Project EDGE

Fairness in Dynamic Operating Envelope Objective Functions

– a report by the University of Melbourne

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Important notice

PURPOSE

This Fairness in Dynamic Operating Envelope (DOE) Objective Functions has been prepared for Project EDGE by the University of Melbourne (UoM).

This report provides the results of the work conducted by the UoM for Project EDGE on the technical, economic, and fairness implications of applying different DOE objective functions.

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- the work of the UoM in preparing this Fairness in Dynamic Operating Envelope Objective Functions report; and
- the support, co-operation and contribution of the other Project EDGE participants and consultants in providing data and information used by the UoM to prepare this report.

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Executive summary

The rapid uptake of distributed energy resources (DER), and the opportunity for DER to actively participate in a DER marketplace have provided strong drivers for the implementation of dynamic operating envelopes (DOEs). The currently used static limits on DER exports are conservative by design but DOEs will allow distribution network service providers (DNSPs) to consider locational and temporal factors when assigning capacity to DER, increasing the capacity that can be allocated. This report focuses on the various methods (DOE objective functions) by which a DNSP may divide the total available capacity between the DER in the network, and specifically what the impact is of trying to do so in a fair way.

Section 2 of this report proposes six DOE objective functions that could be used by DNSPs to calculate DOEs for participating DER. For this report, we have retitled the Objective Functions to make them more accessible to a wider audience and non-technical stakeholders. Both Objective Functions names will be referred to throughout this Report and the companion Executive Summary Slides on the Project EDGE website.

The Objective Functions are:

- *Maximise Export (Maximise NEM Export):* This objective maximises the amount of capacity that can be exported upstream.
- *Policy Outcome (Policy Based):* This objective assigns weightings to each DER based on a pre-defined DNSP policy and then maximises the weighted sum of the capacity that is allocated.
- *Fixed Percentage (Proportional Asset):* Each DER is assigned $X\%$ of their rated capacity, where X is constant across all DER and this objective maximises X.
- *Equal kW Reduction (Equal Individual Conservation):* Each DER has their allocated capacity reduced to Y kW below their rated capacity, where Y is constant across all DER. This objective minimises Y.
- *Level Network Sharing (Shared Equal Individual Allocation):* Each DER is allocated capacity equal to the smaller of Z kW or their rated capacity. Z is constant across all DER and this objective maximises Z.
- *Flat Access (Absolute Equal Individual Allocation):* Each DER is allocated capacity equal to Z kW, where Z is constant across all DER and the objective maximises Z.

In Section 3, metrics are proposed by which the performance of these six DOE objective functions can be assess. Each metric exists on a scale from 0 to 1, with higher values indicating a better performance. The metrics used to assess the performance of these six DOE objective functions are:

- *Network Utilisation:* Indicates how much of the transformer thermal capacity is being utilised to export power upstream.
- *DER Capacity Utilisation:* Indicates how much of the total capacity of the participating DER fleet is being allocated.
- *Renewables Utilisation:* Indicates how much of the total capacity of participating renewable generators is being allocated capacity.

- *Relative Social Welfare:* Indicates the additional economic value that is being unlocked for the participating DER by the application of DOEs.
- *Quality of Service:* Indicates the fairness of the capacity allocation based on the coefficient of variation of the solution. From a customer's viewpoint, this fairness metrics could be interpreted as: "Everyone is entitled to have capacity allocated. To be fair, I should get similar capacity allocated as my neighbours. In addition, the more capacity that we are assigned collectively, the fairer the system is."
- *Quality of Experience:* Indicates the fairness of the capacity allocated based on the standard deviation of the solution. From a customer's viewpoint, this fairness metrics could be interpreted as: "As long as everyone is impacted similarly to me then the system is fair, even if we are getting heavily curtailed".
- *Min-Max Fairness:* Indicates the fairness of the capacity allocated based on the range of the solution. From a customer's viewpoint, this fairness metric could be interpreted as: "The difference between the 'winners' and the 'losers' in the system should be as small as possible."

Section 4 illustrates the fundamental concepts of the work by applying the DOE objective functions to two simple toy networks. In one network a largest DER is closest to the head of the feeder and in the other it is at the end of the feeder. From these results, it appears that *Fixed Percentage (Proportional Asset)* and *Equal kW Reduction (Equal Individual Conservation)* can be very sensitive to the location of DER, which can lead to very high or very low performance, depending on the DER size and location. *Level Network Sharing (Shared Equal Individual Allocation)* is less susceptible to this, and *Flat Access (Absolute Equal Individual Allocation)* is not affected at all. However, this can lead to lost opportunity when DER size and location is favourable. *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* manage to perform well in technical and economic metrics in both networks. The performance of these DOE objective functions can be significantly improved by good sizing and placement of DER. For the *Policy Outcome (Policy Based)* objective, the effectiveness of a specific policy is highly dependent on the DER in the network and may lead to highly volatile outcomes. Therefore, care should be taken when assigning weights to ensure that the results will match the policy aims.

Section 5 and Section 6 apply these DOE objective functions to three representative networks – a *City*, *Suburban*, and *Regional* network. The objective functions were applied to the network over eight different DER penetration scenarios (from 20% to 100%) to determine the number of DER in the network. Each penetration scenario was further divided in four participation scenarios (Low, Mid, High, 100%), to determine the number of DER actively participating in the DER marketplace. The *Flat Access (Absolute Equal Individual Allocation)* objective was applied in the 100% DER participating scenarios to estimate the likely required value of static limits in high DER scenarios to maintain the network within allowable limits. This was then used to compare the performance of the DOEs with static limits.

In general, the results show that imposing fairness requirements into the DOE objective function calculation on the division of capacity allocated to customers participating in the DER marketplace has a detrimental impact on the technical and economic performance of the DOEs. Additionally, this negative impact can become worse with higher DER penetration rates as networks become more constrained. Utilising a DOE objective that directly considers fairness does not guarantee a fairer allocation of capacity for those customers actively participating in the DER marketplace. This report has highlighted some cases *Equal kW Reduction (Equal Individual Conservation)* in the *Regional* network) where using a fair DOE objective function has such a profound negative impact on the capacity allocated that it also reduces the fairness of the DOE objective. Increasing system technical and economic efficiency is likely to provide the most benefits to all customers in the NEM and could be considered to maximise fairness from a whole-of-system perspective. Therefore, in the interest of system efficiency, it is recommended that *Maximise Export (Maximise NEM Export)* be the default DOE objective, and it is strongly advised that DNSPs conduct techno-economic modelling on their networks before implementing other DOE objective functions to fully understand the associated negative technical and economic impacts.

Additionally, whilst not the main focus of this report, it has been shown that currently in some networks the static limits may be highly conservative but moving into a high DER future they will need to be reduced further, as has been seen in Section 6.1. Network type, DER location, and DER phase connection will all have a significant impact on the static limits that can be safely imposed in a network. It is recommended that there is further work conducted into a systematic method of determining appropriate static limits for customers who are not participating in a DER marketplace.

This work proposes a range of DOE objective functions that could be used by DNSPs, as well as methods by which to assess their efficacy. This should provide tools to and discussions between consumer representatives, DER aggregators, DNSPs, market operators, and policy makers for decisions surrounding DER marketplaces, implementations of DOEs, and future changes to static limits.

Glossary

Term	Definition
DER	Distributed Energy Resources
DOE	Dynamic Operating Envelope
DNSP	Distribution Network Service Provider
EDGE	Energy Demand and Generation Exchange
LV	Low Voltage
MV	Medium Voltage
NEM	National Electricity Market
PV	Photo-Voltaic
SWER	Single-Wire Earth-Return
UoM	The University of Melbourne
VPP	Virtual Power Plant

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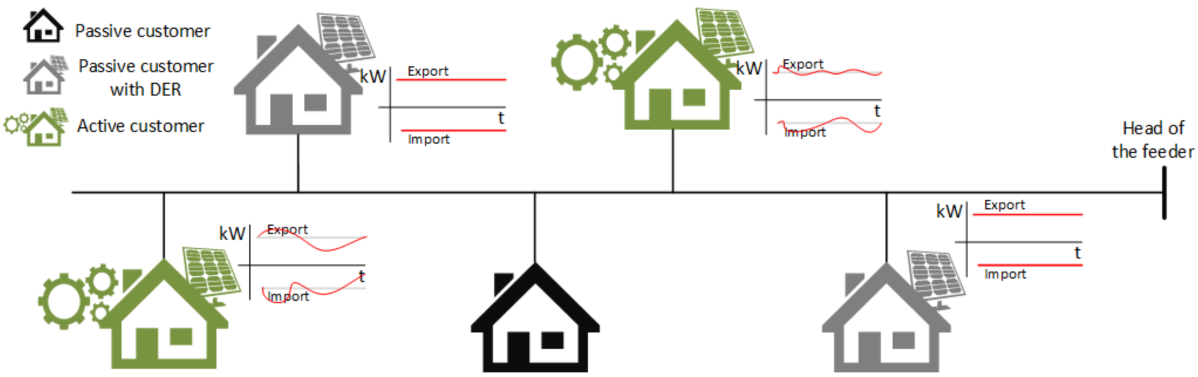
1 Introduction

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. However, when calculating the DOEs a DNSP may have different objective functions, including objective functions to fairly allocated the available capacity between participating customers.

Figure 1 Conceptual illustration of operating envelope



The University of Melbourne (UoM) has been tasked with conducting techno-economic modelling to inform on the potential technical, economic, and fairness impacts of different DOE objective functions. This report details a range of DOE objective functions a DNSP could use, as well as proposing metrics by which to measure the technical, economic, and fairness (specifically from the perspective of the actively participating customers) impacts of different objective functions.

[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 an aggregator.

It should be noted that, while this report focuses on DOEs with respect to exports from participating customers, the objective functions, metrics, and modelling approach are equally applicable to DOEs for imports.

1.1 Fairness

In this work, when the topic of fairness is discussed, it is specifically focussed on the fairness with which available capacity is allocated to customers who are actively participating in a DER marketplace (through enrolling their DER to participate in a trader's virtual power plant (VPP)). Therefore, when fairness is discussed in this report, it is fairness internal to a subset of DER customers in a specific LV network. The fairness metrics that are proposed in Section 3.3 are examining fairness through this lens and are not measuring the fairness of the entire system for all customers.

To assess the fairness of these DOE objective functions with respect to all customers in the NEM would require further work, with a combination of studies from system level down to household level to understand and quantify the total impact of DOEs to all customers. The wider network implications of widespread implementation of DOEs, and the possible impact this may have on customers not participating in a DER marketplace such as changes to static limits, changes to frequency of enforced export curtailment, impacts on energy prices, or impacts on deferral of network augmentation are areas of interest for future work but are beyond the scope of this report.

However, at a high level the following points can be made with regard to the impacts of DOEs on customers who are not actively participating in a DER marketplace.

- Implementation of DOEs should not necessitate a negative impact on customers who remain on static limits, as these static limits are taken into account during the calculation of DOEs. DNSPs may make the decision to reduce static limits to encourage customers to sign up for DOEs, but this decision should not be impacted by the choice of DOE objective function, and is a separate decision made by the DNSP.
- It is expected that implementation of DOEs will increase the amount of power that LV networks can safely export. However, exporting more power may impact network voltages at higher voltages, and may have a knock-on effect on other LV networks on the same MV feeder. This is an operational challenge for DNSPs in managing their networks which may require additional investment in network assets, or new methods of more actively managing network voltages.
- Unlocking DER export capacity could mean significant additional generation capacity is added to the wholesale energy spot market. These DER are likely to be very competitive in their bids, likely leading to reductions in energy spot market prices. If these market prices are reflected in tariffs provided to customers, then unlocking DER capacity could lead to lower energy bills for all customers. The greater the volume of DER capacity that can be unlocked, the greater the potential for cost reduction to all customers. In this way, maximising the efficiency of the capacity allocation can be viewed as the fairest approach from the perspective of all of the customers in the network, as this will provide the most benefits to all. However, this may result in some actively participating customers being assigned less capacity than their peers.

With this being said, this work focuses on methods of incorporating fairness into the allocation of capacity through DOEs to customers participating in a DER marketplace, and the impact that this has on the technical and economic performance of the DOEs (which is a likely indicator of the impact on technical and economic performance of the wider network). At any one time the DNSP has a pool of network capacity to be allocated between these actively participating customers (with non-participating customers having their capacity capped at their static limit). The equity of the allocation of this pool of network capacity amongst actively participating customers (who are the subset of all customers in a specific LV network who own DER and are actively participating in a VPP) is what we are considering when we examine the fairness of capacity allocation.

The methods by which we assess how fair different DOE objective functions are discussed further in Section 3.3.

1.2 Modelling Approach

The techno-economic modelling utilises an unbalanced three-phase optimal power flow formulation to accurately capture the physics of the low voltage (LV) distribution network. For three-phase LV networks, the network modelling extends to the secondary side of the LV transformer. For single-wire earth-return (SWER) networks, the network modelling extends to the secondary side of the isolation transformer. This is consistent with the approach being used to implement the DOEs in the Project EDGE field trials. This requires that the secondary side voltage of the LV transformer / isolation transformer is used as a data input to the techno-economic modelling. To be able to comment on both types of networks without having to distinguish, the secondary side of the LV transformer / isolation transformer will be referred to as the "head of the feeder".

For non-participating customers, the DNSP uses forecasts of active and reactive power to determine the network state. To be consistent with the approach used in the Project EDGE field trials, the rated power of the DER owned by participating customers is used in calculating the DOEs. Therefore, it may occur that more capacity is assigned to a DER than it can use, or choses to use due to market conditions. The techno-economic implications of this approach are a subject of interest but are outside the scope of this work.

2 DOE Objective Functions

One of the aims of this piece of work is to try and compare a wide spectrum of possible DOE objective functions. Six potential objective functions have been identified. In this section, the six DOE objective functions that are analysed in this report are presented and discussed.

2.1 Maximise Export (Maximise NEM Export)

Maximise Export (Maximise NEM Export) focuses on maximising the total active power that can be exported by participating DER in the LV network. This is measured as the total active power export at the head of the feeder, to provide the most efficient allocation of capacity whilst maximising exports. This objective is shown in (1)), where P^{ex} is the active power export at the head of the feeder.

$$\max P^{ex} \tag{1}$$

The only constraints for this DOE are the unbalanced 3-phase power flow equations, the network voltage and thermal limits, and DER rated power limits.

This objective maximises the efficiency of the capacity allocation, and therefore could be viewed as considering fairness from a "whole-of-system" perspective rather than from the perspective of the participating customers. This means that, whilst this objective will maximise the amount of capacity that is allocated, it may result in some participating customer having their capacity allocation reduced more than others due to their location in the network.

2.2 Policy Outcome (Policy Based)

Policy Outcome (Policy Based) provides a DNSP the ability to set a weighting coefficient (α_k) to each DER or customer based on a policy outcome. Examples of these policy outcomes could be prioritising renewable generation, prioritising DER who have paid for priority access, socio-economic priorities, prioritising DER in a specific location, etc.

The objective is shown in (2)), which maximises the sum of the capacity allocated (P_k) to participation customer k multiplied by their weighting coefficient set by the DNSP.

$$\max \sum_{k \in DER} \alpha_k P_k \tag{2}$$

2.3 Fixed Percentage (Proportional Asset)

Fixed Percentage (Proportional Asset) aims to allocated capacity to customers based on their need, which here is assumed to be the rated capacity of their DER. This means that each DER or customer is allocated *X*% of their rated capacity, where the value of *X* is the same for all participating DER and is maximised as part of the DOE calculation. This means that all DER receive the same portion of their rated capacity, which results in bigger DER being allocated more capacity. For example, if the DOE calculation determines that the maximum value for X is 50%, and there is a 6 kW PV and an 8 kW PV, the 6 kW PV would be allocated 3 kW of capacity, whilst the 8 kW PV would be allocated 4 kW.

Using this method, the DNSP aims to maximise the value of X, as in (3)), and it is also subject to the following additional constraint (4)) which enforces the *Fixed Percentage (Proportional Asset)* approach, where P_k^{Max} is the rated capacity of each customer k.

$$\max X \tag{3}$$

$$X P_k^{Max} = P_k \quad , \forall k \in DER \tag{4}$$

2.4 Equal kW Reduction (Equal Individual Conservation)

The aim of *Equal kW Reduction (Equal Individual Conservation)* is that, if there are constraints within the network, then the required reduction in capacity should be distributed evenly across all participating DER. Therefore, each participating customers has their allocated capacity reduced to Y kW below their rated capacity. The value of Y is the same across all participating DER and is calculated to be the minimum possible value (i.e., capacity is reduced by the smallest amount possible) as part of the DOE calculation. Using this method, the DNSP aims to minimise the value of Y, as in (5)), and it is also subject to the following additional constraint (6)) which enforces the *Equal kW Reduction (Equal Individual Conservation)* approach.

$$\min Y \quad (5)$$

$$P_k^{Max} - P_k = Y \quad , \forall k \in DER \quad (6)$$

2.5 Level Network Sharing (Shared Equal Individual Allocation)

Level Network Sharing (Shared Equal Individual Allocation) aims to allocate equal capacity to each customer. However, the capacity that each customer can be allocated cannot be greater than the rated capacity of their DER. This is done so that capacity isn't overallocated to customer with smaller DER who cannot use that capacity. Therefore, each customer is allocated capacity equal to the minimum of Z kW and P_k^{Max} kW (enforced by Equation (8))) and the DOE calculation aims to maximise Z as in (7)).

$$\max Z \quad (7)$$

$$P_k = \min(Z, P_k^{Max}) \quad , \forall k \in DER \quad (8)$$

2.6 Flat Access (Absolute Equal Individual Allocation)

The *Flat Access (Absolute Equal Individual Allocation)* approach aims to allocate equal capacity to each customer, regardless of the size of the customers' DER. Therefore, each customer is allocated Z kW, as in the constraint (9)). This may result in overallocation of capacity to smaller DER. This approach aims to maximise Z as in (7)).

$$P_k = Z \quad , \forall k \in DER \quad (9)$$

2.7 Illustrative Example of DOE Objective Functions

In the previous sections, the mathematics of the DOE objective functions have been presented, and a description of the intended aim. In this section, a basic illustration is provided in Figure 2 to visualise what the result of these different DOE objective functions might look like[4].

It is seen that in the *Maximise Export (Maximise NEM Export)* case, the DER at the head of the feeder are prioritised, and those at the end of the feeder miss out on being assigned capacity. However, in doing so the total capacity that is allocated is the most out of all objective functions.

The *Policy Outcome (Policy Based)* objective allocated the second-highest total capacity, aiming to assign the most capacity to the DER with the highest weighting. However, the physics of the network have an impact on how this capacity is allocated, and it is seen that DER 4 (which has the highest weighting) still does not get assigned full capacity, even though DER 3 (with a lower weighting) does. This illustrates that while *Policy Outcome (Policy Based)* aims to prioritise higher weighted DER, this is not guaranteed if it has a severe impact on the rest of the DER.

For *Fixed Percentage (Proportional Asset)* (and the subsequent objective functions) there is a drop in the total capacity that is allocated as the focus of the objective shifts from efficiency to fairness. Here, each DER is allocated 55% of its rated capacity, so the larger DER are assigned more capacity in an absolute sense.

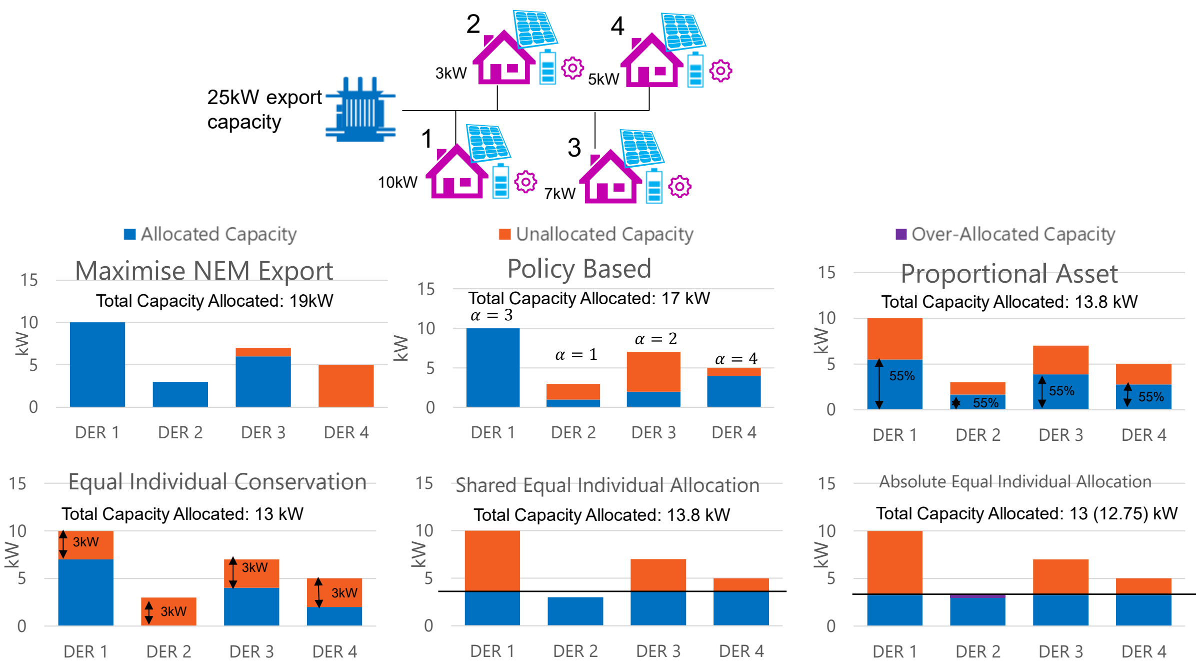
[4] It should be noted that these results are indicative only, and are not the result of an actual DOE calculation

The *Equal kW Reduction (Equal Individual Conservation)* objective assigns capacity by calculating that each DER must conserve 3 kW of capacity. By looking at the graphs it is apparently that whilst each DER conserves the same capacity in an absolute sense, relative to their size DER 2 and DER 4 (which are smaller) are much more effected. In fact, DER 2 (which has a size of 3 kW) is assigned 0 kW capacity.

When applying *Level Network Sharing (Shared Equal Individual Allocation)* DER 1, 3, and 4 are all assigned 3.6 kW of capacity. However, this is larger than the rated size of DER 2, so it is only assigned 3 kW. While DER 2 is assigned full capacity, and DER 4 is assigned the majority of its rated capacity, DER 3 and DER 1 have a significant portion of their rated capacity left unallocated.

Flat Access (Absolute Equal Individual Allocation) determines that each DER can be assigned 3.25 kW. This means that DER 2 is over-allocated capacity, as it only has a rated capacity of 3 kW. The total capacity that this objective allocates (13 kW) is greater than the total capacity that can be utilised (12.75 kW).

Figure 2 Illustrative example of how the DOE Objective Functions would allocate capacity



3 Assessment Metrics

Section 2 provides an overview of the six different DOE objective functions that are analysed in this work. This section details how their performance will be assessed with respect to technical efficacy, economic performance, and fairness. The metrics will allow the subsequent analyses to make observations about general trends in performance, as well as possible relationships between performance in different metrics.

To allow these metrics to be easily compared between DOE objective functions, networks, and use cases, each metric is defined between the values of 0 and 1. For each metric, the value of 1 is associated with the best performance, and the value of 0 associated with the worst.

3.1 Technical Metrics

The following three metrics that are proposed in this work aim to capture different aspects of the technical operation of the network. It should be noted here that these values are associated with the capacity that is being allocated. There is no guarantee that this capacity will be fully utilised. So, these metrics are associated with the technical parameters that are unlocked through the allocation of capacity, rather than the actual capacity that will be utilised by the customers.

3.1.1 Network Utilisation (NU)

This metric details the percentage of the total LV / isolation transformer thermal capacity that would be used if the allocated capacity is fully utilised. This indicates the total network capacity that is unlocked through the use of the DOEs. This metric is calculated in (10)), where P^{Tx} is the rated thermal capacity of the LV / isolation transformer. A value of 0 indicates that there is no active power being exported by the network. A value of 1 indicates that the network is exporting active power equal to the transformer's thermal capacity.

$$NU = \frac{P^{ex}}{P^{Tx}} \tag{10}$$

3.1.2 DER Capacity Utilisation (DCU)

This metric details the percentage of total DER rated capacity that is allocated capacity. It does not mean that this much capacity will be utilised in practice, as this depends on aggregator operation, and DER availability. However, this metric does provide an understanding of how much DER capacity in the system is provided the opportunity to participate in the DER marketplace. This metric is calculated in (11)). A value of 0 indicates that no capacity is allocated to DER in the network. A value of 1 indicates that all DER in the network are allocated capacity equal to their rated capacity.

$$DCU = \frac{\sum_{k \in DER} P_k}{\sum_{k \in DER} P_k^{Max}} \tag{11}$$

3.1.3 Renewables Utilisation (RU)

This metrics details the percentage of total renewable generation DER rated capacity that is allocated capacity. As renewable generation is non-deferrable, if it is not allocated capacity the customer must increase its load to utilise the energy, or it is curtailed and lost. This metric is used to understand how much of the potential renewable generation capacity is unlocked for export through the use of DOEs. Again, it is noted that this does not equate to actual renewable generation, as the DER may not be available to export its full capacity, or an aggregator may choose not to. This metric is calculated in (12)), where $k \in RES$ defines the set of participating DER that are renewable generators. A value of 0 indicates that no capacity is allocated to renewable generators. A value of 1 indicates that all renewable generators are allocated capacity equal to their rated capacity.

$$RU = \frac{\sum_{k \in RES} P_k}{\sum_{k \in RES} P_k^{Max}} \tag{12}$$

3.2 Economic Metric

It is also important to understand the potential economic implications to aggregators of the different DOE objective functions. Whilst the technical and fairness metrics rely solely on the results of the DOE calculation, the economic metrics rely of further modelling that optimises the operation of the aggregator in response to the DOEs and market prices.

This metrics is specifically related to the economic value that can be obtained by the participating customers (or their aggregator) from participating in the wholesale energy market. This does not relate to wider economic impacts that widespread DOEs may cause, such as altering energy prices.

3.2.1 Relative Social Welfare (RSW)

Relative Social Welfare is related to the amount of economic value that is unlocked for the participating customers in the modelled network through the use of DOEs. In this work, the social welfare of the participating customers in the network is the total revenue they obtain from participating in the wholesale energy market R_k, minus the total cost of operating the DER C_k as defined in (13)). To understand how much economic value is unlocked by the DOEs, we must first establish a baseline, which is where no export capacity is allocated to the participating customers. We call this Minimum Social Welfare (MSW). To be able to define the *Relative Social Welfare* metric such that it is bounded between the values of 0 and 1 an upper bound on Social Welfare needs to be identified. By conducting a centralised optimisation that optimises the operation of the participating DER in the wholesale energy market, whilst maintaining the network within allowable limits, the optimal social welfare (OSW) can be found. Therefore, the *Relative Social Welfare* can be calculated as in (14)). A value of 0 indicates that there is no additional social welfare benefit from implementing the DOEs. A value of 1 indicates that there is no other DOE that could unlock greater social welfare.

$$SW = \sum_{k \in DER} (R_k - C_k) \tag{13}$$

$$RSW = 1 - \frac{OSW - SW}{OSW - MSW} \tag{14}$$

3.3 Fairness Metrics

The technical and economic metrics are intuitive to understand because the relate to tangible, objective assets such as active power, or money. Fairness, however, can be viewed as a more subjective attribute, and as such there is no single way of measure the extent to which capacity allocation is fair. However, fairness in network flow problems is a well-researched topic. As such, three fairness metrics from the literature are proposed in this work. Each of these metrics takes a different view on concept of fairness in the allocation of capacity. Readers are again reminded that these fairness metrics are measuring the fairness in the division of capacity allocated to customers actively participating in the DER marketplace. This is not representative of fairness when considering the outcomes for all customers in the network.

In order to be able to deal with allocating capacity (or network flows) to customers requiring different magnitudes of capacity these three metrics all consider the normalised capacity allocated $\overline{P_k}$. That is to say, the percentage of total required capacity that is allocated. This is defined in (15)). In this way the value of normalised capacity allocated will always take a value between 0 and 1, regardless of the size of the customer DER. This in turns allows the fairness metrics to stay bounded between 0 and 1 while considering customers with different sizes of DER.

$$\overline{P_k} = \frac{P_k}{P_k^{Max}} \tag{15}$$

3.3.1 Quality of Service (QoS)

The *Quality of Service* fairness, also referred to as Jain's Fairness Index[5] is a widely used fairness metric. It should be clarified here that this does not refer in any way to the reliability of service provided to customers to satisfy their baseload requirements. This metric is based on the coefficient of variation of the capacity allocation which is defined as $c = \frac{\sigma}{\mu}$, where σ is the standard deviation of the capacity allocated, and μ is the mean of the capacity allocated. Based on this definition, *Quality of Service* can be defined as in (16)), where N is the number of participating customers.

$$QoS = \frac{1}{1+c^2} = \frac{[\sum_{k \in DER} \overline{P_k}]^2}{N \sum_{k \in DER} (\overline{P_k}^2)} \tag{16}$$

From a customer's viewpoint, this fairness metrics could be interpreted as: "Everyone is entitled to have capacity allocated. To be fair, I should get similar capacity allocated as my neighbours. In addition, the more capacity that we are assigned collectively, the fairer the system is."

A value of 0 indicates that all DER are assigned no capacity. A value of 1 indicates that the normalised capacity that is allocated to each DER $\overline{P_k}$ is equal. This also means that all DER are assigned capacity proportional to their rated capacity.

3.3.2 Quality of Experience (QoE)

The *Quality of Experience* fairness index[6] is focused on relative customer satisfaction. This is to say that, unlike Quality of Service, the value of this metric is not impacted by the average capacity that is allocated within the network. It is solely affected by the standard deviation of the capacity allocated σ. The value of *Quality of Experience* is calculated in (17)), where σ^{max} is the maximum possible standard deviation. As the normalised capacity is being used, which always takes a value between 0 and 1, $\sigma^{max} = 0.5$. This would occur when half of the DER are assigned full capacity, and half are assigned no capacity.

$$QoE = 1 - \frac{\sigma}{\sigma^{max}} \tag{17}$$

From a customer's viewpoint, this fairness metrics could be interpreted as: "As long as everyone is impacted similarly to me then the system is fair, even if we are getting heavily curtailed".

A value of 0 indicates that half of the DER are assigned full capacity and half of the DER are assigned no capacity. A value of 1 indicates that the normalised capacity that is allocated to each DER $\overline{P_k}$ is equal. This also means that all DER are assigned capacity proportional to their rated capacity.

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[5] R. Jain, W. Hawe, D. Chiu, "A Quantitative measure of fairness and discrimination for resource allocation in Shared Computer Systems," DEC-TR-301, September 26, 1984

[6] Hoßfeld, T., Skorin-Kapov, L., Heegaard, P.E., Varela, M., 2018. A new QoE fairness index for QoE management. Quality and User Experience 3. doi:10.1007/s41233-018-0017-x

3.3.3 Min-Max Fairness ($\boldsymbol{MMF}$)

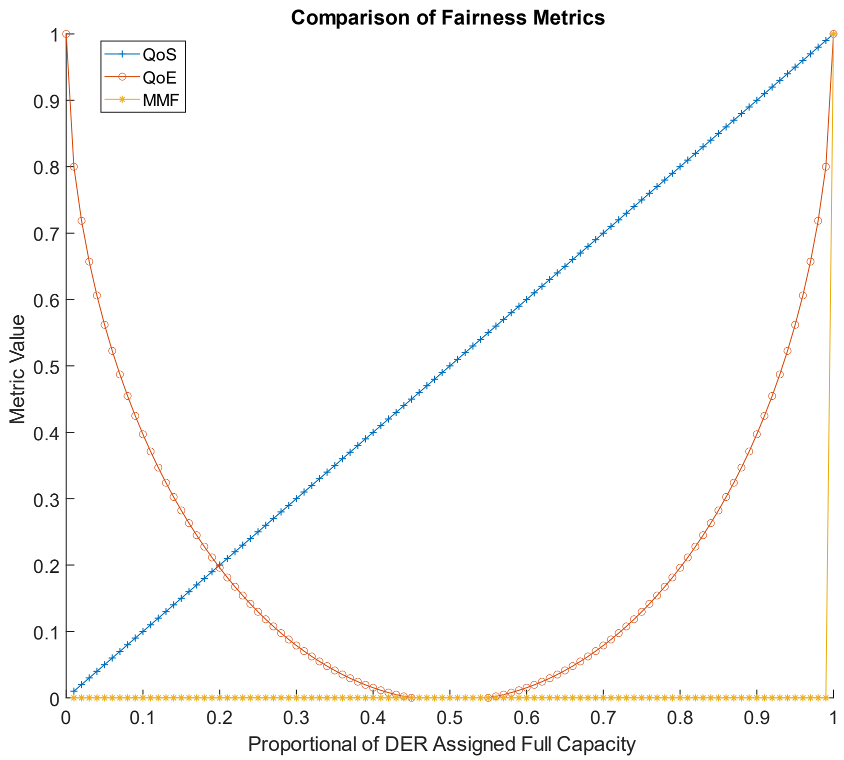
The *Min-Max Fairness* metric focuses on the relative difference between the "winners" and "losers" within the participating customers. It is based around the concept that when there is spare capacity, it should first be allocated to the customer with the least capacity already allocated. The value of *Min-Max Fairness* is calculated in (18)). From a customer's viewpoint, this fairness metric could be interpreted as: "The difference between the 'winners' and the 'losers' in the system should be as small as possible."

$$MMF = \frac{\min \overline{P_k}}{\max \overline{P_k}} \tag{18}$$

A value of 0 indicates that at least one DER has been assigned no capacity. A value of 1 indicates that the normalised capacity that is allocated to each DER $\overline{P_k}$ is equal. This also means that all DER are assigned capacity proportional to their rated capacity.

Figure 3 provides a visual comparison of the three fairness metrics. For this example, DER are either assigned full capacity, or zero capacity. It can be seen that the *Quality of Service* metric increases in value as more people are assigned capacity in the system. *Quality of Experience* begins with a value of 1 when no DER are assigned capacity, drops down to 0 when half the DER are assigned full capacity, and half are assigned zero capacity, then increase back to 1 again when all DER are assigned full capacity. *Min-Max Fairness* remains 0 until all DER are assigned full capacity, as prior to that there is always at least one DER that is assigned zero capacity. As these three metrics can behave in different ways, and each captures a different customer viewpoint of what a fair system is, they are all analysed in the work.

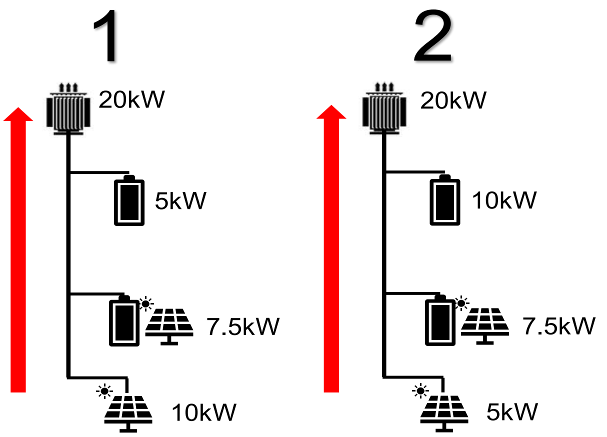
Figure 3 Graph to illustrate how the fairness metrics can differ



4 A Toy Network: Fundamental Results

This section of the report provides an explanation of the fundamental concepts that have been proposed in Sections 2 and 3. This will be done by applying the DOE objective functions to two simple 3-bus systems, and analysing their performances based on the proposed metrics. Network 1 and Network 2 are shown in Figure 4, and are used to demonstrate the fundamental concepts. The network parameters (line impedances, transformer thermal limits, allowable voltage range) are the same for both networks. The difference lies in the size of the resources. In Network 1 the resource at the head of the feeder (closest to the transformer) is smaller than in Network 2. Likewise, the resource at the end of the feeder (furthest from the transformer) is larger in Network 1 than in Network 2. This will facilitate demonstration of the impact of DER size and location on the DOE objective functions. In both of these networks, voltage constraints and thermal constraints mean that full capacity cannot be allocated to all DER. When calculating the *Relative Social Welfare* in this section a high market price is assumed to incentivise exports from all DER.

Figure 4 3-bus systems used to demonstrate the fundamental concepts



4.1 Capacity Allocation in 3-Bus Systems

Figure 5 shows the capacity allocation in Network 1 and Network 2 when *Maximise Export (Maximise NEM Export)* objective is used. In Network 1, the larger DER is located far from the transformer. The two resources closest to the transformer are allocated full capacity. The remainder of the available capacity is then allocated to the furthest DER. In Network 2 the larger DER is located close to the transformer. Similarly, to Network 1, the two resources closest to the transformer are allocated full capacity. The remainder of the available capacity is then allocated to the furthest DER. Because the larger DER are located closer to the transformer, the voltage rise in the network isn't sufficient to constraint the system. This means the DOE can allocate more capacity in Network 2 all the way up until the thermal constraint of the line connecting the DER to the transformer is binding [7].

Figure 5 Results of *Maximise Export (Maximise NEM Export)* DOE on 3-bus systems

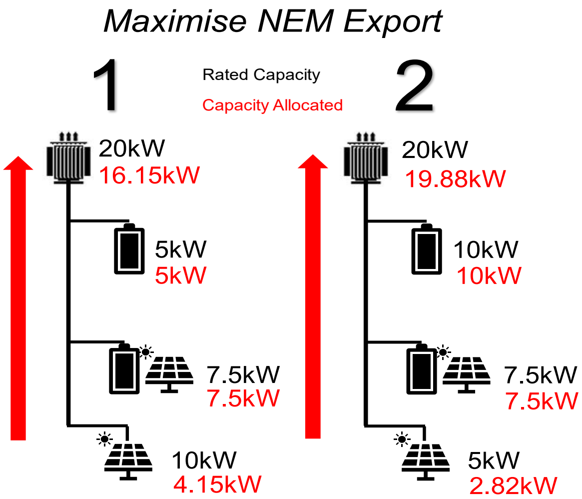
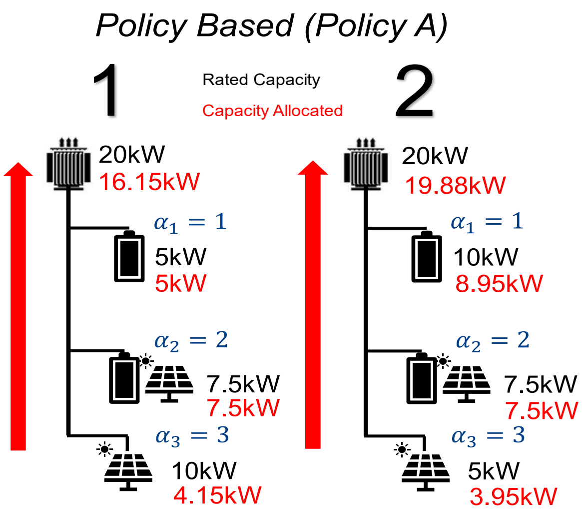


Figure 6 shows *Policy Outcome (Policy Based)* DOE objective being used, implementing policy A with the policy aim to prioritise renewable generation over batteries. Therefore, the PV has the highest weight of 3, the PV and battery hybrid system has a weight of 2, and the battery has a weight of 1. For Network 1, due to voltage drop in the network, reducing active power allocation of the battery by 3 kW does not unlock 1 kW of capacity for the PV. Similarly, reducing power allocated to the PV and battery hybrid by 3 kW does not unlock 2 kW of capacity for the PV. Therefore, the solution is the same as the *Maximise Export (Maximise NEM Export)* solution. The result for Network 2 does differ from the *Maximise Export (Maximise NEM Export)* solution. 1.05 kW of capacity is removed from the battery, and 1.13 kW of capacity is added to the PV. However, due to the losses in the network, this still results in the same transformer capacity being utilised as for *Maximise Export (Maximise NEM Export)*. This change reflects the intent of the DER weightings – to prioritise PV over batteries.

Figure 6 Results of *Policy Outcome (Policy Based)* DOE with Policy A on 3-bus systems



[7] The value of capacity that is being exported by the system is only 19.88 kW because 0.12 kW of active power is lost in the line between the battery and the transformer.

Implementing *Policy Outcome (Policy Based)* DOE with policy A has no impact on the capacity allocated in Network 1. Therefore, policy B is also implemented. This is similar to policy A, except that the weighting for the PV has been increase to 4 as can be seen in Figure 7. An unexpected occurrence can be seen for Network 1. All of the capacity that was allocated to the hybrid system (7.5 kW) has been removed, and instead an additional 3.98 kW of capacity has been assigned to the PV. Even though the battery only has a weighting of 1 it is still allocated full capacity. The capacity allocated closest to the transformer has the least impact on voltage rise, which is why reducing the capacity assigned to the battery would have limited ability to unlock capacity further down the feeder. This shifting of allocated capacity comes at the cost of total capacity allocated. As more of the capacity is allocated at the fringe DER, the total capacity that can be allocated in the network is reduced. For Network 2 the higher weighting applied to the PV as part of policy B has now caused the PV to be assigned full capacity. However, the majority of the extra capacity that is assigned to the PV is taken from the hybrid system rather than the battery at the head of the feeder (which is allocated more capacity than in policy A). This maintains the network voltages within allowable limits, and instead the thermal limit of the 20 kW line connecting the DER and the transformer constrains the system.

Figure 7 Results of *Policy Outcome (Policy Based)* DOE with Policy B on 3-bus systems

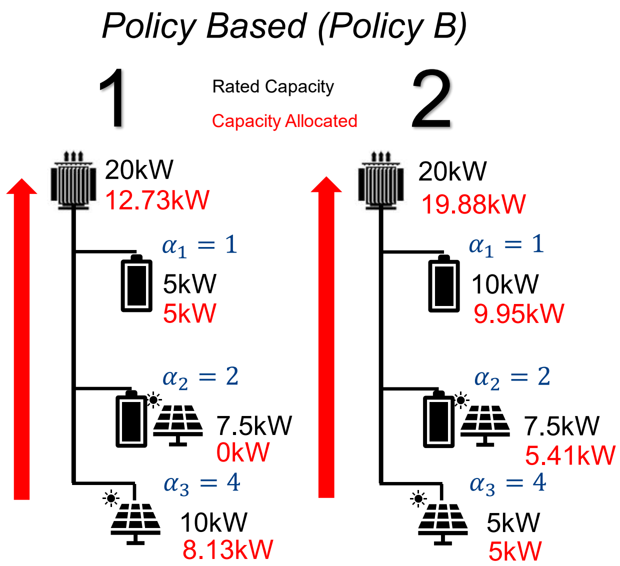
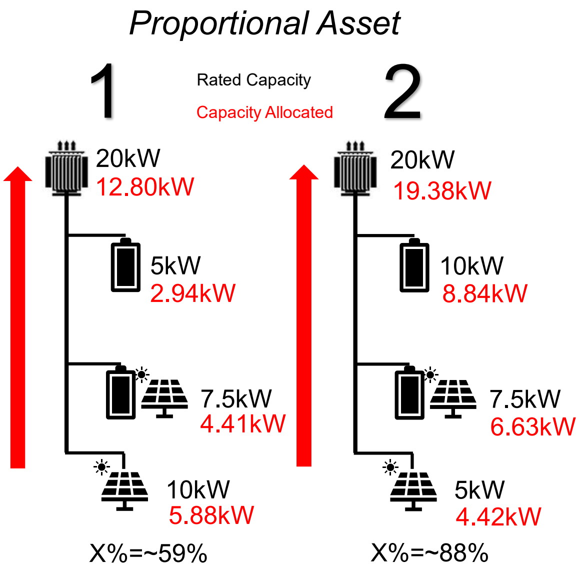


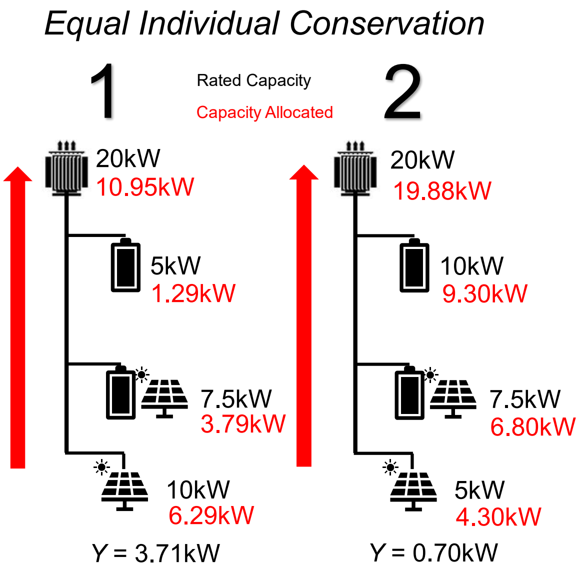
Figure 8 shows the results of applying *Fixed Percentage (Proportional Asset)* where each DER is assigned capacity proportional to its rated capacity. In Network 1, as the largest DER is located at the end of the feeder, this means that a large amount of the network capacity needs to be assigned to the DER at the end of the feeder. Due to the active voltage constraint, this results in less capacity being allocated to all DER. For Network 2 the largest DER is located close to the transformer and the smallest at the end of the feeder. Therefore, a higher proportion can be assigned without large amount of power injection at the end of the feeder causing problematic voltage rises. This means that for Network 2 the DOE calculation results in an 88% of the rated capacity being allocated, compared to just 59% in Network 1.

Figure 8 Results of *Fixed Percentage (Proportional Asset)* DOE on 3-bus systems



A similar issue can be seen for *Equal kW Reduction (Equal Individual Conservation)* in Figure 9. For Network 1, the DOE calculation needs each DER to conserve more capacity to drive down the amount of power that is injected at the end of the feeder, which would cause a high voltage rise. This results in 3.71 kW off the rated capacity not being assigned to each DER. However, in Network 2 where the DER at the end of the feeder is of a smaller size, the reduction in capacity that each DER faces is only 0.7 kW. This results in the network voltages being maintained within allowable limits, and the thermal limit of the line being the active constraint.

Figure 9 Results of *Equal kW Reduction (Equal Individual Conservation)* DOE on 3-bus systems



The performance of the *Level Network Sharing (Shared Equal Individual Allocation)* in Network 1 and 2 is much more similar than the previous DOE objective functions, as seen in Figure 10. The difference in the two solutions occurs because in Network 1 the DER closest to the transformer is only rated at 5 kW, so once the capacity being allocated exceeds that, the rest of the capacity is being allocated further away from the transformer. By contrast, in Network 2 it is the DER at the end of the feeder with the 5 kW rating. Therefore, once that capacity allocation has been reached, the additional capacity is only allocated to the DER closer to the transformer, leading to a lower voltage rise. This means that DER in Network 2 can be allocated up to 5.81 kW as opposed to only 5.30 kW in Network 1.

Figure 10 Results of *Level Network Sharing (Shared Equal Individual Allocation)* DOE on 3-bus systems

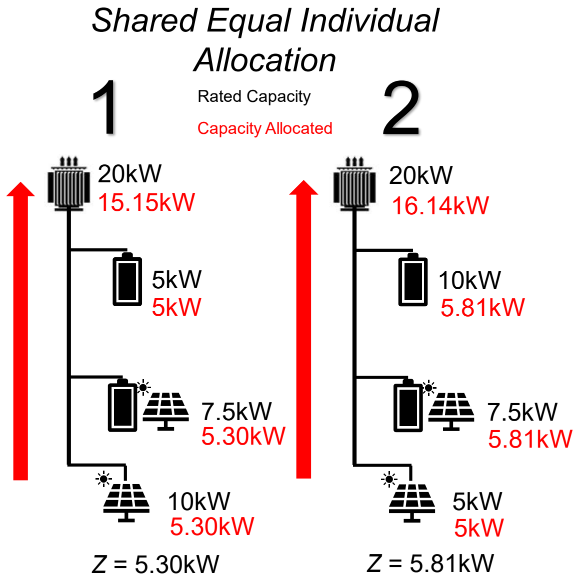
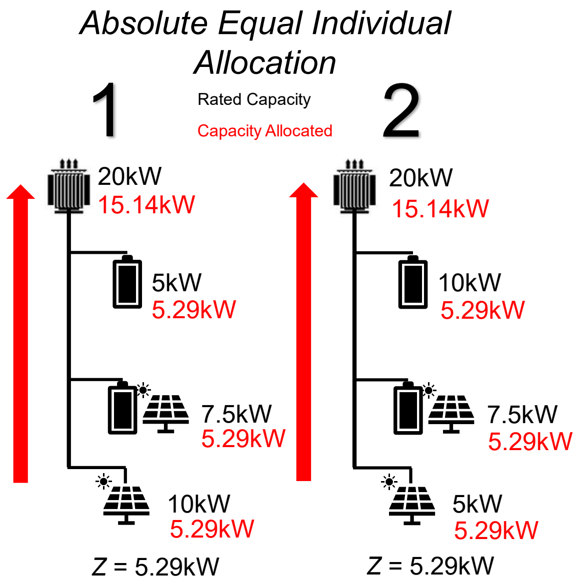


Figure 11 shows that there is no difference between the capacities allocated in Network 1 and Network 2 when *Flat Access (Absolute Equal Individual Allocation)* is used. This is because this objective does not take into account the size of the DER when allocating capacity. In both networks the 5 kW DER is over-allocated capacity.

Figure 11 Results of *Flat Access (Absolute Equal Individual Allocation)* DOE on 3-bus systems



4.2 Metric Values for 3-Bus Systems

Tables 1 and 2 below show the metric results for Network 1 and Network 2 respectively. By comparing the two tables, it is immediately apparent that performance across all metrics is significantly better in Network 2 than in Network 1. This is due to the positioning of the larger DER in the network and indicates that the efficacy of any of the DOE objective is subject to the size and location of DER in the network. In fact, introduction of DER into a network of the wrong size or in the wrong location could have a significant impact on the capacity that can be assigned to all other DER in the network through DOEs.

4.2.1 Network 1

For Network 1 it is shown in Table 1 that *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based) (Policy A)* perform best in *Network Utilisation, DER Capacity Allocation*, and *Relative Social Welfare* (recall that *Policy Outcome (Policy Based) (Policy A)* achieves the same solution as *Maximise Export (Maximise NEM Export))*. However, these two both perform poorly in the fairness. In fact, the only objective that performs worse for fairness is *Policy Outcome (Policy Based) (Policy B)*, which also performs very poorly in technical and economic metrics. This highlights the importance of understanding the physics of the network when trying to determine the appropriate weightings for *Policy Outcome (Policy Based)*. For this simple network, even a small difference in weighting has caused a substantial change in capacity allocation, which has reduced the performance of the DOE. *Policy Outcome (Policy Based) (Policy B)* is not even successful at prioritising PV as can be seen by the fact that *Renewables Utilisation* drops when comparing *Policy Outcome (Policy Based) (Policy A)* to *Policy Outcome (Policy Based) (Policy B)*.

In Network 1, *Level Network Sharing (Shared Equal Individual Allocation)* and *Flat Access (Absolute Equal Individual Allocation)* both perform well in the technical and economic metrics because the capacity they allocate is only loosely linked to the size of DER. Therefore, the larger DER being at the end of the feeder has less of an impact on the capacity that they can allocate. It should also be noted that *Fixed Percentage (Proportional Asset)* achieves a value of 1 for all fairness metrics. This is due to the use of the normalised capacity allocated $\overline{P_k}$ in the calculation of the fairness metrics. This means the *Fixed Percentage (Proportional Asset)* is in fact the definition of the fairest system in all three fairness metrics.

Table 1 Results for Network 1

Metric	NU	DCU	RU	QoS	QoE	MMF	RSW
Maximise Export (Maximise NEM Export)	0.81	0.74	0.61	0.90	0.45	0.41	1.00
Policy Outcome (Policy Based) (Policy A)	0.81	0.74	0.61	0.90	0.45	0.41	1.00
Policy Outcome (Policy Based) (Policy B)	0.64	0.58	0.54	0.66	0.13	0.00	0.79
Fixed Percentage (Proportional Asset)	0.64	0.59	0.69	1.00	1.00	1.00	0.80
Equal kW Reduction (Equal Individual Conservation)	0.55	0.51	0.67	0.90	0.69	0.41	0.68
Level Network Sharing (Shared Equal Individual Allocation)	0.76	0.69	0.69	0.94	0.61	0.53	0.94
Flat Access (Absolute Equal Individual Allocation)	0.76	0.69	0.69	0.94	0.61	0.53	0.94

4.2.2 Network 2

In Network 2 it is seen from Table 2 that the majority of DOE objective functions achieve the same or very similar values for *Network Utilisation* and *DER Capacity Utilisation*. This is because *Maximise Export (Maximise NEM Export), Policy Outcome (Policy Based) (Policy A), Policy Outcome (Policy Based) (Policy B)*, and *Equal kW Reduction (Equal Individual Conservation)* are all limited by the thermal limit of the line rather than the voltage rise at the end of the feeder. This occurs because the amount of DER capacity in the network is around 13% greater than the line thermal capacity. For these DOE objective functions, *Maximise Export (Maximise NEM Export)* has the lower *DER Capacity Utilisation*. This is because, whilst all of these objective functions hit the line thermal limit, *Maximise Export (Maximise NEM Export)* finds the most efficient solution while doing so. This minimises network losses, resulting in slightly less capacity being assigned for the same net export. *Fixed Percentage (Proportional Asset)* follows closely behind the afore mentioned objective functions in *Network Utilisation* performance, with *Level Network Sharing (Shared Equal Individual Allocation)* and *Flat Access (Absolute Equal Individual Allocation)* performing worst in this metric. This highlights a trade-off with *Level Network Sharing (Shared Equal Individual Allocation)* and *Flat Access (Absolute Equal Individual Allocation)*. Whilst they are less susceptible to poor performance due to undesirable DER placement, they also do not capitalise on the benefits of well-located DER.

Table 2 Results for Network 2

Metric	***NU***	***DCU***	***RU***	***QoS***	***QoE***	***MMF***	RSW
Maximise Export (Maximise NEM Export)	0.99	0.90	0.78	0.95	0.59	0.56	1.00
Policy Outcome (Policy Based) (Policy A)	0.99	0.91	0.90	0.99	0.83	0.79	1.00
Policy Outcome (Policy Based) (Policy B)	0.99	0.91	1.00	0.98	0.74	0.72	1.00
Fixed Percentage (Proportional Asset)	0.97	0.88	0.94	1.00	1.00	1.00	0.98
Equal kW Reduction (Equal Individual Conservation)	0.99	0.91	0.93	1.00	0.94	0.93	1.00
Level Network Sharing (Shared Equal Individual Allocation)	0.81	0.74	1.00	0.96	0.66	0.58	0.81
Flat Access (Absolute Equal Individual Allocation)	0.76	0.69	1.00	0.94	0.61	0.53	0.76

Due to their high technical performance, *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based) (Policy A & B)* perform comparably to *Level Network Sharing (Shared Equal Individual Allocation)* and *Flat Access (Absolute Equal Individual Allocation)* with respect to fairness. However, *Equal kW Reduction (Equal Individual Conservation)* which matches their high technical performance manages to significantly outperform them in terms of fairness, almost matching *Fixed Percentage (Proportional Asset)*'s perfect fairness scores. Comparing the performance of *Maximise Export (Maximise NEM Export), Policy Outcome (Policy Based) (Policy A)* and *Policy Outcome (Policy Based) (Policy B)*, it can be seen that when policy A is implemented the network *Renewables Utilisation* increases, indicating that the policy is operating as intended. It is also seen as the weighting of the

PV is increase in *Policy Outcome (Policy Based) (Policy B)* that the *Renewables Utilisation* increases yet again. However, this comes at the cost of performance in the fairness metrics.

4.2.3 Summary

From these results, it appears that *Fixed Percentage (Proportional Asset)* and *Equal kW Reduction (Equal Individual Conservation)* can be very sensitive to the location of DER, which can lead to very high or very low performance, depending on the DER size and location. *Level Network Sharing (Shared Equal Individual Allocation)* is less susceptible to this, and *Flat Access (Absolute Equal Individual Allocation)* is not affected at all. However, this can lead to lost opportunity when DER size and location is favourable. *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* manage to perform well in technical and economic metrics in both networks. The performance of these DOE objective functions can be significantly improved by good sizing and placement of DER (as seen in Network 2). For *Policy Outcome (Policy Based)* objective, the effectiveness of the policy is highly dependent on the DER in the network and may lead to highly volatile outcomes. Therefore, care should be taken when assigning weights to ensure that the results will match the policy aims.

5 Case Studies

This section of the report provides details of the advanced case studies that are used in the modelling, including realistic test networks, DER penetration levels, DER marketplace participation levels, how static limits will be address, and modelling assumptions.

5.1 Networks

Based on the feedback from the preliminary studies, one of the major objectives of this work was to ascertain how these DOE objective functions would function on real-world networks. To try and understand how the DOE objective functions 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[8] categorisation of LV networks in the NEM into *Regional, Suburban*, and *City* networks it was decided that one of each of these types would be modelled in these case studies. One of the networks that is being used in the Project EDGE field trials was chosen as the *Regional* network. Examples of a *City* and *Suburban* network were taken from the CSIRO LV Network Taxonomy report.

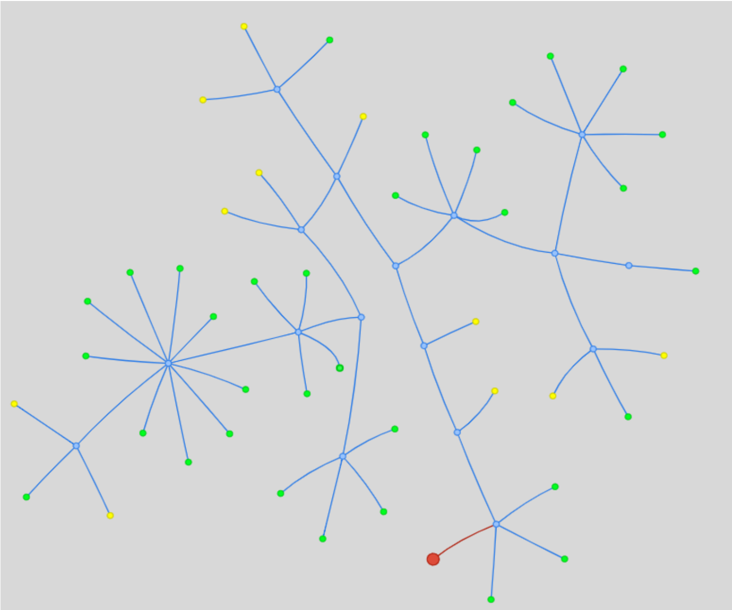
5.1.1 City Network

"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 12, 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

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

UoM so that there was a spread of residential and commercial customer splits across the three networks.

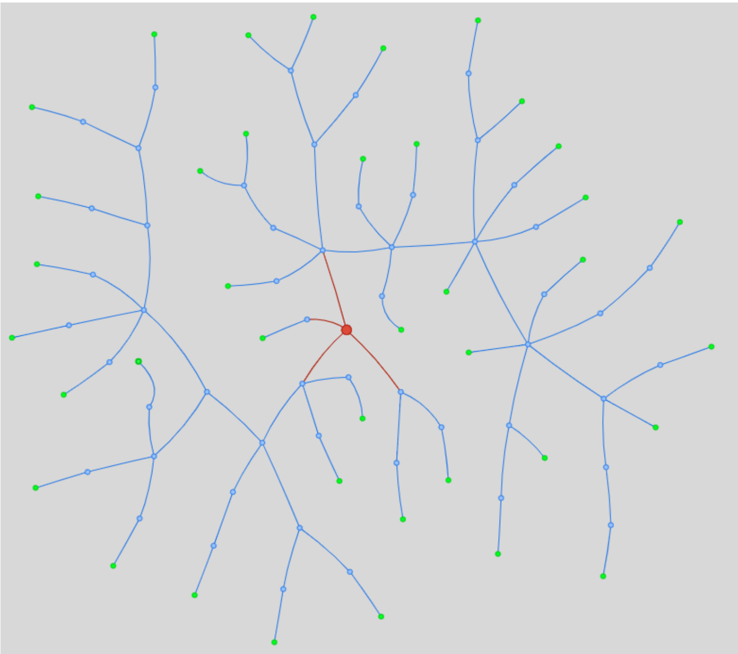
Figure 12 Diagram of the *City* network used in the techno-economic modelling



5.1.2 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 13, where the red node is the head of the feeder, and the green nodes are residential customers.

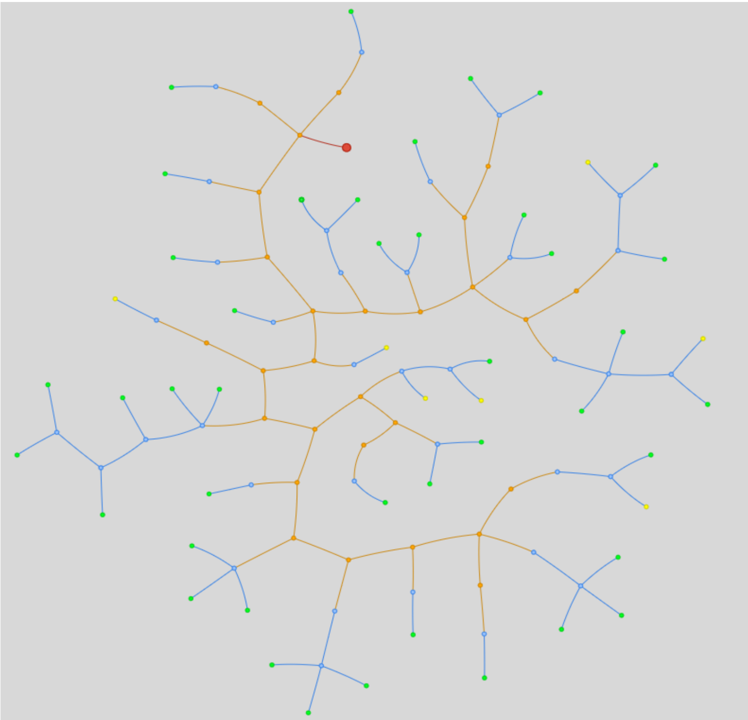
Figure 13 Diagram of the *Suburban* network used in the techno-economic modelling



5.1.3 Regional Network

One of the networks that is being used in the field trials was deemed suitable to be the representative *Regional* network. This is a single-wire earth return (SWER) network and is shown in Figure 14, where the red node is the head of the feeder, orange nodes are medium voltage (MV) nodes, blue nodes are low voltage nodes, the green nodes are residential customers, and the yellow nodes are commercial customers. As this is a SWER network, the head of feeder is the isolation transformer and so the network contains both MV and LV network. This makes it distinct from the *City* and *Suburban* networks, which only contain LV network.

Figure 14 Diagram of the *Regional* network used in the techno-economic modelling



5.2 DER Penetration Levels and DER Marketplace Participation Levels

Another major aim of this work is to investigate how the performance of the different DOE objective functions 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. However, it is also important to understand how these DOE objective functions may perform at higher DER penetration rates, which is why Scenarios 6-8 include much higher DER penetrations. The value for DER penetrations in Table 3 below is the percentage of customers in the network who have DER.

In addition, DER participation rates may also impact the performance of the DOE objective functions. Therefore, a Low, Mid, and High participation rate is proposed for each DER penetration scenario. The participation levels in Table 3 are the percentage of customers 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 3 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%

Additional to the Low, Mid and High participation levels, a 100% participation level is also modelled. As explained in Section 5.4, running a 100% participation level model is necessary for the approach used to address static limits. Therefore, this participation level is also included in the case studies.

5.3 Use Cases

The DNSP's calculation of DOEs contains no time coupling components and can therefore be calculated for each time step independently. This allows modelling to be run for single time periods. Running the techno-economic modelling across multiple time steps, for the different networks, penetration levels, participation levels, and DOE objective functions would result in an extremely large number of models to be run. Additionally, for the majority of the time when the network is unconstrained, all DOE objective functions will provide the same results – that is all DER are assigned full capacity. It is only when the network is operating near its allowable limits that DOEs will become restrictive, and the difference between the objective functions can be seen.

With this in mind, it was proposed that the specific network state where the network is managing peak generation is considered as use cases for this work. As this is the time when the network will be most constrained, this is also where we will see the largest difference between the DOE objective functions.

5.4 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. Additionally, for each DER penetration and participation combination the DOE objective will be compared to the case where only static limits are used. Therefore, capturing the potential change in static limits across differing DER penetration levels is important to the results.

To estimate how the static limits of these representative networks may change with increasing DER penetration, the following approach is proposed for each network and penetration combination.

Firstly, it is assumed that 100% of DER in the network are participating in the DER marketplace. Next the DOE calculation is conducted for the peak generation use case with the *Flat Access (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. *Flat Access (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 and penetration combination.

5.5 Modelling Assumptions

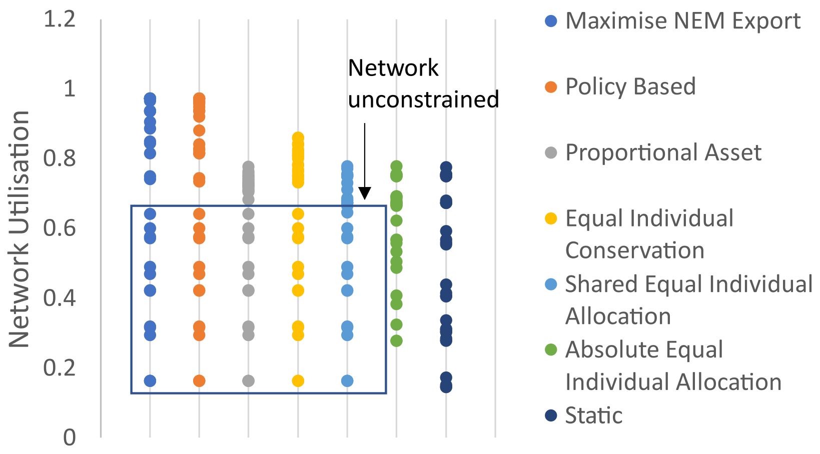
This section lists the assumptions that have been made as part of the modelling

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 DNSP has perfect knowledge of the active and reactive power forecast of the non-participating customer. The impact of uncertainty is being examined in a later piece of work, and this assumption allows comparisons to be drawn more easily between the different DOE objective functions.
3. The initial static limit for 3-phase LV networks is set to be 5 kW, and the initial static limit for SWER networks is set to be 3.5 kW to align with current AusNet practices.
4. Upper and lower voltage limits of LV networks are set to -6% / +10% in line with *AS61000.3.100*.
5. Residential customers may not request capacity greater than 10 kW per phase for the R*egional* network, and 14 kW per phase for C*ity* and *Suburban* networks due to fuse limits. Commercial customers may request greater capacity, up to 20kW per phase for R*egional*, and 28kW for *City* and *Suburban*.
6. The location of new DER introduced into the networks for each penetration scenario is chosen at random.
7. For the calculation of *Relative Social Welfare*, an assumption needs to be made around the price of the wholesale energy market. To incentivise exports, a price of $15,000/MWh (around the ceiling price of the NEM) was chosen. For this modelling, it is assumed that the DER are acting as price takers.
8. To be able to model the *Policy Outcome (Policy Based)* objective in this work, the policy which the DNSP is trying to implement must be set. For this work, the DNSP is trying to prioritise cheaper DER. Therefore, the weighting assigned to each DER is inversely proportional to their cost. These costs, and therefore the weightings, are assigned to DER randomly.

6 Results

This section of the report presents the results of the realistic techno-economic modelling. As mentioned previously, there will only be difference in results between the DOE objective functions if a constraint in the network is encountered when allocating capacity. This is not always the case in the studies defined in Section 5. In Figure 15 below, it is seen that for nine of the penetration and participation combinations there is no network constraint, and therefore all objective functions except for *Flat Access (Absolute Equal Individual Allocation)* and static limits provide the same results – full capacity allocated. Including these cases in the analysis would skew the results, and lead to the objective functions seeming more similar than they are. Therefore, for this results analysis only cases where there is an active network constraint will be analysed.

Figure 15 ***Network Utilisation*** **results for the** ***City*** **network for all DER penetration and participation scenarios**



6.1 Static Limits

As described in Section 5.4, the value of static limits for each network and DER penetration combination is estimated in this work by assuming 100% DER participation and application of the *Flat Access (Absolute Equal Individual Allocation)* DOE objective. The resulting static limits that were enforced can be found in Table 4 below. It is noted that the values in brackets are the solutions to the static limit estimation which are greater than the current default level for static limits (5 kW for 3-phase LV, and 3.5 kW for SWER networks). In these cases, the default value, being the smaller of the two, is applied.

For the case of the *Regional* network, the maximum static limit decreases at the DER penetration increases. The static limit drops sharply between Scenario 4 and Scenario 5 as there happens to be a number of DER introduced into the network on the same long feeder. This limits the static limit that can be applied in the network. Additionally, it is seen with 100% DER penetration, the static limit is much less than the 4 kW after diversity maximum demand level for which these networks are often designed and is much lower that the *City* or *Suburban* networks. This is due to the fact that the network is voltage constrained in this case, with the LV transformers that are located within the SWER network acting to boost the voltage on their secondary sides as is currently the case in the real-world network.

The S*uburban* network illustrates an interesting phenomenon. Between Scenario 5 and Scenario 6 the maximum static limit in the network increases considerably. What is occurring here is that in Scenario 5 there is a significant imbalance in the three phases due to the phases that the DER are connected to. This phase imbalance causes a boost to the voltage on one of the phases. In Scenario 6 a number of DER are brought online on the under-represented phase. This reduces the imbalance, and by doing so reduces the peak voltage. This then allows a higher static limit to be introduced.

Table 4 Static Limits applied for each network in each of the DER penetration scenarios

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

Note: Values in brackets indicate solutions of static limits calculations that are greater than current static limit.

The results in Table 4 show that as well as DER penetration, DER location, and DER phase all have significant impacts on what static limits can be safely applied in a network. It is also clear that static limits are network dependent, as for a given DER penetration the safe static limit can be very different between the three representative networks.

The values in Table 4 have been used in the remainder of the results, applied to customers who are not participating in the DER marketplace.

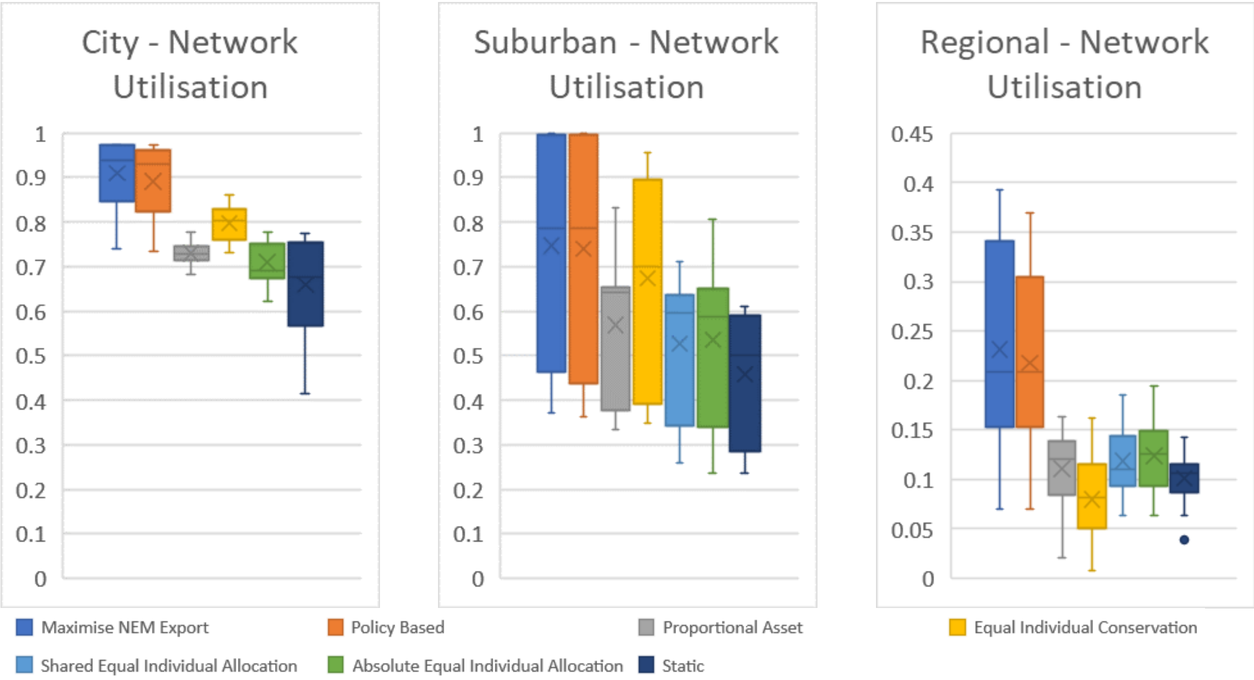
6.2 Network Utilisation

First, it is noted in Figure 16 that the *Network Utilisation* values for the *Regional* network are significantly less than the other networks. This is because the *Network Utilisation* for the *Regional* SWER network is calculated based on the thermal capacity of the isolation transformer. However, it is the thermal capacity of the smaller LV transformers in the network which limit the allocation of capacity.

It can be seen that the *Suburban* network has a larger range of values for all objective functions compared to *City*. This is due to the fact that in this modelling, there are no commercial loads within the *Suburban* network, but there are a significant number in the *City* network. This means that the install DER capacity grows quicker in the *City* network. This is why the average *Network Utilisation* is higher in the *City* network. Across all networks it is seen that *Maximise Export (Maximise NEM Export)* performs best in terms of *Network Utilisation*, as is expected. The *Policy Outcome (Policy Based)* objective is only slightly less effective. In the *City* and *Suburban* networks *Equal kW Reduction (Equal Individual Conservation)* is the next most effective. However, in *Regional* network it is the worst performing objective in terms of *Network Utilisation*. This is due to the fact that the *Regional* network is a more highly constrained network than either *City* or *Suburban*. Additionally, there is a large range of DER sizes due to the commercial customers present in the network. This leads to high levels of curtailment being required which can cause the smaller DER to be fully curtailed, resulting in poor performance.

For the *City* network the fair allocation objective functions cause a drop in *Network Utilisation* on average of 11-20% of transformer capacity depending on the objective. For the *Suburban* network this average drop is 7-22%, and for the *Regional* network 11-15%. The additional *Network Utilisation* unlocked on average by implement *Maximise NEM Service* DOE compared to static limits is 25% in the *City* network, 29% in the *Suburban* network, and 13% in the *Regional* network.

Figure 16 Box plots of *Network Utilisation* for each network type



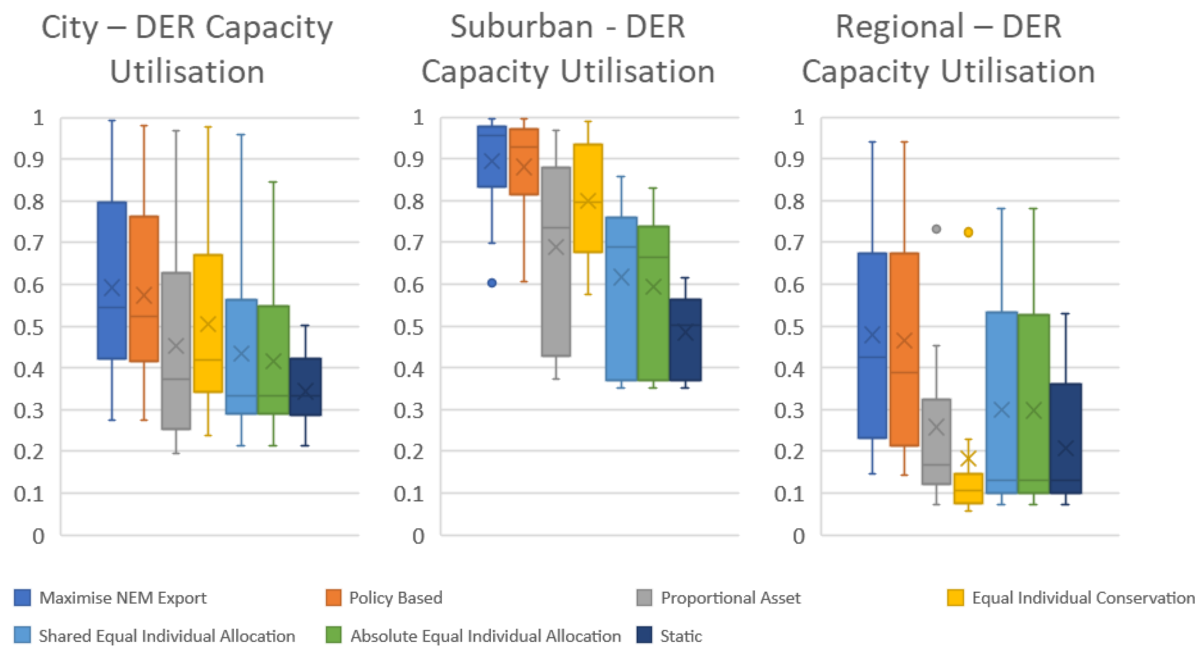
6.3 DER Capacity Utilisation

As with *Network Utilisation*, it is seen in Figure 17 that *Maximise Export (Maximise NEM Export)* performs best in *DER Capacity Utilisation,* with *Policy Outcome (Policy Based)* a close second. Similarly, *Equal kW Reduction (Equal Individual Conservation)* performs well in *City* and *Suburban*, but extremely poorly in *Regional*, mirroring the results for *Network Utilisation. Suburban* network has a much higher average *DER Capacity Utilisation* because it does not include commercial customers, and therefore the total DER install capacity is smaller than in the other two networks. In general, there are similar trends between the *DER Capacity Utilisation* and *Network Utilisation*.

In the *Suburban* network, there is an instance where the *DER Capacity Utilisation* value of *Maximise Export (Maximise NEM Export)* is slightly less than *Policy Outcome (Policy Based)*. In both these cases the *Network Utilisation* value is 1 (i.e., the network is exporting at the transformer's thermal capacity). The *Maximise Export (Maximise NEM Export)* objective finds a more efficient capacity allocation which reduces the losses in the network. However, because *Policy Outcome (Policy Based)* is trying to maximise capacity allocation rather than network exports, it will provide the solution with the most losses. Hence, the *DER Capacity Utilisation* is slightly larger for the same *Network Utilisation*.

For the *City* network, including fairness causes an average drop in *DER Capacity Utilisation* of between 9-18% of total DER capacity. For the *Suburban* network this value is 10-30%, and for *Regional* it is 18-30% depending on which objective is used. The additional *DER Capacity Utilisation* unlocked on average by implement *Maximise NEM Service* DOE compared to static limits is 25% in the *City* network, 41% in the *Suburban* network, and 27% in the *Regional* network.

Figure 17 Box plots of *DER Capacity Utilisation* for each network type



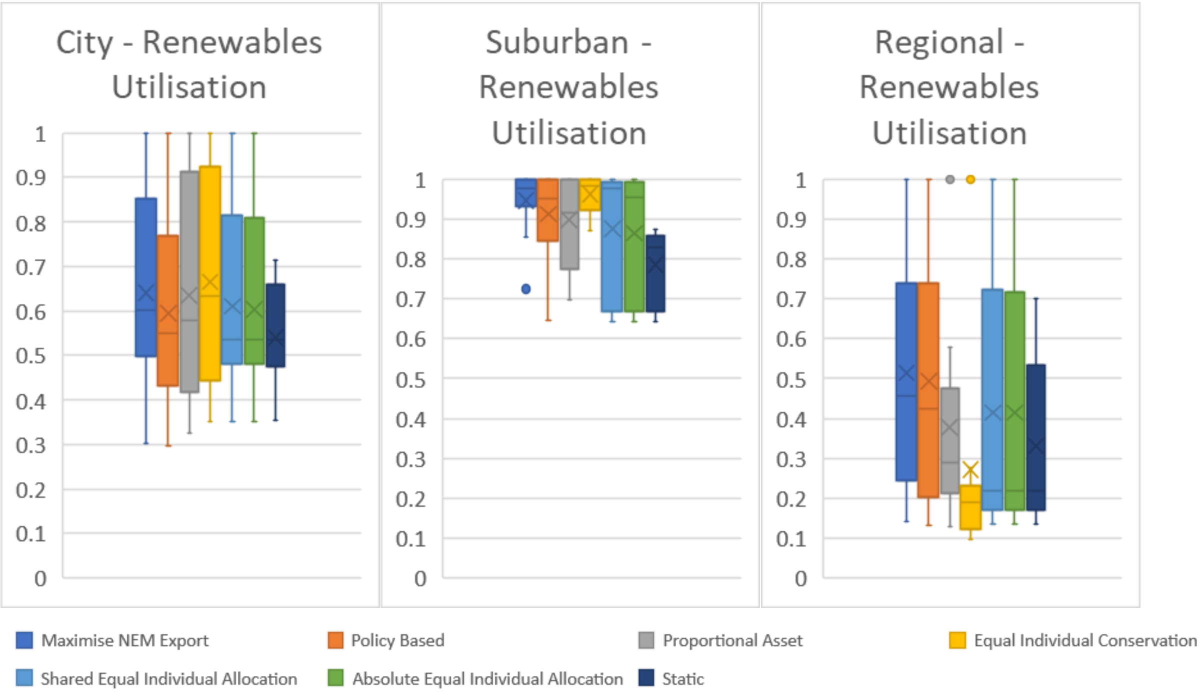
6.4 Renewables Utilisation

This is the only one of the three technical metrics where *Maximise Export (Maximise NEM Export)* and *Policy Outcomes (Policy Based)* don't perform substantially better than the other objective functions. In fact, for *City* and *Suburban* networks *Equal kW Reduction (Equal Individual Conservation)* performs best in Figure 18.

When calculating *Renewables Utilisation*, it is assumed that if export capacity is assigned to a customer with PV and battery, exporting from the PV will be prioritised over the battery. Therefore, any capacity assigned to a customer, up to the rated value of their PV, is assumed to be contributing to *Renewables Utilisation.* It is again noted here that this does not reflect the actual export of renewables, but rather the maximum renewable generation capacity that is unlocked by the DOEs.

For the *City* network, including *Equal kW Reduction (Equal Individual Conservation)* increases *Renewables Utilisation* by 2.5% compared to *Maximise Export (Maximise NEM Export)*. Other objective functions can reduce *Renewables Utilisation* by up to 4%. For the *Suburban* network, including *Equal kW Reduction (Equal Individual Conservation)* increases *Renewables Utilisation* by 2% compared to *Maximise Export (Maximise NEM Export)*. Other objective functions can reduce *Renewables Utilisation* by up to 8%. For *Regional* the *Renewables Utilisation* can be reduced between 10-24% compared to *Maximise Export (Maximise NEM Export)*. The reason that *Fixed Percentage (Proportional Asset), Equal Individual Allocation, Level Network Sharing (Shared Equal Individual Allocation)* and *Flat Access (Absolute Equal Individual Allocation)* perform better in *Renewables Utilisation* compared to the other technical metrics is because any capacity that is allocated to a customer is assumed to be prioritised to the renewable DER. These four objective functions are more likely to ensure that capacity is assigned to all customers, whereas *Maximise Export (Maximise NEM Export)s* is more likely to fully allocate capacity to some customers (for both their PV and battery) whilst assigning zero capacity to others. This makes it more likely for some customers to not have sufficient capacity for their renewable generation, whilst others are assigned capacity greater than their renewable generation. However, the fact that *Maximise Export (Maximise NEM Export)s* manages to assign significantly more capacity in general still means that it unlocks more *Renewables Utilisation* in most cases.

Figure 18 Box plots of *Renewables Utilisation* for each network type

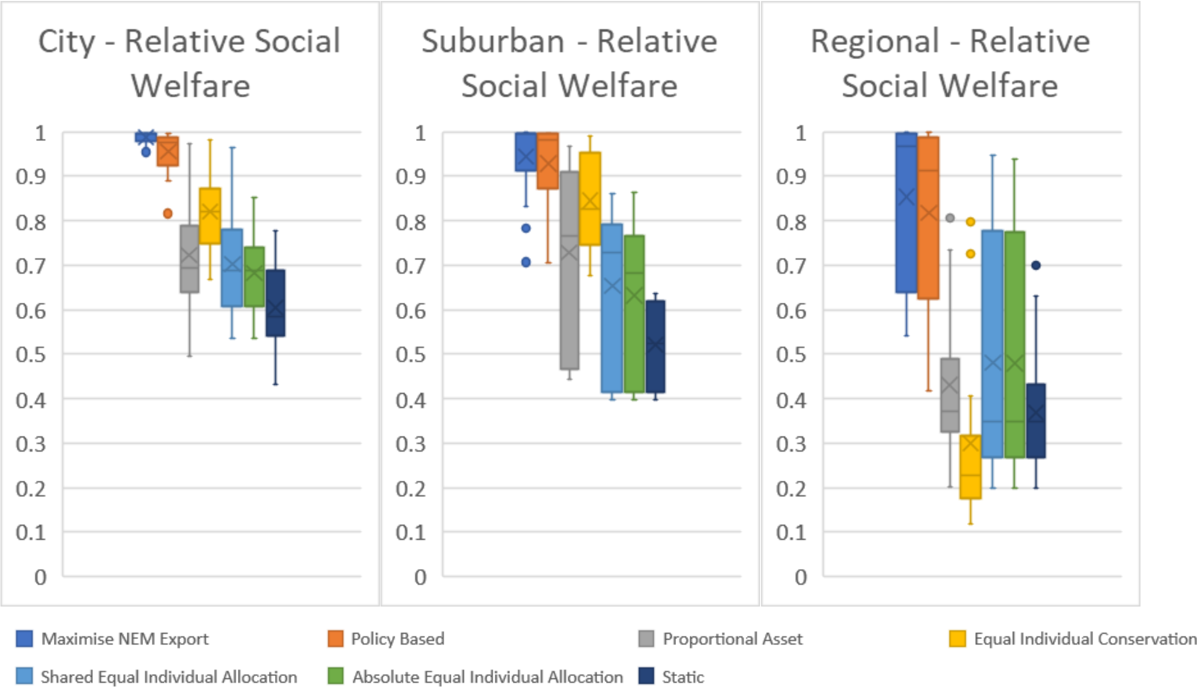


6.5 Relative Social Welfare

As can be seen in Figure 19, the objective functions rank in the same order from best to worst on the *Relative Social Welfare* scale as with the *DER Capacity Utilisation* metric. *Maximise Export (Maximise NEM Export)* still outperforms the economically focused *Policy Outcome (Policy Based)* objective. This is due to the high wholesale market price, which is significantly larger than the DER bids. This means that the performance in *Relative Social Welfare* is driven by the DER Capacity Utilisation rather than prioritisation of cheaper resources. *Maximise Export (Maximise NEM Export)* performs extremely well in *City*, but less so in *Suburban* and *Regional*. This is because in *Suburban*, the optimal social welfare involves some customers DER absorbing active power to address the phase imbalance. In *Regional* network, some customers' DER absorb active power to address the voltage rise on the secondary side of a specific LV transformer.

For the *City* network, including fairness causes an average drop in *Relative Social Welfare* of between 17-31% of total DER capacity. For the *Suburban* network this value is 10-31%, and for *Regional* it is 37-55% depending on which objective is used. The additional *Relative Social Welfare* unlocked on average by implement *Maximise NEM Service* DOE compared to static limits is 38% in the *City* network, 42% in the *Suburban* network, and 48% in the *Regional* network. This highlights that customers in general have a significant economic incentive to participate in the DER marketplace.

Figure 19 Box plots of Relative Social Welfare for each network type



6.6 Quality of Service

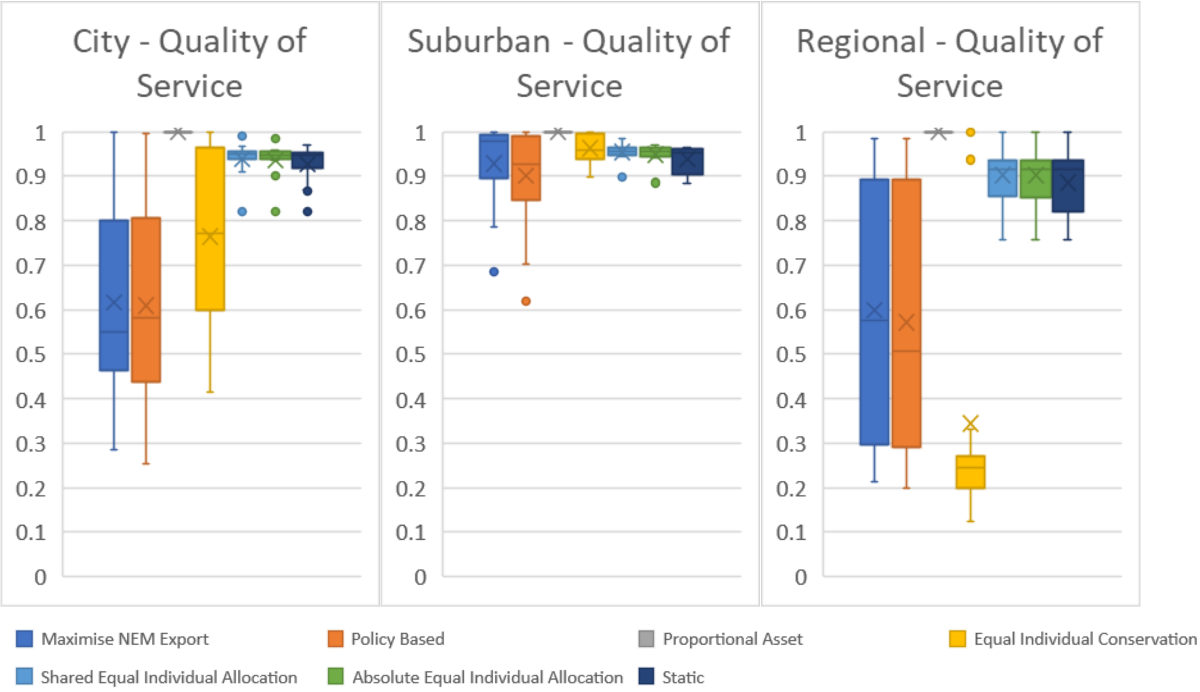
As opposed to the technical and economic metrics, for *Quality of Service* the *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* objective functions perform significantly worse than the other objective functions, shown in Figure 20. Additionally, the other objective functions are much more consistent with their performance, where *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* have a much larger range of values. It should be noted that *Fixed Percentage (Proportional Asset)* obtains a value of 1 in all cases, and this is due to the use of the normalised capacity allocated in the fairness metrics. This means, by definition, *Fixed Percentage (Proportional Asset)* will always achieve a value of 1 across all fairness metrics.

Maximise Export (Maximise NEM Export) and *Policy Outcome (Policy Based)* perform better in the *Suburban* network when compared to *City* and *Regional* because, for the *Suburban* network these objective functions achieve a much higher *DER Capacity Utilisation*, which impacts of the *Quality of Service* score. *Equal kW Reduction (Equal Individual Conservation)* performs so poorly in the *Regional* network because it performs so poorly in *DER Capacity Utilisation.*

This is then an example of how introducing fairness into the DOE objective functions can both reduce the technical performance and the fairness performance.

For *City* network including fairness in the DOE objective increases the *Quality of Service* by 15-38% on average. For the *Suburban* network these values are 2-7%, and for the *Regional* network the value increases by 30-40%, except for the *Equal kW Reduction (Equal Individual Conservation)* where *Quality of Service* is reduced by 25%. It is interesting to note that static limits perform very similarly to *Level Network Sharing (Shared Equal Individual Allocation)* and *Flat Access (Absolute Equal Individual Allocation)*. It is also interesting to see that *Policy Outcome (Policy Based)* performs worse than Maximise Export (Maximise NEM Export) in all the technical and economic metrics, and in Quality of Service.

Figure 20 Box plots of *Quality of Service* for each network type

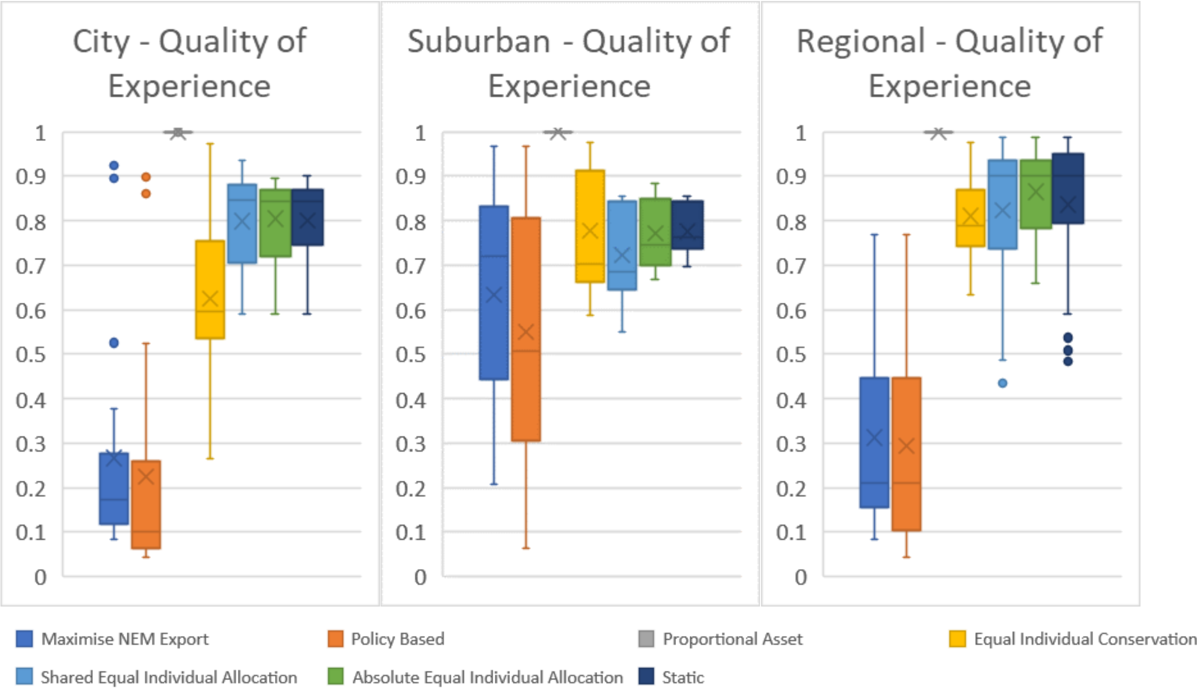


6.7 Quality of Experience

By looking at Figure 21, it is seen that, for the *City* and *Suburban* network, the order of performance of the objective functions is the same *Quality of Service*. However, in the *Regional* network, the *Equal Individual Unallocated* objective performs significantly better than for *Quality of Service*. This is because in its *Quality of Service* performance is hindered by the limited capacity that it assigns. However, for *Quality of Experience*, this fact is not considered in the calculation. Therefore, it performs comparably to *Level Network Sharing (Shared Equal Individual Allocation)* and *Flat Access (Absolute Equal Individual Allocation)*. As with *Quality of Service* it is seen here that static limits perform comparably to the fair allocation methodologies (except *Fixed Percentage (Proportional Asset))*, and in some cases actually performs better.

For the *City* network, including fairness in the DOE objective increases the *Quality of Experience* by 36-73%. For the *Suburban* network, those values are 9-37%. For *Regional* they are 50-69%.

Figure 21 Box plots of *Quality of Experience* for each network type

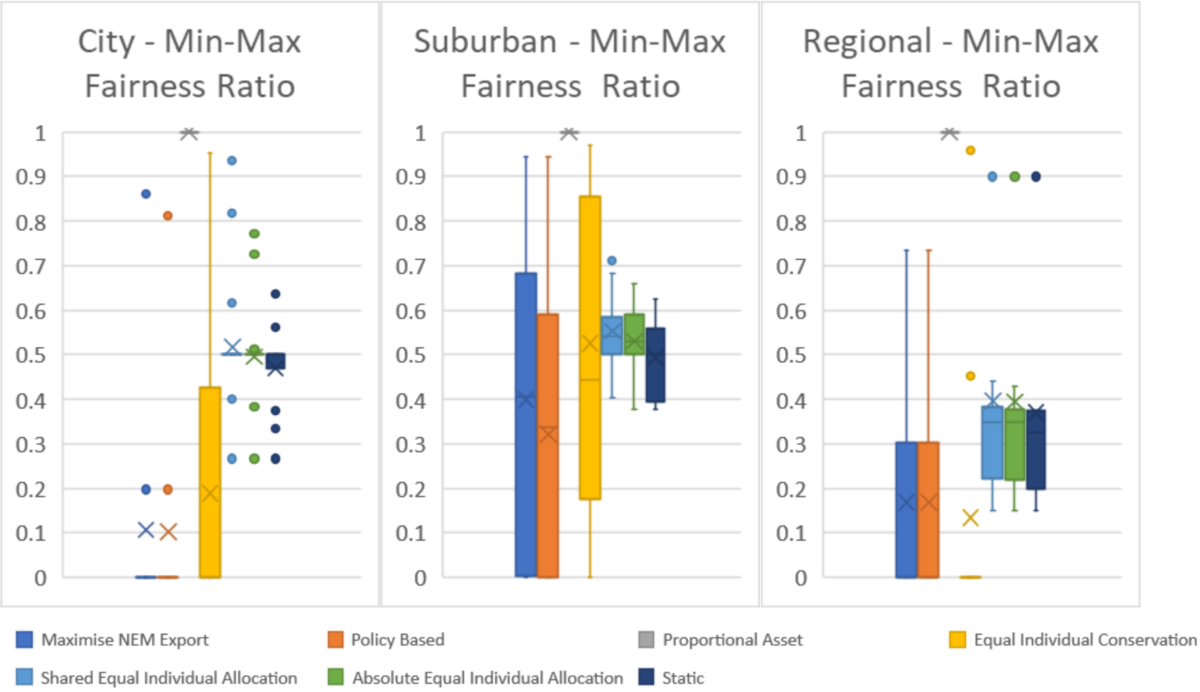


6.8 Min-Max Fairness

By looking at Figure 22, it can be seen that all DOE objectives, with the exception of *Fixed Percentage (Proportional Asset)* perform worse in *Min-Max Fairness* than in the other fairness metrics. This is because the value is driven by the capacity allocated to the customer who is assigned the least normalised capacity. For *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* this is often zero capacity, which is why so many of the cases have a value of 0 for *Min-Max Fairness*. For *Level Network Sharing (Shared Equal Individual Allocation), Flat Access (Absolute Equal Individual Allocation)* and static limits the value of *Min-Max Fairness* can be driven by the relative size difference between the customer with the most DER capacity, and the one with the least. For example, in the *City* network the customer with the largest DER has twice as much as the one with the smallest in a number of cases. This is why there is a concentration of values around the 0.5 value. The only time when *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* are not outperformed by the other DOE objective functions is for *Equal kW Reduction (Equal Individual Conservation)* in the *Regional* network, where due to the highly constrained network and the large range in DER size, some of the smaller DER are being allocated zero capacity, leading to a value of 0 for *Min-Max Fairness*.

For the *City* network, including fairness in the DOE objective increases the *Min-Max Fairness* by 8-90% depending on the DOE objective. For the *Suburban* network, those values are 13-60%. For *Regional* they are 23-83%, although *Equal kW Reduction (Equal Individual Conservation)* actually sees a 3.5% drop in *Min-Max Fairness*.

Figure 22 Box plots of Min-Max Fairness for each network type



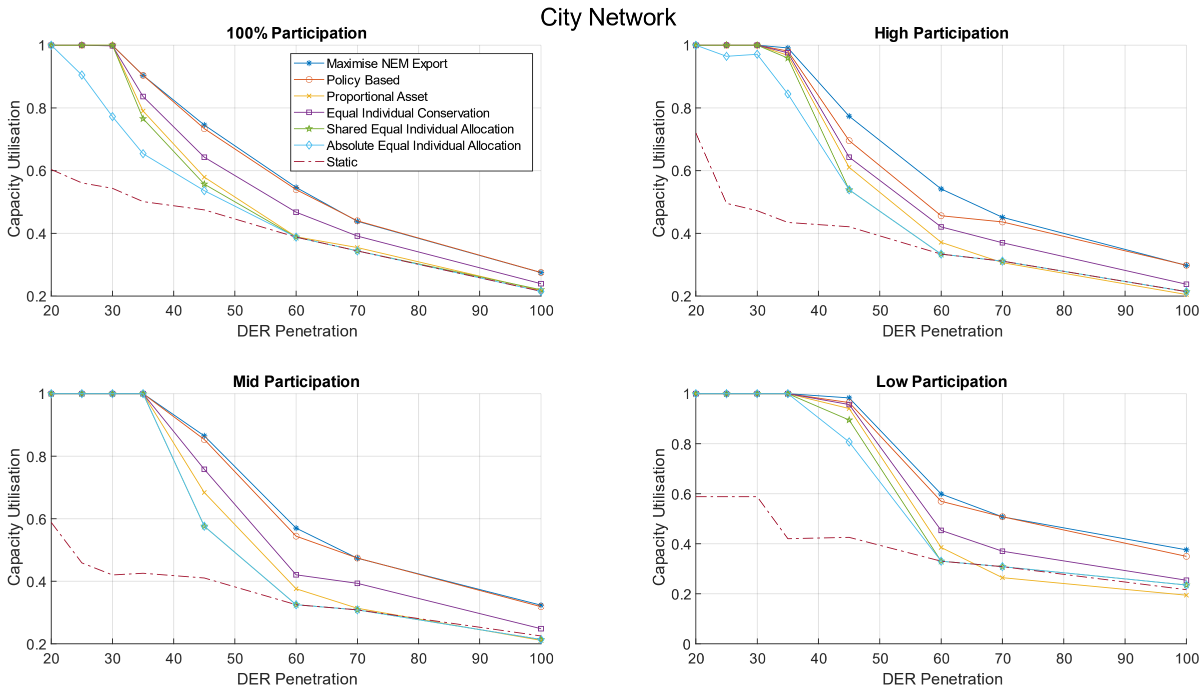
6.9 Summary of Metric Performance

In summary, *Maximise Export (Maximise NEM Export)* performs best in *Network Utilisation*, *DER Capacity Utilisation*, and *Relative Social Welfare*, with *Policy Outcome (Policy Based)* coming a close second. *Equal kW Reduction (Equal Individual Conservation)* can either perform relatively well, or extremely poorly in these metrics, depending on the network type and size range of DER. *Renewable Utilisation* is generally fairly comparable between the different DOE objective functions, with the exception of *Equal kW Reduction (Equal Individual Conservation)* in the *Regional* network. In general, *Equal kW Reduction (Equal Individual Conservation), Level Network Sharing (Shared Equal Individual Allocation), Flat Access (Absolute Equal Individual Allocation)* and static limits all perform significantly better then *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* across the fairness metrics (with the exception of *Equal kW Reduction (Equal Individual Conservation)* performance in *Min-Max Fairness* in the *Regional* network). However, *Equal kW Reduction (Equal Individual Conservation), Level Network Sharing (Shared Equal Individual Allocation), Flat Access (Absolute Equal Individual Allocation)* do not perform significantly better in the fairness metrics compared to static limits. With that being said, they do perform noticeably better in the technical and economic metrics in general.

6.10 Impact of Increased DER Penetration

As well as providing overviews as to the general performance of the DOE objective functions in the various metrics across the different networks, this section examines some examples of how performance changes with DER penetration and participation levels. Figure 23 shows how the *DER Capacity Utilisation* in the *City* network changes with DER penetration and participation levels. When all objective functions (except for *Flat Access (Absolute Equal Individual Allocation)* and static limits) have a value equal to 1, then the DNSP can assign full capacity to participating DER without the network becoming constrained. We can see for Low and Mid participation, this happens at 45% DER penetration, for High and 100% this happens at 35% DER penetration. For all participation levels, *DER Capacity Utilisation* decreases as DER penetration increases. This is as expected, as there is a finite capacity that can be allocated, and more DER being installed in the network.

Figure 23 *DER Capacity Utilisation* in the *City* network changing with DER Penetration and participation



Once 60% DER penetration is reached, the static limit unlocks a similar DER capacity as *Level Network Sharing (Shared Equal Individual Allocation), Flat Access (Absolute Equal Individual Allocation)*, and *Fixed Percentage (Proportional Asset)*. It should be noted however that this does not mean that in general static limits will perform as well as these DOEs, as in times of less constrained operation the DOEs will be able to allocate more capacity, whereas the static limit will still be constraining the DER at this value.

Figure 24 shows the *Network Utilisation* of the *City* network for different DER penetrations and participations. Of special note is that between the DER penetration levels of 45% and 60% the *Network Utilisation* for the *Fixed Percentage (Proportional Asset), Level Network Sharing (Shared Equal Individual Allocation), and Flat Access (Absolute Equal Individual Allocation)* reduces. The same occurs from 70% to 100% DER penetration. This means that introducing more DER into the network at this stage has reduced the amount of power that the network can export, not increased it. This can occur with these DOE objective functions because the capacity that they are allocated is governed by the most constrained DER. Therefore, if a DER joins the network in a congested location, this can limit the capacity that can be allocated to all participating DER. This is why additional DER participation can also cause decreased *Network Utilisation*.

This phenomenon is also seen in the *Suburban* network in Figure 25 between 70% and 100% DER penetrations, although for *Equal kW Reduction (Equal Individual Conservation)* this does not occur, and in fact for the 100% participation scenario, the *Network Utilisation* dramatically increases.

Figure 24 ***Network Utilisation*** **in the** ***City*** **network changing with DER Penetration and participation**

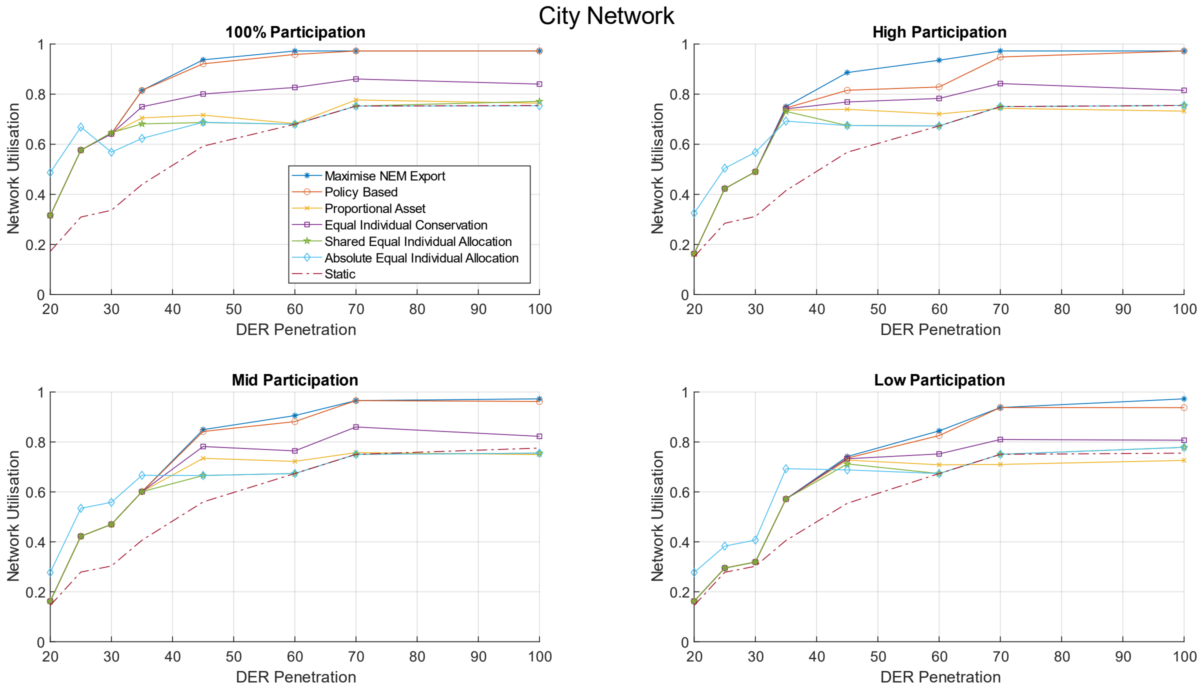
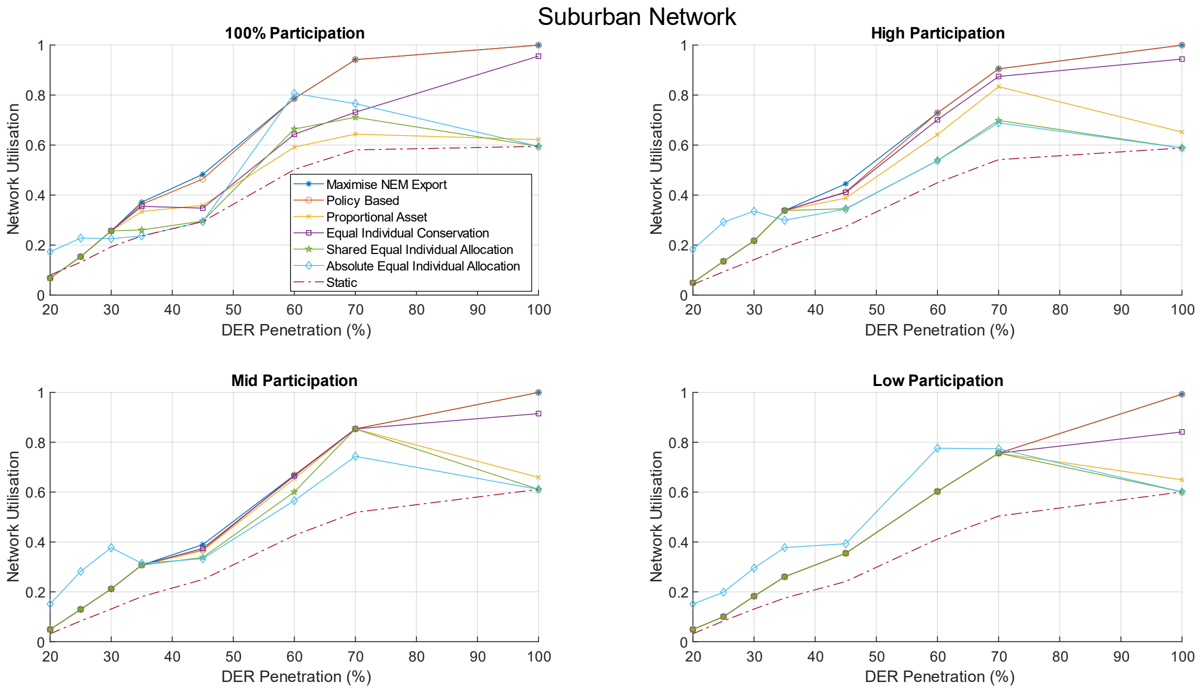


Figure 25 ***Network Utilisation*** **in the** ***Suburban*** **network changing with DER Penetration and participation**



Increased participation in DER marketplaces may also cause reduced *Network Utilisation* in the fair objective functions. In fact, for *Equal kW Reduction (Equal Individual Conservation)* the *Network Utilisation* value decreases slightly between the Mid participation and High participation cases. Similarly, the *Network Utilisation* value for *Level Network Sharing (Shared Equal Individual Allocation)* decreases from the Low participation level to the High participation level.

In Figure 25, the *Network Utilisation* value for *Flat Access (Absolute Equal Individual Allocation)* in unconstrained cases is higher than the actual network export capability that is unlocked. This is because *Flat Access (Absolute Equal Individual Allocation)* can over-allocate capacity, and therefore the value of *Network Utilisation* the calculation believes it has unlocked can be greater than the actual value. This overallocation can also occur in constrained cases.

The impact of 100% DER participation on *Network Utilisation* for the different network types is seen in Figures 24-26. For the *City* network, 100% DER participation unlocks significantly more *Network Utilisation* than the other participation rates at low penetration levels. Then the impact of different DOE objective functions occurs at a lower penetration rate, and the difference between the objective functions is more pronounced than other participation rates. Whilst the *Suburban* network doesn't see the same increase in *Network Utilisation* at low penetration rates, the divergence in DOE objective results is also felt sooner than with lower participation levels. One of the largest impacts of the 100% DER participation rate is seen in Figure 26 for the *Regional* network. For the Low – High participation levels, at the 45% penetration rate *Network Utilisation* drops for all objective functions. This is because DER have been added at the end of a long feeder, and they are not participating in the DER marketplace. Therefore, they drastically reduce the capacity that can be allocated to the participating DER. However, in the 100% participation rate, these DER are participating in the DER marketplace. The result of this is that *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* both increase their *Network Utilisation* dramatically. This highlights the benefits that can be derived from full customer participation, especially if *Maximise Export (Maximise NEM Export)* or *Policy Outcome (Policy Based) D*OE objective functions are being utilised.

In Figure 27, it is shown how *Equal kW Reduction (Equal Individual Conservation), Fixed Percentage (Proportional Asset), Level Network Sharing (Shared Equal Individual Allocation), and Flat Access (Absolute Equal Individual Allocation)* can all become less effective at assigning capacity as participation levels increase. By comparing the High participation and 100% participation for the 20% penetration level, it is apparent that the additional participating DER cause a drastic decrease in some of those DOE objective functions. The same phenomenon can be seen by comparing the Low, Mid, and High DER participation levels for 30% penetration level. At Low participation, all DER capacity is allocated. By the High participation level, capacity allocated was well below 40% for some objective functions. Part of this decrease is due to the fact that there is now more capacity to allocated. However, the fact that the difference between *Maximise Export (Maximise NEM Export)*, and *Equal kW Reduction (Equal Individual Conservation), Fixed Percentage (Proportional Asset), Level Network Sharing (Shared Equal Individual Allocation), and Flat Access (Absolute Equal Individual Allocation)* in these cases increases shows that these DOE objective functions are severely handicapped by the increased DER participation.

Figure 26 *Network Utilisation* in the *Regional* network changing with DER Penetration and participation

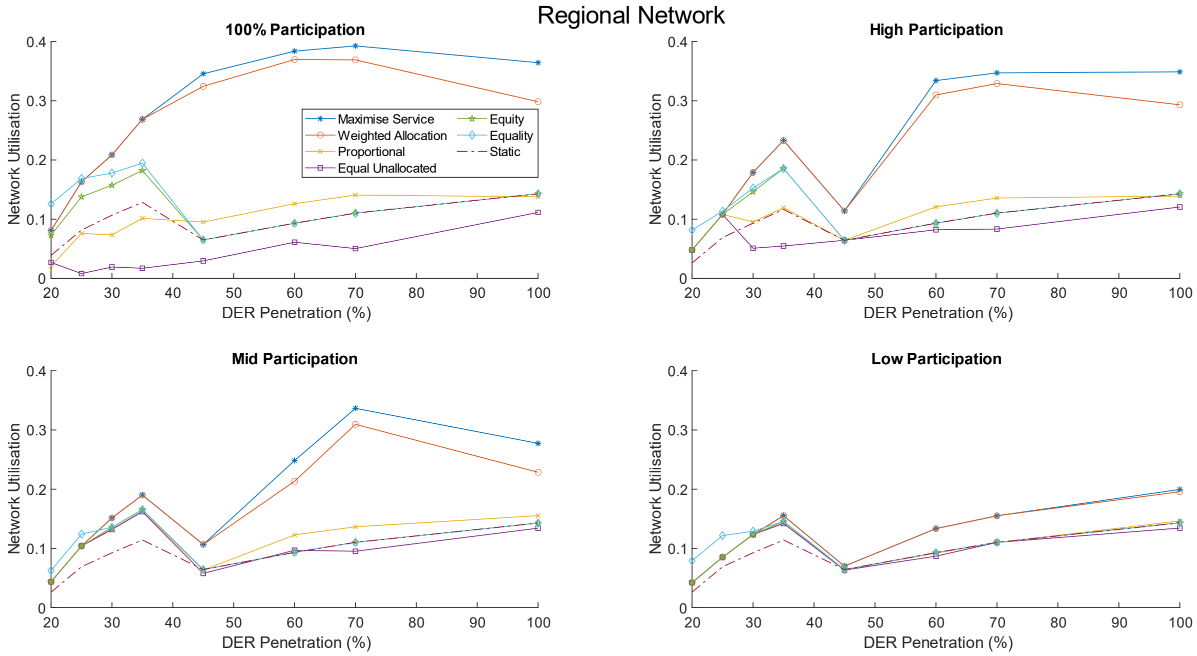
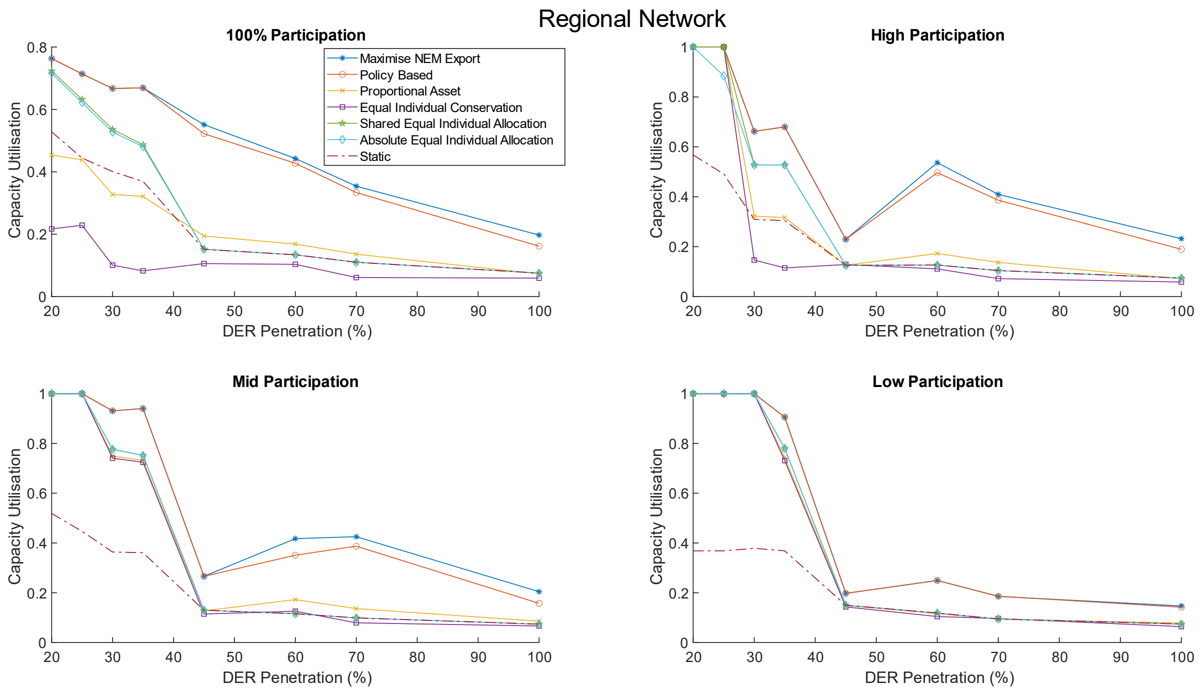


Figure 27 *DER Capacity Utilisation* in the *Regional* network changing with DER Penetration and participation



6.11 Correlation between metrics

Tables 5-7 show the correlation between the different metrics for each of the representative networks. A correlation value of 1 between metric A and metric B means that every time metric A increases or decreases, metric B also increases or decreases moving in the same direction. A correlation value of -1 means that every time metric A increase or decreases, metric B moves in the opposite direction, decreasing or increasing respectively. A correlation of 0 indicates that there appears to be no relationship between the two metrics.

First, it can be seen by examining Tables 5-7 that correlations between the metrics can differ between the different representative networks. In the *City* network, there is a strong negative correlation between *Network Utilisation* and all of the fairness metrics. This implies that in this network, increasing network utilisation generally comes at the cost of fairness or conversely increasing fairness comes at the cost of network exports. However, this correlation is much weaker, although still negative, in the *Suburban* network. That is because the *Suburban* network is less constrained and often manages to allocate very high percentages of the requested capacity. Therefore, it also performs well in the fairness metrics. This is why this correlation is less strong. A strong negative correlation between *Quality of Experience* and *Network Utilisation* is also seen for the *Regional* network.

Table 5 Correlation between metrics for *City* network

	NU	DCU	RU	QoS	QoE	MMF	RSW
Network Utilisation	1.00						
DER Capacity Utilisation	-0.03	1.00					
Renewables Utilisation	-0.29	0.92	1.00				
Quality of Service	-0.77	0.20	0.42	1.00			
Quality of Experience	-0.74	-0.05	0.19	0.89	1.00		
Min-Max Fairness	-0.61	0.14	0.31	0.79	0.87	1.00	
Relative Social Welfare	0.74	0.56	0.29	-0.52	-0.60	-0.39	1.00

Table 6 Correlation between metrics for *Suburban* network

	NU	DCU	RU	QoS	QoE	MMF	RSW
Network Utilisation	1.00						
DER Capacity Utilisation	0.15	1.00					
Renewables Utilisation	-0.01	0.86	1.00				
Quality of Service	-0.28	0.18	0.36	1.00			
Quality of Experience	-0.27	-0.05	0.11	0.88	1.00		
Min-Max Fairness	-0.26	0.08	0.21	0.74	0.89	1.00	
Relative Social Welfare	0.17	0.99	0.85	0.11	-0.12	0.01	1.00

Table 7 Correlation between metrics for *Regional* network

	NU	DCU	RU	QoS	QoE	MMF	RSW
Network Utilisation	1.00						
DER Capacity Utilisation	0.33	1.00					
Renewables Utilisation	0.26	0.97	1.00				
Quality of Service	-0.12	0.33	0.43	1.00			
Quality of Experience	-0.64	-0.22	-0.07	0.57	1.00		
Min-Max Fairness	-0.23	0.29	0.40	0.77	0.64	1.00	
Relative Social Welfare	0.59	0.88	0.79	0.14	-0.58	0.04	1.00

Network Utilisation and *DER Capacity Utilisation* are not strongly positively correlated because, once a network is congested, adding additional DER may not result in significant additional *Network Utilisation*, but will result in a reduction of *DER Capacity Utilisation*. This changing behaviour in *DER Capacity Utilisation* once the network is heavily congested means that it does not have a strong correlation with *Network Utilisation* or any of the fairness metrics. This is similarly why *Renewables Utilisation* does not have a strong positive correlation.

It is expected that *Network Utilisation* and *DER Capacity Utilisation* would have significant positive correlation with *Relative Social Welfare*. This is true in most cases, except for *Suburban* network, where the positive correlation between *Network Utilisation* and *Relative Social Welfare* isn't very strong. This can be attributed to the more gradual increase in total DER capacity installed in the *Suburban* network (due to the lack of commercial customers with DER). This means that for lower DER penetrations, *Network Utilisation* would be low, but *DER Capacity Utilisation* and *Relative Social Welfare* very high. As DER penetration increases, *Network Utilisation* increases but the network will start becoming more constrained. This is where it is likely that the drops in *Relative Social Welfare* will occur, where centralised control of DER would assist in unlocking additional capacity. So as *Network Utilisation* increases, *Relative Social Welfare* remains fairly constant, and once *Network Utilisation* becomes fairly constant, *Relative Social Welfare* starts decreasing. This is why a strong correlation is not seen in this case.

It is seen that all of the fairness metrics experience strong positive correlation amongst themselves. This provides confidence that the chosen metrics, whilst measuring fairness in a different way, generally align in their determination of how fair a certain capacity allocation is.

In *City*, there is a significant negative correlation between *Network Utilisation* and the three fairness metrics. This aligns with the results that we have observed thus far. For the *Suburban* network, this negative correlation occurs, but is much less significant. This is due to the fact that the *Suburban* network is less constrained and has a more gradual introduction of DER (due to the lack of commercial DER customers). Therefore, *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* manage to perform well in the fairness metrics for a more significant portion of the studied scenarios. Thus, the trade-off between technical perform and fairness occurs later in the DER penetration levels, and so is a smaller proportion of the results, leading to a weaker correlation. For the *Regional* network the negative correlation between *Network Utilisation* and *Quality of Experience* is significant, but for the other two fairness metrics it is less so. This can be attributed to the *Equal kW Reduction (Equal Individual Conservation)* DOE objective. This objective performs so poorly in *Network Utilisation* in the *Regional* network that it also performs very poorly in *Quality of Service* and *Min-Max Fairness Ratio*. This does not fit the pattern of poor performance in *Network Utilisation* leading to high performance in the fairness metrics. However, in *Quality of Experience, Equal kW Reduction (Equal Individual Conservation)* does perform well, and so we see the strong negative correlation.

7 Summary of Results

The effectiveness of static limits moving into the future is not only heavily dependent on network strength and number of DER in the network, but also the location of the DER in the network, and the phases on which those DER are connect. It is seen in Table 4 above that DER being installed in the same area of the network (in this case the *Regional* network) can lead to a sharp decrease in the allowable static limit of the network. Additionally, it is also shown in Table 4 (for the *Suburban* network) that imbalance in the phases to which the DER are connected can significantly reduce the allowable static limit. If new DER are connected to the under-represented phase to counteract this phase imbalance, then all sites in the network can receive a higher static limit, even though there are more DER in the network.

With regard to the technical and economic metric performance of DOE objective functions:

- Maximise Export (Maximise NEM Export) and Policy Outcome (Policy Based) consistently outperform Equal kW Reduction (Equal Individual Conservation), Fixed Percentage (Proportional Asset), Level Network Sharing (Shared Equal Individual Allocation), and Flat Access (Absolute Equal Individual Allocation) in Network Utilisation and Capacity Utilisation by 7– 30% on average depending on the network and DOE objective chosen.
- Generally, the difference between the DOE objective functions in Renewables Utilisation is much smaller, and in City and Suburban cases *Equal kW Reduction (Equal Individual Conservation)* performs best on average for Renewables Utilisation. However, in the Regional network, *Equal kW Reduction (Equal Individual Conservation)* performs the worst in all of the technical metrics, even worse than static limits for this high export use case. This highlights the volatility of the performance of *Equal kW Reduction (Equal Individual Conservation)* where, depending on the network, it can perform well or extremely poorly.
- A similar jump in the performance for Relative Social Welfare of Maximise Export (Maximise NEM Export) and Policy Outcome (Policy Based) compared to Equal kW Reduction (Equal Individual Conservation), Fixed Percentage (Proportional Asset), Level Network Sharing (Shared Equal Individual Allocation), and Flat Access (Absolute Equal Individual Allocation) is seen. In fact, this separation in performance is more pronounced with an average difference of 10-55% depending on network and DOE objective.

The trade-off for the high performance of *Maximise Export (Maximise NEM Export)* and *Policy Outcome (Policy Based)* in the technical and economic metrics is that they perform poorly in the fairness metrics applied to the actively participating customers (a subset of customers in the network who own DER and are actively participating in a VPP).

- For Quality of Service and Quality of Experience it is seen that Maximise Export (Maximise NEM Export) and Policy Outcome (Policy Based) perform better in networks with higher Capacity Utilisation scores. However, they consistently perform worse than the other DOE objective functions (with the exception of Equal kW Reduction (Equal Individual Conservation)'s performance of Quality of Service and Min-Max Fairness in the Regional network).
- *Policy Outcome (Policy Based)* in general performs more poorly in all of the metrics when compared to *Maximise Export (Maximise NEM Export)*. However, the performance of this DOE objective is likely to differ depending on the policy that is adopted, and the specific weightings that are chosen to support it. A full analysis of policies and weightings should be conducted by a DNSP before using this DOE objective to help align results with the policy aims. Given the proposed change to the NEO to include carbon emissions, this *Policy Outcome (Policy Based)* objective function could be used in an attempt to maintain the efficiency of capacity allocation whilst prioritising renewable generation and other low emissions technologies.

Network characteristics have a strong influence on the performance of DOE objective functions.

- It was seen in the *Regional* network that additional DER participation in the DER marketplace can cause a dramatic drop in the capacity that is allocated for *Equal kW Reduction (Equal Individual Conservation), Fixed Percentage (Proportional Asset), Level Network Sharing (Shared Equal Individual Allocation), and Flat Access (Absolute Equal Individual Allocation).*

- Additionally, we see that high DER penetration levels can also cause these fairer DOE objective functions to become less effective at unlocking network exports. This phenomenon is seen across all three representative networks.
- When a network becomes constrained, there is a negative correlation between performance in *Network Utilisation* and the three fairness metrics. The more constrained the network, the more significant this correlation. The times when we don't see this occur in the *Regional* network is when *Equal kW Reduction (Equal Individual Conservation)* performs poorly in both metrics, which is not a desirable outcome.

In general, the results show that imposing fairness requirements into the DOE objective function calculation on the division of capacity allocated to customers participating in the DER marketplace has a detrimental impact on the technical and economic performance of the DOEs. Additionally, this negative impact can become worse with higher DER penetration rates as networks become more constrained. Utilising a DOE objective that directly considers fairness does not guarantee a fairer allocation of capacity. This report has highlighted some cases (*Equal kW Reduction (Equal Individual Conservation)* in the *Regional* network) where using a fair DOE objective has such a profound negative impact on the capacity that is allocated that it also reduces the fairness of the DOE objective. Increasing system technical and economic efficiency is likely to provide the most benefits to all customers in the NEM and could be considered to maximise fairness from a whole-of-system perspective. Therefore, in the interest of system efficiency, it is recommended that *Maximise Export (Maximise NEM Export)* be the default DOE objective function, and it is strongly advised that DNSPs conduct techno-economic modelling on their networks before implementing other DOE objective functions to fully understand the associated negative technical and economic impacts.

Additionally, whilst not the main focus of this report, it has been shown that currently in some networks the static limits may be highly conservative and moving into a high DER future they will need to be reduced as has been seen in Section 6.1. Network type, DER location, and DER phase connection will all have a significant impact on the static limits that can be safely imposed in any given network. It is recommended that there is further work conducted into a systematic method of determining appropriate static limits for customers who are not participating in a DER marketplace.

This work proposes a range of DOE objective functions that could be used by DNSPs, as well as detailed methods by which to assess their efficacy. This should provide tools to and inform discussions between DNSPs, market operators, and policy makers for decisions surrounding DER marketplaces, implementations of DOEs, and future changes to static limits.

Appendix A. DOE import limits

The main body of this report is focused on the export limits that the different DOE objective functions can unlock, and the metrics by which their performance can be measured. However, these DOE objective functions and metrics are equally suitable for analysis the DOE import limits which could also be imposed on actively participating customers. This Appendix is provided to highlight how these objective functions and metrics could be applied to DOE import limits. However, there are a number of issues that need to be further addressed for practical implementation of DOE import limits.

A.1 Caveats and Further Considerations

DOE import limits have many complicating considerations that make them more complex than export limits. For example, DNSPs have an obligation to provide customers with sufficient capacity to satisfy their base load requirements (for example when they switch on their kettle or turn on a light). This is distinct from exports, where the DNSP can set export limits to 0 kW for a certain time period if required.

One issue that will need to be addressed is whether the DOE import limits provided to customers encompass both base load and flexible load, or just flexible load. The former would mean that a customer increasing their essential load (such as turning on their kettle) could violate their DOE import limits. This could then lead to a financial penalty for not complying with the DOE limits. However, if the latter option is chosen and the DOE import limits are only issued for a customer's flexible load, then all flexible load must be separately metered to the base load to be able to measure compliance. This approach would ring-fence the customer's base load to ensure that it was not constrained by DOE import limits.

This leads to the issue of the definition of base load vs flexible load. A good example of this is electric vehicles (EV). These resources have the potential to be highly flexible in their charging, responding to DOE limits. However, an EV is someone's mode of transportation, and if the travel that they wish to undertake is essential (e.g., to travel to work), then it could be reasonably asserted that this EV demand should be captured within their base load. Therefore, further thought needs to be given to the distinction between base load and flexible load.

If base load and flexible load are being separated for the calculation and implementation of DOE import limits, then accurate load forecasts for individual customers would be required. When it comes to voltage constraints, the location of power demand is key. This means that a diversified view of customer demand is not sufficient to ensure that network voltage constraints are adhered to. In practice, an accurate forecast for an individual house is not something that can be predicted with a high level of certainty. If a DNSP is confident that under-voltages will not be an issue in the network, then diversified customer demand forecasts may be suitable for ensuring the network thermal limits alone are not breached.

In this report, it is assumed that DOE import limits are applied only to the flexible loads of participating customers and will not constrain base load demand. This in turn would require that flexible loads be metered separately to base load. Additionally, while the total network load is based on the after-diversity maximum demand (ADMD) level of 4 kW per customer, the baseload demand of each individual customers is assigned randomly to obtain the necessary ADMD. This cannot therefore be viewed as a best-case scenario, nor a worst-case scenario, but rather one possible realisation of a given ADMD level. Using these assumptions allows this report to demonstrate the suitability of the DOE objective functions and metrics for DOE import limits.

A.1.1 DOE Objective Functions for Imports

The six DOE objective functions were designed such they could easily be applied to either DOE export limit calculations or DOE import limit calculations. In Section 2, the DOE objective functions were proposed and explained from the view of export limits. In this section, the report will briefly indicate how these objective functions can be applied to DOE import limits too.

A.1.2 Maximise Export (Maximise NEM Import)

For clarity, in this case the name of the DOE objective function has been changed from *Maximise Export (Maximise NEM Export) to Maximise NEM Import*. The names of the other objective functions remain the same. *Maximise NEM Import* focuses on maximising the total active power that can be imported by participating DER in the LV network, maximising the amount of flexible load that can be utilised by customers at any time. This is measured as the total active power import at the head of the feeder, to provide the most efficient allocation of capacity whilst maximising imports. This objective is shown in (A1)), where P^{im} is the active power import at the head of the feeder.

$$\max P^{im} \tag{A1}$$

A.1.3 Policy Outcome (Policy Based)

Policy Outcome (Policy Based) provides a DNSP the ability to set a weighting coefficient (α_k) to each DER or customer based on a policy outcome. The objective is shown in (A2)), which maximises the sum of the flexible import capacity allocated (P_k^I) to participation customer k multiplied by their weighting coefficient set by the DNSP.

$$\max \sum_{k \in DER} \alpha_k P_k^I \tag{A2}$$

A.1.4 Fixed Percentage (Proportional Asset)

Fixed Percentage (Proportional Asset) aims to allocate capacity to customers based on their need, which here is assumed to be the rated flexible import capacity of their DER. This means that each DER or customer is allocated *X*% of their rated capacity, where the value of *X* is the same for all participating DER and is maximised as part of the DOE calculation. Using this method, the DNSP aims to maximise the value of X, as in (A3)), and it is also subject to the following additional constraint (A4)) which enforces the *Fixed Percentage (Proportional Asset)* approach, where P_k^{I-Max} is the rated capacity of flexible imports of each customer k.

$$\max X \tag{A3}$$

$$XP_k^{I-Max} = P_k^I \quad , \forall k \in DER \tag{A4}$$

A.1.5 Equal kW Reduction (Equal Individual Conservation)

The aim of *Equal kW Reduction (Equal Individual Conservation)* is that, if there are constraints within the network, then the required reduction in flexible import capacity should be distributed evenly across all participating DER. Therefore, each participating customer has their allocated flexible import capacity reduced to Y kW below their rated flexible import capacity. The value of Y is the same across all participating DER and is calculated to be the minimum possible value (i.e., capacity is reduced by the smallest amount possible) as part of the DOE calculation. Using this method, the DNSP aims to minimise the value of Y, as in (A5)), and it is also subject to the following additional constraint (A6)) which enforces the *Equal kW Reduction (Equal Individual Conservation)* approach.

$$\min Y \tag{A5}$$

$$P_k^{I-Max} - P_k^I = Y \quad , \forall k \in DER \tag{A6}$$

A.1.6 Level Network Sharing (Shared Equal Individual Allocation)

Level Network Sharing (Shared Equal Individual Allocation) aims to allocate equal flexible import capacity to each customer. However, the flexible import capacity that each customer can be allocated cannot be greater than the rated flexible import capacity of their DER. This is done so that flexible import capacity isn't overallocated to customers with smaller DER who cannot use that flexible import capacity. Therefore, each customer is allocated flexible import capacity equal to the minimum of Z kW and P_k^{I-Max} kW (enforced by Equation (A8)) and the DOE calculation aims to maximise Z as in (A7)).

$$\max Z \tag{A7}$$

$$P_k^I = \min(Z, P_k^{I-Max}) \quad , \forall k \in DER \tag{A8}$$

A.1.7 Flat Access (Absolute Equal Individual Allocation)

The *Flat Access (Absolute Equal Individual Allocation)* approach aims to allocate equal flexible import capacity to each customer, regardless of the size of the customers' DER. Therefore, each customer is allocated Z kW, as in the constraint (A9)). This may result in overallocation of flexible import capacity to smaller DER. This approach aims to maximise Z as in (A7).

$$P_k^I = Z \quad , \forall k \in DER \tag{A9}$$

A.2 Metrics

The metrics proposed in the main body of the report are for export limits. However, with slight tweaking, they are suitable for import limits also. *Network Utilisation* can be calculated using the total network power import P^{im} as in (A10)).

$$NU = \frac{P^{im}}{P^{Tx}} \tag{A10}$$

DER Capacity Utilisation can be calculated using the import capacity that is assigned to each DER P_k^I, and the rated import capacity of each DER P_k^{I-Max} as in (A11)).

$$DCU = \frac{\sum_{k \in DER} P_k^I}{\sum_{k \in DER} P_k^{I-Max}} \tag{A11}$$

Renewables Utilisation can be calculated using (A12)). However, none of the flexible loads are renewable generators, so by default the value of *Renewables Utilisation* for DOE imports is '0'.

$$RU = \frac{\sum_{k \in RES} P_k^I}{\sum_{k \in RES} P_k^{I-Max}} \tag{A12}$$

The *Relative Social Welfare* calculation does not differ from that in (13) and (14)). The fairness metrics are also calculated as in (16)-(18). However, the value of normalised capacity allocated $\overline{P_k}$ must now be calculated as in (A13)).

$$\overline{P_k} = \frac{P_k^I}{P_k^{I-Max}} \tag{A13}$$

In this way, all of the metrics proposed in this report can now also be used to assess the DOE import limits.

A.3 Results

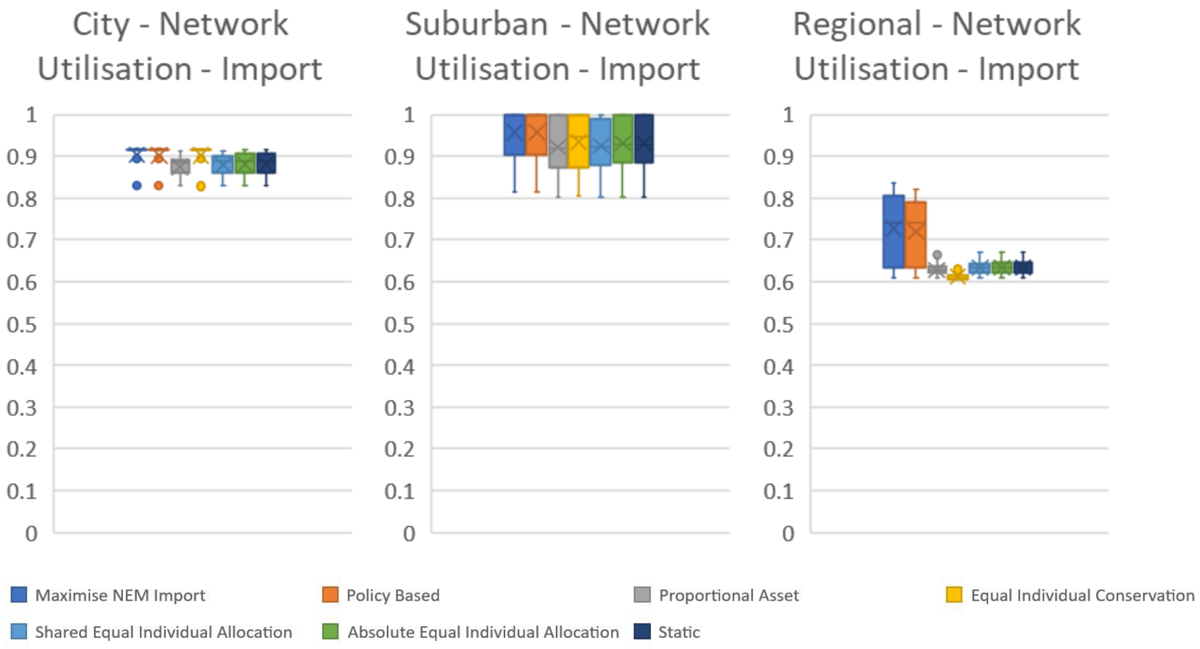
The results in this section are from the same studies that were conducted in Section 6 of the main report, including the same networks, DER penetration scenarios, and DER participation levels. The main difference is, for the DOE import limits we are assessing the use case where the network is at peak demand, rather than the peak generation use case that was used in the assessment of the DOE export limits. It should be noted that for imports the static limits results are identical to the *Flat Access (Absolute Equal Individual Allocation)* because, if customers are not actively participating in the DER marketplace, their import DOE will be 0 kW, as all of their demand is assumed to be base load. Additionally, there are no results for *Renewables Utilisation* because renewable generation is associated with exports only.

A.3.1 Network Utilisation

The Network Utilisation values for import DOE limits are much more closely grouped than the export DOE limit equivalents. This is due to the fact that this metric also captures the baseload that the network is supplying. By the design of the use case, this base load is very close to network capacity. For the City network, the current rating of the lines leading to the LV transformer are met with very little flexible load.

In fact, for the *City* network at low voltages the current flow in the lines is the binding thermal constraint, rather than the LV transformer. So, in the *City* network *Maximise NEM Import, Policy Outcome (Policy Based)*, and *Equal kW Reduction (Equal Individual Conservation)* are thermally constrained for the majority of scenarios, as seen in Figure 28.

Figure 28 Box plot of Network Utilisation for each network type for import DOE limits

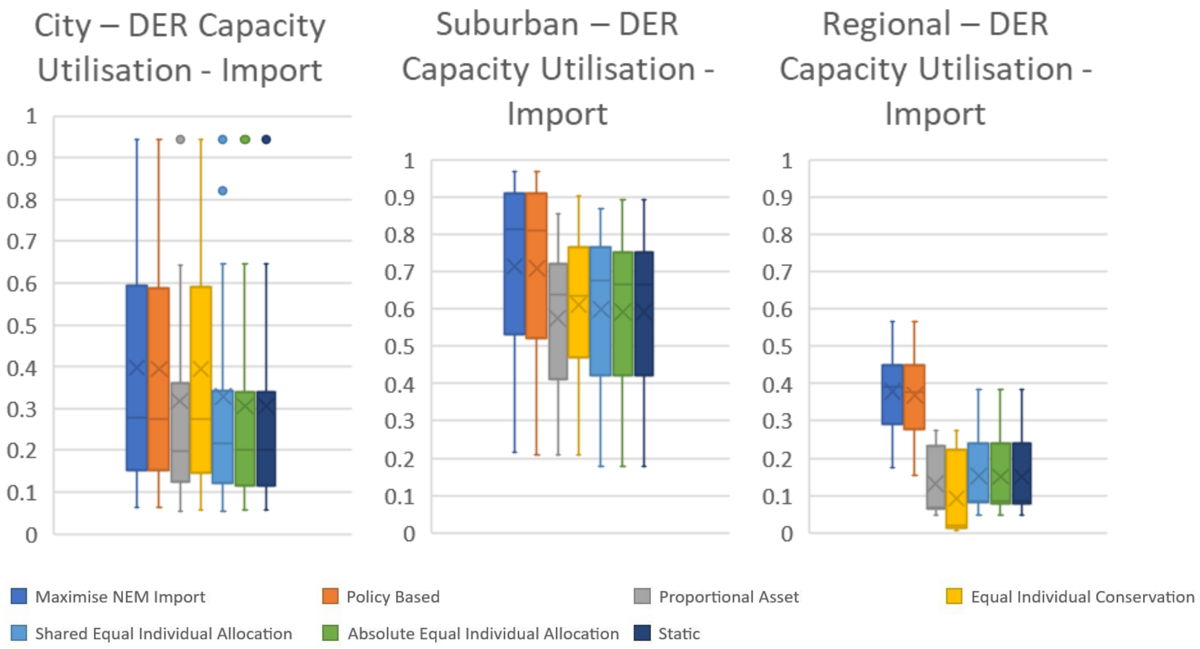


The difference between *Maximise NEM Import / Policy Outcome (Policy Based)* and the other DOE objective functions is only clearly delineated in the *Regional* network. In *City* and *Suburban*, the amount of available DER capacity far outweighs the available network capacity, so the DER objective functions have similar results. The *Regional* network is additionally constrained by the thermal limits of the LV transformers in the SWER network, which can leave *Fixed Percentage (Proportional Asset), Equal kW Reduction (Equal Individual Conservation), Level Network Sharing (Shared Equal Individual Allocation),* and *Flat Access (Absolute Equal Individual Allocation)* heavily constrained. For example, if one LV transformer is heavily loaded due to the base load of customers, that LV transformer may not be able to supply an active customer significant addition capacity for its flexible load. Due to the fairness constraints in these four DOE objective functions, this would mean that none of the active customer would be allocated significant additional import capacity.

A.3.2 DER Capacity Utilisation

The differences between the different DOE objective functions can be seen more clearly in the *DER Capacity Utilisation* metric. This is because this metric is only considering the flexible load of the actively participating customers, and not the base load of the network. Another reason why the changes can be better seen with *DER Capacity Utilisation* in Figure 29 than with *Network Utilisation* is that the magnitude of flexible load is much smaller than the peak network baseload. As with export, we see that *Maximise NEM Import* and *Policy Outcome (Policy Based)* perform the best across the three networks. *Equal kW Reduction (Equal Individual Conservation)* performs the next best in *City* and *Suburban*, but performs the worse in *Regional*. The rational for this is provided in Section 6.3.

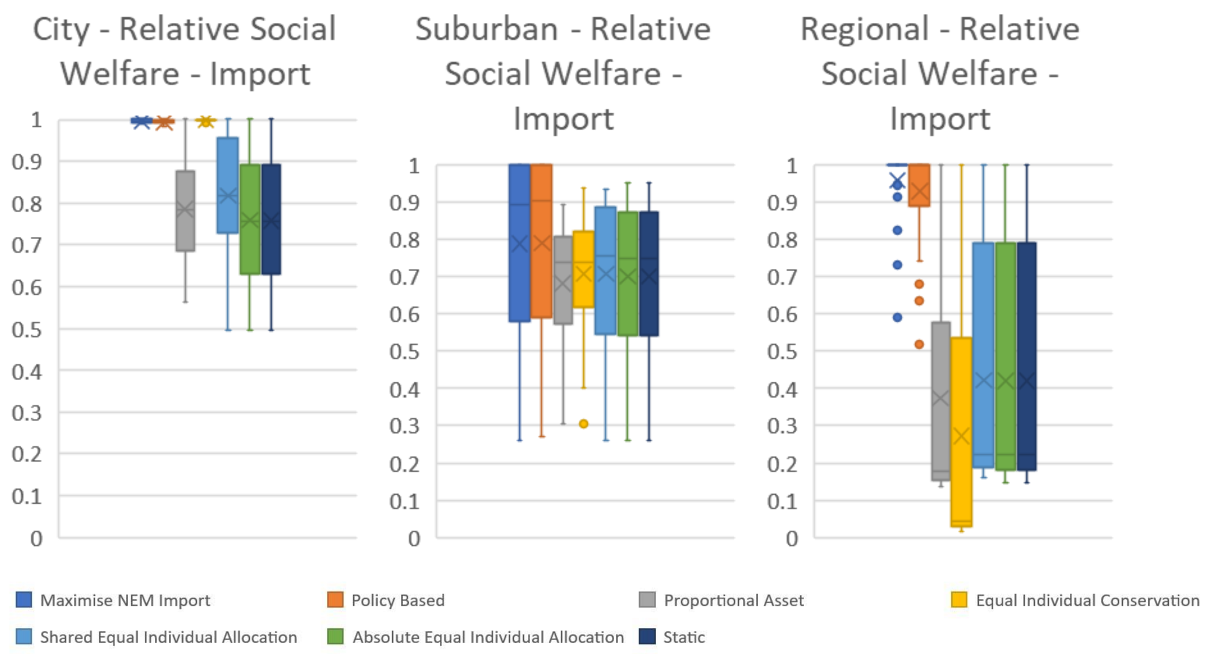
Figure 29 Box plot of DER Capacity Utilisation for each network type for import DOE limits



A.3.3 Relative Social Welfare

It is seen in Figure 30 that there is high Relative Social Welfare performance in the City network for all DOE objectives (higher than in the export case). This is due to the very consistent Network Utilisation values for the City network. *Equal kW Reduction (Equal Individual Conservation)* essentially manages to match the technical and economic performance of Maximise NEM Import in the City network. In the Suburban network *Equal kW Reduction (Equal Individual Conservation)* performs more in line with *Fixed Percentage (Proportional Asset)*, *Level Network Sharing (Shared Equal Individual Allocation)*, and *Flat Access (Absolute Equal Individual Allocation)*. In the Regional network (as in the export case) *Equal kW Reduction (Equal Individual Conservation)* performs the worst.

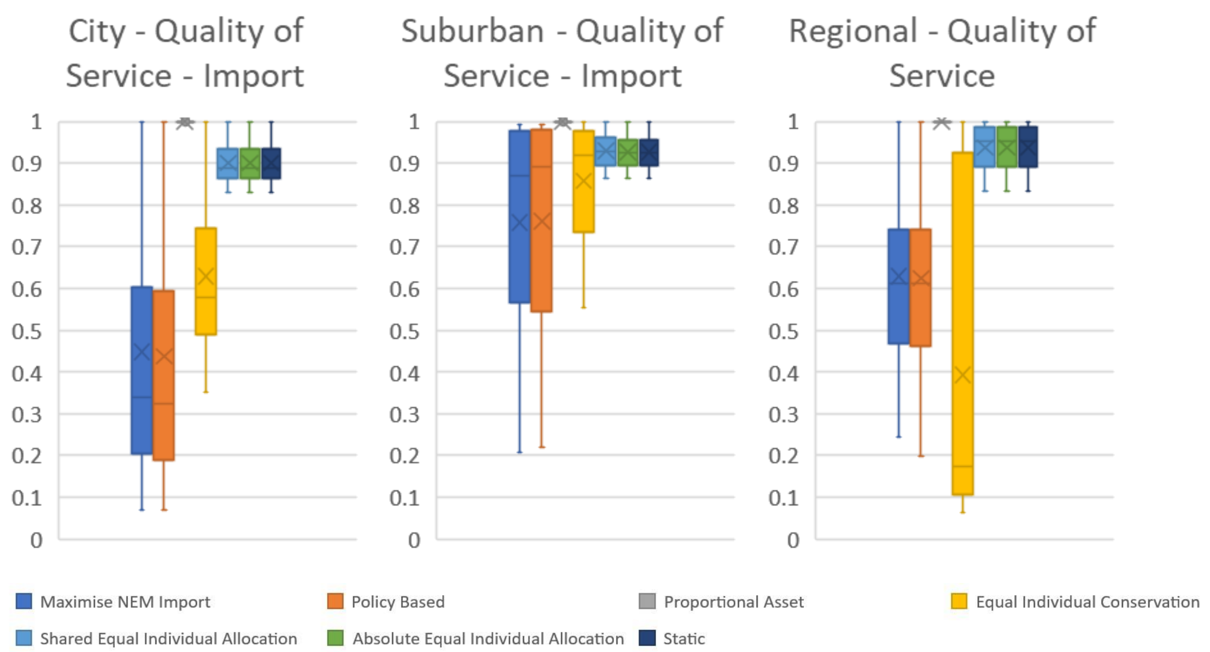
Figure 30 Box plot of Relative Social Welfare for each network type for import DOE limits



A.3.4 Quality of Service

Similar to the export case, *Maximise NEM Import* and *Policy Outcome (Policy Based)* perform the worst in *Quality of Service*, except in *Regional* where *Equal kW Reduction (Equal Individual Conservation)* performs the worst. All of the DOE objectives (except *Fixed Percentage (Proportional Asset))* perform worse in the import case than in the export. This is due to the fact that the *DER Capacity Utilisation* performance is also lower, due to the high baseload in the network.

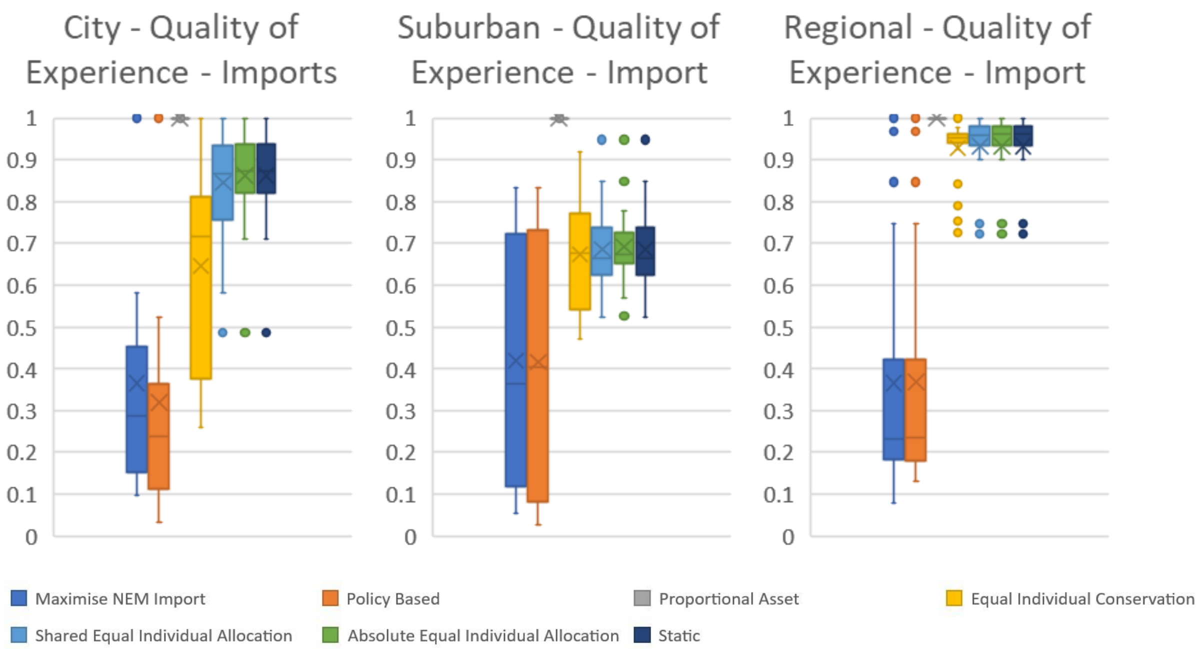
Figure 31 Box plot of Quality of Service for each network type for import DOE limits



A.3.5 Quality of Experience

The Quality of Experience performance for DOE import limits in Figure 32 follows similar trends to the DOE export limits. For the City and Suburban network, the order of performance of the objective functions is the same Quality of Service. However, in the Regional network, the Equal Individual Unallocated objective performs significantly better than for Quality of Service. This is because in its Quality of Service performance is hindered by the limited capacity that it assigns.

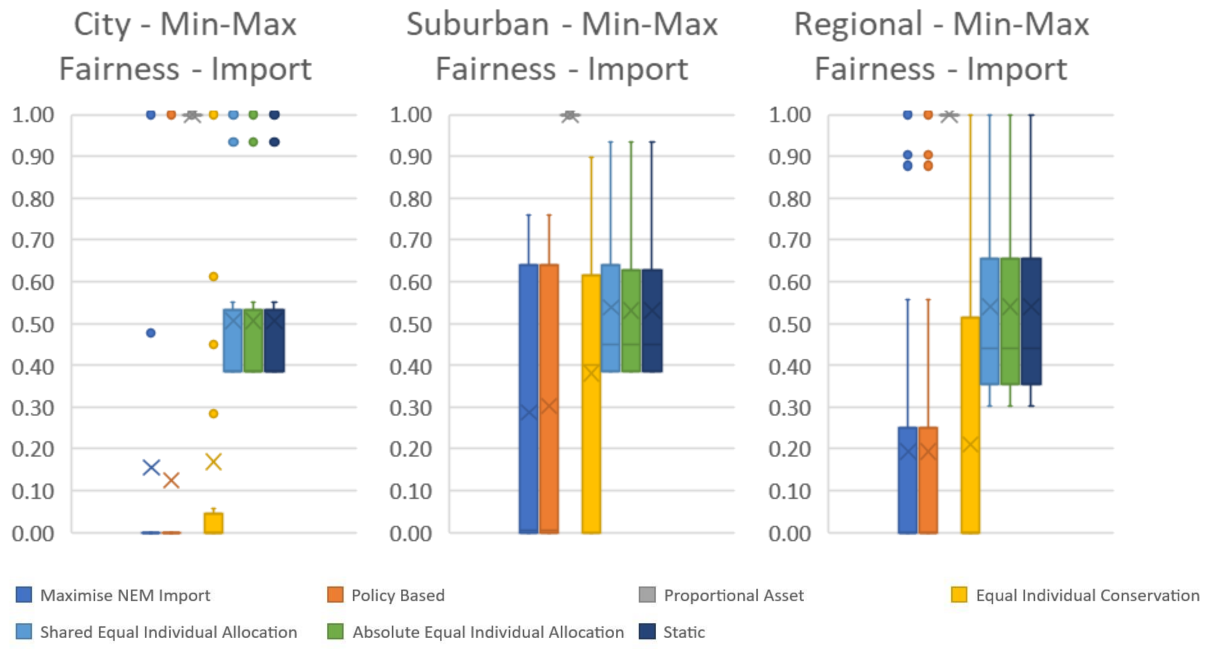
Figure 32 Box plot of Quality of Experience for each network type for import DOE limits



A.3.6 Min-Max Fairness

By looking at Figure 33, all DOE objectives, with the exception of *Fixed Percentage (Proportional Asset)* perform worse in *Min-Max Fairness* than in the other fairness metrics. This is because the value is driven by the capacity allocated to the customer who is assigned the least normalised capacity. For *Maximise NEM Import* and *Policy Outcome (Policy Based)* this is often zero capacity, which is why so many of the cases have a value of 0 for *Min-Max Fairness*. We see that *Equal kW Reduction (Equal Individual Conservation)* performs significantly worse than *Level Network Sharing (Shared Equal Individual Allocation)*, and *Flat Access (Absolute Equal Individual Allocation)*, but still better than *Maximise NEM Import* and *Policy Outcome (Policy Based)*.

Figure 33 Box plot of Min-Max Fairness for each network type for import DOE limits



A.3.7 Correlations

What is shown in Tables 8-10 is that there is still a strong negative correlation between *Network Utilisation* and the three fairness metrics in the DOE import limits case. However, the correlations between other metrics seem to be highly dependent on the network type.

Table 8 Correlation between metrics for *City* network import limits

	NU	DCU	QoS	QoE	MMF	RSW
Network Utilisation	1.00					
DER Capacity Utilisation	-0.67	1.00				
Quality of Service	-0.64	0.33	1.00			
Quality of Experience	-0.55	0.03	0.79	1.00		
Min-Max Fairness	-0.76	0.41	0.82	0.80	1.00	
Relative Social Welfare	0.17	0.34	-0.47	-0.44	-0.33	1.00

Table 9 Correlation between metrics for *Suburban* network import limits

	NU	DCU	QoS	QoE	MMF	RSW
Network Utilisation	1.00					
DER Capacity Utilisation	-0.40	1.00				
Quality of Service	-0.49	0.52	1.00			
Quality of Experience	-0.48	0.19	0.82	1.00		
Min-Max Fairness	-0.55	0.38	0.78	0.89	1.00	
Relative Social Welfare	-0.48	0.98	0.57	0.23	0.41	1.00

Table 10 Correlation between metrics for *Regional* network import limits

	NU	DCU	QoS	QoE	MMF	RSW
Network Utilisation	1.00					
DER Capacity Utilisation	0.48	1.00				
Quality of Service	-0.40	-0.02	1.00			
Quality of Experience	-0.84	-0.75	0.48	1.00		
Min-Max Fairness	-0.55	-0.18	0.80	0.66	1.00	
Relative Social Welfare	0.36	0.91	0.07	-0.58	0.02	1.00

A.4 Conclusion

In these results we see similar phenomena to those for export limits, which have been analysed in greater detail in Section 6. The aim of this Appendix is to demonstrate that the proposed DOE objective functions and assessment metrics are also suitable for use in DOE import limits. However, a more detailed and extensive analysis on DOE import limits will require significant discussion within the industry of how DOE import limits can be implemented in practice, and solutions decided for the issues discussed in Section A.1. The decisions made on these issues will have a significant impact on the analysis of these results. For example, if DOEs are to include both base load and flexible load, then the results seen would be more similar to the export results, where the network is not as heavily constrained. However, some of the DOE objectives, such as *Maximise NEM Import* would be unsuitable for use, because it could leave participating customers with a 0 kW import limit, which would not be acceptable network operation.