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Prosumer-Driven Optimisation of Dynamic Operating Envelopes: Towards Fair and Efficient Capacity Allocation

AR-PST Topic 8 Stage 5

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Executive summary

Australia is recognised as a global leader in the deployment of distributed energy resources (DERs), particularly rooftop solar photovoltaic systems. This rapid growth of DER, together with periods of excess distributed generation, is creating increasingly complex operational challenges for electricity distribution networks. Dynamic Operating Envelopes (DOEs), which provide DER systems with time-varying export and import limits, have emerged as a key mechanism for managing network congestion, while enabling the continued integration of DER.

Current industry practices for allocating DOEs typically rely on equal allocation approaches, prioritising simplicity and regulatory compliance. While operationally simple to implement, these methods may not fully utilise available network capacity and often overlook the diverse circumstances and preferences of individual consumers.

This work proposes a prosumer-led approach to DOE allocation, in which prosumer operating preferences (intended DOEs) are incorporated into a mathematical optimisation problem that aligns DOE allocations with prosumers' intentions while respecting distribution network constraints. By embedding prosumer-intended DOEs within the allocation process, we aim to improve fairness while enabling more efficient utilisation of distribution network capacity.

Central to our proposed optimisation-based DOE determination approach is a weighting scheme that assigns prosumer-specific weights based on their electrical position within the distribution feeder and dynamically adjusts these weights over time according to historical DOE allocations. Incorporating this weighting scheme into the optimisation problem renders DOE allocation fairer and more equitable by evenly distributing export/import opportunities and mitigating locational bias toward prosumers nearer the feeder head.

Moreover, we present an architecture for implementing the proposed optimisation-based DOE allocation method, leveraging the Common Smart Inverter Profile- Australia (CSIP-AUS) and outlining the necessary interactions between prosumers and the Distribution Network Service Provider (or aggregator).

A DOE case study is also presented to demonstrate the benefits of the proposed allocation approach for both prosumers and network utilities, highlighting how fair and efficient DOE allocation outcomes can be achieved across the broader distribution network.

1 Introduction and Background

1.1 Background and motivation

As one of the global frontrunners in *distributed energy resource (DER)* integration, Australia is experiencing operational challenges associated with high levels of DER penetration [1]. DERs are small-scale energy resources connected to electricity distribution networks, often at or near customer premises. These resources include rooftop photovoltaic (PV) systems, battery energy storage systems (BESSs), electric vehicles (EVs), flexible loads, and other controllable or semi-controllable behind-the-meter energy assets. In Australia, rooftop solar PV systems have been deployed at particularly high levels, making the distribution network an increasingly active part of the electricity system rather than a passive infrastructure designed only to deliver electricity from centralised generators to end users.

Historically, electricity distribution networks were planned and operated for one-directional power flows, where electricity was generated by large, centralised power stations, transported through transmission networks, and then delivered through distribution networks to end users. However, the rapid uptake of DERs has changed this operating paradigm. Many customers are no longer only consumers of electricity; they are also producers of electricity. These customers are often referred to as *prosumers*. A prosumer is an electricity customer who both consumes electricity from the grid and produces electricity, typically through rooftop solar PV or other DER technologies. For example, a household with rooftop solar may consume electricity during the evening but export surplus solar generation during the middle of the day. If the household also owns a battery or an EV, it may have further flexibility to shift, store, import, or export electricity at different times.

The increasing number of prosumers creates both opportunities and challenges for distribution network operation. On the one hand, DERs can support decarbonisation, reduce reliance on centralised fossil-fuel generation, improve customer participation, and defer some network investments when appropriately coordinated. On the other hand, uncontrolled DER operation can create technical issues in distribution networks, particularly in low-voltage networks where many customers are connected and where visibility and monitoring have traditionally been limited. One of the most significant challenges is reverse power flow, which occurs when electricity exported by customers exceeds local demand and flows back through the distribution network. High levels of simultaneous reverse power flow can lead to excessive voltage rise, thermal overloading of network assets, phase unbalance, and broader power quality concerns. To address these challenges, including excessive reverse power flows and related voltage management issues, Australian network utilities have introduced operating envelopes.

Operating envelopes define the technical limits within which customers (*sites*) may import electricity from, or export electricity to, the distribution grid. An import limit specifies the maximum power that a customer may draw from the network, while an export limit specifies the maximum power that a customer may inject into the network. These limits are necessary to ensure that customer behaviour remains within the technical capability of the distribution network and does not cause voltage or thermal constraint violations.

1.2 From static limits to dynamic operating envelopes

Traditionally, customer import and export limits have often been implemented as static limits. A static operating limit is a fixed limit that does not change with time or with actual network operating conditions. For example, a customer may be assigned a fixed maximum export limit for rooftop solar (e.g. 5 kW per phase), regardless of whether the network is heavily loaded, lightly loaded, constrained, or unconstrained at a particular time. Static limits are simple to implement and easy to communicate, but they are inherently conservative. Because they must remain safe under a wide range of possible network conditions, they may restrict customer exports even when there is spare network capacity available.

Dynamic operating envelopes (DOEs) have emerged as a more flexible alternative to static export limits. Of particular interest in this study are DOEs, which define time-varying import and export boundaries for DERs and customer connection points to ensure that the distribution network operates within its technical constraints. Unlike static limits, DOEs can change over time according to the state of the network. For example, a customer may be allowed to export more electricity during periods when the local network has spare capacity and may be assigned a lower export limit during periods of network congestion. Here, the term *network congestion* is used to describe situations where customer demand or DER export would cause one or more network constraints to be violated. These constraints may include voltage limits, line or transformer thermal limits, phase imbalance limits, or other technical requirements specified by standards and network operating practices. DOEs therefore provide a mechanism for managing congestion while enabling higher utilisation of existing network infrastructure.

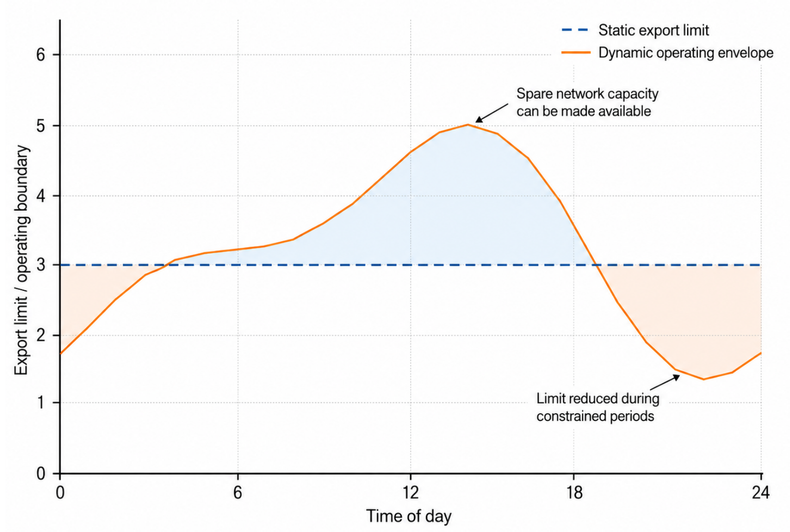

Figure 1.1 Static operating limits and dynamic operating limits

In this research study, *DOE allocation* refers to the process of determining import and export limits for individual customers (prosumers) or "sites", while ensuring that the simultaneous operation of all customers (sites) remains feasible within the safe operating limits of the distribution network.

1.3 The fairness challenge in DOE allocation

The allocation of DOEs is not only a technical network management problem but also a *fairness* and equity problem. In a distribution network, different customers may have different impacts on network constraints depending on their location, phase connection, distance from the distribution transformer, service line characteristics, and local network conditions. For example, prosumers located closer to the feeder head or distribution transformer may be able to export more electricity without causing voltage problems, while prosumers located further away may experience lower available export capacity due to higher voltage sensitivity. As a result, a DOE allocation method that only maximises total network export may favour some prosumers over others.

Current industry practices for allocating DOEs often rely on relatively simple equal allocation methods. In an equal allocation approach, available network capacity is distributed in a similar or identical manner across participating customers. Such approaches are attractive because they are transparent, simple to implement, and easier to align with regulatory expectations. However, equal allocation may not fully utilise available network capacity, particularly when customers have different network impacts or different operating preferences. It may also overlook the diverse circumstances of individual prosumers, including their DER capacities, household energy needs, storage availability, EV charging requirements, and willingness or ability to shift demand or export generation.

In this context, fairness refers to the impartial and just treatment of customers when assigning network access. Equity refers to the broader goal of accounting for differences between customers and network conditions so that outcomes are reasonable and not systematically biased. Equality, by contrast, refers to assigning the same or identical outcome to all customers. These terms are related but distinct. In DOE allocation, an equal allocation is not necessarily the fairest or most efficient allocation, because customers are not always connected under the same technical conditions and may not have the same operating intentions. A fair DOE allocation method should therefore consider both the technical constraints of the network and the implications of allocation decisions for different prosumers over time.

1.4 Prosumer-led DOE allocation

This work proposes a *prosumer-led* approach to DOE allocation. In this approach, prosumer operating preferences, referred to as *intended DOEs*, are incorporated into the DOE allocation process. An intended DOE represents the import or export operating preference of a prosumer, subject to the capability of their DER system and their expected energy behaviour. For example, a prosumer with rooftop solar and a battery may prefer to export during certain periods, charge the battery during others, or reserve capacity for household consumption or EV charging. By incorporating intended DOEs into the allocation process, the DOE calculation can better reflect prosumer needs rather than treating customers as passive recipients of network-imposed limits.

The proposed approach formulates DOE allocation as a *mathematical optimisation problem*. Mathematical optimisation provides a systematic way to determine DOE allocations by defining an objective function and a set of constraints. In this context, the objective is to align allocated DOEs with prosumer intended DOEs as much as possible, while the constraints ensure that the resulting import and export limits do not violate distribution network operating limits. These constraints may include voltage limits, thermal limits of lines and transformers, and other network security requirements. This allows the DOE allocation process to *balance* prosumer preferences with the physical capability of the distribution network.

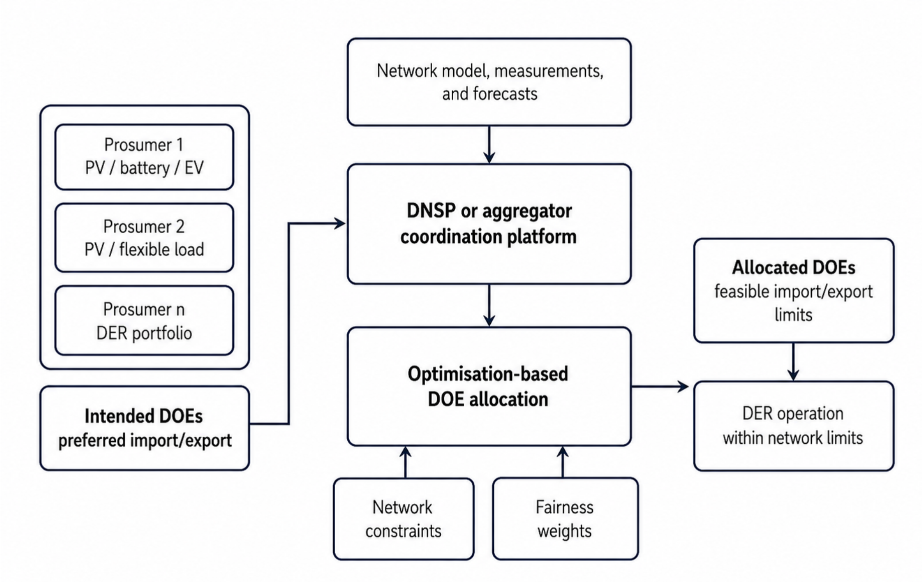

Figure 1.2 Proposed prosumer-led DOE allocation concept

A central feature of the proposed approach is a *prosumer-specific weighting scheme*. These weights are designed to account for the *electrical position* of each prosumer within the distribution feeder and to adjust dynamically over time according to historical DOE allocations. Electrical position refers to how a prosumer is connected within the network and how strongly their import or export behaviour affects network constraints. For instance, prosumers located near the end of a feeder may have a stronger impact on voltage rise during export than those located closer to the feeder head. Without appropriate correction, DOE allocation may therefore favour prosumers who are electrically better positioned. The proposed weighting scheme aims to mitigate this locational bias and distribute import and export opportunities more equitably over time.

By embedding prosumer intended DOEs and dynamic weights within the optimisation problem, the proposed approach seeks to improve both fairness and network utilisation. Rather than applying a purely equal allocation or a purely network-efficiency-based allocation, this method aims to provide DOE outcomes that are technically feasible, more responsive to prosumer preferences, and less biased by network location. This is particularly important as DER participation increases and as customers begin to use more diverse technologies such as batteries, EVs, and flexible loads.

1.5 Implementation context and communication requirements

For DOE allocation to be useful in practice, it must be supported by an appropriate communication and implementation architecture. In Australia, the *Common Smart Inverter Profile – Australia*, commonly referred to as *CSIP-AUS*, provides an important pathway for communication between network utilities, aggregators, and DER systems. CSIP-AUS is based on the IEEE 2030.5

communication standard and supports the exchange of information needed to coordinate DER operation, including operating limits and control signals.

In the context of this work, a *Distribution Network Service Provider (DNSP)* is the organisational entity responsible for planning, operating, and maintaining the electricity distribution network. An aggregator is an entity that coordinates multiple customer-owned DERs and may act as an intermediary between individual prosumers and the DNSP. Under a prosumer-led DOE allocation architecture, prosumer preferences may be communicated either directly to the DNSP or through an aggregator, depending on the market and technical arrangements. The DNSP or aggregator would then use network information, prosumer intended DOEs, and relevant operating constraints to determine technically feasible DOE allocations.

The practical implementation of such an approach requires careful consideration of data availability, interoperability, privacy, communication latency, and customer participation. Network utilities require sufficient visibility of the distribution network to determine feasible limits, while prosumers require transparent and understandable signals to guide the operation of their DER systems. The success of a prosumer-led DOE framework therefore depends not only on the optimisation method itself but also on the supporting architecture through which information is exchanged and DOE limits are implemented.

1.6 Scope of the work

The scope of this study is to develop and evaluate a prosumer-led approach to DOE allocation in distribution networks with high penetration of DER. The proposed mathematical formulations are developed to be applicable to both import and export dynamic limits. That is, the optimisation-based allocation approach can, in principle, be used to determine both the maximum power that prosumers may import from the distribution network and the maximum power that they may export to the distribution network, while respecting network operating constraints.

A numerical case study is presented to demonstrate the potential benefits of the proposed approach for both prosumers and network utilities. Specifically, this case study examines how fair and efficient DOE allocation outcomes can be achieved across a distribution network while ensuring compliance with network operating constraints.

However, the case study presented in this report is limited to export-limit allocation. This focus is motivated by the importance of export limits in managing reverse power flows, voltage rise, and network congestion associated with high rooftop solar PV penetration. The application of the proposed formulation to import-limit allocation, including flexible load and EV charging use cases, is not examined in the case study and is identified as a potential direction for future work.

It is also worth noting that this study does not seek to replace the technical role of distribution network constraints in DOE calculation. Instead, it recognises that network security remains the primary requirement of DOE allocation. The proposed approach operates within these technical limits but aims to improve how available network capacity is shared among prosumers. In doing so, this work addresses the interaction between network efficiency, customer fairness, and prosumer participation. The report also presents an architecture for supporting the interactions required between prosumers, aggregators, and the DNSP, when implementing the proposed approach.

1.7 Report organisation

The remainder of this report is organised as follows. Chapter 2 presents the literature review and background, including existing approaches to DOE allocation, fairness considerations, and relevant DER communication standards. Chapter 3 details the proposed prosumer-led DOE allocation approach, including the formulations of the optimisation problem and the weighting scheme. Chapter 4 presents the case study and results, demonstrating the performance of the proposed method for export-limit allocation under representative distribution network conditions. Chapter 5 maps this work against the Stage 1 Roadmap for Topic 8: DERs. Chapter 6 concludes the report and outlines potential future research directions for Topic 8: DERs.

2 Literature Review

This chapter presents the background on DOEs and the literature review conducted during the initial phase of the project, encompassing DOE implementation practices from Australian DNSPs as well as relevant academic research on DOE allocation.

2.1 Dynamic Operating Envelopes (DOEs) - Background

The concept of utilising DOEs, in which DERs are assigned flexible import and export limits, has been explored as a promising approach to manage the increasing operational challenges associated with high DER penetration. Various research initiatives and industry-led projects have investigated DOEs as a mechanism to enable greater DER integration while maintaining secure and reliable network operation [2].

In Australia, several jurisdictions are currently trialling DOEs, in which the import and export limits are determined by the DNSP based on the network's operational and physical constraints, including voltage limits and the thermal limits of network assets. The resulting DOE limits are then communicated to DER devices or aggregators ahead of the operational period, enabling DERs to adjust their behaviour accordingly.

2.1.1 History of DOEs - Flexible Exports for Solar PV Trial

Led by SA Power Networks (SAPN), South Australia's regulated electricity distributor, the Flexible Exports for Solar PV Trial (2021–2023) [3] was one of the earliest large-scale demonstrations of DOE operations using CSIP-AUS [4]. In particular, this trial provided a clear blueprint for the wider industry, offering guidance to Australian DNSPs and international utilities pursuing DOE adoption. The trial was undertaken through a collaborative partnership involving SA Power Networks, AusNet Services (a major electricity distribution and energy network business in Victoria), SwitchDin (an Australian energy technology company specialising in DER orchestration), Fronius (a solar inverter and energy solutions provider), SMA Solar Technology (a global provider of photovoltaic inverter and solar technology solutions), and SolarEdge (a renewable energy technology company providing smart solar inverter and energy management solutions). Together, these organisations developed and tested a Flexible Exports connection framework for residential solar PV customers who would otherwise have faced zero or near-zero export limits.

As part of the Flexible Exports for Solar PV Trial, SwitchDin developed a modular, IEEE 2030.5 and CSIP-AUS–compliant Utility Server, which was deployed by SA Power Networks and AusNet Services to communicate flexible export limits to participating customer sites. The modular architecture of this Utility Server was designed to enable other DNSPs to adopt the solution efficiently following the completion of the trial. This modular approach also allows DNSPs to maintain protocol-agnostic backend systems, while incorporating additional protocol converters as DER technologies and communication standards evolve. The functional design of the Utility Server was jointly developed by SwitchDin, AusNet Services, and SA Power Networks to ensure interoperability and consistency across the participating networks. The implementation by SwitchDin utilised the Droplet, a compact gateway device that enabled legacy or non-compatible solar inverters to participate in the Flexible Exports program. In parallel, Fronius developed a cloud-based integration that allowed its Gen24 inverter series to participate without requiring additional hardware at customer premises. Collectively, these solutions represented the first commercially available CSIP-AUS–capable technologies supporting DOE operations. In addition to the communication infrastructure, both SA Power Networks and AusNet Services developed new operational platforms capable of calculating and publishing flexible export limits, thereby enabling the practical implementation of DOE-based network management.

SA Power Networks initiated the trial involving more than 400 residential customers, initially targeting highly constrained substation areas. Ausnet Services also participated in this trial and started implementing reduced export limits at a small number of low-voltage substations that had reached capacity due to increasing rooftop solar penetration across their network. A key objective of this trial was to develop and test a standards-based approach, using CSIP-AUS, for communicating flexible export limits between DNSP systems and DER systems supplied by multiple manufacturers. The trial also contributed to the rapid adoption of Flexible Exports in other jurisdictions, by minimising rework effort by equipment manufacturers in ensuring their products are compatible with CSIP-AUS.

Building on the success of this trial, SA Power Networks offered Flexible Exports as an option to customers since 2021. Subsequently, the Dynamic Exports Guideline [5] was introduced in South Australia in 2023, alongside an update to South Australian electricity regulations, requiring all new PV inverters to be capable of receiving a DOE via CSIP-AUS.

At present, DOEs and flexible export arrangements are being offered, trialled, or progressively implemented by DNSPs in Victoria, South Australia, and Queensland, three of the five states and one territory within the National Electricity Market (NEM) on Australia's east coast. In South Australia, SA Power Networks offers DOEs through its Flexible Exports program, which enables eligible customers with compatible internet-connected inverters to export up to 10 kW per phase when sufficient network capacity is available. In Queensland, Energex and Ergon Energy Network offer Dynamic Connections for energy exports, allowing customers to access higher dynamic export limits than standard static connections, while enabling the network operator to adjust export levels in response to local network conditions. In Victoria, AusNet Services, United Energy, CitiPower, and Powercor have also been developing flexible services trials using DOEs to support higher flexible export connections and build low-voltage DER management capability. These programs demonstrate the increasing practical adoption of DOE-based connection arrangements by

Australian DNSPs as a mechanism for integrating higher levels of rooftop solar and other DERs while maintaining safe and reliable network operation [6].

2.1.2 How DOEs operate?

The operation of DOEs through CSIP-AUS involves a structured end-to-end process, from DER connection and registration to DOE compliance and fail-safe operation. The following provides a detailed description of each step, in line with the process illustrated in Figure 2.1.

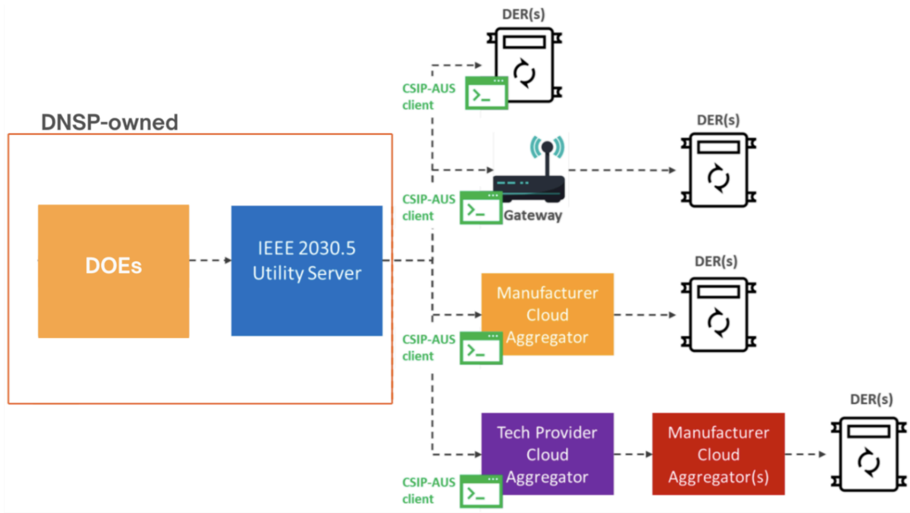

Figure 2.1: DOE operation enabled by CSIP-AUS

Step 1: DER connection and registration

The process begins with the installation of a new solar PV system equipped with a CSIP-AUS-compliant smart inverter, which functions as the *CSIP-AUS Client*. During installation, the system is commissioned by the installer, who tests the inverter and registers the Client with the DNSP. A critical component of the registration process is the establishment of a secure, encrypted connection between the CSIP-AUS Client and the *CSIP-AUS Utility Server*. This secure handshake, implemented using digital certificates, is a mandatory requirement under the CSIP-AUS technical standard to ensure robust communication security.

Step 2: DOE allocation

The methodology for determining DOEs varies across DNSP jurisdictions and typically involves two main steps:

a) Calculation of hosting capacity

Hosting capacity refers to the maximum DER generation that can be accommodated on a distribution network without violating operational constraints, such as voltage limits and thermal loading. This is calculated using real-time network measurements combined with forecasting techniques to anticipate future network conditions.

For example, Energex determines hosting capacity at the low-voltage (LV) transformer using telemetry data from power quality monitors and synthetic power flow models [6].

Given the limited visibility of the LV network, SA Power Networks calculate hosting capacity using a template-based approach, where a heuristic links voltage constraints at customer sites to reverse real-power flow limits at the LV transformer, defining the *voltage hosting capacity* for typical LV networks. The Constraints Engine then estimates load and generation at each site (using live meteorological data to account for variability in generation and demand), aggregates these estimates at the transformer level, and compares them against the transformer's voltage hosting capacity to determine the hosting capacity available for Flexible Exports customers [3].

b) DOE calculation for individual sites

Once the hosting capacity has been determined, the DNSP calculates the available spare capacity at each LV transformer, representing the margin before reaching its nominal capacity. DOEs are then allocated to individual sites, defining the safe operational limits for DER injection. Currently, DOEs are allocated uniformly (or equally) across all sites within a given time interval and are recalculated according to the DNSP's update frequency, for instance, Energex updates DOEs every 5 minutes, whereas SA Power Networks updates them every 15 minutes. Recent DOE projects have introduced more sophisticated approaches, enabling improved network utilisation, equitable DER integration, and the potential for site-specific DOE allocation. More discussion on this is presented in Section 2.2.

Step 3: Dispatching DOE setpoints

The calculated DOE setpoints are communicated from the CSIP-AUS Utility Server to each Client over the secure CSIP-AUS communication path. Within the CSIP-AUS framework, DOE setpoints are transmitted as DERControl events that specify site-specific import and export limits along with their validity periods. These events are structured as part of a DERProgram within the DERProgramList resource. Upon receipt, the DER Client confirms and acknowledges the instruction.

As shown in Figure 2.1, for sites hosting multiple DER devices, a local *gateway* Client (such as a Home Energy Management System supporting SEP2.0 communications) can coordinate downstream

DERs. Alternatively, a third-party cloud proxy or aggregator can act as a virtual gateway, aggregating and managing communication with individual devices to ensure correct distribution of DOE setpoints across all end-devices at the site.

Step 4: Inverter compliance

The smart inverter adjusts the PV system's generation to comply with the received DOE setpoint. The Client continuously reports its operational status and actual export levels back to the Utility Server, enabling the DNSP to monitor compliance and refine future DOE calculations.

Step 5: Fail-safe mechanism

To ensure network stability in the event of communication failure, the CSIP-AUS standard requires that the inverter revert to a conservative, static export limit (e.g., 1.5 kW per phase) if it cannot refresh the DOE setpoint within a mandated time period. This fail-safe feature ensures that DERs cannot unintentionally destabilise the local network, maintaining safe and reliable grid operation even during outages or connectivity disruptions.

2.2 DOE Allocation Strategies

A critical challenge for DNSPs when implementing DOEs is determining how available network hosting capacity should be allocated among participating customers. In previous stages of the AR-PST program, substantial work has been undertaken to review and assess DOE allocation algorithms [7], [8]. In what follows, we examine contemporary strategies for DOE allocation, with a particular attention to the trade-offs between technical efficiency and different interpretations of fairness.

DOE calculation can be formulated as an optimisation problem in which the decision variables represent the operating limits assigned to participating prosumers. For export DOEs, these decision variables may correspond to the maximum active power export allocated to each prosumer at a given time interval, while for import DOEs, they may represent the maximum active power import permitted for each prosumer. Depending on the level of modelling detail, additional decision variables may include DER active and reactive power set-points. The optimisation problem is subject to a set of technical constraints that ensure the resulting DOE allocations are feasible for the distribution network. These constraints may include power flow equations, voltage magnitude constraints, thermal constraints of lines and transformers, DER power quality constraints and any minimum access or customer participation requirements imposed by the network operator. Within this feasible operating space, different objective functions can be used to reflect different allocation principles. For example, the objective may seek to maximise aggregate export capacity, minimise curtailment, allocate capacity equally among prosumers, reduce inequality in allocated limits, align allocations with prosumer-intended DOEs, or balance network efficiency with fairness.

In this context, maximising aggregate exports from all prosumers, and thereby improving the utilisation of available distribution network capacity, can be framed as a *competitive, efficiency-driven* allocation problem. Early work such as [9] adopts a real-time optimal power flow (OPF)-based framework focused on maximising PV utilisation, where fairness is not explicitly considered and outcomes are largely driven by network constraints. From a system-wide perspective, this may enhance social welfare by increasing supply and potentially reducing wholesale electricity prices. However, it often leads to *locational unfairness*. Customers at the end of long radial feeders are frequently curtailed first and most severely due to voltage rise issues, while those near the substation maintain full export capabilities. Consequently, although the approach is efficient in "aggregate" terms, it raises concerns regarding equity and fairness across participants.

To address the issue of locational bias, the most widely adopted approach in industry is the *equal allocation* of distribution network hosting capacity across participating prosumers. For example, Energex distributes available capacity equally among all connected sites [6]. SA Power Networks employs a *waterline* allocation method, which initially assigns equal capacity to all sites and returns any unused portion to a common pool for redistribution [3]. Equal allocation is often regarded as fair from a rights-based perspective because it offers identical export rights to all customers regardless of their individual characteristics, network location, or DER capacity. In this sense, it avoids systematically favouring prosumers who are electrically better positioned within the feeder, such as those located closer to the distribution transformer.

However, equal allocation does not necessarily produce fair or efficient outcomes in practice. By assigning the same export limit to all customers, it may fail to recognise differences in customer circumstances, DER investment, and technical capability. For example, prosumers who have invested in larger PV systems may be disadvantaged because their greater generation capacity remains underutilised, even during periods when the network could accommodate higher exports. Conversely, prosumers with smaller systems may receive an allocation that exceeds their actual export capability, resulting in unused capacity that must be redistributed or otherwise remains unutilised. Therefore, while equal allocation may appear fair in a procedural sense, it can lead to inefficient utilisation of available hosting capacity and may not reflect the diverse needs and capabilities of participating prosumers.

The primary advantage of equal allocation lies in its simplicity and ease of practical implementation. It avoids the need for detailed, prosumer-specific DOE calculations, which can be complex and resource-intensive, particularly in real-world deployment settings involving heterogeneous customer assets, limited visibility of low-voltage network conditions, and incomplete information about behind-the-meter DER behaviour. For this reason, equal allocation remains attractive for DNSPs seeking a transparent and operationally manageable allocation method. Nevertheless, its limitations suggest the need for more advanced allocation approaches that can better balance simplicity, fairness, and efficient utilisation of distribution network capacity.

In the literature, equal DOE allocation approaches have been considered in [10], [11]. In [10], fairness is incorporated by enforcing the operating envelopes to be identical for all active customers. This approach embeds a notion of equality by ensuring that each participating customer is assigned the same level of network access. In [11], fairness is instead addressed through the even distribution of curtailment across prosumers, while ensuring that the resulting allocations remain feasible with high probability under uncertainty. Together, these studies demonstrate that equal allocation and equal curtailment are commonly used mechanisms for introducing fairness into DOE allocation; however, they also highlight that fairness can be defined and operationalised in different ways depending on the allocation objective and the treatment of network uncertainty.

Fairness in DOE allocation is inherently complex, and neither uniform allocation nor competitive allocation necessarily produces truly fair outcomes.

An alternative approach is *proportional allocation*, in which allocations are determined based on the relative size of each prosumer PV system. Under this scheme, export limits are assigned in proportion to installed capacity, such that prosumers experience curtailment as a comparable percentage of their available generation. Proportional allocation may therefore be regarded as equitable under an investment-based interpretation of network access, where export rights scale with the level of financial commitment made by customers in DER assets. From this perspective, although all prosumers may be curtailed, the impact of curtailment is shared relative to the scale of each prosumer's investment and generation capability.

However, proportional allocation can be more difficult to justify from a broader social equity perspective. Because larger PV systems are more likely to be owned by households with greater financial capacity to invest in DER technologies, proportional allocation may assign a larger share of a common network resource to already advantaged customers. This can reinforce existing inequalities by providing greater access to those with higher DER investment, while customers with smaller systems receive a smaller share of available hosting capacity. Therefore, while proportional allocation may appear fair when viewed through the lens of investment and asset utilisation, it may produce inequitable outcomes when assessed against principles of equal access, social justice, and inclusive participation in the energy transition.

Max–min fairness-based allocation is a lexicographic optimisation approach that prioritises improving the allocation of the worst-off participant before increasing the allocations of others. In the context of DOE allocation, this means that the method first seeks to maximise the minimum export capacity assigned to any participating prosumer, thereby protecting customers who would otherwise receive very limited access due to network constraints. Under a purely competitive allocation model, prosumers located in electrically constrained parts of the feeder may receive little or even zero export capacity, particularly where their exports have a strong impact on voltage limits. In contrast, max–min fairness ensures that these prosumers receive a non-zero share of available hosting capacity, although this may come at the expense of overall system efficiency and reduce the total amount of solar energy exported to the grid.

In [12], the authors explore max-min fairness for DOE allocation, with the objective of maximising the capacity allocated to the worst-off customer and thereby ensuring a guaranteed minimum level of grid access for all participants. A key contribution of this work is its demonstration that inexact Second-Order Cone Relaxation (SOCR) solutions can produce what is referred to as phantom capacity. If the relaxation is not exact, the calculated operating envelopes may be physically unrealisable or may misrepresent the true network hosting capacity. This has important implications for fairness. Mathematical accuracy is a prerequisite for genuinely fair DOE allocation because fairness can only be meaningfully assessed when allocations are based on a physically valid representation of network constraints. If the underlying optimisation model does not accurately capture the network physics, some customers may receive more or less than their fair share of the actual physical headroom. Therefore, in fairness-oriented DOE allocation, the choice of optimisation formulation and the accuracy of the network model are not merely technical details; they directly affect the legitimacy and equity of the resulting allocation outcomes.

In [13], the authors propose a method for calculating robust DOEs by identifying a maximal hyperrectangle within the feasible operating region of the distribution network. Their approach first solves a convex optimisation problem to fit the largest hyperellipsoid within the feasible region, before expanding the resulting hyperrectangle using the Motzkin Transposition Theorem to improve utilisation of the available network capacity. From a fairness perspective, the use of a logarithmic objective function implies a proportionally fair allocation of DOEs among customers. This means that the allocation process seeks to balance improvements across customers in relative terms, rather than simply maximising aggregate capacity or enforcing identical limits for all participants. The authors further note that *alpha-fairness*, which generalises both proportional fairness and max–min fairness, can also be applied within their DOE allocation framework. Alpha-fairness provides a flexible mechanism for tuning the balance between efficiency and equity, allowing allocation designers to select different fairness-efficiency trade-offs depending on regulatory objectives, operational requirements, and customer equity considerations.

> In the context of DOE allocation, fairness can be understood as the strategic balance between maximising overall network utilisation and ensuring non-discriminatory access to distribution network capacity, while preserving the physical feasibility of the power flow solution. However, achieving an appropriate balance between fairness and efficiency remains challenging, as allocation methods that maximise aggregate DER exports may disproportionately favour some prosumers, whereas methods that prioritise equal access may underutilise available network capacity.

The authors in [14] propose a method for calculating DOEs under uncertainty by identifying worst-case active and reactive power utilisation scenarios. These scenarios are derived through an analysis of phase voltage sensitivities to customer demand, which are computed using demand perturbations and unbalanced three-phase power flow simulations. To improve the tractability of the resulting non-convex optimisation problem, the authors apply sensitivity-based filtering and scenario reduction techniques. These techniques reduce the number of scenarios by merging redundant cases and retaining those most relevant to critical voltage constraints. Fairness is incorporated through the comparison of different allocation strategies, including maximum efficiency, proportional fairness, and alpha fairness. These strategies provide different mechanisms for balancing aggregate network utilisation with equitable access to network capacity, while ensuring that DOE allocations remain within operational constraints.

Another stream of research focuses on the use of *local energy markets* for DOE allocation. In literature, references [18], [19], [20] have investigated local energy market mechanisms for active and reactive power trading within peer-to-peer (P2P) networks. These approaches promote decentralised market participation by enabling prosumers to trade energy or flexibility services locally, while ensuring that transactions remain consistent with distribution network constraints. In this context, DOEs can be used to define the technically feasible operating region within which local energy trading can occur, thereby linking market outcomes with the physical limits of the network.

The deployment of DOE-based local energy markets among participating prosumers can provide several benefits. First, it can support fairer access to network capacity by ensuring that market transactions do not allow some prosumers to use disproportionate network headroom at the expense of others. Second, it can enhance local grid stability by constraining active and reactive power exchanges within voltage, thermal, and other operational limits. Third, it can improve the utilisation of DERs and existing network assets by encouraging local balancing of supply and demand, reducing unnecessary curtailment, and enabling prosumers to provide flexibility where it is most valuable. Therefore, DOE-based local energy markets represent a promising pathway for integrating market-based coordination with technically secure distribution network operation.

Another technique used in the literature is the *Nash bargaining* approach, which can be applied to DOE allocation by selecting a Pareto-efficient distribution of export or import capacity that maximises the product of individual gains relative to a defined baseline. In this way, the Nash bargaining provides a mechanism for balancing efficiency and fairness across prosumers located at different points in the distribution network. The approach is often attractive because it discourages purely self-interested allocation outcomes while still recognising differences in DER investment, flexibility, and customer capability. In contrast, max–min fairness is generally more suitable where the primary objective is to guarantee a minimum level of network access for all participants, particularly under regulatory or social equity considerations.

In [13], the authors formulate DOE allocation as a cooperative game that balances network security constraints with the individual preferences and flexibility of DER owners. Their findings suggest that a bargaining-based approach can achieve a more equitable distribution of export and import limits compared with conventional DOE allocation methods. In [14], fairness is addressed by incorporating uniform export and import curtailments within the DOE allocation process, ensuring that network access is distributed without systematic bias across customers while maintaining distribution network integrity. The study further extends the fairness concept to the peer-to-peer trading stage through a coalition graph game framework, which promotes stable and equitable payoff allocation among participants. Overall, these approaches demonstrate that fairness in DOE-based coordination can be considered at multiple levels: first, through the allocation of physical network access, and second, through the distribution of economic benefits arising from local energy trading.

While the aforementioned methods make important contributions to incorporating fairness into DOE allocation, a recurring limitation in the literature is that fairness is often defined primarily at the level of the allocation rule itself, rather than in relation to the heterogeneous technical and social circumstances of individual customers. In practice, prosumers differ substantially in terms of installed PV capacity, demand profiles, export capability, network location, flexibility, and underlying generation potential. Consequently, an allocation strategy that appears fair under one interpretation may be perceived as inequitable under another. For example, equal allocation may be viewed as fair because all customers receive the same export limit, yet it may disadvantage customers with larger DER systems or higher available generation. Conversely, proportional allocation may better reflect DER investment but may also allocate greater network access to customers with higher financial capacity to invest in larger systems.

This highlights that fairness in DOE allocation is inherently multidimensional and cannot be reduced to a single mathematical objective alone. A robust fairness framework should therefore consider not only the numerical distribution of allocated limits, but also the customer circumstances, network impacts, historical allocation outcomes, and broader equity implications associated with those limits. This provides the motivation for exploring DOE allocation approaches that can account for prosumer heterogeneity and support a more balanced trade-off between efficiency, fairness, and practical implementation.

Beyond explicit fairness functions, another emerging direction is to incorporate customer intent directly into the DOE allocation process. Rather than treating all available export capability as equally valuable, *intent-aware* approaches seek to align allocated envelopes with each prosumer's intended operating point or preferred import/export profile. This represents an important shift in the way fairness is conceptualised. In practice, fairness is not only determined by the amount of network capacity allocated to each customer, but also by whether that allocation meaningfully supports the customer's expected use of their DER assets. For example, two prosumers may receive the same export limit, but the value of that allocation may differ substantially depending on their PV generation profile, household demand, battery state of charge, or planned EV charging behaviour. Incorporating customer intent therefore provides a pathway to move beyond purely rule-based notions of fairness and towards allocation methods that are more responsive to prosumer needs, preferences, and operating circumstances. For example, in [16], fairness among prosumers is promoted by minimising the squared distance between each prosumer's intended operating point and the DOE assigned by the DNSP. This objective reduces the extent to which prosumers' preferred operations are curtailed or modified, while ensuring that the final DOE allocations remain feasible under network constraints. In particular, the approach aims to avoid disproportionately penalising prosumers located farther from substations, who may otherwise be more strongly constrained due to their greater impact on voltage limits.

2.3 Summary

Overall, the literature demonstrates that no single fairness criterion is universally appropriate for DOE allocation. Equal, proportional, max–min, bargaining-based, and efficiency-driven allocation methods each reflect different normative interpretations of fairness and different assumptions about how limited network hosting capacity should be shared among prosumers. Equal allocation emphasises identical access rights, proportional allocation reflects DER investment and generation capability, max–min approaches prioritise the worst-off participants, bargaining-based methods seek mutually acceptable and Pareto-efficient outcomes, and competitive allocation prioritises efficient utilisation of available network capacity.

However, a common limitation across many existing approaches is the insufficient treatment of customer-specific heterogeneity within a unified allocation framework. In practice, prosumers differ not only in their installed DER capacity, but also in their demand profiles, export capability, flexibility, intended operating behaviour, and electrical position within the feeder. These differences can substantially influence both the technical impact of a prosumer on network constraints and the practical value of the DOE allocated to them. This motivates the need for DOE allocation methods that are physically feasible and operationally efficient, while also explicitly accounting for each prosumer's intended import and export requirements, DER capability, historical allocation outcomes, and network location. Such an approach is essential for achieving DOE outcomes that are technically robust, fair across heterogeneous prosumers, and socially acceptable in practical deployment.

3 Problem Formulation & Proposed Approach for DOE Allocation

3. 1 Proposed Architecture for Prosumer-Led DOE Coordination

Figure 3 presents an overview of the proposed architecture, highlighting the bidirectional interaction between prosumers and the DNSP for determining DOEs within a CSIP-AUS-compliant architecture. The adoption of communication standards for DER coordination, as well as their practical feasibility and potential benefits for real-time distribution network management, is already being explored through industry trials, including those conducted by SA Power Networks [3].

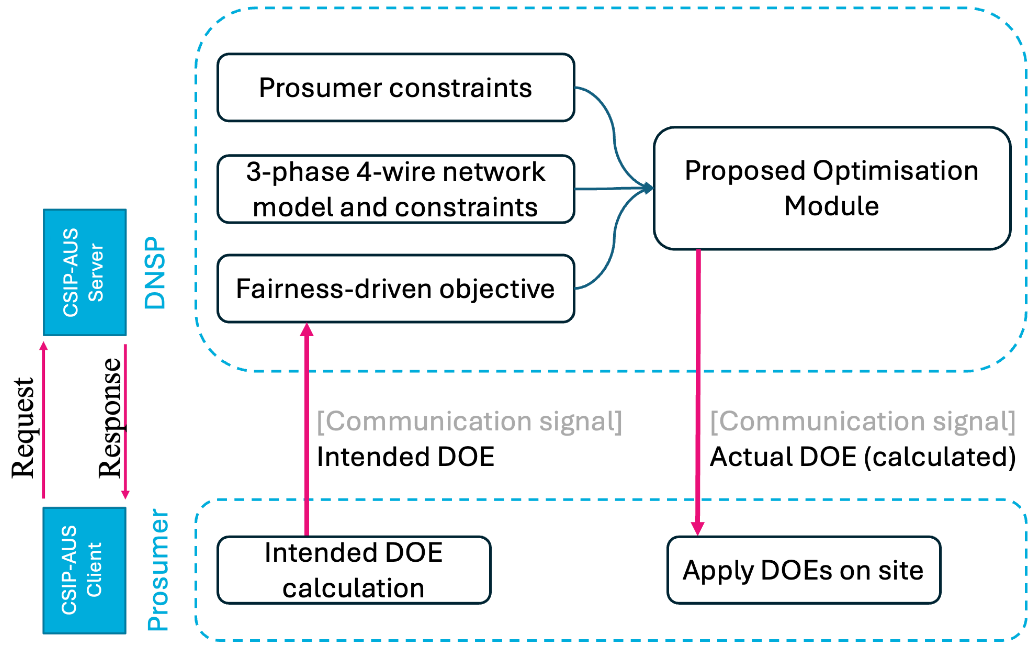

Figure 3.1: Proposed architecture for DOE calculation

Figure 3.1 presents the proposed architectural framework for prosumer-led DOE calculation within a CSIP-AUS-compliant communication architecture. The framework consists of two main layers: the prosumer side and the DNSP side. At the prosumer side, the smart inverter, gateway device, or cloud proxy agent functions as the *CSIP-AUS client*. At the DNSP side, the utility server operates as the *CSIP-AUS server*. Together, these components form a client–server architecture that enables the exchange of DOE-related information between prosumers and the DNSP.

At the prosumer side, the *intended DOE* calculation module determines the prosumer's preferred import or export capacity. This intended DOE reflects local operating preferences and site-level conditions, such as household demand, rooftop PV generation, battery state of charge, inverter limits, and other device-level constraints. The calculated intended DOE is then transmitted to the DNSP through the CSIP-AUS communication pathway. In this proposed approach, the intended DOE represents the prosumer's preferred operating envelope before the DNSP applies network-level feasibility checks.

At the DNSP side, the received intended DOE is incorporated into the proposed optimisation module. This module combines three key inputs: (i) prosumer-specific constraints, (ii) a detailed three-phase four-wire distribution network model with associated network constraints, and (iii) a fairness-driven objective. The network model and constraints ensure that the calculated DOEs respect the physical limits of the distribution network, including voltage and thermal limits. The fairness-driven objective guides the allocation of available network capacity among participating prosumers in a way that aims to reduce inequitable outcomes and avoid systematic bias.

The proposed optimisation module then calculates the *actual DOE*, which refers to the DNSP-approved import or export operating envelope assigned to the prosumer. Unlike the intended DOE, the actual DOE is network-feasible and reflects the combined effects of prosumer preferences, network constraints, and fairness considerations. Once calculated, the actual DOE is sent back to the prosumer through the CSIP-AUS architecture. The prosumer then applies the assigned DOE on-site through the local control system, such as inverter control or an energy management system. This ensures that the prosumer's DER operation remains within network-secure limits while still considering the prosumer's intended operating behaviour as far as technically feasible.

3.2 Proposed Optimisation Module for DOE Calculation

3.2.1 Modelling prosumers and their constraints

Let $\mathcal{J}$ denote the set of $\mathcal{N}$ prosumers connected to the distribution network. For each prosumer $i \in \mathcal{J}$, let P_i^{DOE} denote the DNSP-prescribed, maximum export or import limit, which cumulatively forms the prosumer's DOE profile as a time series. At the connection point of each prosumer $i \in \mathcal{J}$, let P_i^d and Q_i^d denote the active and reactive residential power demand, respectively, and let P_i^{pv} and Q_i^{pv} denote the DER active and reactive power injection, respectively. Accordingly,

$$P_i^{net} = P_i^{pv} - P_i^d; \quad \forall i \in \mathcal{J}, \tag{1}$$

$$Q_i^{net} = Q_i^{pv} - Q_i^d; \quad \forall i \in \mathcal{J}. \tag{2}$$

We adopt the following sign convention: Positive values of P_i^{net} and Q_i^{net} correspond to power injected by the prosumer (exports), whereas negative values correspond to power drawn from the grid (imports).

Consistent with prevailing industrial practices for DOEs [14], we consider active power control as the sole flexibility mechanism. This design choice ensures practical relevance while focusing on enhancing the utilisation of existing LV network capacity. This simplifies the reactive power injection to $Q_i^{pv} = 0$, leading to $Q_{i,t}^{net} = -Q_{i,t}^{d}$.

Each prosumer $i \in \mathcal{I}$ has an intended DOE, P_i^{intd}, reflecting their generation in excess of demand, which is given by,

$$P_i^{intd} = min\left(P_i^{net}, \overline{P}_i\right) \quad if\ P_i^{net} \geq 0(export); \quad \forall i \in \mathcal{I}, \tag{3}$$

$$P_i^{intd} = P_i^{net} \quad if\ P_i^{net} < 0(import); \quad \forall i \in \mathcal{I}, \tag{4}$$

where the intended export is bounded by DNSP-defined export limit $\overline{P}_i$, while imports are unrestricted.

If a prosumer intends to export power, the DNSP may reduce the export down to zero; however, the prosumer cannot be compelled to import power, nor can they be allowed to export more than the intended amount.

$$0 \leq P_i^{DOE} \leq P_i^{intd} \quad \text{if} \quad P_i^{intd} \geq 0; \quad \forall i \in \mathcal{I}. \tag{5}$$

Similarly, if a prosumer intends to import power, they cannot be forced to export, nor can they be required to import more than the intended amount. That is,

$$P_i^{intd} \leq P_i^{DOE} \leq 0 \quad \text{if} \quad P_i^{intd} < 0; \quad \forall i \in \mathcal{I}. \tag{6}$$

Or equivalently, as a compact inequality,

$$min\left(P_i^{intd}, 0\right) \leq P_i^{DOE} \leq max\left(P_i^{intd}, 0\right); \quad \forall i \in \mathcal{I}.$$

3.2.2 Modelling the distribution network and related constraints

We consider a four-wire, three-phase, radial LV distribution network served by a delta–wye grounded distribution transformer. The network comprises three phase conductors and an explicitly modelled neutral conductor, with the neutral grounded at the transformer side. Prosumers are connected along the feeder on a phase-to-neutral basis, where each prosumer connection is characterised by a current injection and its corresponding phase-to-neutral voltage. Figure 3.2 illustrates the schematic of the considered distribution network, showing the radial feeder structure, the neutral conductor, and the phase-to-neutral connections of prosumers along the feeder.

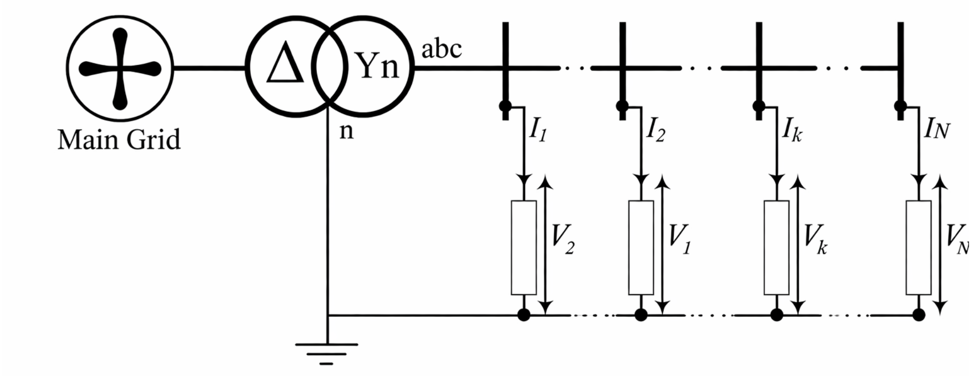

Figure 3.2: A 3-phase radial LV distribution feeder

As shown in Figure 3.2, the main grid is connected to the LV distribution network through a Δ-Yg (delta–wye grounded) transformer, which provides a neutral conductor for phase-to-neutral prosumer connections. Each prosumer connection has a current injection I_i and corresponding phase-to-neutral voltage V_i. The neutral conductor is explicitly drawn and grounded at the transformer side, which is typical for LV distribution. The radial structure is represented by the series of connection points along the feeder.

Let the number of prosumers connected to phase a, b and c be $\mathcal{N}_a$, $\mathcal{N}_b$, and $\mathcal{N}_c$, respectively, such that the total number of customers is $\mathcal{N}$ = $\mathcal{N}_a + \mathcal{N}_b + \mathcal{N}_c$. For notational convenience, customers are indexed such that all phase-a customers appear first, followed by phase-b and then phase-c.

The electrical coupling between prosumers is represented by the aggregated complex impedance matrix $\boldsymbol{Z} = [Z_{ik}]_{i,k\in\mathcal{J}} \in \mathbb{C}^{\mathcal{N}\times\mathcal{N}}$, where each entry is given by $Z_{ik} = R_{ik} + jX_{ik}$. Here, $R_{ik} \in \mathbb{R}$ and $X_{ik} \in \mathbb{R}$ denote the resistance and reactance associated with the electrical coupling between prosumer connections i and k, respectively. The impedance matrix $\boldsymbol{Z}$ can be decomposed into phase and mutual components as, $\boldsymbol{Z} = \boldsymbol{Z}^{phase} + \boldsymbol{Z}^{mutual}$. Here, $\boldsymbol{Z}^{\boldsymbol{phase}}$ captures the intra-phase coupling and is block-diagonal corresponding to the three phases. That is,

$$\boldsymbol{Z}^{phase} = \left[Z_{ik}^{phase}\right]_{i,k\in\mathcal{J}} = \left[R_{ik}^{phase} + jX_{ik}^{phase}\right]_{i,k\in\mathcal{J}} = \begin{bmatrix} Z^a & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & Z^b & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & Z^c \end{bmatrix}$$

Here, $\mathbf{Z}^{\phi} = \left[Z_{ik}^{phase}\right]_{i,k\in\mathcal{J}^{\phi}} \in \mathbb{C}^{\mathcal{N}^{\phi}\times\mathcal{N}^{\phi}}$ for $\phi \in \{a, b, c\}$ represents the phase-specific impedance submatrix for prosumers connected to phase ϕ. R_{ik}^{phase} and X_{ik}^{phase} represents the resistance and reactance, respectively, of the common electrical path shared by prosumers i and k from their connection points up to the feeder head, when both prosumers are connected to the same phase.

If prosumers i and k are connected to different phases, the corresponding phase-coupling terms are set to zero.

The mutual matrix $\boldsymbol{Z}^{mutual}$ captures inter-phase electromagnetic coupling arising from mutual impedances between conductors and is generally dense (although in practice some entries may be small).

$$\boldsymbol{Z}^{mutual} = \left[Z_{ik}^{mutual}\right]_{i,k\in\mathcal{I}} = \left[R_{ik}^{mutual} + jX_{ik}^{mutual}\right]_{i,k\in\mathcal{I}} = \begin{bmatrix} M^{aa} & M^{ab} & M^{ac} \\ M^{ba} & M^{bb} & M^{bc} \\ M^{ca} & M^{cb} & M^{cc} \end{bmatrix}$$

where $\mathbf{M}^{\phi\psi} \in \mathbb{C}^{\mathcal{N}_\phi \times \mathcal{N}_\psi}$ for $\phi,\ \psi \in \{a, b, c\}$. Each block $\mathbf{M}^{\phi\psi}$ represents the mutual impedance contribution between prosumers connected to phase ϕ and prosumers connected to phase ψ. Specifically, Z_{ik}^{mutual} denotes the element corresponding to row i and column k of $\boldsymbol{Z}^{mutual}$, representing the impedance effect induced by prosumer k connected to phase ψ, on prosumer i connected to phase ϕ. The diagonal blocks $\boldsymbol{M}^{aa}$, $\boldsymbol{M}^{bb}$, and $\boldsymbol{M}^{cc}$ capture mutual impedance contributions among prosumers connected to the same phase, while the off-diagonal blocks capture inter-phase mutual coupling between prosumers connected to different phases. The full matrix $\boldsymbol{Z}$ is expanded as,

$$\boldsymbol{Z} = \begin{bmatrix} \boldsymbol{Z}^{a} + \boldsymbol{M}^{aa} & \boldsymbol{M}^{ab} & \boldsymbol{M}^{ac} \\ \boldsymbol{M}^{ba} & \boldsymbol{Z}^{b} + \boldsymbol{M}^{bb} & \boldsymbol{M}^{bc} \\ \boldsymbol{M}^{ca} & \boldsymbol{M}^{cb} & \boldsymbol{Z}^{c} + \boldsymbol{M}^{cc} \end{bmatrix}$$

Here, $Z_{ik} = R_{ik} + jX_{ik}$, $R_{ik} = R_{ik}^{phase} + R_{ik}^{mutual}$ and $X_{ik} = X_{ik}^{phase} + X_{ik}^{mutual}$.

Let I_i denote the complex current injection at prosumer connection i, which is given by

$$I_i = \frac{\sqrt{(P_i^{net})^2 + (Q_i^{net})^2}}{\widetilde{V}_i} \angle tan^{-1}\left(\frac{Q_i^{net}}{P_i^{net}}\right) + \widetilde{\psi_i}$$

where $\widetilde{V}_i$ and $\widetilde{\psi_i}$ denote the nominal voltage magnitude and voltage phase angle, respectively, at the connection point of prosumer i. In this work, the nominal voltage is taken as 230 V, while the nominal phase angles of phases a, b and c are assumed to be 0°, -120°, and 120°, respectively.

Accordingly, the real and imaginary parts of complex voltage at prosumer i can be expressed as

$$V_i = V^{nl} + \sum_{k\in\mathcal{I}} Z_{ik} I_k = V^{nl} + \sum_{k\in\mathcal{I}} (R_{ik} + jX_{ik}) I_k$$

where R_{ik} and X_{ik} are the resistance and reactance components corresponding to the i-th row and k-th column of the aggregated complex impedance matrix $\boldsymbol{Z}$, respectively. Furthermore, V^{nl} is the no-load voltage at the secondary side of the distribution transformer. This formulation captures the contribution of all prosumer current injections to the voltage at connection point i, including both self-impedance and mutual coupling effects represented within the aggregated impedance matrix.

The primary operational requirement of the distribution network is to maintain prosumer voltages within acceptable statutory and technical limits. Accordingly, the voltage magnitude at the connection point of prosumer i is constrained as follows.

$$V^{min} \leq |V_i| \leq V^{max}; \quad \forall i \in \mathcal{I}, \tag{7}$$

V^{min} and V^{max} are the minimum and maximum prescribed voltage limits.

To account for the thermal limits of network lines, the current flowing through each line is constrained by its maximum allowable current rating, denoted by I_i^{max}. Accordingly, the following constraint is enforced:

$$|I_i| \leq I_i^{max} \tag{8}$$

Remark: While this study considers only voltage and thermal constraints, additional operational constraints can be incorporated into the distribution network model in a similar manner, depending on the requirements of the DOE application and the level of network modelling detail available.

3.2.3 Least squares DOE tracking

Many fairness-oriented DOE calculation studies formulate an objective function that minimises the squared deviation between the intended DOEs and the DNSP-prescribed actual DOEs. This approach seeks to allocate operating envelopes that remain as close as possible to prosumers' preferred import or export requirements, while ensuring that the final allocations satisfy both prosumer-level constraints and distribution network operating constraints. The corresponding *DOE tracking* optimisation problem, incorporating both prosumer and network constraints, is formulated as follows:

$$\min_{\{P_i^{DOE}\}_{i\in\mathcal{I}}} \sum_{i\in\mathcal{I}} \left(P_i^{intd} - P_i^{DOE}\right)^2 \tag{P1}$$

$$s.t. \quad prosumer\ constraints\ (1)-(6),$$

$$network\ constraints\ (7)-(8).$$

However, once network constraints are incorporated into the above optimisation problem $(P1)$, the resulting DOE allocations may still disadvantage prosumers located farther from the feeder head. In particular, prosumers at increasing distances from the feeder head, including prosumers at electrically weaker or more voltage-sensitive locations, may be assigned lower P_i^{DOE} values, because their exports are more likely to trigger network constraint violations, such as over-voltage conditions. As a result, curtailment tends to occur first at the most electrically stressed connection points. This means that prosumers located near the end of the feeder may repeatedly receive lower DOE allocations and experience disproportionately high curtailment, as they reach voltage limits earlier than prosumers located closer to the transformer. In contrast, prosumers closer to the feeder head may be curtailed less frequently, even though the objective function minimises squared deviations between intended and actual DOEs across all prosumers. Therefore, while least-squares DOE tracking improves alignment with prosumer intentions, it may not fully address locational bias unless additional fairness mechanisms are introduced.

> The underlying network physics can implicitly prioritise certain prosumers, potentially leading to inequitable DOE outcomes even when the optimisation problem is formally designed to promote fairness.

3.2.4 Impedance-weighted least squares DOE tracking

To prioritise end-of-feeder prosumers located in electrically weaker parts of the network and mitigate the locational bias introduced by the underlying network physics, we introduce *location-based weighting factors* for prosumers along the distribution feeder. These weights are designed to act as a proxy for the level of electrical stress associated with each prosumer's connection point. In particular, prosumers located farther from the feeder head typically have higher electrical impedance to the transformer and are more likely to experience voltage rise under export conditions. As a result, their injections may contribute more strongly to voltage constraint violations than those of prosumers located closer to the transformer.

The proposed weighting mechanism assigns higher weights to prosumers whose injections produce larger voltage changes at their own connection point, or whose connection points exhibit stronger electrical coupling with other prosumers in the network. By increasing the penalty associated with deviations from the intended DOEs of these electrically constrained prosumers, the optimiser is encouraged to provide greater protection to end-of-feeder customers. This reduces the likelihood that such prosumers are repeatedly curtailed simply because of their location in the feeder.

A physically meaningful way to represent this locational effect is through the aggregated complex impedance matrix $\boldsymbol{Z}$, which captures both self-impedance and mutual coupling effects between prosumer connection points. Specifically, we assign an impedance-based weight, s_i, to each prosumer $i \in \mathcal{I}$, reflecting their electrical distance from the feeder head and their sensitivity to network constraints. This weight can be calculated using either the 1-norm (or 2-norm) of the i-th row of $\boldsymbol{Z}$. Accordingly, the weight s_i for prosumer $i \in \mathcal{I}$ is calculated as $s_i = \sum_{k \in \mathcal{I}} |Z_{ik}|$ (or alternatively, $s_i = \sqrt{\sum_{k \in \mathcal{I}} |Z_{ik}|^2}$). The 1-norm formulation captures the total electrical coupling between prosumer i and all other prosumer connection points, while the 2-norm formulation gives greater emphasis to larger impedance terms. In both cases, a larger value of s_i indicates that prosumer i is more electrically sensitive or more strongly affected by network impedance. Therefore, prosumers located farther from the feeder head, or those with greater voltage sensitivity, receive larger weights in the DOE tracking objective.

To ensure that the weights are comparable across prosumers and do not arbitrarily scale the optimisation objective, the impedance-based weights are normalised such that $\widetilde{s_i} = \frac{s_i}{\frac{1}{N}\sum_{j\in\mathcal{J}} s_j}$.

The optimisation problem for *impedance-weighted DOE tracking* is now formulated as follows:

$$\min_{\{P_i^{DOE}\}_{i\in\mathcal{J}}} \sum_{i\in\mathcal{J}} \widetilde{s_i}\left(P_i^{intd} - P_i^{DOE}\right)^2 \qquad (P2)$$

$$s.t. \quad prosumer\ constraints\ (1)-(6),$$

$$network\ constraints\ (7)-(8).$$

3.2.5 Weight-adjusted least squares DOE tracking

While the weighted objective function in $(P2)$ helps protect end-of-feeder prosumers, it may also introduce a new form of locational bias by systematically favouring prosumers located farther from the feeder head. Although this is useful for mitigating the disadvantage experienced by electrically constrained prosumers, a fairness-oriented DOE allocation method should also avoid over-correcting in a way that disadvantages prosumers located closer to the transformer.

Therefore, to achieve a more balanced allocation across both end-of-feeder and near-transformer prosumers, a *mixed weighting scheme* is required. To represent the relative priority of prosumers located closer to the feeder head, we define an inverse-impedance-based weight factor for each prosumer $i \in \mathcal{J}$. This is given by, $e_i = \frac{1}{\sum_{l\in \mathrm{path}(i)} Z_l + \epsilon_z}$, where $\mathrm{path(i)}$ denotes the set of network line segments between prosumer i and the feeder head, Z_l is the complex impedance of line segment l, and $\epsilon_z > 0$ is a small positive constant introduced to avoid division by zero. Under this definition, prosumers located closer to the transformer have smaller path impedances and therefore receive larger inverse-impedance weights. Conversely, prosumers located farther from the feeder head have larger path impedances and receive smaller inverse-impedance weights.

To ensure comparability across prosumers, the inverse-impedance weight e_i is normalised such that $\widetilde{e_i} = \frac{e_i}{\frac{1}{N}\sum_{j\in\mathcal{J}} e_j}$. This normalisation ensures that the average inverse-impedance weight is equal to one, while preserving the relative differences between prosumers according to their electrical proximity to the feeder head.

Now, to ensure fair treatment of prosumers at both ends and along the distribution feeder, we define a mixed weight w_i that combines $\widetilde{s_\iota}$ (which prioritise electrically constrained end-of-feeder prosumers) with $\widetilde{e_\iota}$ (which provide balancing priority to prosumers closer nearer the distribution transformer). The combination is realised through an additive mixing scheme, in which a tuning parameter $\alpha \in [0,1]$ governs the relative contribution of $\widetilde{s_\iota}$ and $\widetilde{e_\iota}$ and controls the relative emphasis placed on end-of-feeder protection versus near-transformer balancing. That is,

$$w_i(\alpha) = \alpha\widetilde{s_\iota} + (1 - \alpha)\widetilde{e_\iota}.$$

When α is close to zero, the allocation gives greater priority to prosumers closer to the feeder head. Intermediate values of α provide a balanced weighting structure that can reduce locational bias in both directions. More specifically, the choice of α can be guided by fairness considerations, such as selecting the value that maximises Jain's fairness index or guarantees that the DOE allocation for the worst-off customer remains above a specified threshold. The additive weights are normalised such that $\widetilde{w_\iota}(\alpha) = \frac{w_i(\alpha)}{\frac{1}{\mathcal{N}}\sum_{j\in\mathcal{I}} w_j(\alpha)}$.

3.2.6 Accounting for historical DOE allocations

The mixed weight $\widetilde{w_\iota}(\alpha)$ may be applied directly in its current form to balance the allocation priority between end-of-feeder and near-transformer prosumers. However, the weighting scheme can also be extended to account for historical DOE allocations, thereby further improving fairness over time. This is important because fairness should not be assessed only at a single operating interval. A prosumer may receive a relatively fair allocation at one time step but may still be disadvantaged over a longer period if they repeatedly receive only a small fraction of their intended DOE.

By accounting for past DOE allocations, we can adjust current DOE (P_i^{DOE}) allocations, thereby compensating prosumers who have previously received a smaller fraction of their intended DOE (P_i^{intd}). That is, the allocation history of each prosumer can be monitored by comparing the DNSP-prescribed DOE (P_i^{DOE}) with the corresponding prosumer-intended DOE (P_i^{intd}), over previous time intervals.

Let c_i denote the historical DOE delivery ratio of prosumer $i \in \mathcal{I}$, computed over D historical days and across T time intervals. That is,

$$c_i = \frac{\sum_{t=1}^{T}\sum_{t=1}^{T} P_i^{DOE}(d,t)}{\sum_{t=1}^{T}\sum_{t=1}^{T} P_i^{intd}(d,t)},$$

where $P_i^{DOE}(d,t)$ and $P_i^{intd}(d,t)$ denote the actual DNSP-prescribed DOE and the corresponding intended DOE of prosumer $i \in \mathcal{I}$, respectively, on the d-th historical day at time interval t. As such, c_i measures the average fraction of the intended DOE that has historically been delivered to prosumer $i \in \mathcal{I}$, over the D historical days and T time intervals. A value of c_i close to 1 indicates that the prosumer has, on average, received DOE allocations close to their intended operating requirements, whereas a lower value indicates that the prosumer has historically received only a smaller fraction of their intended DOE and has therefore experienced greater curtailment or restriction.

Let h_i denote the historical adjustment factor for prosumer $i \in \mathcal{J}$, defined as the inverse of the historical DOE delivery ratio c_i. This factor is introduced to increase the allocation priority of prosumers that have experienced significant curtailment in previous DOE allocation periods. Accordingly, $h_i = \frac{1}{c_i + \epsilon_h}$, where $\epsilon_h > 0$ is a small positive constant introduced to avoid division by zero and to ensure numerical stability. Under this definition, a prosumer with a lower historical delivery ratio c_i receives a larger value of h_i, thereby increasing its weighting in the current DOE allocation problem. Conversely, prosumers that have historically received allocations close to their intended DOEs receive smaller adjustment factors.

To ensure comparability across prosumers, the historical adjustment factors h_i are normalised such that $\widetilde{h_i} = \frac{h_i}{\frac{1}{N}\sum_{j \in \mathcal{J}} h_j}$. This normalisation ensures that the average historical adjustment factor is equal to one, while preserving the relative differences in historical curtailment experience among prosumers.

Next, the normalised historical adjustment factor $\widetilde{h_i}$ is combined with the previously defined mixed weight $\widetilde{w_i}(\alpha)$ to form the final composite weight $\widehat{w_i}(\alpha)$, given by $\widehat{w_i}(\alpha) = \widetilde{w_i}(\alpha).\widetilde{h_i}$. This composite weighting structure accounts for both the electrical position of the prosumer within the feeder and the prosumer's historical DOE allocation outcomes. As a result, the optimisation problem gives greater priority to prosumers that are either electrically disadvantaged, historically curtailed, or both. Accordingly, the optimisation problem for *weight-adjusted least-squares DOE tracking* is formulated as follows:

$$\min_{\{P_i^{DOE}\}_{i \in \mathcal{J}}} \sum_{i \in \mathcal{J}} \widehat{w_i}(\alpha)\left(P_i^{intd} - P_i^{DOE}\right)^2 \qquad (P3)$$

$$s.t. \quad prosumer\ constraints\ (1) - (6),$$

$$network\ constraints\ (7) - (8).$$

3.3 Compensation for prosumers

In addition to improving fairness through the DOE allocation formulation itself, fairness can also be supported through compensation mechanisms. In this study, we propose a methodology for identifying prosumers who may be adversely affected by the proposed weight-adjusted least-squares DOE tracking approach, relative to an equal allocation of hosting capacity. Equal allocation is used as the benchmark because it represents a simple and widely adopted industry approach for distributing available DOE capacity among participating customers. By comparing the proposed allocation with this benchmark, it is possible to quantify the extent to which each prosumer receives less capacity than they would have received under an equal allocation rule.

For each prosumer $i \in \mathcal{I}$, let P_i^{DOE} denote the DOE allocated under the proposed weight-adjusted least-squares DOE tracking method, and let P_i^{EQ} denote the corresponding allocation under an equal sharing of available hosting capacity. A prosumer is considered negatively impacted if the proposed allocation is lower than the equal allocation, i.e., if $\left(P_i^{DOE} < P_i^{EQ}\right)$. In such cases, the shortfall $(P_i^{EQ} - P_i^{DOE})$ represents the amount of network access that the prosumer has forgone relative to the equal allocation benchmark.

The (monetary) compensation for each prosumer $i \in \mathcal{I}$ is then defined as

$$\mathcal{R}_i = k \ \max\left(0, (P_i^{EQ} - P_i^{intd}) - (P_i^{DOE} - P_i^{intd})\right),$$

where k (\$/kW) is the compensation coefficient (or unit reward rate), which converts the unmet allocation difference into a monetary payment per kilowatt of shortfall. The use of the maximum operator ensures that compensation is provided only to prosumers whose proposed DOE allocation is lower than the equal allocation benchmark. Prosumers receiving an allocation equal to or greater than P_i^{EQ} do not receive compensation under this mechanism.

However, to avoid compensating capacity that the prosumer did not actually intend to use, a better export-only formulation is:

$$\mathcal{R}_i = k \ \max\left(0, \ (min\,\{P_i^{EQ}, P_i^{intd}\} - P_i^{DOE})\right),$$

which compensates only the shortfall relative to the lower of the equal-allocation benchmark and the prosumer's intended export capacity.

This compensation approach provides a complementary fairness mechanism to the optimisation-based allocation method. While the proposed DOE tracking formulation aims to improve the overall fairness and efficiency of capacity allocation, some prosumers may still receive lower allocations than they would under an equal allocation rule. The compensation mechanism helps address this residual fairness concern by recognising and monetising the disadvantage experienced by those prosumers. In this way, the proposed approach can support a more balanced outcome that combines technically efficient DOE allocation with a transparent mechanism for compensating customers who are adversely affected relative to the current industry benchmark.

4 Results

4.1. Case Study

Australian low-voltage (LV) distribution feeders are typically configured as four-wire networks, with three phase conductors and a neutral conductor. The neutral is commonly grounded at the distribution substation and at, or near, customer connection points. These networks are generally operated at a nominal voltage of 400/230 V, with an allowable voltage variation of ±10%.

In this case study, the proposed prosumer-led DOE allocation approach is evaluated through numerical simulations using an LV distribution feeder extracted from a realistic Australian medium-voltage (MV) feeder dataset with associated LV feeders[15]. The selected LV feeder comprises 123 single-phase residential customers, of which 90 are modelled as prosumers equipped with rooftop PV systems and 5 kVA inverters. The PV systems are assumed to operate at unity power factor. For the results presented in this case study, only export limits are considered when determining DOE allocations, although the proposed mathematical formulation is applicable to both import and export DOEs.

Figure 5 presents the DOE allocations obtained for participating prosumers under the different allocation methods considered in this study, as defined below.

1. **Competitive allocation:** Under competitive allocation, export limits are assigned to prosumers with the objective of maximising the aggregate export capacity of all participating prosumers, while ensuring that all distribution network operational constraints are satisfied. This approach represents an efficiency-driven allocation strategy, as it prioritises maximum utilisation of the available network hosting capacity. However, because the allocation is governed primarily by network physics, prosumers located in electrically favourable locations, such as those closer to the feeder head, may receive higher export limits than prosumers located in more constrained parts of the feeder. The corresponding optimisation problem can be formulated as:

$$\max_{\{P_i^{DOE}\}_{i\in\mathcal{I}}} \sum_{i\in\mathcal{I}} P_i^{DOE} \qquad (P5)$$

$$\begin{aligned} s.t. \quad & prosumer\ constraints\ (1)-(6), \\ & network\ constraints\ (7)-(8), \end{aligned}$$

2. **Equal allocation**: Under equal allocation, all participating prosumers are assigned an identical export limit, while ensuring that the resulting network operation remains within the prescribed technical limits. This approach reflects common industry practice and is often perceived as fair because all customers are treated equally and receive the same export entitlement. It also provides a simple and transparent allocation mechanism that can be readily implemented in practical settings. However, equal allocation may underutilise available network capacity, particularly when some prosumers are capable of exporting more without causing network constraint violations. The corresponding optimisation problem can be formulated as:

$$\max_{\{P_i^{DOE}\}_{i\in\mathcal{I}}} \sum_{i\in\mathcal{I}} P_i^{DOE} \tag{P4}$$

$$\begin{aligned} s.t. \quad & prosumer\ constraints\ (1)-(6), \\ & network\ constraints\ (7)-(8), \\ & P_i^{DOE} = P_j^{DOE}, \qquad \forall i,j \in \mathcal{I}. \end{aligned}$$

3. **Log fairness-based allocation**: Under log-fairness-based allocation, export limits are assigned according to a logarithmic utility function that seeks to balance individual prosumer outcomes with overall system performance. This method maximises the sum of the logarithms of the allocated export capacities, thereby encouraging a more balanced distribution of export limits among prosumers. Compared with competitive allocation, log fairness provides greater protection to prosumers with lower allocations. Compared with equal allocation, it allows greater utilisation of available network capacity by not forcing all prosumers to receive the same export limit. This logarithmic objective corresponds to proportional fairness and can be interpreted as a special case of the broader alpha-fairness family. In this family, α = 0 corresponds to the competitive allocation objective, while larger values of α place increasing emphasis on fairness and protection of lower-allocated prosumers. The respective optimisation problem is

$$\max_{\{P_i^{DOE}\}_{i\in\mathcal{I}}} \frac{1}{1-\alpha}\left(\sum_{i\in\mathcal{I}} P_i^{DOE}\right)^{1-\alpha} \tag{P4}$$

$$\begin{aligned} s.t. \quad & prosumer\ constraints\ (1)-(6), \\ & network\ constraints\ (7)-(8), \end{aligned}$$

4. **DOE tracking**: The DOE tracking method determines export limits based on the optimisation problem $(P1)$. In this approach, each prosumer provides an intended DOE, representing their preferred export capacity. The DNSP then determines the actual DOE by minimising the squared deviation between the intended DOEs and the DNSP-prescribed DOEs, while

ensuring that all network constraints are satisfied. This method attempts to align the final DOE allocation with prosumer preferences as closely as possible.

5. **Weight-adjusted DOE tracking**: The weight-adjusted DOE tracking method determines export limits based on the optimisation problem $(P3)$. The weight-adjusted DOE tracking method extends the DOE tracking formulation by incorporating prosumer-specific weighting factors into the least-squares objective. These weights are designed to improve fairness by accounting for factors such as the prosumer's electrical position within the feeder and their historical DOE allocation outcomes. In this approach, deviations from intended DOEs are penalised differently across prosumers according to the composite weight. This allows the optimisation to provide greater priority to prosumers who are electrically disadvantaged, historically curtailed, or otherwise more likely to receive lower DOE allocations under unweighted methods. This method therefore aims to retain the intent-aware nature of DOE tracking while improving fairness across prosumers with different network locations and historical allocation experiences.

In Figure 4.1, the shaded bars labelled as 'Requested' denote the intended DOEs, P_i^{intd}, for each prosumer, with prosumers indexed along the x-axis. Figure 4.1 also illustrates the DOE allocation for each prosumer, P_i^{DOE}, obtained using the allocation methods defined above, with each method represented by a different colour. This comparison illustrates how closely each allocation method aligns with the prosumers' intended DOEs, while also highlighting the differences in export capacity distribution across prosumers.

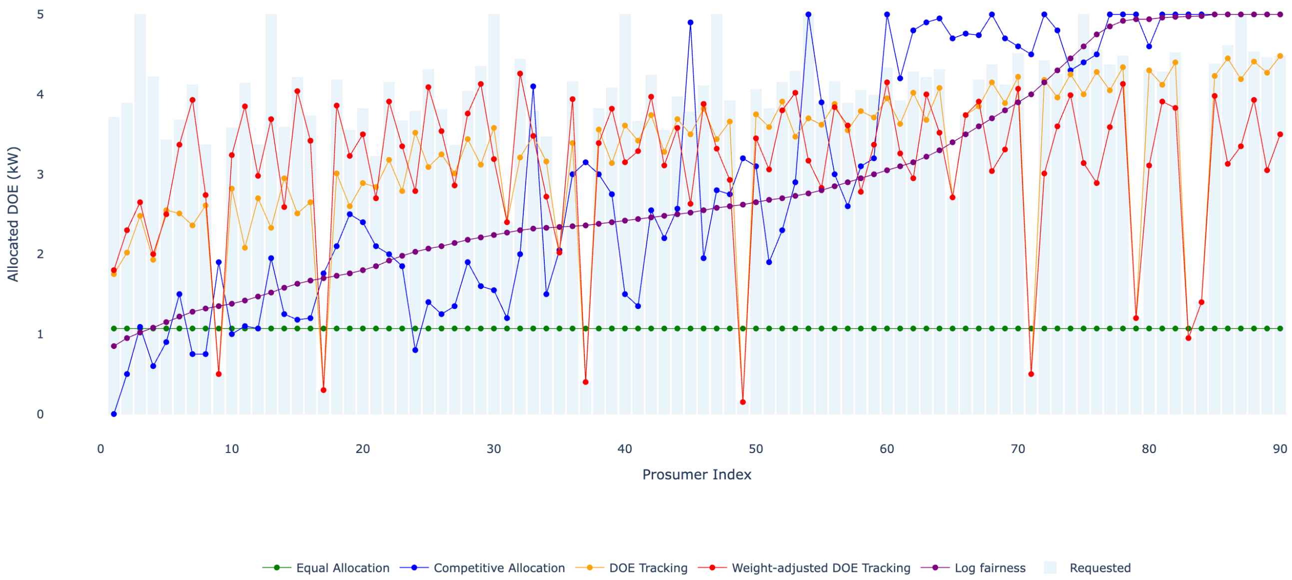

Figure 4.1: Comparison of DOEs under various allocation methods. 'Requested' denotes the intended DOE.

Table 1 presents the aggregate PV injection (in kW) achieved by all prosumers under each allocation method. In addition, Table 1 records Jain's fairness index for each method, which is a widely used metric for quantifying fairness in resource allocation problems. In this study, Jain's fairness index is evaluated based on the ratio of the DOE served to the intended DOE for each prosumer (P_i^{DOE}/P_i^{intd}), thereby measuring how evenly the intended DOE requirements are satisfied across the participating prosumers.

According to the results presented in Figure 4.1 and Table 1, the equal allocation method assigns each prosumer an export limit of approximately 1.07 kW, resulting in an aggregate PV injection of 99 kW across the entire feeder. It is evident that the export limits obtained under equal allocation are relatively low and fall significantly short of the prosumers' intended export limits, which reflect their available on-site excess generation. This indicates that, although equal allocation provides identical export rights to all prosumers, it can substantially restrict the utilisation of available renewable energy.

Under the competitive allocation method, the aggregate PV injection increases substantially to 260 kW. However, this improvement in network utilisation is achieved at the expense of fairness. In particular, one prosumer receives a zero export limit, while several other prosumers receive lower export limits than they would under the equal allocation method. This demonstrates that competitive allocation can maximise the use of available network capacity but may disproportionately disadvantage prosumers located in more constrained parts of the feeder.

These results highlight the fundamental trade-off between efficiency and fairness in DOE allocation. Equal export limits, while often perceived as fair and equitable, can lead to significant underutilisation of available renewable energy. In contrast, competitive allocation improves aggregate export capacity but may produce highly uneven outcomes across prosumers.

The log-fairness-based method provides a more balanced outcome, achieving an aggregate PV injection of 248 kW across the distribution feeder, which is significantly higher than that obtained under equal allocation and close to the competitive allocation result. At the same time, it improves fairness among prosumers by avoiding the most extreme allocation outcomes observed under the competitive method. Therefore, the log-fairness-based method represents a more balanced and equitable approach to DOE allocation when compared with both equal and competitive allocation schemes.

According to Figure 4.1, the DOE tracking method closely follows the trend observed under competitive allocation, while also accounting for each prosumer's available solar generation through their intended DOE. The few allocations that fall below the equal-allocation line correspond to prosumers whose intended export levels are themselves lower than the equal allocation value. This indicates that lower allocations in these cases are not necessarily the result of network-imposed curtailment, but rather reflect the prosumers' lower requested export capacity.

Notably, under DOE tracking, all prosumers are assigned non-zero export limits, and the aggregate PV injection exceeds that achieved under the competitive allocation method. This demonstrates that incorporating prosumers' intended DOEs into the optimisation problem can provide additional opportunities to improve the utilisation of available network capacity. However, the allocation outcomes remain influenced by the electrical location of prosumers within the distribution feeder. In particular, the method still tends to allocate higher DOEs to prosumers located nearer the feeder head, as their exports are generally less likely to trigger voltage constraints.

In comparison, the weight-adjusted DOE tracking method produces a fairer allocation by mitigating this locational bias relative to the unweighted DOE tracking method. By incorporating prosumer-specific weights, the method provides greater protection to prosumers who are electrically disadvantaged or historically more likely to experience curtailment. This improved fairness is achieved with only a modest reduction in aggregate PV injection, which remains high at 272 kW. These results suggest that the proposed weight-adjusted approach can provide a more balanced trade-off between network utilisation and fairness, enabling efficient use of available export capacity while reducing systematic disadvantage across prosumers.

Table 4.1 Comparison of different DOE allocation methods. Jain's fairness score is calculated based on the ratio of the DOE served to the intended DOE for each prosumer.

ALLOCATION METHOD	AGGREGATE PV INJECTION (KW)	JAIN'S FAIRNESS SCORE
Competitive	260	0.52
Equal	99	0.34
Log-fairness	248	0.75
DOE tracking	285	0.82
Weight-adjusted DOE tracking	272	0.93

The differences between the allocation methods become more apparent when individual prosumers are examined in detail. Let us now examine selected individual prosumers more closely to assess how different DOE allocation methods affect fairness at the prosumer level.

- For a prosumer located at the end of the feeder with an intended export of 3.65 kW, the competitive allocation method assigns an export limit of 0 kW. This is substantially below the prosumer's available export potential and illustrates how competitive allocation can severely disadvantage customers located in electrically constrained parts of the feeder. Under equal allocation, the same prosumer receives 1.07 kW, while the log-fairness-based method assigns 0.9 kW. In contrast, the DOE tracking method increases the allocation to 1.75 kW, and the weight-adjusted DOE tracking method further improves it slightly to 1.78 kW. This demonstrates that incorporating prosumer intent, together with location-aware weighting, can provide improved access for end-of-feeder prosumers compared with competitive, equal, and log-fairness-based approaches.

- For a prosumer located approximately midway along the feeder, indexed as ($i = 45$), the intended export is 3.9 kW. This prosumer receives 4.9 kW under competitive allocation, indicating that the network can accommodate a relatively high export from this location under an efficiency-driven objective. The log-fairness-based allocation assigns 2.5 kW, continuing its gradual upward trend across the feeder, while the equal allocation method assigns only 1.07 kW. Under DOE tracking, the allocation increases to 3.4 kW, which is closer to the prosumer's intended export. The weight-adjusted DOE tracking method further increases the allocation to 3.6 kW, representing a local peak for this method. This result suggests that the proposed weighting mechanism can better align the allocation with prosumer intent while still maintaining network feasibility

- For a prosumer located closer to the feeder head with an intended export of 4.5 kW, both competitive allocation and log-fairness-based allocation assign an export limit of 5 kW, which is slightly above the intended DOE. This reflects the electrical advantage of prosumers located closer to the transformer, whose exports are less likely to trigger voltage constraints. In contrast, equal allocation assigns only 1.07 kW, which is considerably below the prosumer's available export potential. DOE tracking assigns 4.41 kW, closely matching the intended export, while weight-adjusted DOE tracking assigns 3.53 kW. The lower value under the weight-adjusted method reflects the effect of the fairness weighting scheme, which redistributes some capacity away from electrically advantaged prosumers to improve outcomes for more constrained prosumers elsewhere in the feeder.

Overall, these individual examples highlight the different fairness implications of each allocation method. Competitive allocation can provide high aggregate export capacity but may assign zero or very low limits to constrained end-of-feeder prosumers. Equal allocation avoids extreme disparity but substantially underutilises available export capacity for many prosumers. Log-fairness-based allocation improves the balance between fairness and efficiency, but does not explicitly account for prosumer intent. DOE tracking better reflects individual intended exports, while the weight-adjusted DOE tracking method further moderates locational bias by improving allocations for disadvantaged prosumers, even if this requires reducing allocations for some electrically advantaged customers.

These observations clearly demonstrate the ability of the weight-adjusted DOE tracking method to produce fairer DOE allocations by better balancing prosumer intended exports across the feeder. In particular, the method helps mitigate location-dependent disparities by improving access for electrically disadvantaged prosumers, while still utilising a substantial portion of the available PV generation.

The fairness of the weight-adjusted DOE tracking method is further supported by the Jain's fairness scores presented in Table 1, where it achieves the highest score among all evaluated methods.

Table 4.2 Comparison of different DOE allocation methods. The asset utilisation factor (AUF) measures the proportion of intended DOE capacity that is ultimately allocated across all prosumers and time intervals. Standard deviation relative to the mean intended DOE measures how much the allocated DOE values vary around the average export capacity that prosumers intended to receive.

ALLOCATION METHOD	STANDARAD DEVIATION (KW)	ASSET UTILISATION FACTOR (AUF)
Competitive	1.75	0.52
Equal	2.71	0.28
Log-fairness	2.21	0.75
DOE tracking	1.19	0.84
Weight-adjusted DOE tracking	0.95	0.80

The asset utilisation factor (AUF) measures the proportion of intended DOE capacity that is ultimately allocated across all prosumers and time intervals. It is calculated as the ratio of total allocated DOE capacity to total intended DOE capacity. DOE tracking achieves the highest AUF of 0.84, indicating that it retains the largest share of prosumers' intended export capacity. Weight-adjusted DOE tracking follows closely, with an AUF of 0.80, while also providing a more consistent alignment with intended DOE values.

Standard deviation relative to the mean intended DOE measures how much the allocated DOE values vary around the average export capacity that prosumers intended to receive. It is highest under equal allocation (2.71 kW), showing that equal limits can differ substantially from individual prosumer intentions. In contrast, weight-adjusted DOE tracking produces the lowest standard deviation (0.95 kW), followed by standard DOE tracking (1.19 kW). This indicates that the DOE-tracking approaches, particularly the weight-adjusted formulation, better reflect intended prosumer export levels while maintaining high network asset utilisation.

Remark: It is also worth noting that, when prosumer-intended DOEs cannot be incorporated, the log-fairness-based method can serve as a practical fallback strategy. This may occur in situations where prosumer preferences are unavailable, communication capability is limited, or the required information cannot be reliably obtained in real time. Under such conditions, the log-fairness-based method provides a considerably fairer approach to DOE allocation than both equal and competitive allocation. Unlike equal allocation, it allows greater utilisation of available network capacity by avoiding unnecessarily restrictive identical limits for all prosumers. At the same time, unlike competitive allocation, it reduces the likelihood that electrically disadvantaged prosumers receive very low or zero export limits. Therefore, while the proposed weight-adjusted DOE tracking method is preferred when prosumer-intended DOEs are available, log-fairness-based allocation provides a useful fairness-aware fallback option for practical DOE implementation.

4.2 Discussion

The results presented in this chapter demonstrate the potential value of incorporating prosumer preferences into the allocation of DOEs. In contrast to conventional equal allocation approaches, the proposed prosumer-led, optimisation-based method explicitly considers prosumers' intended DOEs while ensuring that the resulting allocations remain within distribution network operating constraints. This allows the allocation process to better reflect the operating intentions of individual prosumers, while still maintaining network security. The case study results indicate that such an approach can improve the utilisation of available export capacity and provide fairer outcomes across prosumers, particularly when network capacity is limited.

A key observation from the results is that DOE allocation is strongly influenced by the electrical position of prosumers within the distribution feeder. Prosumers located closer to the feeder head or distribution transformer are generally less constrained by voltage rise and may therefore receive higher export limits under allocation methods that primarily maximise total export capacity. While such outcomes may be technically efficient from a network utilisation perspective, they can create persistent locational bias and reduce fairness for prosumers located further along the feeder. The proposed weighting scheme addresses this issue by assigning prosumer-specific weights based on their electrical position and dynamically adjusting these weights using historical DOE allocations. This enables export opportunities to be distributed more equitably over time, rather than repeatedly favouring prosumers who are electrically better positioned.

The inclusion of historical allocation information is particularly important from a fairness perspective. A DOE allocation that appears fair at a single time step may still lead to inequitable outcomes when considered over a longer operating period. For example, some prosumers may repeatedly receive lower export limits due to their location or sensitivity to network constraints. By accounting for historical DOE allocations, the proposed approach can compensate for such repeated disadvantage and support a more balanced distribution of export opportunities. This is important for improving customer acceptance of DOEs, as prosumers are more likely to support dynamic network access arrangements if the allocation process is transparent, justifiable, and not systematically biased against particular customers.

The results also highlight the trade-off between fairness and efficient network utilisation. Equal allocation methods are simple and transparent, but they may not fully utilise the available export capacity in the network. Conversely, purely efficiency-driven methods may maximise aggregate exports but can lead to unequal outcomes among prosumers. The proposed prosumer-led approach provides a mechanism for balancing these competing objectives. By incorporating intended DOEs and fairness weights into the optimisation problem, the method can improve alignment with prosumer preferences while avoiding unnecessary curtailment where network capacity is available. This suggests that fairness does not need to be treated as a separate consideration after DOE calculation but can instead be embedded directly within the DOE allocation formulation.

It is also worth noting that, in cases where prosumer-intended DOEs cannot be incorporated, the log-fairness-based allocation method can serve as a practical fallback strategy. In real-world implementation, intended DOEs may be unavailable for several reasons, including limited customer participation, incomplete DER communication capability, failures in communication (e.g., packet losses), privacy concerns, forecasting limitations, or the absence of a suitable interface through which prosumers can express their preferred operating behaviour. Under such circumstances, the DOE allocation process may need to rely only on network constraints and available DER capacity information. The results indicate that a log-fairness-based method provides a considerably fairer approach compared with both equal and competitive allocation. Unlike equal allocation, it does not unnecessarily restrict all prosumers to the same level of access when additional network capacity can be safely utilised. At the same time, unlike competitive allocation, it avoids strongly favouring prosumers who are electrically better positioned in the feeder. Therefore, while the proposed prosumer-led method remains the preferred approach when intended DOEs are available, log-fairness-based allocation provides a useful fairness-aware fallback option for practical DOE implementation.

The proposed method also has important implications for practical DOE implementation. In practice, the successful deployment of prosumer-led DOEs would require sufficient visibility of the distribution network, including network topology, asset ratings, voltage conditions, and estimates or measurements of customer demand and DER behaviour. While low-voltage networks have historically had limited monitoring and modelling data, the increasing deployment of smart meters, advanced distribution management systems, and DER communication infrastructure provides opportunities to improve this visibility. The proposed approach does not require prosumers to directly manage network constraints. Rather, prosumers provide their intended operating preferences, and the DNSP or aggregator determines feasible DOE allocations using the optimisation framework and available network information.

From an implementation perspective, communication standards such as CSIP-AUS provide an important pathway for exchanging DOE-related information between DNSPs, aggregators, and DER systems. The proposed framework can therefore be viewed as complementary to emerging DER communication and orchestration architectures. Under such an arrangement, prosumers or their energy management systems would provide intended DOEs, while the DNSP or aggregator would calculate allocated DOEs that satisfy network constraints. These allocated limits could then be communicated back to prosumers or DER devices for implementation. However, practical deployment would require further consideration of communication latency, data quality, interoperability, customer participation, and privacy.

Another important consideration is the accuracy and truthfulness of prosumer intended DOEs. The proposed approach assumes that intended DOEs reasonably represent prosumer operating preferences and DER capabilities. In practice, a prosumer may unintentionally or strategically provide an intended DOE that does not reflect their actual capability or expected operation. For example, a prosumer may request a higher export limit than their DER system can realistically deliver. This issue could be addressed through validation using DER ratings, historical smart meter measurements, and consistency checks between intended and actual behaviour. Where required, penalties could also be developed to discourage unrealistic or untruthful submissions. The design of such mechanisms is beyond the scope of this work but represents an important area for future research.

Scalability is another important factor for real-world implementation. DOE allocation may need to be performed at regular operational intervals, such as every 5 minutes or every 15 minutes, depending on the network management process and communication architecture. The optimisation problem must therefore be solved within a practical time frame. The case study demonstrates the feasibility of the proposed approach for the network and scenarios considered in this report. For larger distribution networks, scalability could be improved by solving the optimisation problem only for constrained areas of the network, decomposing the network into smaller sub-networks, or running independent optimisation problems in parallel where network areas are weakly coupled. Further computational testing would be required to assess performance at larger scales and under more complex operating conditions.

Finally, uncertainty remains an important challenge in DOE allocation. Forecast errors in solar generation, customer demand, DER availability, and network conditions can affect the feasibility and performance of DOE allocations. Shorter decision intervals can help reduce uncertainty by allowing DOE allocations to be updated more frequently. However, uncertainty cannot be fully eliminated. Future work could incorporate uncertainty through stochastic or robust optimisation formulations, although these approaches would require probabilistic information or uncertainty bounds for relevant inputs. A simpler practical alternative is to apply conservative safety margins to network constraints, creating a buffer between calculated operating limits and actual technical limits. Such conservatism is already common in distribution network operation, but further work is required to understand how these margins affect fairness, network utilisation, and prosumer outcomes.

Overall, the results presented in this chapter support the conclusion that prosumer-led, optimisation-based DOE allocation can provide a more flexible and fairer alternative to simple equal allocation approaches. By incorporating intended DOEs, network constraints, electrical position, and historical allocation outcomes, the proposed method provides a structured way to share available export capacity among prosumers while maintaining secure network operation. Although further work is needed to address implementation, uncertainty, scalability, and import-limit applications, the proposed approach provides a promising foundation for fairer and more efficient DER integration in distribution networks.

5 Tracking against the Stage 1 Roadmap for Topic 8: DERs

This research study aims to address the following research questions from the Stage 1 Roadmap for Topic 8: DERs. The discussion below maps the contributions of this project against the relevant roadmap questions and explains how the proposed prosumer-led DOE allocation method contributes to the broader objectives of DER orchestration in Australian distribution networks.

RQ1.2 For each DER control approach, what is the most adequate decision-making algorithm (solution method)?

This project addresses RQ1.2 by developing an optimisation-based decision-making algorithm for determining DOEs. The proposed method accounts for fairness considerations, distribution network physics, and network operational requirements. In doing so, it provides a structured solution approach for allocating DOEs in a way that reflects both the technical constraints of the network and the operating preferences of participating prosumers.

The proposed optimisation framework captures the objectives and constraints of key stakeholders, including DNSPs and prosumers. From the DNSP perspective, the allocation must ensure that network operation remains within prescribed technical limits, including voltage and thermal constraints. From the prosumer perspective, the allocation should, as far as technically feasible, align with the prosumer's intended DOE and avoid disproportionate curtailment. The project therefore formulates DOE allocation as a constrained optimisation problem that balances network security, hosting capacity utilisation, and customer fairness.

More specifically, this project enhances fairness in DOE allocation by deriving operating envelopes that account for prosumer intent, electrical position within the feeder, and historical allocation outcomes. The proposed weight-adjusted DOE tracking method enables the allocation process to reduce locational bias while still making effective use of available network capacity. In this way, the project demonstrates that optimisation-based decision-making can provide a suitable solution method for DER coordination, supporting both fairer DOE allocation and improved utilisation of distribution network hosting capacity.

RQ2.1 For each of the potential technical frameworks for orchestrating DER and the corresponding decision-making algorithms, what are the minimum communication and control requirements?

This project addresses RQ2.1 by proposing a prosumer-led coordination framework that enables structured communication between prosumers and DNSPs for the calculation and updating of DOEs. The proposed framework uses CSIP-AUS as the communication pathway for exchanging DOE-related information between customer-side DER systems and the DNSP.

Specifically, the proposed architecture adopts a bidirectional communication mechanism. On the prosumer side, customers determine their intended DOEs based on local operating preferences, DER capability, and site-level constraints. These intended DOEs are communicated to the DNSP and incorporated into an optimisation-based DOE allocation framework. The DNSP then determines feasible DOEs that account for prosumer preferences, distribution network constraints, and fairness considerations. The resulting DNSP-prescribed DOEs are subsequently communicated back to prosumers for implementation through their local DER control systems, such as smart inverters, gateway devices, or energy management systems.

Within this architecture, prosumer-side devices or agents act as CSIP-AUS clients, while the utility server operated by the DNSP acts as the CSIP-AUS server. This client–server arrangement is consistent with CSIP-AUS communication standards and provides a practical mechanism for coordinating DER operation across a technologically diverse and increasingly widespread DER fleet. By supporting communication between DNSPs and heterogeneous DER systems, the proposed approach provides a scalable and standards-aligned approach for DER orchestration in Australian distribution networks.

RQ5.1 What are the necessary organisational and regulatory changes to enable the provisioning of ancillary services from DERs?

This project partially contributes to RQ5.1 by identifying how fairness-aware DOE allocation can support the broader provision of DER-based services. While DOEs are typically calculated by DNSPs to reflect customer-level distribution network constraints, including voltage and thermal limits, the concept can also be extended to the TNSP–DNSP interface to support coordination between local network operation and wider system service requirements.

From an organisational perspective, this requires clearer roles and responsibilities for DNSPs, TNSPs, aggregators, retailers, and prosumers. DNSPs need sufficient network visibility to determine feasible DOEs, while aggregators and market participants require clear operating boundaries within which DER flexibility can be safely dispatched. Interoperable communication standards, such as CSIP-AUS, are therefore important for enabling timely and reliable information exchange.

From a regulatory perspective, DER service provision requires transparent rules for network access, DOE compliance, customer compensation, and the allocation of benefits and costs. In particular, fairness becomes critical when some prosumers are constrained more often than others due to their network location or technical impact. The proposed prosumer-led DOE framework contributes to this by incorporating customer intent, network constraints, electrical position, and historical allocation outcomes into the DOE allocation process.

6 Conclusion and Future Work

6.1 Key contributions

The key contributions of this report are as follows.

First, the report provides a detailed discussion of the role of DOEs in enabling higher DER integration in Australian distribution networks. It explains the transition from static operating limits to DOEs and highlights the importance of active network management in low-voltage networks with high levels of prosumer participation.

Second, the report introduces and defines the concept of prosumer intended DOEs as a mechanism for representing prosumer operating preferences within the DOE allocation process. This allows DOE allocation to move beyond a purely network-centric approach and towards an approach that better reflects customer needs and DER operating intentions.

Third, the report proposes an optimisation-based DOE allocation method that aligns allocated DOEs with prosumer intended DOEs while respecting distribution network constraints. The proposed mathematical formulations are applicable to both import and export limits.

Fourth, the report develops a weighting scheme that accounts for prosumer electrical position and historical DOE allocation outcomes. The purpose of this weighting scheme is to improve fairness by reducing locational bias and distributing network access opportunities more equitably over time.

Fifth, the report presents an implementation architecture based on CSIP-AUS and outlines the required interactions between prosumers and the DNSP. This supports the practical implementation of the proposed DOE allocation approach within the Australian DER communication context.

Finally, the report demonstrates the proposed approach through a DOE case study focused on export-limit allocation. The case study highlights the potential benefits for both prosumers and network utilities by demonstrating how a prosumer-led, optimisation-based DOE allocation approach can improve fairness while enabling more efficient utilisation of available export capacity in the distribution network. Our results demonstrate that, (1) by engaging prosumers in the DOE determination process through the incorporation of their intended DOEs into the optimisation, and (2) by assigning appropriately designed weight factors to prosumers, it is possible to enhance distribution network capacity utilisation while achieving fair DOE allocation outcomes. These findings have important implications for distribution companies in Australia and internationally that seek to improve DOE allocation methodologies using more advanced algorithms, addressing both capacity allocation and fairness considerations.

6.2 Future work

In what follows, we outline several research directions that may be pursued as extensions of the work presented in this report.

6.2.1 Dynamic import limits

For actively managed loads, such as flexible or controllable EV charging, dynamic import limits are also relevant. Dynamic import limits enable flexible loads to self-consume when offset by on-site generation. These import limits are considered conditional (i.e., soft limits), as they can be exceeded by unmanaged or essential loads. However, loads operating under a dynamic connection agreement may be required to adjust their consumption so that the site import limit is not exceeded.

To date, DOE calculations in industry-led programs and previous AR-PST work have primarily focused on export limits, reflecting the immediate challenges associated with rooftop solar exports, reverse power flows, and voltage rise in Australian low-voltage distribution networks. Consistent with this focus, the case study presented in this report is limited to export-limit allocation. However, the proposed mathematical formulations are applicable to both import and export DOEs. Therefore, the same general approach could be extended to import-limit allocation in future work, particularly for applications involving EV charging, flexible demand, and battery charging. Investigating how dynamic import limits interact with DOE calculation through detailed case studies would therefore be valuable, as such extensions would support broader DER coordination use cases, including peak demand management and the integration of flexible loads.

In the case of import DOEs, the proposed approach could also be combined with soft DOE limits and dynamic pricing mechanisms to encourage compliance while allowing controlled deviations where appropriate. For example, a tiered pricing structure could be applied in which imports up to 5 kW are charged at price level A, imports between 5 kW and 7 kW at price level B, and imports above 7 kW at price level C. Such a mechanism would allow higher import levels to be accommodated, when necessary, while reflecting the increasing network impact of exceeding the assigned DOE. This concept could also be extended to more granular time- and location-dependent dynamic pricing schemes, providing a flexible pathway for coordinating flexible demand and improving network utilisation.

6.2.2 Behind-the-meter DER optimisation under DOEs

Existing DOE approaches primarily focus on network-to-site coordination and the allocation of DOEs at the site-scale. However, when multiple DERs are present behind the meter, further research is needed to determine how a site-scale DOE, comprising both import and export limits, should be allocated across individual DER assets, including managed and unmanaged loads, batteries, and generators. This allocation needs to account for the differing flexibility, priorities, technical constraints, and operational characteristics of each DER.

Addressing this challenge requires the development of suitable behind-the-meter optimisation methodologies for energy management. Such methodologies would determine how customer-side DERs should be scheduled or controlled to remain within the assigned DOE while still meeting customer preferences and maximising the value of available DER flexibility. This also highlights the need for interoperable standards and control interfaces that enable coordinated operation across heterogeneous DER devices. Future work could therefore investigate how behind-the-meter optimisation can be integrated with DOE-based network coordination to support more effective, flexible, and customer-responsive DER management.

6.2.3 Optimising voltage control devices for enhanced DOE calculation

Devices such as on-load tap changers, voltage regulators and STATCOMs, can have a significant impact on voltage profiles within distribution networks. Therefore, future DOE calculation methods should explicitly account for the controllability of these devices when determining feasible import and export limits.

For example, DOE calculations could be improved by simultaneously optimising tap settings, reactive power support, and DOE limits. By co-optimising network control actions and DER operating envelopes, the calculated DOEs can more accurately reflect the true hosting capacity of the network. This would help avoid unnecessarily conservative DOE allocations and enable greater utilisation of available network capacity while maintaining voltage and thermal constraints within acceptable limits.

6.2.4 DOE market integration

Integrating DOEs into energy markets can enable prosumers to participate more actively in grid operation and flexibility provision. Market-integrated DOEs extend the conventional DOE concept by allowing market signals, such as prices, flexibility bids, or network support requirements, to influence DOE allocation. This can help align distribution network operation with economic efficiency while ensuring that DER dispatch remains within network-secure limits.

By reflecting both real-time network capacity and the market value of flexibility, DOEs can support more informed dispatch decisions, enable demand response, facilitate local flexibility markets, and promote more efficient utilisation of DERs without compromising network reliability. In this context, DOEs can act as a technical boundary within which market-based DER coordination can occur safely.

Appropriate compensation mechanisms are also important, as DOE allocation may impose different levels of curtailment or flexibility requirements on different customers. An initial simplified compensation approach for affected prosumers has been presented in this report; however, this could be further extended to more comprehensive compensation schemes. By aligning financial rewards with the value of flexibility provided to the network, such schemes can improve customer acceptance, encourage efficient DER operation, and support the scalable deployment of DOEs while maintaining fairness across participating customers.

6.2.5 Reactive power support for enhanced DOEs

This work considers active power export and import limits as the main decision variables in the DOE allocation formulation. However, reactive power control, particularly when provided by DERs located toward the end of distribution feeders, can assist with voltage regulation and may reduce the need for active power curtailment in some circumstances. Localised reactive power support can help mitigate voltage constraint violations, reduce reliance on active power curtailment, and thereby enable greater utilisation of available network capacity.

An important future research direction is therefore to develop DOE optimisation methods that jointly consider both active and reactive power at individual sites, rather than being limited to active power-only calculations. Such an approach would allow DERs to provide voltage support while also participating in export or import capacity allocation, potentially improving both network performance and DER utilisation.

However, incorporating reactive power would increase the complexity of the DOE allocation problem, as multiple combinations of active and reactive power injection or absorption may be capable of addressing the same network constraint. Additional work would therefore be required to determine how prosumer preferences, fairness objectives, inverter capability limits, and network constraints should be balanced when both active and reactive power flexibility are considered.

References

[1] Australian Bureau of Statistics, “Australian National Accounts: National Income, Expenditure and Product,” 2025.

[2] Australian Renewable Energy Agency , [Online]. Available: https://arena.gov.au/knowledge-bank/review-of-dynamic-operating-envelope-adoption-by-dnsps/. [Accessed 1 March 2026].

[3] SA Power Networks, “Flexible Exports for Solar PV Trial – Final Report,” 2023.

[4] ARENA, “Common Smart Inverter Profile – Australia, Version 1.1a2,” Australian Renewable Energy Agency, 2023.

[5] South Australia Department for Energy and Mining, “Dynamic Exports Compliance Timeline,” 2023.

[6] Energex, [Online]. Available: https://www.energex.com.au/our-services/connections/residential-and-commercial-connections/solar-connections-and-other-technologies/dynamic-connections-for-energy-exports/about-dynamic-connections. [Accessed 1 March 2026].

[7] CSIRO, “Stage 3 Research Program Summary Report for Australia’s Global Power System Transformation (G-PST) Research Roadmap,” CSIRO, Australia, 2024.

[8] F. Geth, K. Lucas, J. Clark, N. Nimalsiri, and R. Heidari, “Four-Wire-OPFBased DOE Quantification Incorporating Volt-var/Watt Response,” GridQube and CSIRO, Australia, 2025.

[9] G. Lankeshwara, “A Real-time Control Approach to Maximise the Utilisation of Rooftop PV Using Dynamic Export Limits,” in *Proceedings of the 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies – Asia (ISGT Asia)*, Brisbane, Australia, 2021.

[10] M. Z. Liu et al., “Grid and Market Services From the Edge: Using Operating Envelopes to Unlock Network-Aware Bottom-Up Flexibility,” *IEEE Power and Energy Magazine,* vol. 19, no. 4, pp. 52-62, 2021.

[11] Yi, Yu, and Gregor Verbič, “Fair operating envelopes under uncertainty using chance constrained optimal power flow,” *Electric Power Systems Research,* vol. 213, 2022.

[12] H. Moring and J. L. Mathieu, “Inexactness of Second Order Cone Relaxations for Calculating Operating Envelopes,” in *IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids*, Glasgow, United Kingdom, 2023.

[13] B. Liu and J. H. Braslavsky, “Robust Dynamic Operating Envelopes for DER Integration in Unbalanced Distribution Networks,” *IEEE Transactions on Power Systems,* vol. 39, no. 2, pp. 3921-3936, 2024.

[14] B. Liu and J. H. Braslavsky, “Computation of robust dynamic operating envelopes based on non-convex OPF for unbalanced distribution networks,” *CSEE Journal of Power & Energy Systems ,* 2024.

[15] D. Viktorija, et al., “Impact of local energy markets integration in power systems layer: A comprehensive review,” *Applied Energy,* vol. 301, 2021.

[16] Capper, Timothy, et al., “Peer-to-peer, community self-consumption, and transactive energy: A systematic literature review of local energy market models,” *Renewable and Sustainable Energy Reviews,* vol. 162, 2022.

[17] Jogunola, Olamide, et al., “Peer-to-peer local energy market: opportunities, barriers, security, and implementation options,” *IEEE Access,* vol. 12, pp. 37873-37890, 2024.

[18] Z. Jiang and Y. Guo, “Bargaining-Based Approach for Dynamic Operating Envelope Allocation in Distribution Networks,” *IEEE Transactions on Smart Grid,* vol. 15, no. 5, pp. 3588-3600, 2025.

[19] M. I. Azim, M. M. Hoque, M. Khorasany, R. Razzaghi, M. Jalili and D. J. Hill, “Dynamic Operating Envelope-Integrated Cooperative Energy Trading: A Fair Allocation Approach,” *IEEE Transactions on Power Systems,* vol. 40, no. 4, pp. 2845-2859, 2025.

[20] K. Petrou et al., “Ensuring Distribution Network Integrity Using Dynamic Operating Limits for Prosumers,” *IEEE Transactions on Smart Grid,* vol. 12, no. 5, pp. 3877-3888, 2021.

[21] M. Liu and N. Ochoa, “Project EDGE–Knowledge Sharing Report: Electrical Model Validation and Operating Envelope Calculation,” Australia, 2023.

[22] F. Geth, R. Heidari, J. Clark, K. Lucas and N. Nimalsiri, *Realistic Australian Medium Voltage Feeder with Associated Low Voltage Feeders,* CSIRO Data Access Portal, 2025.

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