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Overlooked factors in transparent hosting capacity calculations

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Abstract

The EU Electricity Market Design reform requires transmission and distribution system operators to provide transparent information on the available grid capacity for new connections, commonly referred to as hosting capacity maps. These maps aim to inform the decision-making of new grid users, as well as renewable energy installers and flexibility service providers, thereby (safely and reliably) maximising grid utilisation and accelerating the energy transition. A key assumption influencing the available grid capacity is the definition of hosting capacity itself, of which currently no consensus seems to exist, both in academia and in practice. This paper examines five publicly available hosting capacity maps alongside relevant hosting capacity literature and identifies seven factors where different assumptions are applied to hosting capacity quantification. Furthermore, we qualitatively assess the potential impact of overlooking these factors in hosting capacity calculations (i.e., the tendency to over- or underestimate available grid capacity). In this way, we aim to contribute to the discussions on the harmonised definition and pan-European overview of grid hosting capacity, which are currently being developed under the EU Action Plan for Grids.

Keywords

hosting capacity maps, hosting capacity definition, qualitative assessment

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Introduction

European grid users invest in renewable generation or electrify their demand at a faster pace than network investment decisions, and the capacity of distribution networks (DNs) is rapidly exhausting [1,2]. Critical congestion is already observed in EU Member States like the Netherlands, leading to increasing queues and waiting times for new connection requests [3]. To tackle such challenges, the Clean Energy Package included provisions to support the development of flexibility procurement and DN plans [4]. More recently, the Electricity Market Design (EMD) reform introduced the concepts of flexible connection agreements and hosting capacity (HC) maps to maximise the use of the existing distribution grid and improve transparency on the remaining capacity to new users [5]. For example, the maps may incentivise renewable energy installers and flexibility service providers to target areas with higher opportunities, potentially reducing connection request queues.

The EU DSO Entity reports that, currently, HC maps or similar tools are available in more than 20 Member States [3]. However, as these maps typically started from individual initiatives by system operators and the description of the EMD provisions on HC maps remains high level, different practices can be observed. Based on a survey with participants from 16 European countries, Eurelectric [6] gives a first overview of publicly available HC maps and identifies some best practices to provide information to new grid users. While informative, [6] does not discuss technical assumptions and influencing factors for HC calculations. Ember & RAP [7] develop recommendations and list ideal features of HC maps based on 15 practices by European Transmission System Operators (TSOs) and Distribution System Operators (DSOs). Transparency in the assumptions is high on the list and is considered a <<no-regret tool>> [7].

This paper complements [6,7] by discussing a number of factors that are neglected in these (relatively non-technical) comparison studies, but that highly affect the transparency and interpretability of HC maps.

One such factor is the mathematical definition of the remaining available grid capacity. Currently, there is no consensus (neither in academia nor in practice) on the HC definition to use, and on how existing grid users and flexibility services can be included in the calculations [8]. While Action 6 of the EU Action Plan for Grids might align some assumptions upon its delivery in mid-2025, it is still unclear to which extent and in which direction the harmonised definition for available grid HC will be developed [9,10]. The fact that the Grid Action Plan also requires a pan-European overview of remaining grid capacity to be established by mid-2025 calls for a better understanding of the methodology behind HC maps so that a refined interpretation of this European overview and an appropriate comparison between Member States can be made.

Benzerga et al. [8] provide a general framework to evaluate and compare different HC definitions and papers from the literature. However, [8] does not include a discussion on how presently available TSO and DSO HC maps fit this framework.

Our paper contributes to the discussion on best practices and transparency in HC calculations by:

- Determining differences in the methodology behind five presently available HC maps in Belgium, France, Ireland, the Netherlands and Spain;
- Identifying technical assumptions that might typically be neglected in scientific literature;
- Qualitatively discussing the possible impact caused by these overlooked factors on the HC calculations.

The results are synthesised into seven key factors that should be considered when comparing and interpreting HC maps:

1. Modelling shortcuts and power flow simplifications
2. Data quality issues and system reconfigurations
3. Uncertainties in grid parameters and end-user profiles
4. Temporal aspect of operational grid limit violations
5. Future infrastructure expansions and grid connections
6. Flexibility quantification by grid operators and users
7. Bottlenecks at “parent” substations

Finally, note that most HC maps include a disclaimer that the reported value serves as indicative information and new connection requests will always be accompanied by a specific grid study. Thus, the recommendations from this paper provide guidance when comparing and interpreting grid hosting capacity maps but do not necessarily cover the final grid connection decision.

2. Choice of hosting capacity maps

Based on the examples provided by [6, 7, 9] as of December 2024, 27 websites for HC maps were found. Four criteria have been applied to reduce them to a selection of five maps:

- As the paper focuses on the distribution level, we exclude maps that are solely TSO-oriented.
- As most maps provide information for new generators, we exclude HC maps that are solely demand-oriented.
- As part of our analysis is based on the information described in user guides or disclaimers on the HC maps websites, we did not select any maps where no further details on the methodology or interpretation of the available hosting capacity are given.[1]
- Finally, we select maps from different Member States. Therefore, if multiple maps are available in a country, we choose the map with the most transparent and extensive information on the adopted methodology.

Table 1 features an overview of the chosen HC maps. We observe that all capacity values in the maps ultimately refer to those of one or multiple transformers. The values are typically provided for new medium voltage (MV) connections, with the exception of the Irish case where also information on low voltage (LV) connections is shown. Furthermore, we find that the DSO-only maps, such as Belgium (BE), Ireland (IE) and Spain (ES), provide information about their region of competence. In contracts, the examined HC maps where TSOs and DSOs cooperate, like The Netherlands (NL) and France (FR), are for the whole country. Finally, the HC values for the cases of Belgium and Ireland are defined in terms of apparent power (MVA), whereas all other ones are in active power terms (MW), which appears a more practical quantity to communicate to the user, but which is in dissonance with transformer ratings being defined in apparent power terms.

1 According to Art. 2(10) of Directive (EU) 2024/1771, DSOs shall include information on the criteria for the calculation of available grid capacity in HC maps, but we found that this is currently not always the case in practice.

Table 1: Overview of the examined hosting capacity maps

Country	Level	Connection type	Unit
BE[2]	DSO	Generation+Demand	MVA
FR[3]	DSO+TSO	Generation	MW
IE[4]	DSO	Generation+Demand	MVA
NL[5]	DSO+TSO	Generation+Demand	MW
ES[6]	DSO	Generation	MW

3. Factors affecting HC calculations

Quoting [8], HC can be defined as:

> << (…) *the amount of new resources that can be hosted by a network before facing any issues, i.e., compromising its operational limits or violating safety constraints.* >>

These limits and constraints can be, for example, the N-1 constraint, as explicitly stated on the French and Belgian HC maps, as well as the power quality criteria contained in European grid codes, such as the national implementations of standard EN50160. While ref. [8] provides several examples of how HC can be expressed (i.e., number of new customers, maximum capacity of new installation,...), the analysed maps all indicate the remaining available HC as MW or MVAr per cabin/substation. Hereafter, we discuss the seven factors listed in Section 1 and their qualitative impact on the remaining available grid capacity.

3.1. Modelling shortcuts and power flow simplifications

Network modelling shortcuts are (often deliberate) simplifications of the mathematical representation of DNs that reduce the modelling complexity, and, usually, computational time. A well-known example is the reduction of LV DN to three-phase three-wire equivalent models (instead of four-wire), through *Kron's reduction. A similar example is the use of a (single-phase) balanced model, which is considered acceptable for transmission but not for DNs. As they approximate power flow calculations, these shortcuts may result in inaccurate HC calculations. We refer the reader to [11,12] for an extended discussion on how modelling shortcuts impact power flow solutions, noting that HC maps typically do not report enough calculation details to assess whether any shortcut has been used.*

Similarly to modelling complexity, which leads to the use of shortcuts, the non-convex nature of power flow equations often drives operators and modellers to use mathematical approximations/relaxations of the network's physical behaviour. These simplifications present favourable features (scalability and convergence guarantees, notably) towards the implementation of software tools for power system analysis. Like modelling shortcuts, power flow simplifications are common practice, and may affect the HC accuracy. Their use is typically not mentioned in the description of HC maps, which seem to lack details in this sense, but their impact is largely discussed in the literature [13,14]. Bespoke formulations embed "conservativism", i.e., consistently under-/overestimate quantities of interest (e.g., overestimating voltage magnitudes when addressing overvoltage issues) [14], which would result in underestimating the available HC. However, this does not hold for all simplifications in the literature/practice, which might result in overly optimistic HC estimates. In general, each formulation would require a dedicated analysis.

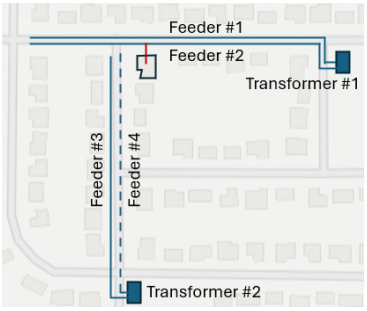
2 https://opendata.fluvius.be/pages/map_perceel/.
3 https://www.services-rte.com/en/learn-more-about-our-services/consult-the-reception-capacity-of-the-grid-capareseau.html.
4 https://www.esbnetworks.ie/new-connections/generator-connections-group/availability-capacity-map.
5 https://capaciteitskaart.netbeheernederland.nl/.
6 https://www.i-de.es/conexion-red-electrica/produccion-energia/mapa-capacidad-acceso.

3.2. Data quality issues and system reconfigurations

Industry and academia are increasingly aware of the differences between real networks and their digital representations/data, like those in system operator databases. Such differences are mainly due to legacy reasons: details on cable types/impedances, as well as connectivity (e.g., network topology) have not always been digitally recorded. Ref. [15] provides an exhaustive overview of common data quality issues in operator datasets. Reconstructing improved DN models may be possible thanks to, a.o., geographic information systems (GIS) and digital telemetry, but the process may remain error-prone. An illustration is given in Fig. 1, where the GIS-based connectivity reconstruction wrongly assigns the highlighted house to the solid-line feeder, as this is the closest to the building, and thus the most logical electric connection. However, due to incremental neighbourhood development, that feeder did not exist at the time the house was built, and the latter is actually connected to the dashed line. When grid users are assigned to the wrong feeder/substation, the HC calculations can be incorrect. The available HC maps do not discuss how this and other potential data quality issues are addressed. We observe that both over- or underestimations of HC may result from different error types, and there is little to no literature on how to account for uncertain parameters in HC calculations, e.g., with probabilistic methods.

Additionally, DNs are not static, and reconfigurations are among common maintenance and operations actions that periodically cause changes in network topologies. Thus, if these reconfigurations are not recorded, differences between DNs and their digital models might exist. This was also recognised in the Belgian map, which explicitly states that to effectively deliver the available capacity, the configuration of transformer stations might need to be adjusted.

Fig. 1: Illustration of a connectivity error, where a building is assigned (red line) to the wrong feeder and transformer



3.3. Uncertainties in grid parameters and end-user profiles

Different deterministic and probabilistic HC definitions have been proposed in the literature and may yield significantly different estimates [8,16]. The examined HC maps are not necessarily specific about their probabilistic assumptions (e.g., whether/how uncertain network and end-user parameters are accounted for). However, some maps do provide insights with respect to which scenarios of customers' grid usage are accounted for. The Dutch map, for example, assumes that the end-users' contribution to the occupied grid capacity is equal to the contracted capacity in their connection agreement. Depending on national practices of grid connection agreements, the actual capacity utilised by end-users might be lower than the contracted capacity. As a result, this assumption might in some cases lead to more conservative HC estimations.

Other HC maps, like the Belgian and Irish cases, seem to define the user's contributions based on measured or calculated injection and consumption peaks. Typically, these peaks are adjusted with projections of future demand and production growth, which are also uncertain and might affect the HC calculation. Numerous research addresses the integration of uncertainties on demand and generation profiles, e.g. [8, 16]. While this may depend on deliberate design choices, [16] observes that incorporating probabilistic notions in HC definitions, e.g., through chance-constrained optimisation, tendentially results in less conservative HC estimations, with the relative societal benefits.

3.4. Temporal aspect of operational grid limit violations

Congestion and voltage violations may have negligible impact on the network if they only occur for a limited time. This is reflected in power quality standards, like EN50160, which allows the excess of some nominal operating conditions for a certain amount of time, e.g., voltage magnitude variations above 10% can occur for up to 5% of the week based on 10-minute rms values [17]. We note that this temporal aspect is often neglected in literature (possibly to be on the safe side) and HC cut-off values are typically calculated after constraints are violated at single time instance. This approach tendentially results in more conservative estimates of available HC, and might be adopted to reduce computational time, or to simplify the mathematical modelling of an otherwise multi-period problem. The examined HC maps websites do not provide sufficient details on how this time dimension is included in their calculations.

3.5. Future infrastructure expansions and grid connections

System operators often include only the existing grid infrastructure in their HC calculations. However, this might lead to maps that are more rapidly outdated and underestimate the actual HC that might be available in the short-term future. An exception is the Spanish map, where the HC analysis considers the infrastructure approved in their investment plan and to be commissioned in the same year. Furthermore, grid investments that are planned for the coming years might be communicated through HC maps, such as the Netherlands. The inclusion of future infrastructure expansions is usually neglected in the scientific literature as well.

The opposite effect (HC overestimation) might occur when planned grid connection projects that use HC are not considered. The Belgian map, for example, mentions that reserved projects are not considered in the HC calculation. As a result, the map might indicate that capacity is still available for new connections, while this has in fact been granted to accepted projects that have yet to be realised. On the contrary, the Spanish map considers new generators that are not yet connected but have an access and connection permit as occupied generation capacity. Finally, in the maps of Ireland and France, a part of the total grid capacity is reserved for future grid connections in the context of grid connection queue management. In Ireland, new generator projects are evaluated in batches under the Enduring Connection Policy. As a result, the available grid capacity may differ depending on grid users accepting or withdrawing their connection offers during each batch of studies. In France, part of the total grid capacity can be reserved for renewable energy projects under the regional S3RenR schemes. This reserved grid capacity is thus no longer available for other new connections, as indicated in the map.

3.6. Flexibility quantification by grid operators and users

More grid capacity than initially indicated in HC maps might become available when considering flexibility provided by new and existing grid users and embedded in grid operations, e.g., in the form of time-varying power injection limits like dynamic operating envelopes [18]. On the HC map of Ireland, the available grid capacity for both firm and non-firm connections of new generators is given. Another example is the Dutch HC map, which indicates areas where congestion management might make additional grid capacity available with a separate colour. Other flexibility instruments could also be considered, such as market-based flexibility or technical flexibility of system operators. However, as only little information was available on the examined HC map websites, it is currently not possible to rigorously assess how flexibility is included in HC calculations.

3.7. Bottlenecks at "parent" substations

Regarding the consideration of bottlenecks at "parent" substations, the practice appears to be ahead of the scientific literature. While the available grid capacity of some maps, like Spain, refers exclusively to the distribution grid, several maps do include a reduction of the distribution network's HC if the upstream transmission network has limited or no capacity left. In the case of the Netherlands, where system operators collaborate to develop the HC map, different layers exist to show the available capacity at distribution level, transmission level and the combination of both. Another example is the case of Belgium, where the HC map is DSO-oriented but strives to consider the capacity available in upstream networks as much as possible. On the contrary, scientific literature on HC for DNs usually does not include constraints due to bottlenecks at the TSO level, which may lead to overestimations of HC.

4. Conclusion

Capacity maps are recognised as an important tool to enhance transparency on the available hosting capacity in transmission and distribution networks, supporting investment decisions for new connections. While these maps are becoming widespread across EU Member States, the underlying assumptions used to calculate the given capacity values are often unclear, and several factors with non-negligible impact on the transparency of these maps are overlooked.

Table 2: Overview of the factors affecting hosting capacity (HC), including their qualitative impact and discussion in HC maps or relevant references. Abbreviations: Belgium (BE), Ireland (IE), France (FR), the Netherlands (NL), and Spain (ES).

Overlooked factor	Effect on HC (over- or underestimation)	Examples of HC maps or relevant references
Modelling shortcuts and power flow simplifications	Both, but some simplifications like [14] embed underestimation	[11], [12], [13], [14]
Data quality issues and system reconfigurations	Both, depending on the error type	BE, [15]
Uncertainties in grid parameters and end-user profiles	Both, but likely underestimation	BE, IE, NL, [8], [16]
Temporal aspect of operational grid limit violations	Underestimation if neglected	[17]
Future infrastructure expansions and grid connections	Both, depending on realisation of projects	BE, IE, ES, FR
Flexibility quantification by grid operators and users	Both, but underestimation if omitted	IE, NL, [18]
Bottlenecks at “parent” substation	Overestimation if not included	BE, ES, NL

Based on the comparison of five presently available hosting capacity maps and a selection of academic literature, this paper highlights seven factors that might influence the outcome of hosting capacity calculations but are typically overlooked in current discussions. Table 2 presents an overview of these factors, including relevant references and an indication of whether they tend to under- or overestimate the available hosting capacity. Recognising the different practices and their possible impact is crucial, as they might lead to imperfect signals for end-users or misinterpretations when comparing available grid capacity in different countries, thereby undermining the primary purpose of these maps.

Finally, we identified two policy implications. First, we observe that, at the time of writing, publicly available maps do not always provide comprehensive details on the criteria used to calculate the remaining hosting capacity. Providing more information in this regard could significantly improve the transparency of hosting capacity maps and support the implementation of the EU Electricity Market Design provisions. Second, the factors identified in this paper could support the discussions on the harmonised definition and pan-European overview of available grid hosting capacity, which are being developed under the EU Action Plan for Grids.

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