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University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

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Non-bias Allocation of Export Capacity for Distribution Network Planning with High Distributed Energy Resource Integration

Juan J. Cuenca, *Graduate Student Member, IEEE,* Barry P. Hayes, *Senior Member, IEEE*

***Abstract*—A novel distributed energy resources (DER) allocation method focused on grid constraints that avoids topological bias is proposed for distribution networks. A technology-agnostic approach is used, where a non-bias allocation of export capacity (NAEC) not specific to generation type is calculated. Moreover, the proposed NAEC is extended from an export capacity into a hosting capacity (HC) using a statistical approach. The methods are tested using the IEEE 33-bus distribution system, and two typical Irish distribution feeders -one urban, one rural- as case studies. Using a high-resolution year-long quasi-static time series simulation (QSTS) and three different generation profiles, the proposed NAEC method is validated against current practices and state of the art allocation methods in terms of active balancing, security of supply, interactions between users, operational concerns, and fairness. Results show that an equivalent or higher level of DER penetration is achieved using the proposed methodology. There are no additional constraint violations using the NAEC methodology, moreover, time slots with violations are reduced, improving security of supply. Furthermore, results suggest that avoiding topological bias makes the network accessible for more users, and prioritises self-consumption.**

***Index Terms*—Energy resources, resource management, power distribution planning, power generation planning, power distribution reliability, search methods.**

I. Introduction

PLANNING studies for power systems involve the prediction of future load and generation conditions. This allows designers, policy makers, operators, and users to make informed decisions about the network, including how to operate it safely, how to schedule generation and infrastructure investments, and how to allocate network charges for maintenance and technical losses. Given recent interest from industry and the research community in renewable energies, efficiency, and security of supply, an important part of modern planning studies involves defining the path towards grids with higher penetrations of distributed energy resources (DER).

Traditionally there has been a clear distinction between transmission and distribution networks from a planning studies perspective. Transmission network planning involved prediction of clusters of aggregated loads, and how to generate enough power in the most efficient and cost-effective way to feed these loads. This must be done considering the existing meshed transmission infrastructure, technical-economical limits, and localised generating plants available [1]. Losses play an important role in these studies as there are multiple paths for power flow depending on the load-generation state [2]. Distribution network planning on the other side, involved a *reactive* approach that consists of a simpler prediction of future peak loads, and determining if the radial network can securely and reliably operate to serve them [3]. This separation between transmission and distribution planning implied the first to consider many possible scenarios with a complex decision-making process, while the latter is more focused on the grid keeping up with the expected radial power flows within technical constrains, and *reacting* with infrastructure changes if necessary.

The introduction of DER into this equation has changed planning studies for both transmission and distribution networks to a different degree: for transmission networks, DER represent additional generating plants with more stochastic availability when compared to the traditional generators, however the already-stochastic nature that traditional planning studies have in the transmission level make the inclusion of DER a relatively small concern. In contrast, for the distribution network, *reactive planning* has become obsolete because the direction of power flows in the system is harder to predict.

The benefits of DER have been broadly studied in the literature. These installations avoid the costs of transporting electricity effectively reducing losses [4]. Compared to large centralised generation stations, small localised installations represent costs savings [5]. Moreover, when DER comes from sustainable sources the dependency on fossil fuels is reduced, which is a paramount strategy against climate change, priority for governments, regulators and the general public [6]. Aside from these, it is important to enumerate the less-obvious yet important motivations for this work: (1) Fairness and governance in distribution networks [7], (2) prioritising self-consumption [8], [9], and (3) transaction permissions considering grid constraints in local energy trading environments [10].

Accordingly, the paper offers a novel allocation method with focus on distribution network studies addressing the problem of planning future distribution networks with high DER penetrations. Its purpose is to provide a useful planning tool to assist designers, policymakers, and grid operators through the energy transition at the distribution level. The main

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J. Cuenca and B. Hayes are affiliated with the School of Engineering and Architecture, University College Cork, Cork, Ireland.

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contributions of the paper are:

- Presenting a real-life-applicable allocation method for distribution networks that achieves high penetration of DER while avoiding topological bias.
- Eliminating the stochastic nature present in state-of-the-art allocation methods by focusing the formulation on technical constraints of the grid rather than uncertain demand-supply operational scenarios.
- Highlight the connection between DER distribution among participants, and active power balancing (i.e., more dispersed DER allocations are linked with an increase in self-consumption).

The paper is structured as follows. Section II presents the state of the art and limitations, both from industry and the research community. This is followed by section III where a novel approach to allocation (i.e., sizing and location) of DER for distribution networks is introduced. Section IV presents details of the quasi-static time series (QSTS) simulation proposed to validate the methodology against the state of the art in terms of fairness, security of supply, interactions between users, and operational concerns. Results are presented in Section V, and Section VI concludes.

II. State of the Art

The focus from industry and research community gravitates around the topics of Hosting Capacity (HC), and DER allocation methods. The first is defined as the headroom of DER that allows the grid to operate safely within technical and economic constraints [11]. The second, is the grouping of different algorithms aiming to find the best location and size of DER for a distribution grid. As there is consensus on the fact that the possible amount of DER to install at the distribution level within technical constraints is finite [12], both DER allocation and HC methodologies are attempts at finding secure paths for the transition towards grids with high penetration of DER.

There is a number of reviews available in the literature presenting surveys on DER allocation and HC studies at the distribution level [11–18]. This section will present a concise overview of the common practices and most relevant methods from the literature, these will be compared with the proposed methodology ahead. Through this survey, the gaps in the literature are identified, a brief a discussion about these is presented at the end of the section.

A. Current Practices

On one hand, future grids saturated with generating resources are expected to present operational challenges to the point of requiring significant infrastructure upgrades [12]. On the other hand, the energy transition and sustainability concerns motivate large and fast DER developments. The need to balance these, have inclined distribution system operators (DSO) to develop a conservative approach for allocation. Common techniques for this are:

1) Rules of Thumb: As seen in [19], the most common allocation method consists of proportions of either the peak load or the distribution transformer apparent power rating in the node of analysis. However, these rules of thumb do not consider the locational impact of DER, and the possibility of the grid being saturated before achieving a high penetration of generation resource.

- **Transformer ratings.** As seen in Table I a range of values between 15% and 100% of the kVA rating of the distribution transformer applies as a limit for aggregated DER. For validation purposes, this work will consider the most conservative of these allocations: 15% of the medium voltage (MV) distribution transformer kVA rating.
- **Peak Load.** Multiple DSOs use historical demand data to define the cap for DER installations. The typical value used is 15% of the yearly peak load as seen in Table I.

TABLE I
SURVEY OF DSO ALLOCATION RULES [20–22]

Country	Limits for DER Installations in MV
Australia	$\leq$ 10 kVA for single-phase
	$\leq$ 30 kVA for three-phase
Belgium	$\leq$ 100% MV Transformer rating
Canada	$\leq$ 25% Transformer rating for single phase
	$\leq$ 50% Transformers with rating under 50 kVA
	$\leq$ 60% Transformers with rating over 50 kVA
Ireland	$\leq$ 6 kW for single-phase LV
	$\leq$ 11 kW for three-phase LV
	$\leq$ MV rating defined by DSO
Italy	$\leq$ 65% Transformer rating
	$\leq$ 60% Feeder thermal limit
New Zealand	$\leq$ 10 kVA for single-phase
	$\leq$ 30 kVA for three-phase
Portugal	$\leq$ 25% Transformer rating
South Africa	$\leq$ 15% Peak load
South Korea	$\leq$ 100 kW
	$\leq$ 15% Transformer rating
Spain	$\leq$ 50% Transformer rating
	$\leq$ 50% Feeder thermal limit
Sweden	$\leq$ 40 kW
United Kingdom	Capacity(MVA) x Distance to feeder (km) $\leq$ 4
United States	$\leq$ 15% Peak load

2) Other Criteria: As discussed in [20], other allocation strategies used by DSOs include fixed active power limits, limits based on distribution electrical losses, load-generation ratios, short-circuit capacity, etc. For validation, the focus of this work will be the local allocation strategy of the selected case studies:

- **Irish DSO allocation strategy.** The case study's allocation strategy consists of two layers of limits: [21] presents the simplified connection process for micro-generation. The low voltage (LV) limit allowed for an installation to be considered micro-generation is 6 kW for single-phase and 11 kW for three-phase installations. Furthermore, the upper layer consists of a capacity range for each MV transformer, this range is defined by the DSO as seen in [22]. The upper MV layer limit is restricting the penetration of DER. The most conservative allocation proposed by the DSO at the MV level was selected for validation purposes.

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B. Allocation Methods in the Literature

Different DER allocation methods are presented in the literature to reach a hypothetical scenario of high penetration of DER often presented as an "optimal solution", "optimal size" or "optimal placement" [23]. Through an extensive review, the authors found over 60 comparable distribution network DER allocation papers published over the last 30 years, of these, the top ten most-cited papers over the last decade in high impact journals were selected as a frame of reference to contrast against the proposed solution [24–33]. As some of these allocation methods offer multiple solutions (i.e., DER distributions) according to variations of their parameters, the authors selected the highest viable penetration of DER for this study.

C. Gaps in the Literature

Through this review the authors found a pattern: current practices involve the allocation of DER on a capped, first-come first-served basis, the cap for individual allocations is based on a rule of thumb or a capacity analysis based on transformer and feeder ratings, whereas the methods in the literature are attempting to find an "optimal allocation" of DER adapting the traditional transmission planning approach: through a stochastic analysis of load-generation scenarios, while optimising one or multiple operational parameters.

As a result, the solutions end up prioritising a limited number of the potential locations to achieve a high level of DER penetration. Consequently, despite these methods being excellent academic exercises, they are not applicable in real-life scenarios, this is reflected in the fact that 30 years of allocation publications have not yet caught the attention of designers, policymakers, and grid operators past pilot projects [19], [34]. These are the most notable limitations from current methods found as part of the review:

- **A limited, relatively small number of nodes have the possibility to install large amounts of resource.** While high DER penetration is achieved, this criterion of limited locations restricts the applicability of these methods. Opposed to the transmission level, in distribution networks investments on DER are usually not centralised: sparse users define where and how much DER is to be installed, with no optimal criteria rather than their own location in the grid, and their willingness to do so [7]. This is connected to concepts of fairness and governance.
- **Current allocation methods use stochastic and uncertain generation and demand profiles as input.** This potentially under/overestimates the distribution grid's capacity to host DER. While using stochastic scenarios works for transmission networks because the loads and generators are highly aggregated -reducing uncertainty-, that level of aggregation is not possible for distribution networks [35].
- **The literature does not offer a framework to define and allocate users with charges for grid maintenance and technical losses.** In their proposed scenario with high penetration of DER it is not clear which participants are using the grid the most and therefore are responsible for these charges.

III. Proposed Method: Non-bias Allocation of Export Capacity

To overcome the limitations and offer a real-life-applicable method it is important to change the paradigm and focus the formulation on the capabilities of the grid rather than stochastic load-generation scenarios. The non-bias allocation of export capacity (NAEC) is hereby defined as the maximum amount of active power (regardless of source type) that a distribution feeder can receive simultaneously from all its potential nodes under no-load conditions. This is calculated using technical constraints relevant in the distribution level: line loading limits, voltage restrictions, transformer ratings, limit of export to the upstream grid, protection limitations, etc.

The absence of demand and generation profiles in this approach eliminates the uncertainty associated with the method and increases the reliability of the results. Additionally, it is decided from the beginning which nodes can participate and to which degree, which is an important improvement in terms of fairness and governance for users of the distribution network.

A. Mathematical Formulation

In a typical distribution network, under hypothetical no-load-no-generation conditions, it is expected that the voltages in every node are very close to the input voltage of the feeder, and all the line flows are very close to zero. This changes once every node is demanding from or providing the grid with electricity. The suggested method consists of keeping the load at zero and gradually increasing the generation state in every candidate node (i.e., all the generated resource is exported) to the same level: voltages in every node and line flows are expected to change. It is proposed that the simultaneous amount of export from the candidate nodes possible before breaching the limits represents the ability of the grid to host DER exports.

1) Defining the Limits of the Grid: Depending on the grid operator, distribution network regulation in place, and grid component specifications, the grid must respect a number of constraints. Provided these constraints can be quantified, and the maximum value allowed for each parameter is known, they can be expressed in a general way as a percentage of the constraint reached. This logic can be applied to all the quantifiable constraints relevant in the study.

Given a grid with a set of nodes N and a set of lines L connecting them, the percentage of the constraint $X_{l,i}^{\%}$ over each node i and/or line l being studied can be defined as follows:

$$X_{l,i}^{\%} = (X_{l,i}/X_{l,i}^{MAX}\ ) \times 100\ ;\ \forall\ i \in N,\ l \in L \qquad (1)$$

Where $X_{l,i}$ is the level of the constraint studied, and $X_{l,i}^{MAX}$ is the known maximum possible value of that constraint.

While generality is given in (1), this work will focus on the most studied constraints in the distribution level: voltage

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deviations for each node, and loading limits for each line, depending on their physical characteristics.

The values for voltage deviation ΔV_i in node i can be expressed as a percentage $\Delta V_i^{\%}$ of the predefined limit.

$$\Delta V_i^{\%} = (\Delta V_i / \Delta V_i^{MAX}) \times 100 \; ; \forall \; i \in N \tag{2}$$

Where ΔV_i^{MAX} is the maximum possible voltage deviation. While it is common to find in distribution networks that a single voltage limit applies to every node (e.g., typically ±2%, ±5% or ±10% voltage deviations are allowed by regulation or by decision of the grid operator [36]), the method allows different voltage deviation limits for every node.

Similarly, line loading S_l for each line l can be expressed through a percentage $S_l^{\%}$ of the maximum line loading rating S_l^{MAX}, provided by the manufacturer, grid operator or regulatory entity.

$$S_l^{\%} = (S_l / S_l^{MAX}) \times 100 \; ; \; \forall \; l \in L \tag{3}$$

2) Limit Percentage Function: By choosing to work with percentage values for each constraint, all characteristics can be placed in the same plane and they can be compared without further manipulations. At this point, a curve that represents not one constraint, but all is proposed: a discontinuous function that takes the maximum percentage of every limit as output. The input a can be defined as the active power export in every possible candidate node.

$$f(a) = Max \begin{Bmatrix} \Delta V_i^{\%}(a) \\ S_l^{\%}(a) \\ \vdots \\ X_{l,i}^{\%}(a) \end{Bmatrix} ; \; \forall \; i \in N, \; l \in L \tag{4}$$

Thus, for every potential export capacity a, the limits will reach a different level, and the function f will display the maximum percentage of a limit associated to that export capacity as a result.

Note that in (4) every candidate node is assumed to be exporting the same level of active power a, this assumption is based on fairness (i.e., this allows every candidate node to have an equal level of power export capability). However, this can be modified if it is necessary for each particular case, by applying a multiplier vector $\vec{k}$ that contains the proportions in which every candidate node can export in the result.

$$f(a \cdot \vec{k}) = Max \begin{Bmatrix} \Delta V_i^{\%}(a \cdot \vec{k}) \\ S_l^{\%}(a \cdot \vec{k}) \\ \vdots \\ X_{l,i}^{\%}(a \cdot \vec{k}) \end{Bmatrix} ; \; \forall \; i \in N, \; l \in L \tag{5}$$

The application of this multiplier is particular to each case study. In some cases, there are economical/technical reasons to increase or decrease the participation of one or more nodes in comparison to the rest. Using this method, it is possible to predetermine the level of access certain users will have to the export capabilities of the grid. Nonetheless, for this study it is preferred to use (4).

Considering how the function f was defined, it is expected that past one value of export capacity a, one or more of the limits in any of the elements will be reached. The maximum value of a that does not trigger a limit violation is by definition the NAEC of the grid. By doing this, the allocation is allowed to remain agnostic (i.e. not specific to a generation technology).

3) Solution Method: The NAEC was computed from the previously defined function f, using two methods:

- A combination of a full ac power flow from the power systems analysis tool OpenDSS and MATLAB© [37], [38].
- A linear programming optimisation algorithm adjusted to this problem [39].

Initial results from the test network defined in the next sections suggest that the linearised alternative presents difficulties obtaining an accurate solution: it results in a 29% overestimation for the NAEC. This increase is explained by the fact that the linearised model is on average underestimating voltage by 1.5%, line flow by 12% and line losses by 49%, when compared to the full ac power flow.

The search algorithm selected was the secant numerical method [40] to find zeros in a discontinuous function. Given two initial guesses a_0 and a_1, it is possible to iteratively obtain the NAEC with a pre-set tolerance ϵ as follows.

$$a_j = a_{j-1} - f(a_{j-1}) * \frac{a_{j-1} - a_{j-2}}{f(a_{j-1}) - f(a_{j-2})} \tag{6}$$

$$\epsilon \geq a_j - a_{j-1} \tag{7}$$

For an answer with a tolerance of 0.01 Watt when applied to the test network defined ahead, this method was more than 90,000 times faster than the incremental value, and more than 1.2 times faster than the bisection methods found in [40]. Inverse quadratic interpolation was also tested but the solution did not converge, this is because this last method requires a continuous function to work. For these reasons, the solution method preferred to find the NAEC is the full ac power flow using the component object model (COM) interface between OpenDSS and MATLAB©, and the secant search algorithm.

B. NAEC Enhancement: From Export Capacity to HC

The NAEC is determined by the capabilities of the existing network (i.e., until this point, no mention has been made regarding demand or generation profiles), and the result is an export capacity. In contrast, the literature is offering hosting capacities/installed capacities. To effectively compare the methodologies, it is important to understand this export capacity as an initial step towards HC allocations.

In theory, different demand states increase the available headroom past the export capacity because the resource will partially go to self-consumption before contributing to limit reaching. Furthermore, not all nodes are expected to be generating at full capacity all the time, resource may be unavailable depending on the technology used. Because of this, considering the NAEC value obtained as HC is a very conservative allocation: depending on the type of generation

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technology, and the demand profile of a node, the initially assigned NAEC can be translated into a larger HC.

Even though an effective strategy to convert NAEC into HC is not in the scope of the present work, a simple statistical approach to test the potential for enhancement is in turn presented: once the NAEC of the grid is determined, an additional allocation based on statistically representative values of the demand profile of every individual node can be added. These additional values will be capped at:

- Minimum load of the year in each node,
- Quartile 1 minimum load of the year in each node,
- Quartile 2 minimum load of the year in each node,
- Quartile 3 minimum load of the year in each node,
- Maximum load of the year in each node.

These additional allocations are presented as a mere test to validate that the NAEC is obtained in an agnostic way (i.e., providing generality, making the method applicable to every potential distribution network) and it can be extended depending on the particularities of each node's demand profile and potential DER technology.

C. Assumptions and Limitations

Every effort was made towards an effective contrast between the proposed method and the literature without benefit to any: The proposed allocation uses the same information available for other methods in the literature, and the demand profiles used for validation are respecting the peak load in the documentation. Nonetheless, it is important to acknowledge that the demand and generation profiles used in the validation stage vary from those used by other methods, and this may give advantages to some allocations over others.

Long-term planning studies are not limited to the solution proposed with this allocation of DER, it is important to address several topics in future work: flexibility resources, topological changes, the electrification of heat and transport, etc. This work is expected to trigger a paradigm shift for distribution network planning, and it represents solely an initial step.

IV. Validation

A thorough validation process is proposed. First, NAEC values were obtained for a test network widely used in allocation methods' papers in the literature [11–18], [24–33], this way a contrast between the obtained export allocation and the most recent and cited HC allocations is possible. Second, NAEC results were calculated for two real distribution networks (one urban and one rural, medium voltage (MV) feeders), and these are contrasted against the rules of thumb and the DSO allocation method selected from the review. Third, a year-long quasi-static time series (QSTS) simulation was run on the three networks using homogeneous demand residential profiles, plus distinct profiles for exclusive dispatchable, exclusive PV, and exclusive wind generation, respectively. This way it is possible to quantify the benefits and limitations of the proposed solution when compared to the alternatives. Fourth, the QSTS is run again considering the proposed NAEC-to-HC enhancement using an exclusively PV generation profile to explore the potential of the proposed export capacity methodology as an initial step for higher HC allocations. Details of the test network, case studies, QSTS and profiles are presented in this section.

A. Test Network

The most widely used test network for DER allocation papers in distribution networks is a modified version of the IEEE 33-bus radial distribution system consisting of 33 buses and 32 branches. The base voltage is 12.66 kV and a synchronous generator represents the point of connection that feeds the system. The base load of this test system consists of a total active and reactive load of 3.7 MW and 2.3 MVAr respectively. The branch data and base load for each node can be found in [41].

The test case documentation does not specify voltage or line loading limits. As these are central to the NAEC methodology, for the purpose of this study the allowed voltage variation will be capped at ±10% of the base voltage -common for distribution networks and in several allocation papers that use this test network-, and the thermal limits for the branches were taken from those proposed in [42].

B. Case Studies

To better capture the reality of distribution networks, two typical Irish MV feeders were selected, the allowed voltage variation at any point of the feeder is ±5%. The thermal limits of the lines are known. Whereas the peak loads are known, there is no information on the demand profiles. The selected feeders represent a typical situation at the distribution level: unbalanced loads, single-phase branches, voltage violations at peak-load moments of the day, etc.

1) Urban Distribution Feeder: This 83-bus urban feeder operates at a base voltage of 10 kV, it is composed of 83 three-phase and 6 single-phase branches for a total of 6.16 km in lines, the longest electrical point is located at 2.80 km from the feeder. The base active and reactive loads of the network are 1713.6 kW and 589.1 kVAr respectively, distributed over 20 loaded buses, four of which are single-phase buses. This grid presents no voltage or line-loading violations at peak load.

2) Rural Distribution Feeder: The rural feeder is more extensive with a total of 1171 buses operating at 10 kV base voltage. 389 of the buses are loaded, with only 39 of these being three-phase. 484 three-phase and 615 single-phase branches compose the total 131.36 km in lines, while the furthest electrical point is 23.70 km away from the feeder. The base active and reactive loads are 1728.6 kW and 591.6 kVAr respectively. This grid presents significant voltage problems. The DSO has installed three voltage regulators that improved the voltage profile in some parts, yet some nodes still violate the voltage limit at peak load. Note however that for the NAEC formulation to work, voltage regulation in this case study must be switched off. The voltage adjustment due to regulation for different exports will make it impossible for the algorithm to converge and find a solution.

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C. Year-long Quasi-static Time Series Simulation

Provided the same grid is used in each iteration while keeping the demand and generation profiles, it is possible to objectively compare the methods from different points of view. The following criteria and associated parameters observed in each time slot of the simulation were:

- Security of Supply.
  - Voltage per node and power flow per line.
- Power Balancing and Interactions Between Participants.
  - Active and reactive power demand per node,
  - Active and reactive power generation per node,
- Operational Constraints.
  - Voltage unbalance per node,
  - Power flow unbalance per line,
  - Losses.

1) Demand Modelling: While the base load information for the test network and case studies is known, detailed demand profiles for each node were not available. To fill this gap, the CREST demand model [43] from the Loughborough University was used, it is an open-source stochastic model with high-resolution for domestic electricity demand that produces data with one-minute resolution.

The active power demand data obtained from the CREST model is paired with reactive power demand equivalent to the power factor of the load in the documentation. For the test case, no load-voltage dependency was considered. In contrast, the loads for the case studies were modelled following the non-linear ZIP curves provided by the system operator.

For consistency purposes, for each node the dwelling data was the same for a leap year equivalent to 2020. By doing this, according to its base load (and the number of customers known in the case studies) every node counts with a different set of 527,040 data points of demand equivalent to 366 days times 24 hours times 60 minutes.

2) Generation Modelling: To effectively compare the methodologies, three generation profiles are suggested. First, a generation profile for every possible DER unit allocated with capacity factor 100% during the entire year, equivalent to a dispatchable unit with no scheduled maintenance or unavailability. This hypothetical dispatchable generation profile will put the network to the highest stress possible with each allocation, providing insights on security of supply. Second, a PV generation profile including seasonal and weather variations from the geographical location of the case studies was obtained using the respective functionality of the CREST model. For simplicity, all generators were modelled with a constant power factor equal to one. Third, a generation profile that represents wind energy is used in the test case for validation purposes, meteorological data on wind speed corresponding to the geographical location was collected from [44] and translated into electricity generation using the methodology proposed in [45].

To have a reference for performance of the network regardless of the allocation method, an additional scenario was simulated, the hypothetical initial state of the grid where zero DER resource is assigned to every candidate node. A summary of the simulations performed is presented in Fig. 1, for a total of 66 possible permutations.

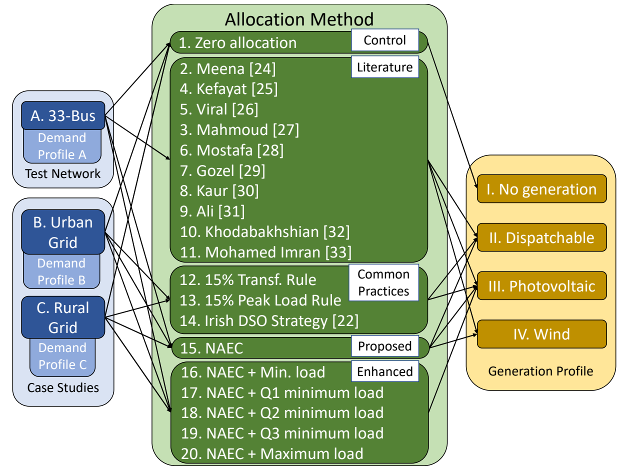

Fig. 1: Overview of the simulated scenarios. Each scenario consists of a studied topology, using an allocation method and a generation profile. Demand profiles are particular to the network studied.

V. Results

This section presents the results obtained for the proposed methodology and compares the allocated resource with state of the art and common practices. Subsequently, the QSTS simulation results are given for the test network and case studies to see performance of the method.

A. Allocation Method Results

The results of the algorithm are presented together with the state of the art in Table II. Using the NAEC method, an individual allocation of 105.9 kW was obtained for the test network, the urban case study resulted in a single-phase allocation of 54.5 kW, whereas the rural case study obtained a single-phase allocation of 2.6 kW. The difference in these three allocations is explained by the fact that the method responds to each grid's topology and constructive characteristics.

Focusing on the test network, four of the selected allocation methods from the literature present a higher total allocation, up to 12% less is allocated using the NAEC methodology. However, the presented methodology still presents a higher-than-average grid allocation.

The resource allocated to the case studies vary significantly depending on the allocation method. For the urban network the NAEC methodology is allocating between 10% and 90% more resource, whereas for the rural network the allocation is between a 47% reduction and a 79% increase of grid-wide resource. The strong variation of results between methods is a symptom of how irregular current practices for allocation of DER are.

B. QSTS Simulation Results

To test that the proposed methodology is safe and beneficial for the individual participants and the DSO, this subsection presents the results of the simulated QSTS.

1) Security of Supply: The dispatchable generation profile represents the most possible stress for the grid under any of the proposed methodologies, therefore it is preferred to study

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TABLE II
COMPARISON OF DER ALLOCATION METHODS

Studied Grid	Method	Grid Allocation [kW]	Participating nodes	Individual Allocations [node(s)/kW]
Test Case: 33-Bus Network	**NAEC**	**3,389.8**	**32 / 32**	2-33/105.9.
	Meena [24]	3,852.0	3 / 32	14/1057, 24/1054, 30/1741.
	Kefayat [25]	3,500.3	6 / 32	6/842.3, 11/358.5, 16/371, 20/282, 24/963.8, 31/682.7.
	Viral [26]	3,427.4	3 / 32	6/1435.4, 14/803.5, 24/1188.5
	Mahmoud [27]	3,095.0	3 / 32	13/806, 29/1258, 30/1031.
	Mostafa [28]	3,000.0	5 / 32	5/1300, 8/400, 12/300, 18/300, 25/700.
	Gozel [29]	2,998.0	1 / 32	6/2998.
	Kaur [30]	2,940.0	3 / 32	13/800, 24/1090, 30/1050.
	Ali [31]	2,502.5	2 / 32	13/1039.5, 30/1463.
	Khodabakhshian [32]	1,970.0	2 / 32	14/840, 30/1130.
	Mohamed Imran [33]	1,793.0	3 / 32	14/589.7, 18/189.5, 32/1014.6.
Case Study: Urban Network	**NAEC**	**2,530.4***	**52 / 52****	- various allocations -
	15% Transformer	691.5	45*** / 52**	- various allocations -
	15% Peak load	257.2	52 / 52**	- various allocations -
	Irish DSO [22]	2,280.0	45 / 52**	- various allocations -
Case Study: Rural Network	**NAEC**	**1,218.0**	**467 / 467****	- various allocations -
	15% Transformer	607.5	102*** / 467**	- various allocations -
	15% Peak load	259.1	467 / 467**	- various allocations -
	Irish DSO [22]	2,300.0	102 / 467**	- various allocations -

* The allocation of some nodes was reduced to match the capacity of the MV/LV transformer when exceeded.
** The number of loaded buses and participants are different. Three-phase nodes were modelled as three single-phase participants.
*** The documentation has missing information about transformer ratings, this is modelled as non-participating nodes.

security of supply concerns. As seen in Fig. 2, the NAEC methodology does not produce any new voltage or thermal violations in the test network or the urban case study when compared to the zero-allocation state. Furthermore, the rural case study has 65% of time-slots with voltage violations under initial zero-allocation, presenting a significant reduction compared to the initial state of the network (i.e., when considering the maximum stress situation, the NAEC allocation does not produce new violations, and even reduces already-existing violations).

Additionally, the methods proposed by Meena [24], Mahmoud [27], and Gozel [29] force the grid to operate under violated-constraints situations, making them unsafe under the highest stress generation profile. Considering this, only the methods proposed by Kefayat [25] and Viral [26] offer a larger yet safe grid-wide allocation (3% and 1% more than the NAEC, respectively).

The allocation methods and common practices that offer a considerably larger allocation than the one proposed, present new/extra voltage or thermal violations, the methods that offer a smaller allocation do not. This suggests that the NAEC methodology offers a robust, safe result in terms of security of supply.

2) Active balancing and Interactions Between Users: It was discovered that the distribution of the resource determines the destination of the same more than the total amount allocated. As seen in Fig. 3, Fig. 4 and Fig. 5, for the test network the NAEC methodology results in a higher proportion of self-consumption using the three generation profiles. For methods that have the lowest number of participating nodes (e.g. Gozel [29], Ali [31], and Khodabakhshian [32]), most of the generated resource goes towards local trading and the upstream grid instead of self-consumption.

For the test network, considering the dispatchable profile,

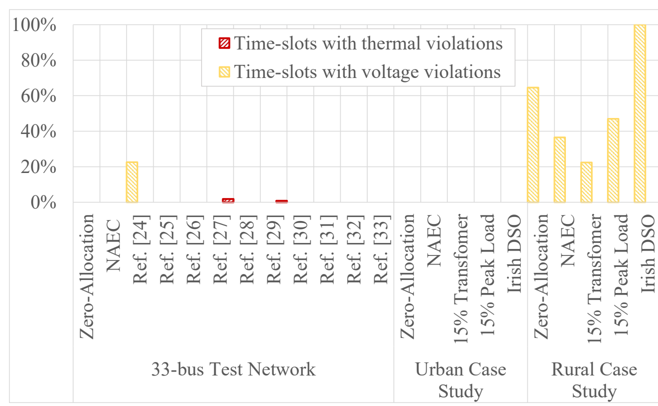

Fig. 2: Voltage and thermal limit violations for each method considering the dispatchable generation profile.

self-consumption is between 70% and 98% larger with the NAEC methodology compared to the other methods. On one hand, using the PV profile, self-consumption is between 51% and 96% larger, on the other hand, using the wind profile this increase is between 59% and 97%.

Results from the case studies support this claim. On one hand, all the methods for the urban feeder present a similar, high level of user participation (i.e., a high number of the possible participants have allocated resource), the ratio between self-consumption and local trading is very similar for all methods despite the total allocated resource (See Fig. 6 (a) to (d)). Contrasting on the other hand, for the rural feeder participation is very low using the 15% transformer and Irish DSO methods, because of this, self-consumption represents a larger proportion using the NAEC allocation when compared to common practices, this can be seen in Fig. 6 (e) to (h).

3) Operational Concerns: It is important to verify that the proposed allocation is not creating an unnecessary bur-

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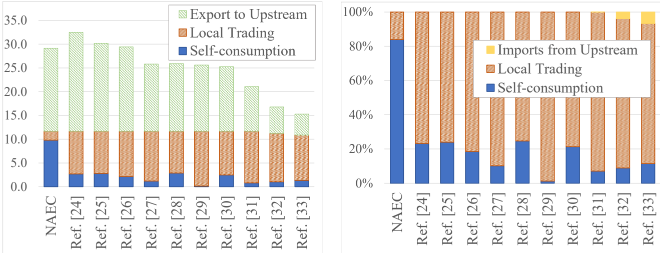
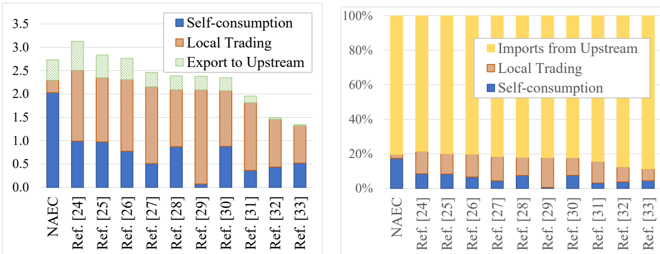


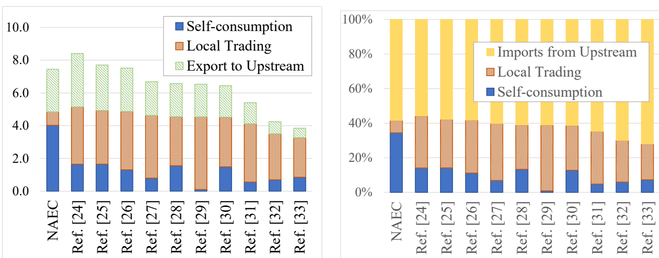
(a) (b)

Fig. 3: QSTS results for scenario A.II: Active power balancing for the test network using the dispatchable generation profile. For each method, (a) presents the destination of the generated active power [GWh], (b) presents the origin of the total energy consumed [%].



(a) (b)

Fig. 4: QSTS results for scenario A.III: Active power balancing for the test network using the PV generation profile. For each method, (a) presents the destination of the generated active power [GWh], (b) presents the origin of the total energy consumed [%].



(a) (b)

Fig. 5: QSTS results for scenario A.IV: Active power balancing for the test network using the wind generation profile. For each method, (a) presents the destination of the generated active power [GWh], (b) presents the origin of the total energy consumed [%].

den through increases of technical losses. Using the NAEC allocation, under 5% of the total energy demand using the highest-stress dispatchable profile are losses. Moreover, using the PV profile, a reduction in losses between 17.5% and 28% compared to the zero-allocation scenario was achieved. These results suggests that while loss increase is a possibility during certain time-slots, and using certain generation technologies, there is no major concern in this regard.

Considering that the test cases involve unbalanced loads, single-phase sections, and unbalance DER allocations, as a sanity check, voltage unbalance and power flow unbalance were monitored as part of the QSTS to explore any concerning tendencies. All the simulations resulted in average voltage unbalances well below 1% and line-flow unbalance under 15%. Although further studies are required, this initially suggests that the NAEC method does not contribute towards operational concerns of this nature.

C. NAEC-to-HC enhancements, QSTS Results

After evaluating the potential benefits and challenges of the NAEC as a conservative HC allocation, it is important to explore its prospects for enhancement. Using the statistical approach based on the demand profiles' quartiles (see Subsection III-B), the NAEC was extended into a HC as follows:

- From the test network's initial allocation of 3,389 kW to 3,732 kW, 4,615 kW, 4,858 kW, 5,142 kW and 6,859 kW.
- From the urban case study's initial allocation of 2,530 kW to 2,620 kW, 2,851 kW, 3,233 kW, 3,471 kW, and 4,245 kW.
- From the rural case study's initial allocation of 1,218 kW to 1,309 kW, 1,540.99 kW, 1,926 kW, 2,165 kW, and 2,946 kW.

Running the QSTS with these new allocations using the PV profile shows the potential for NAEC-to-HC enhancement: no additional violations for the test network were registered until the 5,142 kW allocation which represents a no-violation enhancement of 52%. For the urban case study, no violations were registered for any of the new allocations, representing 62% more allocated resource, with the possibility of further enhancement. The most interesting result was found for the rural case study, where the maximum enhancement of 142% not only presented no new violations, but improved the voltage profile, further reducing the already existing violations to 48% of the time-slots (from the no-allocation level of 65%), further potential enhancements for the rural case study are possible.

VI. Conclusion

A novel method was proposed to allocate DER in distribution networks, it avoids topological bias reaching a high penetration and incentives self-consumption over local trading and exports to the upstream grid. The allocation method was validated against state-of-the-art methods and common DSO practices, passing the test of high penetration, security of supply and operational concerns, while offering benefits in terms of fairness, governance, and participation. The computational burden is very small, and the mathematical simplicity of the method offers generality, future work can contemplate further complexity and specificity in methods based on this proposition. As more users are allowed to install resource when compared to other methods in the literature, decision power is increased as well as grid access, an important improvement in terms of fairness. Furthermore, as the proposed methodology is based on topological constraints, the method is less susceptible to obsolescence (i.e., changes in the allocation method occur only after significant changes in topology), the alternative allocations in contrast may require constant reformulation due to the stochastic nature of the inputs. For these reasons, in addition to its generality and simplicity, the proposed methodology is deemed more applicable than the alternatives.

It is hypothesised that once the NAEC of a grid is known, individual users can make an informed decision about their DER capabilities. Three paths to use the NAEC are visualised: (1) installing the NAEC as a conservative HC, (2) depending

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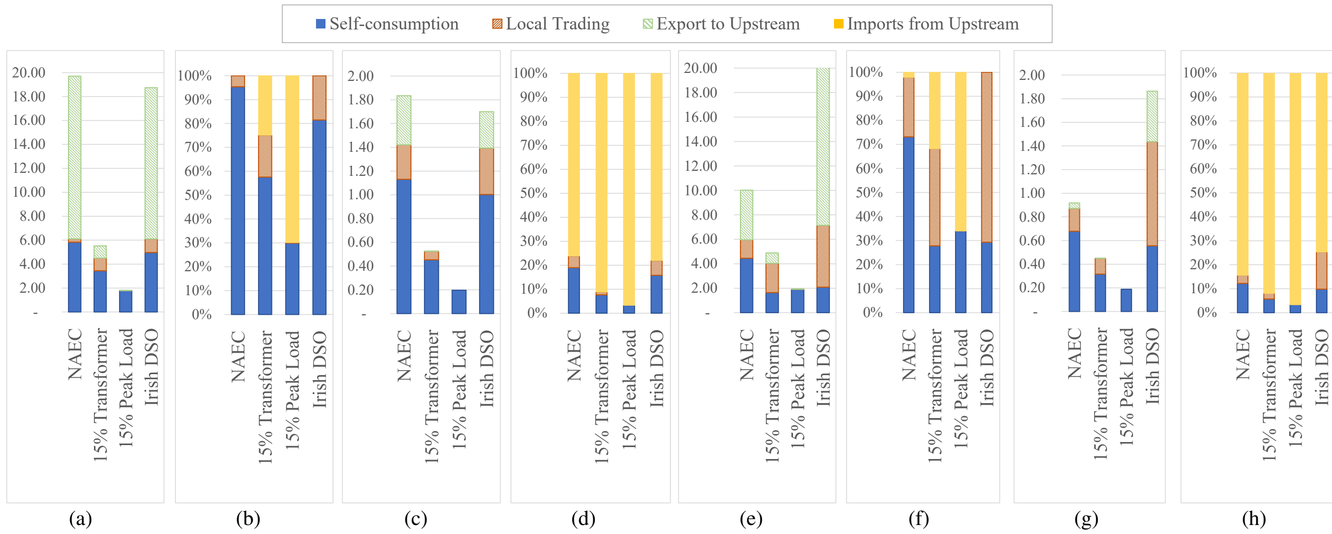

Fig. 6: QSTS results for the case studies: Active power balancing for the urban case study is presented in (a)-(d), rural case study in (e)-(h). Destination of the generated active power [GWh] in (a), (c), (e) and (g). Origin of the total energy consumed [%] in (b), (d), (f), (h). Dispatchable generation profile used in (a), (b), (e), and (f), PV profile used in (c), (d), (g) and (h).

on the demand profile and generation technology, a NAEC-to-HC enhancement method allows a larger HC installation, or (3) participants can choose to install as much resource as they want, provided they can afford to turn off their installation or store energy in moments were the NAEC is exceeded.

The proposed NAEC methodology is expected to be improved in future work: flexibility resources (e.g. voltage regulation, storage, demand side management, power factor correction, etc.), topological changes, and the electrification of heat and transport require further investigation. Furthermore, a robust algorithm must include other technical constraints of the grid when the information is available.

As this method provides insights on how future grids with high penetration of DER will look, it also offers a framework that allows researchers, and policy-makers to address allocation of network charges.

Future developments should include the concurrent simulation of LV-MV grids, to account for the variation in certain values studied, especially losses, voltage drop, and voltage unbalance. Furthermore, the authors envision the obtained allocation in the MV level being translated into smaller allocations in the LV that follow similar rules as those presented in this work.

Another novel research opportunity that arises from this work is the trading of allocations. Once the NAEC is allocated to the potential participants, a market for the trading of export capacities is possible. This hypothetical market allows participants interested in larger allocations to borrow, buy, or lease the allocation of another participant in the short, medium or long term.

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Juan J. Cuenca (GS'20) was born in Neiva, Colombia, in 1992. He received the B.E. degree in electrical engineering from the Colombian School of Engineering "Julio Garavito", Bogotá, Colombia, in 2016, and the M.Eng. degree in electrical and electronic engineering from the Auckland University of Technology, Auckland, New Zealand, in 2018. He is currently working towards a Ph.D. in electrical engineering at University College Cork, Cork, Ireland. He has worked as research assistant for the Hydrogen Research Institute in Trois-Rivieres, Quebec, Canada (2015) investigating on Li-Ion batteries' thermal management. In industry, he worked for 3 years at EHS Ltda, Colombia (2016-2019) in construction and maintenance projects for medium voltage distribution grids. His research interests include sustainability, energy policy, grid integration of distributed energy resources, planning of distribution networks, and energy communities.

Barry P. Hayes (S'09–M'12–SM'17) is an Assistant Professor in Electrical Power Engineering at University College Cork (UCC) and a Funded Investigator in the MaREI Research Centre. Prior to joining UCC, he was an Assistant Professor at National University of Ireland Galway (2016-2018), and a Marie Sklodowska-Curie research fellow at IMDEA Energy in Madrid (2013-2016). He holds a PhD in Electrical Power Systems Engineering from the University of Edinburgh (2013), and has held visiting researcher positions at National Grid UK (2011) and at the University of Tennessee (2016). Barry's research group focuses on the electricity grid integration of sustainable energy technologies, and the operation and planning of future power systems.

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