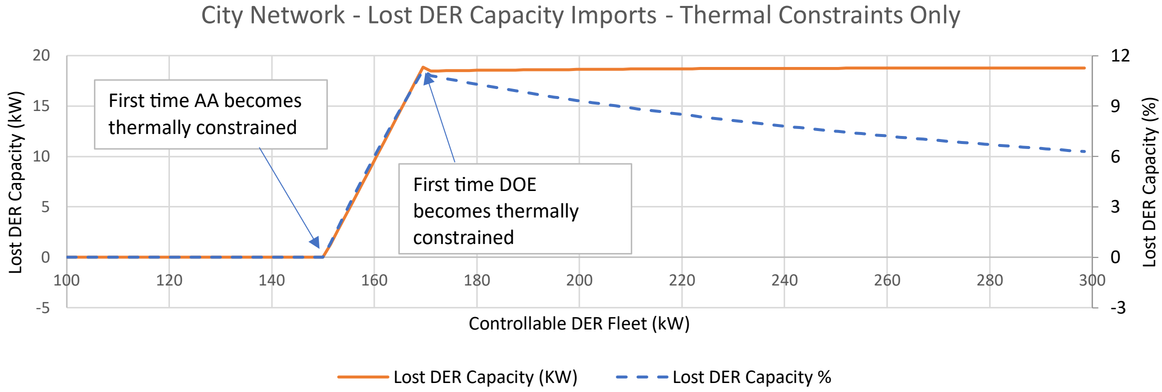


4.1.1.2 Imports – Thermally Constrained

When a network is thermally constrained only the lost DER capacity curve is much simpler as shown in Figure 12. The Approximation Algorithm and Basic DOE allocate the same capacity until the Approximation Algorithm becomes thermally constrained. The Approximation Algorithm will become thermally constrained first due to its conservative estimate of network demand. During the period that the Approximation Algorithm is thermally constrained and the Basic DOE is not (this will depend on the specific time period and the magnitude of the difference between the Approximation

Algorithm estimate and the Basic DOE forecast) the lost DER capacity will increase linearly. Once the DOE becomes thermally constrained the lost DER capacity in kW will essentially remain constant, however when measured as a percentage of the controllable DER fleet it will start reducing slowly as the constant lost DER capacity in kW becomes a smaller and smaller portion of the overall DER fleet capacity.

Figure 12 The capacity allocation in kW (left axis) and as a percentage of the controllable DER in the network (right axis) that is lost when using Approximation Algorithm rather than Basic DOE for a single time step and increasing DER size for the City network in a thermally constrained network



4.1.2 Suburban Network – Voltage Constrained

For the *Suburban* network, we also use a high demand use case. In general, we would expect that the Approximation Algorithm would perform similarly in the *Suburban* network when compared with the Basic DOE, but this is not the case. The curve in Figure 13 starts in a similar way to the *City* network curve in Figure 10. The Basic DOE and Approximation Algorithm allocate the same capacity because the network is unconstrained in both cases (black markers). Then the Approximation Algorithm becomes voltage constrained, and the lost DER capacity increases.

What we see in Figure 13 is that when the Basic DOE becomes voltage constrained in all three phases (purple) it remains voltage constrained for a significant period of time. This is because the phase imbalance in the *Suburban* network means that the voltage constraints become binding earlier than in a balanced network and effect the trajectory of the curve. However, the peak in lost DER capacity in an absolute sense still occurs around the transition from the Basic DOE being voltage constrained to being thermally constrained.

The shape of the lost DER capacity as a percentage of the controllable DER fleet for the *Suburban* network in Figure 14 is also different from the *City* curve. The *Suburban* curve peaks at the point where the Basic DOE becomes voltage constrained in all three phases. In the *City* network this purple section of the curve was short and close to linear, whereas in the *Suburban* network it spans over 400kW of installed DER capacity and changes gradient several times, including having a second lower peak at the transition between the Basic DOE being voltage constrained in all three phases, and in only one phase.

Figure 13 The capacity allocation (in kW) that is lost when using Approximation Algorithm rather than Basic DOE for a single time step and increasing DER size for the Suburban network

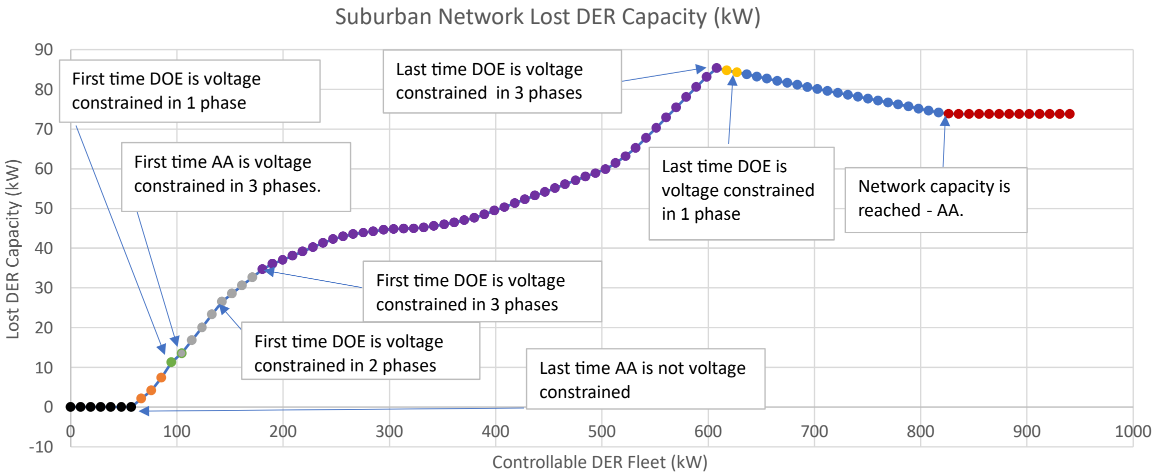
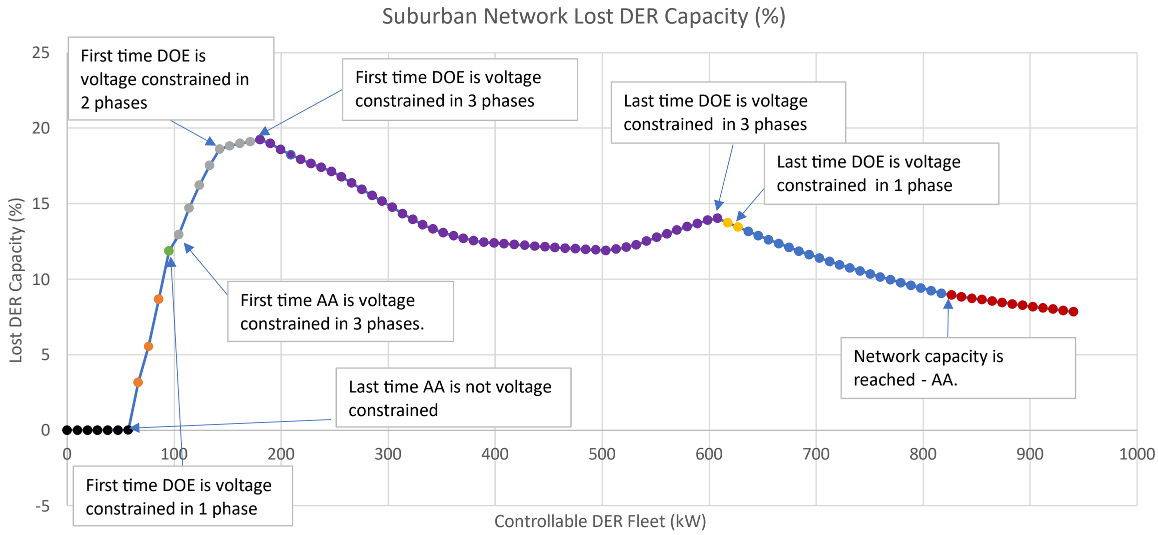


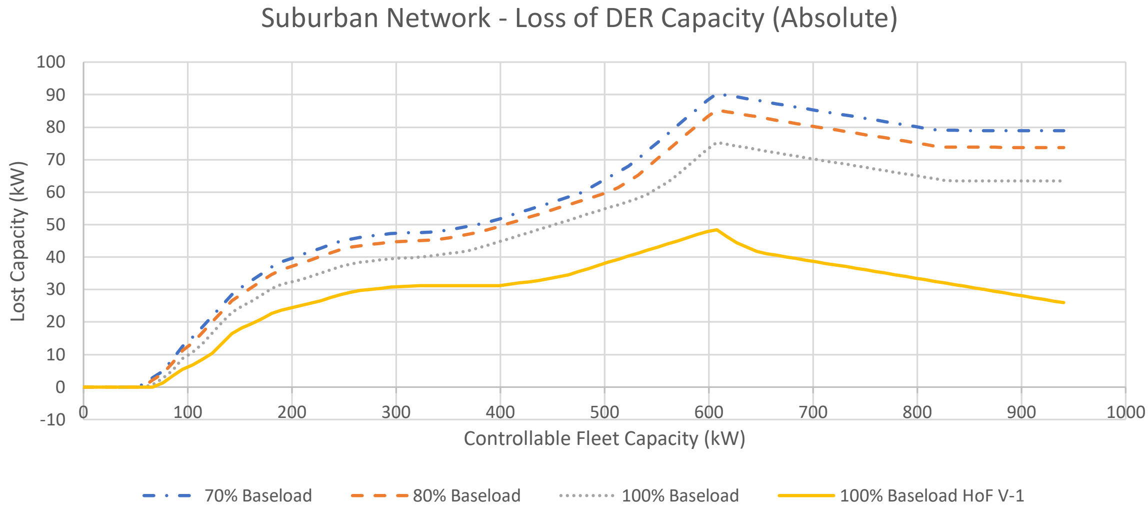
Figure 14 The capacity allocation (as a percentage of the controllable DER in the network) that is lost when using Approximation Algorithm rather than Basic DOE for a single time step and increasing DER size for the Suburban network



The capacity allocation that is lost by the Approximation Algorithm compared to the Basic DOE will be influenced by the distribution of the historical data used to determine the 99th percentile HoF voltage and network demand. To illustrate this 26 shows the lost capacity curve for the *Suburban* network with different levels of conservatism in the Approximation Algorithm. It shows the 1st percentile demand profile being 70% of the forecast demand profile, 80%, and 100%. Additionally, it shows an instance where the Approximation Algorithm and Basic DOE assume the same network demand, but the difference in HoF voltage is reduced by 1V. We see that changing how conservative the Approximation Algorithm assumption of network demand is has little effect on the overall shape of the lost capacity curve, but the more conservative, the higher the lost capacity. It also has little effect on when the Approximation Algorithm begins constraining the allocated capacity. This is because the point at which the voltage constraints becoming binding will be controlled mainly by the HoF voltage. By contrast, we see that changing the HoF voltage by 1V has a significant impact. The curve is generally the same shape, although with a much lower peak. This shows that the conservative nature of the hosting capacity of the transformer (which is modelled by the proxy approach as the

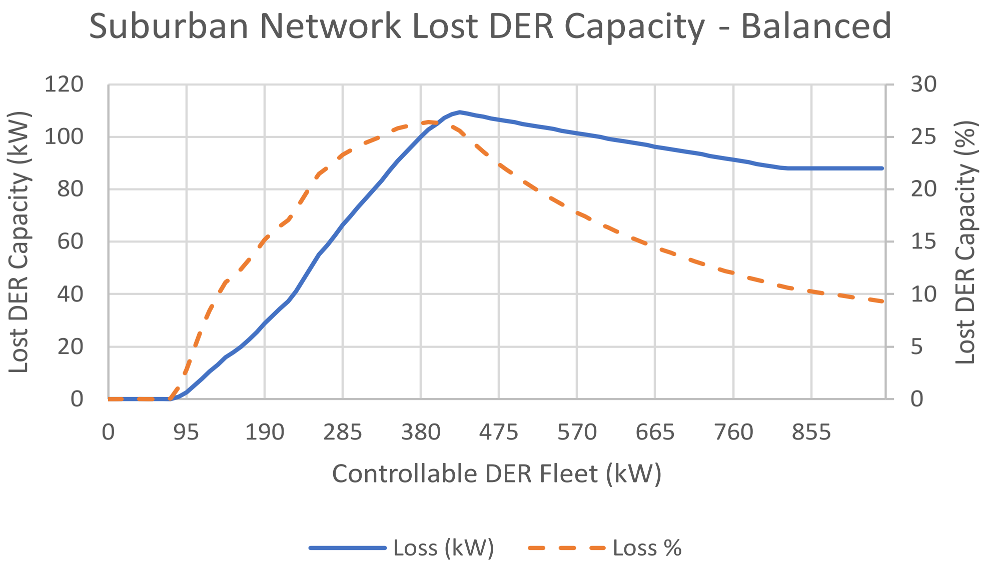
HoF voltage) is likely to have a larger impact of Approximation Algorithm technical efficacy compared to the conservative network demand assumption.

Figure 15 The capacity allocation (in kW) that is lost when using Approximation Algorithm rather than Basic DOE for a single time step and increasing DER size for the Suburban network when different network demand and HoF voltage uncertainties



The phase imbalance in the *Suburban* network is the cause for the more complex behaviour seen in Error! Reference source not found. and Error! Reference source not found. when the network is voltage constrained. To show this a use case was run where the DER were redistributed across phases (but remain at the same locations) so that the phase distribution was balanced. The Basic DOE and Approximation Algorithm were re-run, and the resultant lost DER capacity is shown in Error! Reference source not found.. Now both the absolute lost DER capacity and the percentage lost DER capacity curves align more with the shape of the curves seen for the *City* network. This shows that the phase imbalance was the main driver of the changed behaviour in the *Suburban* network and that, in general, we can expect this standard shape for lost DER capacity curves for well-balanced networks.

Figure 16 The capacity allocation both in kW and as a percentage of the controllable DER in the network) that is lost when using Approximation Algorithm rather than Basic DOE for a single time step and increasing DER size for the Suburban network with phase balanced DER location



4.1.3 Summary

This section has shown how using the Approximation Algorithm rather than the Basic DOE may cause a loss in the DER capacity that is allocated, depending on the network state and the amount of DER in the network. In general, this lost DER capacity peaks around the time that the Basic DOE voltage constraints start becoming thermal constraints. Phase imbalance can have a large influence on the lost DER capacity from using an Approximation Algorithm, but in balanced networks, the shape of the lost DER capacity curve is similar across networks. However, this section identified the lost DER capacity for a single time step only. It is of interest how these two approaches compare in different network conditions over the course of a day. The next two sections model a full day of operation with differing HoF voltages and compare the total DER capacity lost throughout the day.

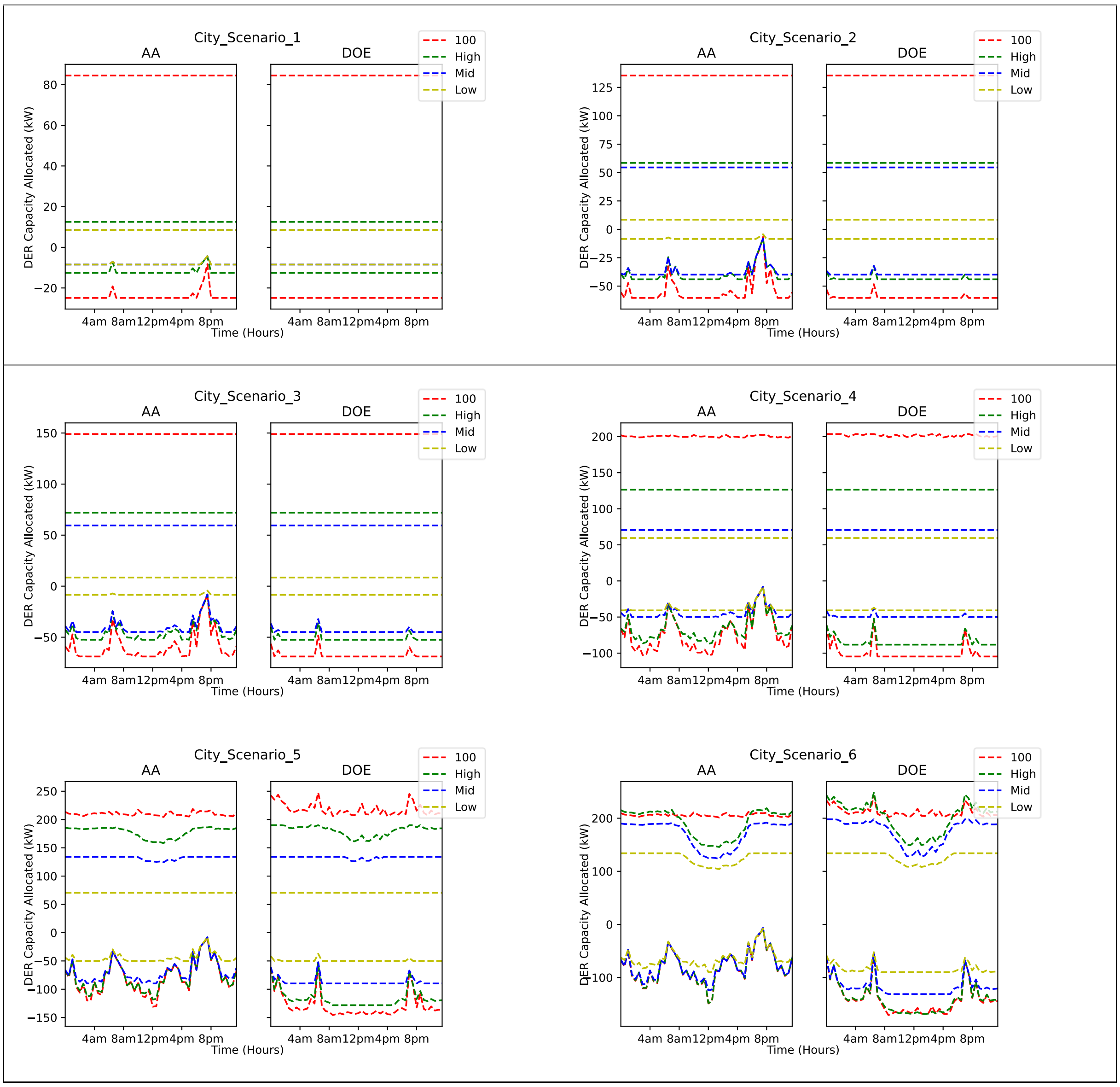
4.2 *Low HoF Voltage Use Case*

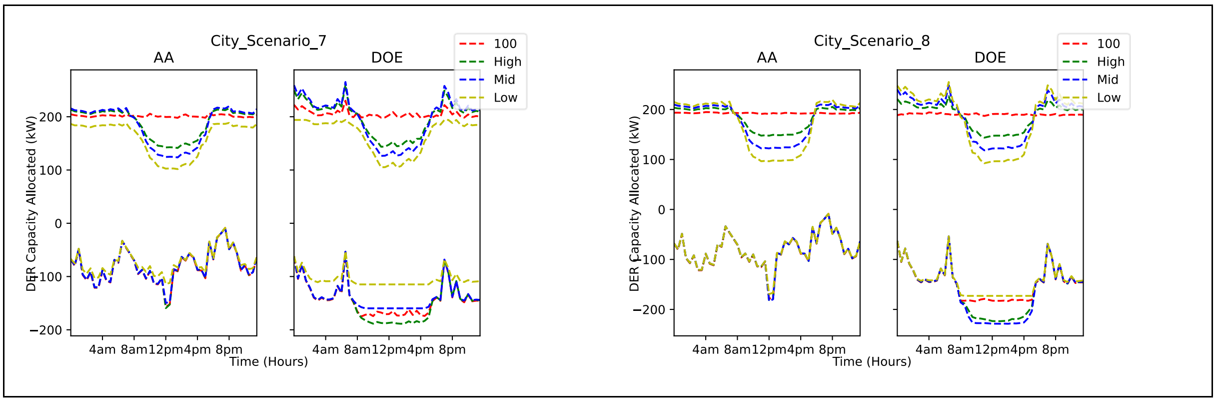
For this use case the HoF voltage is fairly low with an average forecast value of 234V. This leads to most of the network constraints coming from thermal constraints rather than voltage constraints.

4.2.1 City Network

The total DER capacity that is assigned in the network for each DER penetration level and participation level in the *City* network for both the Approximation Algorithm and the Basic DOE is shown in Error! Reference source not found.. Note that these graphs include both the total DER capacity for import and the export. In *Scenario 1* the *City* network is largely unconstrained, with only a few times steps constrained for imports in the Approximation Algorithm case aligning with the morning and evening demand peaks, and no constraints on exports. This is to the more conservative assumption on network demand used in the Approximation Algorithm. The Basic DOE imports begin being constrained from *Scenario 2*. In both the Approximation Algorithm and Basic DOE cases, these imports are being constrained by the thermal capacity of the network. Once *Scenario 4* is reached, it is seen in Error! Reference source not found. that Approximation Algorithm imports are constrained at every time step, as are the exports. Through the scenarios, the total export capacity allocated by the Approximation Algorithm and the Basic DOE are very similar. This is because they are both thermally constrained, and therefore the capacity that they can allocate is governed by the difference in the assumed demand profiles between the Approximation Algorithm and Basic DOE. As can be seen in Error! Reference source not found., during the middle of the day the forecast is close to the 1% demand curve, so there is little difference between the export capacity allocated. There is a much bigger difference between the forecast and the 99% demand profile, which is why can see a much large difference in import capacity allocation occurring, especially at higher penetration levels.

Figure 17 Total DER capacity allocated in the *City* network for each participation level in each penetration scenario for both Approximation Algorithm (AA) and Basic DOE (DOE) in the *Low HoF Voltage* use case



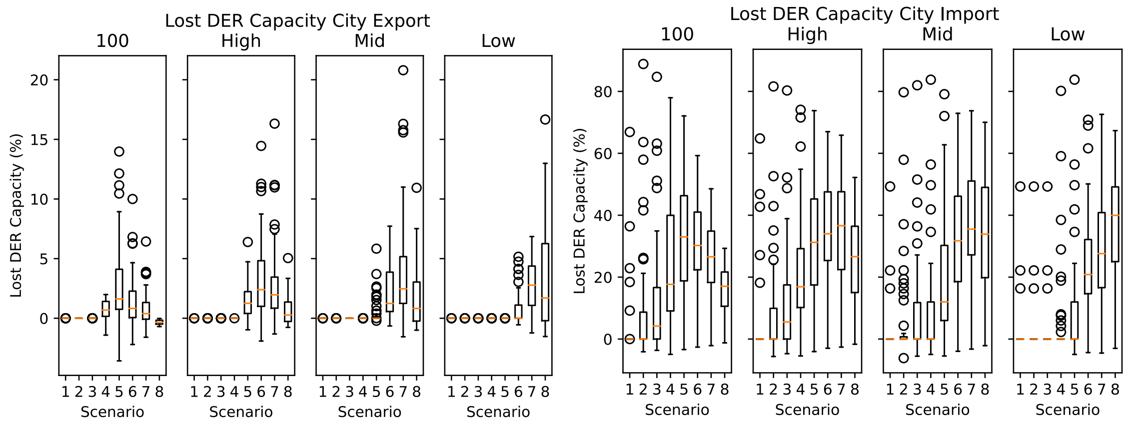


Error! Reference source not found. shows box plots of the amount of the total DER capacity that is lost (as a percentage of the controllable DER fleet rated capacity) when allocated by the Approximation Algorithm compared to the Basic DOE for each penetration and participation level. Each box plot is created from the results of the 48 time steps modelled throughout the day. Therefore, the average lost DER capacity is the average lost DER capacity across each time step throughout the whole day. For both the Approximation Algorithm and the Basic DOE we see that the lost capacity starts very low, increases to a peak, and then starts decreasing again. The DER penetration scenario at which this peak is located varies across different DER participation levels.

The difference between the two approaches starts at zero when the network is unconstrained. Then, the Approximation Algorithm will start constraining DER capacity allocation first in various time steps across the day, due to the conservative assumptions around network demand. This is where the lost capacity starts increasing. Once the Basic DOE starts having to reduce capacity allocation to deal with network thermal constraints in some time steps, then the gap between the Basic DOE and Approximation Algorithm starts decreasing (as shown in Figure 18, remembering that the box plots are measuring the lost DER capacity as a percentage of the controllable DER fleet capacity).

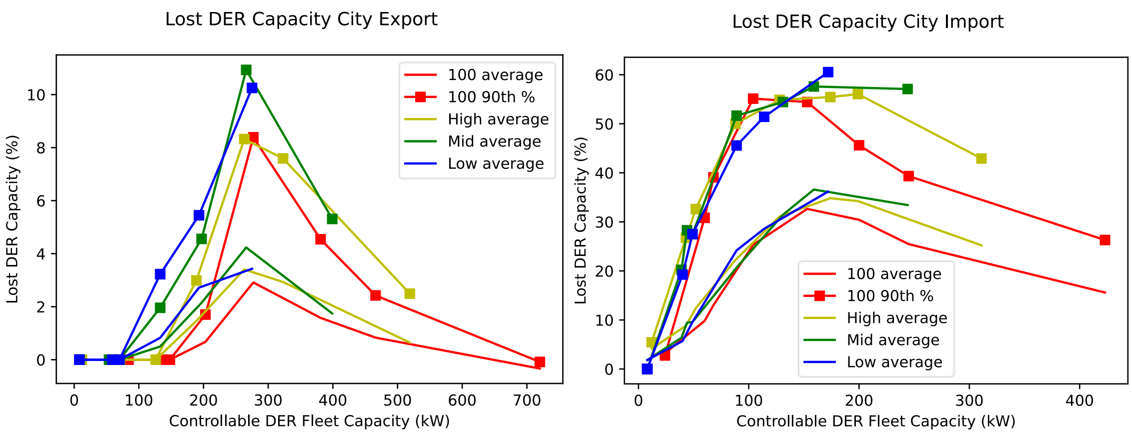
We can see that there is a much larger difference in DER capacity allocated for imports rather than exports. This is due to the stricter thermal constraint on imports (due to there also being base load that needs to be satisfied) and the fact that as shown in Figure 18 for most of the day the forecast network demand is much closer to the 1st percentile than the 99th percentile, meaning that there is a larger disparity between Approximation Algorithm and Basic DOE network demand when calculating the import DOE.

Figure 18 Box plots of the total DER capacity allocation lost as a percentage of the controllable DER fleet capacity be utilising the Approximation Algorithm rather than the Basic DOE for different scenarios for the *City* network



The impact of the different participation levels can more clearly be seen in Figure 19 which plots the average and 90th percentile lost DER capacity from using the Approximation Algorithm against the size of the controllable DER fleet. From this graph we can see that generally the higher participation level leads to a lower peak in lost DER capacity, and a swifter decline in lost capacity after that peak. Although, the participation level seems to have limited impact in the lower DER penetration levels. It is clearer to see in Figure 19 (right) that the shape of both the average and 90th percentile the Lost DER capacity for imports aligns with the general shape seen in section 4.1. For exports this shape is a lot sharper, due to a reduced number of non-zero data points, but also because the rated capacity of exports for the DER fleet for each scenario is greater than for imports and the peak lost capacity is smaller, so the lost DER capacity as a percentage of the controllable DER fleet capacity decays quicker in the export case than in the import case.

Figure 19 Plots of the lost DER capacity (as a percentage of the controllable DER fleet capacity) against the controllable DER fleet capacity for exports (left) and imports (right). The standards lines are the average DER lost capacity over the course of the use case day, and the line with square markers is the 90th percentile DER lost capacity over the course of the use case day for the City network.



Another insight from Figure 19 is that the lower the DER participation level, the higher the peak lost DER capacity. In fact, it does not seem that the *Low* participation rate has yet to reach its peak lost DER capacity of imports or exports.

4.2.2 Suburban Network

Due to the high strength of the *Suburban* network, and smaller total DER fleet due to fewer customers, and fewer commercial customers, there are limited differences between the Approximation Algorithm and the Basic DOE in the *Low HoF Voltage* case, especially for exports. This can be seen in Figure 20. Only during *Scenario 8* is there any constraints on DER exports for either algorithm and import constraints only become widespread in *Scenario 7* and *8*. These highlights how, if there is a strong network, or a network with few DER, the Approximation Algorithm would likely match the Basic DOE capacity allocation for the majority of the time due to the unconstrained nature of the network. The import capacity allocation is constrained by the thermal limit of the network. So, the progression on DOE capacity allocation by the Approximation Algorithm is similar to that seen in the *City* network in Figure 17, although at a slower rate. This is because the *Suburban* network has less customers, and no commercial customers, so the DER penetration rate must reach a higher level in order to cause thermal constraints in the network.

Figure 20 Total DER capacity allocated in the *Suburban* network for each participation level in each penetration scenario for both Approximation Algorithm (AA) and Basic DOE (DOE) in the *Low HoF Voltage* use case.

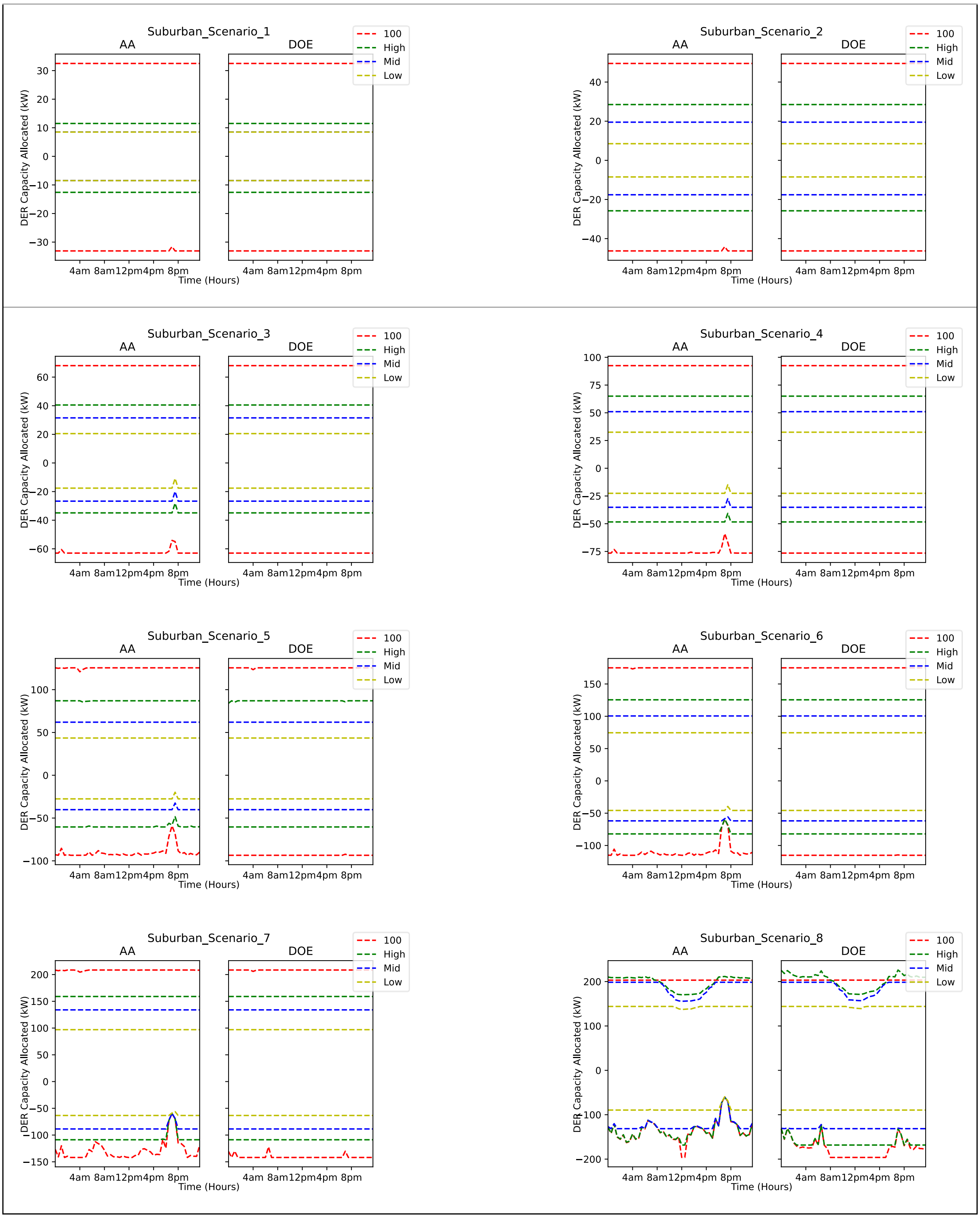
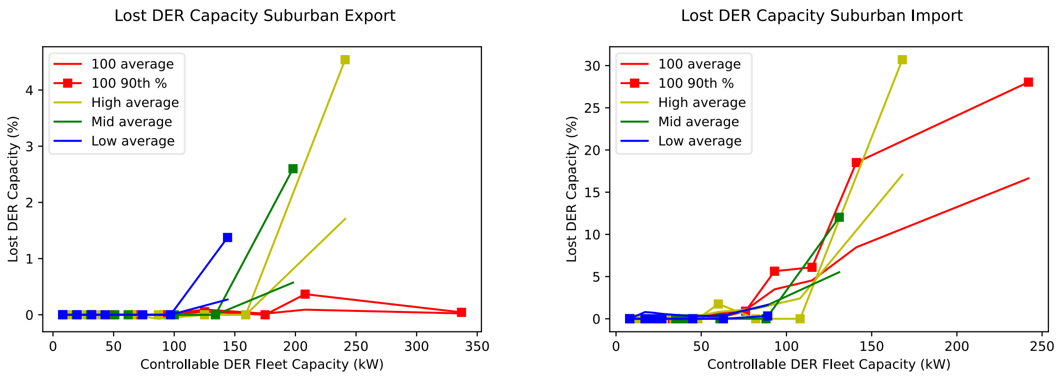


Figure 21 shows the lost DER capacity (as a percentage of the controllable DER fleet capacity) for exports (left) and imports (right) in the *Suburban* network. The exports in this case are only thermally constrained, and so it is seen that the lost DER capacity remains zero until the Approximation Algorithm hits its thermal capacity and then the lost DER capacity sharply increases. This is true expect for the 100% participation level, where the increase is very minor, and the lost DER capacity manages to reduce back down to zero. This is because in the 100% DER participation scenario with 100% DER participation, conservative network demand no longer has an impact of the DOEs (as all customers are controlled) and there is no voltage constraint in either case. Therefore, both approaches would provide the same solution. For the Approximation Algorithm imports, the *100%* and *High* participation levels have time steps that become voltage constrained during *Scenario 5*. However, after that the *High* level does not have a significant number of time steps constrained until *Scenario 8* (due to the phase imbalance in the network being partially addressed in *Scenario 6*). For the *100%* participation, lost DER capacity doesn't increase significantly between *Scenario 5* and *6* as the number of timesteps constrained remains similar. It isn't until *Scenario 8* that the Basic DOE has significant thermal constraints on its imports, which is why up to that point we see a continued rise in lost DER capacity.

Figure 21 Plots of the lost DER capacity (as a percentage of the controllable DER fleet capacity) against the controllable DER fleet capacity for exports (left) and imports (right). The standards lines are the average DER lost capacity over the course of the use case day, and the line with square markers is the 90th percentile DER lost capacity over the course of the use case day for the *Suburban* network.



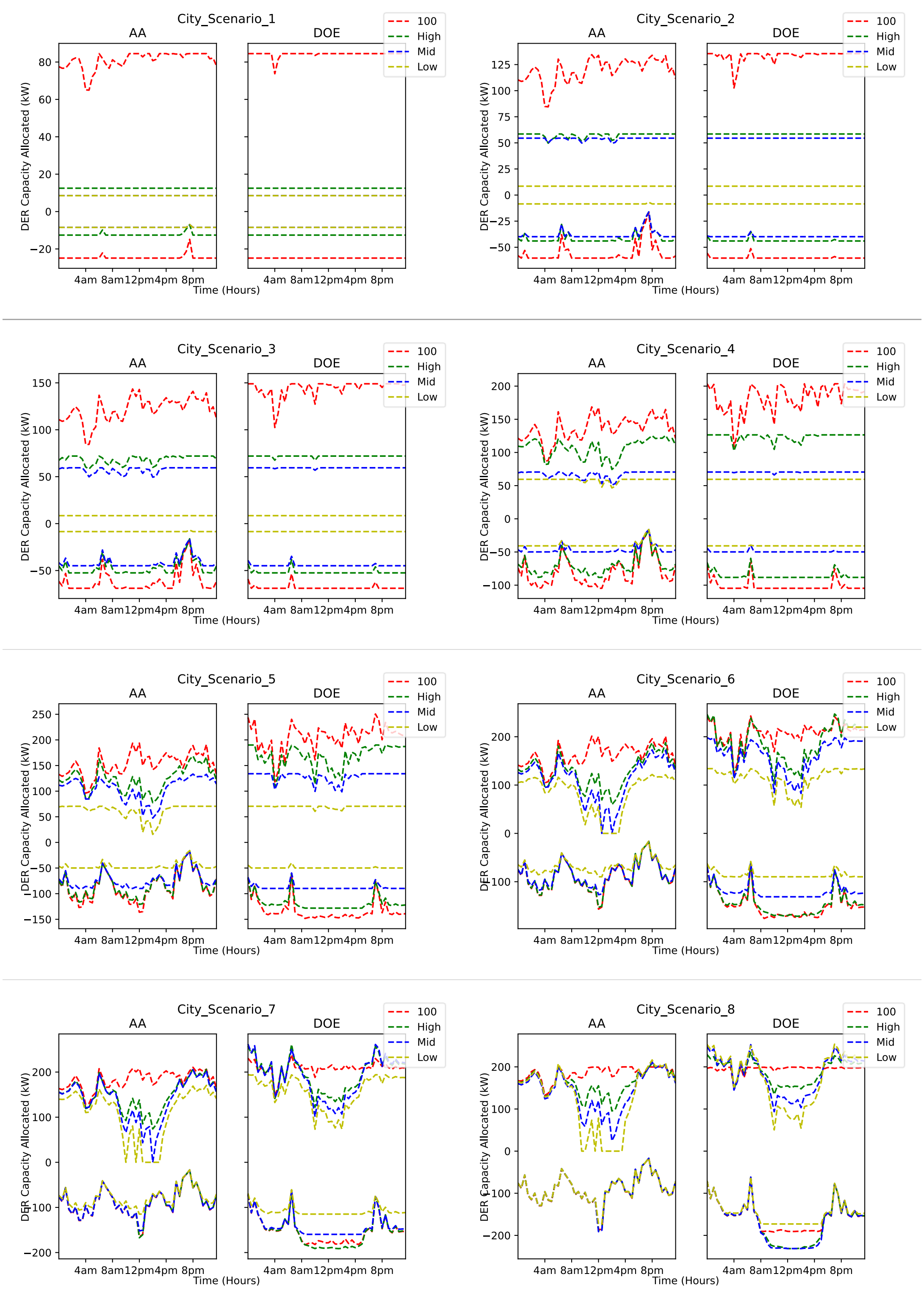
4.3 *High HoF Voltage Use Case*

For the *High HoF Voltage* use case, the 1st percentile, 99th percentile, and forecast voltages have all been boosted by 10V compared to *Low HoF Voltage*. This means that the average forecast value is now 244V. The trajectory of the voltages throughout the day remains the same, but they are all slightly closer to the upper voltage limit of the LV network.

4.3.1 City Network

By comparing Figure 22 to Figure 20 it is apparent that the increase in HoF voltage has not had a significant impact on the total import capacity that is allocated by the Approximation Algorithm or the Basic DOE. This is to be expected, as the import capacity allocation is thermally constrained rather than voltage constrained and increasing the HoF voltage would only help alleviate any voltage constraints that may occurs for import DOEs. However, there is a marked difference in the export DER capacity allocation. The higher HoF voltage means that, even from *Scenario 1*, both algorithms have some time steps that are voltage constrained for the *100%* participation scenario. In *Scenario 2* the *High* and *Mid* participation levels are also starting to be voltage constrained in the Approximation Algorithm. As the DER penetration increases, both the Approximation Algorithm and Basic DOE exports become more constrained. From *Scenario 6* onwards, for the Approximation Algorithm the *Low* participation level has some time steps during the middle of the day where no capacity can be allocated (this phenomenon will be explored further in Section 4.4). It appears that at the higher penetration levels, the difference between the *100%* participation capacity allocation of the Approximation Algorithm and Basic DOE exports decreases as explained in Section 4.2.2.

Figure 22 Total DER capacity allocated in the *City* network for each participation level in each penetration scenario for both Approximation Algorithm (AA) and Basic DOE (DOE) in the *High HoF Voltage* use case.



In Figure 23 the same peaking behaviour is seen to occur across all participation levels, with the peaks resulting in a high loss of DER capacity for lower participation levels. Looking at the box plots alone it seems that the higher participation levels peak earlier. But by examining Figure 24, which plots the average and 90th percentile losses in DER capacity against the total size of the controllable DER fleet the peaks occur around the same time for *100%, High,* and *Mid* participation levels, and slightly earlier for *Low* participation level, which also has a much higher 90th percentile peak. This peak occurs around 200kW, which is the rated capacity of the LV transformer in the network. This is when more time steps start having their exports thermally constrained rather than voltage constrained, which aligns with the analysis provided in Section 4.1. However, prior to this we see that a lower DER participation rate leads to a higher peak in lost DER capacity.

Figure 23 Box plots of the total DER capacity allocation lost be utilising the Approximation Algorithm rather than the Basic DOE for different scenarios for *High HoF Voltage* – export only, *City* network

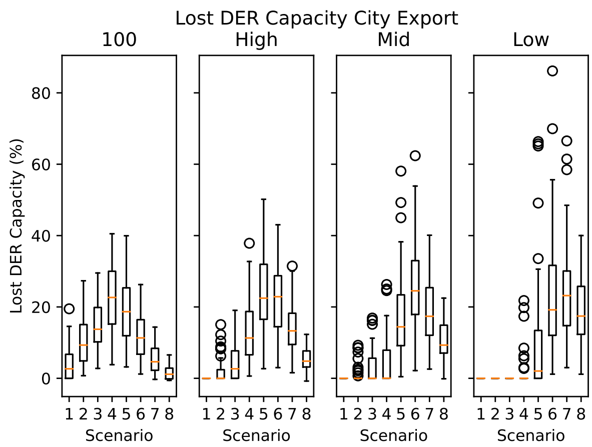
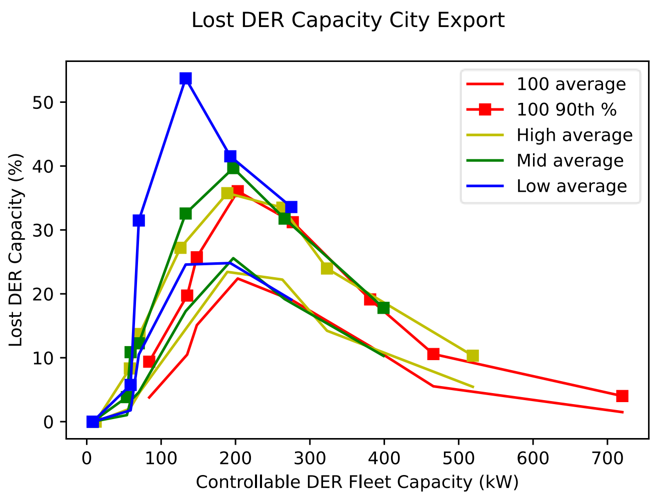


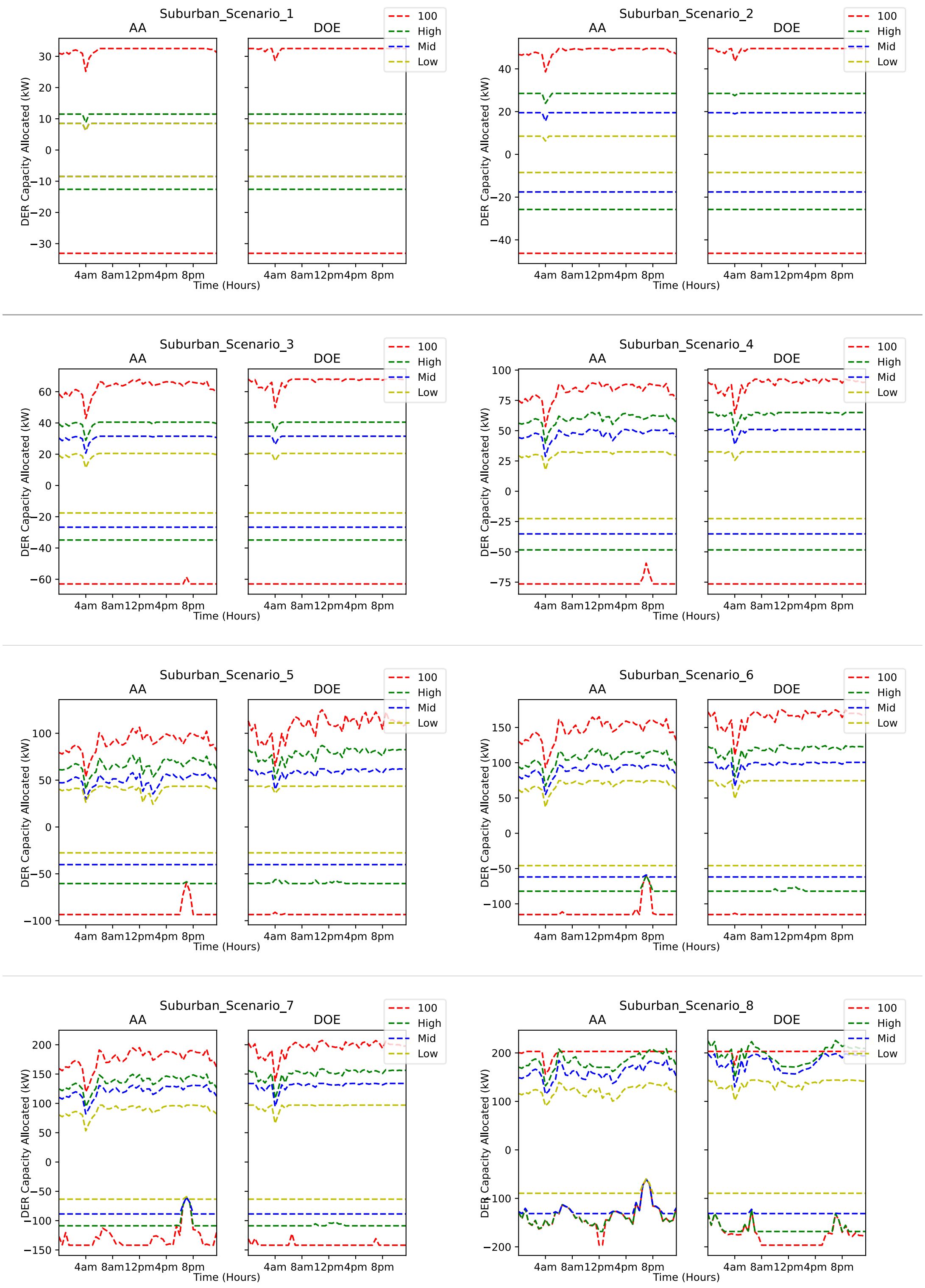
Figure 24 Plots of the Lost DER Capacity as a function of Controllable DER Fleet Capacity for exports. The standards lines are the average DER lost capacity over the course of the use case day, and the line with square markers is the 90th percentile DER lost capacity– *City* network



4.3.2 Suburban Network

By comparing Figure 25 to Figure 20 it is again apparent that the increase in HoF voltage has not had a significant impact on the total import capacity allocated by the Approximation Algorithm or the Basic DOE in the *Suburban* network.

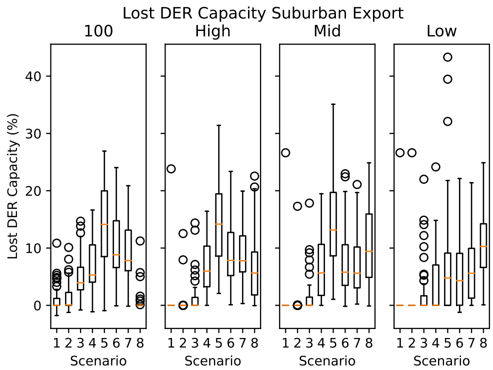
Figure 25 Total DER capacity allocated in the *Suburban* network for each participation level in each penetration scenario for both Approximation Algorithm (AA) and Basic DOE (DOE) in the *High HoF Voltage* use case



However, while previously there was very few occurrences of network constraints on the exports, with the higher voltage constraints occur from *Scenario 1*. The difference in the total DER capacity allocated for exports does not seem to differ as much in the *Suburban* network as it did in the *City Network*.

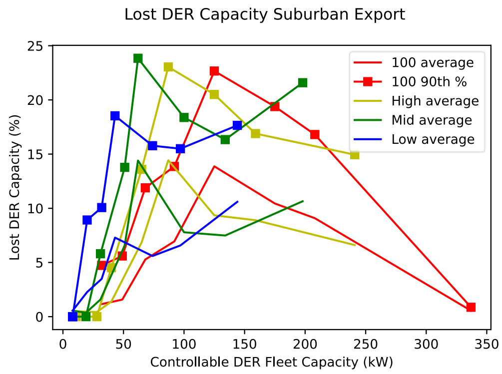
This can be seen to be true by comparing the scales of the box plots for the *City* network in Figure 23 and the box plots for the *Suburban* network in Figure 26. For the *City* network the highest average lost DER capacity is around 30%, whereas for the *Suburban* network this sits around 15%. While the higher DER participation levels exhibit the same peaking behaviour as seen in the other network and use case, *Mid* and *Low* DER participation show the behaviour less strongly. This is because the *Suburban* network has large phase imbalances in the scenarios 1-5. This means that in *Scenario* 6 when these phase imbalances are partially addressed (via the introduction of DER into the underrepresented network), the network voltage constraints are lessened. So *Mid* and *Low* DER participation reduce their lost DER capacity in *Scenarios 6 & 7*, but both increase again for *Scenario 8*. This would indicate that for the more balanced *Suburban* network, they are yet to reach their peak.

Figure 26 Box plots of the total DER capacity allocation lost be utilising the Approximation Algorithm rather than the Basic DOE for different scenarios for *High HoF Voltage* – export only, *Suburban Network*



We can see that this fundamental change in network conditions that comes with the reduction of phase imbalances means that Figure 27 does not exhibit the same neat behaviour we see in Figure 24 where all of the curves are relatively similar. This is because this change in network state occurs when the controllable fleet capacity is different for each participation scenario. I.e., the controllable fleet capacity for *Scenario 6 – 100% Participation* will be much greater than the controllable fleet capacity for *Scenario 6 – Low Participation.* Although we do see that in the early scenarios in general the higher DER participation level leads to a better performance of the Approximation Algorithm. Additionally, as we have shown in Section 4.1.2, the phase imbalance also effects the fundamental shape of the lost DER capacity curve. We see that all of the participation levels have a peak in lost DER capacity in *Scenario 5* where the phase imbalance in the network is at its highest. Whilst the higher participation levels consistently reduced their lost DER capacity from this point, the *Low* and *Mid* participation levels show an increase in lost DER capacity in the higher DER penetration levels. It is unclear if there would be a higher peak for these participation levels if higher DER capacity was added into the system. Based on the other results it seems likely that the *Low* participation scenario will peak at a value greater than the lost DER capacity of the other participation levels.

Figure 27 Plots of the Lost DER Capacity as a function of Controllable DER Fleet Capacity for exports. The standards lines are the average DER lost capacity over the course of the use case day, and the line with square markers is the 90th percentile DER lost capacity over the course of the use case day –*Suburban* network



4.3.3 Different Voltage and Demand Forecasts

So far in both the *Low HoF Voltage* and *High HoF Voltage* use cases, the demand forecast has been the same. The voltage forecast has also been the same relative to the 99th and 1st percentiles (i.e., when the offset was applied to the lower voltage profile to obtain a higher voltage profile, the forecast, 99th percentile and 1st percentile voltages were all offset by the same amount. In this section we shall briefly examine how the results of the *High HoF Voltage* use case changes if a new forecast for the HoF voltage and network demand is used.

Figure 28 and Figure 29 compare the box plots of lost DER capacity of the original forecast and the new forecast for *City* network and *Suburban* network respectively. What is seen is that while the amount of DER capacity that is lost by using the Approximation Algorithm differs in the time steps with the extreme values, the average values of lost DER capacity for timesteps throughout the day remains broadly similar. This indicated that while the behaviour of individual time steps will differ due to the changed forecast, the overall behaviour throughout the day is governed in general by the network and DER. Additionally, the trends across DER penetration levels and DER participation levels remain the same for both forecasts. The peak in the lost DER capacity occurs at the same DER penetration level in for both forecasts.

However, it is noted that the peaks in the lost DER capacity does change between the two representative networks. This is unsurprising, as the network constraints for the *City* and the *Suburban* start becoming binding at different time steps in different scenarios, due to the network configuration and impedance, DER size, location, and phase.

Figure 28 Box plots of the total DER capacity allocation lost by utilising the Approximation Algorithm rather than the Basic DOE for different scenarios for *High HoF Voltage* – export only, *City* network for the original forecast (left) and new forecast (right)

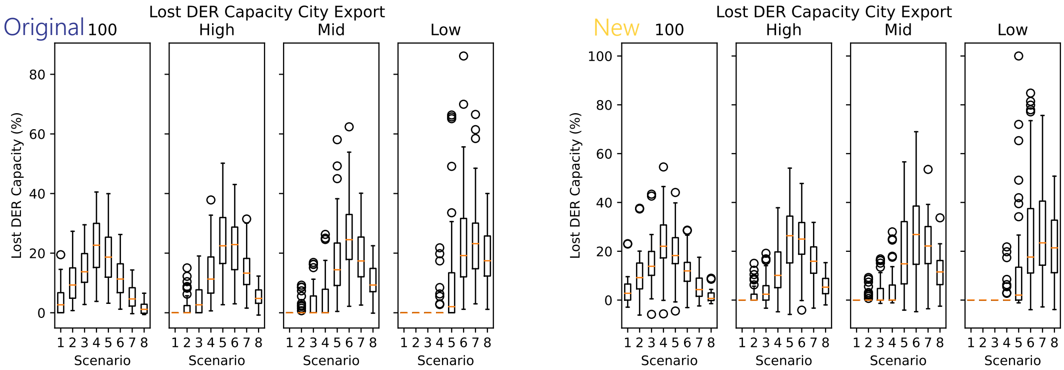
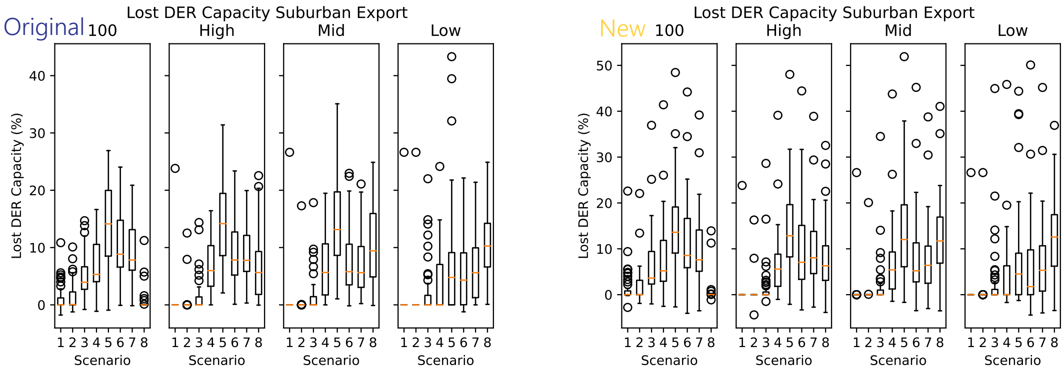


Figure 29 Box plots of the total DER capacity allocation lost be utilising the Approximation Algorithm rather than the Basic DOE for different scenarios for *High HoF Voltage* – export only, *Suburban* network for the original forecast (left) and new forecast (right).



4.4 *Extreme Generation/Demand Use Case*

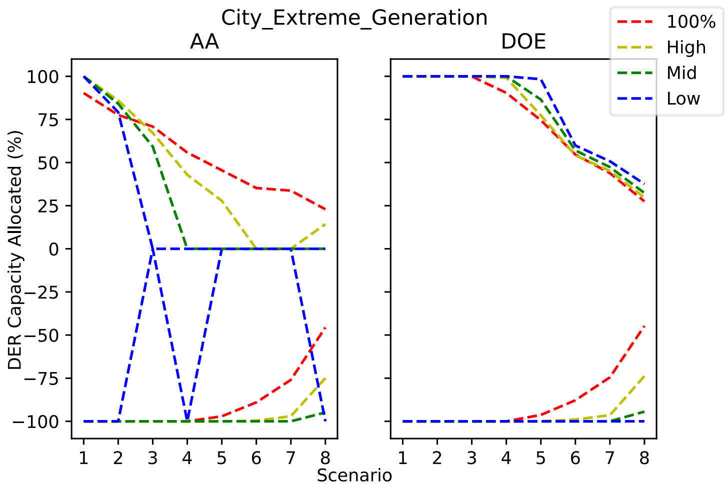
As well as understanding the difference between the Approximation Algorithm and Basic DOE in common network conditions, it is also of interest to see how the Approximation Algorithm would behave in extreme generation and demand use cases. For this analysis we use the extreme generation and demand use cases that were proposed for the report on fairness in DOE objectives. The extreme demand use case is based on an after diversity maximum demand of 4kW, and the maximise generation use case varies between scenarios dependent on the amount of PV present in the network.

As the network demand levels that we are considering in these use cases are extreme, it is assumed that the $99^{th}/1^{st}$ percentile demand levels align with the forecast maximum demand/generation profiles respectively. Therefore, the difference between the Approximation Algorithm and the Basic DOE approaches for these use cases lies in the conservative assumption of the HoF voltage value for the Approximation Algorithm.

4.4.1 City Network

Figure 30 shows the total DER capacity that is allocated in the *City* network for each scenario by both the Approximation Algorithm and the Basic DOE in the extreme network generation case. Looking at the Basic DOE, we see that for both import and export the DER capacity allocation starts at 100% with the low penetration scenarios. As the penetration levels increase, the higher participation scenarios start limiting capacity allocation first. For exports, the DER capacity allocation in percentage terms ends up fairly similar between the four participation levels. As the higher participation levels will have large DER fleets, this will equate to greater absolute DER capacity being allocated in the higher participation scenarios. For the Approximation Algorithm in Figure 30 this decline in capacity allocation is much more rapid for the lower participation levels. For exports we see that the *Low* participation scenario is infeasible (and as such allocates no capacity) from *Scenario 3* onwards. The *Mid* participation level is infeasible from *Scenario 4* onwards. This is due to the high HoF voltage, and high uncontrolled DER generation, meaning that the DNSP would need to curtail customers not actively participating in the DER marketplace. This highlights the conservative nature of the Approximation Algorithm, as the Basic DOE manages to fully allocated export capacity in some of these scenarios.

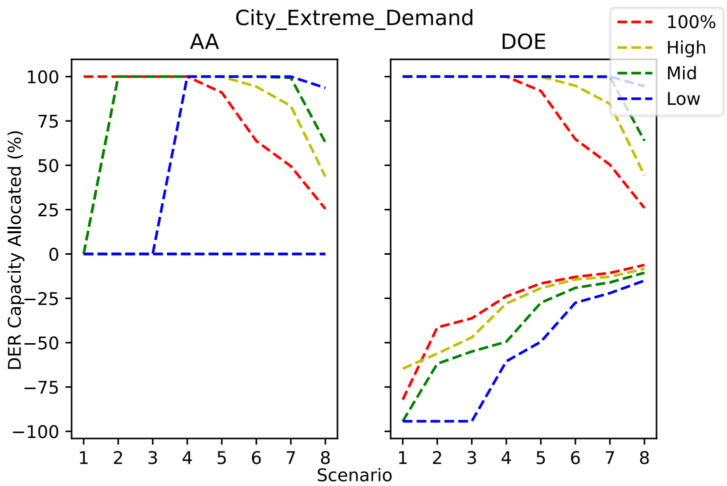
Figure 30 DER capacity allocated in the *City* network for each scenario using the Approximation Algorithm (AA) (left) and Basic DOE (DOE) (right). The graphs show both export and import capacity allocation for the Extreme Generation Use Case.



The *Low* participation level has an interesting behaviour for imports when using the Approximation Algorithm. It begins allocating full capacity, and then, as with exports, in *Scenario 3* it becomes infeasible. However, in *Scenario 4* it becomes feasible again and allocates full capacity. The *Low* participation Approximation Algorithm becomes infeasible in *Scenario 3* as there is not sufficient controllable flexible load to reduce the voltage in the network to a feasible level. However, in *Scenario 4*, additional controllable loads are introduced that allow the voltage upper bound to be respected. However, as more generation is added in the network this is no longer sufficient, which is why *Scenarios 5-7* are also infeasible. Then, similarly to *Scenario 4*, *Scenario 8* has sufficient controllable load to maintain the voltage within its upper bound.

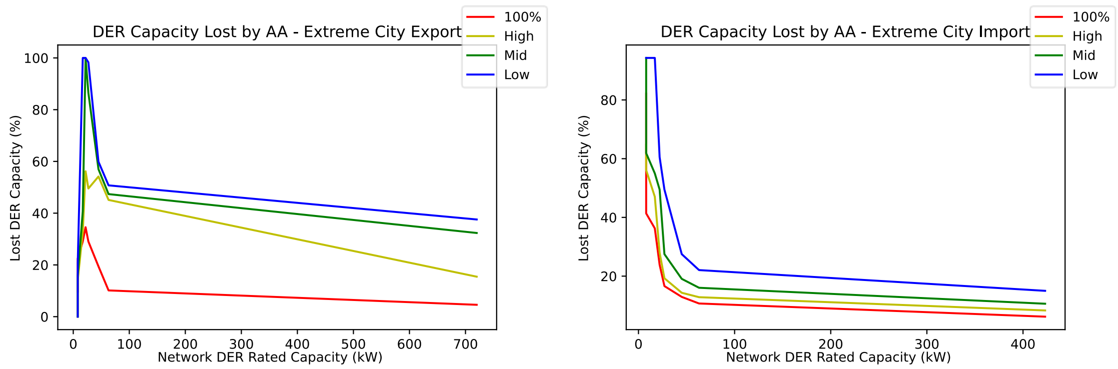
The extreme demand use case for the *City* network is shown in Figure 31 for the Approximation Algorithm (left) and Basic DOE (right). Immediately it can be seen that the Approximation Algorithm cannot generate import DER capacity allocation in any penetration or participation level. This is due to the conservative estimate on the HoF voltage. In the Basic DOE case import capacity is allocated through all scenarios and participation levels, with high percentages being allocated in the early scenarios. The percentage of total DER import capacity that can be allocated by the Basic DOE decreases as the penetration level of DER in the network increases due to the thermal limits of the network. For exports, in the lower penetration and participation scenarios, the Approximation Algorithm fails to allocate any export capacity. This is because there is not enough controllable DER to offset the voltage drop and maintain the voltage within the allowable lower bound. However, once the *Low* and *Mid* participation levels hit this threshold, they manage to allocate 100% of DER capacity. However, in the higher penetration scenarios, the exports become constrained by the thermal limit of the network. This also occurs with the Basic DOE, which is why the same export capacity is allocated in later scenarios.

Figure 31 DER capacity allocated in the *City* network for each scenario using the Approximation Algorithm (AA) (left) and Basic DOE (DOE) (right). The graphs show both export and import capacity allocation for the Extreme Demand Use Case.



The DER capacity not allocated (as a percentage of total available DER capacity) by the Approximation Algorithm that would be allocated by the Basic DOE is illustrated in Figure 32. The left shows the lost export capacity for the extreme generation case, and the right shows the lost import capacity for the extreme demand case. As the Approximation Algorithm is unable to allocate any import capacity in the extreme demand case, the graph on the right just shows the amount of capacity that is allocated by the Basic DOE. This can be thought of as the same lost DER capacity graph shape seen in Section 4.1, except it is beginning after the peak has occurred. The graph on the left which shows the lost DER exports for the extreme generation use case exhibits the peaking behaviour that has been seen previously.

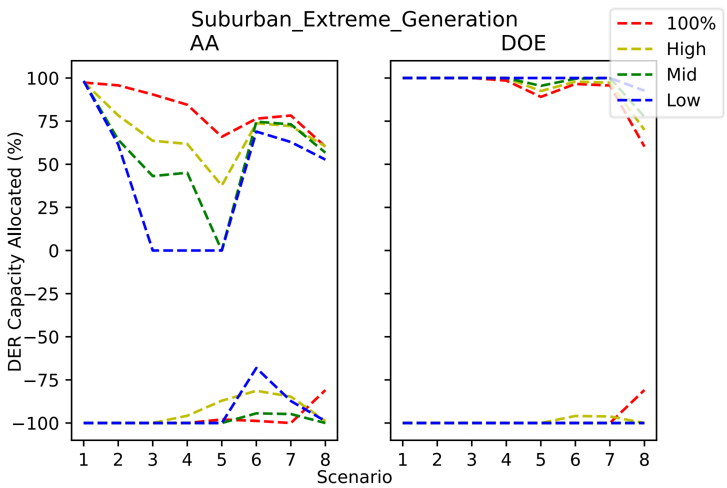
Figure 32 The lost DER capacity (as a percentage of the total controllable DER fleet size) plotted against the total DER capacity in the network for the export capacity in the extreme generation case (left) and import capacity in the extreme demand case (right) for the *City* network



4.4.2 Suburban Network

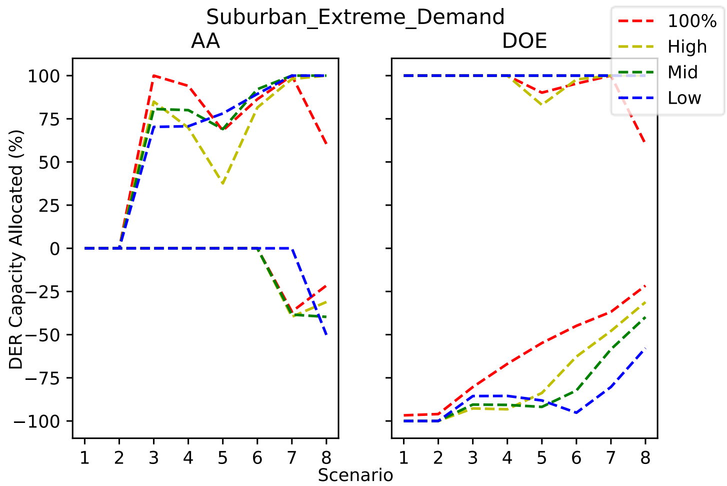
For the extreme generation use case in the *Suburban* network (Figure 33) the Basic DOE is very effective at allocating export capacity. Only at the higher DER participation levels does significant curtailment of DER capacity allocation occur, due to network voltage constraints. However, due to the conservative assumptions around the HoF voltage of the Approximation Algorithm, this capacity allocation is voltage constrained from *Scenario 1*. We see that the DER capacity allocation reduces most steeply for the lower participation levels, highlighting a significant improvement in the performance of the Approximation Algorithm assigning export capacity with higher participation levels like what is shown in Figure 30. In *Scenario 6*, the phase imbalance of the network is somewhat counteracted by the location of newly installed DER. This leads to a large improvement in export DER capacity allocation (as the phase imbalance caused a voltage boost). However, when allocating import capacity (especially for the *Low* participation scenario, these new DER that are uncontrolled are now generating power and cause a phase imbalance for imports. This leads to a reduction in the import capacity that can be allocated.

Figure 33 DER capacity allocated in the *Suburban* network for each scenario using the Approximation Algorithm (AA) (left) and Basic DOE (DOE) (right). The graphs show both export and import capacity allocation for the Extreme Generation Use Case.



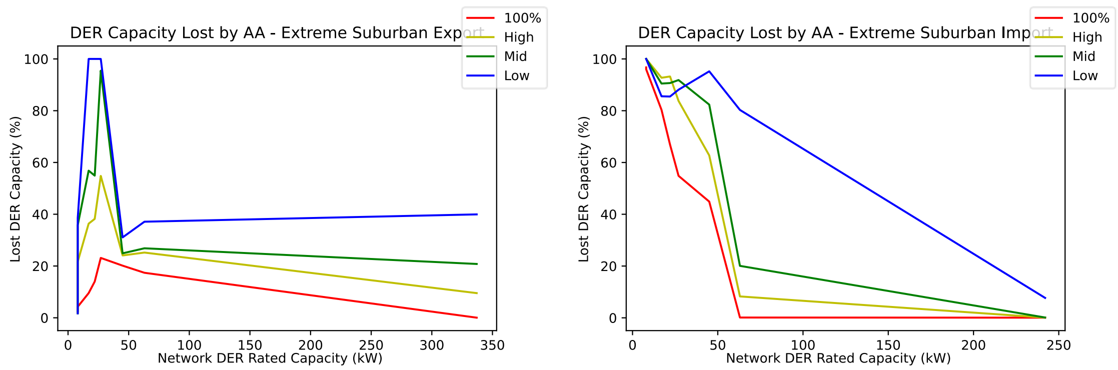
In Figure 34 the capacity allocation in the *Suburban* network for the extreme demand scenario is shown. For the Approximation Algorithm, we see that no import capacity can be allocated until *Scenario 7*. It is only at this point that there is sufficient DER controllable load available in the network to counteract the network imbalances in the load. For the Basic DOE case, in lower DER penetration scenarios the majority of the DER capacity can be allocated, and this percentage decreases and the DER penetration level increases.

Figure 34 DER capacity allocated in the *City* network for each scenario using the Approximation Algorithm (AA) (left) and Basic DOE (DOE) (right). The graphs show both export and import capacity allocation for the Extreme Demand Use Case.



The difference between the DER capacity allocated by the Basic DOE and the Approximation Algorithm is shown in Figure 35 – specifically the difference in export capacity for the extreme generation use case, and the difference in import capacity for the extreme demand use case. For the export DER capacity allocation (Figure 35 (left)) we see a similar peaking behaviour as we have seen previously. This is altered slightly in the lower participation cases by the sudden change in network conditions in *Scenario 6* due to the reduction in phase imbalance. However, for the higher participation levels this behaviour is more evident. In Figure 35 (right), for the import capacity allocation as the Approximation Algorithm doesn't assign any import capacity for the majority of the scenarios, the graph plotted it almost exactly the DER capacity allocated by the Basic DOE. This changes for the last two scenarios, when the Approximation Algorithm is able to assign capacity again. For *100%*, *High* and *Mid* participation levels in *Scenario 8* the lost DER capacity is 0%. This is because in this case both the Basic DOE and Approximation Algorithm are thermally constrained, and because in this extreme scenario there is no different in the network loading, only the HoF voltage, both allocate the same capacity.

Figure 35 The lost DER capacity (as a percentage of the total controllable DER fleet size) plotted against the total DER capacity in the network for the extreme export (left) and extreme import (right) cases for the *Suburban* network



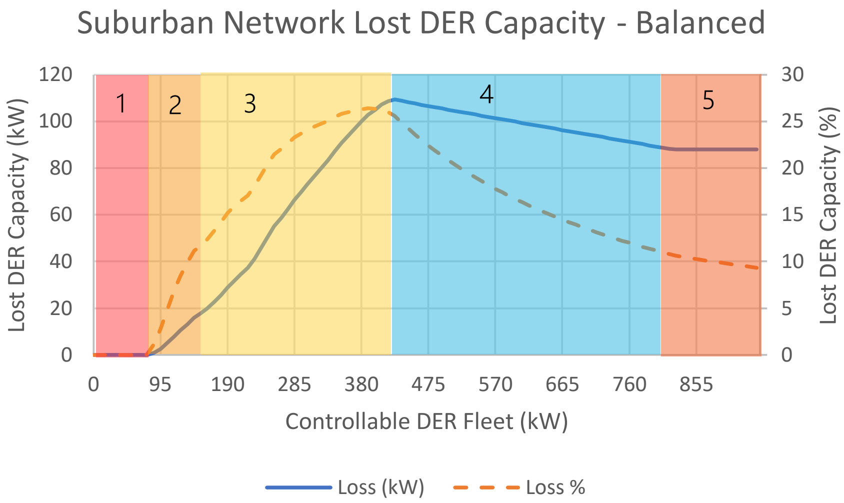
4.5 Summary

In general, for a single time step the lost DER capacity measured in kW for a voltage constrained network can be thought to be in one of these 5 stages:

- Stage 1: Basic DOE and Approximation Algorithm allocate the same capacity, because the system is unconstrained in both cases. So expected loss in capacity allocation is 0.
- Stage 2: The Approximation Algorithm becomes voltage constrained but not the Basic DOE. During this stage the loss in capacity allocation will increase as DER penetration increases. This is because Approximation Algorithm will reduce the amount of capacity it can allocate, while Basic DOE still allocates full capacity.
- Stage 3: Basic DOE now begins to be voltage constrained. However, the network is less heavily constrained in the DOE case as it has only just become constrained, so it has more options to allocated additional capacity. This means that lost DER capacity will continue to increase, but more slowly.
- Stage 4: Once Basic DOE hits thermal limits then the expected loss in capacity allocation will reduce, as the Basic DOE is now unable to increase the absolute capacity it is allocating, whilst the Approximation Algorithm is still able to.
- Stage 5: It is possible, if the DER fleet in the network is sufficiently large (oversized) that the Approximation Algorithm could also reach the thermal capacity of the transformer. Then at this point, there is again no difference between Basic DOE and Approximation Algorithm. This means the lost DER capacity will remain constant.

These five stages are illustrated in Figure 36. In which stage a network will fall for any given time step is dependent on the DER location and phase, penetration, participation, and demand and generation of uncontrolled customers in the network.

Figure 36 Graph showing the five stages of lost DER capacity for the balanced *Suburban* network high demand example in Section 4.1.2



For a network which is not voltage constrained, but rather thermally constrained, there is a simple 3 stage process for the lost DER capacity measured in kW is:

- Stage 1: Basic DOE and Approximation Algorithm allocate the same capacity, because the system is unconstrained in both cases. So expected loss in capacity allocation is 0.

- Stage 2: Due to the conservative assumption on network demand/generation the Approximation Algorithm will hit the network thermal constraint before the Basic DOE. During the period where the Approximation Algorithm is constrained but the Basic DOE isn't the lost DER capacity allocation increases almost as fast as the DER fleet size increases.
- Stage 3: The Basic DOE now also becomes thermally constrained. At this point, the lost DER capacity allocation (in kW) will remain fairly constant, and this gap will be governed by the gap between the conservative network demand estimate of the Approximation Algorithm and the network demand forecast of the Basic DOE.

In time periods of high network stress, either from high network demand, or high network generation the Approximation Algorithm may fail to allocate any capacity. This is more likely to happen with there is a low DER participation rate in the marketplace. Additionally, the results shown is this report indicate that in a high network demand event, there may be times where the Approximation Algorithm fails to allocate export capacity as well as import capacity. The opposite is also true for high generation events. It is not clear whether the Approximation Algorithm utilised in practice will also exhibit this behaviour, but if it does, being unable to allocate export capacity in times of high network demand removes some of the ability of the DNSP to deal with these high demand events.

4.5.1 Exports

We see the average daily lost DER capacity (as a percentage of controllable DER fleet capacity) is initially low for lower DER penetration, and then increases to a peak, and reduces afterwards. Considering exports, for the test day considered in this report, when the HoF voltage was low, the daily average lost DER capacity peaks around 0-4% of the controllable fleet capacity and occurred with a controllable DER fleet of around 250-300kW in an LV network with a 200kW rated transformer. For a high HoF voltage this daily average lost DER capacity peaks around 15-25% of the controllable fleet capacity and occurred at around 200kW fleet capacity for the *City* network, and anywhere between 50 – 150 kW for the *Suburban* network.

It is important to recognise here that the allocated capacity will not always be fully utilised. In fact, it is unlikely that all export capacity assigned between the late evening and early morning the following day will be used. Therefore, the lost DER export capacity that occurs during this time is unlikely to have a significant impact on aggregators and customers. However, during the middle of the day when the export capacity is most in demand is also when we are likely to see the peak in lost DER export capacity from the Approximation Algorithm. For the *City* network *High HoF Voltage* use case, these peaks in lost DER export capacity varied from 40% - 80% of the controllable DER fleet capacity for the worst performing DER penetration scenarios.

4.5.2 Imports

In general, the imports in these networks are thermally constrained, rather than voltage constrained. Currently, networks manage to leverage load diversity when designing and sizing networks. This uses the concept that it is unlikely that the load profiles of individual households will align, and so while some households have peak load, others may be consuming very little. This allows DNSPs to design networks for an after-diversity maximum demand load (commonly 4kW per customer), even though individual customers may demand significantly more than this at any given time. However, when applying import DOEs, the concept of load diversity can no longer be applied as the DNSP must assume that any capacity that is allocated can be used. This is why we see significant reductions in import capacity allocated as DER penetration increases, and thermal constraints quickly becoming binding in Approximation Algorithm and Basic DOE calculations. The conservative estimate of the transformer hosting capacity that is used by the Approximation Algorithm also often leads to a large amount of lost DER import capacity when applying the Approximation Algorithm. For the *High HoF Voltage* use case that average lost DER export capacity peaks around 20%, and the 90th percentile around 35-55%. For imports the average lost DER capacity peaks 30-35% and the 90th percentile was 55-60%.

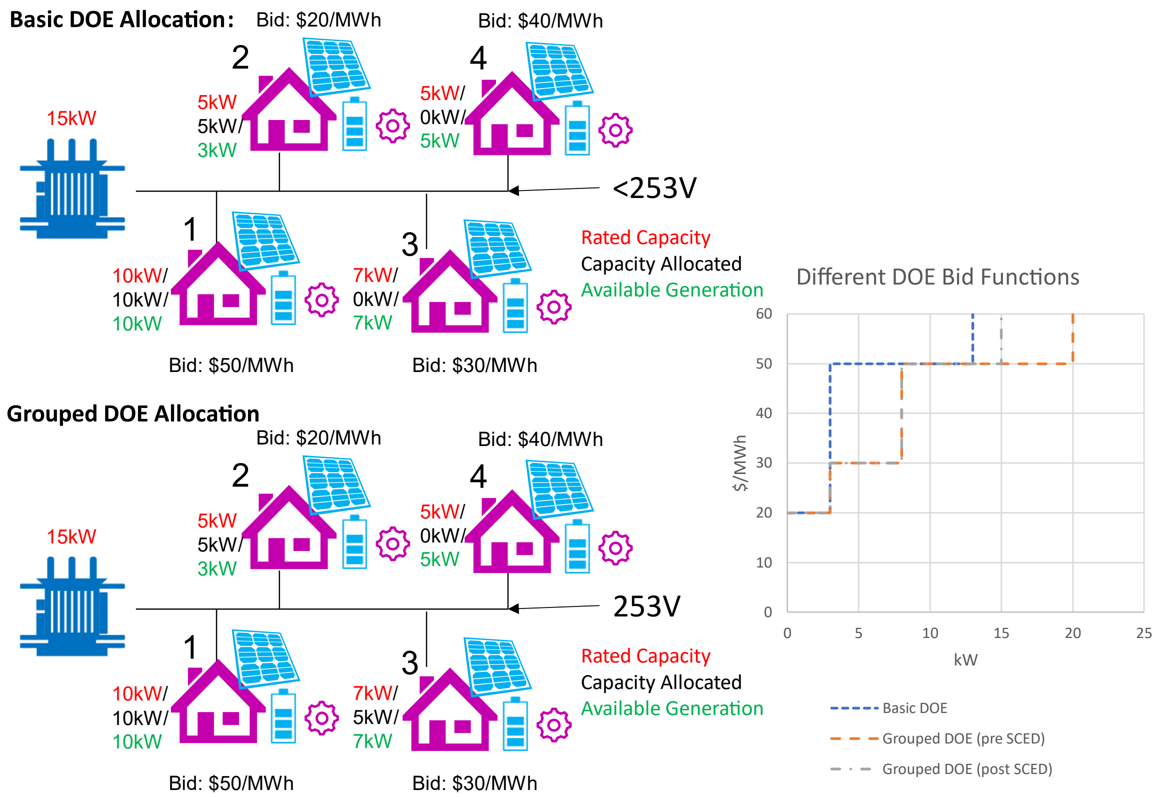
5 Grouped DOEs

5.1 Basic DOE vs Grouped DOE Example

An example of the different outcomes if a Basic DOE or a Grouped DOE is applied to a thermally constrained network is illustrated in Figure 37, which shows the initial capacity allocation of both the Basic DOE and Grouped DOE, as well as the resultant aggregate bid functions of the network. For simplicity of the example, each customer is associated with a constant cost and the aggregator creates their bid by stacking these.

For simplicity of explaining this analysis, it is assumed AEMO operate the SCED however it is important to note that this responsibility is not meant to prescriptive. A Grouped DOEs arrangement would require alignment between DER aggregations and the location of the binding thermal constraints. Depending on the topographic prominence of this alignment it may be more appropriate for DNSPs to operate a SCED.

Figure 37 Illustrative example of the benefits of Grouped DOEs in cases when the network is thermally constrained



5.1.1 Basic DOE Operation

For the Basic DOE allocation (top network in Figure 37) the allocation is constrained by the thermal capacity of the transformer. As the Basic DOE is utilising the *Maximise NEM Export* objective function it will prioritise customers near the head of the feeder, minimising system losses. However, it has no consideration for the bid functions of the customer, or the actual available generation (as it assigns capacity based on rated DER capacity). Therefore, in the Basic DOE customer 1 is allocated 10kW, and customer 2 is allocated 5kW. Customers 3 and 4 are allocated 0kW of capacity.

Now the aggregator uses these DOE constraints when creating their bid functions. The aggregator knows that customer 2 can only export 3kW during at this time, so it creates the Basic DOE bid function seen in Figure 37 (right). We see that the bid curve bids the first 3kW (available export of customer 2) at $20/MWh, and the remaining 10kW (available export of customer 1) at $50/MWh. Note that because customer 2 cannot export its full capacity, the network is now only exporting a maximum of 13kW, even though the transformer thermal constraint isn't binding until 15kW, and the network voltage constraint isn't binding.

5.1.2 Grouped DOE Operation

For the Grouped DOE allocation (bottom network in Figure 37) the DNSP allocates capacity to customers, ignoring the transformer thermal constraint and only considering the voltage constraints in the network. This means that the DNSP allocates greater capacity (20kW total) amongst customers in the network. In addition to the 10kW allocated to customer 1 and 5kW allocated to customer 2 (as in Basic DOE), customer 3 is also allocated 5kW of capacity. Now, the aggregator uses these DOE constraints to create their bid functions using these constraints which is the "Grouped DOE (pre SCED)" bid function in Figure 37. This deviates from the Basic DOE bid function in two ways. Firstly, the bid curve between 3kW and 8kW is set to $30/MWh, because customer 3 can now be included. Secondly, the bid curve continues to 20kW, as this is the amount of capacity that the DNSP allocated.

Now, AEMO takes this bid curve, along with the branch flow constraints from the DNSP and conducts a Security Constrained Economic Dispatch (SCED). For this example, this is simple as AEMO can just assign capacity to the cheapest customer, and then the next cheapest, and so on until the total thermal capacity of the network has been assigned. If this is done, then the bid curve that is passed from the SCED to market clearance would be "Grouped DOE (post SCED)" in Figure 37. This curve differs from the pre-SCED bid curve in that it is terminated at 15kW (the thermal capacity of the transformer). It is clear comparing the Basic DOE bid function and the Grouped DOE (post SCED) bid function that in this case using Grouped DOE has both delivered a less expensive bid function, and a bid function that can deliver greater capacity to the market.

5.2 Grouped DOE Analysis based on Techno-Economic Modelling Results

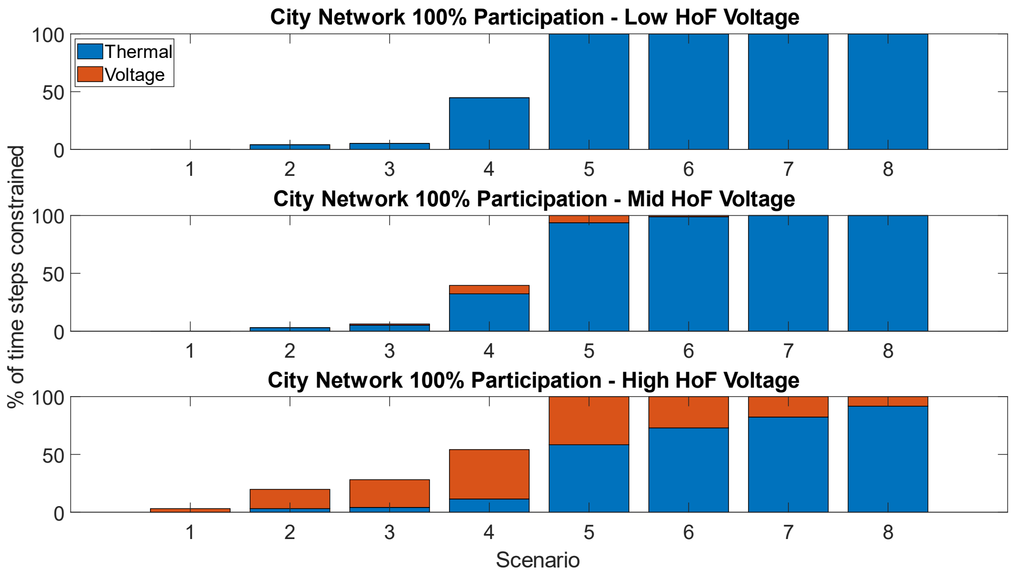
As was discussed in Sections 2.3 and 5.1, the grouped DOE only provides additional value to the DER marketplace in cases where the network is thermally constrained, rather than voltage constrained. If the network is thermally constrained, then the benefits of Grouped DOEs are twofold. Firstly, the aggregator bid functions that are passed to the market are upper bounded by the bid functions passed to the market if the Basic DOE is used. This means that any bid functions created by the Grouped DOE will at worst be the same as those created by the Basic DOE but are likely to be cheaper in certain bidding intervals. The second benefit is that the Grouped DOE can unlock additional capacity by ensuring that the thermal capacity of the network is fully utilised (if possible). Both of these phenomena were illustrated in Figure 37.

In principle, it is apparent that there are potential benefits to be gained from the utilised of the Grouped DOEs. However, implementation of Grouped DOEs is more complex that the Basic DOEs. For example, due to additional data exchange between the DNSP and AEMO in the form of the branch flow constraints, and the fact that AEMO must also conduct a SCED. Therefore, it should be considered how often these benefits from the Grouped DOE may be obtained, if there are specific network conditions that make this more likely, and how this may change in an increasingly high penetration DER future.

In general, due to current operational practices of DNSPs, when constraints occur in the distribution network exports are constrained by voltages rise, and imports to the LV network are constrained by thermal limits. In the *Low HoF Voltage* use case in Section 4.2, the *City* network constraints were almost exclusively thermal, for imports and for exports. For the *Suburban* network the import constraints were largely unconstrained until *Scenario 8*, which almost exclusively thermal. So, for the *City* network in this *Low HoF Voltage* use case, the Grouped DOE would consistently be of benefit.

In Figure 38 it is shown how the number of constrained time steps over the course of the use case day changes with increasing DER penetration, and with changing HoF voltage for both imports and exports using the Basic DOE. We see that for the *Low HoF Voltage* that there are no voltage constraints in any DER penetration scenario. By the time *Scenario 4* is reached the majority of export timesteps are thermally constrained, and by *Scenario 5* all exports and imports are also thermally constrained. (It is noted that for *City* network 100% participation *Scenario 5* has 278kW of rated export DER capacity and 154kW of rated import DER capacity in a 200kW transformer system). When the HoF voltage increases by 5V we still see a similar results to the *Low HoF Voltage* use case, although there are a number of time steps that now have their exports voltage constrained in *Scenarios 3-6*. For the *High HoF Voltage* case (which is 10V greater than the *Low HoF Voltage* use case) we see the system become more constrained at earlier DER penetration scenarios. These early scenarios are now dominated by voltage constraints in the export direction. However, after *Scenario 4* the number of voltage constrained time steps begins to decrease as they become thermally constrained with the increased DER fleet size.

Figure 38 Bar chart showing how the number of time steps that are constrained (and the type of constraint) changes which DER penetration level and with HoF voltage for the Basic DOE



With increased distributed generation in the network, and with the distribution network presently operated to boost distribution network voltages to accommodate for demand, it is likely that distribution networks will be operating on the higher end of the allowable voltage scale, and so we shall see voltage constraints coming into play before thermal constraints for exports. However, DNSPs are aware that voltage rise in the distribution network is an operational challenge and are exploring ways of combating this (including as part of the local service provision in Project EDGE). This could include changing the way existing network assets (such as Online Tap Changes (OLTCs)) are operated or installing new network assets to assist in voltage regulation. This problem could also be addressed by the DER and their use of reactive power, either through more aggressive Volt-Var control, or through a reactive power service/market. If DNSPs are successful at combating this voltage rise issue in the LV network, then thermal constraints on the network (or at least DOEs that limit their capacity allocation due to possible thermal constraints) may become more prevalent. This would result in Grouped DOEs having increased utility.

As mentioned in Section 4.5.2, the lack of load diversity when it comes to allocating import capacity for DOEs may act to significantly limit the amount of import capacity that can be allocated by DOEs. For the use cases run for this report we have seen that import capacity allocation is almost exclusively constrained by the thermal capacity of the network. Additionally, the use of import capacity that is allocated by aggregators is likely to be more sporadic than exports as it is likely to be driven by individual customer behaviour (both energy usage and travel behaviour if a customer has an EV) as well as market prices and forecasts. There may then be substantial benefit for Grouped DOEs to be used in the allocation of import capacity. The Grouped DOEs delay the final decision on import capacity allocation until the aggregator has made their bids into the market. This means that the Grouped DOE can utilise load diversity in a way that the Basic DOE cannot, as at this stage there will likely be diversity in aggregator operation that could not be modelled in the Basic DOE.

For export capacity with *High HoF Voltage* (as is often the case), the early DER penetration scenarios are dominated by voltage constraints. It is not until *Scenario 7* that the majority of the export constraints become thermal rather than voltage constraints (for *Scenario 7 100%* DER participation the controllable DER fleet has a rated export capacity of 467kW and a rated import capacity of 245kW). For lower DER participation rates, the voltage constraint in the export direction stays as the majority cause of capacity allocation constraint through all the *High HoF Voltage* use case.

5.3 Summary

In summary, it is likely that Grouped DOEs could provide significant benefits for assigning DOE import capacity, due to the inability of Basic DOEs to incorporate load diversity of flexible loads into their calculations. Import capacity allocation is predominantly thermally constrained and delaying the final import capacity allocation until aggregators have finalised their bids would allow the diversity of aggregator operation for imports to be factored back into the final allocation of import capacity. As distribution networks are currently operated, with high HoF voltages, exports are predominately voltage constrained, and will remain so (apart from in cases of very oversized DER fleets) unless the DNSPs find new ways of managing the network voltage. Successful new approaches to voltage regulation may lead to more occurrences of export capacity allocation being thermally constrained, rather than voltage constrained. If this occurs, and thermally constrained export capacity allocation becomes more common, then Grouped DOEs will become of greater value and may assist in delaying network investment more significantly than Basic DOEs alone due to their ability to maximise the network capacity utilised in practise.

6 Summary of Results

For the individual time step analysis of the *City* and *Suburban* network in Section 4.1, the Approximation Algorithm began constraining the export DOEs around 40% earlier than the Basic DOE. These will be dependent on the difference in value between the Approximation Algorithm conservative estimates of network state and the Basic DOE forecasts. For the *Suburban* network the Approximation Algorithm began constraining export capacity at 57kW controllable DER fleet, whereas the Basic DOE began constraining at 95kW. For the *City* network the Approximation Algorithm began constraining export capacity at 132kW controllable DER fleet, whereas the Basic DOE began constraining at 216kW. These values differ due to different network topologies and impedances, and difference DER locations, phases, and sizes.

The results of the techno-economic modelling are presented in Section 4. The results show that for a 3-phase LV network that is voltage constrained, the lost DER capacity associated with using the Approximation Algorithm rather than the Basic DOE can be divided into 5 stages. In general, for a single time step the lost DER capacity measured in kW can be thought to be in one of these 5 stages:

- Stage 1: Basic DOE and Approximation Algorithm allocate the same capacity, because the system is unconstrained in both cases. So expected loss in capacity allocation is 0.
- Stage 2: The Approximation Algorithm becomes voltage constrained but not the Basic DOE. During this stage the loss in capacity allocation will increase as DER penetration increases. This is because Approximation Algorithm will reduce the amount of capacity it can allocate, while Basic DOE still allocates full capacity.
- Stage 3: Basic DOE now begins to be voltage constrained. However, the network is less heavily constrained in the DOE case as it has only just become constrained, so it has more options to allocated additional capacity. This means that lost DER capacity will continue to increase, but more slowly.
- Stage 4: Once Basic DOE hits thermal limits then the expected loss in capacity allocation will reduce, as the Basic DOE is now unable to increase the absolute capacity it is allocating, whilst the Approximation Algorithm is still able to.
- Stage 5: It is possible, if the DER fleet in the network is sufficiently large (oversized) that the Approximation Algorithm could also reach the thermal capacity of the transformer. Then at this point, there is again no difference between Basic DOE and Approximation Algorithm. This means the lost DER capacity will remain constant.

For a system with significant phase imbalance the five stages of operation remain the same, but the DER capacity during which the network is in each stage may vary greatly when compared to a balanced network. This will cause some changes in the shape of the overall lost DER capacity curve.

For a network which is not voltage constrained, but rather thermally constrained, there is a simple 3 stage process for the lost DER capacity measured in kW is:

- Stage 1: Basic DOE and Approximation Algorithm allocate the same capacity, because the system is unconstrained in both cases. So expected loss in capacity allocation is 0.

- Stage 2: Due to the conservative assumption on network demand/generation the Approximation Algorithm will hit the network thermal constraint before the Basic DOE. During the period where the Approximation Algorithm is constrained but the Basic DOE isn't the lost DER capacity allocation increases almost as fast as the DER fleet size increases.
- Stage 3: The Basic DOE now also becomes thermally constrained. At this point, the lost DER capacity allocation (in kW) will remain fairly constant, and this gap will be governed by the gap between the conservative network demand estimate of the Approximation Algorithm and the network demand forecast of the Basic DOE.

In very high demand or generation time steps that it appears that the Approximation Algorithm may fail to allocate any capacity, even when the Basic DOE is still able to assign full capacity. This is due Approximation Algorithm determining that there is no additional hosting available to the transformer due to its conservative assumptions of network state. The conservative assumptions around the transformer hosting capacity (which for the proxy used in this report is represented by the conservative assumption of the HoF voltage) is likely to have a larger impact on allocated capacity compared to the conservative assumption of customer voltage (which for the proxy used in this report is represented by the conservative assumption of network demand).

The daily use cases that are examined in this report show a similar behaviour to the lost capacity allocation curve for individual time steps. At low DER penetration levels, it is small and gradually increases until it peaks, and begins decreasing again. This peak in the middle aligns with the DER penetration where the number of voltage constrained time steps in the Basic DOE peaks. Once the Basic DOE becomes predominately thermally constrained, the Approximation Algorithm begins to more closer to the Basic DOE effectiveness.

The Approximation Algorithm is most effective when the network is sufficiently unconstrained that, even with the conservative assumptions, it can still allocate full capacity. It can also be somewhat effective when the DER fleet in the network is sufficiently oversized so that the capacity allocation is thermally constrained rather than voltage constrained. Although, the lost DER capacity at this point will be dependent on how conservative the assumption of network demand is compared to the Basic DOE forecast. For voltage constrained networks, the Approximation Algorithm performs most poorly for export capacity when the Basic DOE is heavily voltage constrained. The more time periods where the Basic DOE is voltage constrained, the worse the Approximation Algorithm will perform over the day. The lost DER capacity allocation in these voltage constrained time steps is worse for lower DER participation scenarios. For networks that are not voltage constrained, the largest loss in DER capacity allocation occurs at the point just before the Basic DOE becomes thermally constrained, and the Approximation Algorithm is already thermally constrained. Therefore, the more time periods that occur in a day when the Approximation Algorithm is thermally constrained and the Basic DOE is not, the worse the Approximation Algorithm will perform over the day.

For DNSPs to make a decision around when to transition from the Approximation Algorithm approach to the Basic DOE approach would require a full cost benefit analysis for a given network. When the Approximation Algorithm starts losing DER capacity allocation, and the speed at which this lost DER capacity allocation increases will be dependent on the physical network, the DER within the network, and the conservatism of the estimates of network state used by the Approximation Algorithm. However, the general shape of the lost DER capacity curve seems similar across networks. From these results it is recommended that while the Approximation Algorithm allocates capacity in a largely unconstrained way, there is little benefit in making the investment required to transition to the Basic DOE. Once the Approximation Algorithm begins becoming constrained, the lost DER capacity increases quickly as new DER are added to the network. The controllable DER fleet capacity will likely need to be significantly oversized for the lost DER capacity stops increasing, so it is not recommended that DNSPs wait on their transition to the Basic DOE for this to occur, as this will results in near constant network constraint events. An increase in the severity or frequency of Approximation Algorithm capacity allocation being constraint should be a warning to DNSPs that they are potentially losing significant amounts of DER capacity by not transitioning to the Basic DOE, and the problem will only keep getting worse.

As mentioned previously, lost DER capacity allocation does not necessarily translate to lost DER capacity in practice. Export capacity between the late evening and early morning is unlikely to be fully utilised, and so the lost DER export capacity allocation will likely have a limit impact during these periods. However, the time steps where the network is most constrained are also the time steps where there will be the largest difference between the Approximation Algorithm and the Basic DOE and will be the time steps where the capacity is most likely to be fully utilised. DNSPs should therefore consider how the capacity is being used in each time step as well as the lost DER capacity allocation when making their decision.

With increasing amounts of flexible loads (including batteries and electric vehicles), the Approximation Algorithm will be the approach that will first have to constrain import capacity allocation in light of thermal constraints. As load diversity cannot be assumed when assigning import capacity, thermal constraints on DOEs for imports may soon become an issue in distribution networks. Moving from Approximation Algorithm to Basic DOE will assist in unlocking additional import capacity allocation, but it is envisioned that transitioning to Grouped DOEs will likely have the largest impact in this respect. The ability for import capacity to be re-allocated based on the aggregator bids re-introduces a level of load diversity into the import capacity allocation that could be key in delaying network reinforcement.