Integrating PV+Battery Residential Microgrids in Distribution Networks: How Is the Point of Common Coupling Agreed Upon?

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Abstract. The anticipated development of decentralized electricity generation is expected to strengthen the opportunities of prosumers in the residential areas of cities, in line with the predicted establishment of renewable energy generation and storage. Based on academic research and on successful case studies, the opportunity for residential prosumers to organize in microgrids emerges as a viable and promising solution. This paper focuses on microgrids that are planned to generate electricity with a PV unit and use a shared storage system, and that opt to have a connection with the main grid. However, the point of common coupling needs to be agreed first between the microgrid operator and the network operator, and this agreement is determined by several factors and conditions beyond the basic technical and regulatory requirements. A survey of academic literature on the determinant factors for such an agreement exposes the fact that current research either focuses on the integration of individual prosumers in the main grid, or regards the point of common coupling as a given component of microgrids. We argue that neither of the two approaches is helpful in the case of microgrids vs. main grid, seeing as the agreement is not self-evident under just any circumstances, nor can the microgrid be equated to a single, large prosumer. Therefore this short paper compiles a set of determinant factors for the microgrid integration, as they emerge from academic literature, with the aim to document further research needs and support the discussion on microgrid integration.

Keywords: Decentralization · Microgrids · Point of common coupling · Residential prosumers

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Nomenclature

DG	Distributed Generation
DNO	Distribution Network Operator
DSM	Demand Side Management
ESS	Electricity Storage System
EV	Electric Vehicle
HC	Hosting Capacity
LV	Low Voltage
MG	Microgrid
PCC	Point of Common Coupling
RES	Renewable Energy Sources
TSO	Transmission Service Operator

1 Introduction

Advantages of distributed generation (DG) are documented by both academic literature and successful case studies, and they range from decongestion of the main grid to improvements in reliability and power quality [45,62]. Solutions such as microgrids (MGs) can in fact include any energy sources, but they are found to be a promising vehicle for the integration of renewable energy sources (RES) [75], featuring in roadmaps for the development of energy network towards climate change mitigation [27], especially in cities [9,15].

In fact, the current EU projections and policies regard the retail electricity market and individual consumers as having a fundamental role in the energy transition, with a special attention to the ways in which consumers can become 'prosumers' with RES such as PV panels and electricity storage systems (ESS) [19]. ESS such as batteries complement photovoltaic electricity generation [24] by making the PV units controllable, supporting peak shaving and helping mitigate the so-called 'duck curve' at the level of residential prosumers. Pooling a shared ESS in MGs has been found to be especially beneficial in terms of resilience and power quality [4,39,49], and for economic viability [43].

The technological development along with the lower prices of ESS and PV panels [30] on the one hand, and the favourable social and political context on the other hand, outline a scenario for the future in which microgrids interconnecting residential prosumers with rooftop PV panels and batteries become widespread in European cities.

Problem Identification and Research Question. An urban residential MG matching the scenario outlined above would feature, apart from the PV unit and the ESS, a connection to the main grid, realized through one point of common coupling (PCC). The underlying assumption of this set-up is that the PCC is regarded as a given, whereas in reality it only exists if both sides of the PCC, the MG operator and the district network operator (DNO), reach an agreement. This oversight can be attributed to the straightforward nature and clear scope of the interconnection standard IEEE 1547 [29]: a comprehensive list of technical requirements that, if fulfilled, guarantee a functioning PCC. An additional legal aspect is addressed usually at the country- or state level.

We argue that after complying with all technical and regulatory requirements, there are further factors and conditions affecting the agreement between the DNO and the MG party.

However, a review of relevant literature reveals that the factors and conditions governing the PCC are not being addressed together as such, but instead separately and rather indirectly. The major research gap that we identify consists in the fact that the individual prosumers are being investigated in their relation with the DNO (DG as single households), while communities of prosumers (DG as integrated MGs) – less so. However communities of prosumers – such as, in our case, MGs – cannot be regarded as one single large prosumer, mainly due to their robust control capabilities, smoothened load curve and resilience [63], which can constitute a service offered to the DNO.

In this context, our work addresses the research gap by compiling an overview of the factors and conditions governing the PCC. The resulting paper seeks to provide clarity and facilitate further discussion on urban residential MGs.

2 Method

For this survey 42 academic papers have been reviewed, published between 2005 and 1 Jun 2019. The search and selection process has been carried out by first using a dedicated software (Publish or Perish) with the following keywords: "microgrid DNO", "point of common coupling", "distribution network microgrids", "microgrid integration". A twofold sorting of the results was carried out: the first, by number of citations; the second, by publication date. Review articles were preferred. The selection process was then augmented by following references from the resulting papers, whenever necessary.

The 42 papers consulted come from academic journals (37) and conference proceedings (5). The most academic journals from which the consulted articles originate are the following: Applied Energy (7), International Journal of Electric Power and Energy Systems (5), Renewable and Sustainable Energy Reviews (4), Energy Policy (4).

Players and Roles. The residential MG is a community (e.g. an apartment building, a street of houses, a real estate development) having one common PV unit or several PV units pooled together for common use. The ESS (e.g. Li-Ion battery) is, similarly, either a common purchase or several units pooled together for shared use. On the other side, the DNO is an intermediary between the transmission service operator (TSO) and the consumers, in charge of transforming the electricity to low voltage (LV) at substations, providing the connection between the substations and clients, balancing the power flow and charging the customers for consumption.

By seeking a connection to the main grid, the MG is in fact looking for a backup electricity source, a possibility to sell excess electricity, and support in frequency stabilization. In exchange, it offers peak shaving, resilience, and benefits to the power quality. Both parties would agree to connect if the costs are compensated by benefits.

Assumptions. We acknowledge that the challenges of coupling one single prosumer at a substation are lower than connecting and balancing several consumers. Therefore this research case assumes the perspective of connecting the nth MG, where $n + 1 \leq HC$, the maximum Hosting Capacity of the substation (see [53]). The distribution network is considered at LV and radial. It is assumed that the distribution of costs, obligations, benefits and roles within the MG is already settled, and that the remaining last step is the connection of the main grid with a PCC. In the interaction between the MG and the DNO, the DNO regards the MG as a single unit represented by a cooperative, an aggregator business, or similar.

3 Literature Review

There is a significant body of research regarding DG integration, identifying the shortcomings and solutions for improvement. While acknowledging that the current electricity networks are not prepared for the future system requirements [7], it is clear that DG cannot be regarded as a 'negative load' [42]. Engineering research addresses the negative effects of high penetration of PV such as voltage issues, power issues, frequency issues, unintentional islanding [31,35,53,66]. The intermittency of the PV source can be compensated by the ESS [8], which is why the PV+Battery combination is particularly attractive, both technically [12] and economically [40]. However, as mentioned before, current research is largely focused on the integration of single prosumers.

For this review we have focused on DG as integrated MGs and found that the realization of a PCC needs first to be feasible, and second to be attractive, both technically and economically. On the level of feasibility there are technical requirements, rules and obligations clearly laid out in national guidelines (e.g. the Small Generator Interconnection Agreement in the US, [57]) which are based on the IEEE 1547 interconnection standard and make the PCC contract possible under the conditions in each country.

In the following subsection we briefly address the requirements that make the PCC feasible (technical and regulatory criteria) and after that we elaborate on the further factors and their implications.

3.1 Factors Which Make the PCC Feasible

The main factors that ensure interconnection feasibility can be found directly in the pro-forma agreements developed under the supervision of the energy regulatory bodies (e.g. [57] in the US, [70] in Germany). They document the requirements governing the PCC agreement such as the interconnection procedures, obligations of insurance and cost allocation methodologies [51].

In order to fulfill said requirements, the main concern from the point of view of the DNO when integrating DG regards harmonics, for which there are technical standards in place (e.g. IEEE 519 [28]). The perturbations at the PCC are subject to extensive research in technical literature (see [14,16,74]).

From the point of view of the MG the two great challenges of MGs are control and protection [34,44,76], as well as the issues of power flow stabilization [47]. It is worth noting at this point that the technical requirements constitute the category of factors where research seems to be most advanced and with the most clear results.

3.2 Factors Which Make the PCC Attractive

Technical: While the technical requirements for the existence of a PCC are found to have a clear scope, the range of improvements suggested by academic research is broad. Among the main identified factors were found: optimal MG position and distance to the substation; sizing of the battery at the MG; the energy scheduling and management within the MG with existence of demand side management (DSM); the use of DC current by the MG; the existence of electric vehicles (EV).

One of the main features of MGs in relation to the DNO, as mentioned above, is to help enhance resilience. That is mainly achieved by the MG being able to quickly disconnect and go into island mode [25,35,68] and help restore power supply in case of extreme weather conditions [73].

However, the sizing and controllability of the battery emerges as the one factor that can markedly improve the technical performance of PV+Battery systems in terms of stability [5,10,11,37]. In fact, higher ESS capacities coupled with appropriate management strategy mitigate net load variance and avoid costs for the DNO [18].

The storage power optimal scheduling is a well-documented area, with a consistent body of research investigating various optimization methods [59]. In addition to that, the existence of demand side management (DSM) control capabilities avoids power losses and reduces peak demand [71].

In order to mitigate the risk of overvoltage when there is bidirectional power flow, the distance between the PV units and the distribution substation should be minimized [32,69,72]. In the planning of a PCC, another determinant factor has been found to be whether electric vehicles (EV) should be taken into account, as their batteries require significantly higher charging power [22,26]. If the MG operators decides to use DC current in the MG, the overall system efficiency is improved [13].

The DNO can, in turn, improve the technical attractivity of the main grid with voltage regulators and improved grid planning measures [6].

Non-technical: A wealth of research is being carried out regarding the energy management within the MG, closely mirroring the technical features of DSM and battery control capabilities. Both stochastic and robust optimization models are being examined [52,64]. In turn, the DNO also has the possibility to optimize the coordination of multiple MGs, thus making the integration of MGs more economically sound [2,46,61].

A further major aspect that ensures fair transactions at the PCC is the electricity pricing. By including RES in MGs, the prosumers will inevitably be subjected to local regulation aimed at supporting PV production and/ or self-consumption. From the most widespread pricing mechanisms, the net-metering has been shown to actively disincentivize the use of batteries [60], the feed-in tariff promotes exchange with the grid over self-consumption [36], whereas the time-of-use tariffs have been found to best support DSM [65] but strain the substations with peak demand [54]. However, it is worth noting that volumetric pricing schemes might be unsuitable for PV+Battery MGs, as is has been found that energy-based tariffs neglecting the impact of prosumers aggravates the regional distributional disparities [23]. The discussion on pricing is not settled yet at this point, due to the pricing policies designed to support residential PV production through an encouraged exchange with the grid. This puts the PV generation in conflict with the desirable integration of ESS in the system, as the ESS do not benefit from policies that would support energy saving.

However, the key aspect in reaching the agreement between the MG and the DNO seems to be a fair allocation of costs. As research points out, the representation of fairness appears different in the two respective views. It is shown for example that "with the current grid tariff schemes, operators of PV installation and storage can reduce their grid fees without reducing the costs they cause to the grid", especially under the net-metering scheme [33]. When it comes to benefits, it is possible that the generators capture more benefits than the DNOs and than the society [67]. Furthermore there is a danger that passive consumers (non-prosumers) would find themselves contributing to the cost recovery of the DNO or to the newly necessary network upgrades, without having incurred any costs to begin with [2,61]. Solutions proposed in order to even this out include charging for smart connections [3] or simple stand-by charges [1].

From the MG perspective, the benefits are still not allocated fairly, but the reason is that some externalities are not monetized – such as the flexibility provided by the resources in a MG [20]. A solution is proposed in form of contract deferral schemes [21,55] or simply the formalization of grid balancing services [39]. In fact, the flexibility feature can be further captured by allowing for peer-to-peer trading [41,78,79], and make the case for a new business entity that coordinates the behind-the-meter assets [50].

4 Summary and Discussion

Our literature survey has summarized the factors that constitute minimum requirements for the feasibility of a PCC, and revealed an additional number of factors that, while not strictly addressed by the PCC contract, can increase or decrease the attractiveness of a PCC between a MG and a DNO.

Figure 1 provides an overview of the factors and assigns them to the party which can do something about them. For example in the case of minimum requirements, technical aspects have to be agreed upon by both sides. However, among those technical factors, there are aspects of control and protection which are in the scope of the MG operator, whereas the DNO can (and is required to) address the concerns regarding harmonics and perturbations. In the lower half of 1, which summarizes those factors outside of the bare-minimum, the non-technical aspects can regard addressing energy management solutions from the point of view of the MG operator, whereas the DNO can improve the attractiveness of the PCC by improving their energy pricing system.

In a further step of our analysis we look at list of factors identified in Fig. 1 and trace them back to the academic literature from which we have drawn them, in light of the question 'Is it based on MG-specific literature? Or is the insight based on DG-literature?'. In this case we refer to literature about integrating individual prosumers as 'DG-literature'. The background of this question is that the factors identified from DG-literature have to be reassessed in the context of a MG (as shown in the introduction, a MG is different than a sum of individual prosumers).

Table 1 summarizes the factors found in our literature survey and further structures them based on the following criteria:

- Whether the factors are technical (Tech.) or non-technical (nTech.);
- Identifies the agent who can initiate the identified influence, between the MG operator (MG) and the distribution network operator (DNO);
- Whether the article(s) cited address the case of DG as individual prosumer (DG-lit) or indeed the integration of a microgrid as such (MG-lit)

Table 1. Summary of factors

Factor	Tech	non-Tech	Agent	DG-lit	MG-lit	References
Emergency response	✓		MG		✓	[25, 35, 68, 73]
MG siting and sizing	✓		MG		✓	[32, 69, 72]
ESS sizing	✓		MG	✓	✓	[5, 10, 11, 18, 37]
EV vehicles	✓		MG		✓	[22, 26]
Energy scheduling	✓		MG	✓		[38, 59, 77]
DSM capabilities	✓		MG	✓		[17, 71]
Use of DC in the MG	✓		MG		✓	[13]
Voltage regulators	✓		DNO	✓		[6, 48]
Grid planning	✓		DNO	✓		[6, 56]
Energy management in MG		✓	MG		✓	[52, 64]
Optimized MG coordination		✓	DNO		✓	[2, 46, 61]
Electricity pricing		✓	DNO	✓	✓	[23, 36, 54, 60, 65]
Smart/standby charges		✓	DNO	✓	✓	[1, 3]
Deferral schemes		✓	MG	✓		[21, 55]
Grid balancing services		✓	MG		✓	[20, 39]
Peer-to-peer trade		✓	MG		✓	[41, 78, 79]

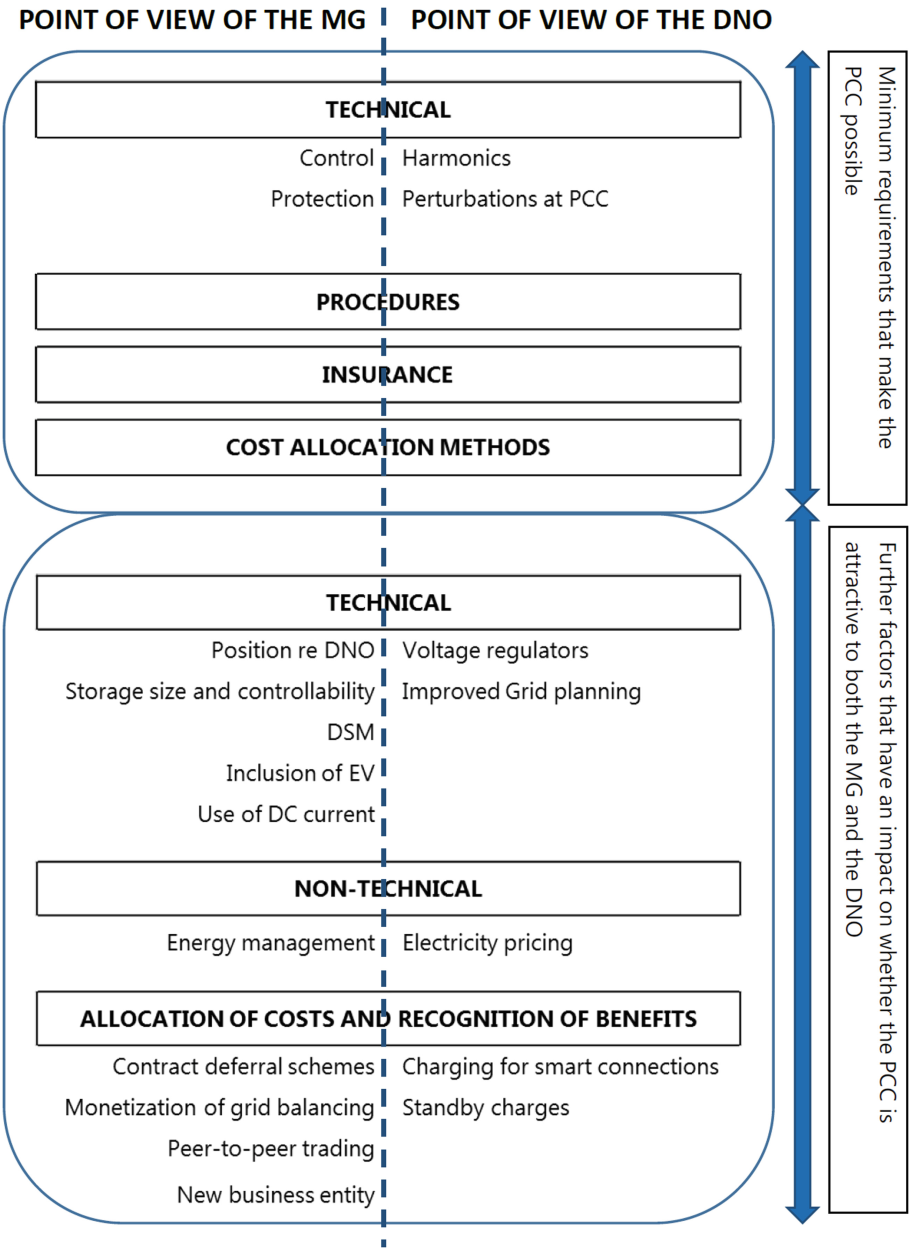

Fig. 1. Summary of factors identified in literature to impact feasibility and attractivity of the PCC, from both the point of view of the MG and of the DNO

For example in the case of "ESS sizing": it is a factor that has been found to have an impact on how advantageous (i.e. attractive) the MG project is, since the appropriate sizing of the battery brings advantages to both the MG (peak shaving, demand shifting, cost savings) and to the DNO (flexibility). However, it is a technical measure that has to be taken by the MG planner/operator – the "Agent", in this case is the MG. The five references [5,10,11,18,37] on which the identification of this factor is based are addressing both research of DG as individual consumers, and DG as integrated MGs.

On the other hand, the measure of incurring smart charges or stand-by charges is a non-technical factor (does not primarily depend on installing a new device or reprogramming a controller) that surely has to be accepted by the MG operator before agreeing upon a PCC. In this case the agent is the DNO, who imposes the charges (although possibilities of negotiation cannot be excluded, it is still the DNO who imposes and collects the charges). The two references on which we have based our finding are researching microgrid integration, what we have labeled as MG-literature.

A look at Table 1 points to a number of insights. First, the factors labeled as primarily technical mostly correspond to the agent MG, whereas the non-technical factors are mixed. We can explain this imbalance with the fact that the MG is smaller and more flexible, able to adopt new solutions in order to become more efficient and persuasive in favour of the PCC. Second, the fact that while the options MG operator are mostly towards improving the perspective of an agreement, the DNO can work in the opposite direction as well, by increasing charges or by providing electricity pricing that makes the MG function at a loss. This insight agrees with the mismatch identified in literature in how distributed energy projects are financially evaluated between the private sector and utilities, which suggests in turn that the DNO is in fact interested in maintaining the status-quo [58].

Third, we notice that some of the factors have been identified based on literature that is dedicated to individual prosumers, and not to DG as integrated MGs – which illustrates the research gap as it was mentioned in the introduction.

Finally, the table points to the limitation of our study: the fact that is does not provide an assessment as to whether the identified factors have a *positive* or a *negative* influence on the attractiveness of the PCC. This is due to several facts. First, the academic papers which argue in favour of novel solutions such as the peer-to-peer trade suggest that by adopting that solution the strengths of the MG will be improved, or the weaknesses will be alleviated, thus making the interconnection more appealing to the DNO and the PCC possible. However, for the sake of balance, the point of view of the DNO should be included, but to the best of our knowledge so far the research from the point of view of the utilities does not mirror closely the findings of novel solutions. Second, the implementation of a novel measure – e.g. installation of voltage regulators by the DNO at relevant substations to sustain reliable PCCs – can be considered to have a positive impact on the perspective of the interconnection. However, most of the studies do not provide a cost-benefit analysis of the proposed solutions, therefore it is not clear whether the voltage regulators, while having a positive impact on MG integration, might in fact be too expensive and hence not a realistic proposal.

The factors listed in Table 1 have been labelled as 'technical' or 'non-technical', but it is understood that a) they can be translated into economic benefits or savings (e.g. the appropriate ESS sizing at the MG can save grid upgrading costs at the DNO), and b) they can interact (e.g. offering grid balancing services influences the ESS sizing, and in part the MG siting). A closer examination and mapping of the interactions is an avenue for further research within the current discussion on burden sharing between MGs and DNOs.

5 Conclusion

The integration of microgrids in distribution networks takes place by connecting the MG to the main grid via one point of common coupling. We have found that in academic literature the PCC is either regarded as a given, or equated to a connection point between the main grid and an individual prosumer. While the MG cannot be equated to a large prosumer, we argued that the PCC cannot be a formality either. In this paper we have briefly reviewed the factors which amount to basic requirements that make the PCC possible: compliance with IEEE standards and protection measures important for the MG. Having established that, we surveyed the academic literature and compiled a list of factors which are not obligatory requirements for the existence of the PCC, but they can determine how appealing the interconnection is for both parties.

The resulting list of factors proposes a starting point for further additions and discussions, and offers right from the beginning a clear illustration of the imbalance between the agency power of the MG operator and the one of the DNO. It also suggests that the main strength of MGs consists in its small size and flexibility, making it capable to quickly include improvements in technical equipment and operation.

At this stage of our research we can conclude that an agreement on a PCC between the MG and the DNO can be influenced by the MG mainly through technical measures, whereas the DNO tends to have stronger non-technical instruments at its disposal.

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