ELECTRIC POWER RESEARCH INSTITUTE

Impact Factors and Recommendations on How to Incorporate Them When Calculating Hosting Capacity

Technical Brief — *Integration of Distributed Energy Resources Program*

EXECUTIVE SUMMARY

Throughout the industry there has been a great deal of attention on the methods used to calculate hosting capacity and the applications of those hosting capacity results. However, an important piece that is often overlooked are the factors that have greatest influence on the results – the actual inputs and associated assumptions that go into the methods that calculate hosting capacity.

This report explains the impacts of those inputs and provides recommendations on how to incorporate them when calculating hosting capacity as to not over or underestimate the distribution systems ability to accommodate distributed energy resources (DER). Hosting capacity is not a single value, but rather a range in values that is defined by those original inputs. Depending on the application of hosting capacity results, the inputs and associated results might change. This information is important to fully grasp the complexities of hosting capacity studies. Knowledge of these impact factors can also help further define hosting capacity, and probabilistic hosting capacity might evolve to garner light into the full variance of system conditions and how often they occur.

Specific takeaways from this report include:

1. **Hosting capacity results are driven by the impact factors considered.** The input data assumptions and factors considered are the main driver of the results produced by a hosting capacity analysis. Because it is impractical to consider the full range of all impact factors, careful consideration should be given to evaluating the appropriate variance of those impact factors. This is key to improving result accuracy. Understanding what is considered and its implications is necessary to know how to apply results and communicate with the industry to set expectations.
2. **There are important impact factors to consider regardless of application.** To accurately capture the boundary conditions that define the range of hosting capacity values, there are important impact factors that need to be considered. While other impact factors may inform results, they are not the main drivers. Recommendations for analysis include:
   - Focus on a few carefully chosen load, DER, regulation, and control scenarios rather than time-series analysis
   - Analyze the maximum and minimum load conditions that exist when there is a potential for the DER to be at or near full output
   - If voltage regulation is present, shift to the maximum and minimum cap/tap positions within the regulated bandwidth
   - Connected DER should be included after the baseline powerflow analysis with control equipment locked to capture full impact on voltage metrics
   - Output of connected DER should be adjusted based on type of resource considered in the hosting capacity analysis
   - Control of connected resources should be considered by analyzing both when control is available and when it is not available
   - The impact of source impedance should be included
   - Alternative grid configurations (e.g., load transfers) should be considered when applicable
   - DER at specific locations on a feeder in addition to DER at multiple locations should be considered
   - Analysis should be conducted for each specific DER type – output, timing, grid interface
3. **Variance in impact factors should be driven by application of results.** It is important to consider impact factors when determining hosting capacity for applications that inform the public, assist interconnection screening, and enable planning with DER, however, the full variance among those impact factors is not always necessary. In the case of some applications, applying the full variance is important to determine the upper and lower hosting capacity boundary conditions, while for other applications, applying only a partial variance among those factors to focus on the lower hosting capacity boundary condition may be needed.
4. **Hosting capacity methods utilize different impact factors in different ways.** Hosting capacity requires a complex analytical assessment. The methods utilized to calculate hosting capacity are important and each have pros and cons that must be understood. Because methods vary and are evolving, ongoing comparison and validation is important to understand what impact factors are considered and how they may impact results.
5. **Impact factors and methods will change as the scenarios become more complex.** Further innovations in hosting capacity analytics will be critical as the distribution system becomes even more complex. Grid modernization initiatives, using DER as non-wires solutions, transactive energy, controlled sources, will all increase the complexity of a hosting capacity analysis.

INTRODUCTION

Hosting capacity, like all model-based calculations, is an approximation. From detailed studies it has been shown that the capacity of the grid to accommodate distributed energy resources (DER) is highly dependent upon a number of factors that are difficult, and in some cases near impossible, to consider in entirety. This is particularly the case with distribution grid-edge calculations which are affected by present and future conditions difficult to capture.

The many factors that affect hosting capacity have varying degrees of impact, sometimes opposing and other times complimenting each other. As such, effective use requires thoughtful consideration of the input assumptions and associated hosting capacity impact factors. Proper consideration of the assumptions and factors yields useful outcomes for various utility and stakeholder applications. This report expands upon this topic and provides better context into how hosting capacity results can vary and why.

Critical Impact Factors	
Grid	Configuration
	Source Impedance
	Voltage Load
	Connected Load
	Connected DER
	Control of Resources
DER	Location
	Technology
Misc.	Metrics
	Algorithm

Background

The industry is increasingly faced with making decisions on how to evaluate the growing penetration of DER. New sets of challenges for planning and operating the grid, especially on the distribution systems that serve these resources, has arisen. With these challenges in mind, utilities across the world are beginning to look at new analytical methods to help assess and integrate DER into the distribution system. A foundational element of such assessments is evaluating the ability of the distribution grid to "host" DER – aka hosting capacity. With hosting capacity methods in hand, utilities are looking to utilize results across a range of applications including to inform the public, assist in interconnection screening, and enable planning with DER.

The amount of DER a feeder can host depends on a wide range of factors, some of which are well known (DER location, DER type, feeder configuration, etc.). However, there are a wide range of additional factors that significantly impact hosting capacity – mainly the inputs and assumptions used for DER and grid models in the analysis.

Hosting capacity is defined as the amount of DER that can be accommodated without adversely impacting power quality or reliability under existing control configurations and without requiring infrastructure upgrades.

Given its applications, hosting capacity analyses should be considered just as all grid planning and interconnection analyses are performed today – by designing and studying the realistic, worst-case conditions to ensure customers do not experience adverse impacts to reliability and grid services. As such, hosting capacity should capture a realistic range of values, looking at worst-case conditions to understand the potential lower limits of the distribution system but also the best-case conditions to understand the potential upper limits. Figure 1 illustrates the potential range on hosting capacity when considering only three impact factors. These realistic "boundary conditions" should drive decision making.

This leaves the engineer asking the question "What impact factors and what variance among those factors should be analyzed to determine a realistic boundary for hosting capacity?". Eventually, the industry will evolve such that probabilistic techniques[1] can be used to better quantify the likelihood and evaluate the risk of a range of conditions. However, until these methods are available, boundary conditions must be determined without striding too far into a detailed analysis that becomes unmanageable to solve across an entire system. With this in mind, the following sections discuss the important impact factors including the metrics they influence and recommendations for considering them within a hosting capacity assessment.

HOSTING CAPACITY IMPACT FACTORS

The challenge of determining hosting capacity is that it is a multi-dimensional problem driven by the specific characteristics of the DER as well as the grid itself. Therefore, the solution space is vast making hosting capacity analysis an art that must be well-crafted. To illustrate just how vast the solution space can be, Table 1 provides an example for calculating hosting capacity across an entire system considering a large set of impact factor variables. This is contrasted on the same system with a moderate and limited set of impact factor variables. The large set is not inclusive of all impact factor variables. Similarly, the moderate set is

1 Considerable work and research is needed to evolve the data requirements, methods for assessment, and tools to evaluate probabilistic (risk-based) methods for this to be realized.

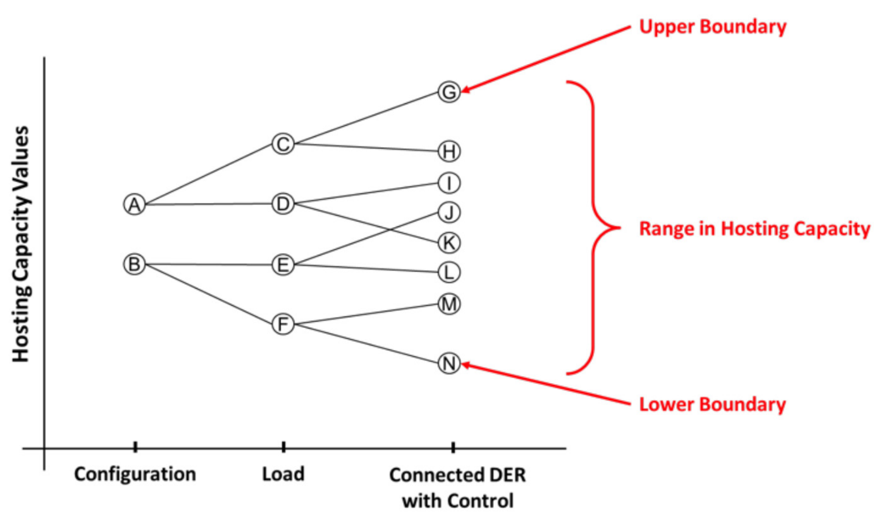

Figure 1 – Illustration of hosting capacity range when considering three impact factors

not a recommended reduced set of those variables, but rather provides an example where less variables are considered. The limited set also does not provide a recommended set of variables, but rather shows that the range of some variables considered can increase while others decrease with the overall goal to improve accuracy and decrease simulation time.

What is evident is that the time required to perform the analysis is greatly impacted by the set of variables included. In the case of the large set of impact factor variables, there is a lot of unnecessary redundancy. The art of hosting capacity is in eliminating redundancy by knowing the primary impact factors and variables to consider, thus reducing the simulation space without sacrificing results. As is shown in the Table, this can be done by reducing the number of load levels or considering variable-size penetration increments such that fewer DER levels are analyzed. In the end, solution time may be reduced, but the question remains, at what cost to accuracy. To remove the unnecessary variables requires fully understanding the impact/error that may be induced in the results of the simulation and how it would impact its application.

The remainder of this report discusses each of the potential impact factors that have been found to alter the results of a hosting capacity analysis. These impact factors are chosen based on how they relate to accuracy of hosting capacity results.

Feeder Metrics

Feeder metrics are the issues for which hosting capacity is ultimately defined – voltage, thermal, protection, and reliability. Each of the metrics also has a set of components as defined in Table 2. These metrics characterize the feeder response due to the different grid and DER impact factors. However, not all feeder metrics are affected by each of the grid and DER impact factors. Depending on what feeder metrics need to be considered, the range in applied impact factors can change. Also, the table is not all inclusive, as DER can impact harmonics, flicker, and other power system phenomenon that require detailed studies to properly address rather than a hosting capacity study.

When analyzing each metric independently in the hosting capacity assessment, the analysis can provide visibility into each metrics hosting capacity. Alternatively, each of the metrics can be examined simultaneously. This approach can still provide hosting capacity for each individual metric, however, a brute force approach must be taken to examine each metric at predefined simulation steps. Most important in applying the results from a hosting capacity study is to have access to the hosting capacity of each individual metric.

Table 3 identifies how these feeder metrics are mapped to the impact factors considered in the analysis to determine hosting capacity boundary conditions. What follows is a summary of each impact factor, the metrics that are impacted, how that will influence hosting capacity results, and recommendations for consideration in the analysis.

2 Timing of 1 milli-second per simulation assumed for illustration purposes only. Some tools/methods can take more or less time.

3 *Impact Factors, Methods, and Considerations for Calculating and Applying Hosting Capacity.* EPRI, Palo Alto, CA: 2018. 3002011009.

Table 1 – Example of Impact Factors and Total Analysis Time for System-wide Hosting Capacity[2]

Sample Set of Impact Factors	Large Set of Variables	Moderate Set of Variables	Limited Set of Variables
Feeders in system	500	500	500
Possible grid configurations	3	1	3
Possible load conditions	8760	576	2
Possible future DER locations per feeder	500	100	500
Possible future DER penetration levels to consider per location	100	100	10
Total simulations	~657,000,000,000	~2,880,000,000	15,000,000
Total analysis time at 1ms/simulation	20.8 years	33.3 days	4.17 hours

Table 2 – Feeder Metrics[3]

Voltage	Thermal	Protection Coordination	Reliability
Overvoltage	Power flow ratings	Nuisance operation	Islanding
Undervoltage	Reverse power flow	Misoperation	Operational flexibility
Regulator Voltage deviation			
Voltage deviation			

Table 3 – Feeder Metrics Mapped to Impact Factors

		Feeder Metrics								
	Impact Factors	Overvoltage	Undervoltage	Regulator Voltage Deviation	Voltage Deviation	Thermal Ratings	Reverse Power Flow	Protection Coordination	Unintentional Islanding	Operational Flexibility
Grid Factors	Configuration	X	X	X	X	X	X	X	X	X
	Source Impedance	X	X	X	X			X		X
	Voltage Regulation	X	X	X						X
	Connected Load	X	X	X	X	X	X	X	X	X
	Connected DER	X	X	X	X	X	X	X	X	X
	Control – Autonomous	X	X	X	X	X	X		X	X
	Control – Managed	X	X	X	X	X	X		X	X
	Time	X	X	X	X	X	X		X	X
DER Factors	Location – Site Specific	X	X	X	X	X	X	X	X	Xx
	Location – Distributed	X	X	X	X	X	X	X	X	X
	Technology – Output	X	X	X	X					X
	Technology – Timing	X	X	X	X	X	X		X	X
	Technology – Interface	X	X	X	X			X	X	X
	Portfolio	X	X	X	X	X	X	X	X	X

Grid-based Impact Factors

Grid-based impact factors describe the current state of the system and are a main driver of the hosting capacity of a feeder. The most significant impact on hosting capacity is seen when the feeder voltage and/or impedance is impacted. For the grid impact factors discussed, almost all influence the feeder voltage while many influence impedance. This is reflected in the factors of importance and recommendations for their consideration.

Configuration

A primary requirement for a hosting capacity assessment is the grid configuration and therefore the feeder model itself. Each feeder is unique and has a unique hosting capacity. Because of this, methods to extrapolate hosting capacity from a group of representative feeders have been shown to be insufficient.[4]

In addition to the base feeder model in a normal configuration, alternative grid configurations also exist. While most distribution systems are radial in nature, they typically aren't static in configuration. This ability to reconfigure the distribution system is known as "Operational Flexibility," where the operator has the "flexibility" to open/close switches throughout the system to optimize the delivery of electric service. This is possible because the system has been analyzed for these different configurations. The primary example is seasonal switching to maintain reliable power quality during routine maintenance. As the grid is further modernized with distribution automation, the grid will become more and more dynamic in configuration.

What is important to consider in a hosting capacity analysis are the conditions in which the feeder is known to normally and alternatively be operated. Contingency switching for unforeseen operations greatly increases the solution space, thus alternative configurations considered must remain practical. As such, hosting capacity assessments should consider the normal "as-designed" state of the system and take into consideration the abnormal or "reconfigured" state as illustrated in Figure 2. Table 4 describes the impacted metrics and recommendations to consider this impact factor.

Source Impedance

Source impedance is an important part of a distribution feeder model as it represents the impedance of the system upstream from the distribution feeder. This impedance directly affects the total impedance to every location on a feeder and therefore all voltage and protection hosting capacity metrics. Some utilities represent the source impedance as an equivalent value, derived from tools such as Aspen, to represent the transmission system, sub-transmission system, and distribution substation. Others explicitly model the substation transformer along with the equivalent value for just the transmission and sub-transmission system.

What is important to consider in a hosting capacity study is that voltage change due to DER at any location on a feeder is dependent on this value. Substation load tap changers can be used to mitigate voltage change due to source impedance, however, in the time period prior to operation, the impact of source impedance will be experienced. Figure 3 illustrates the voltage profile of a feeder with/without source impedance modeled when there is no load tap changer. As can be seen, the voltage profile is higher when the source impedance is not modeled. Source impedance is also critical to include in the model as it relates to protection impacts that are based on short circuit fault currents. Table 5 describes the impacted metrics and recommendations to consider this impact factor.

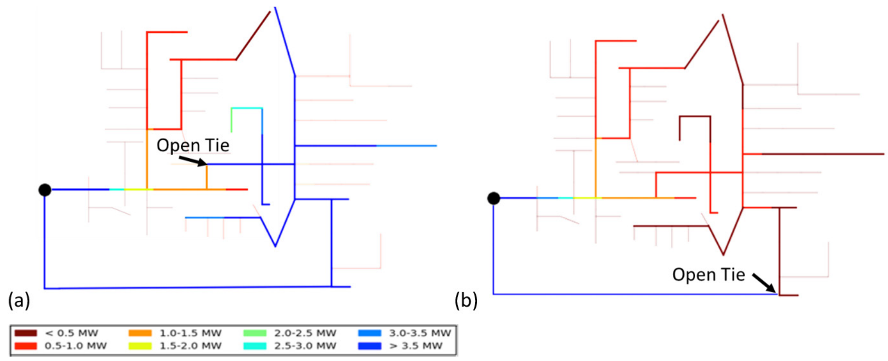

Figure 2– Hosting Capacity During Condition (a) Normal (b) Reconfigured

Table 4 – Grid Configuration – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility, Protection coordination
Recommendation	Consider to the extent possible alternative grid configurations to maintain operational flexibility.

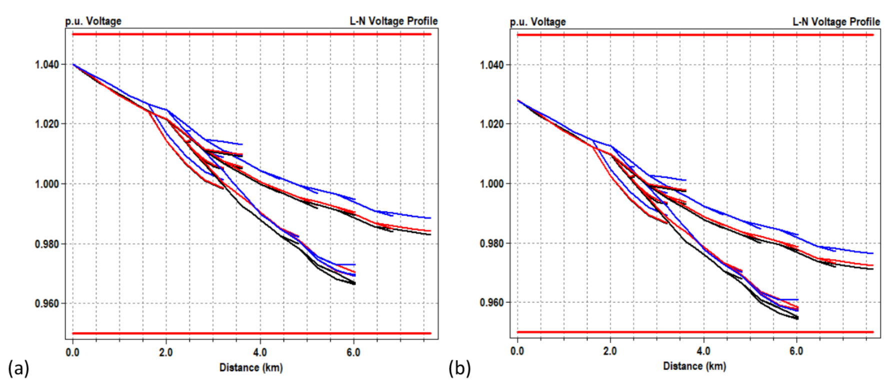

Figure 3– Voltage Profile with 1.04 pu Source Voltage a) Without Source Impedance b) With Source Impedance Defined Based on 10,000 Amp 3-phase Short Circuit Current at the Feeder Head.

Table 5 – Source Impedance – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Operational flexibility, Protection coordination
Recommendation	Source impedance should be included in the feeder model along with its impact on hosting capacity.

4 *Determining the Effectiveness of Feeder Clustering Techniques for Identifying Hosting Capacity for DER.* EPRI, Palo Alto, CA: 2015. 3002005795.

Voltage Regulation

The most common approach utilities use to provide cost-effective voltage control is to deploy assets such as substation load tap changers (LTCs), line regulators, capacitors or combinations thereof. The primary function of these assets is for voltage regulation to prevent undervoltage during peak load periods, but they can also be used to prevent overvoltage as well.

What is important to consider in a hosting capacity analysis is the range of voltage profile produced from these regulating devices. LTCs and regulators allow voltage to fluctuate on the feeder within a predefined bandwidth and capacitors can automatically be switched in or out of service based on associated bandwidths. Capturing the range of the potential voltage profile is necessary to determine over and under voltage issues while the actual bandwidth of the devices is necessary to determine potential increase in operations.

Figure 4 illustrates the impact that the bandwidth of voltage regulators can have on hosting capacity. In the field, there are feasible scenarios when regulating devices are pushed to the edge of their range of operation. These scenarios of operation are not always captured in a single power flow solution. In order to capture this full range of impact in hosting capacity assessments, additional power flow solutions, manual adjustments, or initialization of devices to the operating bandwidth must be made. Table 6 describes the impacted metrics and recommendations to consider this impact factor.

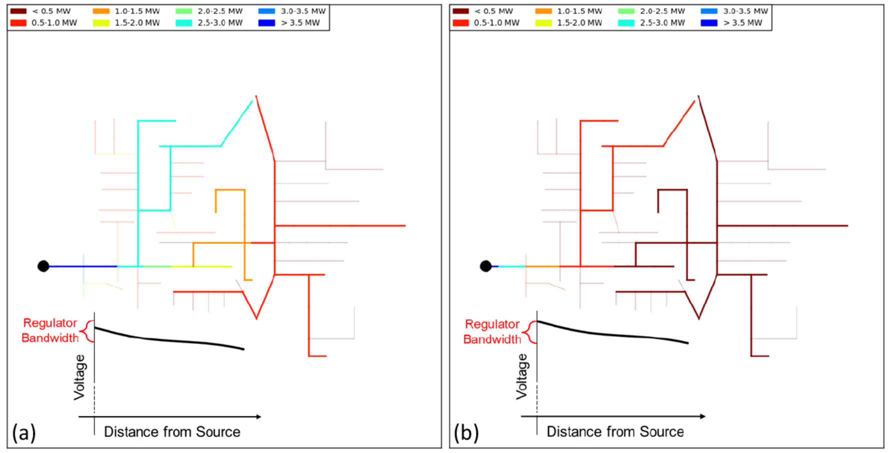

Figure 4– Overvoltage Hosting Capacity During 20% of Peak Load on IEEE 123-Bus Test Feeder with Regulator Tap Position Based on a) Power Flow Solution b) Power Flow Solution with Manual Adjustment to Upper Edge of Bandwidth.

Table 6 – Voltage Regulation – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Operational flexibility
Recommendation	Feeders that utilize voltage regulation will require accurate modeling of those resources for hosting capacity analysis. To assess the range in operation, regulating devices should be considered across their full range of operation.

Table 7 – Connected Load – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility, Protection coordination
Recommendation	Model load using the best available information. This could leverage allocation methods or AMI data. Use multiple load levels to assess hosting capacity.

Connected Load

Loads are represented in distribution models based on estimates. This is due to the sheer number of customers on a distribution feeder (100's-1000's) and wide diversity in customer usage profiles. The estimates are used to create "average" load models that reflect load impacts to distribution. Additional methods are also utilized to adjust/allocate loads to represent other conditions which are important for assessing DER impacts. In all cases, loads are diverse by nature and difficult to quantify and forecast precisely at the distribution level. Load profiles can vary throughout the day, season, etc. and change year to year as new customers interconnect and disconnect from the grid.

What is important to consider in a hosting capacity analysis is the range in amount, location, and type of load along a feeder as these directly impact not only thermal loading of assets but also the voltage profile. Load will also impact a protection analysis because depending on load type, they can parasitically pull current during the fault. As such, hosting capacity is impacted by how loads are modeled and the assumptions used to develop/allocate them. Table 7 describes the impacted metrics and recommendations to consider this impact factor.

Connected DER

Similar to load, the amount, location, type, and control of connected DER along a feeder directly impacts not only the thermal loading of assets but also the voltage profile across the feeder. As such, hosting capacity is impacted by how connected DER is modeled and assumptions used to develop those models.

What is important to consider in a hosting capacity study is how the impact of connected DER may change the ability to accommodate additional DER. Considering the impacts of connected DER in a hosting capacity analysis can be done in two ways.

1. Include the connected DER to create a new baseline state of the system.
2. Include the connected DER and its impacts during the hosting capacity analysis.

In the first method, the baseline state of the system assumes the connected DER with a predetermined output and adjusts all regulation as necessary. When hosting capacity is calculated, it is relative to this new baseline scenario. The issue with this method is that the aggregate voltage impacts due to connected DER will not always be captured. In doing so, this approach will potentially mask the impact of the connected DER in the hosting capacity assessment.

By contrast, the second method captures the impact of connected DER. The connected DER is not included in the baseline state of the system, but rather included in the analysis of hosting capacity. In this approach, the amount, location, type, and control of connected DER are all known and used in the analysis of hosting capacity at each location on the system. A requirement for this method is that DER must be modeled separately from load.

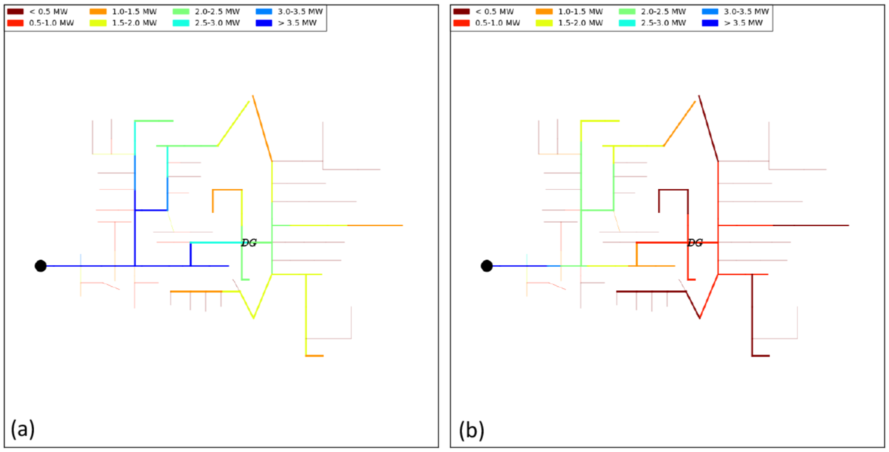

Figure 5– Voltage Deviation Hosting Capacity with a Connected 2-MW PV System (DG) Considered with a) Method 1 b) Method 2.

Table 8 – Connected DER – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility, Protection coordination
Recommendation	Connected DER as defined by location, size, type and control, are all needed for hosting capacity analysis. The impact of connected DER should not be masked for any application. Connected DER should be included in the model separate from load and considered in the analysis of remaining hosting capacity.

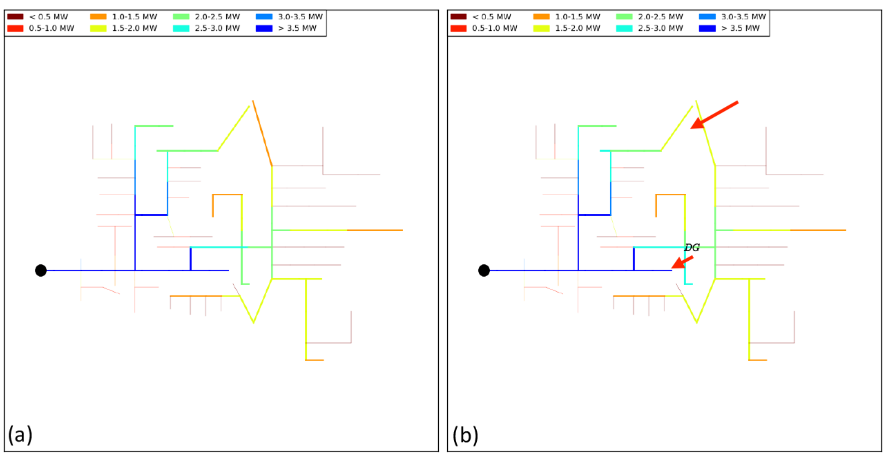

Figure 6– Voltage Deviation Hosting Capacity a) Baseline Without Connected DER b) With a Connected 2-MW PV System (DG) at 0.9 Inductive Power Factor (Arrows Indicate Increase in Hosting Capacity).

Table 9 – Autonomous Control – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility
Recommendation	The range in control scenarios should be considered which include connected DER with and without autonomous control.

Figure 5 illustrates the difference in voltage deviation hosting capacity results obtained from the two methods when connected DER exists on the feeder. As can be seen, there is a significant difference in the hosting capacity results across the feeder which could then point to different decisions when applying the results. Table 8 describes the impacted metrics and recommendations to consider this impact factor.

Control of Connected Resources

Control of connected resources is an important factor as it relates to the ability to reduce potential impact from connected DER by changing its operation. When control of active and reactive power is available, the feeder can potentially integrate more DER when appropriate settings are used.

However, being able to count on the benefit that control provides to reduce impact from connected DER depends on the resources being available when and where they are needed. Therefore, careful consideration needs to be given to how control of connected resources is included in DER hosting capacity assessments and what impacts that has on the application of the results. There are two basic types of DER control to be considered: Autonomous and Managed.

Autonomous Control

DER can respond to local conditions based on predefined curves and settings with autonomous control. In cases where the DER is coordinated with grid operations, the amount of DER that can be interconnected can exceed the hosting capacity because the DER itself mitigates adverse impacts such as voltage rise.

However, once the DER is connected with autonomous control it can lead to overestimating the feeder's ability to accommodate future DER because the connected DER control may become unavailable due to the system being down for maintenance, weather conditions, etc. This is illustrated in Figure 6. Figure 6 (a) shows the feeders baseline hosting capacity without autonomous control prior to interconnection of DER. The DER site is chosen and labeled DG in Figure 6 (b), while the heatmap illustrates the feeders remaining hosting capacity if the connected DER is operated at 0.9 inductive power factor (DG reactive power in opposite direction of DG active power flow). In this case, the remaining hosting capacity relies on the connected DER to draw reactive power. At some locations (indicated by arrows), the remaining hosting capacity exceeds the value shown in (a), which is only possible if the connected DER is in-fact online providing that reactive power grid support.

What is important to consider in a hosting capacity analysis is the impact that the autonomous control of connected DER will have on the remaining hosting capacity. Some autonomous control strategies may portray an increase in hosting capacity while others will not. To identify the hosting capacity boundary conditions for accommodating future DER, the autonomous control of connected DER must be taken into consideration as well as if the connected DER control can be relied upon when needed. This consideration is important as it represents a potential risk that must be managed in grid planning and operation. Table 9 describes the impacted metrics and recommendations to consider this impact factor.

Managed Control

Managed control can also increase the amount of DER that can be interconnected by manually adjusting the output and/or control settings of connected DER in addition of other resources such as controllable load to prevent adverse impacts. This could be done by updating active power production limits or regularly updating autonomous settings. However, doing it effectively depends on having the data, monitoring, analysis, management and communications systems, and personnel. It also relies on having failsafe functional settings in case of a malfunctioning management scheme.

Similar to autonomous control, the managed control can reduce the adverse impacts from DER at a particular location and potentially help integrate more DER. However, once that DER is connected, the availability, reliability, and confidence of the operation of that control, needs to be understood.

What is important to consider in a hosting capacity analysis is the impact that the managed control of resources will have on the remaining hosting capacity for future DER interconnection. To identify the hosting capacity boundary conditions, the managed control must be taken into consideration as well as if and when that control may be unavailable. Due to the wide variety of control parameters, it would be difficult to consider managed control in its entirety in a system-wide hosting capacity analysis. Table 10 describes the impacted metrics and recommendations to consider this impact factor.

Table 10 – Managed Control – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility
Recommendation	The range in control scenarios should be considered which includes with and without managed control.

Time

Considering time in a DER impact analysis has several benefits. The primary benefit is that when load and DER are varied in time, many different scenarios occur on the feeder and the analysis reflects the actual combined impact of load, DER, regulation equipment, and control (previous four impact factors). A secondary benefit is that time-specific impacts can be determined.

Although this time-series impact analysis can be informative, there are shortcomings with regards to hosting capacity and identifying the boundary conditions. First, the feeder boundary conditions still need to be assessed at each time interval. This means analyzing the range of each of the previous four impact factors at each time interval. Second, unless each time interval is analyzed this way, the range in time-specific hosting capacity is not determined.

What is important to consider in a hosting capacity analysis is the range in load and DER as well as regulation equipment and control. The idea that time-series can be a replacement for the aforementioned four impact factors is only valid if the forecasted load, DER, regulation, and control are known at each time interval. Otherwise, the range of each impact factor should be considered during each time interval. Table 11 describes the impacted metrics and recommendations to consider this impact factor.

Table 11 – Time – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility
Recommendation	Time-based hosting capacity should still consider the range in impact factors at each time interval.

Additional Considerations[5]

A number of additional grid factors have an impact on overall hosting capacity results, including:

- Accuracy of the underlying models (conductor data, phasing, transformer parameters, latency in model updates, etc.)
- Modeling the reactive power consumed by customers. These values are usually estimated at a default power factor and are typically inaccurate at low load levels.
- Service transformers and service drops which are not typically modeled
- Grounding practices
- Protection system design
- Granularity of medium voltage models (number of buses/nodes)
- Transmission grid reconfiguration/ dispatch

These additional grid factors are typically addressed in a detailed interconnection study, but difficult to consider to their entirety in a system-wide hosting capacity analysis. Therefore, assumptions are typically applied, which include using the underlying model as-is.

DER-based Impact Factors

Similar to grid factors, there are DER factors that are instrumental in hosting capacity assessments. These DER factors relate to future DER that is not currently interconnected. These are the core variables in the DER hosting capacity analysis that must be considered for all locations on all feeders in the system-wide study.

Location

The location of DER on the distribution system is perhaps the most critical DER-specific factor in hosting capacity assessments. The location of DER applies to single-site and multi-site DER scenarios.

Single-Site Location

The single-site scenario pertains to DER analyzed at each and every specific location, one at a time, on a feeder because each of those locations is a potential interconnection point for DER. Every location must be examined as hosting capacity can abruptly change on a feeder.

What is important to consider in a hosting capacity analysis is the impact of DER at every location. DER systems interconnected to distribution near the substation (or through express feeders) have a significantly different impact than if they are connected near the end of the feeder. Similarly, hosting capacity along a feeder can vary as thermal ratings abruptly change between elements or when the feeder changes from three-phase to single-phase. By not examining each potential DER location, hosting capacity can be over or underestimated depending on what value a specific unanalyzed location estimates as shown in Figure 7. The value estimated could be based on the analyzed upstream or downstream location. In the illustration (b), the values at unanalyzed locations are estimated

5 *Distribution Modeling Guidelines: Recommendations for System and Asset Modeling for Distributed Energy Resource Assessments.* EPRI, Palo Alto, CA: 2015. 3002006115.

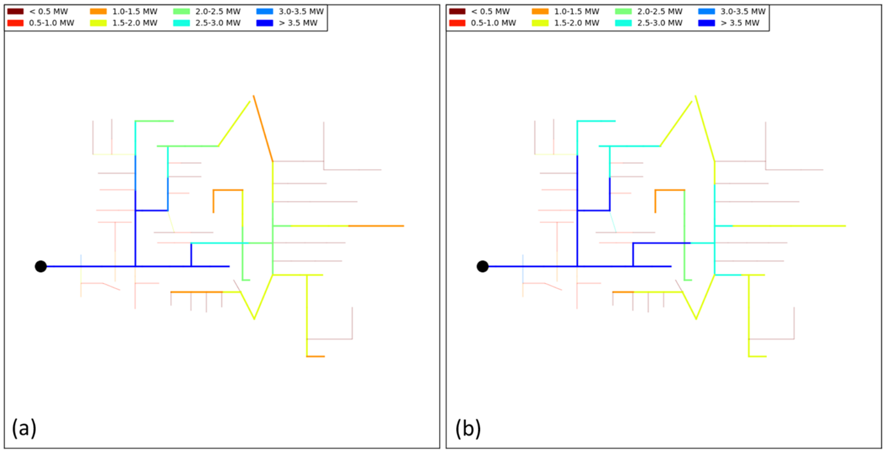

Figure 7– Voltage Deviation Hosting Capacity Determined for a) All Locations b) Limited Set of Locations.

Table 12 – Single-Site Location – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility, Protection coordination
Recommendation	Hosting capacity should be determined for every potential DER location.

Table 13 – Multi-Site Location – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility, Protection coordination
Recommendation	Distributions of DER should be considered in the hosting capacity assessment.

Table 14 – Technology Output – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Operational flexibility
Recommendation	Consider the output variability of the specific DER technology under examination based on region and use cases.

Table 15 – Technology Timing– Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility
Recommendation	Consider the time of day when the specific DER technology under examination is at or near full power.

based on the analyzed upstream location. Estimations based on analyzed downstream locations are just as erroneous as multiple analyzed downstream locations could exist. Table 12 describes the impacted metrics and recommendations to consider this impact factor.

Multi-Site Location

Hosting capacity analyses are not limited to determining the amount of DER that can be accommodated at each specific location in the system. Hosting capacity should also depict a feeder's ability to accommodate a distribution of DER at multiple locations throughout the feeder. This requires another dimension to the analysis where stochastic DER distributions may lead to a wide range of additional scenarios to analyze.

On a feeder with many potential DER locations, there are a near infinite number of random distributions. Additionally, distributions could further be divided based upon utility-scale DER and customer-scale DER. The result is a very complex variable to consider in its entirety.

What is important to consider in a hosting capacity analysis are the impacts from a distribution of DER, particularly for the use case 'to enable system planning'. DER adoption forecasts are most frequently estimating growth of DER over a wide area and therefore would need DER considered at multiple locations across a feeder in order to identify areas within the system that may require infrastructure upgrades. Table 13 describes the impacted metrics and recommendations to consider this impact factor.

Technology Characteristics

Understanding the behavior of particular DER technologies is important in order to define DER characteristics to analyze for hosting capacity. Variable generation can have widely varying impacts on system response when compared to fixed or dispatchable DER like fuel cells, energy storage, or rotating machines. The technology considered in the hosting capacity assessment ultimately defines the hosting capacity for that particular type of resource. The DER technology can be defined by its output, timing, and interface.

Technology Output

Intermittent DER, with output that varies throughout the day, can produce voltage fluctuations and/or increased operation and maintenance on voltage regulation schemes. In some cases, this can reduce hosting capacity.

What is important to consider in a hosting capacity analysis is the output variation of the DER technology under consideration. This value should be based on regional variability for solar and wind resources, and might be a planned value for other types of DER that fluctuate based on local use cases or objectives. Table 14 describes the impacted metrics and recommendations to consider this impact factor.

Technology Timing

The time of day when the DER is available to inject/absorb active and/or reactive power also impacts hosting capacity. Some resources will be available at all hours, while other resources like PV will only be available during the daylight hours.

What is important to consider in a hosting capacity analysis is the time when the DER technology under consideration is online and at or near full output. This time of day will relate to the Grid Factors used in the analysis, such as connected load and connected DER to consider. Table 15 describes the impacted metrics and recommendations to consider this impact factor.

Table 16 – Technology Interface – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Unintentional islanding, Operational flexibility, Protection coordination
Recommendation	Consider the interface for the specific DER technology under examination.

Table 17 – Portfolio – Metrics Impacted and Recommendation

Metrics impacted	Overvoltage, Undervoltage, Regulator voltage deviation, Voltage deviation, Thermal ratings, Reverse power flow, Unintentional islanding, Operational flexibility, Protection coordination
Recommendation	Portfolio hosting capacity should be defined by the characteristics of the aggregate resource.

Technology Interface

The specific DER interface grid-interface technology, such as inverter-based or machine-based, has an impact on the hosting capacity for the particular resource due to the magnitude and dynamics of fault currents produced. The interface technology will also define the control options for the resource such as volt/var and volt/watt for inverter-based technologies.

What is important to consider in a hosting capacity analysis is how the DER interface technology changes the potential fault contribution of the resource. Moving beyond hosting capacity and into integration of DER, the interface will also provide potential options for customer-side control. Table 16 describes the impacted metrics and recommendations to consider this impact factor.

Portfolio

Portfolios of DER are an extension of the individual DER technology characteristics. The DER portfolio can still be characterized by its output, timing, and interface. A portfolio of DER might consider a mix of resources at a particular location such as the combination of solar, storage, and smart load.

What is important to consider in a hosting capacity analysis are the characteristics of the aggregate resource. But due to the vast possibilities of an aggregate resource, it would be difficult to consider in its entirety in a hosting capacity analysis. Table 17 describes the impacted metrics and recommendations to consider this impact factor.

Additional Considerations

A number of additional factors have an impact on overall hosting capacity results, including:

- Panel orientation (PV systems)
- System DC/AC ratio (Inverter-based systems)
- DER efficiency
- DER vendor manufacturer
- DER plant layout

The main factor to consider from each of these is how it affects when the DER will potentially be at or near full output. A shift in panel orientation may skew the DER peak to earlier/later in the day. A change in the DC/AC ratio would change the duration that the system can remain at peak output. Knowing these characteristics allows for a more tailored analysis of the feeder's hosting capacity. These additional impact factors are typically addressed in a detailed interconnection study, but are difficult to consider in their entirety in a hosting capacity analysis across an entire system.

CONSIDERATION OF IMPACT FACTORS

Consideration of all DER and grid impact factors are a significant driver in the computational requirements and accuracy of hosting capacity assessments. Impact factors can be considered individually or simultaneously. Individual assessments provide insight into the sensitivity of the hosting capacity result to the particular impact factor, but the accuracy of the overall assessment relies on all impact factors being considered simultaneously. Because of this, it is extremely important to consider only those factors that matter most and balance accuracy with computational requirements. Otherwise, the solution space to analyze a complete system becomes unmanageable as previously depicted in Table 1.

Figure 8 is a sample illustration of the dependence of hosting capacity at a single location to that of the number of impact factors simultaneously considered in the analysis. Only analyzing one impact factor results in a high hosting capacity error. By including two impact factors, the error drops considerably. At least three impact factors are necessary to significantly reduce overall error and improve accuracy. Generally, as the number of impact factors increases, the accuracy of the hosting capacity results increases and the error continues to shrink. However, not all additional impact factors improve the hosting capacity assessment equally.

Due to computational intensity, data required, and engineering time to consider all impact factors in a hosting capacity assessment, it is recommended that the analysis focuses on impact factors and conditions that identify the lowest (worst-case) and highest (best-case) hosting capacities. This is particularly important when using the results for assisting with interconnection requests and informing developers. Currently, the lowest hosting capacity limits are the focus in the industry. However, to interconnect DER beyond the hosting capacity lower limit, the upper limit will be necessary to inform how large the DER could be assuming it is managed to maintain power quality and reliability. This upper limit is effectively the maximum allowable power output of the DER that may not necessarily occur except in the most ideal conditions.

One important point is that the hosting capacity error shown in Figure 8 does not converge to zero. Assumptions are necessary due to the uncertainties in underlying data and therefore a single "100% accurate" answer is not achievable. Assumptions around future load profiles, DER profiles, control, etc., all impact hosting capacity. However, if sound assumptions are utilized and the implications are well understood then the outcome can be extremely valuable.

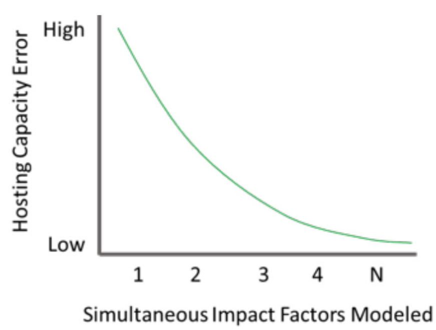

Figure 8 – Error in Single Location Hosting Capacity Based on Analyzed Impact Factors.

RECOMMENDATION FOR COMBINED IMPACT FACTOR ANALYSIS

Hosting capacity studies addressing potential DER impacts should be considered just as all grid planning and interconnection is done today – design and study for the realistic, worst-case conditions to ensure adverse impacts to reliability and grid services does not occur for other customers. As such, hosting capacity should consider realistic, worst-case conditions to better understand the potential lower limits but also the best-case conditions and potential upper limits. These boundary conditions should drive decision-making and application of hosting capacity.

Table 18 identifies the primary impact factors necessary to determine hosting capacity boundary conditions, and the following sections provide recommendations on how to consider them to establish those boundary conditions without striding too far into a detailed analysis that, as previously shown, is not practical to solve. There is nothing wrong with considering additional impact factors or variance among those factors, but the factors listed and recommendations made herein are the minimum to consider the potential range in hosting capacity with the least amount of error while being cognizant of computational time.

Table 18 – Primary Impact Factors

Critical Impact Factors	
Grid	Configuration
	Source Impedance
	Voltage Regulation
	Connected Load
	Connected DER
	Control of Resources
DER	Location
	Technology
Misc.	Metrics
	Algorithm

Grid-based Factors

If done accurately, a full time-series analysis can provide valuable insight into impacts from DER at multiple load levels, DER levels, regulation equipment, and control. However, determining hosting capacity at each time-period of the time-series analysis still requires consideration of alternative load levels, DER levels, regulation equipment states, and/or controls. Due to this, calculating the hosting capacity boundary conditions should forgo a time-series analysis and focus on a few carefully chosen load, DER, regulation, and control scenarios on each feeder model.

The primary load conditions that should be analyzed are the maximum and minimum load that exist when there is potential for the DER to be at or near full output. These load conditions are what drive the thermal constraints of the feeder and bring light to the greatest and most minimal voltage drop across the feeder as well as any range in system fault currents. The voltage scenarios include the impact from source impedance and are sufficient to determine the voltage constraints on the feeder in cases where there is no voltage regulation. To account for the range in potential voltage regulation impacts, controlled capacitors should be initialized in either their enabled or disabled state to create a baseline scenario with them considered online/offline (unless control strategies again force them to switch). At the same time, voltage regulators should be shifted to the maximum/minimum tap positions within the regulated bandwidth to finally arrive at the extremes of the voltage profile.

Connected DER should be included in the hosting capacity assessment, but not in the baseline analysis of the primary load conditions. Rather, it should be layered in afterward with control equipment locked such that the calculation of remaining hosting capacity considers the connected DER impact on voltage, thermal, and protection metrics. This requires modeling DER and load separately. If this is not done, the full potential impact of the connected DER can be masked. The output of the connected DER should also be adjusted based on the type of resource being considered for hosting capacity. For instance, PV hosting capacity assessments should only consider connected DER that is online during the day.

Autonomous and managed control of connected DER and other resources is also another important factor that can change the impact of future DER on the feeder. To account for the full range in boundary conditions, the control needs to be considered such as if it is operating as planned and potentially as if it is unavailable. Examination of hosting capacity without control may identify the lower hosting capacity boundary condition, while including that control may identify the upper hosting capacity boundary condition. The actual impact that control has on the remaining hosting capacity will depend on the objective of that control.

Finally, alternative grid configurations represent the dynamic state of the system, and those states should be considered when applicable to find the upper and lower hosting capacity boundary conditions.

Other important grid factors such as phasing, reactive power of loads, and all other modeling characteristics should be known and modeled as such. Variations in these parameters are influential to hosting capacity results but the variance only depicts inaccuracies in the underlying model. If the model does not account for these factors, then their variance should be applied in the hosting capacity analysis to determine the boundary conditions. These variations are important to be aware of, and to understand, for the proper application of the hosting capacity results.

DER-based Factors

The DER factors are the main variables driving a hosting capacity analysis, and therefore they need to be treated as such with their full range considered in the hosting capacity assessment. This allows the hosting capacity analysis to fully reflect the range in impact to all feeder metrics with the aforementioned grid factors.

Each location on the feeder should be analyzed to prevent missing a critical change in hosting capacity as the value does not vary linearly across the feeder for each issue. Even issues such as overvoltage can have non-linearity in hosting capacity due to losses, location of connected DER, and/or line regulation.

Multi-site DER should be considered along with single-site DER to fully understand and utilize the results from a hosting capacity assessment. There are an infinite number of distributed multi-site DER scenarios, but a basic understanding of upper and lower hosting capacity boundaries can be attained by considering a few distributions of DER skewed across each feeder.

At this time, careful consideration should be given to the type of DER that is analyzed for hosting capacity. The hosting capacity assessment can be conducted for specific DER types which are defined by the output, timing, and interface characteristics. The same approach can be taken when considering a portfolio of DER in a hosting capacity assessment. Agnostic approaches that consider the output characteristics of a default DER type and then interpolate the hosting capacity results to another DER type have not been verified but do appear to work well for most feeder metrics as shown in Figure 9. The figure shows the hosting capacity based on three DER types and two DER portfolios for several voltage and protection metrics. The 'Explicit' results are based on modeling and quantifying impact through OpenDSS, while the 'Implicit' results are determined for a default DER type and interpolated to the specific DER type/ portfolio based on the characteristics correlation. In most cases the correlation works well based on similarity between the 'Implicit' and 'Explicit' results. The primary difference in results occurs for protection issues with non-inverter based DER. This is because the correlation of fault current produced due to different DER interfaces is much more complex

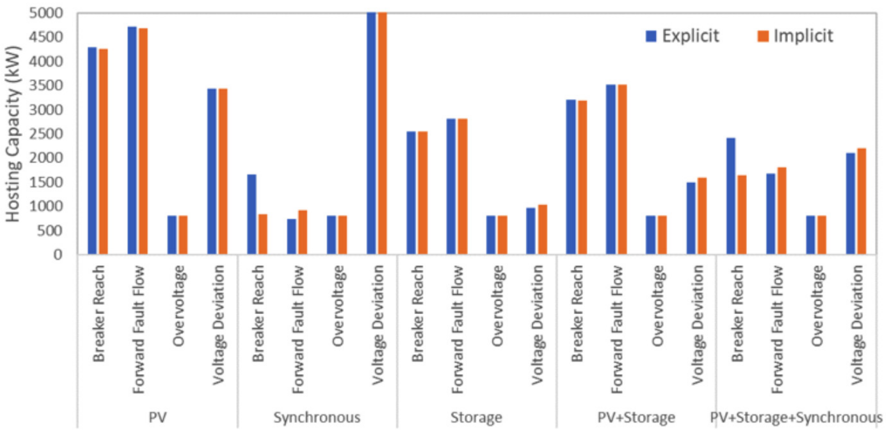

Figure 9– Comparison of Explicit-Analysis and Implicit-Derived Hosting Capacity for Several DER Types/Portfolios and Several Feeder Metrics at One Location.

than the correlation of power fluctuation due to different DER output characteristics.

Miscellaneous Factors

Each of the utility selected feeder metrics should be considered in the hosting capacity assessment for each scenario described by simultaneously modeling impact factors. This allows the user to specifically understand the limiting constraints for DER. The independent analysis of each metric can improve the efficiency of the overall assessment algorithm by making educated steps in DER penetration size when determining hosting capacity as well as simplifying the analysis. An example of simplifying the analysis includes removing specific branches from the feeder model when 1) locations on those branches are not currently being considered for hosting capacity and 2) locations on those branches will not be impacted by the location currently being considered for hosting capacity.

Finally, hosting capacity is the amount of DER that can be accommodated. Therefore, any grid or customer mitigation required to integrate the resource should be excluded from the hosting capacity analysis and reserved for an integration analysis. This includes autonomous/managed control of DER as well as using existing distribution automation and voltage regulation. These mitigation options do help integrate higher levels of DER, but to achieve those levels of DER it should be noted that mitigation is required.

CONCLUSIONS

The industry's understanding of hosting capacity assessments is evolving and its application will continue to be a vital piece of considering DER on the distribution system. This report outlines the factors that are most important when it comes to implementing a hosting capacity analysis for the purpose of informing interconnection, planning, and developers. Specific takeaways include:

1. **Hosting capacity results are driven by the impact factors considered.** The input data assumptions and factors considered are the main driver of the results produced by a hosting capacity analysis. Because it is impractical to consider the full range of all impact factors, careful consideration should be given to evaluating the appropriate variance of those impact factors. This is key to improving result accuracy. Understanding what is considered and its implications is necessary to know how to apply results and communicate with the industry to set expectations.
2. **There are important impact factors to consider regardless of application.** To accurately capture the boundary conditions that define the range of hosting capacity values, there are important impact factors that need to be considered. While other impact factors may inform results, they are not the main drivers. Recommendations for analysis include:
    - Focus on a few carefully chosen load, DER, regulation, and control scenarios rather than time-series analysis
    - Analyze the maximum and minimum load conditions that exist when there is a potential for the DER to be at or near full output
    - If voltage regulation is present, shift to the maximum and minimum cap/tap positions within the regulated bandwidth
    - Connected DER should be included after the baseline powerflow analysis with control equipment locked to capture full impact on voltage metrics
    - Output of connected DER should be adjusted based on type of resource considered in the hosting capacity analysis
    - Control of connected resources should be considered by analyzing both when control is available and when it is not available
    - The impact of source impedance should be included
    - Alternative grid configurations (e.g., load transfers) should be considered when applicable
    - DER at specific locations on a feeder in addition to DER at multiple locations should be considered
    - Analysis should be conducted for each specific DER type – output, timing, grid interface
3. **Variance in impact factors should be driven by application of results.** It is important to consider impact factors when determining hosting capacity for applications that inform the public, assist interconnection screening, and enable planning with DER, however, the full variance among those impact factors is not always necessary. In the case of some applications, applying the full variance is important to determine the upper and lower hosting capacity boundary conditions, while for other applications, applying only a partial variance among those factors to focus on the lower hosting capacity boundary condition may be needed.
4. **Hosting capacity methods utilize different impact factors in different ways.** Hosting capacity requires a complex analytical assessment. The methods utilized to calculate hosting capacity are important and each have pros and cons that must be understood. Because methods vary and are evolving, ongoing comparison and validation is important to understand what impact factors are considered and how they may impact results.
5. **Impact factors and methods will change as the scenarios become more complex.** Further innovations in hosting capacity analytics will be critical as the distribution system becomes even more complex. Grid modernization initiatives, using DER as non-wires solutions, transactive energy, controlled sources, will all increase the complexity of a hosting capacity analysis.

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