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Sharing the grid: The key to equitable access for small-scale energy generation

Juan J. Cuenca ^{a,*}, Hannah E. Daly ^{a,b}, Barry P. Hayes ^{a,b}

^a School of Engineering and Architecture, University College Cork, College Road, Cork, T12 K8AF, Ireland

^b MaREI, the SFI Research Centre for Energy, Climate and Marine, Environmental Research Institute, University College Cork, Lee Road, Cork, T23 XE10, Ireland

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ABSTRACT

Small-scale distributed generation (DG) installations, like rooftop solar photovoltaics, are adopted earlier in high-income households than in other portions of society. This can limit grid electricity export capacity for latecomers, causing inequitable access and slower renewables deployment. In search for an equitable solution, this work challenges current DG permissioning practices: instead of applying rules of thumb to assign DG, we propose a policy that represents grid limitations at all hierarchies of the grid (i.e., customer, distribution, sub-transmission and transmission levels). A method to predict interest in household DG installations over time based on demographic and socioeconomic variables is presented and validated. This is leveraged to test a novel policy for small-scale DG deployment: *sharing the grid*; and to explore its potential to improve equity in grid access and speed of renewables deployment. Proposed, current and alternative policy paths on small-scale DG adoption are tested to identify benefits and trade-offs. Using Ireland's national utility as case study, we perform a long-term simulation of solar photovoltaic adoption. Sharing electricity export capacities increases participation from 77.9 % to 100 %, unlocking access to the grid for 364,064 electricity customers compared to current policy—without the need for infrastructure upgrades. Furthermore, the proposed policy achieves the same overall level of installed capacity as current policy 44 % faster, accelerating small-scale DG rollout, benefiting households and decarbonisation targets. Ultimately, to determine equity, we connect these results to demographic variables and find that grid limits are not biased towards any demographic group studied, suggesting that policy can be tailored to prevent DG access inequity.

1. Introduction

Numerous benefits from small-scale distributed generation (DG) have been studied in the literature: loss reduction [1,2], savings to the utility because the investments are customer-led [3], increased self-consumption [4], local energy markets [5], governance and empowerment [6], and lower carbon footprints in the case of renewable energy sources [7]. While most of these benefits are exclusive to small-scale DG, there is a prevalence of utility-owned large-scale installations of renewable energies to date [8–10]. As a response, certain countries and regions developed energy policy that encourages growth of small-scale DG installed by customers connected to distribution grids (e.g., with economic incentives, tax-deductions, monetary compensation for energy spilled to the grid, etc. [11,12]).

This has helped trigger fast growth of DG connections that resulted in these pioneering national and regional grids being saturated; where in some cases it is not possible to accommodate more small-scale DG due to technical restrictions [13,14]. Therefore, only early adopters

are taking advantage of DG benefits while latecomers are waiting for infrastructure upgrades to unlock their participation. Many countries are at an early stage in their DG rollout and have developed ambitious energy policy to achieve sustainable development and decarbonisation goals [7].

The case of California's small-scale solar photovoltaic (PV) deployment is a clear example of why this research is important: after years of aggressive pro-solar policy (through feed-in tariffs and net metering), the state's Public Utilities Commission is proposing to remove all incentives with the objective of incentivising self-consumption and energy storage installations to reduce the strain on the grid [15]. Grids are not being able to cope with increasing amounts of DG penetrations: they are saturated with PV, incentives are being removed, and new-comers are waiting in line for infrastructure upgrades. A recent study conducted on this case's customer installed capacity [16] shows that certain blocks of society are being left out. The study found that DG installed capacity is disproportionately smaller in households from disadvantaged census blocks [16].

* Corresponding author.

E-mail addresses: j.cuenca@umail.ucc.ie (J.J. Cuenca), h.daly@ucc.ie (H.E. Daly), barry.hayes@ucc.ie (B.P. Hayes).

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The main purpose of energy policy is to stimulate and incentivise a transition to a low-carbon energy system. Policy aims at triggering transformation, this means they are not conclusive. This work aims at understanding how policy can be designed to address the problem of inequity in grid access while keeping the original goal of transitioning to zero-carbon energy in the centre. This research presents a comparison of three different approaches to small-scale DG assignment: *Business as usual* in which an optimisation objective is used to find the best suitable distribution of DG amongst participants, *Splitting the grid* in which an equality objective is sought, to distribute DG equally amongst participants, and ultimately *Sharing the grid* in which an equity goal is for the first time put forward as means to balance competition and cooperation goals of the other two objectives.

1.1. Motivations

Recent reports on electricity grid infrastructure limits [16], policies and business models [13] suggest that equity in access to small scale DG is paramount to fulfil sustainable development and decarbonisation goals worldwide. While previous literature explored the justice and equity challenges of the clean energy transition [17], a solution to the problem of small-scale DG rollout equity (that does not involve prohibitively expensive infrastructure upgrades [7]) has not yet been offered.

The current international political climate has permeated the energy sector, and energy security concerns are becoming evermore relevant [18]. Now that the energy supply of many European countries is at risk, electricity users that installed small-scale energy generation locally over the previous years are expected to be significantly less impacted. Simultaneously, those users that are unable to do so (due to availability being already taken) will be disproportionately vulnerable to energy curtailment, rationing and price spikes [19]. This calls for a study to explore the possibilities for a policy framework that allows for an effective small-scale DG rollout, including an equitable dimension.

As it is the case in other areas, equity might conflict with other priority goals. One could argue that getting as much DG on the grid as fast as possible is the overarching goal, for which current energy policy is adequate. Previous research shows that often the public associate equity with maximum deployment because climate change will affect low-income portions of society the hardest [20]. In this sense, including an equity dimension in energy policy must not decelerate deployment. However, there seems to be a “problem” with existing grid access: early-comers are taking up all availability, blocking access to late-comers. Current small-scale DG policy is therefore deemed inadequate if this additional equity concern is considered. This manuscript aims at including this equitable dimension to the policy-making process for small-scale DG, without losing sight on the dominant goal of achieving a sustainable energy sector fast.

1.2. Objectives, contributions and structure of this study

This work demonstrates that access to the grid is not inherently biased. It is hypothesised that simultaneous first-come first-served schemes and overestimation of grid limits allow high-income portions of society greater grid access and reap greater financial benefits. Furthermore, to prevent these inequities a novel energy policy path is proposed for grid access. Ultimately, based on demographics and simulating customer interest over a long-time horizon, it was found that using this policy path reduces inequities in grid access. Comparing current and proposed energy policies, this study suggests that seeing the grid as a shared resource has the potential to increase small-scale DG penetration swiftly.

A novel method that uses demographic, economic and technical information is presented to simulate interest to install small-scale DG. This allows to study the progression of the energy transition given different policy paths. By accounting for the real limitations of the grid

at different hierarchical levels, the final overall small-scale DG installed capacity and the speed of the transition is studied. Using Ireland as case study, the possibility of grids to accommodate the goals laid out in policy for small-scale DG is investigated.

This manuscript is structured as follows. Section 2 presents the important concepts and background of the research problem. Section 3 presents an overview of the literature on the concepts of optimality, fairness, equity and equality, and relevant works in grid access. Section 4 presents the proposed methodology, and Section 5 offers the details of the proposed case study. This is followed by Section 6 where results are presented and the paper is closed with discussion and conclusions in Section 7.

2. Definition of concepts and background

To better understand the challenge of equity in small-scale DG adoption, this section presents an overview of the literature. First, it is important to define what “access to the grid” means and why is it limited. Subsequently, this section points out to the literature on increasing limited grid access.

2.1. Small-scale DG definition

DG is defined as energy generation installations often from renewable sources that are located close to consumption centres, and consequently have a lower reliance on transmission and distribution infrastructure [21]. There are numerous alternatives for technology, ownership, size and operation of DG and each of these have different economic and technical characteristics.

For the purpose of this study, small-scale DG is defined as an installation that is built in an already existing customer connection. Regardless of technology, the DG considered here has a limitation in size often given by the system operator, because its purpose is mainly self-consumption for an existing user—even when in some cases users are allowed to sell their energy excess.

Each case study, according to system operator rules and regulations in place has a different limit for small-scale DG therefore a generic definition on size is not offered [6]. Ultimately it is useful to state that for the purpose of this work “customer”, “household”, “industry”, and “commercial” electricity user are interchangeable because small-scale DG installations are by definition applicable regardless of the type and size of customer. Typically, when an electricity customer wishes to have a larger installation, the system operator has a different set of rules and regulations that allow for it under additional technical considerations. The latter are no longer small-scale, and are not the purpose of this study.

2.2. Limitation of access in electricity grids

Under normal circumstances a user can access the electricity grid requesting permission from the utility in the form of maximum import capacities (MICs) for loads – permission to draw power from the grid –, and maximum export capacities (MECs) for generators – permission to feed power to it – [22]. Two key concepts explain how MICs and MECs are more likely granted or rejected upon customer requests, and in turn affect potential customer access to the grid:

- **Diversification.** On one hand, diversification is the ability to aggregate resources that are not operating simultaneously, therefore use the grid infrastructure asynchronously [23]. Based on the small probability of simultaneous use, the utility can assign MICs to a significantly larger extent than the real capacity of the grid [24]. In contrast, generation resources that rely on the same primary source are active and use the grid simultaneously, therefore are not diversifiable (e.g., PV depends on irradiance and that is approximately homogeneous over the span of the grid it is

connected to). The utility can only assign MECs that represent the real capacity of the infrastructure they are connected to [24].

Consider a distribution transformer and its associated network that has a nominal capacity of 10 MVA. The maximum aggregated exports from DG installations it will be able to handle is 10 MVA. The same transformer can have a total load installed exceeding 2 to 4 times that value because it is unlikely for all loads to be active at the same time [25].

- **The traditional electricity market structure.** On the other hand, the electricity sector traditionally has a centralised market structure in the form of an oligopoly. The utility (grouping a relatively small number of suppliers, grid operators and generators) sells electrical energy to large numbers of consumer loads, and in this frame, any new MIC or load connection request represents a new source of income for the utility.

MIC request acceptance is business-led: even if the new load connection requires infrastructure upgrades, the utility has an economic incentive to accept it, to make the necessary investments in infrastructure, and in some cases to operate the grid beyond the operational limits [26]. In contrast, a connection request for a generator (i.e., MEC) enters in direct competition with the market structure (i.e., any unit of energy that is generated by a small-scale DG participant, whether it goes towards self-consumption or local energy trading, is a unit of energy that the utility do not sell). This is true even if generation, transmission and distribution are unbundled as it is the case of the European electricity market. Because of this, MEC requests are policy-led and accepted on the capacity of the infrastructure only: the utility is not incentivised to make upgrades to accommodate MEC requests, and they would ultimately fall under the responsibility of the customer that made the request [26], and cannot afford the upgrade. A good example of the economic dynamics at play is the growing number of utility-funded infrastructure for electric vehicle charging stations [27] (i.e., load intensive points of connection) while there are no equivalent investments to accommodate new small-scale DG.

Given the current regulatory frame and the market structure, when compared to MECs, MIC requests are expected to be granted more often due to diversification, and the economic interests of the utility. Ultimately, MEC availability is the representative limiting factor for equitable access to small-scale DG, and as such it was the focus of this article.

2.3. Increasing access beyond grid limitations

While the grid presents limitations represented by the MEC values at different hierarchical levels, it is important to note that since it corresponds to export capacities, it does not automatically mean maximum DG size. In principle, the size of a DG installation is limited by the relevant MEC only because in a worst case scenario, all the energy generated will be exported to the grid. If small-scale DG is complemented with other measures, the installation size can be increased while respecting the MEC. This subsection explores the alternatives for customers to extend access using export capacities in a more effective way, or to increase their MEC.

2.3.1. Investments in energy storage

Energy storage investments make it possible for a customer to extend access to the grid even if its MEC limit has been reached [28]. The DG installation size can be increased respecting the customer's MEC if local generation exceeding this export capacity is stored for later use or export. As an example, a customer with a MEC of 2 kW can invest in a larger PV installation (e.g., 6 kW) if it is paired with an appropriately sized battery energy storage system. The user has the ability to export through its MEC, and if the generated electricity exceeds this threshold,

the battery can store the excess for future use. Depending on local energy trading rules, it may be beneficial for a customer to decide whether to export electricity or store it locally for future use/export to reap maximum economic benefit.

Note that if a customer is denied a MEC (i.e., if there is no availability), it is also possible to install DG when combined with energy storage. There is a caveat: having a MEC equal to zero, the customer is not able to benefit from exports, it cannot participate in local electricity markets, and it will effectively have an islanded DG installation in terms of interactions with the utility and its neighbours [29].

2.3.2. Load shifting

It is possible for a customer to change its consumption patterns to increase self-consumption of energy generated locally by its DG installation. If the load of the customer and its DG output are coincidentally high, self-consumption will reduce the amount of exports, in turn using a smaller portion of its MEC. This is known in the literature as load shifting or demand side management [30]. In this frame, a customer can decide to install a larger DG unit than its MEC, provided it will use the difference for self-consumption in moments of significant production of electricity.

Load shifting that occurs outside of the customer's installation can play a role in the future. Changes in energy demand beyond the installation of the customer (e.g., neighbouring electric vehicles scheduled to charge [31,32]) might consume electricity before the MEC of a substation is used. The research community is addressing the theory behind: to account for this, extensive stochastic simulation work is required. Nonetheless, in practice it is still very difficult to predict consumption patterns that occur outside of area of influence of a customer [33]. Ultimately it is not a robust planning strategy to use non-local load shifting alone as decision-making criterion to over-size a DG installation past the customer's MEC.

2.3.3. Generation curtailment

Primary resources for small-scale DG installations are variable throughout the day, but also seasonally [34] (e.g., there are months of the year where wind and sun are more abundant/sparse). This means that a customer can size a larger DG installation than its MEC, provided it is willing to curtail the excess to match the MEC limit during certain moments of the day or year where production is high [35]. Curtailment means effectively not using energy generated, and as such it is wasteful, this requires a good economic analysis to take into account forecasted availability of primary sources. The installation can be sized based on a certain amount that a customer is willing to accept as "waste". This can be economically feasible because for the rest of the day or year (i.e., when production is not as high), there will be more energy generated within the possibilities given by the customer's MEC.

2.3.4. Customer-led infrastructure upgrades

It was discussed in Section 2.2 that the utility is not incentivised economically or from a regulation standpoint to make investments to accommodate additional DG (i.e., to increase MEC availability). However, it is possible for individual customers, or a group of co-operating customers to make these investments themselves. Once the MEC limitations for a customer/cooperative are known, it is possible to determine the best candidates for infrastructure upgrades in their feeder (i.e., changing conductor sizes, increasing transformer ratings, installing voltage regulation, etc.) that would achieve the desired MEC increase.

Nonetheless, this is often not economically viable, as the customers must take in their charge the DG installation costs, plus these high infrastructure upgrade costs [7]. When a customer is denied a MEC, the utility or system operator provides additional technical assistance on what changes would be required at the grid level to accommodate that installation. Evidence shows that in most cases, customers decide to abandon the project, or they use alternative ways to make

their installation possible without upgrades [36] (e.g., through energy storage systems, load shifting or curtailment, as described above). In addition to this, there are other non-economic reasons that make infrastructure upgrades an impossibility: project delays from the pre-feasibility and feasibility analysis from the system operators, rejection from neighbours to have additional cables or works in their property, rejected planning permissions, etc. [37].

3. Literature review

Since its conception, the energy sector has largely focused on optimality of technical and economic constraints (i.e., how to optimally invest on infrastructure depending on the needs of users, and how to use the existing infrastructure in the most efficient way). As new decentralised technologies become part of the energy mix, the relatively new concepts of equality and equity in the energy sector are becoming increasingly relevant (e.g., recent works start introducing sharing economy concepts to the picture [6]). This section presents the connection of existing literature and industry approaches to the problem of equity and equality in the energy sector. Additionally, framed in the energy transition, grid access is explained as the result of superposing technical, socioeconomic and policy layers over time.

3.1. Different objectives for small-scale DG deployment

The development of clean and cost-effective small-scale technologies for local generation and flexibility makes it possible to produce and consume energy locally, and to create local electricity markets to trade excess electricity from these new technologies [2]. This has revolutionised the way the energy sector is conceived, and alternative objectives to that of optimality are being proposed (e.g., for the first time, the planning of infrastructure is being framed around equality and equity considerations). The potential objectives and approaches, and how existing literature aligns with them are presented below.

3.1.1. Optimality objective

The electricity sector traditionally focused on first, understanding the needs of users (i.e., where are consumption centres located and what are their energy needs); second, the possibilities to provide for these needs (i.e., where are primary energy sources located, and how can these be exploited); and third, the necessity to transport energy from one location to the other. At first, the electricity grid was designed to reliably and securely provide users with energy produced in large centralised remote generation locations using distribution and transmission infrastructure [23]. The necessary investments for generation, transmission and distribution were in charge of public and private entities with oversight from government and regulatory entities that guarantee users access to electrical energy [1]. In this frame, centralised technical-economic studies to find cost-effective ways to use existing and future infrastructure, and to get electrical energy from production to consumption centres were performed.

An optimality objective worked well so far because electricity was a service provided by some, and perceived by others. This clear distinction in roles makes it possible to have a fair definition of which responsibilities and benefits are assigned to each participant. The service providers are responsible for the planning, development and maintenance of the infrastructure, and will receive in exchange some economic benefit from those that receive the service. The users of this service (i.e., consumers) pay for all the costs associated to this planning, development and maintenance, in exchange for uninterrupted and non-discriminatory access to electricity [23].

The optimality objective is centred in the concept of competition: if there are different solutions to the planning problem (e.g., different locations, primary sources and technologies for electricity generation), an optimal solution is the one that performs best according to the

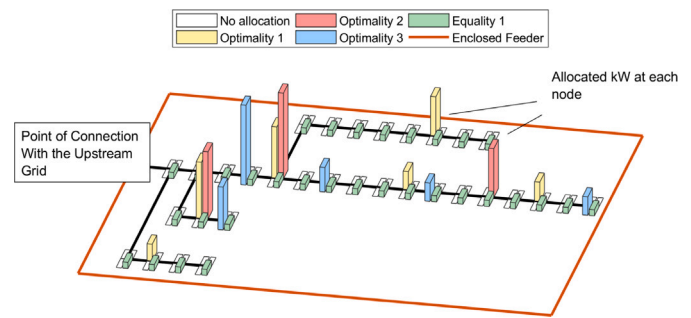


Fig. 1. DG allocations in the IEEE modified 33-bus distribution network using different algorithms. Optimality 1 in [40], Optimality 2 in [41], Optimality 3 in [42], and Equality 1 in [43].

optimality parameters (e.g., cost effectiveness, technical viability, etc.) [38].

With the introduction of DG (i.e., local energy production), new roles are being created and interactions between participants are changing. A user that installs DG can become a prosumer [6], acquiring some characteristics from the role of provider, and keeping its role as consumer. The optimality objective with a centralised structure results in unfair outcomes for DG assignment because the roles, benefits and responsibilities are not the same for all [17]. Nonetheless, numerous works in the literature propose optimality as a solution for small-scale DG assignment (i.e., the DER allocation problem, or DER hosting capacity problem), the reader is encouraged to consult a recent compilation of these works in [39] for industry, and in [38] for academia.

3.1.2. Equality objective

As discussed in [16], the current paradigm of optimality may create unfair conditions that enhance existing inequalities, because competing consumers, prosumers and producers have discriminatory (i.e., infrastructure, financial and other) constraints. A natural next step is to propose equality as an objective and removing existing constraints for all. This could be called the *level playing field* condition [44]: If everyone has an equal chance at installing DG, or if at least they are not unreasonably prevented from doing so, we can expect a fair result.

Equality means that all participants are assigned an equivalent capacity to install DG. The participant who chooses merely to consume electrical energy is assigned the same chance, compared to the participant whose choice is to make significant investments in DG. In search of common ground, several participants can put aside discriminatory constraints, and focus on the technical capabilities of the grid. This was proposed for the first time in [43], where an equal level of MEC is assigned to all participants in distribution networks (i.e., every participant has an equal chance at installing DG, without affecting the chance of others). Simulation results from this study suggest that there are significant benefits to an equality approach: increased participation, improved security of supply, reduction in technical losses, increased overall DG installed capacity, etc.

To illustrate the contrast between the optimisation and equality objectives, Fig. 1 presents the results of three optimal [40–42] and one equal [43] DG allocation algorithms in the literature when applied to the academic network IEEE modified 33-bus distribution grid. While all these distributions represent an equivalent level of DG, it is clear that *Equality 1* in green fulfils the *level playing ground* condition, and is therefore considered more fair than the remaining three.

An equality objective is centred in the concept of cooperation: regardless of different solutions performing better from a technical and economic perspective, an equal assignment of DG that is respectful of these constraints, can be perceived as more fair. Note however that this paradigm of equality is novel in the electricity sector and in the assignment of DG (i.e., it is only theoretical). Studies on different

areas of human behaviour suggest that an imposition of equality can be perceived negatively: numerous psychological experiments suggest that society regards egalitarianism as deeply unfair [45]. As it will be detailed later in Section 4.1, the concept of equality as policy path for small-scale DG assignment will be tested to determine its adequacy in terms of fairness.

3.1.3. Equity objective

Fairness is defined as the search of balance between the instinct to compete and the benefits of cooperation [44]. In this sense, a third objective that has not been explored in the literature is put forward: equity. The principle is that by accepting mutually agreed rules, even if these do not give us an advantage, some level of participation and cooperation from all is enabled. In this regard, equity brings forward community consensus so that everyone has some chance of success, but understanding that not everyone can benefit equally from the circumstances. Equity is some form of equality in which the size of a contribution and the individual needs are considered. Too much emphasis on competition (i.e., as in the optimality objective) will see some participants discriminated and subject to unfair treatment. Too much emphasis on cooperation (i.e., as in the equality objective) prevents individual advantages from being exploited.

In line with this, governments around the world are beginning to use fairness and justice as keywords next to the energy transition and in their targeted policies, with the most notable examples being the European Union and the United States. The European Commission created its just transition mechanism that includes the Just Transition Fund (JTF) of € 19.2 billion, the inclusion of a budgetary guarantee for the Territorial Just Transition Plan (TJTP) in the InvestEU funding programme, and the creation of a Just Transition Platform (JTP) that provide collectively technical and financial support to “ensure that the transition towards a climate-neutral economy happens in a fair way, leaving no one behind” [46]. The United States have developed its Justice40 initiative that includes federal investments to benefit communities in seven areas including climate change, clean energy and energy efficiency [47]; as well as the creation of a Climate and Economic Justice Screening Tool (CEJST) [48].

Previous works that consider equity implications in power systems studies include the following. [49] proposes the inclusion of energy justice values in the cost-benefit analysis of microgrids, quantifying not only the technical and economic constraints. The authors in [50] provide a review of burdens and benefits distributed amongst users of the power grid, this is frame in grid resilience and disaster management (i.e., there is an important focus on the justice implications of grid outages affecting more certain blocks of electricity users). The usefulness of microgrids to improve energy access and grid resiliency is studied in [51]. No previous technical work has been conducted to propose equity as a fair approach towards DG deployment, but numerous studies highlight its necessity [6,7,16,17]. This is the research gap that this work targets.

3.1.4. Existing approaches towards these objectives

As it will be detailed later in Section 4.1, the concepts of optimality, equality and equity will be assessed as potential policy paths for small-scale DG assignment. At this point it is important to mention some methods used in the literature to solve these objectives, these include robust optimisation as well as stochastic nature-inspired programming. The work in [52] presents a hybrid genetic algorithm—monte carlo simulation (GA-MCS) approach for the location and sizing of DG installations, dynamic voltage restorers (DVR) and distribution static compensators (DSC) considering system power factors and voltage profiles. The article in [53] presents an improved Elephant Herding Optimisation (EHO) algorithm to formulate and solve a multiobjective DG planning problem. A nature-inspired Ant Lion Optimisation (ALO) algorithm for optimal sizing of DG with loss reduction as objective can be found in [54]. As discussed above, [43] is the first work that

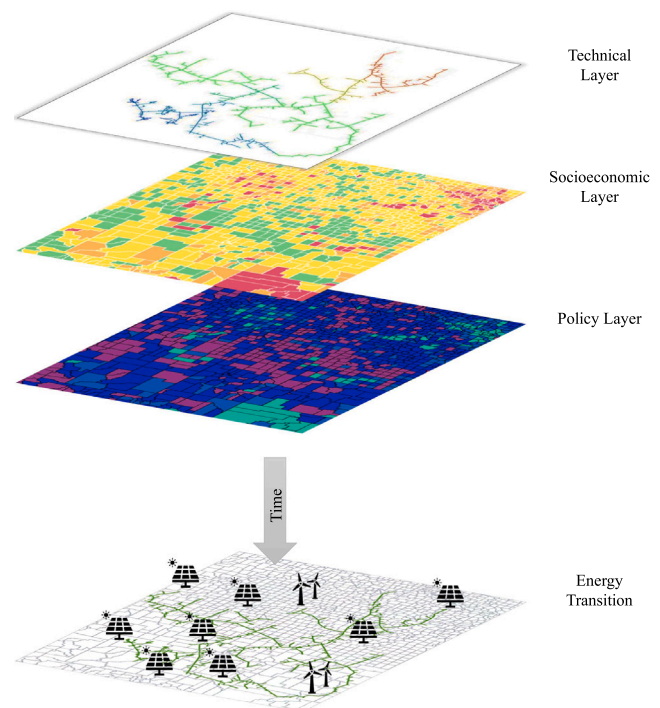


Fig. 2. Three layers defining the picture of the energy transition.

put forward DG assignment through an equality objective, and it uses technical restrictions of the grid to calculate iteratively the MEC of all participants to guarantee non-discriminatory participation.

These approaches are conceived with the optimisation and equality objectives defined above in mind. They aim at calculating the optimal location and size of DG installations using a technical or economic parameter in mind (e.g., loss reduction, revenue maximisation, etc.). However, they are the body of work that will serve for future applications to calculate future DG allocations with an equity objective in mind. Note the important distinction between objectives and approaches. The first will define what is the goal of the study to be conducted (i.e., what problem needs to be addressed), and the second deals with the mathematical approach at calculating the values that represent a solution to the problem.

3.2. The layered challenge of equity in electricity grids

Existing literature identifies different disciplines or factors that shape the energy transition. Three perspectives are taken to understand energy transitions globally: technology, economic development, and policy change [55]. The transition towards a more sustainable energetic paradigm is therefore abstracted as the superposition of three independent layers as seen in Fig. 2.

3.2.1. The technical layer

Numerous studies speak of a great potential for clean energy globally [56,57], this includes small-scale applications relevant to this study. Such applications require robust and flexible transmission and distribution systems to take electricity generated locally, to places where it is needed – in real time –. This is because the physics of electricity require demand and supply to be balanced at all times [28].

These transmission and distribution systems were designed to bring bulk and dispatchable – not sparse, unpredictable, and small-scale – electricity from remote locations to consumption centres when it is needed [43]. The non-dispatchable nature of renewable energy makes it impossible for the current infrastructure to cope with the great

potential mentioned above [7]. This is why the energy transition is a challenge: infrastructure capabilities are a great constraint to how much society can benefit from clean non-dispatchable energy.

Aside from infrastructure-born limitations, there are additional barriers for the adoption of DG. The study in [57] found that certain characteristics prevent users from installing solar PV (e.g., the orientation of the roof in a dwelling). Together, these limitations represent what is defined here as the technical layer.

3.2.2. The socioeconomic layer

Previous empirical studies suggest that investments in DG are influenced by home ownership, income, social context, household practices, attitudes, and beliefs towards the environment [58] (e.g., it has been found that households with children and those with higher levels of education tend to adopt these technologies before [59]).

It has been discussed that high-income households have better credit scores and consequently access to better interest rates [59] (i.e., credit constraints for low-income households may exacerbate the difficulty to access). To counterbalance, there are certain economic incentives in the form of tax deductions and grants that are not biased towards the economic situation of the household/business/industry and are based solely on the decision to invest [60].

The socioeconomic layer is defined by the multidimensional characteristics from electricity users that may influence their interest and ability to invest in DG. This layer is in practice difficult to model because of the subjective nature of the social component [55,58]. Analysis is restricted to the economic portion that can be more objectively quantified.

3.2.3. The policy layer

In an effort to accelerate the energy transition, local, regional and national governments have developed energy policy that stimulates small-scale applications [11,12]. Aware of the existence of the technical layer defined before, the possibility to benefit from small-scale energy generation has been capped using different rules of thumb. As seen in Table 1, percentages of transformer ratings, peak loads and arbitrary values are often used as criteria to restrict the size of small-scale DG. These rules of thumb do not account for the locational impact of DG, and they may create inequitable conditions for late-comers.

4. Proposed methodology

On one hand, improving the technical layer would require substantial investments to increase infrastructure capacity [7]. On the other hand, while governments are constantly trying to address disparities, the end of socioeconomic inequality is not in sight [61]. In contrast, the policy layer can be improved: seeking a more equitable energy transition starts there.

Studying the small-scale DG rollout and how to make it more equitable requires understanding each of its layers. After modelling the technical and socioeconomic layers, this paper offers a scalable policy path to complement the rules of thumb in Table 1: *sharing the grid*. The existing paradigm and this novel policy path are modelled to determine the benefits and trade-offs of the recommended policy.

To do so, this work presents a multi-year simulation of MEC request progression based on technical limitations and customer demographics. The purpose is not to predict where small-scale DG will be located, but to understand how the different policy frameworks impact DG uptake [62,63], equity in small-scale DG grid access [16], and how often investments are accepted or rejected due to MEC availability [13]. This work aims at exploring how equitable the energy transition is with different policy frameworks.

Table 1
Survey of small-scale MEC allocation rules per country [43].

Country	Limits for small-scale DG installations
Australia	≤10 kVA for single-phase ≤30 kVA for three-phase
Belgium	≤100% MV Transformer rating
Canada	≤25% Transformer rating for single phase ≤50% Transformers with rating ≤50 kVA ≤60% Transformers with rating >50 kVA
Ireland	≤6 kW for single-phase LV ≤11 kW for three-phase LV ≤Upper-level rating defined by DSO
Italy	≤65% Transformer rating ≤60% Feeder thermal limit
New Zealand	≤10 kVA for single-phase ≤30 kVA for three-phase
Portugal	≤25% Transformer rating
South Africa	≤15% Peak load
South Korea	≤100 kW ≤15% Transformer rating
Spain	≤50% Transformer rating ≤50% Feeder thermal limit
Sweden	≤40 kW
United Kingdom	Capacity(MVA) x Dist. to feeder (km) ≤4
United States	≤15% Peak load

4.1. Potential policy paths for DG access

It was discussed that current policy in the form of rules of thumb may cause inequitable conditions for the assignment of DG. To address this, the literature suggests a fair approach to assigning access [43], where the MEC of each customer is calculated by dividing the possibilities of the grid, while maximising participation of all customers: *splitting the grid*. The latter would guarantee some access for all, but it would also reduce the MEC for everyone potentially slowing down the small-scale DG rollout (i.e., if availability is reduced, investments in DG would be reduced).

To contrast against current policy and the approach from the literature that divides the grid capabilities equally, this paper proposes another path: *sharing the grid*. Policy that follows the logic behind dividing the grid, but allowing customers the opportunity to share their access to neighbours, monetising their unused MEC. To represent the potential policy layers of the energy transition, the authors envision and model three policy paths for distribution grids when it comes to approaching small-scale DG as seen in Table 2.

4.2. Reformulating small-scale MEC limits

Access to the grid in the form of MEC can mistakenly be perceived by customers as a quantity guaranteed by policy. Small-scale (industry, commercial or residential) customers read in policy that they can install distributed generation up to a certain MEC value as seen in Table 1 (e.g., a “fit and inform” simplified connection process [64]). Customers could understand that there are no other limitations to the amount of generation installed locally, while the reality is different. This is a negative consequence of the application of rules of thumb: there are other technical constraints associated to the capacity of the grid at different hierarchical levels, and it is wrongly implied that every customer has an equivalent chance to access the grid from a technical standpoint [43].

This interpretation of MEC limits creates inequitable conditions for some as the energy transition evolves: those participants that can access the grid first will take all availability, leaving late-comers waiting for infrastructure upgrades. Consequently, making grid access equitable requires at first improving the understanding of grid limits for small-scale

Table 2
Policy paths modelled for small-scale DG deployment.

Policy framework	Description	Limits	Possibility to extend limits
(1) <i>Business as usual</i> [39]	There is a rule of thumb to cap the size of installations and priority is given on a first-come first-served basis until the MEC limit of one of the parent substations is reached	Customer limit for small-scale DG	Energy storage, load shifting, curtailment, and customer-led infrastructure upgrades
(2) <i>Splitting the grid</i> [43]	The cap size of small-scale DG installations is calculated for each customer dividing the available MEC of parent substations at different hierarchical levels; available DG is reduced for everyone to allow latecomer access and participation	Customer limit for small-scale DG and upper-level grid availability split equally	Energy storage, load shifting, curtailment, and customer-led infrastructure upgrades
(3) <i>Sharing the grid</i> (proposed)	Small-scale DG for customers is capped also dividing the MEC of parent substations at all levels, but customers can now monetise unused MEC by transacting with neighbours interested in larger installations	Customer limit for small-scale DG and upper-level grid availability split equally	Energy storage, load shifting, curtailment, customer-led infrastructure upgrades, and acquisition of neighbouring unused limits

generation. This article highlights the importance to consider higher level limits to account for these technical constraints. It is proposed that the real MEC limit of each customer must be calculated in an equitable way considering all hierarchical limits. This calculation is not as trivial as dividing the available MEC at each substation between connected customers: some parts of the feeder having less customers may leave unused MEC and the resource will not be correctly distributed to account for the real capabilities of the grid. An incremental algorithm was used to quantify these grid capabilities.

4.3. Interest and ability to install

To represent the socioeconomic layer, an equivalent interest or ability to invest for all users will be modelled by a fixed percentage of their disposable income accumulating every month [65], this percentage is based on the average amount spent by users in energy bills [66,67]. First, the monthly disposable income of year zero $I_{m,year=0}^{disp}$ is calculated dividing the difference between known yearly income $I_{year=0}$ and spends $E_{year=0}$ of the household by the twelve months of the year, as in (1). Then, monthly disposable income values for subsequent years are adjusted to account for changes in incomes and inflation [68] using $i\%$ in (2). Ultimately, the monthly interest to install in a year $\Gamma_{m,year}$ (i.e., money available every month of that year for DG installations) is calculated multiplying the disposable income of the month $I_{m,year}^{disp}$ by the fixed interest or ability to invest $\gamma\%$, using (3).

$$I_{year=0}^{disp} = \frac{I_{year=0} - E_{year=0}}{12} \tag{1}$$

$$I_{m,year+1}^{disp} = I_{m,year}^{disp} \times (1 + i\%) \tag{2}$$

$$\Gamma_{m,year} = I_{m,year}^{disp} \times \gamma\% \tag{3}$$

It is important to account for the price reduction trend of DG installations [69,70]. For this, (4) adjusts the cost of DG installation per kW of a year C_{year} using the cost of the previous year C_{year-1} and a projected cost reduction $\alpha\%$.

$$C_{year} = C_{year-1} \times (1 - \alpha\%) \tag{4}$$

The decision to install small-scale DG in the proposed model is triggered by an initial investment (i.e., a percentage $\Omega\%$ of the installation costs of the year C_{year}), with the remainder being paid over monthly instalments. As in (5) if all monthly savings from interest to install Γ_m exceed the trigger $\Omega\%$, the installation is requested, the savings are spent, and future savings are going towards paying the rest of the installation (i.e., further installations are on hold until the previous installation is paid in full).

If

$$\sum_{m=1}^{current_month,year} \Gamma_m \geq C_{year} * \Omega\%$$

Then

$$installation_months \leftarrow current_month \tag{5}$$

current_month,year

$$\sum_{month=1} \Gamma_m = 0$$

$$\Gamma_{current_month} = -C_{year} \times (1 - \Omega\%)$$

End

It is proposed to complement this with any tax deductions, funding, credit benefits or any financial incentives applicable to the case study. Pairing this with market constraints (e.g., local installation prices for DG) it is possible to predict customer interest and ability to install small-scale DG: the socioeconomic layer.

4.4. Resulting layer: the small-scale DG rollout picture

Independently superposing the technical and socioeconomic layers with the three policy paths, the evolution of the small-scale DG rollout associated to these can be studied. For each customer, the expected progression of DG installations can be calculated. Considering the economic variables and the definitions for interest and ability to install, it is possible to determine at which moments customers are expected to install small-scale DG (i.e., make a MEC request).

For each policy environment, MEC requests are simulated over time. Following the expected progression calculated before, and prioritising through simple random sampling, all customers with an expected installation in any given time slot are given the possibility to make a MEC request. If there are available MECs at all hierarchical levels associated to it, the customer is allowed to install DG, and the request becomes a MEC acceptance. If on the contrary one or more hierarchical levels have no available MEC, the request becomes a MEC rejection.

For the policy framework *sharing the grid*, customer that have a MEC rejection has the opportunity to verify if there is unused MECs in the parent substations. If it is possible, the rejected MEC becomes an indirectly accepted MEC. The process is repeated for each customer, time slot and policy environment until all grid limits are reached (i.e., the small-scale DG rollout is completed). The results of this simulation are final installation sizes for each customer, given the three policy paths, paired with the progression of accepted and rejected MEC requests.

4.5. Search of bias in grid access and the technical layer

After the small-scale DG rollout under different policy paths is completed, it is possible to assess if certain customer blocks have increased access. Following up on a previous study [16], an analysis to understand the relationship between the grid limits before, installed capacities after the three policy-constrained small-scale DG rollouts, and customer demographics is proposed. Linear and non-linear models are used to understand which demographic attributes correlate, and if there are inherent bias (e.g., if a certain customer group is having less access compare to others).

Customers can be batched according to demographic attributes (i.e., average income, household expenditure, population density, language isolation, nationality and household composition—please refer

to Appendix B): dividing the span of each attribute in equally distant portions and grouping households that fall into each of these divisions. Any demographic variable can be represented using N brackets between its maximum and minimum value, every customer falls into one of these brackets. Calculating the mean, standard deviation, standard error, 10th, 30th, 70th and 90th percentile represents the bracket. Subsequently, using the number of households per bracket these values are weighted to plot the locally estimated scatterplot smoothing (LOESS) curves that represent the mean, 60% and 80% of the data [71].

Linear regressions, R^2 values and the root mean square error (RMSE) of each data set [72,73] are proposed to unveil any relationship. Additionally, the correlation coefficients between each demographic attribute and the three sets of grid limits can be calculated. Instead of a train-test split, this study proposes using all the data to evaluate the models because the objective is to represent the entire population rather than predict missing data points.

5. The Irish case

Ireland was selected as case study for three reasons: (1) Ireland’s energy transition to date focused mainly on grid-wide renewable energy installations, there are no significant advances in small-scale DG [74], this gives the country a status of “blank slate” where grids are far from small-scale DG saturation, (2) despite its reputation for grey skies, there is an important role for solar energy installations which is expected to trigger a boom in small-scale solar PV installations in the near future [57,75–77], and (3) Ireland is introducing incentives for small-scale DG [11,12,78], including a feed-in tariff named “Clean Export Guarantee”, a monetary compensation for electricity fed to the grid by small-scale DG [79,80]. Considering that many countries are at an early stage in their small-scale DG deployment, this work was designed to be applicable for any national or regional grid according to their unique energy policy, utility guidelines, and market constraints.

As small-scale DG progression is mainly expected to be in the form of rooftop PV installations rather than small-scale wind turbine [81,82], the simulation of DG progression considers exclusively this technology. The inclusion of other technologies is however possible given constraints particular to other case studies.

Grid operators have strategic planning processes for infrastructure upgrades (i.e., grids are constantly modernised and expanded). The total distribution infrastructure in Ireland is valued with a regulated asset base (RAB) of € 8.4b in 2020 [83], and the capital investments towards grid reinforcement for the period 2021 to 2025 is recommended by the Irish Commission for the Regulation of Utilities (CRU) to be € 345.1 m [84]. Considering these scales of magnitude (e.g., yearly investments that represent approximately 0.8% of the current value of the entire installation), it is assumed that the planned infrastructure upgrades’ effect on MEC availability increase is negligible over the study period. However, the authors acknowledge this marginal extension of MEC availability as an opportunity for inclusion in future models.

5.1. Aggregation of demographic and technical information

Grid operators normally have access to partial demographic profiles of their customers, however this information is considered sensitive under data protection laws at the European and national level [85–87]. In response to this, synthetic demographic profiles were created for each customer across the Irish grid using geographic, demographic, and technical information from official sources following the structure in Fig. 3.

ESB Networks provided information on how many individual customers are connected to the distribution level substations (i.e., the lowest level). Thanks to the publicly available “availability capacity map” [88], connections between substations in the grid hierarchy are known (i.e., which is the parent of each substation), and their corresponding MEC. This data was filtered and organised to (1) identify

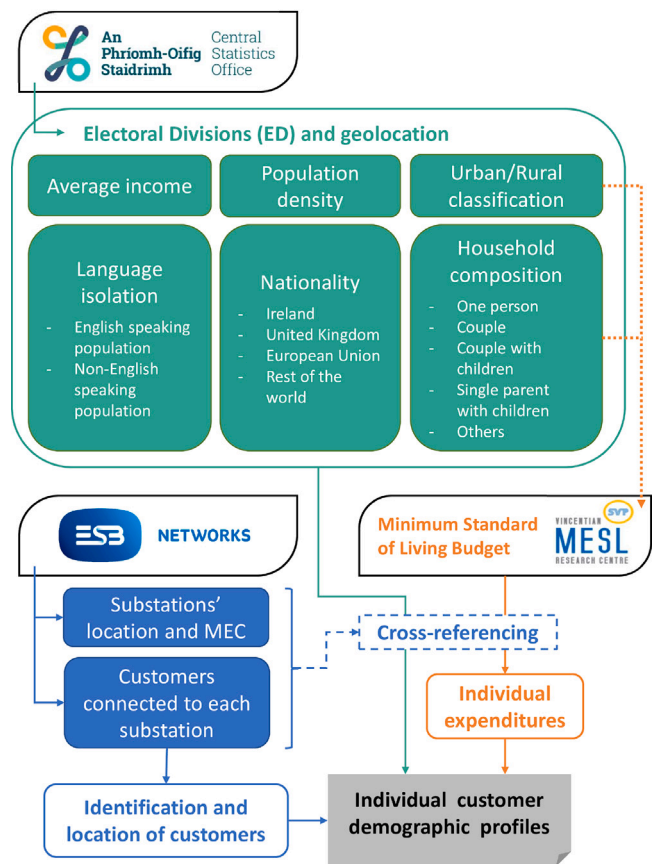


Fig. 3. Flow diagram on demographic data processing to build individual demographic profiles.

every customer in Ireland and connect them with every parent substation at every level, and (2), store the available MEC in every substation at all levels.

Since substations are georeferenced, the location of customers within the country and their demographic profiles can be abstracted. Thanks to the official information from the Central Statistics Office Ireland, each electoral division (ED) – the geodemographic unit for the case study – is connected to demographic variables in its area of influence [89]. EDs are also georeferenced [90], therefore it is possible to cross-reference ED demographic attributes to each distribution substation by location. To represent the technical layer, it was assumed that every customer connected to a substation is also located within the ED in which the substation is located. As a result, individual demographic profiles were assigned to each customer to account for its average annual income, ED population density, language isolation, nationality mix, and household composition.

In Ireland, demographic information on household expenditure is not defined as an average value for each ED, it is associated to household composition and its urban/rural classification [66,67]. Using the population of the ED, its urban or rural classification, and the expected spends according to categories of household composition, each customer was connected to its expected annual expenditure and that was ultimately included in their demographic profile. This was done to represent the socioeconomic layer.

5.2. Incongruent limits in energy policy and the grid

The distribution grid operator in Ireland, ESB Networks, has 1,647,316 low-voltage customers (i.e., households, businesses, and industries) served by 44,400 distribution, 434 sub-transmission, and

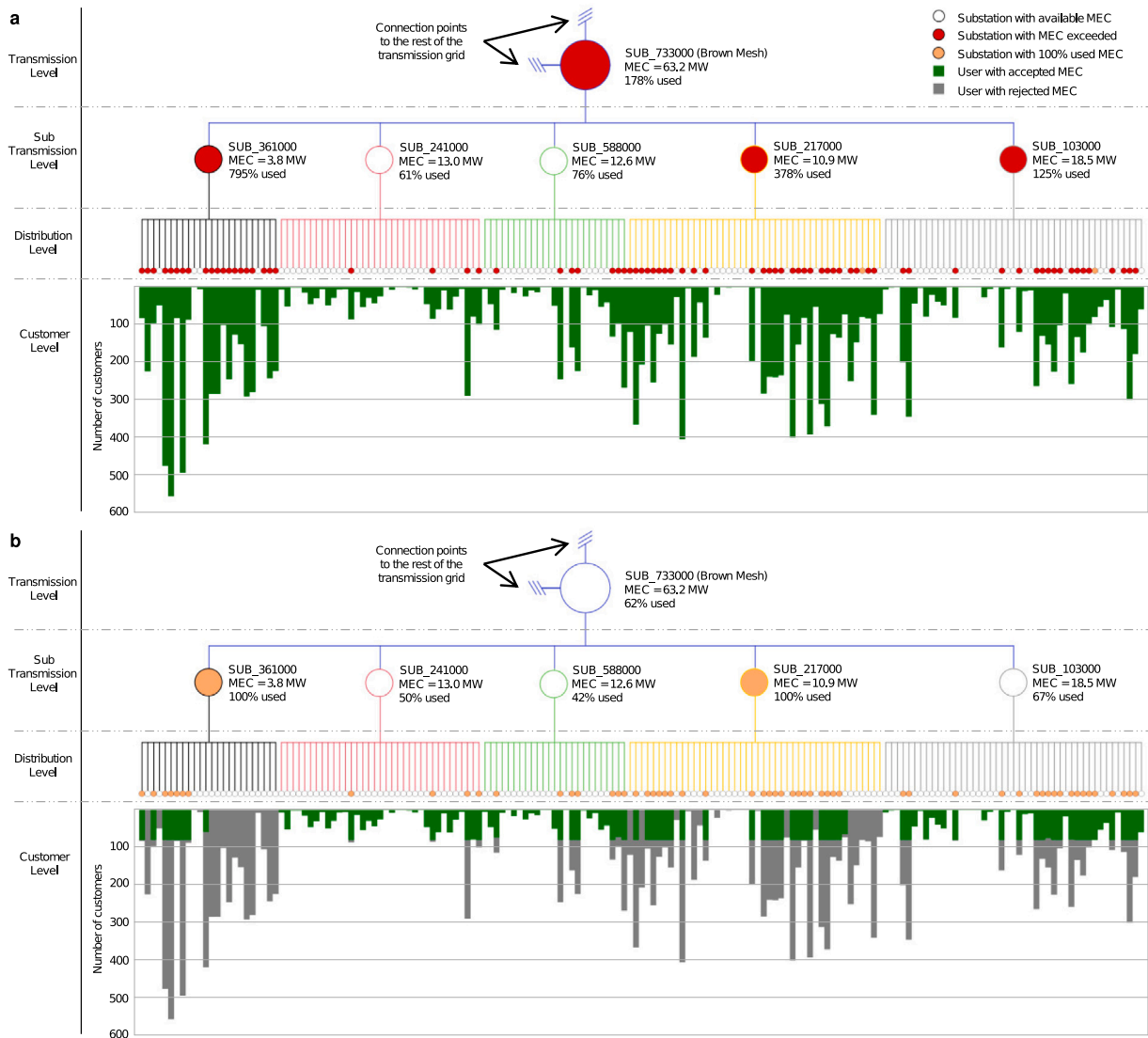


Fig. 4. Brown Mesh feeder detailed MEC deployment analysis, 6 kW MEC for individual customers: (a) assigning without consideration for higher-level limits (b) assigning until all higher-level limits are at their maximum level.

70 transmission substations [91]. They are connected in a radial hierarchical way: every individual customer is connected to one substation in each level of the hierarchy. To facilitate customer connections, ESB Networks published an “availability capacity map” that includes an estimate of the available capacity for generation in each substation of the grid at all hierarchical levels (i.e., the MEC of each distribution, sub-transmission and transmission substation) [88]. The aggregated small-scale DG of all customers connected must respect the MEC limits of every substation. In parallel, Irish energy policy states that any customer is entitled to a base generation installation of up to 6 kW for single-phase and 11 kW for three-phase connections, without requesting permission from the utility (i.e., fit and inform process with installations capped using a rule of thumb). This means that from a policy point of view, every customer in Ireland can request MECs of at least 6 kW [64].

Using these estimates for capacity availability as higher-level MECs, it is possible to assess future saturation of Irish grids at different hierarchical levels. To this end, Table 3 shows the total MEC available at each level. As discussed before, MECs from the same primary source cannot be diversified implying a significant discrepancy in the ability of the grid to take potential MECs at different levels.

Table 3

Total available MEC in Ireland at each hierarchical level.

Hierarchical level	Source	Value	Nationwide MEC (GW)
Customers	Energy policy [64]	6 kW/cust. ^a	9.88
Distribution	Availability map [88]	Various	10.39
Sub-transmission	Availability map [88]	Various	4.13
Transmission	Availability map [88]	Various	3.22

^aMost customers in Ireland have a single-phase connection.

This analysis suggests that if all customers request their policy-given 6 kW MEC, the aggregated 9.88 GW requests will greatly exceed the estimated capacity of the sub-transmission and transmission level substations (4.13 GW and 3.22 GW respectively), and the utility will have to restrict access to late-comers. This would be exacerbated if three-phase participants were to request their policy-granted 11 kW MEC.

A single-feeder analysis reports additional information on this problem in Fig. 4. Considering it is the appropriate size for illustration purposes, one urban feeder in the city of Dublin was selected for close

Table 4
Simulated installed PV in Ireland at the end of the small-scale DG rollout given different policy frameworks.

Policy framework ^a	Total PV [GW]	Customers with max PV (6 kW)	Customers with some PV	Indirectly benefited customers
(1) <i>Business as usual</i>	2.82	77,671 (4.72%)	1,283,252 (77.90%)	–
(2) <i>Splitting the grid</i>	1.36	27,312 (1.66%)	773,150 (46.93%)	–
(3.1) <i>Sharing the grid</i> (up to 1 kW)	2.43	40,108 (2.20%)	1,339,320 (81.30%)	307,996 (18.70%)
(3.2) <i>Sharing the grid</i> (up to 2 kW)	2.72	47,553 (2.89%)	1,321,070 (80.20%)	326,246 (19.80%)
(3.3) <i>Sharing the grid</i> (up to 3 kW)	2.82	54,445 (3.30%)	1,317,271 (79.96%)	330,045 (20.04%)
(3.4) <i>Sharing the grid</i> (up to 4 kW)	2.86	55,896 (3.39%)	1,315,780 (79.87%)	331,536 (20.12%)
(3.5) <i>Sharing the grid</i> (up to 5 kW)	2.88	60,037 (3.64%)	1,315,612 (79.86%)	331,704 (20.14%)
(3.6) <i>Sharing the grid</i> (up to 6 kW)	2.89	75,741 (4.60 %)	1,315,599 (79.86%)	331,717 (20.14%)

^aFor policy framework (3), customers that reach their individual limit were allowed to acquire access from a neighbouring customer's unused limit in exchange for an agreed benefit, up to the amount shown in parenthesis.

inspection. The transmission substation “Brown Mesh” serves 5 sub-transmission substations, 173 distribution substations and a total of 18,725 customers. First, the policy-given 6 kW was assigned to all customers associated to the feeder, as a result the higher-level limits are exceeded (Fig. 4a). This is not feasible because in some cases, the total MEC associated with a substation exceeds its estimated capacity more than seven-fold. The utility cannot grant MECs that exceed the capabilities of the grid without making upgrades, therefore a realistic scenario for the Brown Mesh feeder is one where higher level MEC limits are considered as well (Fig. 4b). Analysing the hierarchical limits of the Brown Mesh feeder, it was found that only 6491 customers connected to this feeder would be granted a MEC of 6 kW as the policy states: approximately 65% of customers are left out. The realistic scenario in Fig. 4b while hypothetical, appears to mirror the situation present in national and regional grids saturated with small-scale DG [17,92] where early-comers are blocking access to latecomers. This initial analysis of the case study illustrates the inadequacy of current policy design for equitable grid access.

6. Results and discussion

Given the calculated grid limits (i.e., technical layer), and demographic profiles (i.e., socioeconomic layer), customers adopt rooftop solar PV over time up to 6 kW constrained by the three different policy frameworks discussed above in Table 2. The details of the resulting small-scale DG rollout are presented in this section.

6.1. A look into future policy for small-scale DG

Once the small-scale DG rollout is completed, using *business as usual* policy results in an overall installed capacity of 2.8 GW of rooftop solar PV. Only 77.9% of potential customers in Ireland are allowed to install some level of PV, leaving the rest reliant on infrastructure upgrades. Furthermore, only 4.7% of customers are able to install enough PV to match the policy limit of 6 kW MEC. Given current regulation it was found that less than 5% of all customers in Ireland will be granted permission to install small-scale DG to match what is laid out in policy due to limited electricity export capacity availability. Furthermore, 22% will not be able to install DG at all without infrastructure upgrades. While it is challenging to estimate the cost of upgrades that

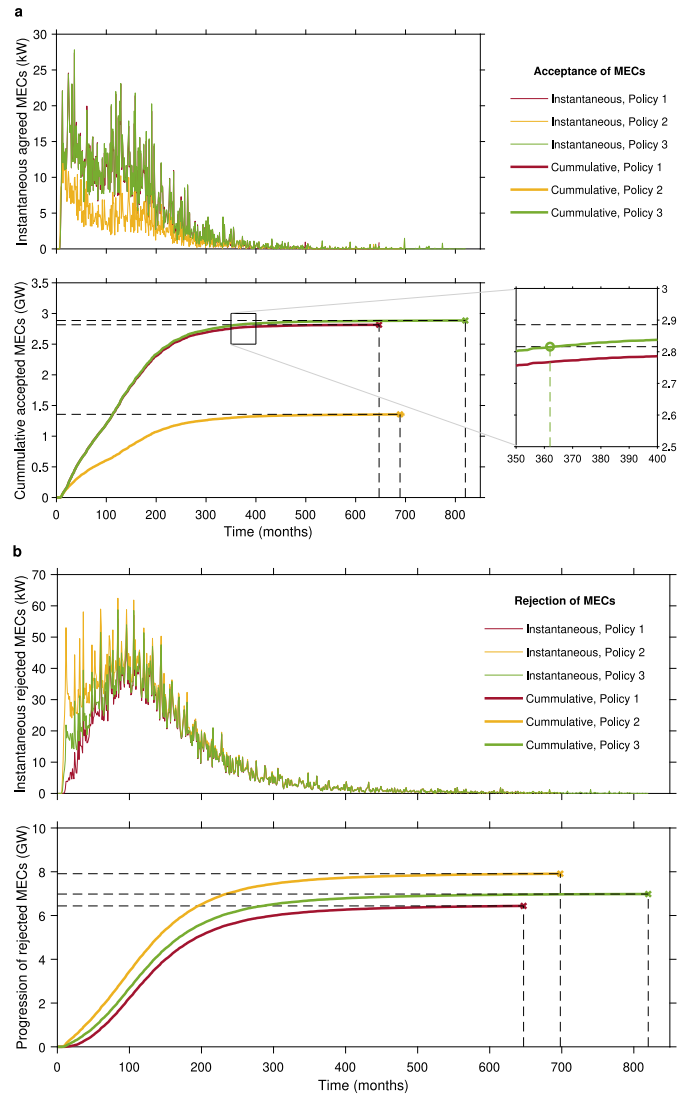


Fig. 5. Evolution of small-scale DG rollouts under different policy frameworks. (a) Progression of MEC acceptance, and (b) progression of MEC rejections.

would provide access for all [26], this shows the scale of the problem and serves as additional motivation for an alternative solution like that of this work. The *splitting the grid* policy, where all customers are guaranteed a position in the grid, results in a lower rate of participation (46.9%) and installed capacity (1.36 GW).

Ultimately, using *sharing the grid* represents an improvement on both fronts: when users are able to share neighbouring unused limits of 3 kW or larger, overall installed capacity is increased, and participation is greatly improved: approximately 80% of customers have direct participation, and 20% receive an indirect benefit, all potential customers are benefiting from small-scale DG. We find that there is a trade-off between *business as usual* and *sharing the grid* when 1 kW or 2 kW unused limits are shared: while participation is still increased, a reduction of 0.39 GW and 0.1 GW respectively is seen. Results can be found in Table 4.

Fig. 5 presents the progression of acceptance and rejections of MEC when customers are allowed to acquire up to 6 kW of neighbouring unused limits. The progression of 1 kW PV installations across the country was predicted given different policy frameworks. Installations of 1 kW were used to keep track of grid constraints over time. However, installations are expected once per household (i.e., resizing PV installations is prohibitively expensive). It is useful to illustrate using

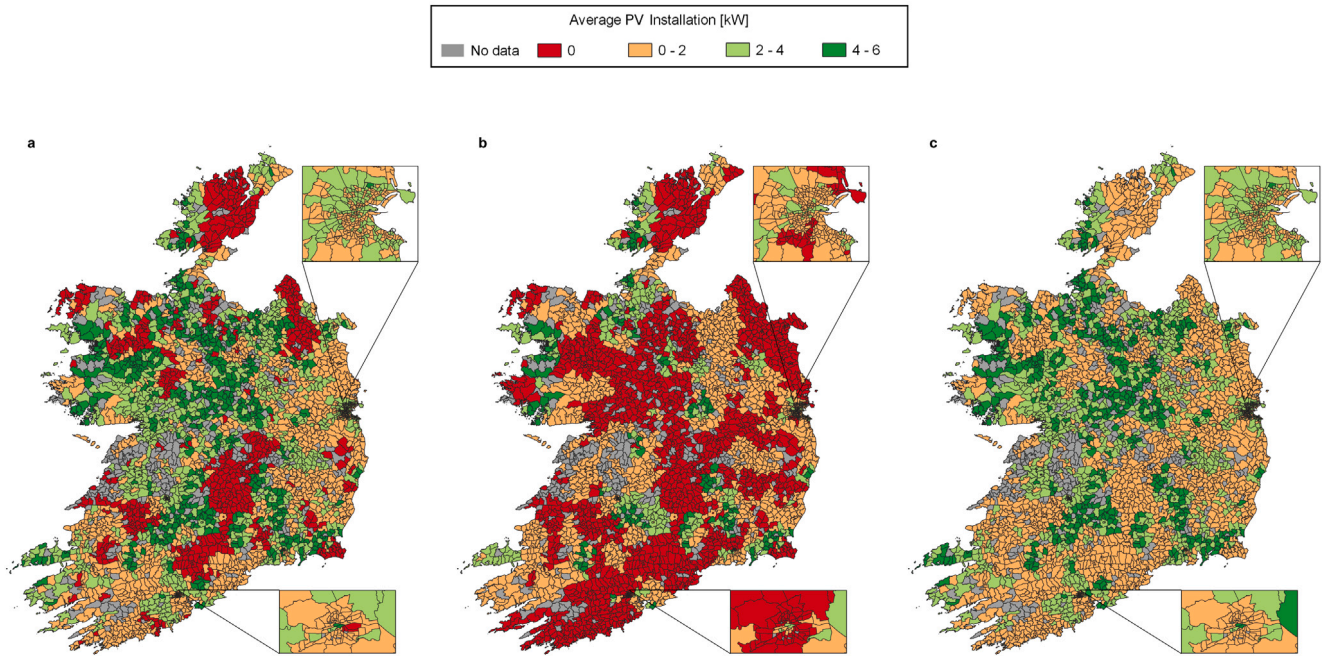


Fig. 6. Geographic representation of simulation results. Average per-household PV at each ED in Ireland after the small-scale DG rollout using policy path (a) business as usual, (b) splitting the grid, and (c) sharing the grid. Grey-coloured regions correspond to EDs without substations or customers.

an example: it is not realistic to think that a customer installed 3 kW of PV 1-kW at a time in months 25, 73 and 116, the installation costs of resizing would not allow this. To account for installation cost constraints, we normalised the final installations of every customer. Following the example, we placed the 3 kW in the last installation moment, when all the investments have been secured (i.e., month 116). After normalisation, we registered MEC acceptance and rejections, and we reported their progression over time.

Results in Fig. 5a show that at some point in time all availability is taken (i.e., the last MEC is agreed), this marks the end of the small-scale DG rollout for each policy framework. The first policy path to reach the end is *business as usual*, followed by *splitting the grid*, with *sharing the grid* finishing last, at months 647, 689 and 820 respectively. In principle it appears there is a trade-off between the large overall installed capacity achieved with *sharing the grid* and a fast-paced rollout with *business as usual*. However, when looking at the inset in Fig. 5a, it is visible how *sharing the grid* achieves the maximum installed capacity of *business as usual* much earlier: at month 362. These results suggest that using the proposed policy path, a reduction of 44% is seen from the base timeline.

The benefits of applying the *sharing the grid* policy come from indirect acceptance: users that cannot use their MEC can offer it to interested parties. This increases participation and unlocks investments without creating inequitable conditions for grid access. While the adoption of *business as usual* results in fewer investment rejections compared to the other policy paths (See Fig. 5b), participation is key [93]: it can be argued that when more participants are able to install PV, subsequently rejected investments can be redirected to alternative technologies (e.g., battery storage systems [94,95]). This would not be practical if the first investment is rejected as it happened to many customers in *business as usual* (i.e., if there is no initial installation, subsequently rejected investments cannot be redirected and remain blocked).

6.2. Geographic representation

The average customer installation per substation $EDAveragePV$ was aggregated at an ED level, calculated by dividing all installations connected to the substations at each ED by the number of customers connected, using (6). This allows for the representation of the geographic granularity of participation responding to the application of each policy scenario for each ED. The open-source geographic information system software QGIS 3.16 was used for this [96].

$$EDAveragePV = \frac{\sum_{subs \in ED} InstalledPV}{\sum_{subs \in ED} NumberCustomers} \quad (6)$$

Fig. 6 shows how the first policy path results in some EDs with relatively high levels of PV (i.e., ≥ 4 kW on average) installed per customer and numerous EDs with no PV installed at all (See Fig. 6a). In contrast, the third policy path presents a more even distribution of grid access (See Fig. 6c). Notably, in *sharing the grid* there is a prevalence of areas with more than 0 kW and less than 2 kW average installed PV per customer. This suggests that *sharing the grid* is the preferred policy path to equitable access for small-scale DG, because of its increased level of participation, speedy transition, and higher level of overall installed capacity.

6.3. Equity before and after the small-scale DG rollout

A previous study shows that in grids saturated with small-scale DG, access is smaller in households from disadvantaged census block groups, and concludes that such inequity is attributed to grid limits being bias against these households [16]. To verify this and validate our work, it is important to assess if there are inherent inequalities in the grid limits “before” the small-scale DG rollout and “after” the proposed policy frameworks are implemented. To represent grid access “before”, the maximum possible MEC was distributed to all participants respecting the limits of all hierarchical levels. We used the simulation results as reference for “after” the small-scale DG rollout given the different policy frameworks. The correlation between “before” grid limits,

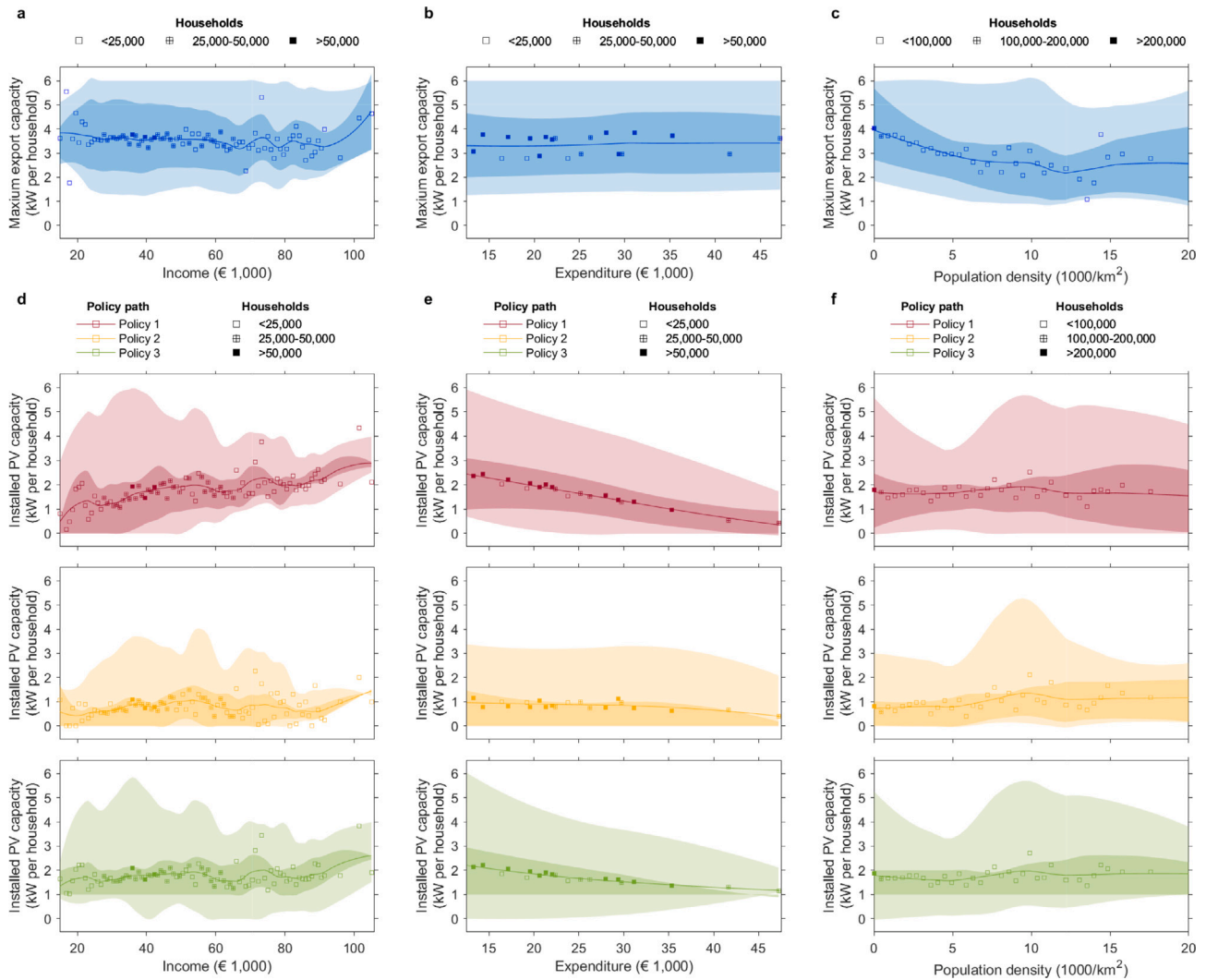


Fig. 7. Equity assessment. MEC availability for Irish households “before” the small-scale DG rollout given demographic variables: (a) Income, (b) expenditure, and (c) population density; household installed PV capacity “after” the rollout for different policy paths given demographic variables: (d) Income, (e) expenditure, and (f) population density. Darker and lighter bands represent respectively 60% and 80% of the data.

“after” PV installations as predicted in our model, and demographic variables is analysed using linear and non-linear models, a graphical representation of this can be found in Fig. 7.

Inspecting Fig. 7a and b, no visible correlation is found between MEC availability and household income or expenditure. From Fig. 7c, a tendency from households located in low population density areas to have a marginally larger available MEC is seen. This is explained when common design practices are considered: in distribution network planning installations are oversized expecting population growth [97], but in the case of rural locations where population density is smaller, growth is slower (if there is any) keeping the installation oversized for longer (e.g., population living in highly rural or remote areas fell 0.6% between 2011 and 2016 in Ireland [98]). This ultimately increases per-household MEC availability compared to more populated areas.

This analysis implies that grid access do not present any inherent bias towards any portion of the customer pool “before” the small-scale DG rollout. Grid codes used for design and construction of electricity grids are built around technical rigour, and do not discriminate [99, 100], which supports this claim (i.e., grid codes do not apply differently to less advantaged portions of society).

This changes “after” the implementation of current policy (i.e., Policy 1): we found a positive correlation with income (see first subset in Fig. 7d) and a negative correlation with expenditure (see first subset in

Fig. 7e) for installed PV using policy framework *business as usual*, which mirrors results from a previous study [16]. This correlation is considerably reduced for Policy 2 and Policy 3 (i.e., *splitting the grid* and *sharing the grid* respectively). Similar results are found when considering other demographic variables studied (i.e., language isolation, nationality, urban/rural classification and household composition). This suggests that any bias comes not from grid limits, but from early comers’ ability to gain a position in the grid: it is expected that high-income, less-expenditure sectors of society will accumulate the limited-available MECs leaving out lower-income portions of society [17]. This can potentially enhance existing multidimensional inequities for the lifetime of DG installations. Ultimately, this is evidence that policy plays a central role in grid access: including an equity dimension in policy design resulted in small-scale DG benefits more evenly distributed among electricity customers—aside from achieving a larger DG penetration faster as discussed before.

6.4. Validation

Contrasting these results against data of neighbouring countries in small-scale DG implementation, it was found that the simulated evolution of PV installed capacity in Ireland has a similar behaviour [101–103]. Fig. 8 shows the small-scale PV progression for United Kingdom,

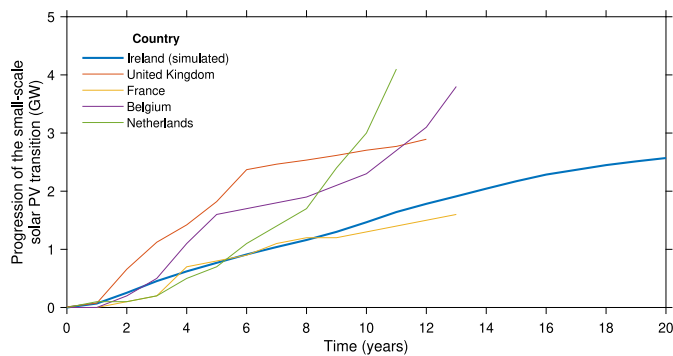


Fig. 8. Progression of the small-scale solar PV transition. Validating results against documented small-scale solar PV rollouts in neighbouring countries.

France, Belgium and the Netherlands taking the year at which they introduced small-scale DG energy policy as zero reference in time. There is a particular resemblance to the evolution in the United Kingdom where incentives for rooftop solar PV in the form of a feed-in tariff were introduced in 2010 [104]. Considering that the demographic profiles are comparable, and the grid planning structure in Ireland is largely based on United Kingdom regulations, this serves as validation for the interest-to-install methodology. The authors acknowledge that the planning structure in Ireland may not remain the same as in the United Kingdom against the background of Brexit. This impacts how the latter's energy transition will further evolve, and how comparable it is to the proposed case study. Nonetheless, this sanity check presents useful insights on the validity of the proposed methods.

6.5. Limitations from this work

The energy transition and the small-scale DG rollout studied are complex subjects that span over numerous spheres: the technical, economic, environmental, social, behavioural, etc. To bound this study it was important to focus on the portions that allow for an appropriate representation of the problem to be studied. Accordingly, the following assumptions and limitations are noted.

- This work does not perform a quantitative comparison of benefits for single customers of having their own DG installation versus societal benefits of others installing (e.g., in the form of reduced emissions and competitive energy prices). It is assumed that even in the presence of societal benefits when others install DG, the economic and governance benefits of participating directly with some form of ownership is inherently more appealing for single customers.
- Designers often define the “optimal” size of a DG installation with the objective to minimise energy costs or maximise self-consumption for single customers. Regardless of this, in the absence of energy storage to balance supply and demand, a DG installation producing in excess results in exported electricity to the grid, or curtailment. This work does not include the details of DG installation sizing. Instead, it is assumed that if the technical limits defined by the system operator are respected, users will desire an installation as large as possible and this will not result in curtailment.
- Case-specific characteristics of certain customers reduce their ability to install DG (e.g., a multi-story building has limited roof space for customer PV). It is not feasible to include these limitations in our model due to scalability, and the authors acknowledge this to be an important limitation. Note however that with current policy, these “limited” customers will only perceive the societal benefits of the energy transition (i.e., they cannot effectively participate). In contrast, the proposed policy allows

these customers to monetise their position on the grid. Even if this is not modelled, the problem of “limited” customers is expected to be addressed by the proposed policy.

- Typically, early adopters of any technology advancement are perceived as necessary to initiate cost reduction and open up the market for further customers. This is an important system role from early-comers that is not considered in this model. It is assumed instead that current DG installation prices paired with financial and tax benefits from energy policy are attractive enough to make this negligible. The authors acknowledge that customers who install DG earlier, pay a larger installation cost because DG prices tend to go down in time. The potential benefits of moving early versus waiting for price reductions are not addressed in this study.
- Small-scale DG installations from renewable energies are predominantly rooftop solar PV. Previous studies show that small-scale wind generation carries significant technical challenges [81,82]. In response to this, the case study only considered rooftop solar PV as small-scale DG installations. However, the model is built technology-agnostic, and future work can apply alternative DG or a mix of technologies.

7. Conclusions

Renewable, small-scale DG installations, with their capacity to reduce technical losses, and zero-carbon emissions, play a paramount role in helping society on the path towards carbon neutrality. Electricity users with small-scale DG such as rooftop solar PV are less dependent on electricity from the central grid, which increases their energy resiliency, and reduces their vulnerability to the risk of blackouts and price fluctuations. This article confirms what was found in previous research [16], that existing energy policy from grids pioneering the rollout of DG resulted in inequitable distributions across households: less advantaged sections of society see reduced access to local clean generation. In a world where energy security is a leading concern in an unstable international political climate, it is expected that certain customers having reduced access to these technologies, can enhance existing inequities and widen socioeconomic gaps.

Accordingly, this article presents and validates a method to model interest to install small-scale DG for individual customers over time. Socioeconomic, demographic and technical information is used where all hierarchical limits of the grid are accounted for. This is leveraged to study three different policies for small-scale rooftop solar PV deployment: current policy, an alternative where the grid capabilities are split amongst all users, and a proposed path where these capabilities can be shared between customers. Results from the case study showcase the benefits of the last policy scenario: participation is significantly increased, the small-scale DG rollout is accelerated and it results in a more equitable distribution of benefits.

While significant research has been devoted to the necessity for infrastructure upgrades to accommodate additional small-scale DG, our results suggest that inequity can be tackled from an assignment policy point of view. We find that *sharing the grid* as a policy path is an interesting alternative to increase access and installed capacity, and accelerating the small-scale DG rollout. Note however that the benefits seen in this study are conservative: inequities would be further accentuated if it was possible to accurately model the ability to invest considering qualitative and case-specific variables as well.

If a customer has a MEC request accepted (even if it is small), it will not be limited to that small initial installation: further interest to install can be channelled into energy storage systems to enhance the accepted DG, potentially increasing the PV penetration beyond an initial installation. In contrast, if due to capital, technical or availability reasons a customer is rejected its first MEC request, subsequent investments are blocked and it will not be allowed to export any electricity into the grid. Any installation – including PV combined with energy storage

– is limited to exclusive self-consumption (i.e., the customer can only make use of its local energy production for its own needs, it cannot participate in local energy markets because of its inability to export). This would be equivalent an islanded DG installation, that falls out of scope of the study because it is not benefiting from grid access. As a consequence, increased participation from applying the proposed policy path may result in additional capacity extensions not quantified in this work.

In most cases the electricity grid is not technically or legally owned by customers, however it can be considered a shared resource. By coordinating access, this work shows that latecomers can better participate in the energy transition. If in parallel the transfer of resource that cannot be used due to technical, capital, or additional (e.g., building adequacy, planning permission, etc.) restrictions is allowed, we stimulate highly interested parties to unlock their investments while benefiting the restricted user. The prospect of sharing the grid, gives participants with such limitations an opportunity to benefit from their position in the grid. The authors envision a market for export capacities in which participants can trade, rent, or give their unused MEC to other neighbouring participants in exchange for monetary or in-kind compensation. Market structures can be designed to merge local energy trading systems and MEC trading environments to avoid market overheads, but this will be addressed in future work.

One of the most appealing characteristics of small-scale DG installations is that investments come from customers, and the resulting social benefits are perceived by all [105]. This means that the overarching goal of the energy transition is to get as much clean energy resources as fast as possible. *Sharing the grid* for DG assignment achieves the largest DG capacity of the studied policies faster, and it is presented as the preferred policy path. This comes with a costs trade off: more participation represents smaller, costlier systems (i.e., due to economies of scale, larger installations are cheaper per capacity unit). It is proposed for future work to define which parameters can be included in initiatives like the one offered in this article to assess social acceptance of this extra cost.

These extra costs from smaller installations may be offset through increased levels of self consumption. Greater levels of customer participation are associated with increased self-consumption rates and reductions of technical losses [43]. In these terms, a cheaper relatively-large-sized installation produces electricity that must be distributed among participants using the physical infrastructure; in contrast, costlier numerous smaller local installations that represent the same size produce electricity that will be (at least partially) used in site and represents a higher potential for decarbonisation.

Some works in the literature include social welfare as part of an operational process, maximising social welfare through economic variables or participant consensus (e.g., as in [106,107]). This work proposes in contrast the inclusion of another form of social welfare: making grids more equitable through MEC and MIC sharing. This research shows that it is possible to coordinate grid capacities to have a swift small-scale DG rollout that benefits all portions of society. This can be implemented at early stages in the planning process of future electricity grids, or it can be adjusted as an operational problem in which capacities are shared dynamically through different high-low consumption-generation moments. This work highlights for the first time the potential to transfer some benefit to users that have capacity limitations (e.g., due to infrastructure, financial or other reasons), which is a representative advancement in making the energy transition truly for all.

To close, this work contrasted the initial state of the case study's grid and policy-resulting small-scale DG rollouts with demographic variables, obtaining similar results to those from previous studies on grids highly saturated with small-scale DG. We prove that the limits of the electricity grid are not inherently biased, but it is the first-come first-served scheme of resource assignment paired with a systematic overestimation of the limits (i.e., *business as usual*) what explains their

inequities. Alternative policy that better represents the constraints of the grids and addresses accumulation that would block latecomers, can overcome this challenge. This work is especially useful for grids with an early state of DG penetration because policy can be introduced to prevent inequities. However, grids with a high degree of small-scale DG penetration can extrapolate these results to modify their policy, prevent further inequities, and to reduce those already in their grids. In any case, this work suggests that the energy policy-making process requires a greater focus on grid access equity.

CRediT authorship contribution statement

Juan J. Cuenca: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hannah E. Daly:** Writing – review & editing, Investigation, Conceptualization. **Barry P. Hayes:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Excluding the number of customers served by ESB Networks per distribution substation, data sets are publicly available [66,67,88–90,98]. Ready-to-run, filtered and organised data sets and scripts are available from the corresponding author on reasonable request.

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Glossary

ALO	Ant-lion optimisation
CEJST	Climate and economic justice screening tool
CRU	Commission for the regulation of utilities
DG	Distributed generation
DSC	Distribution static compensator
DVR	Dynamic voltage restore
ED	Electoral division
EHO	Elephant herding optimisation
GA-MCS	Genetic algorithm monte carlo simulation
GW	Giga-watt
JTF	Just transition fund
JTP	Just transition platform
kW	Kilo-watt
LOESS	Locally estimated scatterplot smoothing
LV	Low voltage
MEC	Maximum export capacity
MIC	Maximum import capacity
MV	Medium voltage
MVA	Mega-volt-ampere

MW Mega-watt
 PV Photovoltaic
 RAB Regulated asset base
 RMSE Root mean square error
 TJTP Territorial just transition plan

Parameters and variables

I_{year} Yearly income of a household.
 E_{year} Yearly spends of a household.
 $i^{\%}$ Annual adjustment for income an inflation.
 $\gamma^{\%}$ Fixed interest of households to install distributed generation.
 C_{year} Cost of distributed generation installations per kW in a year.
 $\lambda^{\%}$ Annual decrease in distributed generation installation prices.
 $\rho^{\%}$ Investment trigger for distributed generation installations.
 $I_{m,year}^{disp}$ Monthly disposable income of a household in a year.
 $\Xi_{m,year}$ Monthly economic savings of a household towards distributed generation installations (interest to install) in a year.

Appendix A. Parameters

In the case of Ireland, a grant differential for the size of the installation in steps of 1 kW is applied as an economic filter for DG installations [78]. Accordingly, the simulation was performed at a 1 kW granularity on rooftop solar PV [108]. The simulation is performed with a monthly resolution.

The price of DG installations varies widely across technology, time, and international markets, this is based on externalities, economies of scale and production ramping of equipment [109]. The installation costs for solar PV have plummeted in the last two decades and are expected to continue decreasing [69,70]. Table B.5 details the parameters used for the simulations in this work, together with a description and source.

Appendix B. Equity analysis

To obtain the results in Section 6.3 a statistic analysis was performed. First, the span of each demographic attribute was divided in equally distant portions, the customers that fell into each of these divisions were grouped. Each demographic variable was represented using 100 brackets between its maximum and minimum value, every customer falls into one of these brackets. We calculated the mean, standard deviation, standard error, 10th, 30th, 70th and 90th percentile MEC limit and PV installed to represent the bracket. Subsequently, using the number of households per bracket we weighted these values to plot the locally estimated scatterplot smoothing (LOESS) curves that represent the mean, 60% and 80% of the data for Fig. 7.

Linear regressions were performed, the R^2 values and the root mean square error (RMSE) of each data set were calculated [72,73]. We computed the correlation coefficients between each demographic attribute, grid limits, and installed PV resulting from each policy implementation.

All the data was used to evaluate the models instead of running a train-test split because we are interested in representing the entire population rather than predicting missing data points. For each model we used every available demographic variable (i.e., attributes) in customer profiles: (1) average income, (2) household expenditure, (3) population density, (4) language isolation, (5) four subsets for nationality, and (6) four subsets for household composition.

Table B.5
 Simulation parameters.

Symbol	Details	Value
$i^{\%}$	Yearly changes forecasted in incomes and inflation, based on the historic change in customer price index (CPI) for Ireland [68]	5%
$\gamma^{\%}$	Interest or ability to invest on DG, based on monthly energy bills expenses [66,67]	2%
$C_{year=0}$	Cost of PV installations in Ireland for year zero including value-added tax (VAT) [110]	€ 2500
$\alpha^{\%}$	Yearly reduction in PV prices forecasted for Ireland [69]	2%
$\Omega^{\%}$	Percentage of the installation costs that trigger an investment	50%

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