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Characterizing the Value of Flexible Interconnection Capacity Solutions (FICS)

Technical Brief — *DER Integration Program (P174)*

This brief discusses the concept of flexible interconnection and its potential to provide benefits to both distributed energy resource (DER) developers/owners as well as utility system operators. It defines flexible interconnection along with the rationales and influences governing its application, examines the economic value of FICS with illustrative examples, and suggests topics that can be explored via real-world demonstration to further discern the concept's merits.

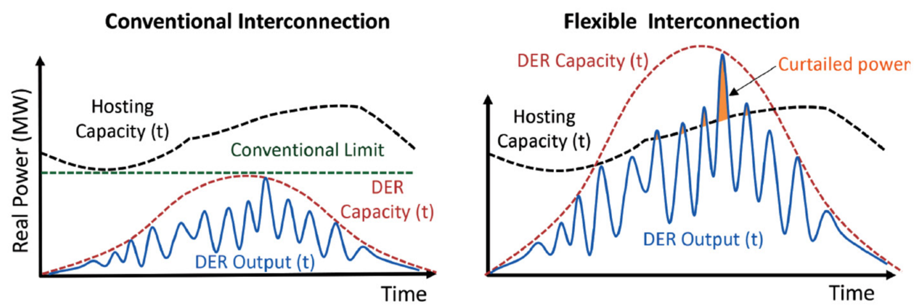

Figure 1. Conventional Interconnection Versus Flexible Interconnection

Table 1. Potential Benefits of Flexible Interconnection Solutions

Benefit	Description
Lower interconnection costs	Adding controls and curtailing available generation can be cheaper than conventional network reinforcements. In many cases, conventional upgrades may be prohibitively expensive, constraining DER project development. FICS may provide a less costly interconnection option by instituting limited curtailment in lieu of grid upgrades.
Faster interconnection times	Adding controls can be a faster solution than many conventional upgrades (e.g., constructing a dedicated feeder). FICS can also be used as a temporary solution for customers who want a firm connection; it allows them to grid connect while they wait for the network reinforcement to occur.
Increased network utilization	FICS allows for more DER generation per unit of delivery capacity available, maximizing use of existing grid assets.
Facilitated renewable generation growth	FICS can expand renewable generation and meet renewable portfolio standards by using existing network infrastructure.

What Is Flexible Interconnection?

Flexible interconnection is a DER control strategy used to defer system upgrades and/or increase distribution system utilization. In general, it involves defining DER operating behavior at key times when the transmission and/or distribution system are constrained. In practice, flexible interconnection is typically used to limit or curtail real power exports from DER units in order to avoid grid violations.

The amount of DER power export that can be accommodated on the distribution system is inherently time varying because the underlying load, generation, temperature, control settings, circuit configuration, and other system parameters fluctuate over time. Traditionally, DER customers are connected under a fixed capacity agreement (or firm interconnection); this fixed export capacity is granted based on "worst case" grid conditions, such that the grid can absorb the full power generated by the DER whenever it appears while ensuring grid reliability and power quality. By contrast, the flexible interconnection approach aims to grant higher export capacity to DER units seeking to connect on circuits where the available fixed export capacity is less than the maximum export capability of the DER unit. It requires that the operation of the DER units be reliability managed if grid congestions appear. The approach aims to increase grid utilization by supporting greater energy exports from DER units and larger DER sizes in more locations than otherwise permissible under a fixed capacity agreement (see Figure 1).[1]

How Can FICS Help?

Rising grid penetrations of DER are beginning to challenge the accommodation limits of existing distribution infrastructure in certain locations. In some cases, circuit capacity limits can be expanded; however, the required system upgrades can add significant costs and delay to interconnecting projects. Alternatively, FICS can be implemented in select circumstances—either as a temporary or more permanent solution—to provide an efficient and economically viable option for DER interconnection and operation. (Table 1 provides a description of potential FICS benefits.) A utility strategy that

1 For further details about the basic concepts of flexible interconnection, see *Understanding Flexible Interconnection*, EPRI, Palo Alto, CA: 2018. 3002014475.

coordinates infrastructure upgrades with FICS offers a pathway for pursuing least cost solutions that optimize DER grid connection and distribution system utilization.

Business, Economic and Policy Relevance of Flexible Interconnection

Flexible interconnection arrangements supporting higher DER penetrations have the potential to be beneficial to multiple stakeholders, including DER customers, utility ratepayers, and policymakers. When flexible interconnection is offered and demonstrated in one region, DER developers and other industry stakeholders may expect similar options elsewhere. This outlook underscores the importance of understanding the concept and how it might impact utility processes.

DER customers connecting under a flexible interconnection agreement can potentially accelerate connection times while avoiding costly reinforcements (see Table 1). Flexible connections can be a permanent solution provided that the level of export curtailment is financially sustainable to the project; they can also be a temporary solution allowing DER projects to start generating revenues faster while waiting for completion of scheduled network reinforcements, or for a critical mass of DER projects to connect in the same area, and eventually share the network reinforcements costs enabling transition to firm interconnection.

Ratepayers may also benefit from the development of flexible interconnection. Conventional network reinforcement required under traditional firm connections are funded, in part or total, via distribution and other system charges passed down to ratepayers as authorized by the relevant regulatory entity. Specifically, for larger DER customers, the costs of network reinforcements necessary for a specific DER asset to export ("sole user assets") are usually fully charged to that customer. However, for smaller customers, part of the upgrade costs may be socialized across all ratepayers. In addition, larger DER customers sharing use of substations with other DER and non-DER customers only pay a portion of the reinforcement costs based on their export capacity, while the remaining costs are socialized across all ratepayers.

Policy objectives may benefit from flexible interconnection if FICS can accelerate progress towards DER penetration goals and/or emission reduction targets. Additional benefits of accelerated DER connections may include positive impacts on the local economy in the form of energy-based financial benefits (e.g., developers offering discounted electricity to local residents), or non-energy-based financial benefits (e.g. growth of tourism, employment of local suppliers and contractors).

How Does Hosting Capacity Affect FICS and Its Value?

The concept of hosting capacity (HC), which describes the limits in scale and quantity of DER that can be accommodated on a distribution system, is a key factor for determining the relevance and value of flexible interconnection. There are technical constraints for voltage regulation, thermal loading, protection, and power quality. These constraints derive from time and location varying load, existing distributed generation, and the electrical characteristics of the power system.

Overall, it is important to identify the total hosting capacity—what would be possible if no DER were deployed—and the remaining hosting capacity—what DER can be deployed in addition to existing plants. Each time a DER is deployed at any grid location, the remaining hosting capacities change throughout the system. However, hosting capacity is inherently time-varying because the underlying load, generation, temperature, control settings, circuit configuration and other system parameters vary with time. Figure 2 illustrates the time dependent nature of hosting capacity. The single-site hosting capacity (black-dashed curve) is determined by the lesser of the time-varying thermal and voltage limits. The capacity changes over time, including daily, weekly, and seasonal variations. To be permitted at a site, a DER's output cannot exceed the single-site hosting capacity at any time.

These constraints are location-dependent, due to the nature of circuit characteristics, control elements, load concentrations and other DER. This means that the single-site hosting capacity can vary from location to location (see Figure 3). As a result, the value and viability of FICS, as well as mitigation and grid upgrade costs, can vary from for each location and DER capacity. FICS may be the least cost solution in some cases, while upgrading grid infrastructure may be the least cost solution in others. For this reason, a detailed analysis of hosting capacity and FICS is needed to fully understand the least cost solution for each location.

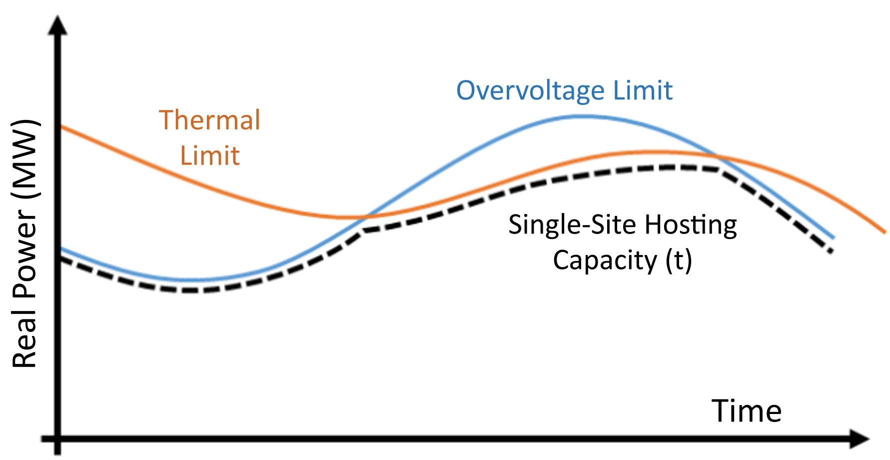

Figure 2. Time Dependence of Hosting Capacity

Figure 3. Location Dependence of Single-Site Hosting Capacity

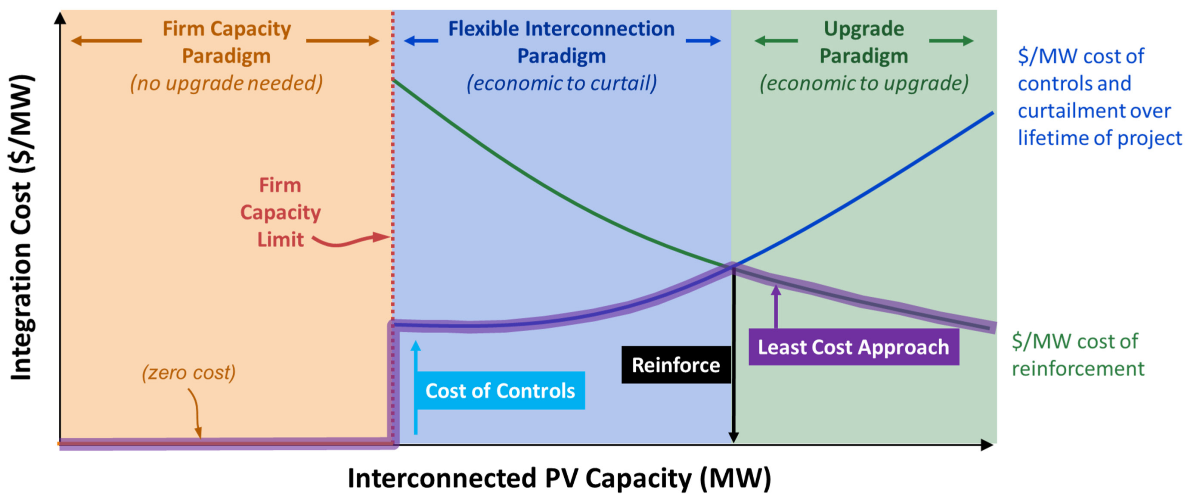

Figure 4. Illustration of least cost solar PV integration approaches

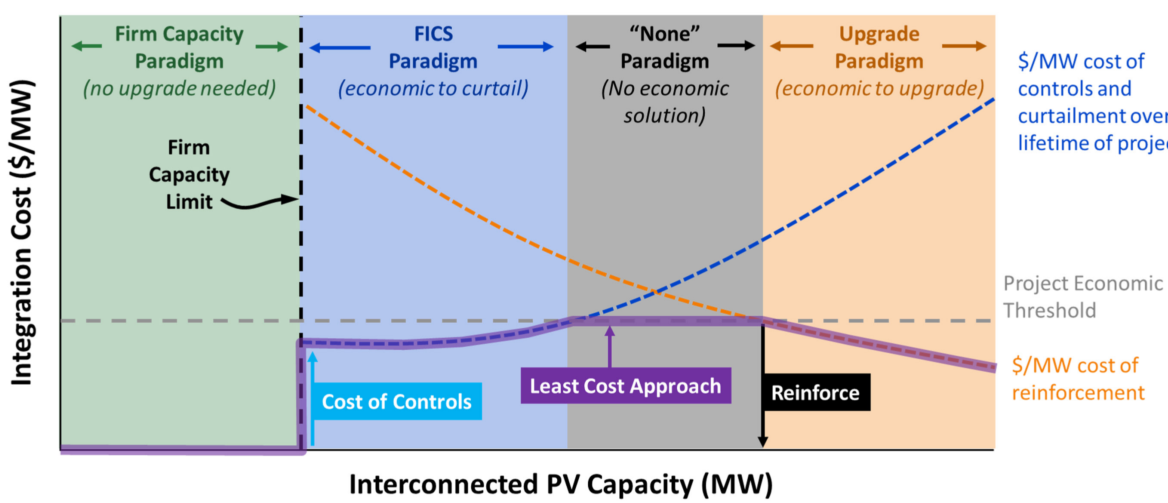

Figure 5. Illustration of four solar PV integration outcomes

Qualifying DER Grid Integration Solutions and Least Cost Approaches

Flexible interconnection and infrastructure upgrade represent two potential least cost approaches for grid integrating DER. Determining which approach is more economically appropriate depends on a range of factors, including available hosting capacity, grid upgrade costs, expected curtailment costs from DER output management, the developer's cost threshold associated with grid interconnection, among others.

Figure 4 (previous page) provides a conceptual illustration of the least cost DER grid integration approach based on the level of interconnected PV capacity. At low penetration levels (orange area), no upgrades are needed given the existing hosting capacity of the network. Once the firm capacity limit is reached, the cost of conventional upgrades (green line) may be much higher than the cost of controls and curtailed DER output (blue line). As penetrations rise, the per unit cost of a conventional reinforcement falls as it is spread across a greater amount of DER capacity. Meanwhile, curtailment costs increase given the higher propensity of binding constraints on the network. At high enough penetrations, the least cost approach (highlighted purple line) is to move back to a firm connection by making the conventional grid reinforcements. Essentially, FICS reaches a critical mass such that the cost of collectively financing all network reinforcements necessary to upgrade to fixed capacity connections is less, over a given time horizon, than the lost revenues that would result from power export curtailments of flexible capacity connections.

An alternative outcome can occur if both FICS curtailment costs and upgrade costs are too high to be financially supported by a particular DER project. This range is illustrated by the gray region in Figure 5 (previous page), where both the flexible interconnection solution costs and conventional mitigation measure costs are above the project's cost threshold.

Examining the Economic Value of FICS

Quantifying the value of FICS depends on the objective associated with a specific perspective. For example, the regulatory perspective may ask what the value of FICS is to achieve high penetrations of distributed PV.[2] Alternatively, the developer perspective may seek to understand the impact of FICS on a project's return on investment.[3] As a result, the value of flexible interconnection can vary greatly and is dependent on a variety of factors, shown in Table 2.[4]

Table 2. Factors influencing the value of flexible interconnection

Factor to Consider	Influence on Conventional Mitigation Measures	Influence on Value of FICS
PV Size	High	High
PV Location	High	High
DC/AC-Ratio	Depends	Depends
DERMS Control Type	No Influence	Moderate
Curtailment Margins	No Influence	Moderate
Load Profile	Mild	Mild
PV Data Source	No Influence	Mild
Location of PV Profile	No Influence	Low

Per Table 2, PV plant size and the location of a project's interconnection are the most influential factors for determining the value of flexible interconnection. For thermal constraints, the costs of conventional mitigation measures increase with PV system size as more lines and other distribution equipment become overloaded and need to be upgraded. For voltage constraints, the flexible interconnection opportunity is more difficult to predict because the system voltage profile is highly dependent upon the location and settings of deployed voltage regulating equipment. However, the degree to which flexible interconnection can provide value is highly correlated to how often the voltage constraints are binding in the future. More generally, the curtailment necessary to avoid grid violations tends to increase as PV capacity increases. All other factors constant, there is an optimal PV size range that yields the highest value for flexible interconnection on a per-kilowatt capacity ($/kW) basis.

The control logic of a distributed energy resources management system (DERMS) represents a moderate influence on the value of FICS. A DERMS is the software platform that can enable additional DER capacity to be interconnected as a managed resource (i.e., by curtailing DER output or enforcing other limits to avoid voltage, thermal and protection violations under infrequent worst-case conditions). The manner in which the DERMS allocates curtailment instructions to a managed resource can result in significant differences in curtailment between individual PV systems and thus, the value of FICS from a developer's perspective. It therefore needs to be considered carefully when deploying FICS as an option. Additionally, differing approaches to communication and con-

2 From the regulatory perspective (i.e. considering total societal costs), the total value of FICS is the avoided cost of conventional mitigation measures less the opportunity cost of curtailment over the project lifetime, less the cost of communications and controls to enable curtailment.

3 From the developer perspective, the value of FICS considers the upper bound to the integration costs that can be supported by a given project. It encompasses the avoided cost of conventional mitigation measures and the developers cost threshold (i.e., willingness to pay for the communication and controls capability to enable FICS) less the opportunity cost of curtailment over the project lifetime.

4 For more information, see *The Value of Flexible Interconnection for Solar Photovoltaics Enabled by DERMS Detailed Techno-Economic Analysis in New York State*, EPRI, Palo Alto, CA: 2021. 3002018505.

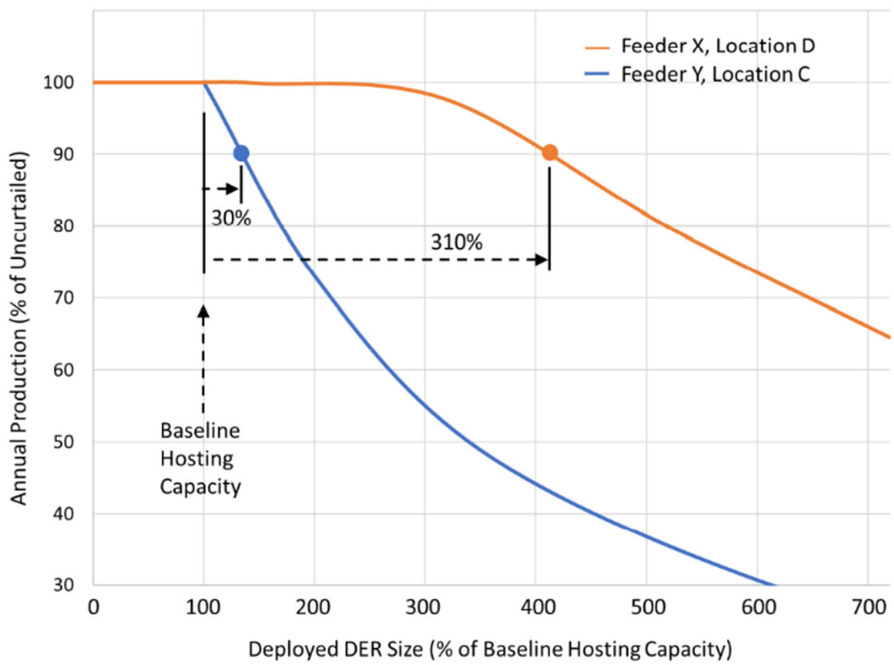

Figure 6. Example FICS opportunity at two PV sites on Feeders X and Y

trol (e.g., centralized DERMS vs. local DERMS[5]) can influence curtailment outcomes at specified times and locations as well as introduce certain requirements, such as the need for accurate forecasts.

A final key challenge for determining the value of FICS is obtaining an adequate estimate of curtailment. The amount and frequency of curtailment directly affects the flexible interconnection opportunity at a given location.

To fully describe the flexible interconnection opportunity a curve can be plotted that shows the estimated production of a DER as a function of its size. This curve is developed from extensive power flow modeling of different sized plants at a location of interest. Figure 6 shows the calculated FICS opportunity at two example PV sites, based on anticipated curtailment associated with DER size.[6] It depicts how different the FICS opportunity may be from one site to another. At location D on Feeder X (orange curve), the production opportunity remains relatively constant as DER size is increased beyond the baseline hosting capacity (i.e., the static hosting capacity limit). In contrast, at location C on Feeder Y (blue curve), the production opportunity drops off sharply once the DER size exceeds the baseline hosting capacity. It is not uncommon to see these variations at different locations on the same feeder.

A single representative number can help compare the viability of FICS across multiple sites. For example, the increase in DER size (above the baseline hosting capacity) that can be made before expected annual production drops to 90% of the uncurtailed value can be used as a general indication of the FICS opportunity at a given node. EPRI refers to this as "FICS90". As labeled in Figure 6, the deployed DER system size on Feeder X location D can be increased by 310% of the baseline hosting capacity before expected production drops to 90% of the uncurtailed value (i.e., the FICS90 as a percentage increase is 310%). In contrast, the FICS90 at the Feeder Y location C is only 30%. This demonstrates that there can be a wide variation in flexibility depending upon the location and the type of constraint that is driving the need for curtailment.

Once an estimate for curtailment is established, and location-dependent integration costs for each assessed DER plant are developed based on location-dependent factors, the integration value of FICS for a specific location can be assessed. Example FICS analyses are illustrated in Figures 7, 8, and 9 for three studied locations. These examples are meant to be illustrative and are not intended to represent expected outcomes for general usage.

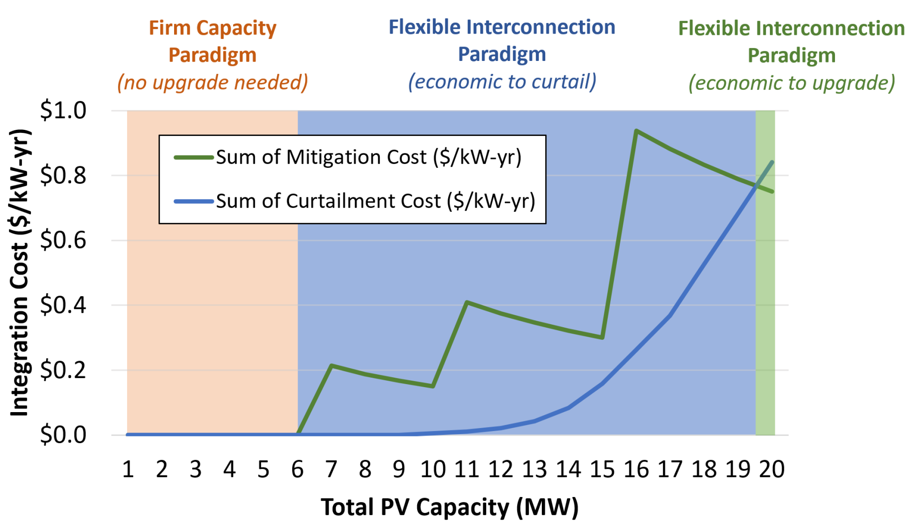

Figure 7. PV integration cost option by PV capacity for Scenario 1 – Location A

5 A DERMS is commonly classified by how it is positioned within the grid architecture, for example, centralized and local DERMS. A centralized DERMS oversees an organization's complete DER portfolio, and it is often integrated with enterprise systems. A local DERMS manages an individual DER or grouping of DERs.

6 For more information, see *Maximizing DER Hosting and Grid Utilization, Flexible Interconnection Capacity Solutions*, EPRI, Palo Alto, CA: 2019. 3002015742 and *Maximizing DER Hosting and Grid Utilization through Flexible Interconnection: Active Power Management*, EPRI, Palo Alto, CA: 2020. 3002018617.

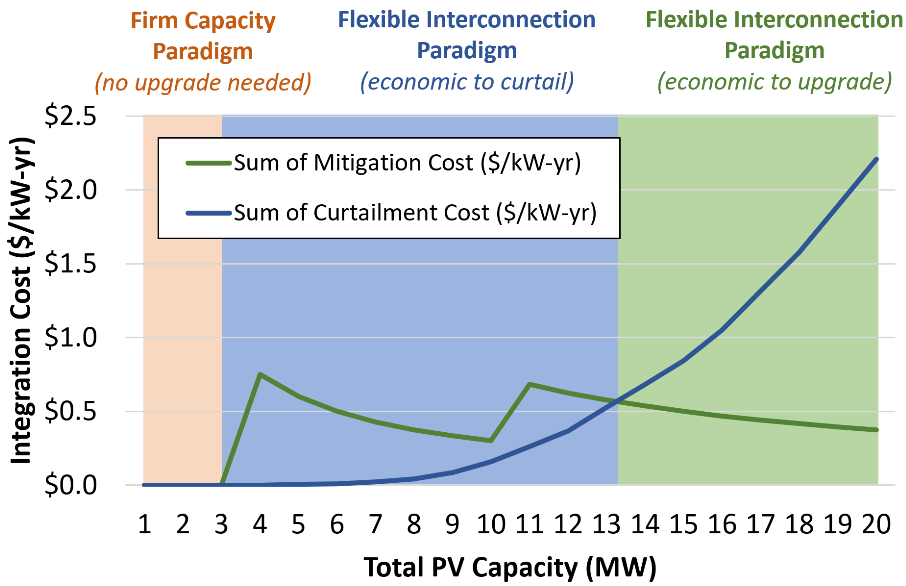

Figure 8. PV integration cost option by PV capacity for Scenario 1 – Location B

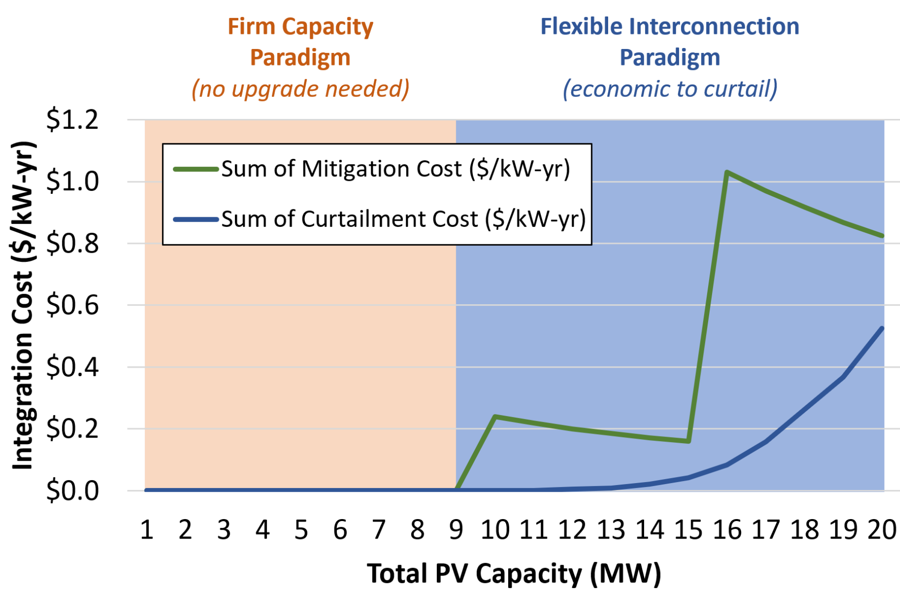

Figure 9. PV integration cost option by PV capacity for Scenario 1 – Location C

For location A (Figure 7), with the cost of curtailment and cost of conventional mitigation measures accounted for, FICS is shown to be economically advantageous as PV capacity expands beyond 6 MW (blue region). However, at a PV capacity above 19 MW, conventional grid reinforcement costs (green line) become lower than FICS curtailment costs (blue line), indicating that it is more economic to upgrade (green region).

The sum of the calculated mitigation costs (green line) increases as more mitigation efforts are needed to accommodate additional PV capacity. However, on a $/kW-yr basis, these mitigation costs decrease as total PV capacity increases. This relationship is reflected in the green line's spiky nature, where at 7 MW, 11 MW and 16 MW, and based on modeling assumptions, transmission thresholds are exceeded and reconductoring is needed to allow for further PV capacity additions. Consequently, mitigation costs jump. But as total PV capacity continues to increase, mitigation costs slowly decrease due to the ratio of total PV capacity to integration cost on a $/kW-yr basis. This in mind, mitigation costs shown in Figure 7 slowly decrease until increased PV capacity requires additional mitigation efforts, causing another jump in mitigation costs. Although Figure 7 uses reconductoring costs as an example of mitigation measures, it is important to evaluate all potential mitigation measures, such as PV site active and reactive power settings and voltage regulating equipment settings, when performing an economic analysis.

A similar outcome is observed for location B (Figure 8), where above 3 MW, flexible interconnection makes it economically viable to curtail energy (blue region) until a PV capacity of 13 MW, where grid reinforcement costs make it economic to upgrade (green region). In contrast, due to the costs of grid reinforcements needed for location C (Figure 9), it is only economic to curtail via flexible interconnection at the PV capacities studied. The economic advantageousness of implementing FICS are moderate for location A, more measured for location B, and more pronounced for location C.

Conclusions and Key Takeaways

Flexible interconnection, when coordinated with infrastructure upgrades, has the potential to offer multiple strategic benefits. Successful coordination, however, will depend on a range of factors such as DER system size, project location, hosting capacity, estimated curtailment, and mitigation costs.

It is expected that as more PV is interconnected to the electric distribution system, the number of grid constraints will increase and the economic potential for FICS will improve. Locations that are thermally constrained due to hosting capacity and where increases in system capacity (e.g., larger substation transformers, reconductoring) may be needed will typically offer the most economically viable FICS opportunities.

That said, few real-world examples of FICS exist today around the world, and those in operation are at an early stage. The more advanced field demonstrations are located in Europe, particularly the U.K. and France, and are exploring the feasibility and value of a range of flexible interconnection approaches. Key ingredients for success have thus far included the presence of challenging network constraints alongside strong demand for new DER connections, geospatial heat maps that signal FICS opportunities to project developers, ample stakeholder engagement, and visibility and transparency to build trust (e.g., openness about dispatch rules, cost apportionment rules, auditable constraints logs, etc.).

Additional pilot demonstrations are needed to further evaluate the various influences on FICS economics and the potential for FICS to help accelerate DER deployment. Findings based on detailed analyses can complement and build upon modeled outcomes, as well as inform both structural and administrative approaches to implementing FICS.

Key areas of inquiry might include:

- The economic efficacy of FICS at multiple feeder locations based on differing circumstances, described in Table 2.
- The factors to consider in the economic evaluation of FICS and their analytical impact.
- The approach and accuracy of estimating curtailment to inform developers about whether to pursue a FICS interconnection.
- The method of allocating curtailment across DER to address a binding constraint and the influence it has on developer participation and cost allocation considerations.
- The fixed versus dynamic value of FICS (e.g., whether the ability for a specific location on a distribution feeder or substation to accommodate a certain amount of DER varies over time).
- How contributions to future upgrade costs can be treated.
- The value of a DERMS, whether local or remote, in terms of its ability to reliably manage DER output to the grid at specified times and locations.
- How the economics of flexible interconnection vary with control method.

Further real-world study and field demonstration can help quantify the technical and economic feasibility of a FICS option for specific scenarios. Findings can, in turn, improve industry and DER developer understanding of the circumstances in which FICS can serve as a least cost solution, and enable both higher levels of DER interconnection, as well as greater distribution system utilization.

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