Distributed Energy Resource Interconnection Roadmap: Identifying Solutions to Transform Interconnection by 2035

DRAFT REPORT – For Comment Only, Not for Citation

Contents

Authors [Preliminary – To be updated]

The primary authors of this report are:

Diane Baldwin, Pacific Northwest National Laboratory (PNNL)
Jessica Kerby, PNNL
Devyn Powell, PNNL
Robert Margolis, NREL
Jarett Zuboy, NREL
Karyn Boenker, PNNL
Eran Schweitzer, PNNL
Thomas McDermott, PNNL (Retired)

i2X Team and Partner Contributors:

Department of Energy (DOE) Solar Energy Technologies Office (SETO):
Michele Boyd, Ammar Qusaibaty, and Dexter Hendricks

DOE Wind Energy Technologies Office (WETO):
Jian Fu, Cynthia Bothwell, Bret Barker, Alice Orrell, and Colette Fletcher-Hoppe

DOE Vehicle Technologies Office (VTO):
Fernando Salcedo

National Renewable Energy Laboratory (NREL):
David Narang, Michael Ingram, Ian Baring-Gould

Lawrence Berkeley National Laboratory (LBNL):
Ryan Wiser, Joseph Rand, Will Gorman, Joachim Seel, and Julie Kemp

Pacific Northwest National Laboratory (PNNL):
Daniel Glover, Todd Wall, Frank Tuffner, Shahnawaz Siddiqui, Tanya Burns (contractor), Prathit Dave, Brent Eldridge, Christine Holland, Jaime Kolln, Danielle Preziuso, Jess Shipley, Abhishek Somani, Brittany Tarufelli, Will Hutton, Rebecca Tapio, and Jeremy Twitchell

Sandia National Laboratory (SNL):
Matthew Reno, Michael Ropp, Rachid Darbali-Zamora

Interstate Renewable Energy Council (IREC):
Radina Valova and Cynthia Finley

Acknowledgments

The authors would like to acknowledge the support of the U.S. Department of Energy Solar Energy Technologies Office (SETO) and Wind Energy Technologies Office for work conducted under Award Number 39631 funded by the Bipartisan Infrastructure Law (BIL).

The authors thank the following DOE reviewers:

<Add List of DOE Reviewers>

The authors would also like to thank the following external reviewers/commenters:

<Add List of External Reviewers/Commenters>

List of Acronyms

ADMS	advanced distribution management system
AI	artificial intelligence
AMI	advanced metering infrastructure
BATRIES	Building a Technically Reliable Interconnection Evolution for Storage
BES	bulk electric system
BESS	battery energy storage system
BPS	bulk power system
CESER	Cybersecurity, Energy Security and Emergency Response
CPUC	California Public Utilities Commission
CRD	Certification Requirement Decision
DER	distributed energy resource
DERMS	distributed energy resources management system
DOE	U.S. Department of Energy
DSO	distribution system operator
DTT	direct transfer trip
EEJ	equity and energy justice
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EJScreen	Environmental Justice Screening and Mapping Tool
EMT	electromagnetic transient
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ESIG	Energy Systems Integration Group
ESJ	Environmental and Social Justice
EV	electric vehicle
FERC	Federal Energy Regulatory Commission
GEO	Governor’s Energy Office
HBCU	Historically Black Colleges and Universities
HCA	hosting capacity analysis

i2X	DOE’s Interconnection Innovation e-Xchange
IBR	inverter-based resource
IEEE	Institute of Electrical and Electronics Engineers
IIJA	Infrastructure Investment and Jobs Act
IREC	Interstate Renewable Energy Council
ISO	independent system operator
LBNL	Lawrence Berkeley National Laboratory
LEAD	Low-Income Energy Affordability Data
ML	machine learning
MSI	Minority Serving Institutions
NARUC	National Association of Regulatory Utility Commissioners
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
NWA	non-wire alternatives
NYSEG	New York State Electric and Gas
OEM	original equipment manufacturer
PCS	power control system
PHIL	power hardware-in-the-loop
PNNL	Pacific Northwest National Laboratory
POI	point of interconnection
PRECISE	PREconfiguring and Controlling Inverter Setpoints
PSC	Public Service Commission
PUC	public utility commission
PV	photovoltaic
QF	qualifying facilities
RECS	Residential Energy Consumption Survey
RTO	regional transmission organization
SDO	standards development organization
SETO	Solar Energy Technologies Office of EERE
SMUD	Sacramento Municipal Utility District

STEM	science, technology, engineering, and math
UFLS	under frequency load shedding
V2G	vehicle-to-grid
VPN	virtual private network
WETO	Wind Energy Technologies Office

Executive Summary

Distributed energy resources (DERs) are poised to contribute significantly to meeting U.S. decarbonization goals. DERs include a diverse and evolving set of technologies. The scope of this roadmap encompasses DERs that require interconnection and primarily provide electricity to consumers, such as distributed solar photovoltaics (PV), distributed wind, and battery energy storage. To date, distributed PV growth has been dramatic. For example, between 2010 and 2023, the number of U.S. residential PV systems grew from 89,000 to 4.7 million. In 2023 alone, almost 800,000 residential PV systems were installed in the United States.[1] Recently, deployment of distributed energy storage systems and electric vehicle (EV) charging infrastructure has also grown rapidly. Distributed wind technologies have significant growth potential as well. This multifaceted DER growth has stressed interconnection processes at the distribution and sub-transmission system levels. DER deployment is expected to continue growing over the next decade, driven by a combination of declining costs and policy incentives. If the potential for DER deployment is to be realized, interconnection processes must evolve to handle large and growing volumes of DER interconnection requests.

The challenges preventing the fast, simple, and fair interconnection of DERs can be summarized in five categories.[2] For DERs broadly, these challenges include timeline and process delays, high grid upgrade costs, lack of grid transparency, and incomplete or outdated technical standards. For example, in some areas, deployment of DERs precedes system upgrades that might otherwise be triggered by load growth through grid planning activities. As DER deployment grows and grid capacity becomes constrained, the utility interconnection process requires proposed DER projects that exceed their load (and thus export electricity to the grid) to cover the cost of enabling grid upgrades, reduce their proposed size, or curtail their generation at times of high production to minimize impacts on the grid. Distributed energy storage projects are additionally challenged because many U.S. interconnection rules have not caught up with the unique characteristics of these projects.

The distinctive characteristics of different types of DERs complicate efforts to address interconnection requirements. For example, among the types of DERs addressed in this roadmap, wind, PV, small hydropower, and energy storage have significantly different resource availability, technology capabilities, and grid impacts. In addition, the pace of deployment and reforms needed to mitigate interconnection challenges varies depending on the market, regulatory, and resource availability landscape. Approaches must be tailored to local conditions

---

[1] SEIA/Wood Mackenzie Solar Market Insight 2023 Year-in-Review. https://www.woodmac.com/industry/power-and-renewables/us-solar-market-insight/

[2] Valova and Brown, 2022, "Distributed energy resource interconnection: An overview of challenges and opportunities in the United States." *Solar Compass*, v.2, August.

and account for when DER deployment impacts broader transmission system design or operation.

This roadmap serves as a guide to key actions that the interconnection community can take within the next 5 years and beyond to implement solutions designed to address current DER interconnection challenges. While DER interconnection processes have been evolving in the U.S. over the past decade, anticipated growth in deployment of a diverse set of DER technologies over the next 5-10 years motivates continued efforts to propose solutions. This document serves as a starting point for future conversations around these solutions.

This DER interconnection roadmap is a result of the Interconnection Innovation e-Xchange (i2X),[3] launched by the U.S. Department of Energy in June 2022 to address interconnection challenges. It complements the Transmission Interconnection Roadmap developed under i2X and recently published by DOE.[4] In contrast to the Transmission Interconnection Roadmap, which focuses on systems connected to the bulk power system, this roadmap focuses on DER systems connected to the distribution[5] and sub-transmission systems.[6] While the line between these systems may vary among jurisdictions, DERs are defined here to include Tribal and state-jurisdictional interconnections for systems up to 80 MW.[7] These systems generally have voltages below 100 kV. In this roadmap, DERs are defined to include systems that meet all the following criteria:

- Systems with points of interconnection at voltages below 100 kV, typically belonging to the distribution and sub-transmission systems, traditionally considered as those not under FERC jurisdiction.
- A range of system sizes from small behind-the-meter, kW-scale systems to larger, in-front-of-the-meter systems less than 80 MW.
- A range of technologies that are not connected to the bulk power system (BPS), such as distributed PV, wind, and energy storage.
- Technologies that primarily provide electricity to meet consumer demand.

---

[3] Office of Energy Efficiency and Renewable Energy (EERE). i2X. www.energy.gov/eere/i2x/interconnection-innovation-e-xchange.
[4] Office of Energy Efficiency and Renewable Energy (EERE). DOE Transmission Interconnection Roadmap: Transforming Bulk Transmission Interconnection by 2035. https://www.energy.gov/eere/i2x/doe-transmission-interconnection-roadmap-transforming-bulk-transmission-interconnection
[5] The electrical facilities that are located behind a transmission-distribution transformer that serves multiple end-use customers. See SPIDERWG Terms and Definitions Working Document (NERC, 2020).
[6] The networked Bulk Power System operated at less than 100 kV, but still above primary and secondary distribution voltages (e.g., greater than 35 kV). See SPIDERWG Terms and Definitions Working Document (NERC, 2020).
[7] 80 MW is the capacity cap for qualifying facilities (QFs) under the Public Utilities Regulatory Policy Act, as clarified by FERC in 2021. See "FERC Clarifies Determination of 80-MW Capacity Cap for QFs" https://www.ferc.gov/news-events/news/ferc-clarifies-determination-80-mw-capacity-cap-qfs

Demand-response and energy-efficiency technologies, such as controllable thermostats, can also be considered DERs, but because they are not typically subject to interconnection processes, they are not a focus of this report.

The solutions identified in the roadmap are possible strategies, not prescriptive fixes. Some solutions are complementary: to be most effective, they may need to be implemented in tandem with others. In other cases, multiple solutions offer different ways to address similar challenges and may be mutually exclusive. The interconnection community should consider a range of approaches and tradeoffs when identifying solutions that best suit their priorities and regional needs.

The i2X process engaged a diverse set of stakeholders, which reflects the fact that reform is a group effort. Regulators and utilities play a role in shaping the reform process along with others, such as interconnection customers, equipment manufacturers, consumer advocates, equity and energy justice (EEJ) communities, advocacy groups, consultants, and the research community, which includes DOE. Members from all these groups engaged in the Solution e-Xchanges, and the solutions described in this roadmap are for this broader community of actors.

The roadmap is organized into four primary goal areas, each important to the overall i2X mission to enable simpler, faster, and fairer interconnection of clean energy resources while enhancing the reliability, resiliency, and security of our electric grid.

Goal #1: Increase Data Access, Transparency, and Security for Interconnection

Solutions in this section show how execution and analysis of interconnection studies could be enhanced by more transparent and accessible data sharing and strategic use of automation. Utilities providing access to grid data must balance the value created with the strains on workforce and computing requirements and with the confidentiality and security of the data. Regulators have a key role in providing guidance to utilities who are beginning to develop methods to access grid and interconnection queue data, as well as those expanding and enhancing data access.

Solutions:

Solution 1.1: Establish guidelines for collecting and sharing grid data that consider tradeoffs between value created, effort required, and data security and accessibility concerns (short-term, low deployment).
Solution 1.2: Expand and standardize reporting of interconnection data, including project attributes and interconnection cost estimates (short-term, medium deployment).
Solution 1.3: Standardize and clarify the technical data that developers of large DER systems must provide on interconnection applications to facilitate interconnection studies (short-term, low deployment).

Solution 1.4: Establish and maintain frequently updated capacity analysis tools that perform repeated studies for increasing amounts of multiple DER technologies at differing locations along a feeder circuit (short-term, medium deployment).
Solution 1.5: Broaden the use of hosting capacity analysis (medium-term, high deployment).

Goal #2: Improve Interconnection Process and Timeline

This goal focuses on solutions to streamline the interconnection process—mitigating bottlenecks that result from misalignment between queues designed for a small number of interconnection requests and rapid growth of DERs requesting connection to the grid. This section covers solutions to improve queue management practices, inclusive and fair processes, and workforce development.

Queue Management

Several incremental queue management solutions may help reduce DER queue volumes and interconnection delays in the near term while enabling utilities to handle larger and variable DER queue volumes in the longer term.

Solutions:

Solution 2.1: Provide pre-application educational materials and self-service options for smaller DER projects (short-term, medium deployment).
Solution 2.2: Require that large DER interconnection applicants meet clear criteria for commercial readiness and queue dwell-time (short-term, medium deployment).
Solution 2.3: Implement and enforce appropriate DER interconnection study timelines and consider penalties for delays in completing studies. (short-term, medium deployment)
Solution 2.4: Continue automating the DER interconnection process (short-term, medium deployment)
Solution 2.5: Automate parts of the DER interconnection study process. (medium-term, high deployment)
Solution 2.6: Enable flexible interconnection so DERs can avoid grid-upgrade costs and delays in exchange for curtailing generation. (medium-term, high deployment)
Solution 2.7: Use a group study process to address existing queue backlogs or avoid anticipated queue backlogs. (short-term, medium deployment)

Inclusive and Fair Processes

While the roadmap goals aim to promote a fair interconnection process for all, not all of the interconnection community starts with the same tools and resources. Achieving equitable outcomes in DER interconnection processes requires intentionally designing systems, technologies, procedures, and policies for the entire interconnection community. Interconnection customers from socioeconomically disadvantaged or Tribal communities may lack the financing, resources, and capacity needed to navigate the interconnection landscape. Interconnection processes could be made more inclusive and fairer by acknowledging and addressing these barriers to expanding equitable DER interconnection access. In addition to the two solutions below, which exclusively focus on inclusivity and fairness in interconnection, many more solutions of the roadmap aim, in part, to resolve current issues of equity within the interconnection process.

Solutions:

Solution 2.8: Advance equitable interconnection through system planning. (short-term, low deployment)
Solution 2.9: Help under-resourced groups navigate the interconnection process through independent dispute resolution, engineering, administrative, and legal services (medium-term, medium deployment).

Workforce Development

Interconnection requires technical expertise across many professions in the electric sector. Targeted efforts to increase training opportunities and improve compensation for existing staff will improve workforce capabilities, increase retention, and enhance diverse and equitable representation across the interconnection workforce. Also important are broader outreach and recruitment efforts intended to raise awareness of interconnection jobs as a key component of the clean energy workforce and ensure that interconnection skills and knowledge are included in educational curricula.

Solutions:

Solution 2.10: Assess the growth of the interconnection workforce required to support anticipated growth in DER interconnection requests. (short-term, low deployment)
Solution 2.11: Upskill the DER interconnection workforce through continuing education. (short-term, low deployment)
Solution 2.12: Enhance retention and targeted recruitment for DER interconnection-related jobs. (short-term, medium deployment)
Solution 2.13: Grow the interconnection workforce via outreach, curriculum development, and partnerships in post-secondary education. (long-term, medium deployment)

Goal #3: Promote Economic Efficiency in Interconnection

This goal seeks to improve DER interconnection outcomes that meet market and policy objectives fairly at lower costs to ratepayers. This section covers solutions to improve cost allocation, coordination between interconnection and grid planning, and interconnection studies.

Cost Allocation

Interconnection costs can be allocated in various ways to improve economic efficiency and equity. When considering cost allocation with respect to interconnecting DERs, it is important to think beyond the traditional cost-causer-pays model.

Solutions:

Solution 3.1: Reform the existing "cost-causer-pays" model, such that a project developer whose interconnection triggers an upgrade is partially reimbursed by subsequent developers who interconnect to the upgraded feeder circuit. (medium-term, low deployment)
Solution 3.2: Build a reserve fund by collecting fees from all interconnecting DER customers and spend the fund on upgrades triggered by subsequent interconnections. (medium-term, medium deployment)
Solution 3.3: Use a group study process that reduces per-project interconnection upgrade costs by allocating costs among multiple projects based on their contribution to the triggered upgrade. (short-term, medium deployment)
Solution 3.4: Proactively upgrade feeder circuits to accommodate forecasted DER growth and recover costs from future DER developers who share the upgraded feeder circuits. (medium-term, medium deployment)

Coordination Between Interconnection and Grid Planning

Cost inefficiencies in interconnection arise in part because some system-level upgrades are typically triggered through the interconnection process, meaning they often occur in a piecemeal fashion. This type of piecemeal approach can risk imposing costs on interconnection customers or ratepayers depending on how regulators balance risks. Closer alignment of data inputs, assumptions, and process timelines between interconnection and long-term grid planning can help ensure more efficient and forward-looking identification and deployment of potential upgrades.

Solutions:

Solution 3.5: Coordinate interconnection for specific DER projects across the distribution, sub-transmission, and transmission systems. (medium-term, medium deployment)
Solution 3.6: Improve coordination and data sharing between the DER interconnection process and the system planning process to promote synergy between the two. (medium-term, medium deployment)

Interconnection Studies

Interconnection study methods must evolve to promote safe and reliable DER interconnection while reducing the need for costly and time-intensive system upgrades.

Solutions:

Solution 3.7: Distinguish between a generator's nameplate capacity and export capacity in interconnection studies to accurately reflect project impacts. (short-term, low deployment)
Solution 3.8: Account for potential grid benefits and costs due to DERs in interconnection studies (medium-term, medium deployment)
Solution 3.9: Allow flexible interconnection as a way to mitigate system upgrade costs during interconnection studies (medium-term, high deployment).

Goal #4: Maintain a Reliable, Resilient, and Secure Grid

This goal centers around maintaining a reliable, resilient, and secure grid by addressing the performance of inverter-based DERs during normal operation and outage conditions. This section describes solutions to improve interconnection models and tools. It also identifies solutions to encourage widespread adoption of existing standards and support development of new standards for emerging technologies and issues, including growing cybersecurity issues.

Interconnection Models and Tools

Improvements to interconnection models and tools are needed to support deploying DERs while maintaining grid reliability.

Solutions:

Solution 4.1: Proactively develop and implement new DER-ready system protection schemes (medium-term, low deployment).
Solution 4.2: Develop alternatives to address unintentional islanding and provide research-based methods to evaluate their cost-effectiveness (medium-term, low deployment).
Solution 4.3: Optimize development and use of EMT models for evaluating the dynamic performance of DERs (long-term, medium deployment).
Solution 4.4: Improve models for analyzing the seam between the transmission and distribution/sub-transmission systems (medium-term, medium deployment).
Solution 4.5: Collect data from DERs to validate models that ensure compliance with BPS reliability standards and to perform large-scale reliability assessments (medium-term, high deployment).

Interconnection Standards

To ensure reliable operation of newly interconnected DERs, comprehensive interconnection standards are necessary.

Solutions:

Solution 4.6: Accelerate adoption of the IEEE 1547 interconnection standard via collaboration among regulators, utilities, and researchers (short-term, low deployment).
Solution 4.7: Develop standards to mitigate the potential impact of inadvertent export (short-term, low deployment).
Solution 4.8: Use guidance from IEEE 1547.3 to address cybersecurity concerns during the interconnection process (short-term, low deployment).
Solution 4.9: Develop a cybersecurity risk management plan for interconnecting projects (short-term, medium deployment).
Solution 4.10: Develop and adopt standards that address performance from emerging technologies such as grid-forming inverters and vehicle-to-grid systems (medium-term, medium deployment).

Measurable Targets for Interconnection Reform

The targets in this roadmap include the following four areas of improvement:

1) Shorter DER interconnection times

2) Higher DER interconnection completion rates

3) Better availability of interconnection data

4) Improved reliability.

The quantitative target values are listed in Table ES-1. The first two targets are tiered by system size to reflect the fact that small (< 50 kW) and large (≥ 50 kW) DER systems are typically subject to very different interconnection processes. These targets are for 2030, which implies they could be achieved with medium-term (3- to 5-year) interconnection reforms in some locations and are based on a mix of historical values and industry expectations. Over the longer term (2030–2040), a broader group of locations across the country could achieve these or similar targets. The data-availability target applies to all U.S. locations.

Table ES-1. 2030 Roadmap Targets

Target	System Size	2030 Target Value
(1) Median time from DER interconnection request to agreement	< 50 kW	Instantaneous
	≥ 50 kW	< 90 days
(2) Completion rate from entering the queue to execution of interconnection agreement	< 50 kW	> 99% within 1 day
	≥ 50 kW	> 85% within 90 days
(3) Availability of public state-level interconnection queue data	N/A	50 states, Washington DC, and territories have public, detailed, and current queue data
(4) Reliability metric TBD	TBD	TBD

Introduction

Meeting the nation's long-term goals to decarbonize the power sector by 2035[8] and the U.S. economy by 2050[9] will require widespread electrification[10] of every sector: transportation, buildings, industry, and agriculture. Electrification and economic growth are projected to increase global electricity demand by up to three quarters by 2050,[11] which will require dramatically expanded deployment of solar, energy storage, and wind energy generating resources.[12] Meeting this deployment goal is contingent on how quickly these clean energy resources can interconnect while ensuring reliability of the grid.

The interconnection process for distributed energy resources (DERs) involves multiple parties and numerous complex laws, regulations, and technical study processes. Driven by state clean energy policies and declining costs for solar, energy storage, and wind resources, interconnection requests have risen significantly over the past several years and so too has the wait time to interconnect. A combination of the complexities of interconnection and the increasing volume of requests has led to uncertainties, delays, and higher costs for resource developers, and a more complicated decarbonization process for ratepayers, utilities, and their regulators.

This roadmap focuses on a subset of those clean energy resources, namely those that connect to the distribution or sub-transmission systems. While DERs include a diverse and evolving set of technologies, the scope of this roadmap encompasses DERs that require interconnection and primarily provide electricity to consumers, such as distributed solar photovoltaics (PV), distributed wind, and battery energy storage. See the "Roadmap Scope" section below for details about the DERs covered in this roadmap.

To date, distributed PV growth has been dramatic. For example, between 2010 and 2023, the number of residential rooftop PV systems grew from 89,000 to 4.7 million, while the capacity of community solar installations grew from 1 GW_{ac} to 7 GW_{ac}. In 2023 alone, almost 800,000 residential PV systems were installed in the U.S.[13,14] Recently, deployment of distributed energy

---

[8] U.S. Department of Energy's Office of Policy. *On the Path to 100% Clean Electricity.* (May 2023). https://www.energy.gov/sites/default/files/2023-05/DOE%20-%20100%25%20Clean%20Electricity%20-%20Final.pdf

[9] U.S. Department of Energy, *Decarbonizing the U.S. Economy by 2050: A National Blueprint for the Buildings Sector.* (April 2024). https://www.energy.gov/eere/decarbonizing-us-economy-2050-national-blueprint-buildings-sector

[10] Electrification converts a non-electrically powered system (gas, fuel oil, etc.) to one that is electrically powered. See: U.S. Department of Energy's Office of Electricity. *What is Electrification?* https://www.energy.gov/electricity-insights/what-electrification

[11] U.S. Energy Information Administration. *Annual Energy Outlook 2023.* (March 2023). https://www.eia.gov/outlooks/aeo/

[12] National Renewable Energy Laboratory. *NREL's 100% Clean Electricity by 2035 Study.* (November 2022). https://www.osti.gov/biblio/1903178

[13] Xu, Chan, and Kannan, 2024, *Sharing the Sun Community Solar Project Data (December 2023)*, NREL, https://data.nrel.gov/submissions/233.

[14] SEIA/Wood Mackenzie Solar Market Insight 2023 Year-in-Review. https://www.woodmac.com/industry/power-and-renewables/us-solar-market-insight/

storage systems and electric vehicle (EV) charging infrastructure has also accelerated. The deployed capacity of energy storage is expected to quadruple globally by 2030, compared to 2018, largely due to widespread EV adoption.[15] While EVs can be considered a non-stationary energy storage asset, the charging infrastructure that enables their use is studied in terms of load. Tracking the growth of energy storage, inclusive of EVs, therefore also indicates load growth from EV chargers. This multifaceted DER growth has stressed interconnection processes at the distribution and sub-transmission system levels.

DER deployment is expected to continue growing over the next decade, driven by a combination of declining costs and policy incentives. A recent analysis by Wood Mackenzie projects that roughly 51 GW of distributed PV, 14 GW of distributed energy storage, and 135 GW of EV charging infrastructure will be installed in the U.S. between 2022 and 2027.[16] A longer-term analysis by the National Renewable Energy Laboratory (NREL) estimates that total deployment of distributed PV alone could grow to 190 GW by 2035, and that other DERs have the potential to make significant contributions on the same time frame.[17] According to the latest Distributed Wind Market Report, 1.1 GW of distributed wind capacity was installed between 2003 and 2023 across the United States, and recent investment activity suggests the sector is also poised for growth.[18] If the potential for DER deployment is to be realized, interconnection processes must evolve to handle large and growing volumes of DER interconnection requests.

The challenges preventing the fast, simple, and fair interconnection of clean energy resources can be summarized in five categories.[19] For DERs broadly, these challenges include timeline and process delays, high grid upgrade costs, lack of grid transparency, and incomplete or outdated technical standards. For example, in some areas, deployment of DERs precedes system upgrades that might otherwise be triggered by load growth through grid planning activities. As DER deployment grows and grid capacity becomes constrained, the utility interconnection process requires proposed DER projects that exceed their load (and thus export electricity to the grid) to cover the cost of enabling grid upgrades, reduce their proposed size, or curtail their generation at times of high production to minimize impacts on the grid. Distributed energy storage projects are additionally challenged because many U.S. interconnection rules have not caught up with the unique characteristics of these projects.

---

[15] U.S. Department of Energy. *Energy Storage Grand Challenge: Energy Storage Market Report.* (2020). https://www.energy.gov/energy-storage-grand-challenge/articles/energy-storage-market-report-2020

[16] Wood Mackenzie, US Distributed Energy Resource Outlook, June 2023 https://go.woodmac.com/der-outlook-2023.

[17] Denholm et al 2022, Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035, NREL https://www.nrel.gov/docs/fy22osti/81644.pdf

[18] Sheridan et al., 2024, *Distributed Wind Market Report: 2024 Edition*, PNNL, https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-36057.pdf.

[19] Valova and Brown, 2022, "Distributed energy resource interconnection: An overview of challenges and opportunities in the United States." *Solar Compass*, v.2, August.

Generator type, timing of generation and loads, point of interconnection (POI), and system design are all considered when evaluating interconnection applications. Another key factor is the size, or capacity, of the interconnecting resource. Size thresholds are commonly used to determine the level of study required to adequately evaluate the grid impacts of new interconnecting DERs. The capacity threshold between smaller and larger projects is typically set at 50 kW, (in some jurisdictions the threshold is lower, often at 25 kW). Smaller DER systems typically qualify for a "simplified" interconnection process, while larger DER systems often must go through a "fast track" or more complex "study" process (see Box on Tiered Interconnection Processes for DERs). Exact size thresholds vary across utilities, Tribes, and states, although most jurisdictions process interconnection applications according to assigned tracks[20].

Both the thresholds and the tracks themselves are likely to evolve over time as DER deployment increases and even smaller projects may need to be studied more closely. The required track can significantly affect the process timeline, process costs, and total interconnection cost. Data from Massachusetts, New York, and California show that interconnection timelines for DERs under 50 kW have remained consistent. However, DERs greater than 50 kW generally have much higher—and, in some cases, increasing—interconnection processing times. For example, for 50- to 100-kW systems in California, the median period between interconnection application submission and approval was about 60 days in 2010 and 100 days in 2022.[21]

The unique characteristics of different types of DERs complicate efforts to address interconnection requirements. For example, among the types of DERs addressed in this roadmap, wind, PV, small hydropower, and energy storage have significantly different resource availability, technology capabilities, and grid impacts. In addition, the pace of deployment and reforms needed to mitigate interconnection challenges varies depending on the market, regulatory, and resource availability landscape. Approaches must be tailored to local conditions and account for when DER deployment impacts broader transmission system design or operation.

---

[20] Manning, David; McAllister, Richard. *Review of Interconnection Practices and Costs in the Western States.* (NREL, 2018). https://www.nrel.gov/docs/fy18osti/71232.pdf

[21] NREL analysis of data from five states, covering PV projects sized between about 50 kW and 5 MW. For state-level PV data analysis see: *Permitting, Inspection, and Interconnection Data and Analytics. NREL's SolarTRACE.* National Renewable Energy Laboratory. https://solarapp.nrel.gov/solarTRACE.

Tiered Interconnection Processes for DERs of Different Sizes

The roadmap solutions apply to most interconnecting DERs, regardless of size or technology, but utilities often have different application processes for different types of systems. In this roadmap, interconnection process types are consolidated into the three tracks shown below, but the specific categories and thresholds vary across utilities.

“Simplified” Track – This fastest interconnection process applies to interconnection of DERs that either fall below a size or voltage threshold, as determined by the utility or regulator, and are otherwise considered unlikely to impact grid operations based on current deployment levels and grid conditions. Applications can typically be processed through technical screens with limited scope. Based on existing utility track classifications, maximum capacity to qualify for the “simplified” track is often set at 25 or 50 kW. These resources may connect to a single- or three-phase service. No study is required.

“Fast” Track – This interconnection process applies to interconnection of DERs that exceed the simplified track threshold but are still unlikely to impact grid operations. Applications can typically be processed by a combination of initial review screens and supplemental review screens with a wider scope than under the simplified track. These screens may be automated and supplemented by a brief review. Fast-track eligibility is determined based on the generator type, generator size, line voltage, and location of the POI. Based on existing utility track classifications, applicable system sizes are often defined from above 50 kW to 5 MW, with exceptions.

“Study” Track – This more-involved application process applies to interconnection of DERs that exceed the fast-track threshold or fail the fast-track technical screens. These projects require additional studies to determine their potential impacts on grid operations and the facilities required to maintain a reliable grid. Applications can be categorized as requiring study via technical screens, but application processing requires engineering review. Based on existing utility track classifications, applicable system sizes are often defined from above 5 MW to 10 MW, with exceptions.

Roadmap Goals and Organization

This roadmap serves as a guide to key actions that the interconnection community can take within the next 5 years and beyond to implement solutions designed to address current DER interconnection challenges. While DER interconnection processes have been evolving in the U.S. over the past decade, anticipated growth in deployment of a diverse set of DER technologies over the next 5-10 years motivates continued efforts to propose solutions. This document serves as a starting point for future conversations around these solutions. This roadmap also identifies solutions that can provide a more comprehensive set of reforms and is organized into four primary goal areas:

1. Increase Data Access, Transparency, and Security for Interconnection
2. Improve Interconnection Process and Timeline
3. Promote Economic Efficiency in Interconnection
4. Maintain a Reliable, Resilient, and Secure Grid

Increase Data Access, Transparency, and Security for Interconnection

This goal centers on improving data availability and transparency to inform interconnection decision-making and to facilitate monitoring of queue reform outcomes. This section of the roadmap discusses establishing guidelines for collecting and sharing grid data, expanding and standardizing reporting of interconnection data, and standardizing and clarifying the technical data that large DER developers must provide on interconnection applications. It also covers establishing and maintaining capacity analysis tools as well as expanding the use of hosting capacity analysis. For all solutions, the value created by the data must be balanced against the effort required to collect and process it and make it available to those who need it. In addition, data access and transparency must be balanced against concerns about data confidentiality, security, and quality.

Improve Interconnection Process and Timeline

This goal focuses on solutions to streamline the interconnection process—mitigating challenges that result from misalignment between queues designed for a small number of interconnection requests and rapid growth of DERs requesting connection to the grid. This section covers three topics. Under queue management, solutions address how generation interconnection requests are managed, from submission of an interconnection request to final execution of an interconnection agreement. Under inclusive and fair processes, solutions address how the interconnection process can be made more inclusive and fairer. Finally, under workforce development, solutions address how professionals working on interconnection are trained, hired, upskilled, and retained.

Promote Economic Efficiency in Interconnection

This goal seeks to improve interconnection outcomes that meet market and policy objectives fairly at lower costs to ratepayers. This section covers three topics. First, potential approaches for reforming cost allocation are suggested to improve the economic efficiency and equity of interconnection costs compared with the traditional cost-causer-pays model. Second, solutions are provided for better coordinating DER interconnection and grid planning to mitigate the piecemeal nature of system upgrades triggered through the interconnection process, as well as the costs that may fall to interconnection customers. Finally, solutions are identified for improving interconnection studies that enable reliable interconnection while reducing the need for system upgrades.

Maintain a Reliable, Resilient, and Secure Grid

This goal centers around maintaining a reliable, resilient, and secure grid by addressing the performance of DERs during normal operation and system outage conditions. This section describes solutions to improve interconnection models and tools to support the reliable and resilient operation of DERs. It also identifies solutions to encourage widespread adoption of existing standards and support development of new standards for emerging technologies and issues, including growing cybersecurity issues.

Each section of the roadmap contains a collection of solutions that make progress toward each goal described above. Some solutions provide improvements across more than one goal area. Specific solutions are placed in the section of the roadmap that aligns most closely with the potential outcomes of the solution. When multiple goals might be achieved for a given solution, that is noted in the specific solution's description. Solutions can also support each other. For example, standardizing data requirements (Solution 1.3) can support automation (Solution 2.4).

While the roadmap goals aim to promote a fair interconnection process for all, not all of the interconnection community starts with the same tools and resources. Achieving equitable outcomes in DER interconnection processes requires intentionally designing systems, technologies, procedures, and policies for the entire interconnection community. Interconnection customers from socioeconomically disadvantaged or Tribal communities may lack the financing, resources, and capacity needed to navigate the interconnection landscape. Interconnection processes could be made more inclusive and fairer by acknowledging and addressing these barriers to expanding equitable DER interconnection access.

The U.S. Department of Energy (DOE) is committed to energy equity, ensuring that all Americans benefit from the shift to clean energy, regardless of their background or where they live. For this reason, equity considerations are addressed throughout the roadmap. Section 2.2 discusses two solutions focused on enhancing equitable outcomes, and solutions in multiple other sections aim to resolve current equity-related issues within the DER interconnection process. Furthermore, the roadmap identifies how all DER interconnection solutions might serve to enhance or interact with equitable interconnection process outcomes. Where appropriate, these solutions reference state-level experiences with implementing equity-focused DER interconnection policies and processes.

Measurable Targets for Interconnection Reforms

This roadmap seeks to support simpler, faster, and fairer interconnection of clean energy resources while enhancing grid reliability, resilience, and security. Some, but not all, elements of this vision lend themselves to measurable targets. For instance, fairness and equity are more difficult to measure quantitatively using currently available data, but timeline length is more easily translated into targets that can be tracked over time. The targets in this roadmap are not intended to be authoritative or exhaustive, but instead to provide a vision for interconnection reforms and high-level, measurable targets to gauge progress. This roadmap includes targets for the U.S. as a whole. Individual Tribes, states, or utilities can consider developing their own measures of success to track outcomes as they proceed with reforms.

There is significantly less publicly available data on DER interconnection than on transmission interconnection. The Federal Energy Regulatory Commission (FERC) requires transmission-level interconnection data collection and reporting (for much of the country), but no single regulatory body is responsible for DER interconnection. As a result, the type and quality of data collected vary considerably across jurisdictions; states with higher DER deployment tend to have more detailed data collection and reporting practices. The section on Goal 1 in this roadmap discusses solutions for interconnection data access and transparency. As DER deployment expands, it makes sense for jurisdictions to improve data collection and reporting while balancing the costs and benefits of these activities.

The targets in this roadmap include the following four areas of improvement:

1) Shorter DER interconnection times

2) Higher DER interconnection completion rates

3) Better availability of interconnection data

4) Improved reliability.

The quantitative target values are listed in Table 1. The first two targets are tiered by system size to reflect the fact that small (< 50 kW) and large (≥ 50 kW) DER systems are typically subject to very different interconnection processes. These targets are for 2030, which implies they could be achieved with medium-term (3- to 5-year) interconnection reforms in some locations and are based on a mix of historical values and industry expectations. Over the longer term (2030–2040), a broader group of locations across the country could achieve these or similar targets. The data-availability target applies to all U.S. locations.

Table 1. 2030 Roadmap Targets

Target	**System Size**	**2030 Target Value**
(1) Median time from DER interconnection request to agreement	< 50 kW	Instantaneous
	≥ 50 kW	< 90 days
(2) Completion rate from entering the queue to execution of interconnection agreement	< 50 kW	> 99% within 1 day
	≥ 50 kW	> 85% within 90 days
(3) Availability of public state-level interconnection queue data	N/A	50 states, Washington DC, and territories have public, detailed, and current queue data
(4) Reliability metric TBD	TBD	TBD

For the first target, interconnection time is defined as the duration in calendar days between a DER interconnection request and an interconnection agreement. This definition does not cover the time between interconnection agreement and commercial operation, which can be impacted by project developers, energy buyers, permitting agencies, and supply chain issues. Though these issues are also important, they are mostly out of this roadmap’s scope. Many solutions in this roadmap, particularly those under Goal 2 that focus on automation and streamlining parts of the interconnection process, will contribute to shorter interconnection times. In 2022, median interconnection times for systems smaller than 50 kW ranged from 11–88 days across California, Massachusetts, and New York.[22] However, process automation should enable instantaneous interconnection agreements for these small systems in the future. In 2022, median interconnection times for systems of 50 kW and larger in California and Massachusetts ranged from 62–291 days. The target of less than 90 days for these large systems is on the lower end of this range and commensurate with the envisioned acceleration in DER deployment.

For the second target, completion rates measure the share of DER projects that complete interconnection agreements relative to total interconnection requests. Completion rates can be helpful in measuring the efficiency and efficacy of the interconnection process. For this target, the completion rate is defined as the percentage of projects that reach completion within the specified period after the date the interconnection application was submitted. The target for projects smaller than 50 kW is greater than 99% within 1 day, while the target for projects 50 kW and larger is greater than 85% within 90 days. These completion rates are ambitious compared with recent rates observed in California, Massachusetts, and New York. However, they should be achievable with the widespread. implementation of interconnection process improvements, and they are commensurate with the envisioned acceleration in DER deployment.

The third target aims to have a slate of detailed interconnection data available in all 50 states, Washington DC, and U.S. territories. Roadmap Solution 1.2 provides a basis for the data items that should be collected and made available, covering project characteristics and status, location, interconnection timeline, and costs. For comparison, in 2024 only six states—California, Connecticut, Hawaii, Illinois, Massachusetts, and New York—published detailed, current, and accessible interconnection queue data, while very little detailed cost information was publicly available. In fact, New York was the only state that provided specific, project-level cost data.[23]

[Description of Target 4 TBD]

There is significantly less publicly available data on DER interconnection than on transmission interconnection. FERC requires transmission-level interconnection data collection and reporting (for much of the country), but no single regulatory body is responsible for DER interconnection. As a result, the type and quality of data collected vary considerably across jurisdictions; states with higher DER deployment tend to have more detailed data collection and reporting practices. The

---

[22] The first two targets in Table 1 were developed using data from three states with publicly available long-term (at least 10-year) project-level data: Massachusetts, New York, and California. There are significant differences in state interconnection queues' components, processes, data consistency, and data availability that leads to a wide range of interconnection times across data reported by states. This wide variability in the availability, quality, and uniformity of data led to a small group of states with sufficient data to analyze in a consistent manner (California, Massachusetts, and New York). *See* Utility Interconnection in Massachusetts (MA DOER, 2024); Distributed Generation Information (NYS DPS, 2024); and Archived Data (California Distributed Generation Statistics, 2023). Hawaii's primary utility, Hawaiian Electric, also provided an online integrated interconnection queue, but does not include adequate data to indicate when projects were approved. *See* Integrated Interconnection Queue (Hawaiian Electric, 2024).

[23] For a more detailed overview of the research on state interconnection data, see *Analysis of Publicly-Available Distribution Interconnection Queue Data* (U.S. Department of Energy and CADMUS, 2024)

section on Goal 1 in this roadmap discusses solutions for interconnection data access and transparency. As DER deployment expands, it makes sense for jurisdictions to improve data collection and reporting while balancing the costs and benefits of these activities.

Roadmap Scope

This DER interconnection roadmap is a result of the Interconnection Innovation e-Xchange (i2X),[24] launched by the U.S. Department of Energy in June 2022 to address interconnection challenges. It complements the Transmission Interconnection Roadmap developed under i2X and recently published by DOE.[25] In contrast to the Transmission Interconnection Roadmap, which focuses on systems connected to the bulk power system, this roadmap focuses on DER systems connected to the distribution[26] and sub-transmission systems.[27] While the line can between these systems may vary among jurisdictions, DERs are defined here to include Tribal and state-jurisdictional interconnections for systems up to 80 MW.[28] These systems generally have voltages below 100 kV and are labeled "DER" in Figure 1.

DERs can be defined in various ways based on technology characteristics as well as local contexts and policy considerations. These varying definitions of DERs encompass resources that generate or store electricity, resources that improve energy efficiency or provide demand response, and EVs. In this roadmap, DERs are defined to include systems that meet all the following criteria:

- Systems with POIs at voltages below 100 kV, typically belonging to the distribution and sub-transmission systems, traditionally considered as those not under FERC jurisdiction.
- A range of system sizes from small behind-the-meter, kW-scale systems to larger, in-front-of-the-meter systems less than 80 MW.
- A range of technologies that are not connected to the bulk power system (BPS), such as distributed PV, wind, and energy storage.
- Technologies that primarily provide electricity to meet consumer demand.

Demand-response and energy-efficiency technologies, such as controllable thermostats, can also be considered DERs, but because they are not typically subject to interconnection processes, they are not a focus of this report.

---

[24] Office of Energy Efficiency and Renewable Energy (EERE). i2X. www.energy.gov/eere/i2x/interconnection-innovation-e-xchange.

[25] Office of Energy Efficiency and Renewable Energy (EERE). DOE Transmission Interconnection Roadmap: Transforming Bulk Transmission Interconnection by 2035. https://www.energy.gov/eere/i2x/doe-transmission-interconnection-roadmap-transforming-bulk-transmission-interconnection

[26] The electrical facilities that are located behind a transmission-distribution transformer that serves multiple end-use customers. See SPIDERWG Terms and Definitions Working Document (NERC, 2020).

[27] The networked Bulk Power System operated at less than 100 kV, but still above primary and secondary distribution voltages (e.g., greater than 35 kV). See SPIDERWG Terms and Definitions Working Document (NERC, 2020).

[28] 80 MW is the capacity cap for qualifying facilities (QFs) under the Public Utilities Regulatory Policy Act, as clarified by FERC in 2021. See "FERC Clarifies Determination of 80-MW Capacity Cap for QFs" https://www.ferc.gov/news-events/news/ferc-clarifies-determination-80-mw-capacity-cap-qfs

Distinguishing DERs based on interconnecting voltage is not always sufficient. For example, a 5 MW PV system connecting to a 34.5 kV POI within the New York State Electric and Gas (NYSEG) service territory would connect to the sub-transmission system and go through a process governed by the New York State Public Service Commission.[29] By the definition above, this system would be considered a DER and would be within scope of this roadmap. In contrast, the same system connected in Central Maine Power territory that connects to a 34.5-kV transmission line would need to go through the transmission interconnection process. By the definition above, this system would not be considered a DER and would be out of scope of this roadmap.

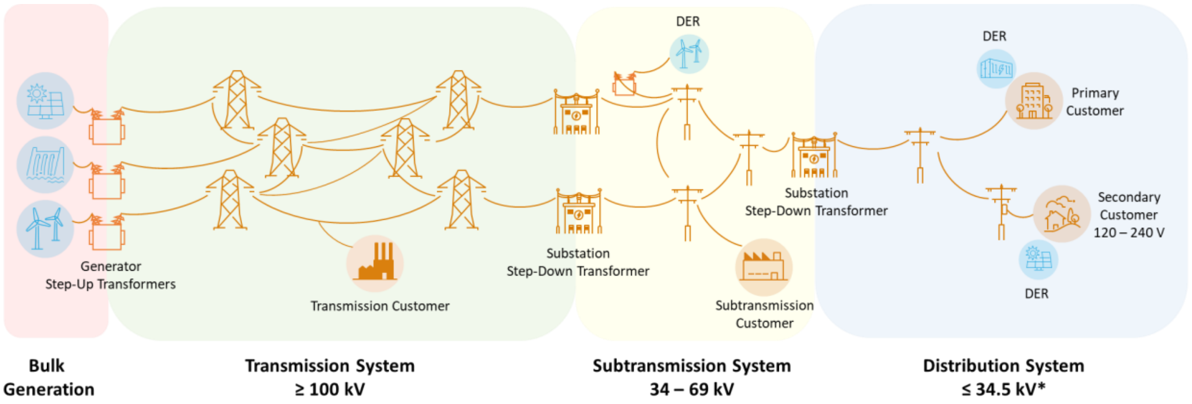

Figure 1. Traditional representation of the power system. This is a simplified representation; other voltages exist at the transmission and distribution levels.

Some jurisdictions refer to voltage levels that are higher than most of the distribution system but still below 100 kV as “sub-transmission.” However, the definition of sub-transmission is not standardized and varies by location. Ultimately, the most important distinction among systems is the purpose of the electric lines. Transmission lines are primarily meant to move electricity over long distances, while distribution and sub-transmission lines primarily serve local customer load.[30]

---

[29] New York State Public Service Commission, New York State Standardized Interconnection Requirements and Application Process For New Distributed Generators and/or Energy Storage Systems 5 MW or Less Connected in Parallel with Utility Distribution Systems, February 2024 https://dps.ny.gov/nys-standardized-interconnection-requirements

[30] For example, NYSEG describes how “34.5kV distribution lines must use a grounded source”, implying that 34.5 sub-transmission might not be grounded. It also describes how “Transmission lines do not directly serve residential customers or other single-phase loads”, that is, non-three-phase circuits are automatically distribution. NYSEG and RG&E Transmission and Distribution Facility Classification Technical Guidance Document, September 2022 https://www.nyseg.com/documents/40132/5899056/NYSEG-RGE+TD+Classification+9-28-2022.pdf/1729fedf-5c99-c287-c1ba-8f975bd7280e?t=1666986692044

Role of Artificial Intelligence (AI) and Machine Learning (ML) in DER Interconnection

AI/ML is expected to play a crucial role in modernizing the grid and deploying clean energy in the U.S.[31] DER interconnection processes and practices could also benefit from AI/ML. AI/ML can support adoption of grid-enhancing technologies such as dynamic line rating and topology optimization to enhance the capacity of the grid, to enable more interconnections, and to reduce interconnection costs.[32] As analyzing the potential impact of interconnection requests becomes more computationally intensive, especially for a utility with high DER deployment, hosting capacity analysis (HCA) and interconnection studies can also benefit from AI/ML approaches and tools. For example, AI/ML could play an important role by improving the performance and automation of power flow modeling tools.[33] This could accelerate the siting and permitting process by reducing the time required to complete interconnection studies. Automation of application completion checks and reviews can also be enhanced by AI/ML capabilities and could help to reduce or eliminate delays at the beginning of the application process and reduce administrative burden.[34]

Applicability of Roadmap Solutions: Deployment Levels and Time Frames

The solutions identified in the roadmap are possible strategies, not prescriptive fixes. Some solutions are complementary: to be most effective, they may need to be implemented in tandem with others. In other cases, multiple solutions offer different ways to address similar challenges and may be mutually exclusive. The interconnection community should consider a range of approaches and tradeoffs when identifying solutions that best suit their priorities and regional needs.

The DER interconnection roadmap only incorporates solutions not yet universally adopted across the United States. Given the significant variation in DER deployment, policies, regulatory structures, market conditions, and other factors nationwide, some solutions may work better in some states or regions than others. Some regions have already adopted a subset of these ideas, while other regions have not. The geographic and temporal variation in solution applicability is expected to continue as the benefits of reforms are weighed against the costs in individual regions. To address this variation, the roadmap assigns a deployment level and a time frame for which each interconnection solution is most appropriate.

---

[31] White House *"Executive Order on the Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence"* 2023. https://www.whitehouse.gov/briefing-room/presidential-actions/2023/10/30/executive-order-on-the-safe-secure-and-trustworthy-development-and-use-of-artificial-intelligence/

[32] U.S. Department of Energy "*AI and Energy: Opportunities for a Modern Grid and Clean Energy Economy*" 2024. https://www.energy.gov/sites/default/files/2024-04/AI%20EO%20Report%20Section%205.2g%28i%29_043024.pdf

[33] Islam, M.T.; Hossain, M.J. *Artificial Intelligence for Hosting Capacity Analysis: A Systematic Literature Review. Energies* 2022, 16, 1864. https://doi.org/10.3390/ en16041864

[34] DNV *The DER Interconnection Backlog: How AI Can Speed Workflows* 2024 https://resources.industrydive.com/the-der-interconnection-backlog-how-to-accelerate-approvals

Low, medium, and high deployment levels are defined based on the three-stage "evolutionary framework" for DER integration and utilization proposed by DOE's Office of Electricity (Table 2).[35] Regions with low deployment and correspondingly low numbers of annual interconnection applications likely can handle applications with existing processes and personnel. Regions with high deployment and high numbers of annual applications likely cannot accommodate every interconnection application, leading to higher application withdrawal rates, delays, and upgrade fees, indicating a need for process improvements and workforce expansion. These levels are rough guideposts, not rigid definitions. They are intended to help the interconnection community understand which solutions apply to their unique situations.

Table 3 defines the range of time frames assigned to each interconnection solution: short, medium, and long term. Most solutions may require ongoing activities. For example, a solution that must be addressed in the short term, such as developing standards to mitigate the potential impact of inadvertent export from DERs (see Solution 4.7), would also require an ongoing effort to determine how to incorporate emerging technologies into the standards as they come into the market. In general, short- and medium-term activities have the potential to require longer-term, ongoing activities, where that makes sense.

Table 2. Deployment levels used in the roadmap to indicate the applicability of interconnection solutions.

Deployment Level	Description
Low **(Stage 1, Grid Modernization)** *Low DER adoption* *(<5% of distribution system peak)*	The local distribution or sub-transmission system can often—but not always—accommodate DERs without significant system upgrades or planning and operational changes. Deployment of grid modernization efforts, including advanced communication and control technologies, is recommended to enhance efficiency and help ensure DERs do not impact grid reliability or safety.[36]
Medium **(Stage 2, Operational Markets)** *Wider scale* *(5%-<15% of distribution system peak)*	DER adoption—including EV charging infrastructure—is increasingly common, and DERs may be used for advanced purposes, including to enhance resilience, act as non-wires alternatives, and offer wholesale capacity and ancillary services. Integrated system planning, widespread adoption of grid modernization technologies, and other upgrades may be required.
High **(Stage 3, DER Optimization)** *Large scale* *(>15% of distribution system peak).*	Widespread adoption of DERs and EV infrastructure, including microgrids. DERs may be more widely used for resilience purposes. Individual and aggregated DERs are optimized to support grid service requirements for distribution and transmission systems. Aggregation and

---

[35] Department of Energy Office of Electricity, "Distribution System Evolution," April 2024 https://www.energy.gov/sites/default/files/2024-05/Distributed%20System%20Evolution%20April%202024_optimized.pdf

[36] Grid modernization is the process by which increasingly obsolete electric infrastructure is made "smarter" and more resilient using advanced technologies, equipment, and controls that communicate and work together to deliver electricity more reliably and efficiently. For example, smart technologies can enable utilities to better view and measure conditions on the grid, communicate information to customers, and respond automatically to disturbances so the duration and impact of outages are minimized.

	system-level energy transactions, as outlined in FERC Order 2222, may occur and require coordination across jurisdictions. More sophisticated interconnection solutions are required.

Table 3. Time frames used in the roadmap to indicate the applicability of interconnection solutions.

Time frame	Description
Short-term *1-3 years (by end of 2027)*	Solution can be implemented within the next one to three years.
Medium-term *3-5 years (by end of 2029)*	Solution can be implemented within the next three to five years but will likely require activities to begin soon to enable eventual implementation.
Long-term *>5 years (after 2030)*	Solution would require additional exploration and development, which could begin today, but would require more than five years to implement.

A Collaborative Roadmap

The scale of the interconnection challenges ahead requires that the entire interconnection community be committed to the roadmap goals of increasing data access and transparency, improving interconnection processes and timelines, promoting economic efficiency, and maintaining a reliable, resilient, and secure grid. To that end, each solution in the roadmap includes an “actors and actions” table, which identifies the entities required to implement the solution as well as the actions those entities could take, falling into three categories:

1. Engineering and technical (e.g., developing generator models, standards, study methods)
2. Markets and regulatory (e.g., designing and implementing cost-allocation policies and ensuring compliance)
3. Administrative and organizational (e.g., changing interconnection processes, identifying workforce needs).

These tables draw on information gathered during workshops held between 2021 and 2023, a series of virtual meetings called Solution e-Xchanges[37] held from April to August 2023, and a request for information published by DOE in August 2024 to solicit public feedback and comments on a draft version of this document.

This process engaged a diverse set of the interconnection community, which reflects the fact that reform is a group effort. Regulators and utilities play a role in shaping the reform process along with others, such as interconnection customers, equipment manufacturers, consumer advocates, equity and energy justice (EEJ) communities, advocacy groups, consultants, and the research community, which includes DOE. Members from all these groups engaged in the Solution e-Xchanges, and the solutions described in this roadmap are for this broader community of actors.

---

[37] See i2X Solution e-Xchanges (DOE, 2023)

Primary actors captured in the roadmap tables include the following:

- **Regulators:** Various government entities with authority over interconnection policy or funding initiatives. This includes regulatory entities such as public utility commissions; state, local, and Tribal governments; and community choice aggregators.
- **Utilities:** Investor-owned utilities, municipal and other public utilities, and electric cooperatives.
- **Interconnection Customers:** Resource developers, generator owners, and their original equipment manufacturers (OEMs).
- **Research Community:** Academic, government (including but not limited to DOE), and NGO researchers involved in creating new analyses, reports, and solutions.
- **Software Developers:** Entities that develop software products for other actors within the interconnection process.
- **National Trade and Utility Associations:** Organizations that represent trade and utility interests, such as the National Rural Electric Cooperative Association, the American Public Power Association, the National Association of Regulatory Utility Commissioners, the Distributed Wind Energy Association, and the Solar Energy Industries Association.
- **Educators:** People and organizations from higher education and continuing education that interact with the current and future interconnection workforce.
- **Standards Agencies:** Organizations working to develop standards designed to promote safe and best practices within the industry, such as IEEE and UL.

Additional key actors include other industry participants, ratepayers, and public interest, advocacy, and community groups. Impacts on relevant groups are discussed in each solution where appropriate and should be considered and included in engagement activities as part of adopting any reforms. It is expected that these groups will engage in the reform process in a variety of different roles and responsibilities, depending on their specific area of expertise.

DOE plays several key roles in executing the solutions outlined in the roadmap. These roles include convening stakeholders, facilitating the adoption of solutions, offering technical support, providing loans, and backing the research community. Various DOE offices are involved in interconnection-related activities. These include the Office of Cybersecurity, Energy Security and Emergency Response (CESER), the Office of Electricity (OE), the Office of Energy Justice and Equity (EJE), the Grid Deployment Office (GDO), the Industrial Efficiency and Decarbonization Office (IEDO), the Loan Programs Office (LPO), the Solar Energy Technologies Office (SETO), the Vehicle Technologies Office (VTO), the Water Power Technologies Office (WPTO), the Wind Energy Technologies Office (WETO), and the Joint

Office of Energy and Transportation (collaboration with the Department of Transportation). These offices contribute to the implementation of the roadmap's solutions through funding for research, pilot projects, standards development, and stakeholder engagement. A comprehensive list of ongoing interconnection-related activities and programmatic priorities can be found in Appendix A. Many of these offices have transmission system interconnection-related activities and programmatic priorities that can be found in the DOE Transmission Interconnection Roadmap.

1. Increase Data Access, Transparency, and Security for Interconnection

Data access and transparency vary substantially across states and utilities in the United States. Utilities in approximately half of all U.S. states, plus Washington, DC and Puerto Rico have begun to develop hosting capacity maps to provide developers with information on where interconnection costs may be lower due to the ability of the utility facilities to integrate additional generation while maintaining reliability and facility limits, and where interconnection may trigger expensive upgrades due to capacity constrained feeder circuits.[38] Adoption of these maps can help reduce information-seeking interconnection requests and enhance equitable outcomes by improving information accessibility, identifying areas that could benefit from infrastructure upgrades, and providing demographic and equity layers to aid resource siting. While adoption of these maps is increasing, it is not currently a nationwide or standardized practice. Additionally, they also present some important trade-offs that need to be evaluated by decision makers: they can be resource-intensive to develop and maintain, and they may contain competitively sensitive information about developers and utilities that needs to be kept secure.

Additional improvements to interconnection data transparency have several aims that support comprehensive interconnection reform:

- Improve interconnection customers' ability to screen and site potential projects.
- Facilitate shared understanding of analytical techniques, including more process automation.
- Enhance understanding of the need for DER projects to be studied by transmission operators under an affected system study.
- Enhance competition while ensuring equitable outcomes.
- Enable benchmarking, tracking, and auditing of interconnection processes and reforms.

Key Takeaways

Execution and analysis of interconnection studies could be enhanced by more transparent and accessible data sharing and strategic use of automation. Utilities providing access to grid data must balance the value created with the strains on workforce and computing requirements and with the confidentiality and security of the data. Regulators have a key role in providing guidance to utilities who are beginning to develop methods to access grid and interconnection queue data, as well as those expanding and enhancing data access. Some utilities are providing hosting capacity maps, and utilities can consider options for expanding the capabilities of these

---

[38] See U.S. Atlas of electric distribution system hosting capacity maps (Office of Energy Efficiency and Renewable Energy, 2023) for a list of publicly available hosting capacity maps by state and utility.

maps, including increased accuracy, granularity, and frequency of updates. Again, a balance must be maintained between the effort needed to produce and visualize the hosting capacity analysis and the value created.

Solutions Content

Solution 1.1: Establish guidelines for collecting and sharing grid data that consider tradeoffs between value created, effort required, and data security and accessibility concerns (short-term, low deployment).

Making grid data transparent and accessible can provide value to multiple parties in the interconnection process. The National Association of Regulatory Utility Commissioners' (NARUC) Grid Data Sharing Playbook[39] provides a framework for public utility commissions (PUCs) and interested parties to address questions related to grid data sharing and provides a basis for regulatory decision-making. It also provides several use cases that discuss how grid data sharing might be leveraged to create value for multiple groups. For example, the playbook argues that grid data sharing can create value for DER developers by helping them identify locations where there is a greater likelihood of interconnection success, enabling them to realize fewer interconnection process delays, and minimizing interconnection costs. In this use case, value can also be created for the utilities via creating shorter interconnection queues. This can improve cost and efficiency by helping utilities reduce the number of upgrades that need to be made in response to interconnection requests outside of grid planning cycles. Greater data accessibility can also help enhance utilities' ability to manage DERs in ways that better take advantage of their capabilities to contribute to grid reliability and operational resilience.[40].

Transparent and accessible grid data also benefits researchers, whose work can further improve interconnection outcomes. For example, the DOE-sponsored Open Energy Data Initiative Solar Systems Integration Data and Modeling Platform integrates data from multiple sources with the goal of facilitating power system analysis, software development, and—ultimately—widespread DER deployment.[41] The datasets collected and the requirements for data exchange should be clearly identified. Data sharing can bring greater value for all parties when efforts are directed toward standardizing information models, communication protocols, and data requirements.[42]

Data collection and sharing can entail significant effort, which should be balanced against the value added. For example, an online tool that enables prospective interconnection applicants to estimate costs may be more useful than a simple list of prices for equipment used in

---

[39] See NARUC grid data sharing playbook (NARUC, 2023).

[40] See *Seeing Behind the Meter* (Oxford Economics and Siemens, 2024) for discussion of how grid transparency can enable, for example, adoption of use of distributed energy resource management systems (DERMS), which can help utilities manage the grid, improve reliability, and offer other customer benefits.

[41] See OEDI Solar Systems Integration Data and Modeling https://openei.org/wiki/OEDI-SI/Overview.

[42] PNNL. 2023. Power Sector Transmission & Distribution Data and Information Webinar Series, Topic 2. Cross-sector & Open Data Sharing and Risks. https://www.pnnl.gov/sites/default/files/media/file/Topic2Webinar_PresentationSlides-v0_website.pdf.

interconnection upgrades, but it requires more resources to create and maintain. Thus, to date, only a few utilities provide even estimated upgrade cost tables for DER interconnection.[43]

The risks associated with data collection and sharing—including risks to consumer privacy, security, or commercial interests—should also be considered. For example, in 2021, the New York Public Service Commission (PSC) ordered that system data at the distribution level be publicly available unless it can impact customer privacy or critical infrastructure protection. The New York PSC has continued to work collaboratively to develop a risk-based approach for assigning cybersecurity and privacy requirements that balances the benefits and risks of data sharing.[44] The NARUC playbook includes other examples of how PUCs have addressed risk related to data collection and sharing.

Standardizing data reporting in tabular, machine-readable formats and making them available for extended periods would improve accessibility. As of fall 2023, dozens of states had considered grid data sharing in various contexts, from advanced metering deployment to electric vehicle charger siting to DER interconnection queues. However, only a few state PUCs have engaged utilities and other groups in a comprehensive discussion of or rulemaking process on grid data sharing.[45] Developing data collection and sharing protocols collaboratively maximizes the value of the data and its use by the interconnection community.

Table 4. Solution 1.1 Actors and Actions — Establish guidelines for collecting and sharing grid data that balance the value created with the effort required while accounting for data security and accessibility.

<table>
<tr><th>Actor</th><th>Engineering and Technical</th><th>Market and Regulatory</th><th>Administrative and Organizational</th></tr>
<tr><td>**Regulators**</td><td colspan="3">- Establish or enhance data-sharing regulatory guidance according to categories described in the NARUC Grid Data Sharing Playbook[46]: use case; state priorities; current practices, requests, and options; desired outcomes; data details; potential impacts; and data sharing tactics.</td></tr>
</table>

---

[43] Eversource in Massachusetts published a table with typical distribution and substation modification costs for DER projects (Eversource, Distributed Energy Resources (DER) Project Costs https://www.eversource.com/content/residential/about/doing-business-with-us/interconnections/massachusetts/distributed-energy-resources-project-costs). Central Maine Power published a similar table: (Central Maine Power, Distributed Generation Project Costs, January 2022 https://www.cmpco.com/documents/40117/115964135/Typical%2BSystem%2BModifications%2Bfor%2BDG%2B01.28.22.pdf/4db88be5-74ee-eb6c-52eb-dfd4ebcf7d51).

[44] See State of New York Public Service Commission Order Adopting A Data Access Framework and Establishing Further Process (April 15, 2021) in Case 20-M-0082 - In the Matter of the Strategic Use of Energy Related Data. https://jointutilitiesofny.org/sites/default/files/ORDER%20ADOPTING%20A%20DATA%20ACCESS%20FRAMEWORK%20AND%20ESTABLISHING%20FURTHER%20PROCESS.pdf

[45] NARUC, "Grid Data Sharing: Brief Summary of Current State Practices (2023), https://pubs.naruc.org/pub/145ECC5C-1866-DAAC-99FB-A33438978E95. According to NARUC, states that have opened proceedings related to grid data sharing are California, Colorado, Connecticut, Delaware, Georgia, Hawaii, Illinois, Maryland, Massachusetts, Michigan, Minnesota, Nevada, New Hampshire, New Jersey, New York, North Carolina, Oregon, Rhode Island, Vermont, Virginia, Washington, and Washington, DC.

[46] NARUC Grid Data Sharing Playbook (2023). https://pubs.naruc.org/pub/E2E50FD7-CD1B-62D5-1071-8D8362AD1E6D?_gl=1*5dylaq*_ga*MjA0ODQ3NDkyOC4xNjkwODQwNTk0*_ga_QLH1N3Q1NF*MTcwMzAyMjc1Mi4zLjAuMTcwMzAyMjc1NS4wLjAuMA.

	- Convene the interconnection community to explore data sharing in terms of value creation and to facilitate shared understanding of the risks and potential impacts of grid data sharing.		
Utilities	- Develop and support development of data-sharing practices.	- Comply with requirements for data sharing.	- Participate in collaborative processes to provide context on the burden, risks, and potential impacts of grid data sharing.
Interconnection customers	- Review and inform utility of any errors in data.	- Review and inform utility of any missing datasets.	- Participate in collaborative processes to inform prioritization of shared data. - Review and inform utility of any data accessibility concerns.
Research community (including DOE)	- Support development of data-sharing practices.	- Propose additional datasets and metrics. - Support development of infrastructure and recommendations for standards that enable secure and efficient data sharing and transparency.	

Solution 1.2: Expand and standardize reporting of interconnection data, including project attributes and interconnection cost estimates (short-term, medium deployment).

As DER deployment increases, interconnection data reporting should be expanded and standardized in a manner that balances costs and benefits. Currently, data requirements vary widely. At the end of 2023, 21 states required utilities to provide itemized upgrade cost estimates to interconnecting applicants, 15 states required utilities to publish annual data on interconnection timelines and costs, and only 4 states required utilities to publish queues that enable tracking of timelines associated with each step of the interconnection process for each project in the queue. Thirteen states have not adopted statewide interconnection procedures and thus have not established any data collection and transparency requirements.[47]

Interconnection data—such as queue volumes, processing times, costs, and project location, size, and type—can provide multiple benefits. The data can be used to inform siting decisions, observe grid trends, monitor and improve interconnection processes and outcomes, and track the progress of reforms. This information can benefit developers by mitigating the risk of unexpected fees, delays, and cancellations which can be especially beneficial to EEJ communities and resource constrained projects.

Utilities in regions that have reached medium levels of DER deployment should consider collecting the following items for each project that enters the queue, to aid in tracking interconnection time and cost in the context of project and community characteristics. This list was informed by i2X Solutions e-Xchange participants during the Grid Data Transparency topic

---

[47] See Freeing the Grid (IREC, 2023)

meetings. These items should be readily available to utilities[48]: items 1–6 come from DER applications, and items 7–12 are generated by utilities as part of the application review process.

1. Technology
2. Rated power (kW)
3. Stored energy (kWh)
4. Institute of Electrical and Electronics Engineers (IEEE) 1547 Reactive Power Category, commonly referred to as voltage and reactive power capability[49]
5. IEEE 1547 Disturbance Category, commonly referred to as voltage and frequency ride-through capability.
6. Location (Census Block Group)
7. Application date and interconnection agreement date
8. Construction completion date and permission to operate date
9. Status (active, operational, withdrawn, suspended)
10. Estimated cost of studies and fees ($ quoted by the utility)
11. Estimated cost of all system upgrades, including facilities charges and network upgrades ($ quoted by the utility)
12. Final cost of interconnection, including costs of all studies and any required system upgrades ($ billed by the utility)

A common format for DER interconnection data reporting, including standardized software for uploading data, would facilitate analysis. For example, for the BPS, transmission interconnection queue analysis is supported by a uniform data reporting format based on FERC and Energy Information Administration (EIA) reporting requirements. The standard format facilitates understanding of the BPS data, identification of data gaps, and resolution of those gaps.[50]

Table 5. Solution 1.2 Actors and Actions — Expand and standardize reporting of interconnection data, including project attributes and interconnection cost estimates.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Expand and improve data collection and reporting requirements.	- Aggregate, organize, and publish interconnection data.
Utilities	- Collect and organize data as needed. - Automate data compilation and reporting. - Share data as appropriate with DER aggregators.	- Ensure compliance.	- Share data management best practices across utilities. - Determine whether information technology infrastructure requires updating.

---

[48] Interstate Renewable Energy Council. *Model Interconnection Procedures: 2023 Edition.* (IREC, 2023) https://irecusa.org/resources/irec-model-interconnection-procedures-2023

[49] Narang et al, An Overview of Issues Related to IEEE Std 1547-2018 Requirements Regarding Voltage and Reactive Power Control (NREL, 2021) https://www.nrel.gov/docs/fy21osti/77156.pdf

[50] *Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection* (Lawrence Berkeley National Laboratory, 2023) https://emp.lbl.gov/queues

Interconnection customers	- Develop tools to leverage data to improve pre-request screening.	- Participate in the regulatory process to provide context to the value of information.	
Research community (including DOE)	- Support data collection, compilation, and synthesis. - Increase scope, depth, and frequency of data analysis.	- Coordinate with regulators and utilities for data sharing.	- Engage with regulators, developers, and utilities to determine data needs.

Solution 1.3: Standardize and clarify the technical data that developers of large DER systems must provide on interconnection applications to facilitate interconnection studies (short-term, low deployment).

Developers and utilities can benefit from ensuring that adequate DER technical data are included in interconnection applications to determine whether interconnecting a specific DER will require grid upgrades. A transparent interconnection process successfully communicates all data requirements to interconnecting developers upfront to allow applicants to prepare for and provide all necessary information at time of applying. Potential benefits include lower numbers of information-seeking interconnection applications, lower withdrawal rates, and shorter time frames for projects to progress through queues. Prioritizing usability and clarity of interconnection application requirements upfront not only improves the quality of interconnection applications, but avoids confusion, delays, and additional communications to the utility seeking clarification.[51]

Interconnection applications for large DERs may require a detailed interconnection study and should clearly elicit standardized technical information needed for any required studies, including technical data requirements for power system models and compatible formats required for the utility's modeling platform. Additional requirements for communication between the applicant and utility—if technical data change during the study time frame—should be clearly spelled out.[52]

The necessary data may include operational parameters. For example, how energy storage and EV charging infrastructure interact with the grid can be influenced by the time of day and energy prices. The interactions of PV-plus-storage systems with the grid can depend on how they are operated to balance storing versus selling power to the grid. Distributed wind turbines have varying operational characteristics and control functions that can mitigate integration concerns. Interconnection applications must accurately capture these different types of operating profiles.

---

[51] Horowitz, Kelsey, Zac Peterson, Michael Coddington, Fei Ding, Ben Sigrin, Danish Saleem, Sara E. Baldwin, et al. 2019. An Overview of Distributed Energy Resource (DER) Interconnection: Current Practices and Emerging Solutions. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72102. https://www.nrel.gov/docs/fy19osti/72102.pdf.

[52] i2X Solutions e-Xchange participants highlighted the importance of explicit and timely communication between utility and applicant to ensure efficient and accurate application process, *Grid Data Transparency Solution e-Xchange,* May 31st, 2023. Recording: https://youtu.be/spqL-0wqGv8. i2X Solutions e-Xchanges: https://www.energy.gov/eere/i2x/i2x-solution-e-xchanges

To ensure grid reliability, it is important that the proposed operating profiles of interconnecting DERs remain accurate; once interconnected and operational, monitoring and verification strategies can be employed to ensure DER systems comply with their proposed operating schedules.[53]

Table 6. Solution 1.3 Actors and Actions — Standardize and clarify the technical data that developers of large DER systems must provide on interconnection applications to facilitate interconnection studies

Actor	Engineering and Technical	Markets and Regulatory	Administrative and Organizational
Regulators		- Expand and improve requirements for study data and transparency in study assumptions.	
Utilities	- Describe study methods and requirements for supporting data that accurately model various DER technologies.	- Engage with industry trade groups to determine additional information needs for various types of DER.	- Better integrate data updates with interconnection application processing updates.
Interconnection customers		- Engage with utilities to determine additional information needs.	- Become familiar with data requirements and file correct application from the start.
Research community (including DOE)	- Develop requirements for supporting data that accurately model emerging technologies. - Update standards and certification process to account for evolving technical and operational capabilities of DER technologies	- Verify and educate industry on operating characteristics of evolving DER technologies	

Solution 1.4: Establish and maintain frequently updated capacity analysis tools that perform repeated studies for increasing amounts of multiple DER technologies at differing locations along a feeder circuit (short-term, medium deployment).

Hosting capacity analysis uses modeling to evaluate the grid's infrastructure and load patterns in order to enable more efficient interconnections and grid planning. HCA models can provide a snapshot of the grid's ability to host additional DER at specific locations without system upgrades or studies, as well as insights into the cost of interconnection at different locations. HCA can provide valuable information to resource developers, utilities, and regulators alike: HCA can be used internally by utilities to aid in distribution planning activities, or externally to help developers make informed siting decisions when HCA results are published in the form of maps. HCA results can also be incorporated directly into the interconnection process by

---

[53] Building a Technically Reliable Interconnection Evolution for Storage (BATRIES). *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage.* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

informing fast-track and screening of projects. As of August 2024, HCA maps were available for utilities in 26 states plus the District of Columbia and Puerto Rico.[54] The DER technologies included in these maps (PV, storage, EVs), their level of detail, and accessibility vary by utility. The existing HCA maps should be viewed as a starting place: they do not include some emerging DER technologies, such as distributed wind, and they typically do not account for the interactions between DER technologies. More widespread adoption of and further development of HCA tools and maps can help enable more transparent, efficient, cost-effective, and equitable interconnection and grid planning for developers and utilities alike.

HCA tools work by performing repeated studies for increasing amounts of DER at differing locations along a feeder circuit. HCA typically focuses on investigating DER impact on voltage, power quality, protection, and thermal limits of grid equipment. This analysis incorporates similar technical inputs and considerations as an interconnection study, with the key difference that it can be done for multiple DERs at multiple locations. The required steps are shown in Figure 2.

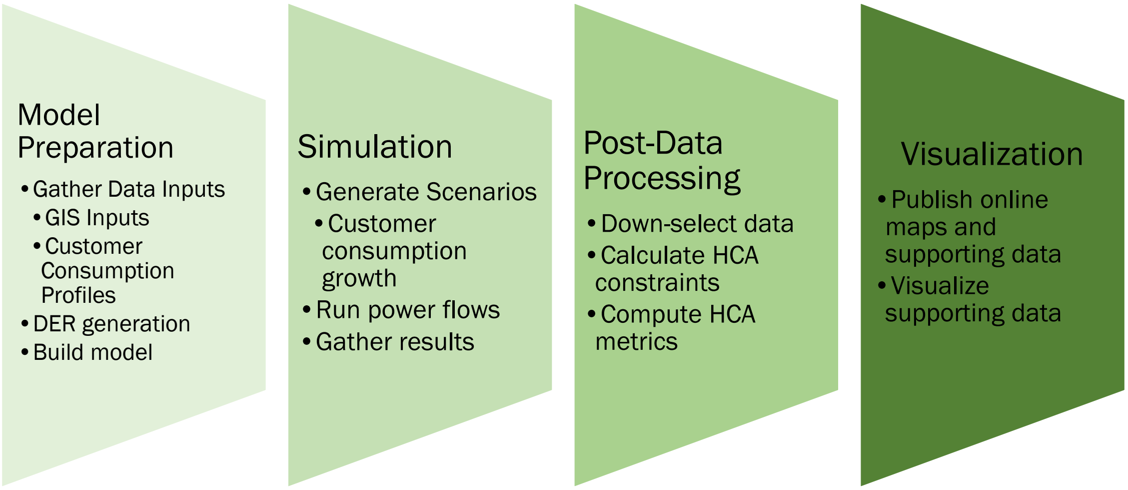

Figure 2. Hosting capacity analysis steps[55]

The data required for the hosting capacity analysis includes models of existing distribution and sub-transmission systems, a model of interconnecting generators, and approximate specifications for forecasted project equipment. The resulting hosting capacity maps can improve the accessibility and transparency of interconnection data, which can enable developers to make informed decisions during project planning and reduce the need for information-seeking

---

[54] See U.S. Atlas of electric distribution system hosting capacity maps (Office of Energy Efficiency and Renewable Energy, 2023) for a list of publicly available hosting capacity maps by state and utility.

[55] Nagarajan, Adarsh and Yochi Zakai. 2022. Data Validation for Hosting Capacity Analyses. (Presentation. NREL and IREC, 2022) https://www.nrel.gov/docs/fy22osti/82884.pdf

interconnection requests.[56] HCA can also help improve equitable outcomes by mitigating barriers to accessing queue information.[57] However, effectively using HCA for siting and fast-tracking may require different levels of data granularity and update frequency that are suitable to different HCA methodologies and tools. For example, for HCA results to be integrated into interconnection screening processes, HCA tools must be capable of performing highly granular and up-to-date analysis.[58] It is important to note that in order to maximize the benefits and utilization of HCA, published results must be trusted and reliable; this requires a robust and transparent data validation and tracking process.[59]

Developing consistent tools to visualize and analyze interconnection data will likely require an industry-wide effort and ongoing discussions among the interconnection community to determine which kinds of data visualizations and analyses are most appropriate as well as the scheduled update cadence and types of changes that trigger an unscheduled HCA update, even if only for that section or feeder circuit. The Interstate Renewable Energy Council's (IREC's) *Key Decisions for Hosting Capacity Analysis* report discusses these considerations in greater detail, emphasizing the importance of making key decisions upfront about the uses and tradeoffs of HCA in a given jurisdiction.[60] Finally, tradeoffs and limitations of some HCA tools and approaches should be addressed and considered to ensure that HCA accurately models a range of DER technologies and can be effectively used for system planning. These considerations are particularly important in jurisdictions with higher levels of DER deployment and are discussed in Solution 1.5.

---

[56] Stanfield, Sky; Safdi, Stephanie; Shute, Mihlay & Weinberger LLP. *Optimizing the Grid: A Regulator's Guide to Hosting Capacity Analysis for Distributed Energy Resources.* 2017. Interstate Renewable Energy Council. https://irecusa.org/wp-content/uploads/2021/07/IREC-Optimizing-the-Grid-2017-1.pdf

[57] Stanfield, Sky; Zakai, Yochi; McKerley, Matthew; Shute, Mihaly & Weinberger LLP. *Key Decisions for Hosting Capacity Analysis.* 2021. Interstate Renewable Energy Council. https://irecusa.org/wp-content/uploads/2021/10/IREC-Key-Decisions-for-HCA.pdf

[58] Stanfield, Sky; Zakai, Yochi; McKerley, Matthew; Shute, Mihaly & Weinberger LLP. *Key Decisions for Hosting Capacity Analysis.* 2021. Interstate Renewable Energy Council. https://irecusa.org/resources/key-decisions-for-hosting-capacity-analyses/

[59] Nagarajan, Adarsh and Yochi Zakai. 2022. Data Validation for Hosting Capacity Analyses. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81811. https://www.nrel.gov/docs/fy22osti/81811.pdf.

[60] IREC, 2021, Key Decisions for Hosting Capacity Analyses, https://irecusa.org/resources/key-decisions-for-hosting-capacity-analyses/.

Table 7. Solution 1.4 Actors and Actions — Establish and maintain frequently updated capacity analysis tools that perform repeated studies for increasing amounts of multiple DER technologies at differing locations along a feeder circuit.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Hire or contract with distribution planning experts to better inform and evaluate HCA requirements. - Ensure that the HCA maps align with state and local policy goals for DERs.	- Regulatory oversight of HCA tools, analysis and data validation processes to ensure HCA quality, transparency, and usefulness.	- Require periodic metric reports to evaluate utility's performance, accuracy of HCA results, and usefulness of HCA efforts.
Utilities	- Ensure quality control during feeder model development process via rigorous validation and standardized error resolution processes. - Allocate sufficient computational resources to manage computational intensity of HCA processing and analysis. - Use HCA to enable proactive planning for increased DERs in areas with constrained hosting capacity, especially when replacing equipment at the end of life. - When evaluating HCA, ensure that equipment size and location information is complete and accurate	- Standardize and implement best practices in HCA related to data visualization, level of granularity, and balancing of other key tradeoffs, including consideration of different DER technologies.	- Work with regulators to dedicate appropriate level of resources to developing and maintaining HCA capabilities. - Establish metrics to track HCA results over time, such as utilization, accuracy, and role in interconnection processes. .
Interconnection customers	- Engage in active participation with the utility to resolve errors and improve HCA usefulness, data accuracy, and website interface design.	- Refer to HCA results early and often during the project development process to aid in site selection and generator sizing processes. - Engage in collaborative processes to help establish benefits of HCA to inform utility requirements.	- Engage in collaborative processes to help establish benefits to creating HCA, including cost recovery of utility investments.
Software Developers	- Continue to develop specialized analytical tools to analyze and visualize interconnection data.		- Participate in discussions to establish industry best practices for data analysis and visualization.

Research community (including DOE)	- Continue to develop specialized analytical HCA tools and provide impartial assessment of their potential interconnection applications. - Provide technical assistance and share open-source tools and resources to aid utilities in developing HCA processes. - Validate industry best practice for HCA modeling and visual representation of data.	- Research and report on industry best practices, as well as impact of HCA on interconnection process and timelines. - Perform cost benefit analysis of HCA benefits and burdens to aid regulatory processes.	- Engage in collaborative processes to help establish benefits to creating HCA as they relate to meeting policy goals.

Solution 1.5: Broaden the use of hosting capacity analysis (medium-term, high deployment).

There are three primary applications for HCA: 1) supporting market-driven DER deployments by enabling project developers to identify suitable and potentially lower-cost locations for interconnection, 2) streamlining DER interconnections by improving or automating parts of the interconnection screening process, and 3) enabling more robust, long-term system planning, including identification of potential system constraints and proactive upgrades that may be required as DER deployment grows. To date, HCA has mostly been used in the first two applications, i.e., to help guide DER project development and to support technical screening. However, the rapid pace of DER deployment and increasingly limited hosting capacity in many regions highlights the need for more robust long-term planning efforts.[61] In areas with high levels of DER deployment, more rigorous, detailed, and accurate HCA can be a crucial tool to aid in system planning.

One important consideration for ensuring HCA's usefulness in supporting utilities with system planning is ensuring that models accurately capture the behavior and impacts of a wide range of DER technologies. For example, solar and wind have different production profiles, and the relative value of these resources to the grid may depend on local energy use patterns, rate structures (such as time-of-use pricing) and other factors. As a result, HCA outputs are technology specific and may be driven by specific characteristics of the included technologies. It is important that, as HCA tools are more widely adopted, they present results that include all viable DER. Ideally, this should also include considerations of how the complementary generation profiles of wind and solar, for example, impact the grid's hosting capacity.[62]

---

[61] See Hosting capacity analysis and distribution grid data security (Synapse Energy Economics, Inc., 2022)

[62] Singh and Al-Durra, *Implementing hosting capacity analysis in distribution networks: Practical considerations, advancements and future Directions* (IEEE, 2023) https://arxiv.org/pdf/2312.06582

Although HCA is typically conducted using example DER sizes and locations, many companies are trending toward building-specific geocoded data for specific interconnection applications.[63] As adoption of distributed solar, storage, wind, and electric vehicle charging systems becomes more common, such high-resolution data become more important. Higher-resolution data show rates of adoption and help planners estimate future distribution system demand to facilitate prioritization of interconnection processes and solutions.[64]

The type of HCA implemented, and its underlying assumptions, also become more important as DER deployment increases. At higher levels of DER deployment, it may be useful to shift to dynamic hosting capacity analysis, reflective of near real-time grid conditions, to increase data accessibility and transparency. Intentionality is required when scaling up to more resource intensive HCA methodologies to ensure that the benefits of increased utilization merit the additional burden on utilities and that potential data security concerns are addressed.[65] This more complex analysis requires gathering more detailed information about loads, generation, and storage.

For example, California utilities are required to produce highly detailed, hourly hosting capacity models of the distribution system. The availability of such high-resolution data has enabled the California PUC to direct utilities to assess DER interconnection applications according to their expected operating profile (Limited Generation Profile) rather than a static, worst-case scenario total nameplate or export capacity. Evaluating potential grid impacts of interconnecting DERs in this way is anticipated to mitigate the need for grid upgrades and facilitate greater DER deployment levels.[66] Detailed HCA can also be used to enable flexible interconnection, as discussed in Solution 2.6.

Incorporating sociodemographic layer data into hosting capacity maps could help increase HCA utilization by utilities, developers, and policymakers during planning and tracking of policies. Including this type of data can help in meeting regulatory requirements, such as state-level equity targets or federal incentive requirements. Data layers could include energy equity indicators such as energy-burdened census tracts, environmental indicators such as exposure to particulate matter, health indicators such as asthma rates, and climate indicators such as wildfire risk and public safety power shutoff areas. This type of data can be obtained from multiple sources, such as DOE's Climate and Economic Justice Screening Tool,[67] DOE's Low-Income Energy

---

[63] California Energy Commission Staff Report: Big Data and Distribution Resource Planning Market Study (CEC, September 2021) https://www.energy.ca.gov/sites/default/files/2021-09/CEC-200-2021-007.pdf

[64] Electric Vehicles at Scale - Phase II Distribution System Analysis (PNNL, 2022) https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-32460.pdf

[65] Costantini, Lynn P.; Byrnett, Danielle Sass; Stafford, Benjamin; Villarreal, Christopher. *NARUC Grid Data Sharing Playbook.* 2023. https://www.naruc.org/core-sectors/energy-resources-and-the-environment/electric-vehicles/grid-data-sharing/

[66] Public Utilities Commission of the State of California. *Resolution E-5296 Item #5 (Rev. 1).* March 21st, 2024. https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M527/K828/527828730.PDF

[67] https://screeningtool.geoplatform.gov/en/#3/33.47/-97.5

Affordability Data (LEAD) Tool,[68] EPA's Environmental Justice Screening and Mapping Tool (EJScreen),[69] and others, including existing state-level tools.

Maps that highlight areas with considerations that include but are not limited to thermal constraints, such as grid strength, stability, and voltage constraints could be useful, as nominal voltage ratings and operating tolerances on the grid must be maintained according to ANSI C84.1-2016. For high deployments of weather-based DERs such a solar PV, high operating voltages during the day when solar is plentiful and loads are low may drop in the evenings when the sun sets and loads increase, leading to an unacceptable voltage range which may require grid upgrades.

---

[68] See LEAD tool (DOE, 2023).

[69] See EJScreen (EPA, 2023).

Table 8. Solution 1.5 Actors and Actions — Broaden the use of hosting capacity analysis.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Balance tradeoffs, setting requirements for granularity and update frequency, and providing for utility cost recovery of tool development.	- Require periodic metric reports to evaluate usefulness of HCA efforts.
Utilities	- Implement best practices in HCA, including consideration of different DER technologies.	- Evaluate HCA usefulness to aid utility processes and support more efficient use of utility resources. - Establish intended use case of HCA to aid utility processes and support more efficient use of utility resources. It is important to note that HCA for planning vs. interconnection screening have different methodologies, update frequency, and data granularity requirements.	- Work with regulators to dedicate appropriate level of resources to continuing development and maintenance of HCA capabilities. - Establish metrics to track HCA results over time, such as utilization, accuracy, and role in interconnection processes.
Interconnection customers	- Engage in active participation with the utility to resolve errors and improve HCA usefulness, data accuracy, and website interface design.	- Engage in collaborative processes to help establish benefits of HCA to inform utility requirements.	- Engage in collaborative processes to help establish benefits to increased HCA utilization, including cost recovery of utility investments.
Software Developers	- Continue to develop specialized analytical tools to analyze and visualize interconnection data as well as support long-term planning goals.		- Participate in collaborative processes to inform increased use of existing and developing HCA tools.
Research community (including DOE)	- Provide technical assistance and share open-source tools and resources to aid utilities in developing HCA processes.	- Research and report on industry best practices, as well as impact of HCA on interconnection process and timelines. - Perform cost benefit analysis of HCA benefits and burdens to aid regulatory processes.	- Engage in collaborative processes to help establish benefits to creating HCA as they relate to meeting policy goals.

2. Improve Interconnection Process and Timeline

Interconnection backlogs and delays are exacerbated by misalignment between queues designed for a relatively small number of interconnection requests and rapid growth of DERs requesting connection to the grid, including renewable generation, energy storage, and electric vehicle charging infrastructure. The resulting bottlenecks can be exacerbated by staffing constraints such as limited or under-resourced interconnection departments. Information-seeking applications, where developers use the interconnection application process to obtain information about interconnection costs and requirements, may further contribute to bottlenecks.[70,71]

Interconnecting DER projects broadly fall into one of three categories, as defined by state interconnection regulations, or the local utility in absence of statewide mandates: those eligible for simplified interconnection processes, those that exceed the threshold for simplified processing, but can be fast-tracked, and those that require an interconnection study process[72]. Applications deemed unlikely to impact grid operations may proceed through simplified interconnection processing via a series of automated technical screens; applications that exceed that threshold or which fail these screens might then be assigned to fast track processing, which could require additional screening, or a brief supplemental review; finally, additional study and individual engineering review are conducted as-needed to determine the extent of a project's impact to the grid. The interconnection process tracks differ by jurisdiction but are largely determined by the project size and the use of certified inverters, which correlate to potential risks to grid operation. While the interconnection procedures for smaller DERs connected to the distribution system fall under the jurisdiction of individual state PUCs or municipal authorities, DERs larger than 1 MW may be regulated at the state, municipal, or federal level, i.e., by FERC, depending on where they interconnect to the grid.[73] This section covers solutions intended to improve queue management practices, equitable processes, and workforce development:

- *Queue management (Section 2.1)*: how generation interconnection requests are managed, from the submission of an interconnection request to the final execution of an interconnection agreement.
- *Inclusive and fair processes (Section 2.2)*: how the interconnection process can be made more inclusive and fair.

---

[70] Gahl, Dave; Alfano, Melissa; Miller, Jeremiah. *Lessons from the Front Line: Principles and Recommendations for Large-scale and Distributed Energy Interconnection Reform.* (2022). Solar Energy Industries Institute. https://www.seia.org//sites/default/files/2022-06/SEIA%20Interconnection%20Paper%206-14-22%20FINAL.pdf

[71] Beaton, Laura D; et al. *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process.* Interstate Renewable Energy Council. (2023). https://irecusa.org/resources/thinking-outside-the-lines/.

[72] Manning, David; McAllister, Richard. *Review of Interconnection Practices and Costs in the Western States.* (NREL, 2018). https://www.nrel.gov/docs/fy18osti/71232.pdf

[73] FERC's recently issued Order 2023 provides guidance on Small Generator Interconnection Procedures. FERC Order 2023 may therefore provide a helpful glimpse into the future of interconnection process and timeline improvements for DERs. See FERC Order No. 2023 (FERC, 2023) https://www.ferc.gov/media/order-no-2023

- *Workforce development (Section 2.3):* how professionals working on interconnection are trained, hired, and retained.

These are not the only steps that can be taken to improve interconnection processes and timelines. Solutions listed under other goals in this roadmap, such as interconnection study enhancements (Section 3.3), can also help.

2.1 Queue Management

Key Takeaways

Several incremental queue management solutions may help reduce DER queue volumes and interconnection delays in the near term while enabling utilities to handle larger and variable DER queue volumes in the longer term. Providing pre-application educational materials and self-service options can reduce uncertainty and increase alignment between applicants and utility departments. Implementing commercial-readiness and dwell-time requirements may reduce the number of information-seeking and place-holding applicants in the queue. Requiring utilities to adhere to appropriate DER interconnection study timelines could also reduce queue congestion. Automating the DER interconnection process, and interconnection studies in particular, could facilitate efficient queue management. Enabling flexible interconnection could avoid grid-upgrade costs and delays in exchange for DERs curtailing generation when necessary. Finally, using a group study process could address existing queue backlogs or avoid anticipated queue backlogs, but also introduces complexities due to creating project dependencies and could slow the process.

Solutions Content

Solution 2.1: Provide pre-application educational materials and self-service options for smaller DER projects (short-term, medium deployment).

Pre-application educational materials help manage the interconnection queue by reducing uncertainty and increasing alignment between applicants and the utility departments that must process the requests. Educational materials can cover all aspects of the interconnection process and should include a clear description of interconnection process steps, design rules, utility methods, mediation processes, expected response times, statistics, departmental contacts, and frequently asked questions. Capacity maps discussed in Solution 1.4 and 1.5 are an example of an educational tool that can be provided publicly for applicants to explore before they submit an interconnection application. Utilities can consider providing self-service pre-application reports via guidance tools that provide information that meets or exceeds the most current IREC Model Interconnection Procedures.[74]

In most states, utilities must provide a detailed guidebook that allows a prospective applicant to determine their interconnection type (i.e., residential, commercial, or otherwise) as well as the paperwork, design requirements, standard fees, and study levels relevant to their project based on rate class, size, or other relevant characteristics. It is easier to avoid the need for clarifications, corrections, and escalations when contractors and utilities can design and evaluate projects from the same technical perspectives. These guidebooks are typically supplemental to a website or portal that defines and explains interconnection process pathways, options, and expectations at a high level, so applicants can find additional details on topics relevant to their proposed system. If the utility offers non-wires alternatives that avoid or defer upgrades, such as flexible interconnection programs, applicants should be able to find definitions, benefits, and risks for these options in the same place they find information about conventional interconnection approaches.

Sharing data between utilities and developers may be difficult if privacy concerns arise but can also help reduce uncertainty for all parties. Privacy concerns may be mitigated by translating aggregated information into averages and trends. Providing context and examples of possible upgrades that can be triggered by an interconnection application can help prospective applicants either avoid those upgrades or understand their options if an upgrade is needed. For example, utilities may be unable to a create an exact list of common upgrade triggers or costs, because the total price varies by location and condition on the grid. However, they may be able to publish an expected cost range and timeline estimates for upgrade categories such as conductoring, substation, line protection and control, metering, and communications. Utilities can also build out interconnection applications to include optional questions that allow an applicant to indicate interest in non-wire alternatives, tolerance for upgrade costs and shifting to alternative sites, and more.

Table 9. Solution 2.1 Actors and Actions – Provide pre-application educational materials and self-service options for smaller DER projects.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Explicitly state the required educational materials that utilities must provide so that interconnection applicants understand the interconnection process.		- Require utilities to begin tracking and reporting averages and/or ranges for upgrade costs, triggers, and construction timelines to provide summary data for developers.

---

[74] Interstate Renewable Energy Council. *Model Interconnection Procedures: 2023 Edition.* (IREC, 2023) https://irecusa.org/resources/irec-model-interconnection-procedures-2023

Utilities			- Provide and periodically update pre-application materials made available to interconnection applicants. - Engage in stakeholder processes to inform pre-application materials.
Interconnection customers			- Participate in stakeholder processes to inform the types and granularity of information included in pre-application materials.
Research community (including DOE)		- Work with developers to understand the difficulties and misunderstandings that get in the way of efficiently moving through the interconnection process for inclusion in pre-application educational materials.	- Help regulators and other decision makers consider what elements must be defined in directives to create streamlined processes that can be easily explained and defined for the potential applicants.

Solution 2.2: Require that large DER interconnection applicants meet clear criteria for commercial readiness and queue dwell-time (short-term, medium deployment).

Developers of large DER systems sometimes use the interconnection application process to obtain information about interconnection costs and operational requirements, which has contributed to rapid growth in queue volumes, high rates of withdrawal, and longer timelines for all projects in the queue.[75] Developers may also submit interconnection requests before a project is mature in order to secure a place in the queue[76]; this can enable the developer to expedite the project if they find a buyer or respond to a clean procurement program that requires a signed interconnection agreement[77]. Projects can also sometimes remain in the queue long after they have signed interconnection agreements (known as dwell-time), due to non-interconnection related project delays preventing the start of the construction phase. Commercial-readiness and dwell-time requirements can complement data-transparency efforts (see Goal 1) in managing the interconnection queue. However, utilities must balance the need for queue management against the effectiveness, equity, and customer service impacts of any requirements.

Commercial-readiness requirements such as proof of site control or deposits and withdrawal penalties in lieu of site control, may reduce the number of applications submitted to obtain information or hold a place in the queue. For example, Duke Energy requires DER applicants to

---

[75] Virginia Distributed Energy Resource (DER) Interconnection Working Groups. *Final Report for the Virginia State Corporation Commission's DER Interconnection Working Group Process: Volume 1.* (2024). Great Plains Institute. https://www.scc.virginia.gov/getattachment/186afdb1-f701-430c-896f-7224574df16b/DER-Interconnection-WGs-Final-Vol1.pdf

[76] *NARUC Regulator's Roundtables on DER Interconnection: September 2022 – October 2022 Convenings.* (2022). https://pubs.naruc.org/pub/B41CC97A-1866-DAAC-99FB-4690AFA47929

[77] Beaton, Laura D; et al. *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process.* Interstate Renewable Energy Council. (2023). https://irecusa.org/resources/thinking-outside-the-lines/.

provide proof of commercial readiness through an executed term sheet, PPA, or selection through a Duke Energy procurement program. In lieu of evidence of commercial readiness, the project must provide increasing levels of financial security as it proceeds through the interconnection study process.[78] The definition of commercial readiness varies across different utilities; whatever the criteria, it should be clearly established, and applicants should be made aware of any readiness expectations before beginning the interconnection process.

Queue positions for interconnecting projects could be assigned only after an application is deemed complete or readiness requirements are met. Completeness requirements may vary by utility based on the interconnection track process being pursued (fast track or full-study track) but should be clearly communicated to applicants ahead of interconnection application submission. By ensuring that queue positions are only granted to applications ready for review, utility processing should be expedited, and applicants can make informed business decisions.

In setting commercial-readiness requirements, utilities should be sensitive to the needs of Tribal projects, which generally require additional regulatory processes to obtain site control, such as National Environmental Policy Act compliance and environmental impact assessments.[79] Similarly, utilities may want to consider adjusting some requirements, such as application fees, to encourage EEJ projects.

There are multiple reasons a project may continue to dwell in the queue even after signing an interconnection agreement. For example, a project may experience supply-chain delays in acquiring equipment or challenges in raising funds to cover the cost of required upgrades. In some cases, a project developer may decide to build only a portion of the capacity defined in the interconnection agreement. After an agreed-upon amount of time, the utility then amends the interconnection agreement to reflect the built capacity and releases the remaining capacity to future developers. In either scenario, these dwell times slow down the queue, but could be addressed by utilities by setting time limits, or reducing existing time limits, on the validity of interconnection agreements.

Table 10. Solution 2.2 Actors and Actions – Require that large DER interconnection applicants meet clear criteria for commercial readiness and queue dwell-time.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Evaluate and approve commercial-readiness requirements that promote equitable and efficient	- Convene the interconnection community to inform rulemaking	- Look to other jurisdictions for lessons learned from existing commercial-readiness requirements.

---

[78] Beaton, Laura D; et al. *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process.* Interstate Renewable Energy Council. (2023). https://irecusa.org/resources/thinking-outside-the-lines/.

[79] Canis, Jonathan E. *Comments of The Oceti Sakowin Power Authority: The Commission is Required to Adopt Rules and Practices Tailored to the Unique Needs of Tribes and Tribal Energy Development Organizations.* (2022). Oceti Sakowin Power Authority. https://www.ospower.org/wp-content/uploads/2023/10/OSPA-Comments-FERC-RM22-14-000-10.13.2022.pdf

	interconnection application processing.	regarding readiness requirements.	- Collect data and analyze impacts of regulatory changes.
Utilities		- Work with regulators to develop equitable readiness requirements and penalties. -Develop policies or incentives to limit dwell time.	- Communicate expectations and readiness requirements to interconnection applicants.
Interconnection customers	- Provide timely and accurate information at time of interconnection application request providing evidence of project's commercial readiness. - Strengthen ability to evaluate projects before submitting requests.	- Obtain readiness requirements such as proof of site control prior to seeking interconnection and plan for required fees.	- Participate in collaborative processes to help regulators and utilities develop equitable commercial-readiness requirements.
Research community (including DOE)	- Assess the impact of commercial-readiness requirements on queue processing times, withdrawal rates, and equitable access to interconnection.	- Monitor and document changes in requirements and penalties. - Evaluate effectiveness and impacts on access.	- Collect and inform best practices.

Solution 2.3: Implement and enforce appropriate DER interconnection study timelines and consider penalties for delays in completing studies. (short-term, medium deployment)

Interconnection applicants with projects that do not qualify for simplified or even fast track processing are typically required to respond to utility requests within a required time frame based on application phase, or their project will be withdrawn from the queue. Similar limits should be imposed on utilities, requiring adherence to processing time limits, with comparable penalties for delays. Requiring equitable accountability from both the utility and the developer can help ensure fair and efficient application processing. Just as delays from the interconnection applicant can slow the application process and negatively impact the interconnecting utility, delays from the utility can also negatively impact the interconnecting applicant,[80] leading to increased costs, uncertainty, and project withdrawals.[81]

State utility commissions should start by establishing timeline requirements for interconnection application reviews. The required timelines should differentiate between small DERs (simplified or fast track) and large DERs (fast or study track). There is precedent for this type of requirement

---

[80] Horowitz, Kelsey; et al. *An Overview of Distributed Energy Resource (DER) Interconnection: Current Practices and Emerging Solutions.* (2019). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72102.pdf

[81] Gahl, Dave; Alfano, Melissa; Miller, Jeremiah. *Lessons from the Front Line: Principles and Recommendations for Large-scale and Distributed Energy Interconnection Reform.* (2022). Solar Energy Industries Institute. https://www.seia.org//sites/default/files/2022-06/SEIA%20Interconnection%20Paper%206-14-22%20FINAL.pdf

for DER interconnections: some states have begun this process, with policies generally based on the size and application track of the interconnecting system. For example, several states have requirements for the maximum time residential PV systems can spend in interconnection queues waiting for approval from their respective utility. A recent analysis of requirements for distributed PV projects (up to 50 kW) in 24 states found that the average state-mandated timeline in 2020 for the pre-installation approval interconnection phase ranged between 10 and 40 business days[82]. These requirements apply only to PV projects that would typically fall into the simplified or fast-track process. Some states also impose penalties on utilities for failing to meet timeline requirements. Additionally, the onset of online applications and screening criteria for PV and other DER interconnection requests are expected to streamline approval timelines as communication and application tracking processes improve.

A similar but tailored approach should be adopted for larger DERs and for other DER technology types beyond PV. DER systems over 50 kW in size fall into a fast track or study track and generally face longer processing times. An analysis of distributed PV interconnection timelines in California, Massachusetts, New York, and New Jersey) found that projects over 50 kW have much higher processing times than smaller projects, and that timelines for larger projects have generally increased over the past 10 years while smaller project timelines have been more consistent.[83]

In parallel with establishing required study timelines, suitable penalties for failure to meet such timelines may be used to ensure accountability. NREL’s 2022 analysis showed that 8% of 170,000 PV projects considered were not completed within the state-mandated timelines, and these were more likely to be larger projects.[84] State utility commissions could consider more widely penalizing utilities found to be systematically delaying fast- or study-track processing, as a way to compensate interconnection applicants.

Table 11. Solution 2.3 Actors and Actions – Implement and enforce appropriate DER interconnection study timelines and consider penalties for delays in completing studies.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- In coordination with the interconnection community, determine feasible study timelines for larger DERs	- Establish and implement appropriate interconnection study timelines and penalties for delays.	- Engage in collaborative processes to inform rulemaking.

---

[82] Fekete, Emily S., Cruce, Jesse R., Dong, Shiyuan, O'Shaughnessy, Eric, and Cook, Jeffrey J. *A Retrospective Analysis of Distributed Solar Interconnection Timelines and Related State Mandates. United States*: N. p., 2022. Web. doi:10.2172/1841350. https://www.nrel.gov/docs/fy22osti/81459.pdf

[83] Unpublished analysis of data in the SolarTRACE database. For specific state level data see: *Permitting, Inspection, and Interconnection Data and Analytics. NREL’s SolarTRACE.* National Renewable Energy Laboratory. https://solarapp.nrel.gov/solarTRACE.

[84] Fekete, Emily S., Cruce, Jesse R., Dong, Shiyuan, O'Shaughnessy, Eric, and Cook, Jeffrey J. *A Retrospective Analysis of Distributed Solar Interconnection Timelines and Related State Mandates. United States*: N. p., 2022. Web. doi:10.2172/1841350. https://www.nrel.gov/docs/fy22osti/81459.pdf

	and for DER technologies beyond PV.	- Monitor compliance and enforce penalties.	- Track and periodically re-assess duration of timelines and penalties against process improvements.
Utilities	- Implement streamlined study processes for all systems under a specific size, to be defined in collaboration with state regulators.	- Develop strategies for complying with study deadlines.	- Track assessment of penalties on interconnection studies to identify and inform areas of process improvements.
Research community (including DOE)		- Track study timelines, compliance, and penalties. - Assess effectiveness. - Identify and publicize national trends and best practices.	

Solution 2.4: Continue automating the DER interconnection process (short-term, medium deployment)

At low DER deployment levels, a utility can manage the interconnection process through less formal processes. This informal approach is more common among small public and cooperative utilities.[85] However, as deployment grows, it becomes increasingly time consuming and costly for a utility to process interconnection requests by hand. For example, PG&E, a large investor-owned utility in California, experienced very rapid growth in rooftop PV interconnection applications in the early 2010s. Because of increased processing times and costs, PG&E became one of the first utilities to automate its interconnection process, resulting in multiple benefits.[86] Over the past two decades, numerous other utilities have automated parts of the interconnection process by creating online portals to handle interconnection requests and developing software for managing interconnection queues.[87] These utilities have reported being able to process higher volumes of applications, better records management, better integration between departments, and better customer service with fewer customer inquiries.[88]

---

[85] E.g., Town of Forest City, *Interconnection Request Application Form.* (n.d.). https://www.townofforestcity.com/sites/default/files/uploads/departments/utilities-services/Solar/interconnection_request_application_form.pdf; Pend Oreille Public Utility District *Customer Interconnection Agreement.* (2024) https://www.popud.org/assets/PDFs/Applications/af439481c5/Application-Agreements-for-Interconnection.pdf; and Springer Electric Cooperative, Inc., *Standard Interconnection Application Generating Facilities with Rated Capacities Greater Than 10 kW.* (n.d.). https://www.springercoop.com/sites/springercoop/files/documents/InterconnectionApplicationOver10kw.pdf are a few of many examples of small utilities allowing interconnection applications by mail, e-mail, or fax.

[86] Ardani, Kristen, and Robert Margolis. *Decreasing Soft Costs for Solar Photovoltaics by Improving the Interconnection Process: A Case Study of Pacific Gas and Electric*. (2015). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy15osti/65066.pdf

[87] Horowitz, Kelsey; et al. *An Overview of Distributed Energy Resource (DER) Interconnection: Current Practices and Emerging Solutions.* (2019). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72102.pdf

[88] Solar Electric Power Association. *Distributed Solar Interconnection Challenges and Best Practices.* (2014). https://sepapower.org/resource/distributed-solar-interconnection-challenges-and-best-practices/

Automating interconnection processes can benefit utilities and interconnection customers. It can enable utilities to process larger volumes of interconnection requests without scaling up staff or other resources and incurring the associated costs. It can also enable utilities to require developers to provide all necessary data before allowing their application to be formally submitted. This type of data checking can significantly reduce the number of corrective iterations between developer and utility. It can also enable the efficient collection of detailed system data required to model the temporal characteristics of DERs, without which conservative assumptions are often used.[89]

Parts of the interconnection process that have been targeted for automation include application processing, data-management systems, customer interaction and communication systems, and report preparation and sharing. Utilities, market participants, and the research community could help prioritize opportunities for automation and establish the appropriate cybersecurity measures to enable automation, which would help software providers tailor products to utility needs.

While automation offers significant benefits, it incurs costs as well. Thus, the timing and scope of automation must be tailored to the unique circumstances of a utility and their interconnection customers.

Table 12. Solution 2.4 Actors and Actions – Continue automating the interconnection process.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Encourage utilities to identify opportunities for automation to enable process improvement. - Establish regulatory mechanisms to incorporate automation into fast-track processes to expedite projects that qualify.	- Convene the interconnection community to develop pathways to automation and process improvement that benefit all. - Approve cost-recovery mechanisms to enable process automation.
Utilities	- Identify needs and priority areas for automation.	- Identify opportunities for federal funding of automation.	- Participate in collaborative processes to provide utility perspective.
Interconnection customers			- Participate in collaborative processes and provide feedback to utilities and regulators on priority areas for automation.
Research community (including DOE)	- Partner with utilities and software vendors to pilot and support software	- Document needs and priority areas for automation.	

---

[89] Building a Technically Reliable Interconnection Evolution for Storage (BATRIES). *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage.* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

	development for automation.		
Software developers	- Develop and tailor queue software that automates queue functions.		- Participate in collaborative processes to provide software development perspective.

Solution 2.5: Automate parts of the DER interconnection study process. (medium-term, high deployment)

As DER deployment has increased, many in the interconnection community have expressed interest in automating parts of the DER interconnection study process. In contrast to manual collection, review, and evaluation of interconnection applications, automation of the DER study process allows certain tasks to be streamlined via software solutions designed to perform repeated tasks. For example, initial collection of interconnection application data for projects can be completed via secure online platforms with fillable fields or drop-down lists of possible responses. This platform can then be used to automatically assign projects to simplified, fast track, or study track processes based on the developer's answers, all without requiring manual work to collect, process, and store this information. Automation can free utility resources devoted to pre-screening and pre-approval of simplified and fast track projects, which can then be devoted to study processes requiring technical expertise.

Automating interconnection study tools is resource intensive and requires customization to securely interface with utility platforms. Successful implementation depends on the quantity and quality of utility data, and full integration requires development of a new interconnection study process workflow. Automation may not be cost-effective in regions with relatively low DER deployment. For those with sufficient queue volumes to merit automation, utilities can choose to develop in-house software or procure a third-party system that may save time and be more easily adaptable to regulatory and process changes.[90]

Utilities can consider several conditions that may facilitate successful interconnection study automation. DERs that are fairly uniform in technology and size enable the utility to identify a standard list of approved components that can facilitate faster interconnection study and approval via automation. Interconnection customers can be made aware of the DER types, size ranges, and approved components required to enter the automated study process, resulting in quicker decisions and more cost certainty. High-quality system data—typically gained through advanced metering infrastructure (AMI) with data collection functionality enabled and accessible to the

---

[90] Horowitz, Kelsey, Zac Peterson, Michael Coddington, Fei Ding, Ben Sigrin, Danish Saleem, Sara E. Baldwin, et al. 2019. An Overview of Distributed Energy Resource (DER) Interconnection: Current Practices and Emerging Solutions. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72102. https://www.nrel.gov/docs/fy19osti/72102.pdf.

utility—and an advanced distribution management system (ADMS) are also useful and may be cost-effective to implement at higher DER deployment levels.

Specialized tools have been developed to automate portions of common interconnection study tasks. For example, NREL and the Sacramento Municipal Utility District (SMUD) developed PRECISE[91] (PREconfiguring and Controlling Inverter Setpoints), which provides a standardized, repeatable, automated method of evaluating PV interconnection requests that benefits solar developers and the utility. PRECISE enables utility engineers to have visibility at the grid edge and calculates settings for advanced inverter functions if needed for increasing hosting capacity. The tool has been fully integrated at SMUD since 2022.

Automation tools could be implemented more widely and improved by the research community and software developers to address other DERs, EV charging stations, and additional interconnection approval challenges. However, results are directly related to the quantity and quality of utility data, and full integration of an automation framework requires developing a new interconnection study process workflow. A phased approach to automating interconnection studies may help reduce the upfront burden on utilities while incrementally providing improvements.[92]

Table 13. Solution 2.5 Actors and Actions – Automate parts of the DER interconnection study process.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Define rules that allow for adoption of automated interconnection processes.	- Convene the interconnection community to develop processes for automation.
Utilities	- Specify and study standardized DER designs. - Identify criteria for approved components. - Incorporate approved components into interconnection application forms and customer communications.	- Consider a phased approach to implementing automation into the interconnection process.	- Participate in regulatory processes to develop automation framework. - Implement application screening process to filter projects into study tracks.
Interconnection Customers	- Standardize project design to the extent possible.		- Participate in regulatory processes to develop automation framework.
Software developers & research	- Develop software interface options to AMI/ADMS that require less labor-intensive	- Support companies to develop technology that meets standardized designs.	

---

[91] For more information, see PRECISE: PREconfiguring and Controlling Inverter SEt-points (NREL, 2018). https://www.nrel.gov/grid/precise-tool.html.

[92] Horowitz, Kelsey, Zac Peterson, Michael Coddington, Fei Ding, Ben Sigrin, Danish Saleem, Sara E. Baldwin, et al. 2019. An Overview of Distributed Energy Resource (DER) Interconnection: Current Practices and Emerging Solutions. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72102. https://www.nrel.gov/docs/fy19osti/72102.pdf.

community (including DOE)	customization to deploy automation. - Develop and expand automation tools to include other common DERs and charging station infrastructure.		

Solution 2.6: Enable flexible interconnection so DERs can avoid grid-upgrade costs and delays in exchange for curtailing generation. (medium-term, high deployment)

Under a conventional interconnection process for DERs designed to export to the grid, the DER capacity that can be installed is limited by the available hosting capacity at the point of interconnection. To enable DER installation beyond that limit, the grid must be upgraded to accommodate additional capacity. In contrast, a flexible interconnection process allows DER capacity to exceed the available hosting capacity without upgrades (or with fewer upgrades) by ensuring that DERs can be curtailed when necessary.[93] This arrangement is feasible when the export capacity of the DER only sometimes exceeds the real-time hosting capacity of the grid, at which time exports in excess of the grid's capacity are curtailed; a project expected to export far in excess of available hosting capacity is likely a poor candidate for flexible interconnection and would require upgrades or an alternative point of interconnection.

Flexible interconnection provides several potential benefits beyond mitigating grid-upgrade costs. It can keep DER output below capacity limits and connected to the grid under a wider range of voltage and frequency levels. It can mitigate threats from DER output that could trip distribution protection systems installed to keep the grid and customers safe. It can help balance the larger grid by responding to localized signals from incentive programs meant to avoid outages, increase electrification, and/or meet clean energy standards. It can help increase utilization of utility assets.[94] In addition, DER projects can come online initially with a flexible interconnection agreement while waiting for the completion of utility-scheduled or interconnection-triggered network upgrades, or until DER deployment levels or load growth prompt systematic utility upgrades.[95] This option can be especially beneficial for EEJ projects or other projects proposed by developers with limited resources, which may be disproportionately impacted by delays.

Flexible interconnection is achieved contractually through a flexible interconnection agreement that specifies the electricity-export limitations, and it is achieved technically through power

---

[93] EPRI, Principles of Access for Flexible Interconnection: Cost Allocation Mechanisms and Financial Risk Management (2020). https://www.epri.com/research/products/000000003002019635

[94] EPRI, Characterizing the Value of Flexible Interconnection Capacity Solutions (FICS) (2021). https://restservice.epri.com/publicdownload/000000003002022432/0/Product

[95] EPRI, Principles of Access for Flexible Interconnection: Cost Allocation Mechanisms and Financial Risk Management (2020). https://www.epri.com/research/products/000000003002019635

control systems and advanced inverters[96]. Flexible interconnection can result in incremental costs that must be weighed against the benefits. The choice of control scheme enabling the flexible interconnection determines the extent to which additional technologies are required, ranging from a "connect and notify" approach that may not require any additional investment to direct control requiring distributed energy resources management system (DERMS)[97] Developers are also affected by compensation structures and the frequency of demands for curtailment and additional export. Thus, the costs and benefits of flexible interconnection should be compared with the costs and benefits of upgrading the grid or downsizing DERs in the context of specific grid systems.[98]

Increased familiarity with international approaches—plus the development of supporting codes[99], standards[100], and equipment certifications—are helping move flexible interconnection from pilot stage to fuller implementation in the United States. However, additional advances are needed. As more DERs are affecting the distribution and transmission systems, clarity around the procedures for curtailment, including utility override conditions, become more important. Utility approaches to overrides must be standardized and clearly articulated in interconnection agreements, establishing DER performance parameters (e.g., maximum injection limits) and outlining the utility's ability to curtail DERs for reliability. In addition, requirements—including control, communications, and verification—must be developed for specific technologies that are commensurate with potential impacts. System requirements should be carefully balanced so that grid reliability is maintained in an economical and efficient means to all grid participants considering available technology options.

Table 14. Solution 2.6 Actors and Actions – Enable flexible interconnection so DERs can avoid grid-upgrade costs and delays in exchange for curtailing generation.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Explicitly state the requirements, component certifications, communications, and	- Explicitly state which flexible interconnection options are available, when and where.	- Require utilities to report the frequency of, reasons for, and costs of upgrades on the distribution grid to

---

[96] See Solutions 4.8, 4.9, and 4.10 addressing the cybersecurity concerns of enabling such advanced inverter functionality.

[97] For discussion and benefits of "connect and notify" approach, see Gahl, Dave; Alfano, Melissa; Miller, Jeremiah. *Lessons from the Front Line: Principles and Recommendations for Large-scale and Distributed Energy Interconnection Reform.* (2022). Solar Energy Industries Institute. https://www.seia.org//sites/default/files/2022-06/SEIA%20Interconnection%20Paper%206-14-22%20FINAL.pdf

[98] See EPRI, Principles of Access for Flexible Interconnection: Cost Allocation Mechanisms and Financial Risk Management (2020) for discussion of cost-benefit tradeoffs of flexible interconnection and considerations to determine whether the least-cost approach is to curtail or to conduct system upgrades and enable firm interconnection.

[99] UL Solutions Code Authorities and Standards: https://code-authorities.ul.com/about/ulstds/

[100] IEEE Standards Association: https://standards.ieee.org/, International Electrotechnical Commission (IEC) International Standards: https://www.iec.ch/publications/international-standards, International Organization for Standardization (ISO): https://www.iso.org/standards.html

	processes needed to qualify for flexible interconnection.	- Work with utilities to design market structures that fairly allocate the cost and benefits of flexible interconnection.	identify opportunities for flexible interconnection solutions.
Utilities	- Develop study assumptions and protocols to yield results that allow developers to decide between paying for upgrades or signing a flexible interconnection agreement.	- Allow for flexible interconnection agreements where appropriate to help defer or avoid upgrades. - Develop approaches to support control and operation of DER units using flexible interconnection solutions.	- Develop a transparent price range for typical upgrades and export or curtailment payments, as well as a catalogue of standard components.
Interconnection customers	- Use and advocate for flexible interconnection in the project planning phase. - Develop viable designs with flexibility options.		- Use the interconnection application process to communicate the range of acceptable prices for upgrades as well as caps for flexible interconnection that provide favorable project economics.
Software developers/ engineering firms	- Demonstrate and enhance the ability of hardware to curtail generation.	- Clearly define operational data and communications that allow for diverse flexible interconnection policies.	- Work with developers and utilities to create cybersecure systems to support flexible interconnection.
Research community (including DOE)	- Provide international and national assessments to facilitate understanding of the flexible interconnection concept. - Support the development of technology and specific communications and control requirements for flexible interconnection regulations.	- Develop and communicate best practices for development, implementation, and operation of flexible interconnection agreements.	- Work with the interconnection community to identify and overcome barriers to implementation.

Solution 2.7: Use a group study process to address existing queue backlogs or avoid anticipated queue backlogs. (short-term, medium deployment)

Group studies could be more inclusive and fairer than serial processing. Grouping similar projects can improve study efficiency and allow upgrade costs to be distributed among projects according to their contribution to causing the upgrade, as opposed to assigning costs to a single project.[101] However, in areas of high DER deployment and limited hosting capacity where widespread system upgrades are required, adopting a group study approach may be insufficient to address queue backlogs.[102] In these capacity-constrained areas, the grid upgrades required are

---

[101] McAllister, Richard, David Manning, Lori Bird, Michael Coddington, and Christina Volpi. 2019. New Approaches to Distributed PV Interconnection: Implementation Considerations for Addressing Emerging Issues. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72038. https://www.nrel.gov/docs/fy19osti/72038.pdf.

[102] Interstate Renewable Energy Council. *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process.* (2023). https://www.irecusa.org/resources/thinking-outside-the-lines/

often greater than can be supported even by a group of projects and may be more suited to distribution system planning activities. That said, adopting group study processes in DER markets not yet facing severe queue backlogs can enable more efficient and cost-effective interconnection application processing and system upgrades that may avoid such backlogs at higher volumes.

Developing an effective group study process can be challenging for utilities. To be most effective, group study processes must be customized to the queue, grid, and market being served. IREC proposes two initial decision points for consideration[103]: 1) whether group studies should be used for all projects, or only where a cluster of similar projects exist, and 2) whether group studies should be formed on an as-needed basis or according to a regular schedule. The answers to these questions for a given jurisdiction will be based on the scale of interconnection requests, utility resources, how quickly group studies can proceed, and how quickly upgrades can be built, among other factors. Upon completion of the group study process, equitably allocating system upgrade costs among participating projects often requires a combination of per-project and proportional (i.e., per-export capacity or other contribution) allocation strategies. It also requires utilities to provide transparency about how this determination is made. Unintended consequences should also be considered. For example, requiring all projects to be studied in groups could unnecessarily burden and delay smaller projects that are less likely to trigger upgrades and would instead benefit from improved fast-tracking screens and procedures.

---

[103] Interstate Renewable Energy Council. *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process.* (2023). https://www.irecusa.org/resources/thinking-outside-the-lines/

Table 15. Solution 2.7 Actors and Actions – Use a group study process to address existing queue backlogs or avoid anticipated queue backlogs.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Assess whether group study processes are likely to improve interconnection timelines.	- Require mandatory participation in group study if project meets criteria for group inclusion. - Consider allowing utility discretion to study an otherwise qualifying project outside the group if it would increase efficiency and fairness and is nondiscriminatory. - Approve interconnection process framework and cost-recovery mechanisms.	- Require transparency of group study selection criteria, timelines, cost-sharing criteria, and procedures. - Convene collaborative processes to develop effective group study processes for all the interconnection community.
Utilities	- Determine and publicize criteria for selecting electrically related projects to form beneficial groupings that do not unnecessarily overburden unrelated projects or lead to study delays. - Consider factors such as incremental power flow, aggregate power flow, locational voltage impacts, and short-circuit duty tests for determining electrical relatedness.	- Determine criteria for forming group studies instead of individual processing. - Determine whether groups should be formed on an as-needed basis, according to a regular schedule, or both. - Disclose decision criteria for grouping practices upfront. - Consider conducting a feasibility study at the start of the group study process to assess potential for requiring upgrades, after which minor project modifications are accepted. - Design group study procedures that acknowledge the role of restudies in refining the composition of the group and achieving efficient study outcomes. - Consider mechanisms to allow reasonable minor project modifications during the group study process that benefit or do not adversely impact the group.	
Interconnection Customers	- Review and prepare for group study process timeline and deadlines to avoid withdrawal due to non-compliance.		- Participate in collaborative processes to inform the development of group study procedures.
Research community (including DOE)	- Analyze group study processes and cost-allocation procedures to identify best practices and lessons learned.		

2.2 Inclusive and Fair Processes

Key Takeaways

Interconnection processes could be made more inclusive and fairer through system planning that prioritizes equitable outcomes and then tracks progress toward equity-related goals as grid investments are made in under-resourced and under-invested areas. In addition, under-resourced groups could better navigate the interconnection process with support from independent dispute resolution, engineering, administrative, and legal services.

Solutions Content

Solution 2.8: Advance equitable interconnection through system planning. (short-term, low deployment)

The DER interconnection process interacts with the principles of equity in several ways. First, an efficient interconnection process enables under-resourced communities to access DER benefits more rapidly. DERs that displace fossil fuel generation can reduce air pollution, which historically has been worse in these communities.[~~104~~] In addition, DER deployment may reduce the number of households that experience high energy burdens and improve resilience to power outages, which have historically been pervasive in these communities due to underinvestment and disinvestment.[105,106,107,108] Efforts can be made to open interconnection and related planning processes to historically under represented individuals and communities to participate and lead in energy decision-making processes with the authority to make change.[109] Finally, DER interconnection processes occur within the framework of electricity infrastructure shaped by a historical lack of investment in under-resourced communities,[110] which can cause DER interconnection to be slow, expensive, or difficult in these communities.

System planning can promote efficient DER interconnection by helping address the historical inequities embedded in the U.S. electricity system.[111,112] Policy changes are important for

---

[104] Woolf, Tim, et al. 2024. Distributional Equity Analysis for Energy Efficiency and Other Distributed Energy Resources: A Practical Guide. LBNL https://www.energy.gov/sites/default/files/2024-05/bto-distributed-equity-analysis-guide_framework-summary_may2024.pdf

[105] Heeter, J., Sekar, A., Fekete, E., Shah , M., & Cook, J. J. (2021). *Affordable and Accessible Solar for All: Barriers, Solutions, and On-Site Adoption Potential*. N. R. E. Laboratory. https://www.nrel.gov/docs/fy21osti/80532.pdf, p. 1

[106] Federal Energy Regulatory Commission. *Topics to be Addressed in Agency Equity Action Plans*. (2022). https://www.ferc.gov/equity

[107] Mitsova, Diana; Esnard, Ann-Margaret; Sapat, Alka; Lai, Betty S. *Socioeconomic vulnerability and electric power restoration timelines in Florida: the case of Hurricane Irma.* (2018). Natural Hazards. Vol 94, p. 689-709. https://doi.org/10.1007/s11069-018-3413-x

[108] Flores, N.M., McBrien, H., Do, V. et al. The 2021 Texas Power Crisis: distribution, duration, and disparities. J Expo Sci Environ Epidemiol 33, 21–31 (2023). https://doi.org/10.1038/s41370-022-00462-5

[109] S. Carley and Konisky D, “The justice and equity implications of the clean energy transition,” Nature Energy, vol. 5, pp. 569–577, 2020. https://doi.org/10.1038/s41560-020-0641-6

[110] Krasniqi, Qëndresa; Shastry, Vivek; Peek, Alexandria; Hernández, Diana. *Utility Policies and Practices to Alleviate US Energy Insecurity.* (2024). Center on Global Energy Policy at Columbia. https://www.energypolicy.columbia.edu/publications/utility-policies-and-practices-to-alleviate-us-energy-insecurity/

[111] O’Neil, Rebecca; Tarekegne, Bethel; Singhal, Ankit; Twitchell, Jeremy. *Advancing Energy Equity in Grid Planning.* (2022). PNNL-SA-175143. https://www.pnnl.gov/sites/default/files/media/file/Advancing%20Energy%20Equity%20in%20Grid%20Planning%202_05.24.22.pdf

[112] Kazimierczuk, Kamila; DeMenno, Mercy Berman; O’Neil, Rebecca S.; Pierre, Brian J. *Equitable Electric Grid: Defining, Measuring, and Integrating Equity into Electricity Sector Policy and Planning*. (2023). U.S. Department

integrating equitable processes and outcomes into the planning process. For example, the California PUC's (CPUC's) Environmental and Social Justice (ESJ) Action Plan outlines nine goals to ensure "members of ESJ communities participate in CPUC proceedings and decision-making and that investments in clean energy resources, transportation, and communication services benefit all communities."[113] The state of Washington's Clean Energy Transformation Act requires all utilities to evaluate the impacts of their planning decisions on highly impacted or vulnerable communities, and to incorporate feedback from those communities into their plans.[114] Policies such as these promote procedural justice by ensuring that those historically impacted by the burdens of the electricity system are not passive beneficiaries of restorative policies, but are included as active participants in the decision-making process.

Regulators, utilities, and researchers can use data to analyze baseline conditions and track progress toward equitable outcomes and equity-informed goals. For example, disadvantaged communities (DACs) [115] can be identified using indicators such as spatial disadvantage (being located far from substations and thus likely to experience worse voltage profiles and reduced resilience) and income level or eligibility for utility assistance programs (which have been linked to reduced load and inadequate infrastructure).[116] These communities can then be compared with other communities in terms of system benefits and burdens. Metrics can include energy burden (percentage of household income spent on electricity), energy access (percentage of electricity from clean energy sources, DER and EV adoption rates), environmental burden (air pollutant emissions, proximity to emitting generators), reliability,[117] and resilience (restoration efficiency, cost of recovery). Various institutions collect and report on these types of metrics; for example, see DOE's Energy Justice Mapping Tool,[118] DOE's Low-Income Energy Affordability Data

---

of Energy, Office of Electricity. https://www.pnnl.gov/sites/default/files/media/file/MOD-Plan%20Equity%20Paper%20Final.pdf

[113] California Public Utilities Commission. *Environmental and Social Justice Action Plan*. (2019, update: 2022). https://www.cpuc.ca.gov/news-and-updates/newsroom/environmental-and-social-justice-action-plan

[114] Washington State Department of Commerce https://www.commerce.wa.gov/growing-the-economy/energy/ceta/ceta-overview/

[115] U.S. Department of Energy. *General Guidance for Justice40 Implementation* https://www.energy.gov/sites/default/files/2022-07/Final%20DOE%20Justice40%20General%20Guidance%20072522.pdf

[116] A. K. Bharati, A. Singhal, R. Jinsiwale, K. Kazimierczuk, J. Yoshimura and B. Tarekegne, "Advancing Energy Equity Considerations in Distribution Systems Planning," 2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2023, pp. 1-5, doi: 10.1109/ISGT51731.2023.10066350.

[117] SAIDI: System Average Interruption Duration Index; SAIFI: System Average Interruption Frequency Index; CAIDI: Customer Average Interruption Duration Index.

[118] U.S. Department of Energy. *Energy Justice Mapping Tool- Disadvantaged Communities Reporter*. https://energyjustice.egs.anl.gov/

(LEAD) Tool,[119] EPA's EJScreen,[120] and EIA's Residential Energy Consumption Survey (RECS).[121]

With equity-aware and responsive system planning goals in place, members of EEJ communities actively involved in policy and planning processes, and equity-focused metrics established to track progress toward those goals, investments can be directed toward infrastructure upgrades that improve grid reliability and increase hosting capacity in under-resourced areas—thus improving interconnection outcomes for these areas. For example, Duquesne Light Company used data and software tools to integrate socioeconomic and neighborhood factors into their planning processes so they could target grid investments where they are most needed.[122]

Table 16. Solution 2.8 Actors and Actions – Advance equitable interconnection through distribution system planning.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Establish data collection, tracking, and reporting processes for energy equity-focused metrics.	- Establish equity-informed policies to be inclusive of EEJ communities historically left out of the decision-making process and to ensure the benefits and burdens of the electric system are equitably distributed.	- Publish data on energy equity-focused metrics and use these metrics to track progress and impacts of policy and planning activities.
Utilities	- Incorporate principles of equity into hosting capacity and outage analysis for planning purposes, comparing energy equity-focused metrics between disadvantaged and non-disadvantaged users.	- Incorporate collaboration into planning processes, specifically highlighting the voices of marginalized and traditionally excluded communities.	- Incorporate equity considerations and goals in distribution planning activities. - Incorporate results of equity-informed hosting capacity and outage analysis into distribution system planning efforts.
Research community (including DOE)	- Collect and incorporate energy equity-focused data in grid planning research projects.		- Consider equity-related goals in grid planning research projects.

---

[119] Office of State and Community Energy Programs. *Low-Income Energy Affordability Data (LEAD) Tool and Community Energy Solutions.* https://www.energy.gov/scep/slsc/lead-tool

[120] United States Environmental Protection Agency. *EJScreen: Environmental Justice Screening and Mapping Tool.* https://www.epa.gov/ejscreen

[121] U.S. Energy Information Administration. *Residential Energy Consumption Survey (RECS).* (2020). https://www.eia.gov/consumption/residential/index.php

[122] Keen, Jeremy, Julieta Giraldez, Elizabeth Cook, Andy Eiden, Scott Placide, Alan Hirayama, Brian Monson, David Mino, and Fathalla Eldali. 2022. *Distribution Capacity Expansion: Current Practice, Opportunities and Decision Support*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-83892 https://www.nrel.gov/docs/fy23osti/83892.pdf.

Solution 2.9: Help under-resourced groups navigate the interconnection process through independent dispute resolution, engineering, administrative, and legal services (medium-term, medium deployment).

Interconnection is a complex legal process that states and utilities are continuously adapting to meet the needs of the future grid. Navigating this process may be especially challenging for smaller, newer, and under-resourced process participants, including developers of community solar or other DER projects who represent and serve EEJ communities. These participants are more likely to be under-resourced or inexperienced in vetting interconnection requirements and may have limited capacity to interpret interconnection application results or negotiate interconnection requirements.[123]

Developing customer protection and support services to navigate utility procedures can mitigate knowledge and experience gaps for developers, and providing independent negotiation, mediation, and arbitration services can help improve interconnection application completion rates. One approach could be an independent engineering, administrative, and legal interconnection ombudsperson or service at the state level—modeled after FERC's Dispute Resolution Service.[124] Widespread adoption of such services could improve outcomes and DER interconnection application completion rates. By ensuring all the interconnection community can understand and negotiate interconnection requirements, this service could help under-resourced groups resolve disputes within required interconnection time frames, which would save developers and utilities time and costs spent on traditional litigation.

States such as Massachusetts,[125] New York,[126] California,[127] Washington,[128] and Hawaii[129] have established dispute-resolution processes that may serve as examples for other states. These processes often involve good-faith negotiations, mediation, non-binding arbitration, and an adjudicatory hearing—all overseen by an ombudsperson and independent engineer. State PUCs could also consider expanding the role of ombudsperson beyond formal dispute-resolution services to provide technical assistance for developers who need help understanding

---

[123] While not all developers who build projects intended to serve EEJ communities are themselves small and under-resourced, many are. Balaraman, Kavya. *DOE turns to energy storage to build resilience, energy affordability in underserved communities.* (2022). Utility Dive. https://www.utilitydive.com/news/doe-turns-to-energy-storage-to-build-resilience-energy-affordability-in-un/620659/.

[124] Federal Energy Regulatory Commission. *Dispute Resolution Service.* (2020). https://www.ferc.gov/enforcement-legal/legal/alternative-dispute-resolution/dispute-resolution-service

[125] Commonwealth of Massachusetts. *Interconnection Dispute Resolution Guidance.* (2024). https://www.mass.gov/info-details/interconnection-dispute-resolution-guidance

[126] New York State Public Service Commission. *New York State Standardized Interconnection Requirements and Application Process for New Distributed Generators and/or Energy Storage Systems … Section VI. Dispute Resolution.* (2024). https://dps.ny.gov/system/files/documents/2024/02/sir-effective-february-1-2024.pdf

[127] California Public Utilities Commission. *Expedited Interconnection Dispute Resolution.* (2017). https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/rule-21-interconnection/expedited-interconnection-dispute-resolution

[128] Washington's WAC 480-108-100 Dispute Resolution

[129] Hawaii established an Interconnection Dispute Resolution Process under Order No. 39163

interconnection study results, thus supporting procedural justice. Other ombuds or similar programs outside of the interconnection space may serve as models for further development of equitable interconnection dispute resolution, technical assistance, and support services. For example, Colorado in 2022 established an Environmental Justice Ombudsperson housed under the Department of Public Health and Environment. The role addresses complaints, shares information, co-develops resources, and acts as an advocate for marginalized communities in the department's decision-making processes.[130] Ombuds or assistance programs should be accessible to all applicants to ensure transparency, equitable outcomes, and time and cost savings for utilities and developers.[131]

In the states that have adopted interconnection ombuds or dispute resolution services, the positions may be salaried employees of the state's public utility commission, as is the case in Massachusetts.[132] A 2024 bill in Minnesota would create an interconnection ombudsperson role and fund their salary via a $35 surcharge on all DER interconnection applications, an approach that may create tradeoffs.[133]

Table 17. Solution 2.9 Actors and Actions – Help under-resourced groups navigate the interconnection process through independent dispute resolution, engineering, administrative, and legal services.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Consider cost-effective customer protection and EEJ-focused dispute-resolution programs and services. - Continually track and evaluate program costs, benefits, and mechanisms for cost-recovery.	- Develop independent dispute-resolution services, including establishing ombudsperson and/or independent engineer roles. - Consider expanding ombudsperson role to include technical assistance.
Interconnection customer, utilities		- Help design customer protection programs to navigate interconnection process.	- Support equitable and accessible customer protection programs. - Develop technical assistance to support EEJ interconnection customers and communities.

---

[130] Colorado Department of Public Health and Environment, Environmental Justice ombudsperson (n.d.) https://cdphe.colorado.gov/ej/ombudsperson

[131] Bird, Lori; Flores, Francisco; Volpi, Christina; Ardani, Kristen. *Review of Interconnection Practices and Costs in the Western States.* (2018). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/71232.pdf

[132] E.g., Massachusetts Department of Public Utilities, Order on the Distributed Generation Working Group's Redlined Tariff and Non-Tariff Recommendations (March 2013) http://massdg.raabassociates.org/Articles/DPU%2011-75-E-3-13-13.pdf

[133] Minnesota Legislature, HF 5097 (2024) https://www.revisor.mn.gov/bills/text.php?number=HF5097&type=bill&version=0&session=ls93&session_year=2024&session_number=0

Research community (including DOE)	- Expand technical assistance programs and facilitate productive working relationships between utilities and developers.		

2.3 Workforce Development

Key Takeaways

Interconnection requires technical expertise across many professions in the electric sector, including utility engineers, cybersecurity specialists, regulatory officials, attorneys, and many more. There is a high degree of competition and a limited talent pool for critical interconnection-related positions, especially given that technical interconnection roles often require both some degree of engineering and policy experience. Due to the increased scale of DER interconnection applications, utilities, developers, and other organizations have reported that burnout, job quality, and lack of competitive benefits have made it difficult to retain skilled staff. Targeted efforts to increase training opportunities and improve compensation for existing staff will improve workforce capabilities, increase retention, and enhance diverse and equitable representation across the interconnection workforce. Efforts to recruit qualified candidates, upskill the existing workforce, and retain skilled staff should also be paired with broader outreach and recruitment efforts intended to raise awareness of interconnection jobs as a key component of the clean energy workforce and ensure that interconnection skills and knowledge are included in educational curricula. These investments in scaling up a skilled interconnection workforce should ultimately expand overall capacity to process DER interconnection applications.

Solutions Content

Solution 2.10: Assess the growth of the interconnection workforce required to support anticipated growth in DER interconnection requests. (short-term, low deployment)

The deployment of distributed wind, solar, storage, and EV-charging technologies in the United States is expected to continue increasing as technology costs continue to decline,[134] which will increase the volume of DER interconnection requests. As a result, the DER interconnection workforce necessary to process DER interconnection requests efficiently is expected to grow as well.[135] That workforce encompasses a wide range of careers, including engineers, policy and regulatory specialists, project developers and managers, attorneys, financing experts, and

---

[134] U.S. Energy Information Administration. *Annual Energy Outlook 2023*. (2023). https://www.eia.gov/outlooks/aeo/

[135] See discussion on scaling the interconnection workforce from the i2X Solution e-Xchange on July 20, 2023 https://www.energy.gov/sites/default/files/2023-08/7.20%20Slides.pdf as well as other convenings in the series focused on interconnection workforce challenges, needs, and development solutions.

others.[136] The scale of the workforce growth required and the pace of interconnection automation is uncertain.

Quantifying the needed growth in the interconnection workforce will help prioritize the other workforce-development solutions described in this section. For example, if anticipated needs are high, long-term and resource-intensive solutions—such as connecting with higher education to grow the workforce pipeline—may be necessary immediately. If anticipated needs are low, short-term solutions that are easier to implement should be prioritized.

Table 18. Solution 2.10 Actors and Actions - Assess the growth of the interconnection workforce required to support anticipated growth in DER interconnection requests.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
National trade and utility associations	- Clarify specific skill requirements for new engineering and technical staff required to meet DER interconnection needs.		-Establish clear reporting requirements on workforce needs, e.g., personnel hours required to meet forecasted interconnection growth, to facilitate more effective planning, recruitment, and retention. -Facilitate data gathering to allow comparisons across utilities and other groups about workforce requirements, skills, gaps, and needs.
Research community (including DOE)	- Using national-scale DER deployment models, project interconnection workforce growth by region and responsibility.		-Determine data requirements to identify workforce growth. -Analyze data.
Interconnection customers, utilities, regulators			-Provide data on workforce needs and expectations given DER growth.

Solution 2.11: Upskill the DER interconnection workforce through continuing education. (short-term, low deployment)

Interconnection processes and technologies are constantly evolving, which requires the DER interconnection workforce to evolve constantly as well. This workforce encompasses diverse careers related to various aspects of the interconnection process and various organizations.

---

[136] Definition adapted from the i2X Solution e-Xchange on the interconnection workforce on July 11, 2023. See notes https://www.energy.gov/sites/default/files/2023-08/7.11%20i2X%20Slides%20-%20Introduction%20to%20the%20Interconnection%20Workforce.pdf.

However, utilities and other interconnection employers have emphasized the need to train engineers, who must continually adapt to new technologies, tools, approaches, and processes.[137] Despite these needs, opportunities for the interconnection workforce to participate in continuing education—or for other skilled workers in the energy sector to transition into interconnection roles—are limited. Ongoing training and upskilling in specific software and tools required to analyze interconnection applications and conduct hosting capacity analysis, for example, have been identified as a workforce development gap.[138]

Continuing education is needed across regulatory, policy, and technical topics. Courses on designing and implementing new rules could help regulatory and policy staff communicate industry challenges and propose innovative solutions. At the same time, technical staff need continual training on interconnection technologies, control approaches, and engineering standards. For example, a well-trained interconnection workforce is needed to exploit the additional DER interconnection options provided under the latest revision of IEEE Standard 1547. To address continuing education gaps, IEEE began in 2020 to develop an education and credentialing program for electric industry professionals in support of adopting the updated IEEE Standard 1547-2018.[139] More investment in training is also needed to build expertise in battery energy storage system (BESS) smart-charge management and other ancillary services for high-power EV charging stations. In addition, providing grid cybersecurity training to the interconnection workforce is increasingly critical.[140]

Continuing education for the interconnection workforce can provide several additional benefits, including accelerating the application review process, reducing the personnel hours for the technical staff, and maintaining safety and reliability of the interconnection process. Continuing education could also improve staff retention by reducing workloads and keeping staff engaged beyond solely reviewing interconnection applications, which can be perceived as repetitive and monotonous.[141]

---

[137] See discussion on training and upskilling the interconnection workforce from the i2X Solution e-Xchange on August 8, 2023 https://www.energy.gov/sites/default/files/2023-09/8.8%20WF%20SX%20Slides%20-%20Scaling%20Interconnection%20Workforce.pdf as well as other convenings in the series focused on interconnection workforce challenges, needs, and development solutions.

[138] See discussion on training and upskilling the interconnection workforce from the i2X Solution e-Xchange on July 11, 2023 https://www.energy.gov/sites/default/files/2023-08/7.11%20i2X%20Slides%20-%20Introduction%20to%20the%20Interconnection%20Workforce.pdf as well as other convenings in the series focused on interconnection workforce challenges, needs, and development solutions.

[139] Current (2024) status of program unclear. IEEE Standards Association, Distributed Energy Resources Education and Credentialing Program. https://standards.ieee.org/products-programs/icap/programs/der/

[140] U.S. Department of Energy, Office of Cybersecurity, Energy Security, and Emergency Response https://www.energy.gov/ceser/office-cybersecurity-energy-security-and-emergency-response.

[141] Feedback during the i2X Solution e-Xchange on July 11, 2023 (as well as other convenings in the series focused on interconnection workforce challenges) captured specific challenges related to hiring, training, and retaining technical interconnection roles. Several participants shared feedback that interconnection work is both technical and monotonous, e.g. “Many tasks required for DER application review are very repetitive. They are important but

Addressing the knowledge and capacity gaps that hinder interconnection of projects involving under-resourced workers and participants—including EEJ communities, small developers, and smaller cooperative and municipal utilities—should also be key to these efforts. Intentional investment in these members of the interconnection workforce supports procedural justice by ensuring equitable participation.[142] Developing and publicly disseminating educational resources from state regulators, utilities, or industry groups so they can be accessed by all participants in the interconnection process can also help create a level playing field for under-resourced groups.

Education content developers should work with utilities and interconnection staff to identify knowledge gaps and ensure curricula meet near- and mid-term industry needs. There may be opportunities to develop such programs in coordination with institutions related to education, licensing, accreditation, and trades (e.g., National Association of Regulatory Utility Commissioners and Edison Electric Institute). Independent training programs must avoid conflicts of interest, for example, if a company developing training materials has projects in interconnection queues. Partnership with accredited institutions could help avoid such a perceived conflict.[143]

Table 19. Solution 2.11 Actors and Actions – Upskill the DER interconnection workforce through continuing education.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
National trade and utility associations, research community (including DOE)	- Develop training material tailored for educational gaps, such as application of the latest revision of IEEE Standard 1547, leading software tools used to process interconnection studies, and other emerging standards and approaches.	- Partner with education, licensing, and/or accreditation institutions to develop certifications for interconnection workforce training programs.	-Develop training material on past and present interconnection reform initiatives. - Develop educational programs for small municipal and cooperative utilities that serve EEJ communities. - Develop and publicly disseminate educational resources from state regulators, utilities, or industry groups to

---

monotonous and require technical understanding to be performed." https://www.energy.gov/sites/default/files/2023-08/7.11%20i2X%20Slides%20-%20Introduction%20to%20the%20Interconnection%20Workforce.pdf.

[142] See discussion of equitably scaling the interconnection workforce from the i2X Solution e-Xchange on August 8, 2023 https://www.energy.gov/sites/default/files/2023-09/8.8%20WF%20SX%20Slides%20-%20Scaling%20Interconnection%20Workforce.pdf

[143] In the i2X Solution e-Xchange on July 20, 2023, one utility shared an anecdote that a software company had attempted to create an interconnection training program, but RTOs were not receptive because that company also had projects in their queues, which led to concerns about conflict of interest. While this anecdote describes the transmission interconnection process, similar concerns are present for DERs. https://www.energy.gov/sites/default/files/2023-08/7.20%20Slides.pdf

			enhance equitable access to standardized best practices for the interconnection workforce.
Interconnection customers, utilities	- Identify job skill needs and a process to update skill assessments. - Develop in-house mentorship activities		- Make training available and encourage staff to develop and maintain new skillsets, such as by offering professional development funding or opportunities.

Solution 2.12: Enhance retention and targeted recruitment for DER interconnection-related jobs. (short-term, medium deployment)

To handle the increasing needs for DER interconnection, qualified staff—especially technical staff—must be recruited and retained across relevant employers, from resource developers to regulatory agencies to utilities and their consultants.[144] There is a high demand for workers with prior interconnection experience and those who might be considering other opportunities in clean energy or technology. However, regulators, and smaller utilities with fewer resources are not always able to offer competitive compensation.[145]

Improved company and job descriptions can help recruit qualified candidates. Describing interconnection work in the context of advancing the clean energy transition—and transmitting this message through marketing materials, websites, and company correspondence—may help prospective applicants become more aware of and interested in interconnection opportunities.[146] In addition, jobs should be defined and described to distinguish the skillsets required. For example, interconnection-related work at a utility can require customer service skills (for interacting with interconnection customers) and engineering skills (to run studies). However, posting a single job that calls for both skillsets may dissuade engineers who are averse to the customer-interaction component while dissuading customer service specialists who are averse to the engineering component. Similarly, many interconnection roles require both engineering skills

---

[144] See discussion on interconnection workforce challenges and needs from the i2X Solution e-Xchange on July 11, 2023 https://www.energy.gov/sites/default/files/2023-08/7.11%20i2X%20Slides%20-%20Introduction%20to%20the%20Interconnection%20Workforce.pdf

[145] Ibid.

[146] See notes from i2X Solution e-Xchange on August 8, 2023, for discussion of the importance of enhanced outreach and education for recruiting and retaining an interconnection workforce. https://www.energy.gov/sites/default/files/2023-09/8.8%20WF%20SX%20Slides%20-%20Scaling%20Interconnection%20Workforce.pdf

and policy expertise. Posting multiple separate positions may be more effective at recruiting talent.[147]

Paid internship and fellowship programs can bolster the interconnection workforce as well.[148] Some organizations, especially large developers and utilities, have internship programs that can result in full-time hires. These programs can serve as models for smaller utilities, developers, regulatory agencies, and other organizations. DOE's Clean Energy Innovator Fellowship program is an example of a fellowship program that could be scaled and adapted for the interconnection workforce. The program leverages DOE funding to recruit and place diverse recent graduates and early-career professionals in fellowship roles with utilities, regulatory commissions, and Tribal entities in the clean energy sector.[149] These internships and fellowships should be designed with equity in mind. For example, students or young professionals from low-income or disadvantaged communities may not be able to intern without compensation and relocation assistance.[150]

These programs and approaches should also focus, where feasible, on developing a more diverse and representative interconnection workforce. For example, registered apprenticeships—in which a candidate who may lack necessary qualifications is hired at a lower pay rate in exchange for on-the-job training—offer one model to increase access for underserved demographics while supporting the need to scale up the interconnection workforce. These apprenticeship programs may also offer academic credit and generally include clear pathways for apprentices to transition into regular full-time jobs.[151] While there is not yet strong precedent for investment in equitably scaling the interconnection workforce, programs and models targeted at other clean energy sectors offer blueprints. With funding from the IIJA, the Department of Energy in 2022 announced a $13.5 million program to fund workforce development programs designed to offer under-served and under-represented communities career pathways in the solar industry. Funding recipients included apprenticeship and pre-apprenticeship programs, training and certification efforts, curriculum development, and workforce outreach and recruitment.[152]

---

[147] Participants in the 2023 i2X Solution e-Xchange series focused on interconnection workforce development frequently cited the combination of disparate skillsets, including engineering and policy expertise, as a challenge in recruiting and retaining hires. https://www.energy.gov/sites/default/files/2023-08/7.11%20i2X%20Slides%20-%20Introduction%20to%20the%20Interconnection%20Workforce.pdf

[148] "Internship" and "fellowship" are sometimes used interchangeably, but the University of Alaska Fairbanks offers a brief overview of the generally understood difference between the two terms. https://www.uaf.edu/ogca/resources/tools-trade/Tuesday%20Tips-Internships%20vs%20Fellowships-072721.pdf

[149] See Clean Energy Innovator Fellowship (DOE, 2023).

[150] Baker, D. L., & Johnson, M. (2021). Social Inequity on the Network of Schools of Public Policy, Affairs, and Administration's Doorsteps: Unpaid Governmental Internships. Journal of Public Management & Social Policy, 28(1), 5. https://digitalscholarship.tsu.edu/jpmsp/vol28/iss1/5/

[151] Apprenticeship programs for the interconnection workforce, in the context of equitable scaling and recruitment, were discussed at the i2X Solution e-Xchange on August 8, 2023. https://www.energy.gov/sites/default/files/2023-09/8.8%20WF%20SX%20Slides%20-%20Scaling%20Interconnection%20Workforce.pdf

[152] https://www.energy.gov/eere/solar/advancing-equity-through-workforce-partnerships-funding-program

Attractive benefits for interconnection work can help with both recruitment and retention. Offering a competitive package of standard benefits—such as salary, health insurance, and paid time off—is important. However, many of today's workers are also seeking additional benefits including a good work-life balance, geographic freedom, work-from-home opportunities, and professional development.[153]

Actions such as increasing compensation or transitioning unpaid internship programs to paid ones by definition cost potential employers; improving pay and job quality likely will pay dividends by mitigating some recruitment and retention challenges.[154] For under-resourced organizations, such as small utilities, that may lack short-term resources to improve compensation and benefits, public funding and assistance programs like the Clean Energy Innovator Fellowship may help close gaps.

Table 20. Solution 2.12 Actors and Actions – Enhance retention and targeted recruitment for DER interconnection-related jobs.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Entire interconnection community		- Conduct periodic review of market landscape to ensure that compensation and benefits for interconnection staff are competitive.	-Increase compensation and benefits for key interconnection staff. -Improve framing of interconnection-related jobs to showcase impact. -Expand paid internship and fellowship programs. -Expand outreach and career engagement at STEM-focused education institutions, specifically Minority Serving Institutions (MSIs) and those where workforce shortages are most acute. - Develop educational and career platforms to connect potential workers with opportunities. - Define and describe jobs to distinguish the skillsets required.

---

[153] Survey data from the Interstate Renewable Energy Council (IREC) in the report "Cultivating a Diverse and Skilled Talent Pipeline for the Equitable Transition" highlights how younger candidates in the clean energy sector are increasingly prioritizing work-life balance, geographic location, and opportunities for growth. https://irecusa.org/resources/key-recommendations-cultivating-a-diverse-and-skilled-talent-pipeline-for-the-equitable-transition/

[154] See IREC's "Cultivating a Diverse and Skilled Talent Pipeline for the Equitable Transition" report for discussion of how improving job quality can enhance recruitment and retention of workers in the clean energy sector. https://irecusa.org/resources/key-recommendations-cultivating-a-diverse-and-skilled-talent-pipeline-for-the-equitable-transition/

Solution 2.13: Grow the interconnection workforce via outreach, curriculum development, and partnerships in post-secondary education. (long-term, medium deployment)

There is no established pathway to an interconnection-related career. Many skills are often learned on the job, which hinders the hiring of suitable workers, reduces the ability of new staff to ramp up quickly, and exacerbates the impacts of poor employee retention.

Workforce growth and candidate recruitment can be improved through expanded outreach and education efforts focused on students and early-career professionals. Research in the wind energy sector identifies gaps in engaging with potential workers seeking employment, including a dual challenge of employers experiencing challenges in recruiting skilled candidates while students and recent graduates interested in wind careers report difficulties finding jobs in the sector.[155]

Key groups should develop outreach and education programs at institutions of higher education. Such collaborations could be as simple as introducing new content around the interconnection process in key technical and non-technical courses about the electricity system. In addition, partnerships with programs that educate future electrical engineers can be enhanced to increase the pipeline of interconnection-trained staff members. Focused career outreach to students in technical programs—including programs at minority-serving institutions—can help close some of these gaps. This may include partnerships where professionals with interconnection experience support development of electrical engineering and other relevant curricula, to better match training to future workforce needs and increase awareness among students of potential career opportunities in interconnection.[156]

While very limited data exists on the interconnection workforce, the energy sector overall lags in racial diversity and representation from disadvantaged communities.[157] To attract a more diverse workforce, special attention should be placed on establishing partnerships with Historically Black Colleges and Universities (HBCUs), Tribal Colleges and other Minority Serving Institutions (MSIs), professional associations such as the National Society of Black Engineers and Society of Women Engineers, trade schools, and other institutions. These partnerships can leverage public and industry resources alongside the existing networks and local expertise of these institutions. One model that could be scaled is the Department of Energy's HBCU Clean

---

[155] Stefek, J., Christol, C., Smith, T., Kotarbinski, M., & McDowell, B. (2022). Defining the Wind Energy Workforce Gap. https://doi.org/10.2172/1896898
Christol, C., Constant, C., & Stefek, J. (2022). Defining Wind Energy Experience. https://doi.org/10.2172/1896897

[156] See discussion of industry support in curriculum review and student mentorship from the i2X Solution e-Xchange on July 20, 2023, for one example of this approach. https://www.energy.gov/sites/default/files/2023-08/7.20%20Slides.pdf

[157] According to the Department of Energy, "the overall energy workforce lags in Hispanic (18%), Black (9%), Asian (8%), and Indigenous worker (2%) representation." https://www.energy.gov/eere/solar/advancing-equity-through-workforce-partnerships-funding-program

Energy Education Prize, which was launched in early 2024 and granted $100,000 to each winning HBCU to expand curricula and career development efforts focused on work in the clean energy sector.[158] To further ensure that the growth of the interconnection workforce is equitable, education content developers should work with communities and relevant educational institutions directly to identify targeted education gaps related to energy, DER development, and science, technology, engineering, and math (STEM) skills and ensure relevant curriculum development.[159]

Public funding programs like the DOE Clean Energy Education Prize described above should be leveraged to defray some costs associated with outreach and curriculum development. In other cases, funding and time offered by industry experts is likely to pay long-term dividends by investing in the development of a large and diverse pool of future qualified candidates for critical interconnection jobs.

Table 21. Solution 2.13 Actors and Actions – Grow the interconnection workforce via outreach, curriculum development, and partnerships in post-secondary education.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Educators			- Incorporate content about the interconnection process in key courses.
Interconnection customers, utilities, regulators, and trade organizations	- Expand educational outreach efforts, especially to under-represented groups, related to STEM and energy system career development.	- Develop materials to support outreach and engagement.	- Establish partnerships with educational institutions that promote interconnection skills, with a focus on HBCUs and MSIs.

---

[158] Department of Energy Office of Energy Efficiency and Renewable Energy, "DOE Announces First Winners of the HBCU Clean Energy Education Prize Partnerships Track" (February 2024) https://www.energy.gov/eere/articles/doe-announces-first-winners-hbcu-clean-energy-education-prize-partnerships-track

[159] Development of educational materials and curricula for various ages and levels of education, in the context of equitable scaling of the interconnection workforce, were also discussed at the i2X Solution e-Xchange on August 8, 2023. https://www.energy.gov/sites/default/files/2023-09/8.8%20WF%20SX%20Slides%20-%20Scaling%20Interconnection%20Workforce.pdf

3. Promote Economic Efficiency in Interconnection

DER interconnection and electric system planning processes are closely related. New DER projects may or may not align with utility long-term planning efforts, and thus may trigger network upgrades. This dynamic can have implications for both total costs and cost allocation. For example, under the traditional cost-causer-pays model, the DER project that triggers an upgrade pays its costs. Since upgrades add capacity in blocks, projects behind the initial cost causer in the queue may benefit from the upgrade without paying. Upgrade costs for facilities that are at or near their limits could be so high that no single DER project can feasibly support it, but if there were many projects using the same facilities, shared upgrade costs could make projects feasible. Without more equitable cost allocation among DERs, results could include cascading interconnection application withdrawals, project delays, and low DER deployment areas of the grid. This section describes solutions for improving DER interconnection cost allocation (3.1), coordinating DER interconnection and grid planning (3.2), and improving DER interconnection studies (3.3). Some solutions are exploratory, because innovative and equitable cost-allocation, planning, and coordination strategies require thoughtful and collaborative development, which takes time. Interim or pilot-style implementation of these solutions can promote equitable outcomes in the short-term while providing valuable data and the time to develop robust, long-term solutions. Long-term solutions should be capable of supporting additional functions and services for increased DER installations and aggregation, such as the next stage of deployment capabilities and distribution system design considerations outlined in the U.S. DOE-OE Distribution System Evolution report.[160] Other solutions in the roadmap—such as process automation—could also promote economic efficiency and are covered in other sections.

3.1 Cost Allocation

Key Takeaways

Interconnection costs can be allocated in various ways to improve economic efficiency and equitable outcomes. When considering cost allocation with respect to interconnecting DERs, it is important to think beyond the traditional cost-causer-pays model. In this section, we discuss four potential approaches for reforming cost allocation. The first three consider improved allocation among DER developers, while the fourth shares cost among all rate payers. First, the developer whose interconnection triggers an upgrade can be partially reimbursed with funds collected from later developers whose projects interconnect to the upgraded feeder circuit. Second, a reserve fund can be built by collecting fees from all interconnecting customers and then spent on upgrades triggered by subsequent interconnections. Third, a group study process can reduce per-

---

[160] U.S. Department of Energy, Office of Electricity. *Distribution System Evolution*. (2024). https://www.energy.gov/sites/default/files/2024-05/Distributed%20System%20Evolution%20April%202024_optimized.pdf

project interconnection upgrade costs and allocate costs among multiple projects based on their contribution to the triggered upgrade. And fourth, a utility can proactively upgrade feeder circuits in anticipation of projects and then recover costs as projects interconnect to the feeder circuit. Regulators should consider the range of options and engage interconnection participants and non-participants in robust and diverse participatory process to determine the best options for their jurisdiction.

Solutions Content

Solution 3.1: Reform the existing "cost-causer-pays" model, such that a project developer whose interconnection triggers an upgrade is partially reimbursed by subsequent developers who interconnect to the upgraded feeder circuit. (medium-term, low deployment)

Under the traditional cost-causer-pays model, the DER developer whose project interconnection triggers a system upgrade must pay for that upgrade. As a result, one developer may delay their project in the hope that another developer will take on the upgrade burden first, which can slow overall DER deployment.

Implementing an effective reimbursement process could distribute interconnection upgrade costs across all projects that benefit from the upgrade and mitigate the associated barrier to deployment. For example, under New York's "cost-causer post-upgrade cost sharing" model, the first DER project developer is partially reimbursed with funds collected from later developers whose projects interconnect to the upgraded feeder circuit. The contribution of a later interconnecting customer is calculated by multiplying the share (%) of the upgraded feeder circuit's capacity used by that customer by the total cost of the upgrade. As each additional project interconnects, this ratio is calculated for each additional project, and the first developer receives reimbursement until the capacity of the upgrade is fully utilized or the net cost to the initial project falls below $100,000, whichever comes first. Ideally, once the upgrade capacity is built out, the first developer and the subsequent developers end up paying shares equal to their use of the upgrade capacity under this type of approach. The New York Public Service Commission currently views this approach as an interim solution as it assesses various cost-allocation strategies and their potential impacts on developers and ratepayers.[161]

Successful implementation of this approach requires that regulators and utilities collaboratively define and communicate the reimbursement scheme, which includes clarifying the risk that no subsequent projects will interconnect, in which case the first developer would bear the entire

---

[161] New York State Public Service Commission. *New York State Standardized Interconnection Requirements and Application Process For New Distributed Generators and/or Energy Storage Systems 5 MW or Less Connected in Parallel with Utility Distribution Systems.* (2024). https://dps.ny.gov/system/files/documents/2024/02/sir-effective-february-1-2024.pdf

upgrade cost. The cost to the utility of tracking and reimbursing the original project owner must also be considered. One option is to collect a processing fee to cover these costs.

Table 22. Solution 3.1 Actors and Actions – Reform the existing "cost-causer-pays" model, such that a project developer whose interconnection triggers an upgrade is partially reimbursed by subsequent developers who interconnect to the upgraded feeder circuit.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	-Establish method for determining who benefits from an upgrade to equitably assign reimbursement costs. - Establish criteria for which interconnection upgrades are eligible for cost-causer post-upgrade reimbursement.	- Determine what happens if additional developers do not contribute to the upgrade after a given amount of time has passed.	-Communicate the reimbursement method based on proportional benefits to interconnecting customers.
Utilities			- Develop a billing calculator to operationalize payment for incoming developer shares and transfer of cash to first-mover developers.
Interconnection customers	- Review and understand cost-causer post-upgrade reimbursement strategy, acknowledging that subsequent interconnecting projects are not guaranteed.		- Understand and plan for scenario in which no projects follow on the feeder circuit and initial upgrade costs are not shared.
Research community (including DOE)	- Explore methods for assigning upgrade reimbursement portions based on benefits to interconnecting projects.		

Solution 3.2: Build a reserve fund by collecting fees from all interconnecting DER customers and spend the fund on upgrades triggered by subsequent interconnections. (medium-term, medium deployment)

An upgrade reserve fund has the potential to improve the fairness and transparency of the DER interconnection processes. Under this approach, all interconnecting projects (or all those below a size threshold unlikely to trigger major upgrades) pay a fee to interconnect that is either fixed or proportional to their export capacity (depending on their size). Projects that do not require upgrades pay the fee and proceed. For projects that trigger upgrades, they pay the fee, and the reserve fund is used to pay for the required upgrades. This strategy eliminates cost uncertainty from the interconnection process while allocating costs across all new DER projects. The fee schedule can be adapted to advance policy goals such as increased deployment of projects with EEJ benefits.

In 2022, the Minnesota Public Utilities Commission approved a flat fee approach, with an EEJ exemption, for Xcel Energy customers.[162] Under this program, customers seeking to interconnect DER projects under 40 kW pay a $200 fee to cover interconnection upgrade costs up to $15,000. Under-resourced or low-income customers, as identified by the utility, are exempt from this fee.[163]

The design of reserve-fund programs requires careful consideration. Cost caps, such as the $15,000 cap in Minnesota, are an important component to consider. They may cause some projects that require significant upgrades to be excluded from cost sharing, however, they reduce cost-recovery risks for the utility and its ratepayers. Examples of the types of risks include a low number of interconnection projects creating an insufficient reserve, and developers seeking to site multiple projects where expensive upgrades would be triggered.

Table 23. Solution 3.2 Actors and Actions - Build a reserve fund by collecting fees from all interconnecting customers and spend the fund on upgrades triggered by subsequent interconnections.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Establish an interconnection fee based on project export capacity sufficient to cover the cost of triggered upgrades.	- Establish a procedure to cover the cost of upgrades that exceed the current reserve funds. - Periodically reassess the scale of interconnection fees.	
Utilities		- Communicate purpose and method for assigning interconnection fees.	- Communicate scale of reserve funds for upgrades and periodically publish an itemized list of how funds are allocated.
Interconnection customers	- Review interconnection fee method and incorporate expected fee into interconnection application cost planning.		
Research community (including DOE)	- Perform studies to inform method for assigning fees based on export capacity or other relevant criteria.		

---

[162] Interstate Renewable Energy Council. *MN Interconnection Ruling Contains Some Wins and a Major Threat.* (2022). https://irecusa.org/blog/irec-news/mn-interconnection-ruling-contains-some-wins-and-a-major-threat/

[163] Olsen, Jo. *Fresh Energy Statement: New program to make it easier for Xcel solar customers to connect to the grid.* (2022). https://fresh-energy.org/fresh-energy-statement-new-program-to-make-it-easier-for-xcel-solar-customers-to-connect-to-the-grid

Solution 3.3: Use a group study process that reduces per-project interconnection upgrade costs by allocating costs among multiple projects based on their contribution to the triggered upgrade. (short-term, medium deployment)

Group study cost-allocation options can help overcome financial barriers that would otherwise threaten the economic viability of individual DER projects (a group study process can also help with addressing queue backlogs, see Solution 2.7). Under this framework, a utility's cost for completing group studies can be distributed among projects in the group, on a per-project or per-capacity basis, while reducing costs substantially for each applicant. Upgrade costs are then allocated among projects within the group based on contribution to the triggered upgrade. Upgrade costs are often allocated based on project size or export capacity but may also contain a per-project component. For example, the cost of station equipment upgrades can be split equally among all projects within the group, while conductor upgrades may be more appropriately allocated by project size.[164] It is important to consider the difference between using export capacity and nameplate capacity in these types of studies. For example, using nameplate capacity instead of inverter export capacity could end up requiring more extensive upgrades (see Solution 3.7).[165] Regulators and utilities can modify the cost allocation based on local priorities such as promoting EEJ projects. In any case, the utility should be transparent about its methods to prepare applicants and ensure equitable cost allocation.

As one example, the Massachusetts utility Eversource determines system modifications and associated costs for a group and then allocates cost based on the aggregated system design capacity for each applicant's facility.[166,167] The incremental interconnection fees are capped at $500/kW by the Department of Public Utilities.

Group studies can be complex to manage and could slow interconnection timelines, especially for projects that might have a faster path without the study, which can cause projects to drop out. If projects drop out, the entire study must be repeated, and the resulting costs may make the process infeasible for the remaining projects. Thus, smaller projects such as homes with minimal grid impacts do not warrant a group study process with long timelines and financial commitments. Utilities should have discretion to study smaller projects and those that opt out of group study individually. For transmission interconnection in California, the CPUC with CAISO exempted all net-metered systems and all inverter-based systems below 1 MVA from being

---

[164] As in the case of Oregon, highlighted in Interstate Renewable Energy Council, *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process* (2023). https://irecusa.org/wp-content/uploads/2023/10/IREC-Group-Studies-Paper-Final.pdf

[165] Interstate Renewable Energy Council. *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process* (2023). https://irecusa.org/wp-content/uploads/2023/10/IREC-Group-Studies-Paper-Final.pdf

[166] Eversource. *Distribution Group Studies.* (2024). https://www.eversource.com/content/residential/about/doing-business-with-us/interconnections/massachusetts/distribution-group-studies

[167] NSTAR Electric Company d/b/a Eversource Energy. *Standards for Interconnection of Distribution Generation.* (2021). https://www.eversource.com/content/docs/default-source/rates-tariffs/ma-electric/55-tariff-ma.pdf?sfvrsn=943800bb_5

studied in the transmission cluster. A similar approach could be adopted for DER interconnection, i.e., developing a group study process that is open to larger DER projects.

Group study cost-allocation strategies alone may be insufficient to reduce the cost of interconnecting DERs to grids that are already overburdened and in need of substantial upgrades.[168] For such constrained areas, proactive grid investments and cost sharing (Solution 3.4), could help reduce interconnection delays while addressing concerns about placing new burdens on ratepayers.

Table 24. Solution 3.3 Actors and Actions - Use a group study process that reduces per-project interconnection upgrade costs by allocating costs among multiple projects based on their contribution to the triggered upgrade.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Determine appropriate cap on the incremental interconnection fee for cost share, if used. Periodically reevaluate.	- Define what it means to benefit from an upgrade. - Define group processes and limitations for approach. -Define penalties for utilities failing to adhere to interconnection group study timelines.	- Determine a method for translating benefits into proportional cost calculation. - Evaluate the usefulness of interconnection designations, specifically for large residential and non-commercial project types.
Utilities	- Determine how to study projects in groups. - Define size thresholds for individual and group studies.		
Interconnection customers		- Explain potential to view community solar, virtual power plants, microgrids, multifamily buildings, new housing developments, and similar projects as groups.	- Find partner companies or project sets to form intentional groups.
Research community (including DOE)	- Analyze different program parameters.		- Create tools to measure the concept of upgrade benefits.

Solution 3.4: Proactively upgrade feeder circuits to accommodate forecasted DER growth and recover costs from future DER developers who share the upgraded feeder circuits. (medium-term, medium deployment)

Another solution is for utilities to upgrade feeder circuits proactively based on forecasted DER interconnections and then recover costs from future projects that interconnect on those feeder circuits. These types of upgrade investments could be triggered by a specific DER

---

[168] Interstate Renewable Energy Council. *Thinking Outside the Lines: Group Studies in the Distribution Interconnection Process* (2023). https://irecusa.org/wp-content/uploads/2023/10/IREC-Group-Studies-Paper-Final.pdf

interconnection request or be part of a larger system planning process. Utilities in Oregon,[169] New York,[170] and Hawaii[171] already perform DER forecasts as part of their distribution system planning processes and can disaggregate these forecasts to the substation or feeder circuit level, which could help prioritize upgrades in a proactive manner.

New York provides an example of how proactive upgrades can be pursued in response to a specific DER interconnection request. New York approved a new "Cost-Sharing 2.0" process in 2021.[172] Under the previous approach, a DER was responsible for 100% of upgrade costs and could be reimbursed later as other projects interconnected to the feeder circuit (as in Solution 3.1). Under "Cost-Sharing 2.0," the triggering DER pays only a portion of the cost. This approach, as implemented by Central Hudson Gas & Electric Corp., would work as follows. For a DER project requiring a 4,000-kW proposed interconnection, the utility might add 6,000 kW of hosting capacity at a cost of $3 million. In this case, the share of the upgrade costs allocated to the DER project developer would be $2 million (4,000 kW/6,000 kW), and the remaining $1 million would be recovered from future projects that connect to the feeder circuit.[173] If anticipated future projects do not occur, ratepayers would be responsible for paying the remaining cost of the upgrades. Rather than performing numerous isolated upgrades to accommodate single projects, this strategy allows for systematic upgrades along larger sections of the grid to complement utility planning processes and support long-term utility goals. It also helps to address the fact that it is not possible to perfectly size upgrades to specific projects.

Under "Cost-Sharing 2.0" in New York, the utility can also be more forward-looking. For example, under "Multi-Value Distribution" projects, the utility can identify substation upgrades that increase hosting capacity while solving a pre-existing asset condition or capacity issue. If the upgrades align with the projected market growth of DERs, the utility can fund the baseline project to solve the pre-existing condition, while participating DERs are only responsible for the incremental cost above the baseline.[174]

---

[169] Portland General Electric Company. *Distribution System Plan Part 2, Chapter 3.* (2022): https://edocs.puc.state.or.us/efdocs/HAD/um2197had151613.pdf

[170] National Grid. *Distributed System Implementation Plan Update of Niagara Mohawk Power Corporation d/b/a National Grid, Section 2.2.* (2023) https://www.nationalgridus.com/media/pdfs/other/cases-14-m-0101-and-16-m-0411-national-grid-2023-dsip-update.pdf

[171] Hawaiian Electric. *Location-Based Distribution Forecasts.* (2021). https://www.hawaiianelectric.com/documents/clean_energy_hawaii/integrated_grid_planning/20211108_location_based_distribution_forecasts.pdf

[172] State of New York Public Service Commission. *Order Approving Cost-Sharing Mechanism and Making Other Findings.* (2021). https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={73FC964F-A7C2-45D0-BB06-8FB2720F9C5C}

[173] Central Hudson. *Cost Share 2.0.* (2022) https://www.cenhud.com/globalassets/pdf/my-energy/solar-summit/2022/cost-share-2.0-central-hudson.pdf

[174] State of New York Public Service Commission. *Order Approving Cost-Sharing Mechanism and Making Other Findings.* (2021). https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={73FC964F-A7C2-45D0-BB06-8FB2720F9C5C}

Massachusetts provides another example of how proactive upgrades can be implemented. Under the Massachusetts "provisional system planning program," the utility can file an infrastructure upgrade proposal to get ahead of anticipated DER growth. Network upgrades are funded initially in part by ratepayers and reimbursed over time by fees charged to future DER projects that benefit from the upgrade.[175] To mitigate risks to ratepayers, the utility must demonstrate that the upgrade will lead to the anticipated number of connecting projects within the proposed rate-recovery period. However, risks to ratepayers from stranded assets exist even with this requirement.

Table 25. Solution 3.4 Actors and Actions: Proactively upgrade feeder circuits to accommodate forecasted DER growth and recover costs from future DER developers who share the upgraded feeder circuits.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Establish method for allocating benefit from upgrades to inform cost-sharing strategies.	- Assess and mitigate potential ratepayer impacts from cost-sharing approach.	- Translate proportional benefit determinations to cost-allocation strategy.
Utilities	- Define and communicate larger-scale grid upgrade costs triggered by interconnecting customers to seek regulatory approval. - Incorporate DER forecasting into system upgrade plans.	- Seek regulatory approval to proceed with larger-scale grid upgrades triggered by interconnecting DERs or in anticipation of DER growth.	- Communicate cost-sharing expectations for projects that may want to connect to upgraded feeder circuits.
Interconnection customers		- Engage in collaborative processes to highlight potential issues and share DER forecasts.	- Industry groups could help identify where developers are most interested in deploying DERs.
Research community (including DOE)	- Help other actors develop and evaluate forecast and cost-sharing methods.		

3.2 Coordination Between Interconnection and Grid Planning

Key Takeaways

Cost inefficiencies in interconnection arise in part because some system-level upgrades are typically triggered through the interconnection process, meaning they often occur in a piecemeal fashion. This type of piecemeal approach can risk imposing costs on interconnection customers or ratepayers depending on how regulators balance risks. Closer alignment of data inputs, assumptions, and process timelines between interconnection and long-term grid planning can

---

[175] Massachusetts Department of Public Utilities. *Provisional System Planning Program: DPU 20-75.* (n.d.) https://www.mass.gov/doc/provisional-system-planning-summary-0/download

help ensure more efficient and forward-looking identification and deployment of potential upgrades. A range of planning-related solutions apply. Interconnection for specific DER projects can be coordinated across the distribution, sub-transmission, and transmission systems. And coordination and data sharing can be improved between the DER interconnection process and the distribution system planning process.

Solutions Content

Solution 3.5: Coordinate interconnection for specific DER projects across the distribution, sub-transmission, and transmission systems. (medium-term, medium deployment)

Widespread deployment of DERs on the distribution and sub-transmission systems can affect operation of the transmission system, which increases the importance of coordinating DER interconnection across systems. While this solution applies to all utilities, for FERC jurisdictional utilities, FERC Order 2222 further raises the importance of coordination. The order passed in 2020 and is still being implemented across FERC-regulated areas. It enables aggregated DERs to participate in organized wholesale capacity, energy, and ancillary services markets run by regional grid operators. An important directive in Order No. 2222 is the need to establish market rules on coordination between the regional transmission organization/independent system operator (RTO/ISO), DER provider, distribution utility, and the relevant electric retail regulatory authorities. While the physical interconnection of DERs falls under state or local jurisdiction, the RTO/ISO must coordinate with state regulatory authorities to ensure the state policy, and the RTO/ISO policy are aligned. The RTO/ISO must incorporate a process to allow the state jurisdictional utility's review of the individual DER, in which that utility would determine (1) whether each DER's interconnection can physically participate in an aggregation (or is large enough to qualify as an aggregation on its own) and (2) that the participation of each DER will not create a network reliability or safety issue.[176]

The required coordination will encompass distribution system operators (e.g., utilities and load-serving entities) and ISO/RTOs across multiple processes. Communication will be needed between these entities, which have not typically worked together in this manner, including information sharing on DER interconnection, communicating on dispatch and control, and new flows of payments between actors.[177] For example, sharing interconnection data and coordinating DER forecasts between state jurisdictional utilities and ISOs/RTOs can help improve ISO/RTO load forecasts, which can reduce uncertainty and mitigate reliability challenges. More generally, ISOs/RTOs will need to coordinate with load-serving utilities in reviewing and registering DERs

---

[176] Zhou, Ella, David Hurlbut, and Kaifeng Xu. 2021. *A Primer on FERC Order No. 2222: Insights for International Power Systems*. Golden, CO: National Renewable Energy Laboratory. NREL/ TP-5C00-80166. https://www.nrel.gov/docs/fy21osti/80166.pdf.

[177] Energy System Integration Group's Distributed Energy Resources Task Force, DER Integration into Wholesale Markets and Operations (2022). https://www.esig.energy/wp-content/uploads/2022/01/ESIG-DER-Integration-Wholesale-Markets-2022.pdf

for wholesale market participation.[178] Leveraging data from ISO/RTO DER registration and utility interconnection processes can support more efficient DER aggregation reviews.

A distribution system operator (DSO) is an entity responsible for the planning and operational functions associated with a distribution system, including DERs and flexible assets, to ensure safe and reliable system operations.[179] The DSO framework is considered by many to be necessary for ensuring safety, efficiency, and cost-effective delivery of electricity in the distribution grid of the future.[180,181,182,183] Especially with the passing of FERC 2222, the DSO would streamline the new areas of coordination that will be required for DERs to participate in wholesale markets. Under this framework, either an independent entity, community choice aggregator, the load serving utility, or some hybrid organization[184] would ensure that local system loads and resources are accounted for before the wholesale market is cleared by the ISO/RTO. The DSO is not necessarily a separate organization, but a role assumed by an existing actor or actors. The DSO would act at the distribution-transmission interface, aggregating demand bids and supply offers from within its boundaries and submitting a combined demand curve and supply offer to the ISO/RTO. This model could improve coordination between the bulk power system and the local transmission and distribution system, for example, by ensuring that infeasible DER schedules are not cleared by the ISO/RTO. This can also lead to improved grid operational efficiency, reliability and resilience. The DSO would also help manage and coordinate the role of DERs participating in both retail and wholesale markets, improving the economic outlook of DERs and facilitating their deployment.

In 2023, Maine's Governor's Energy Office (GEO) launched a two-part study to evaluate whether a DSO could achieve the following objectives: (1) reduce electricity costs for

---

[178] FERC requires RTOs/ISOs to share with distribution utilities any necessary information and data about the individual distributed energy resources participating in a distributed energy resource aggregation (FERC Order No. 2222, 172 FERC ¶ 61,247 at P 292; see id. PP 236-40.)

[179] Reeve, Hayden M., Widergren, Steven E., Pratt, Robert G., Bhattarai, Bishnu, Hanif, Sarmad, Bender, Sadie R., Hardy, Trevor D., and Pelton, Mitchell A. Distribution System Operator with Transactive (DSO+T) Study: Volume 1 (Main Report). United States: N. p., 2022. Web. doi:10.2172/1842485.

[180] Reeve, Hayden M., Widergren, Steven E., Pratt, Robert G., Bhattarai, Bishnu, Hanif, Sarmad, Bender, Sadie R., Hardy, Trevor D., and Pelton, Mitchell A. Distribution System Operator with Transactive (DSO+T) Study: Volume 1 (Main Report). United States: N. p., 2022. Web. doi:10.2172/1842485.

[181] Black and Veatch Management Consulting, LLC. *Distribution System Operator (DSO) Models for Utility Stakeholders: Organizational Models for a Digital, Distributed Modern Grid.* 2020. https://webassets.bv.com/2020-02/20%20Distribution%20System%20Operator%20Models%20for%20Utility%20Stakeholders%20WEB%20updated%20022720.pdf

[182] Camus Energy. *The Rise of Local Grid Management: Why Electric Cooperatives & Municipal Utilities Are Poised to Lead the DSO Transition.*(n.d.) https://www.camus.energy/resources/the-rise-of-local-grid-management

[183] Givisiez, Arthur Goncalves; Petrou, Kyriacos, Ochoa, Luis F. *A Review on TSO-DSO Coordination Models and Solution Techniques. Electric Power Systems Research.* Vol 189, 2020, 106659. https://doi.org/10.1016/j.epsr.2020.106659.

[184] Black and Veatch Management Consulting, LLC. *Distribution System Operator (DSO) Models for Utility Stakeholders: Organizational Models for a Digital, Distributed Modern Grid.* 2020. https://webassets.bv.com/2020-02/20%20Distribution%20System%20Operator%20Models%20for%20Utility%20Stakeholders%20WEB%20updated%20022720.pdf

consumers, (2) improve electric system reliability and performance, and (3) accelerate progress towards Maine's climate goals and growth of DERs. If the initial study concludes that a DSO could achieve these objectives, part two will entail designing a proposal to identify the scope and characteristics of the DSO.[185] The GEO provided Maine's definition of a DSO as an entity designed to serve the following roles[186]:

- Oversee integrated system planning for all electric grids in the state, including coordinating energy planning efforts across state agencies.
- Operate all electric grids in the state to ensure optimum operations, efficiency, equitable outcomes, affordability, reliability and customer service.
- Administer an open and transparent market for DERs.
- Facilitate achievement of greenhouse gas reduction obligations and climate policies.
- Act as the primary interface between ISO-NE and electricity transmission grids in the state.
- Reside within a state agency.

This two-part study process provides a framework for evaluating and potentially implementing a DSO entity in pursuit of improved coordination, grid reliability, affordability, and deployment of DERs.

---

[185] State of Maine. *Resolve, to Create a 21st-Century Electric Grid: Chapter 67 Resolves. H.P. 599 – L.D. 952.* (June 22nd, 2023). https://www.mainelegislature.org/legis/bills/getPDF.asp?paper=HP0599&item=4&snum=131

[186] Strategen. *Maine Distribution System Operator (DSO) Feasibility Study – Webinar.* (June 20th, 2024). https://www.maine.gov/energy/sites/maine.gov.energy/files/meetings/ME%20GEO%20DSO%20Webinar%20%286.19.24%29.pdf

Table 26. Solution 3.5 Actors and Actions – Coordinate interconnection for specific DER projects across the distribution, sub-transmission, and transmission systems.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Ensure that utility aggregation review processes leverage existing data available through interconnection and ISO DER registration processes.	- Investigate potential role for a DSO. - Convene collaborative processes to establish roles and responsibilities of DSOs.
Utilities	- Share interconnection data and DER forecasts with ISOs/RTOs. Coordinate DER forecasting methods and review of DER participation in wholesale markets with ISOs/RTOs.	- Streamline DER aggregation reviews. - Consider adopting role of DSO or collaborating with outside DSO entity.	- Develop new methods of communication and coordination with ISOs/RTOs on DER aggregation and participation in wholesale markets.
Interconnection customers		- Engage in collaborative processes to establish roles and responsibilities for DSOs.	
Research community (including DOE)	- Continue to research DSO model frameworks, roles, responsibilities, and benefits.		- Collaborate with utilities and other organizations, providing technical assistance where appropriate to stand up DSO models.

Solution 3.6: Improve coordination and data sharing between the DER interconnection process and the system planning process to promote synergy between the two. (medium-term, medium deployment)

Improved coordination and data sharing between the system planning and interconnection processes for DERs will be necessary when many DERs are providing distribution and transmission services. This process may look different across utilities depending on the overlap between the utility's interconnection and planning databases, systems, and departments—the more separate the interconnection and planning functions are, the more effort required. Historically, there has been considerable variation in how utilities have planned for DER growth and associated system investments. As DER deployment levels increase there will be an increased need for improved coordination between DER interconnection processes and system planning processes. For example, system planning that includes DER forecasting, including incorporating it into load forecasting, is a potentially helpful strategy (and can help facilitate Solution 3.4).

Examples of information that could be shared between interconnection and planning processes include DER characteristics, baseline load conditions, expected load growth for growing technologies (e.g., EVs and building electrification), and operational requirements. Aligning data and assumptions between these processes should improve the accuracy of planning processes as well as the evaluation of the impacts of interconnection applications. Inverter settings as defined in interconnection agreements could be incorporated into planning models to better predict the grid impacts of forecasted DER deployment.[187] Closer coordination between these processes will require utilities to revisit organizational structures and ensure that software systems used by different parts of the utility can communicate; although potentially burdensome to facilitate, improved coordination should result in more accurate forecasting and targeted grid investments.

Table 27. Solution 3.6 Actors and Actions – Improve coordination and data sharing between the interconnection process and the system planning process to promote synergy between the two.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Require utilities to incorporate DERs into distribution system planning processes, including DER forecasts into load forecasts.	- Encourage interconnection-planning coordination. - Continue progress on distribution planning reforms. - Provide utilities with rate recovery principles for proactive planning with DERs.	
Utilities	- Ensure coordinated inputs and assumptions. - Align tools and data used in planning, interconnection, and distribution system operations. - Incorporate DER forecasts into load forecasting and other distribution system planning functions.	-Seek cost recovery guidance on proactive planning methodologies for DERs.	- Develop coordinated process timelines. - Ensure utility departments and software platforms have communication approaches in place to streamline interconnection and planning functions.
Interconnection customers	- Provide validated forecasts of DER deployment.		- Participate in and inform collaborative discussions.
Research community (including DOE)	- Document emerging practices for coordination.		

3.3 Interconnection Studies

Key Takeaways

Interconnection study methods must evolve to promote safe and reliable DER interconnection while reducing the need for inefficient system upgrades. A generator's nameplate capacity can be distinguished from its export capacity in interconnection studies to reflect project impacts accurately. The grid benefits provided by DERs can be accounted for in interconnection studies.

---

[187] Energy System Integration Group's Distributed Energy Resources Task Force, DER Integration into Wholesale Markets and Operations (2022). https://www.esig.energy/wp-content/uploads/2022/01/ESIG-DER-Integration-Wholesale-Markets-2022.pdf

Flexible interconnection can be implemented, allowing DERs to avoid some upgrade costs in exchange for being curtailed under constrained conditions.

Solutions Content

Solution 3.7: Distinguish between a generator's nameplate capacity and export capacity in interconnection studies to accurately reflect project impacts. (short-term, low deployment)

To evaluate interconnection applications according to their intended operating conditions, it is critical to align study assumptions with realistic generator operating conditions by distinguishing between a generator's nameplate capacity and export capacity. This can help avoid overestimating potential grid impacts and assigning overly high grid upgrade costs to a given system.[188] This distinction is important both for early screening and study processes.

While this approach applies to all technologies, it is particularly important for projects incorporating energy storage.[189] For example, PV-plus-storage systems are commonly designed to maximize use of PV-generated electricity. The energy storage charges from PV during the day and dispatches that power at night, while remaining PV generation is consumed on site or exported to the grid. In this case, the PV and storage components are not designed to export to the grid simultaneously; in fact, the storage reduces the exported PV electricity. As a result, the export capacity of this PV-plus-storage system can be significantly less than the system's combined nameplate capacity. If the system has an operating agreement with the utility that limits the combined output of the system, then evaluating such a system based on its combined nameplate capacity can trigger unnecessary system upgrades and delay, or even prevent, such a project from interconnecting.[190] This example points out the importance of understanding how a system will be operated, incorporating that into an operating agreement, and accounting for that in the interconnection process.

---

[188] IREC's BATRIES Toolkit, which focuses on specific concerns related to interconnection of energy storage, distinguishes these terms as follows:

- Export Capacity means the amount of power that can be transferred from the DER to the electric system. Export Capacity is either the Nameplate Rating, or a lower amount if limited using an acceptable means.
- Nameplate Rating means the sum of maximum rated power output of all of a DER's constituent generating units and/or ESS as identified on the manufacturer nameplate, regardless of whether it is limited by any approved means.

(See Toolkit and Guidance for the Interconnection of Energy Storage and Solar-Plus-Storage (IREC, 2022).)

[189] Building a Technically Reliable Interconnection Evolution for Storage (BATRIES). *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage.* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/ ("Most states' existing DER interconnection procedures are not designed with storage in mind, which can create unintended time, cost, and technical barriers to storage integration. As one example, most interconnection rules either permit or require utilities to evaluate the impacts of storage on the grid with the assumption that storage systems will export their full nameplate capacity at all times. In reality, this assumption is extreme for several reasons and doesn't reflect how storage is typically operated, thus creating an unnecessary—but solvable—barrier to storage interconnection." P. 11)

[190] Building a Technically Reliable Interconnection Evolution for Storage (BATRIES). *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage.* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

Interconnection screens should require a project's nameplate and export capacity, given how it will be operated, and should determine eligibility accordingly. To avoid confusion, regulators and utilities should specify whether nameplate or export capacity is being referenced when describing the size of an interconnecting system. For instance, IREC suggests a simplified study process for projects with a nameplate capacity under 50 kW and an export capacity below 25 kW. These requirements could be part of broader efforts to expand and standardize reporting of interconnection data at the request stage, as detailed in Solution 1.2.

For projects that are not evaluated by fast-track or simplified study processes, utilities should evaluate project impacts on the electric system based on export capacity, except when evaluating the effects of fault currents, which are evaluated based on the rated fault current.[191] Utilities can consider requiring projects to submit operating profiles or schedules employing certified export controls that can be used to evaluate system impact and incorporating these requirement into operating agreements. In early 2024, the California Public Utilities Commission issued a decision allowing renewable generators and energy storage to interconnect by adhering to export schedules.[192] This regulatory framework aims to reduce some interconnection-driven system upgrades. Developers or system operators must comply by ensuring that a system's export capacity adheres to the required schedules Enforcement is accomplished using power control systems, devices that electronically control the power output of generating facilities, or relays.

---

[191] Building a Technically Reliable Interconnection Evolution for Storage (BATRIES). *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage.* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

[192] Public Utilities Commission of the State of California. *Resolution E-5296.* (2024) https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M527/K828/527828730.PDF, Interstate Renewable Energy Council. *California Regulators Open the Door for DERs to Avoid Interconnection Upgrades and Unlock Flexibility Through Export Scheduling.* (2024) https://irecusa.org/blog/regulatory-engagement/california-regulators-open-the-door-for-ders-to-avoid-interconnection-upgrades/

Table 28. Solution 3.7 Actors and Actions – Distinguish between a generator's nameplate capacity and export capacity in interconnection studies to accurately reflect project impacts.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Evaluate role of advanced power control systems needed to enable export capacity-based regulations for energy storage and other eligible systems.	- Consider adoption of regulations that allow eligible systems to interconnect at lower than their nameplate capacity if export will be lower, such as by requiring systems to follow operating profiles or schedules based on grid constraints. - Work with the interconnection community to develop measurement and verification mechanisms, including penalties, for systems that export outside of agreed-upon schedules or limits.	- Ensure regulations that address the size of a generator specify either nameplate or export capacity.
Utilities	- Evaluate system impacts of eligible systems, including energy storage and hybrid systems, according to restricted export capacity rather than nameplate capacity. - Assess and publish detailed hourly hosting capacity models for each distribution system node, if not already in place, to enable adoption of export capacity-based interconnection agreements for eligible systems. See Solutions 1.4 and 1.5 for a more detailed discussion of hosting capacity utilization.		- Collect both nameplate and export capacity of project applications for initial screening processes. - Reflect operating limits or required schedules in interconnection agreements for eligible systems.
Interconnection Customers	- Develop operating profiles for eligible systems that can be incorporated into an enforceable export limit for interconnection agreements.		

Research community (including DOE)	- Create reference models of system impacts incorporating DER operating profiles under varying conditions, e.g., weather, system load, and real-time prices. - Work with utility, industry, regulatory, and other key groups to set and adopt standards on operational controls, including measurement and verification.		

Solution 3.8: Account for potential grid benefits and costs due to DERs in interconnection studies (medium-term, medium deployment)

Jurisdictions are increasingly allowing, encouraging, or requiring utilities to consider non-wire alternatives (NWA)—which engage services from new or existing DERs to improve system performance—in system planning processes.[193,194] NWAs can align grid needs with DER interconnection, which can mitigate or avoid the need for grid upgrades in some circumstances. For example, Oregon's Portland General Electric identifies the need for volt-var improvements,[195] which can be addressed using smart inverter functions. Oregon recently moved to adopt IEEE Std 1547-2018 under the UM 2111 docket,[196] which requires volt-var capabilities for new DERs and thus aligns the interconnection process with the system needs process. Similarly, the Energy Systems Integration Group (ESIG) identifies vehicle-to-grid (V2G) capability as a way to stabilize voltage changes.[197]

Storage and DER-plus-storage enforceable operating profiles and schedules should be considered in interconnection studies, rather than simply analyzing worst-case scenarios.[198] For example, storage cannot operate at full capacity continuously. To consider the profiles and schedules, however, utilities must be assured that the DER can and will adhere to them, which requires standardization and/or advanced monitoring and control capabilities. In Hawaii, for example, high levels of DER deployment have led to a transition away from traditional net energy

---

[193] For select examples see Section 5 ofN. M. Frick, et. al., "Locational Value of Distributed Energy Resources," Feb. 2021, doi: 10.2172/1765585.

[194] ComEd. *ComEd Multi-Year Integrated Grid Plan, Section 4.5.2.2.* (2023). https://icc.illinois.gov/downloads/public/edocket/578620.PDF

[195] Portland General Electric. *Distribution System Plan: Part 2, Table 58.* (2022) https://edocs.puc.state.or.us/efdocs/HAD/um2197had151613.pdf

[196] Public Utility Commission of Oregon. *UM 211, AR 659.* (2023) https://apps.puc.state.or.us/orders/2023ords/23-319.pdf

[197] The Energy Systems Integration Group. *Charging Ahead: Grid Planning for Vehicle Electrification.* (2024). https://www.esig.energy/wp-content/uploads/2024/01/ESIG-Grid-Planning-Vehicle-Electrification-report-2024.pdf

[198] Building a Technically Reliable Interconnection Evolution for Storage (BATRIES). *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage.* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

metering to implementing time-varying rates for electricity exports, known as export credits. Having already established the grid benefits of increased exports in the evening hours, these credits now provide financial incentives to the interconnection customers to align their exports with grid needs. To implement this strategy, interconnection studies must include these profiles and schedules to accurately determine system impacts and any associated upgrade costs.[199] However, since the grid will change over time, flexibility should also be considered.

The energy service interface[200] and common grid services[201] efforts from the Grid Modernization Laboratory Consortium are promoting standardized mappings between system needs and resource capabilities, via clearly defined communication, control, and measurement requirements. Adoption of such frameworks will allow utilities to better forecast future capabilities from DERs during the interconnection study process, and then realize projected grid benefits during the project's operation.

Table 29. Solution 3.8 Actors and Actions – Account for potential grid benefits and costs due to DERs in interconnection studies.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Request utilities to detail data gap (static, monitoring, or control) to harmonize NWA planning and DER interconnection process.	- Encourage adoption of IEEE Std. 1547-2018 with the advanced capabilities. - Set guidance on distribution system planning horizon.	
Utilities	- Integrate DER forecast and capabilities into NWA planning. - Integrate advanced controls, such as storage schedules, into application and study process.	- Engage in collaborative processes to define methods for validating advanced DER capabilities.	- Provide standardized way for advanced capabilities to be communicated during application process.
Interconnection customers	- Incorporate consideration of wider set of capabilities and services into design cycle.	- Provide verification of advanced capabilities. - Provide operating schedules where applicable.	
Research community (including DOE)	- Evaluate emerging mitigation solutions and their effectiveness. -In collaboration with OEMs, develop models for emerging technologies.	- Continue work on standardization of the Energy Service Interface.	

---

[199] Hawaiian Electric. *Smart Renewable Energy Export.* https://www.hawaiianelectric.com/products-and-services/smart-renewable-energy-programs/smart-renewable-energy-export

[200] R. Brown et al., "Guide to Developing Energy Services Interfaces," Jan. 2024, doi: 10.2172/2280683.

[201] J. T. Kolln, et al, "Common Grid Services: Terms and Definitions Report," Jul. 2023, doi: 10.2172/1992370.

Solution 3.9: Allow flexible interconnection as a way to mitigate system upgrade costs during interconnection studies (medium-term, high deployment).

Flexible interconnection procedures allow DERs to mitigate interconnection upgrade costs in exchange for being curtailed under grid constrained conditions. Flexible interconnection is introduced as a queue-management strategy in Solution 2.5 and is revisited here as a mechanism to improve interconnection study processes. Implementation requires utilities to develop standard procedures for determining the types of violations and related system upgrades that could be avoided through curtailment or re-dispatch of DERs.

Developing and transparently communicating reasonable expectations around the quantity and frequency of curtailment, curtailment methods, commands, and dispatch algorithms is critical for informing participants about the financial impacts of curtailments.[202] As an example, the California Public Utilities Commission recently adopted a flexible interconnection rule allowing some renewable generators and energy storage to interconnect below their export capacity if they adhere to operating schedules that minimize grid impacts.[203]

Utilities should also communicate how project owners will be compensated if the maximum curtailment level is exceeded. For example, in the UK, where flexible interconnection is more prevalent, the utility provides curtailment reports[204] as part of the interconnection process to tell applicants their expected curtailment. While the report provides no guarantees, it enables the applicant to evaluate curtailment implications. If utilities provide the load conditions and hosting capacity assumptions behind the curtailment report, applicants can conduct further studies to evaluate their curtailment risk. Where not otherwise restricted, applicants should be able to choose standard interconnection inclusive of upgrade costs if their assessment of curtailment risk is too high.

Beyond any costs associated with curtailed energy, there is a potential cost for establishing flexible interconnection systems, depending on their level of sophistication. While fixed, time-dependent limits (e.g., seasonal export limits) require little or no additional communication infrastructure, most implementations or pilots require active monitoring and control, which requires investments in additional equipment.[205] The implementation cost will likely establish a

---

[202] Electric Power Research Institute. *Principles of Access for Flexible Interconnection: Cost Allocation Mechanisms and Financial Risk Management.* (2020). https://www.epri.com/research/products/000000003002019635

[203] Public Utilities Commission of the State of California. *Resolution E-5296.* (2024) https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M527/K828/527828730.PDF, Interstate Renewable Energy Council. *California Regulators Open the Door for DERs to Avoid Interconnection Upgrades and Unlock Flexibility Through Export Scheduling.* (2024) https://irecusa.org/blog/regulatory-engagement/california-regulators-open-the-door-for-ders-to-avoid-interconnection-upgrades/

[204] National Grid. *ANM Curtailment Reports.* (2024). https://www.nationalgrid.co.uk/anm-curtailment-reports

[205] For example, the REV Demo project in NY: Avangrid. *Flexible Interconnection: REV Demo Lessons Learned and Scalability Roadmap.* (2022). https://dps.ny.gov/system/files/documents/2022/11/avangrid-flexible-interconnection.pdf

minimum project capacity, below which flexible interconnection is not sensible given the investment.

Table 30. Solution 3.9 Actors and Actions – Allow flexible interconnection as a way to avoid system upgrade costs during interconnection studies.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Set guiding philosophy behind flexible interconnection. For example, is it always available or required? What is a fair allocation of curtailment?	
Utilities	- Develop curtailment reports for prospective flexible interconnection customers. - Establish minimum project threshold for flexible interconnection. - Establish monitoring and control systems fitting for the given sophistication of flexible interconnection.		- Clearly communicate process time and cost differences of flexible versus standard interconnection. - Provide access to data/assumptions used in curtailment reports so interconnection customers can conduct their own evaluations.
Interconnection customers	-Use and advocate for flexible interconnection in the project planning phase. -Conduct studies to determine financial viability of flexible interconnection at expected curtailment levels.		- Use interconnection application processes to communicate a range of acceptable prices for upgrades and caps for flexible interconnection.
Software developers/ Engineering Firms	-Demonstrate and advance the abilities of hardware to effectively curtail generation.	- Clearly define operational data and communications that allow for diverse flexible interconnection policies.	- Work with developers and utilities to create cybersecure system to support flexible interconnection.
Research community (including DOE)	- Work with regulators, interconnection customers, and utilities to develop pilots or case studies that instill confidence in the flexible interconnection concept.		- Work with the interconnection community to identify and overcome barriers to implementation.

4. Maintain a Reliable, Resilient, and Secure Grid

Maintaining a reliable, resilient, and secure grid requires addressing the performance of inverter-based resources (IBRs) during steady-state operation and transient faults. For DER installations, the industry focuses primarily on voltage control, system protection, and the potential for islanding. Industry best practices exist for screening DER projects for reliability and identifying mitigation options when necessary. Interconnecting DER projects fall into one of three categories: those eligible for simplified interconnection processes, those that exceed the threshold for simplified processing but can be fast-tracked, and those requiring an interconnection study process. The track selection differs by jurisdiction but is largely determined by the project size and use of certified inverters, which correlate to potential risks to grid operation. Beyond mitigating risk, interconnecting DERs must also support grid resilience, or the ability to prepare for and adapt to changing operating conditions or disruptions.

Interconnection standards are critical for maintaining a reliable, resilient, and secure grid. FERC and North American Electric Reliability Corporation (NERC) set high-level interconnection requirements specifying generator capabilities and expected performance of IBRs that are interconnected at the transmission level, but consistent requirements do not exist for DERs.[206] Interconnection requirements for DERs are established at the state level by regulators or, in states without statewide interconnection requirements, by individual utilities. These rules vary by state and by utility, and most states do not regulate electric cooperatives and municipal electric companies.[207] Furthermore, existing interconnection standards lack performance specifications for accompanying phenomena during voltage or frequency disturbances.

This section describes solutions to enhance interconnection screening, study approaches, and modeling tools to support reliable and resilient operation of DERs. It also identifies solutions to encourage widespread adoption of existing standards and support development of new standards for emerging technologies and issues, including growing cybersecurity issues.

---

[206] Reliability standards for generators are developed by NERC. In late 2023, FERC issued a rule directing NERC to update reliability standards “to address reliability gaps related to inverter-based resources” related to data sharing, modeling, planning, and performance requirements. See Federal Energy Regulatory Commission, Department of Energy. *Reliability Standards to Address Inverter-Based Resources Docket No. RM22-12-000 Order No. 901.* (2023) https://www.federalregister.gov/documents/2023/10/30/2023-23581/reliability-standards-to-address-inverter-based-resources#citation-2-p74251

[207] National Renewable Energy Laboratory. (2022). *Renewable Energy System Interconnection Standards*. National Renewable Energy Laboratory. https://www.nrel.gov/state-local-tribal/basics-interconnection-standards.html

4.1 Interconnection Models and Tools

Key Takeaways

Improvements to interconnection models and tools are needed to support deploying DERs while maintaining grid reliability. The protection schemes developed for the distribution and sub-transmission systems must be made DER ready. Proactively planning and implementing grid modernization can accelerate DER readiness while reducing costs, improving system reliability, and shortening outage times.

High ratios of DERs to local load raise concerns about islanding—in which DERs continue to operate in isolation from the main grid during system disturbances—and associated risks of property damage and human injury. Utilities often use Direct Transfer Trip (DTT) to mitigate the risk of islanding, but the complexity and cost of DTT are common reasons for larger DER projects to withdraw from the interconnection queue.[208] More cost-effective approaches to evaluating and mitigating the risk of islanding are needed.

Electromagnetic transient (EMT) models are one option for evaluating DER performance, including evaluating the risk of islanding, which may preempt the need for DTT. Because EMT models can also be costly and complex, screening tools should be developed to determine when EMT studies are necessary as DER deployment increases.

Although increasing numbers of DERs on the distribution and sub-transmission systems can affect the transmission system, current tools for analyzing the seams between the systems cannot capture those effects adequately. Improved models and co-simulation methods are needed. Similarly, data from DERs should be collected to validate models that ensure compliance with BPS reliability standards and to perform large-scale reliability assessments.

Solutions Content

Solution 4.1: Proactively develop and implement new DER-ready system protection schemes (medium-term, low deployment).

Distribution and sub-transmission systems have closely coordinated protection schemes to quickly isolate faults and limit overvoltages—limiting damage to electrical system equipment and protecting human life while minimizing service interruptions. The protection schemes in

---

[208] According to data from a survey of developers conducted by New Leaf Energy for the Coalition for Community Solar Access (CCSA), 7 of the 11 companies operating in states where DTT is required reported having to withdraw projects due to high costs and long timelines associated with DTT equipment installation requirement. See slides and notes discussing survey and results from the i2X Solution e-Xchange on May 3, 2023 https://www.energy.gov/sites/default/files/2023-05/Solution%20e-Xchange%20Distribution%20System%20Protection%20with%20High%20DER%20Levels.pdf

widespread use have evolved largely without considering DERs. However, challenges related to system protection exist in systems with high DER deployment relative to load:[209]

- Conventional distribution system overcurrent protection schemes limit the amount of DERs that can be installed, so modifications are required as more DERs are deployed.[210] Because DERs change fault currents, the protective devices may not be coordinated and may require new settings. New protection devices might also be required, such as installing additional reclosers, directional relays, or larger protective equipment due to higher fault currents.
- System protection design slows interconnections of DERs. Pre-interconnection modeling of DERs for protection, e.g., the diversity of DER control responses and ride throughs to faults, is difficult and time consuming.
- DER grounding and reverse power flows can impact transient overvoltages during faults. Depending on the substation protection and grounding, reverse power flows from the distribution system into the transmission system can also cause ground fault overvoltages during transmission faults; see Solution 4.2.
- When connecting DERs to spot and mesh secondary networks protection options are limited by IEEE 1547 and most utility policies.

Proactive grid modernization can make implementation of "DER ready" protection schemes less impactful to interconnection customers and more cost effective. For example, in some systems, fuses are the default protection device on distribution feeder circuits, because they are inexpensive and perform well in a system with few generation resources. Adding DERs can require fuses to be replaced with reclosers, directional overcurrent protective elements, or communication-assisted protection schemes. The interconnection customer typically pays for replacements near the DER POI and often upstream of the POI. Alternatively, the utility could preemptively replace fuses with qualified protection equipment, which generally results in faster, more cost-effective grid modernization, improved system reliability, and shorter outage times[211].

Recent research indicates that, as utilities upgrade to new protection schemes, the protection system will be less sensitive to new DER interconnections. For example, adaptive protection enables the protection system to respond to new interconnections and variability in DER

---

[209] J. Seuss, M. J. Reno, R. J. Broderick, and S. Grijalva, " Determining the Impact of Steady-State PV Fault Current Injections on Distribution Protection," Sandia National Laboratories, SAND2017-4955, 2017. https://doi.org/10.2172/1367427

[210] J. A. Azzolini, N. S. Gurule, R. Darbali-Zamora, and M. J. Reno, "Analyzing Hosting Capacity Protection Constraints Under Time-Varying PV Inverter Fault Response", IEEE Photovoltaic Specialists Conference (PVSC), 2022. doi:10.1109/PVSC48317.2022.9938535

[211] McDermott, TE; Smith, TM; Fan, R; Hambrick, JC; Thekkumparambath Mana, P; Li, Z; Vyakaranam, B; Barnes, AK. *Relaying for Distribution and Microgrids: Evolving from Radial to Bidirectional Power Flow.* (2019). PNNL-29145. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-29145.pdf

generation.[212] Traveling wave protection is another promising non-overcurrent protection scheme.[213] And recent work on spot and low-voltage secondary networks indicates that modifying the network protector settings or adding communication can allow for DER interconnections throughout the network.[214]

Table 31. Solution 4.1 Actors and Actions — Proactively develop and implement new DER-ready system protection schemes.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Develop guidelines for proactively planning protection in evolving systems, balancing costs and benefits to ratepayers. - Develop additional DER capabilities requirements to improve distribution system protection.	- Require utilities to report on evolving system protection as part of grid modernization investments.	
Utilities	- Evaluate alternative protection schemes and protective devices independent of the interconnection study process.	- Inform regulators on costs of system protection improvements to validate cost-effectiveness.	- Qualify new system protection equipment in advance of needed implementation.
Interconnection customers	- Offer flexibility in POI, if possible, when project location impacts system protection options, e.g., under frequency load shedding (UFLS).	- Provide detailed information about DER response during faults.	
Research community (including DOE)	- Support development of novel system protection schemes and system protection devices for high-IBR cases. - Work with commercial protection design software vendors to improve the accuracy of DER modeling. - Provide technical assistance to develop and deploy cost-effective and safe protection methods that support improvements in interconnection processes, timing, and economic efficiency.	- Support updating IEEE 1547 to better allow DER interconnections in low-voltage secondary networks.	

---

[212] M. J. Reno, M. Jimenez-Aparicio, T. Patel, A. Summers, et al. “Adaptive Protection and Control for High Penetration PV and Grid Resilience Final Technical Report,” Sandia National Laboratories, SAND2024-05240, 2024.

[213] M. Jimenez-Aparicio, T. Patel, M. J. Reno, J. Hernandez-Alvidrez, “Protection Analysis of a Traveling-Wave, Machine-Learning Protection Scheme for Distributions Systems With Variable Penetration of Solar PV,” IEEE Access, 2023.

[214] J. A. Azzolini, M. J. Reno, M. E. Ropp, Z. Cheng, E. Udren, J. Holbach, “Increasing DER Hosting Capacity in Meshed Low-Voltage Grids With Modified Network Protector Relay Settings,” IEEE Innovation Smart Grid Technologies Latin America (ISGT LA), 2023. DOI:10.1109/ISGT-LA56058.2023.10328217

Solution 4.2: Develop alternatives to address unintentional islanding and provide research-based methods to evaluate their cost-effectiveness (medium-term, low deployment).

The addition of DERs in higher proportions compared to local loads raises concerns of potential islanding[215] during system disturbances. Islanded DERs may have unregulated voltage and frequency compared to normal grid operation, and in this mode the DERs can cause damage to equipment at the interconnection customer site and all along the islanded feeder circuit. In addition, the existence of DERs operating in unidentified islands is a safety risk for line crews attempting to restore service after a fault. IEEE Standard 1547-2018[216] updates the operating requirements for DERs during grid disturbances, specifying ride-through requirements, and provides guidelines for implementing inverter settings and system protection settings.

DERs must combine hardware and software controls to prevent them from energizing a feeder circuit during unintended electrical islands.[217] Industry standards require that DERs cease to energize unintended islands within 2 seconds, and they specify tests to verify compliance by individual DERs on an idealized feeder circuit in the testing laboratory.[218] For example, Sandia National Laboratories' anti--islanding screens have been in use since 2012.[219] These screens are still widely used by utilities today as a basis for determining whether additional studies on DER projects are needed. The 2012 screens focus on correlating the risk of islanding to certain conditions on the grid and characteristics of the DER. However, the 2012 Sandia screens were written in the context of IEEE Std 1547-2003 and are not compatible with IEEE Std 1547-2018. More recent research[220,221] has focused on updating the 2012 screens for compatibility with 1547-2018. This more recent research suggested that certain DER-resident anti-islanding methods are much more effective than other methods, and it has led some utilities to require DERs to incorporate specific anti-islanding protection capabilities.[222]

---

[215] Islanding refers to the isolation of a system from the grid, in the event of a grid disturbance, to continue operating locally while disconnected from the main grid.

[216] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), vol., no., pp.1-138, 6 April 2018, doi: 10.1109/IEEESTD.2018.8332112.

[217] R. A. Walling, "Application of direct transfer trip for prevention of DG islanding," 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 2011, pp. 1-3, doi: 10.1109/PES.2011.6039727.

[218] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), vol., no., pp.1-138, 6 April 2018, doi: 10.1109/IEEESTD.2018.8332112.

[219] Ropp, M.; Ellis, A. *Suggested Guidelines for Assessment of DG Unintentional Islanding Risk.* Sandia National Laboratories. Albuquerque, NM. (2013). https://energy.sandia.gov/wp-content/gallery/uploads/SAND2012-1365-v2.pdf

[220] Ropp, M. et.al., "Unintentional Islanding Detection Performance with Mixed DER Types," SAND2018-8431, August 2018.

[221] Ropp, M. et. al., "Evaluation of Multi-Inverter Anti-Islanding with Grid Support and Ride-Through and Investigation of Island Detection Alternatives," SAND2019-0499, January 2019. https://doi.org/10.2172/1491604

[222] Pacific Gas and Electric, "Distributed Generation Protection Requirements", February 2023, https://www.pge.com/content/dam/pge/docs/about/doing-business-with-pge/094681.pdf.

Recent studies have also shown that DERs that pass the existing laboratory tests may not always detect islands in the field, primarily due to the mixture of DER sizes and types, plus other variability in load and feeder circuit behaviors[223]. To mitigate this risk, some utilities have required DTT or a detailed anti-islanding study whenever the DER capacity exceeds two-thirds of the minimum daytime load within a potential island.[224,225] The costs and complexities of DTT and detailed studies are typically borne by DER owners and developers but may also impose costs on electric utilities. Developing a practical alternative could benefit the entire interconnection community.[226]

Traditional DTT is often referred to as "tripping DTT," because it uses a dedicated communications link to force the DER's inverter to cease to energize an unintended island, regardless of the reason the island formed, or whether a fault exists in the island. One alternative approach is "permissive DTT."[227,228] Under this approach, the DER's inverter receives a "heartbeat signal" from the normal substation source over distribution feeder circuit wires. If the heartbeat signal is lost at any time, then the DER trips within 2 seconds. Permissive DTT has been demonstrated, but additional research is required to fully understand the cost and performance tradeoffs of using tripping versus permissive DTT. Other potential approaches that require further research and demonstration include use of traditional power-line communications,[229] 4G (LTE) communications,[230] or 5G communications.[231]

---

[223] Ellis, Abraham, and Ropp, Michael. Suggested guidelines for anti-islanding screening. United States: N. p., 2012. Web. doi:10.2172/1039001.

[224] Ellis, Abraham, and Ropp, Michael. Suggested guidelines for anti-islanding screening. United States: N. p., 2012. Web. doi:10.2172/1039001.

[225] Ropp, M.; Ellis, A. *Suggested Guidelines for Assessment of DG Unintentional Islanding Risk.* Sandia National Laboratories. Albuquerque, NM. (2013). https://energy.sandia.gov/wp-content/gallery/uploads/SAND2012-1365-v2.pdf

[226] See Grid engineering practices and standards protection with high adoption of DER and video (i2X Solution e-Xchange, 2023).

[227] M. Ropp et al., "Discussion of a Power Line Carrier Communications-Based Anti-Islanding Scheme using a Commercial Automatic Meter Reading System," in *2006 IEEE 4th World Conference on Photovoltaic Energy Conference*, 7-12 May 2006, vol. 2, pp. 2351-2354, doi: 10.1109/WCPEC.2006.279663.

[228] W. Xu and W. Wang, "Power Electronic Signaling Technology—A New Class of Power Electronics Applications," *IEEE Transactions on Smart Grid*, vol. 1, no. 3, pp. 332-339, 2010, doi: 10.1109/TSG.2010.2066293.

[229] S. Galli, A. Scaglione, and Z. Wang, "For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 998-1027, 2011, doi: 10.1109/JPROC.2011.2109670.

[230] W. An, J. J. Ma, H. Y. Zhou, H. S. Chen, X. Jun, and X. Jian, "Application of an Integrated Protection and Control System for Smart Distribution Grid Based on PTN and 4G LTE Communication," in *2019 3rd International Conference on Smart Grid and Smart Cities (ICSGSC)*, 25-28 June 2019, 2019, pp. 70-75, doi: 10.1109/ICSGSC.2019.00-16.

[231] K. Ghanem, S. Ugwuanyi, R. Asif, and J. Irvine, "Challenges and Promises of 5G for Smart Grid Teleprotection Applications," in 2021 *International Symposium on Networks, Computers and Communications (ISNCC)*, 31 Oct.-2 Nov. 2021, 2021, pp. 1-7, doi: 10.1109/ISNCC52172.2021.9615649.

Table 32. Solution 4.2 Actors and Actions — Develop alternatives to address unintentional islanding and provide research-based methods to evaluate their cost-effectiveness.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators		- Develop options to provide anti-islanding protection over the range of needs in the regulated system.	
Utilities	- Develop acceptable anti-islanding options given the operations and protection philosophy of the specific system.		- Integrate anti-islanding options into DER screens.
Interconnection customer	- Develop DER designs with acceptable anti-islanding options in mind.		
Research community (including DOE)	- Work with utilities and manufacturers to run field tests that instill confidence in anti-islanding options.		

Solution 4.3: Optimize development and use of EMT models for evaluating the dynamic performance of DERs (long-term, medium deployment).

EMT models can clarify the dynamic performance of DERs that interconnect via inverters, because they accurately simulate high-frequency transient phenomena in electrical systems. Ensuring EMT models represent the physical and dynamic characteristics of DERs is crucial for their successful use.[232] The models must be validated using field and experimental data to demonstrate that they emulate behavior in compliance with interconnection standards such as IEEE Std. 1547, UL 1741, and IEEE Std. 2800. In this context, EMT models can help test DER capabilities such as voltage regulation, frequency response, and ride-through capabilities.[233,234] They could also evaluate issues such as harmonics, fast oscillations, or unintended trips due to instantaneous overvoltage or loss of phase-locked loops.

---

[232] G. E. North Piegan, R. Darbali-Zamora, and J. C. Berg, "Development and Validation of a Wind Turbine Generator Simulation Model," *2022 North American Power Symposium (NAPS)*, Salt Lake City, UT, USA, 2022, pp. 1-6.

[233] R. Darbali-Zamora, "Development of a Dynamic Photovoltaic Inverter Model with Grid-Support Capabilities for Power System Integration Analysis," *2023 IEEE 50th Photovoltaic Specialists Conference (PVSC)*, San Juan, PR, USA, 2023, pp. 1-8.

[234] R. Darbali-Zamora, S. T. Ojetola, F. Wilches-Bernal and J. C. Berg, "Development of a Wind Turbine Generator Volt-Var Curve Control for Voltage Regulation in Grid Connected Systems," *2022 North American Power Symposium (NAPS)*, Salt Lake City, UT, USA, 2022, pp. 1-6.

EMT models help in developing and validating anti-islanding detection methods.[235,236] Ensuring DERs comply with the requirements specified in IEEE Standard 1547 for anti-islanding is critical. A detailed anti-islanding or EMT study may be conducted to determine the necessity of DTT. For projects likely to fail an initial anti-islanding, overvoltage, or other preliminary screening regarding transient behavior, EMT models should be submitted early; otherwise, the time to collect all necessary data will delay the interconnection study.[237] As DER deployment increases, previously collected EMT studies can also be used as a resource to accurately model whether an existing feeder circuit can accommodate additional DER interconnections.

Multiple EMT models can be combined with power hardware-in-the-loop (PHIL) in a real-time simulation environment to identify DER issues that might not be evident in purely simulation-based studies.[238,239] PHIL facilitates the study of dynamic interactions between DERs and the grid, including transient responses, harmonic interactions, and the effectiveness of grid-support functions such as voltage and frequency regulation.[240,241] PHIL can be used to perform comprehensive tests required by regulatory bodies and standards organizations, ensuring that DERs meet all necessary criteria for grid integration, including unintentional islanding, ride-

---

[235] E. Desardén-Carrero, R. Darbali-Zamora and E. E. Aponte-Bezares, “Analysis of Commonly Used Local Anti-Islanding Protection Methods in Photovoltaic Systems in Light of the New IEEE 1547-2018 Standard Requirements,” *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, Chicago, IL, USA, 2019, pp. 2962-2969.

[236] N. E. Saavedra-Peña, R. Darbali-Zamora, E. Desardén-Carrero and E. Aponte-Bezares, “Development of Photovoltaic Inverter Model with Islanding Detection Using the Sandia Frequency Shift Method,” *2022 IEEE 49th Photovoltaics Specialists Conference (PVSC)*, Philadelphia, PA, USA, 2022, pp. 0398-0404.

[237] There is inherent conflict between the must-trip requirements of IEEE Std. 1547-2018, its fault ride-through requirements, and the may-trip requirements of the transmission system. Future revisions of IEEE Std. 1547 will likely address this conflict, with implications for needing EMT to address the issue. See “Reliability Guideline: Bulk Power System Reliability Perspectives on the Adoption of IEEE 1547-2018,” NERC, 2023. [Online]. Available: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Guideline-IEEE_1547-2018_BPS_Perspectives_PostPubs.pdf.

[238] J. Montoya, R. Brandl, K. Vishwanath, J. Johnson, R. Darbali-Zamora, A. Summers, J. Hashimoto, H. Kikusato, T. S. Ustun, N. Ninad, E. Apablaza-Arancibia, J. Bérard, M. Rivard, S. Q. Ali, A. Obushevs, K. Heussen, R. Stanev, E. Guillo-Sansano, Mazheruddin H. Syed, C. Cho, and H. Yoo, “Advanced Laboratory Testing Methods using Real-Time Simulation and Hardware-in-the-Loop Techniques: A survey on the Smart Grid International Research Facility Network,” *MDPI-Energie*s, Special Issue: Advancements in Real-Time Simulation of Power and Energy Systems, May 7, 2020.

[239] J. Johnson et al., "Distribution Voltage Regulation Using Extremum Seeking Control with Power Hardware-in-the-Loop," in *IEEE Journal of Photovoltaics*, vol. 8, no. 6, pp. 1824-1832, Nov. 2018

[240] R. Darbali-Zamora, J. Hernandez-Alvidrez, A. Summers, N. S. Gurule, M. J. Reno and J. Johnson, “Distribution Feeder Fault Comparison Utilizing a Real-Time Power Hardware-in-the-Loop Approach for Photovoltaic System Applications,” *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, Chicago, IL, USA, 2019, pp. 2916-2922.

[241] R. Darbali-Zamora and J. C. Berg, “Development of a Wind Turbine Generator Volt-Var Curve Control for Voltage Regulation Using Power Hardware-in-the-Loop,” *2023 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT-LA)*, San Juan, PR, USA, 2023, pp. 280-284.

through requirements, and grid-support functions.[242,243] It can also expedite and automate IEEE Standard 1547 and UL 1741 test requirements.[244]

Development and maintenance of high-quality, validated, and tested EMT models and required hardware can be costly and require highly specialized personnel.[245] For this reason, their use for smaller-scale DER installations is uncommon. As DER deployment increases, it would be beneficial to use EMT models to test and certify devices so individual EMT studies are not required if a system uses certified devices. The research community and standards organizations should develop thresholds, based on system wide EMT studies, below which EMT studies are not automatically required for interconnection. The thresholds should differentiate based on DER size, system voltage and topology (radial vs. networked), other relevant system characteristics, and applicable interconnection codes such as IEEE Std. 1547 vs. IEEE Std. 2800.

Phasor models can also be powerful tools for evaluating DER impacts, and their data and computational burdens are lower relative to EMT models.[246] Phasor models should be validated against EMT models, and appropriate applications for each type of model for the interconnection process should be investigated.

---

[242] E. Desardén-Carrero, R. Darbali-Zamora and E. E. Aponte-Bezares, “Analysis of Grid Support Functionality Dynamics under Ride-Through Requirements Using Power-Hardware-in-the-Loop Implementation,” *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, Fort Lauderdale, FL, USA, 2021, pp. 1795-1802.

[243] E. Desardén-Carrero, R. Darbali-Zamora, N. S. Gurule, E. Aponte-Bezares and S. Gonzalez, “Evaluation of the IEEE Std 1547.1-2020 Unintentional Islanding Test Using Power Hardware-in-the-Loop,” *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, Calgary, AB, Canada, 2020, pp. 2262-2269.

[244] R. Darbali-Zamora, J. Johnson, and M. J. Reno, “Parametric Analysis of Photovoltaic Inverters Under Balanced and Unbalanced Voltage Phase Angle Jump Conditions,” *2023 IEEE 50th Photovoltaic Specialists Conference (PVSC)*, San Juan, PR, USA, 2023, pp. 1-6.

[245] Perera, Lasantha; Jayewardene, Winodh. *EMT and RMS Model Requirements: Findings on concerns raised by the AEMC.* (2017). AECOM Australia Pty Ltd. https://www.aemc.gov.au/sites/default/files/content/ce6543aa-7b77-4105-8bc8-29670c078442/AECOM-report-EMT-and-RMS-Model-Requirements.pdf

[246] Du, Wei. *Droop-based Grid-Forming Inverter Model (REGFM_A1) [Presentation].* WECC Model Validation Subcommittee Annual Meeting. (2023). Pacific Northwest National Laboratory. https://www.wecc.org/Administrative/Du,%20W.,%20-MVS%20-%20Droop-based%20Grid-Forming%20Inverter%20Model-REGFM_A1_September%202023.pdf

Table 33. Solution 4.3 Actors and Actions — Optimize development and use of EMT models for evaluating the dynamic performance of DERs

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Utilities	- Develop screening tools to understand when EMT studies are needed.		- Collect EMT models for large DER projects, i.e., that require detailed studies.
Interconnection customers and their equipment manufacturers	- Conduct EMT model assessment before interconnection application submission. - Develop and validate equipment models in EMT model. - Produce site-specific EMT models for DER plants, if needed.		
Research community (including DOE)	- Develop screening methods and metrics to understand when EMT study is needed. - Develop improved EMT work-flow tools to automate EMT feeder circuit model creation and maintain updated models of feeder circuits with DER. - Adopt standards for interoperability of EMT models across simulation platforms. - Develop EMT model validation standards and examples.		

Solution 4.4: Improve models for analyzing the seam between the transmission and distribution/sub-transmission systems (medium-term, medium deployment).

As more DERs interconnect to the distribution and sub-transmission systems, their aggregate impacts may affect the transmission system. DERs can, for example, influence under frequency load shedding (UFLS) schemes[247] as well as voltage excursions on the transmission system. UFLS schemes begin to disconnect feeder circuits from the system, to reduce load, when system frequency descends below certain thresholds. With increased DER deployment, a feeder circuit

---

[247] "Reliability Guideline: Recommended Approaches for UFLS Program Design with Increasing Penetrations of DERs," NERC, Dec. 2021. [Online]. Available: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Recommended_Approaches_for_UFLS_Program_Design_with_Increasing_Penetrations_of_DERs.pdf

may export power to the system, and thus disconnecting it would produce results counter to the original UFLS objective.[248] Furthermore, following load tripping, DERs that are not tripped due to underfrequency[249] might see voltage rise and may trip on overvoltage settings, leading to further loss of frequency.[250] Transmission planners and operators need to have the situational awareness of distribution system capabilities so that any control actions are aligned for purpose and outcome.

An example of the type of model that has been developed capture the dynamic behavior of DERs, particularly under fault condition is the Electric Power Research Institute's (EPRI's) DER_A model.[251]. The DER_A model is intended to be integrated into transmission system modeling to simulate the impact of DERs on the transient stability of the system under various events. However, DER_A must be correctly parameterized for specific feeder circuits to correctly capture DER behavior at the modeled locations in the system. While guidelines for the parameterization exist[252], including some recommended default values, tuning parameter remains a challenge. In other words, further development is needed in this space.

Another approach to capture interactions across the system seam employs co-simulation,[253] which allows more detailed DER models to be integrated into transmission-level simulations. In co-simulation a detailed distribution feeder model is simulated in conjunction with the transmission system model. The two models exchange necessary values (e.g., voltage and power) for their respective simulations at their connection point(s), such as the substation transformer. Using detailed feeder models, co-simulation can help in the study of distribution system impacts on the transmission system, [254] as well as to validated aggregate models, such as the DER_A.[255]

---

[248] Appendix C of NERC's Recommended Approaches for UFLS Program Design with Increasing Penetrations of DERs describes a case study from Hawaii addressing the issue of changing feeder behavior and shifting to an adaptive UFLS scheme.

[249] The NERC Recommendation is to model R-DER that offset customer load and U-DER that are close to the substation and have a dedicated non-load-serving connection.

[250] Appendix D of NERC's Recommended Approaches for UFLS Program Design with Increasing Penetrations of DERs describes a case study from ISO-NE where the impact of U-DER tripping on overvoltage is illustrated.

[251] Electric Power Research Institute, Inc. *The New Aggregated Distributed Energy Resources (der_a) Model for Transmission Planning Studies: 2019 Update.* (2019). https://www.epri.com/research/products/000000003002015320

[252] "Reliability Guideline: Parameterization of the DERA_A Model for Aggregate DER," NERC, Feb. 2019. [Online]. Available: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_ModelingMerge_Responses_clean.pdf

[253] Y. Liu, R. Huang, W. Du, A. Singhal, and Z. Huang, "Highly-Scalable Transmission and Distribution Dynamic Co-Simulation With 10,000+ Grid-Following and Grid-Forming Inverters," IEEE Transactions on Power Delivery, vol. 39, Art. no. 1, 2024, doi: 10.1109/TPWRD.2023.3302303.

[254] M. Baggu et al., "Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100): Final Report," Mar. 2024, doi: 10.2172/2335361.

[255] V. Ajjarapu et al., "Sensor enabled data-driven predictive analytics for modeling and control with high penetration of DERs in distribution systems," May 2021, doi: 10.2172/1785126.

Table 34. Solution 4.4: Improve models for analyzing the seam between the transmission and distribution/sub-transmission systems.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Prioritize system-wide situational awareness of grid operations as DER deployment increases, focusing on the aggregate impacts of DER on the transmission and sub-transmission systems.	- Promote standardization and communication between distribution, sub-transmission, and transmission system operations.	- Convene collaborative processes to inform model improvements.
Utilities	- Explore techniques for model creation and improvement, such as co-simulation and industry tools.		
Interconnection customer			- Participate in collaborative processes to inform model improvements.
Research community (including DOE)	- Develop and socialize models for analyzing the seam between transmission and distribution/sub-transmission systems.		

Solution 4.5: Collect data from DERs to validate models that ensure compliance with BPS reliability standards and to perform large-scale reliability assessments (medium-term, high deployment).

To ensure compliance with approved reliability standards, FERC requires that the organizations responsible for operating utility-scale IBRs connecting to the BPS register under the NERC Compliance Registry.[256] This requirement originally applied only to IBRs connected at voltages of 100 kV or higher but was expanded in May 2023 to include IBRs connected at 60 kV or higher or with an aggregate nameplate capacity of at least 20 MVA[257]. This change occurred because, at the time, 14% of operational IBRs by nameplate capacity were not covered by the 100-kV standard.[258,259]

---

[256] North American Electric Reliability Corporation. *Inverter-Based Resource Strategy: Ensuring Reliability of the Bulk Power System with Increased Levels of BPS-Connected IBRs.* (2022). https://www.nerc.com/comm/Documents/NERC_IBR_Strategy.pdf

[257] "FERC Docket No. RD22-4-001: Order Approving Registration Work Plan." Issued 2023-05-18. [Online]. Available: https://www.ferc.gov/media/e-1-rd22-4-001

[258] United States of America Federal Energy Regulatory Commission. *Reliability Standards to Address Inverter-Based Resources.* (2023). https://www.ferc.gov/media/e-1-rm22-12-000

[259] North American Electric Reliability Corporation. *North American Electric Reliability Corporation Request for Approval of Proposed Revisions to the Rules of Procedure to Address Unregistered Inverter Based Resources and Request for Expedited Review.* (2024). https://www.nerc.com/FilingsOrders/us/NERC%20Filings%20to%20FERC%20DL/Proposed%20Registry%20Criteria%20ROP%20Revisions.pdf

Thus, although DERs are currently excluded from NERC registration requirements, jurisdictions with high DER deployment should consider collecting DER data, as indicated in a draft version of MOD-32[260], to validate models that ensure aggregate compliance with NERC reliability standards[261][262] and to perform large-scale reliability assessments. MOD-32 identifies steady-state, dynamic, and short circuit data. Steady-state and short circuit are similar to data commonly collected as part of the interconnection process already. While dynamic models are not as common in distribution systems, the certification process for fault-ride-through capabilities according to IEEE Std 1547-2018, mean that EMT models of the inverters likely exist, and dynamic modeling capabilities do exist.[263]

Table 35. Solution 4.5: Collect data from DERs to validate models that ensure compliance with BPS reliability standards and to perform large-scale reliability assessments.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Promote adoption of latest IEEE inverter standards to facilitate large-scale reliability assessments.		
Utilities	- Consider collecting DER data from interconnecting applications according to MOD-32.		- Consider mechanisms to streamline collection of data according to NERC reliability standards, such as via online application screens.

4.2 Interconnection Standards

Key Takeaways

To ensure reliable operation of newly interconnected DERs, comprehensive interconnection standards are necessary. The latest revision of IEEE Standard 1547[264] outlines requirements and best practices for safe and reliable interconnection of DERs, but adoption varies among states

---

[260] Registered distribution providers expected to provide DER dynamic models: North American Electric Reliability Council. *Data for Power System Modeling and Analysis. Number MOD-032-2.* (2022). https://www.nerc.com/pa/Stand/Project202202ModificationstoTPL00151andMOD0321DL/2022-02%20MOD-032-2_Clean_May2023.pdf

[261] North American Electric Reliability Corporation. *Reliability Standards.* (n.d.) https://www.nerc.com/pa/Stand/Pages/ReliabilityStandards.aspx

[262] NERC Workplan to address FERC Order 910: North American Electric Reliability Corporation. *Reliability Standards to Address Inverter-Based Resources. Docket No. RM22-12-000.* (2024). https://www.nerc.com/FilingsOrders/us/NERC%20Filings%20to%20FERC%20DL/NERC%20Compliance%20Filing%20Order%20No%20901%20Work%20Plan_packaged%20-%20public%20label.pdf

[263] Both GridLAB-D and OpenDSS can perform three-phase dynamic simulations.

[264] Completion date for next revision expected 2025–2026.

and utility service territories. Accelerating adoption of this standard nationwide would be beneficial.

Increasing levels of DER deployment will elevate the importance of inadvertent exports—minimal, short-duration power outputs from limited-exporting DERs, which occur during rapid changes in generation or load. Standards must be developed to mitigate the impact of inadvertent export.

Cybersecurity is a growing concern for DERs. The recently published IEEE 1547.3 provides guidance on effective cybersecurity measures for the distribution and sub-transmission systems. This standard can be used to develop a cybersecurity risk management plan for interconnecting projects.

Finally, DERs are diversifying at the same time their adoption is growing. For this reason, the latest standards addressing performance from emerging technologies such as grid-forming inverters and vehicle-to-grid systems should be adopted.

Solutions Content

Solution 4.6: Accelerate adoption of the IEEE 1547 interconnection standard via collaboration among regulators, utilities, and researchers (short-term, low deployment).

The IEEE Standard 1547 family of standards provides technical specifications for connecting DERs to the power grid. The standard ensures safe and reliable interconnection by setting technical specifications for performance, operation, testing, safety considerations, and maintenance for DERs. It includes general requirements, responses to abnormal conditions, power quality, islanding, and test specifications and requirements for design, production, installation evaluation, commissioning, and periodic tests.[265]

The latest revision of IEEE Standard 1547 should be adopted by regulators and implemented by utilities. Adoption of the standard has varied across states and utilities.[266] Historically, California and Hawaii have been early adopters of new revisions to the standard. This is not surprising given the prevalence of DERs on their respective utilities' grids. For states with lower levels of deployment, it is still worthwhile to begin collaborative processes or formal proceedings to ensure that rules are in place by the time certified DER devices are available on the market.[267]

---

[265] See Basso, Thomas. 2014. IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electric Grid https://www.nrel.gov/docs/fy15osti/63157.pdf

[266] Interstate Renewable Energy Council. *IEEE 1547-2018 Adoption Tracker. (*2024). https://irecusa.org/resources/ieee-1547-2018-adoption-tracker/

[267] Interstate Renewable Energy Council. *Making the Grid Smarter: Primer on Adopting the New IEEE Standard 1547-2018.* (2019). https://irecusa.org/resources/making-the-grid-smarter-primer-on-adopting-the-new-ieee-standard-1547-2018/

To support standards adoption, IEEE Standard 1547/UL 1741 certified inverters should be specified during regulatory and procurement processes. Compliance with the latest interconnection standards is intended to ensure safe operation within the distribution system, providing confidence that systems will perform as expected and interoperability will be seamless across distribution system operations.

The effort required to adopt IEEE 1547 depends on the character of a region's DER deployment as well as the capabilities of staff at utilities and regulators. The process can be accelerated by collaboration among jurisdictions and researchers, with feedback provided to standards development organizations (SDOs) for improving the standards.

Table 36. Solutions 4.6 Actors and Actions — Accelerate adoption of the IEEE 1547 interconnection standard via collaboration among regulators, utilities, and researchers.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Encourage rapid adoption of the latest revision of IEEE Standard 1547.[268]	- Establish consumer protections involving customer generation losses, voltage excursions, possible corrective measures, and regular utility reporting.[269]	- Establish working groups to support the adoption of the latest revision of IEEE Standard 1547.
Utilities	- Along with regulators, evaluate, select, and assign different performance categories for different DERs.[270] - Determine when voltage regulation functions should be turned on, which functions and settings should be used, and interaction with interconnection rules.[271]	- Allow for appropriate level of evaluation and commissioning testing to be performed as part of interconnection review process.	- Align fast track and screening processes with relevant evaluation and commissioning protocols.[272] - Participate in the latest revision of IEEE Standard 1547 adoption guidelines developed by SDOs.

---

[268] Interstate Renewable Energy Council. *Making the Grid Smarter: Primer on Adopting the New IEEE Standard 1547-2018.* (2019). https://irecusa.org/resources/making-the-grid-smarter-primer-on-adopting-the-new-ieee-standard-1547-2018/

[269] Interstate Renewable Energy Council. *Making the Grid Smarter: Primer on Adopting the New IEEE Standard 1547-2018.* (2019). https://irecusa.org/resources/making-the-grid-smarter-primer-on-adopting-the-new-ieee-standard-1547-2018/

[270] Interstate Renewable Energy Council. *Making the Grid Smarter: Primer on Adopting the New IEEE Standard 1547-2018.* (2019). https://irecusa.org/resources/making-the-grid-smarter-primer-on-adopting-the-new-ieee-standard-1547-2018/

[271] Interstate Renewable Energy Council. *Making the Grid Smarter: Primer on Adopting the New IEEE Standard 1547-2018.* (2019). https://irecusa.org/resources/making-the-grid-smarter-primer-on-adopting-the-new-ieee-standard-1547-2018/

[272] Interstate Renewable Energy Council. *Making the Grid Smarter: Primer on Adopting the New IEEE Standard 1547-2018.* (2019). https://irecusa.org/resources/making-the-grid-smarter-primer-on-adopting-the-new-ieee-standard-1547-2018/

Interconnection Customer	- Utilize UL 1741 certified inverters or provide technical data to assure the utility of compliance with the requirements of the latest revision of IEEE Standard 1547.	- Participate in working groups to explore use of new capabilities to enable grid services and developing markets.	
Research community (including DOE)	- Describe state-of-the-art and potential future technologies such as grid-forming inverters.		

Solution 4.7: Develop standards to mitigate the potential impact of inadvertent export (short-term, low deployment).

Inadvertent exports are minimal, short-duration power outputs from limited -exporting DERs, which occur during rapid changes in generation or load due to response delays from the plant's power control system (PCS). For example, the interconnection agreement for a 750-kW PV system might allow the system to export no more than 500 kW to the grid, so any export above 500 kW would be inadvertent. Inadvertent export could have adverse voltage, thermal, protection, or power-quality impacts on the system.

Clear standards are needed to mitigate the impact of inadvertent export. Currently, there is debate about what would be a safe response time to mitigate risk. The UL1741 Certification Requirement Decision (CRD) for power control systems[273] set a 30-second open loop response time requirement. However, faster response times are possible and could help to avoid adverse grid impacts under some conditions. The uncertainty about the costs and benefits of requiring faster response times has led to varying requirements from utilities, creating challenges for manufacturers, lengthy study procedures, and uncertainty for limited-export projects.[274] For example, California Rule 21 requires a maximum response time of 2 seconds to align with existing non-exporting relay requirements,[275] while Arizona,[276] and Oregon[277] allow for a 30-second PCS response.

---

[273] UL Power Control Systems Certification Requirements Decision (UL CRD) requires a PCS to demonstrate that it is capable of preventing or limiting export, within a time-delay of up to 30 seconds.

[274] The Storage Interconnection Committee. *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage. Building a Technically Reliable Interconnection Evolution for Storage (BATRIES).* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

[275] California Public Utilities Commission. *Electric Rule 21: Generating Facility Interconnection [Section M].* (2023). https://www.cpuc.ca.gov/rule21/

[276] Office of the Secretary of State, Administrative Rules Division. *Title 14. Public Service Corporations; Corporations and Associations; Securities Regulation. Chapter 2. Corporation Commission – Fixed Utilities.* § R14-2-2603(E)(4) (2022). https://apps.azsos.gov/public_services/Title_14/14-02.pdf

[277] Public Utility Commission. *Chapter 860, Division 82, Small Generator Interconnection Rules. Export Controls.* OR Administrative Rule 860-082-0033(3)(c)(A). (2024). https://secure.sos.state.or.us/oard/viewSingleRule.action?ruleVrsnRsn=312193.

The need for clear standards related to inadvertent exports are particularly pressing related to energy storage systems. To date, most interconnection rules do not define how utilities specify or evaluate inadvertent export for ESS. Instead, most utilities simply screen and study projects with inadvertent export in the same way they assess projects with full export. This approach creates challenges for equipment manufacturers and project developers: projects may be assumed to have impacts they could never produce, adding costs, more in-depth review, customized equipment, or grid mitigation costs to the interconnection process.[278]

The power-quality impact of inadvertent export may be the most important factor to consider.[279] One proposed power-quality screening method, based on rapid voltage changes, applies to projects with a difference greater than 250 kW between the nameplate rating and export capacity.[280] The voltage change due to inadvertent export should not exceed 3 percent,[281] depending on the grid resistance and reactance, apparent power nameplate rating, power factor, and grid voltage.

Table 37. Solution 4.7 Actors and Actions — Develop standards to mitigate the impact of inadvertent export.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Promote development of a standardized range of open loop response time requirements aligned with the impact of inadvertent export.	- Convene the interconnection community to develop standards.	
Utilities	- Maintain a list of approved technologies that meet inadvertent export requirements.	-Work with regulators to develop standards.	- Communicate inadvertent export requirements upfront.
Interconnection customer		- Work with regulators and standards agencies to define standards.	
Standards Agencies	- Work to develop standards to mitigate impact of inadvertent export.	- Promote adoption of new standards.	

---

[278] The Storage Interconnection Committee. *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage. Building a Technically Reliable Interconnection Evolution for Storage (BATRIES).* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

[279] In general, PCS are not considered under fault scenarios. Thus, screens for export-limited resources with PCS would consider the nameplate rather than export capacity, and any impacts of inadvertent export should be captured in existing screens. Conversely, due to short durations (2-30 seconds), thermal impacts are usually not of much concern. Finally, given its short duration, inadvertent export can be evaluated as a short-term root-mean-squared voltage event, which means that overvoltage limits of 110% rather than 105% apply, leaving more headroom.

[280] The BATRIES team determined 250 kW to be a safe threshold below which there is negligible chance of a voltage impact. The Storage Interconnection Committee. *Toolkit & Guidance for the Interconnection of Energy Storage & Solar-Plus-Storage. Building a Technically Reliable Interconnection Evolution for Storage (BATRIES).* (2022). https://energystorageinterconnection.org/resources/batries-toolkit/

[281] The 3% value comes from the rapid voltage change limit in IEEE Std 1547-2018 Clause 7.2.2.

Research community (including DOE)	- Improve understanding of frequency, duration, and impact of inadvertent export to inform all groups.		- Participate in efforts initiated by SDOs to aid development of inadvertent export standards.

Solution 4.8: Use guidance from IEEE 1547.3 to address cybersecurity concerns during the interconnection process (short-term, low deployment).

As more DER connect and communicate with the grid, the risk of cybersecurity incidents increases. Any resource, if not properly secured, creates a vulnerability that could potentially impact the entire system. For example, in 2019, a private solar operator “lost visibility into” 500 MW of wind and solar across three states due to an unpatched and outdated firewall that was able to be exploited. By exploiting these vulnerabilities, malicious actors could gain control over inverter controls, reducing output to zero or even attempting to overheat energy storage resources[282].

The recently published IEEE 1547.3 (Guide for Cybersecurity of DER Interconnected with Electric Power Systems) should be used to guide evaluation of cybersecurity issues on the distribution and sub-transmission systems. The guide provides recommendations informed by field and laboratory experiences, new cybersecurity concepts and technologies, and the cybersecurity features available in protocols specified in IEEE 1547-2018.[283] For example, to protect DER data, it is recommended that local communication networks use secure protocols such as virtual private networks (VPNs). IEEE 1547.3 recognizes that cybersecurity concerns must extend beyond the local DER interface throughout the entire communication system to ensure end-to-end information security and resilience to any cybersecurity problems that could impact safe and reliable operations.

---

[282] Federal Bureau of Investigation: Cyber Division. *Private Industry Notification: Expansion of US Renewable Energy Industry Increases Risk of Targeting by Malicious Cyber Actors.* (2024). https://s3.documentcloud.org/documents/24788637/fbiwarning.pdf

[283] Distributed Generation, Energy Storage, and Interoperability Standards Committee and the Power System Communications and Cybersecurity Committee. *IEEE Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems: IEEE Std. 1547.3.* (2023).

Table 38. Solution 4.8 Actors and Actions — Use guidance from IEEE 1547.3 to adopt cybersecurity requirements during the interconnection process.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Evaluate cybersecurity risks in DER programs and pilots.	- Adopt cybersecurity recommendations and best practices detailed in IEEE Standard 1547.3.	
Utilities	- Consider requiring VPN connections for all DER from a list of approved vendors and requiring them to maintain latest patch levels. - Consider adding verification processes to screen devices as they connect, disabling those that do not pass.		- Include cybersecurity requirements and expectations in interconnection agreements.
Interconnection customers			- Adhere to utility recommendations for use of approved gateways.
Research community (including DOE)	- Participate in SDO efforts to ensure cybersecurity for DER interconnections.		

Solution 4.9: Develop a cybersecurity risk management plan for interconnecting projects (short-term, medium deployment).

It is important to develop a cybersecurity risk management plan and incident response for interconnecting projects, especially those under flexible interconnection agreements, which may involve more robust communication requirements and therefore vulnerabilities, depending on the control scheme. Plans can involve documentation of all connections and interactions within the network; identification of recovery procedures; and assigning ownership of individual risks to inform recovery procedures. The plan should be captured in the interconnection agreement to ensure risks and responsibilities are appropriately documented. Rapid DER deployment has outpaced the required standardization of cybersecurity procedures,[284] therefore the development of risk management plans should be a priority.

Risk is the probability of an event (for example, the integrity of remote measurements being violated by an attacker) multiplied by the impact of that event. Quantifying risk allows for prevention, detection, or recovery actions. When prevention is not possible, rapid detection and recovery can reduce the financial impact of an event.

---

[284] Powell, Charisa, Konrad Hauck, Anuj Sanghvi, Adarsh Hasandka, Joshua Van Natta, and Tami Reynolds. 2019. Guide to the Distributed Energy Resources Cybersecurity Framework. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5R00-75044. https://www.nrel.gov/docs/fy20osti/75044.pdf.

IEEE Standard 1547.3 provides guidance on implementing risk management plans within individual organizations and across the multiple organizations involved in DER interconnection. Cross-organizational risk assessments, agreements, and communications are key to overall security. Recommendations include performing individual risk assessments, communicating results and updates between organizations, and identifying responsibilities for mitigating cross-organizational risks, such as those between third party aggregators or plant control systems. Standards such as NIST SP 800-53[285] and 800-82[286] also offer guidance to implement security controls.

The costs and benefits of risk management measures should be compared, and the party responsible for the costs should be specified. For example, the DER owner, aggregator or third-party operator, utility, and regulators all share responsibility for cybersecurity on the grid.[287]

Table 39. Solution 4.9: Develop a cybersecurity risk management plan for interconnecting projects (short-term, medium deployment).

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Review technical feasibility and considerations related to adoption of IEEE Std. 1547.3 and NIST SP 800-53 and 800-82.	- Consider requiring adoption of IEEE Std. 1547.3 and NIST SP 800-53 and 800-82.	
Utilities	- Consider adoption of IEEE Std. 1547.3 and NIST SP 800-53 and 800-82.		- Work with interconnection customer to support development of a cybersecurity risk management plan for project.
Interconnection customer	- Look to IEEE Std. 1547.3 and NIST SP 800-53 and 800-82 when designing DER systems.		- Work with utility to develop a cybersecurity risk management plan for project.
Research community (including DOE)	- Continue to participate in standards development processes designed to		

---

[285] National Institute of Standards and Technology, U.S. Department of Commerce. *NIST SP 800-53 Rev. 5. Security and Privacy Controls for Information Systems and Organizations.* (2023). https://csrc.nist.gov/pubs/sp/800/53/r5/upd1/final

[286] National Institute of Standards and Technology, U.S. Department of Commerce. NIST SP 800-82 Rev. 3. Guide to Operational Technology (OT) Security. (2023). https://csrc.nist.gov/pubs/sp/800/82/r3/final

[287] Distributed Generation, Energy Storage, and Interoperability Standards Committee and the Power System Communications and Cybersecurity Committee. *IEEE Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems: IEEE Std. 1547.3.* (2023). https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10352402

	bolster cybersecurity on the grid.		

Solution 4.10: Develop and adopt standards that address performance from emerging technologies such as grid-forming inverters and vehicle-to-grid systems (medium-term, medium deployment).

As DER technologies continue to evolve and their deployment grows, there is a need to develop and adopt new standards. For example, grid stability can be bolstered if standards allow grid feeder circuits to operate in islanded mode during contingency events when the substation voltage source is lost.[288] IEEE Standard 1547.4 provides best practices for design, operation, and integration of DER islanded systems, including use of grid-forming inverters.[289,290] This standard is under revision, and an extensive set of updates is expected. Shifting typical utility feeder circuits to islanded operations would require a shift in operation and protection philosophy, which currently conflicts with the unintentional islanding requirements in IEEE Standard 1547-2018. Regulatory change may be needed to allow for the formation of islands.

Developing and adopting new communication standards would help integrate growing EV loads into the grid. Implementation of smart charging requires robust communication and controls architecture across multiple vendors with different risk tolerances. Expedited standards development will be vital to avoid obsolescence of infrastructure investments, especially because many grid planning decisions must be made proactively based on forecasts. Standards can also help protect charging equipment in the case of communication failures. Standards development efforts should use existing interoperability profiles, which outline how different systems can communicate effectively.[291] Developing standards collaboratively would aid implementation by proactively ensuring alignment among vendors.[292] EV-supportive standards are currently being

---

[288] Du, Wei, Tuffner, Francis K., Schneider, Kevin P., Lasseter, Robert H., Xie, Jing, Chen, Zhe, and Bhattarai, Bishnu. Modeling of Grid-Forming and Grid-Following Inverters for Dynamic Simulation of Large-Scale Distribution Systems. United States: N. p., 2020. Web. doi:10.1109/tpwrd.2020.3018647.

[289] "IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems," in IEEE Std 1547.4-2011, vol., no., pp.1-54, 20 July 2011, doi: 10.1109/IEEESTD.2011.5960751.

[290] Grid following inverters track the grid voltage phase and adjust their output to control the output power, they can be modeled as a current source. Grid Forming inverters, on the other hand, establish an internal frequency and it is their angle difference with respect to the grid that determines the power exchange, that is they operate more like voltage sources. See M. Paolone et al., "Fundamentals of power systems modelling in the presence of converter-interfaced generation," Electric Power Systems Research, vol. 189, p. 106811, 2020. Or NERC Primer: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_Grid_Forming_Technology.pdf

[291] Chung, Daisy. *Interoperability Profiles – A Better Way to Buy Grid Technology.* (2020). Smart Electric Power Alliance. https://sepapower.org/knowledge/interoperability-profiles-a-better-way-to-buy-grid-technology/

[292] Energy Systems Integration Group's Grid Planning for Vehicle Electrification Task Force. *Charging Ahead: Grid Planning for Vehicle Electrification.* (2024). https://www.esig.energy/grid-planning-for-vehicle-electrification/

updated. The draft guide to using IEEE Standards 1547, 1547.9-2002, provides some guidance on interconnection of V2G-capable charging stations.[293]

Standards can also facilitate co-deployment of multiple DERs. EVs, as part of a whole building resource, may require additional technology, as well as supervisory or layered local controls. Layered controls require communication specific to individual commercial or residential buildings, as well as between buildings and between buildings and the grid. These local communications and controls must incorporate robust cybersecurity protocols. Alignment between building, utility, and device communication protocols would aid in scaling EVs and other DERs. For example, a utility may use IEEE Standard 2030.5 or SunSpec Modbus to communicate with devices but use MESA-DER (IEEE P1815.2/DNP3) between large energy storage plants or fleets and supervisory control and data acquisition systems. The lesson here is that standards need to evolve to keep pace with technological innovation.3

---

[293] "Approved Draft Guide to Using IEEE Standard 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems," in IEEE P1547.9/D5.6, May 2022 (Approved Draft), vol., no., pp.1-83, 22 June 2022. https://www.osti.gov/servlets/purl/2217359

Table 40. Solution 4.10 Actors and Actions — Adopt the latest standards addressing performance from emerging technologies such as grid-forming inverters and vehicle-to-grid systems.

Actor	Engineering and Technical	Market and Regulatory	Administrative and Organizational
Regulators	- Contribute to language choices within the standards development process.	- Use existing interoperability profiles to align standards implementation efforts. - Require adoption of new standards as applicable.	- Participate in future discussions about emerging standards.
Utilities	- Contribute to language choices within the standards development process.	- Use existing interoperability profiles to align standards implementation effort. - Communicate standards updates in the interconnection process. - Modify interconnection agreements and applications to include the latest standards language.	
Interconnection customer	- Comply with new and updated standards by ensuring new plants are designed with capabilities that align with updates. - Contribute to language choices within the standards development process.		- Participate in future discussions about emerging standards.
Standards Agencies			- Convene technical conferences supporting emerging standards discussions.
Research community (including DOE)	- Provide insights from research to inform standards development process.		

Conclusions

As the renewable energy transition accelerates in the United States, the volume of projects in interconnection queues has increased rapidly. Increasing deployment of DERs has led to unprecedented growth of interconnection queues. Many challenges facing interconnection of DERs mirror issues at the transmission level, including workforce shortages, lengthy backlogs, and high interconnection costs. In other cases, DER interconnection faces distinct challenges, including inconsistencies stemming from the lack of a singular regulating body like FERC.

This roadmap identifies solutions for interconnection challenges facing DERs that could be adopted in the near term, such as improving hosting capacity analysis tools or using group study processes; medium-term actions, such as widespread adoption of flexible interconnection capabilities or using automation to accelerate the interconnection study process; and solutions that require a longer time frame, such as growing the interconnection workforce via outreach, curriculum development, and partnerships in post-secondary education. Short-term solutions can build on existing policies, pilot programs, or other ongoing efforts and could be implemented in 1–3 years. Medium-term solutions could likely be adopted in a 3- to 5-year time frame and may require the development of more tools, adoption of new technologies, or updates to regulations. Long-term solutions, requiring a time frame longer than 5 years, depend on more comprehensive changes to regulations, policies, or standards, and may depend on short- and medium-term solutions to be adopted first. Across time frames, many of these solutions are intended to complement each other.

All the solutions proposed in this roadmap require collaboration across different sectors working on DER interconnection. Since interconnection requires the input of many in the interconnection community and the balancing of many technical, reliability, safety, and policy requirements and considerations, the process of adopting reforms is often complex. The solutions identified in this roadmap identify priority areas for reform and where tradeoffs may exist, but do not provide detailed prescriptions for how these considerations should be weighed or resolved. This document serves as a starting point for those future discussions and conversations.

For most utilities, interconnection reform often occurs through collaborative processes. The creation of this roadmap involved soliciting the input of a wide range of interconnection community members across government, Tribal, industry, regulatory, advocacy, and research roles. Beyond these efforts, the interconnection community continues to discuss challenges and propose new ideas in countless other venues. Reforming a set of challenges as complex as DER interconnection will require ongoing collaboration by all these groups and more. The solutions in this roadmap have been designed to include work that can be undertaken by a wide range of actors across technical, regulatory, and administrative roles.

Across solutions, several themes emerge:

The accessibility and transparency of interconnection data should be enhanced while accounting for data security and balancing the value created with the effort required. Key activities include establishing data collection and sharing guidelines, expanding and standardizing reporting of interconnection data, and clarifying the technical data that developers of large DER systems must provide on interconnection applications (Solutions 1.1–1.3). In addition, tools and practices should encourage increased use and dissemination of hosting capacity analysis (Solutions 1.4–1.5).

Interconnection challenges should be mitigated by adapting queue management processes to handle increasing volumes of DERs requesting grid connection. Several incremental solutions—including flexible interconnection, automation, pre-application education, commercial readiness requirements and study timelines, and group study processes—may help reduce queue volumes and interconnection delays in the near term while enabling utilities to handle larger and variable queue volumes in the longer term (Solutions 2.1–2.7).

Cost-allocation methods should consider other options beyond the traditional cost-causer-pays model to improve the economic efficiency and equitable outcomes of DER interconnection. Options include partial reimbursement of the developer whose interconnection triggers a grid upgrade, maintaining a grid upgrade reserve fund, using a group study process that allocates costs among multiple projects, and proactively upgrading feeder circuits to accommodate forecasted DER growth with costs recovered from future DER developers (Solutions 3.1–3.4).

Interconnection study methods must adapt to a changing generation mix. Studies can be made more realistic by distinguishing DER nameplate capacity from export capacity and by accounting for potential grid benefits as well as costs due to DERs (Solutions 3.7–3.8). In addition, flexible interconnection can enable developers to avoid system upgrade costs during interconnection studies by accepting some level of curtailment (Solution 3.9).

Interconnection and grid planning require coordination. Coordination for specific DER projects must take place across the distribution, sub-transmission, and transmission systems, while coordination and data sharing between the DER interconnection process and the system planning process is improved (Solutions 3.5–3.6). In addition, the equitable outcomes of interconnection can be advanced through intentional system planning that addresses the historical inequities embedded in the U.S. electricity system (Solution 2.8).

Workforce development is integral to interconnection reforms. Creative, dedicated professionals are critical to the development and implementation of interconnection solutions (Solutions 2.10–2.13). Efforts can and should be tailored toward developing and retaining a more diverse interconnection workforce and expanding technical assistance and education opportunities in interconnection, especially for EEJ communities (Solutions 2.9–2.13).

Maintaining reliability must be assured. New models and screening tools must be developed to better consider the characteristics of DERs (Solutions 4.1–4.5). Furthermore, adoption of existing interconnection standards must be accelerated—and new standards must be developed—to address the characteristics of current DERs, the characteristics of emerging technologies, and growing cybersecurity concerns (Solution 4.6–4.10).

DOE will continue to support innovation in activities within the roadmap through individual program office missions and cross-office collaborations. Focused and targeted interconnection reforms can help create future interconnection processes that are transparent, equitable, and able to efficiently process large volumes of interconnection requests, incentivize appropriate grid investments, and maintain the operational reliability of the grid.

Appendix A: DOE Roles Supporting DER Interconnection

Table 41. DOE Roles in Supporting DER Interconnection

DOE Office	Role in Supporting DER Interconnection
Solar Energy Technologies Office (SETO)	SETO supports interconnection queue analysis, stakeholder collaboration on best practices, and technical assistance via i2X. It funds national labs to study interconnection timelines, costs, and provide public datasets and visualizations. SETO also invests in new modeling methods and capacity analysis to enhance interconnection processes, including advanced models for large solar plants and aggregated distributed solar resources. Additionally, SETO funds the UNIFI Consortium, led by NREL, to advance grid-forming inverters and supports national labs in developing industry standards for interconnection, including IEEE 1547-2018 and IEEE 2800-2022.
Wind Energy Technologies Office (WETO)	WETO supports interconnection queue and cost data analysis, facilitates stakeholder collaboration on best practices, and offers technical assistance via i2X. It funds R&D to enhance data, tools, models, and analyses, including an open-source wind data portal, wind EMT models, improved short-circuit models, and cybersecurity efforts. WETO leads the grid-forming research of wind and is co-sponsoring the UNIFI consortium to promote the interoperability among grid-forming inverters, along with supporting IEEE 2800 standards development and adoption.
Energy Justice and Equity (EJE)	EJE plays a convening role to support meaningful stakeholder engagement between program offices and small and disadvantaged businesses, minority educational institutions, and historically underrepresented communities. EJE works closely with DOE program offices, such as GDO, the Office of Indian Energy, and the Office of Clean Energy Demonstrations, as well as technology offices within EERE, to ensure energy equity considerations are incorporated into relevant interconnection funding opportunities. EJE also helps manage two research projects on equitable grid planning and operations as part of the Grid Modernization Initiative. EJE maintains an Energy Justice Mapping Tool that allows users to explore census tracts identified as disadvantaged communities as defined by the Justice40 Initiative. EJE also provides guidance on best practices for community engagement centered on improving transparency and coordination among energy developers, governments, utilities, and local communities.

Office of Cybersecurity, Energy Security, and Emergency Response (CESER)	CESER advances research, development, and deployment of technologies, tools, and techniques to reduce risks to the nation's critical energy infrastructure posed by cyber and other emerging threats. Continuing to increase the security, reliability, and resiliency of our energy infrastructure will help ensure the success of grid modernization and transformation of the nation's energy systems. CESER activities include the ongoing support of RD&D of advanced cybersecurity solutions, acceleration of information sharing to enhance situational awareness, and technical assistance in the development and adoption of best practices. The office is also investing in RD&D of cross-cutting tools and technologies to help make the U.S. energy infrastructure more cyber resilient and secure.
Grid Deployment Office (GDO)	GDO supports interconnection through the GRIP Program which seeks to enhance grid flexibility and improve the resilience of the power system against threats of extreme weather and climate change. Smart Grid Grants are a $3 billion topic area within this program. One focus of Smart Grid Grants is integrating renewable energy at the distribution level, and the program seeks proposals that lead to more rapid processing of interconnection applications and minimize queue-related delays for clean energy. Additionally, the Grid Innovation Program topic area of GRIP is a $5 billion program that seeks to deploy projects that use innovative approaches to transmission, storage, and distribution infrastructure to enhance grid resilience and reliability. This may include projects with innovative approaches to interconnection.
Loan Program Office (LPO)	LPO provides debt financing for high-impact, large-scale energy infrastructure and manufacturing projects in the United States. LPO has issued tens of billions of dollars in strategic debt financing to transform the energy and transportation economy to benefit Americans. LPO loans helped launched the utility-scale solar and wind industries, have expanded domestic manufacturing of electric vehicles, and are reviving nuclear energy in the United States. LPO financing programs support projects across the energy sector, including the Title 17 Clean Energy Financing Program, developed to stand up financing to support clean energy deployment and energy infrastructure reinvestment. Through the Energy Infrastructure Reinvestment category of the Title 17 Clean Energy Financing Program, LPO is seeking to finance projects that retool, repower, repurpose, or replace energy infrastructure that has ceased operations or enable operating energy infrastructure to avoid, reduce, utilize, or sequester air pollutants or greenhouse gas emissions.

Vehicle Technologies Office (VTO)	VTO’s work on interconnection focuses on stakeholder engagement and coordination to develop and distribute best practices for interconnection, provide technical assistance to accelerate electric vehicle charging infrastructure deployment, and support solutions to maintain a reliable and resilient grid. VTO funds multiple efforts dedicated to developing innovative interconnection and load service request, streamlining processes to reduce the soft costs for building out a national EV charging infrastructure. VTO also maintains a strong dialogue with utilities, regulators, and industry to address the current gaps and bottlenecks in interconnection to enable greater vehicle grid integration.
Industrial Efficiency and Decarbonization Office (IEDO)	IEDO’s work on interconnection primarily involves research into distribution-level interconnection issues impacting combined heat and power (CHP) and waste heat to power (WHP) projects in the United States. IEDO conducts these activities through technical assistance and stakeholder engagement, funding cooperative agreements, and national lab research. In response to Section 40556 of the BIL, IEDO initiated a review of CHP and WHP interconnection rules to identify barriers and develop model guidance to integrate CHP and WHP into the electric power grid. IEDO funds research and stakeholder engagement to identify opportunities for CHP and other onsite energy resources to deliver ancillary services to the electric grid. This includes exploring RD&D needs and developing an RD&D portfolio that supports industrial sector interaction with the grid through flexible core processes, onsite generation, energy storage, control systems, and power electronics. Additionally, IEDO provides technical assistance through its Onsite Energy Program and Better Plants Program to help industrial and other large energy issues integrate distributed generation at their facilities, including support related to navigating interconnection procedures and net metering policies.

Office of Electricity (OE)	OE accelerates the advancement and deployment of technologies that improve the reliability, resilience, security, and affordability of the grid. Multiple programs within OE do work relevant to interconnection through modeling, standards development, grid controls, and data interoperability. The OE Storage Division propels U.S. leadership in the development, deployment, and utilization of energy storage technologies by advancing high-potential storage technologies that incorporate safe, low-cost, and earth-abundant elements, validating next-generation storage technologies to be grid- and end-user ready, and enhancing the energy community's ability to analyze and adopt storage. Current OE storage division interconnection-related work includes supporting continued development of IBR-related standards as well as demonstrations of new use cases for storage as a flexibility solution for increasing interconnection or renewable integration capacity. The OE Grid Controls and Communications Division drives RD&D of new controls that allow system operators and planners to maintain and improve system reliability and resilience. This includes advancing the development of coordinated distribution controls, protection planning, and operator tools and data integration. Current Grid Controls and Communications Division interconnection-related work includes development of better power system data standards, sharing frameworks, and governance. The division works to develop advanced grid models, controls, and integrated planning frameworks and demonstrate and validate these technologies with industry partners.
Water Power Technologies Office (WPTO)	The mission of WPTO is to enable research, development, and testing of new technologies to advance marine energy as well as next-generation hydropower and pumped storage systems for a flexible, reliable grid. WPTO's Innovations for Low-Impact Hydropower Growth portfolio has studied and disseminated best practices for small hydropower interconnection, such as at nonpowered dam retrofits or conduit hydropower projects. The HydroWIRES Initiative also touches on interconnection, seeking to understand, enable, and improve hydropower's contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system. HydroWIRES includes research, development, demonstration, and deployment, modeling, analysis, and technical assistance activities on various grid aspects of hydropower and pumped storage hydropower, some of which include consideration of interconnection constraints. WPTO's Marine Energy Program considers interconnection queue issues through analytical work focused on the grid value proposition of marine energy technologies, a focus on microgrids to enable resilience for coastal

	and island communities, and the development of the PacWave testing site off the Oregon coast.
Geothermal Technologies Office (GTO)	GTO's mission is to increase deployment of geothermal energy through RD&D of innovative technologies that enhance exploration and production. GTO is not currently working on interconnection research; rather, its focus has narrowed to means by which mass deployment of geothermal technology can alleviate grid interconnection queues by lowering peak demand and decreasing overall requirement for grid infrastructure. As analyzed in the recent geothermal heat pump impacts report (ORNL, info.ornl.gov/sites/publications/Files/Pub196793.pdf), grid modeling demonstrates that the mass deployment of deep demand-side efficiency measures such as geothermal heat pumps dramatically slashes peak electricity loads, reduces the need for as much as 185 GW of winter capacity otherwise required for resource adequacy, and eliminates the need for more than 43,000 miles (65.3 TW-mi) of interregional transmission in a highly electrified future. GTO continues to work on a variety of analysis and demonstration initiatives designed to help the United State achieve the mass-deployment levels considered in this impacts report.

Glossary

Balancing Authority - The responsible entity that integrates resource plans ahead of time, maintains Demand and resource balance within a Balancing Authority Area, and supports Interconnection frequency in real time.

Balancing Authority Area - The collection of generation, transmission, and loads within the metered boundaries of the Balancing Authority. The Balancing Authority maintains load-resource balance within this area.

Base Load - The minimum amount of electric power delivered or required over a given period at a constant rate.

Battery Energy Storage System (BESS) - Device comprised of series-parallel battery packs to enable storing of excess energy production by renewable energy sources. The energy stored can then be released when the power is required to supplement power demand.

Bulk Electric System (BES) - All Transmission Elements operated at 100 kilovolts or higher and Real Power and Reactive Power resources connected at 100 kilovolts or higher. This does not include facilities used in the local distribution of electric energy.[1]

Bulk Power System (BPS) - (A) facilities and control systems necessary for operating an interconnected electric energy transmission network (or any portion thereof); and (B) electric energy from generation facilities needed to maintain transmission system reliability. The term does not include facilities used in the local distribution of electric energy.

Congestion - occurs when a portion or line segment of the Electric Reliability Council of Texas (ERCOT) transmission grid becomes overloaded with electric power and thus the lowest-cost electricity cannot reach some customers due to these transmission constraints.

Curtailment - A reduction in the scheduled capacity or energy delivery of an Interchange Transaction.

Demand - 1. The rate at which electric energy is delivered to or by a system or part of a system, generally expressed in kilowatts or megawatts, at a given instant or averaged over any designated interval of time. 2. The rate at which energy is being used by the customer.

Direct Transfer Trip (DTT) – a protection scheme that uses low-latency communications to ensure distribution circuit-wide equipment protection by sending a DTT signal to clear a fault by tripping necessary DER.

Distributed Energy Resources (DER) - technologies such as distributed generation, distributed energy storage, and electric vehicles that are not connected to the bulk electric system. An alternative definition describes DER as any resource on the distribution and sub-transmission system that produces electricity and is not otherwise included in the formal NERC definition of the bulk electric system (NERC).

Distribution System Operator (DSO) - an entity responsible for the planning and operational functions associated with a distribution system, including DERs and flexible assets, to ensure safe and reliable system operations.

Energy Resource Interconnection Service - Interconnection Service that allows the Interconnection Customer to connect its Generating Facility to the Transmission Provider's Transmission System to be eligible to deliver the Generating Facility's electric output using the existing firm or nonfirm capacity of the Transmission Provider's Transmission System on an "as available basis".

Equity and Energy Justice (EEJ) - sometimes referred to as energy equity and environmental justice[2], DOE efforts to prioritize EEJ work to improve the health, safety, and energy resilience of communities that have been disproportionately affected by fossil fuels, by ensuring all Americans have access to affordable clean energy. This effort is in alignment with the Justice40 Initiative directing 40% of the overall benefits from federal investments to flow to disadvantaged communities.

Facility - A set of electrical equipment that operates as a single Bulk Electric System Element (e.g., a line, a generator, a shunt compensator, transformer, etc.)

Feeder circuit – as defined by the National Electric Code, a feeder circuit includes all the wires and devices contained within an electrical circuit between the energy supply and the feed side of the branch circuit overcurrent protective devices.

Flexible Interconnection – a type of interconnection agreement that allows the export capacity of the interconnecting resource to exceed the available hosting capacity without requiring grid upgrades (or with fewer upgrades) by agreeing to curtail generation in excess of available capacity when necessary.

Generator Operator - The entity that operates generating Facility(ies) and performs the functions of supplying energy and Interconnected Operations Services.

Generator Owner - Entity that owns and maintains generating Facility(ies).

Interconnection - A geographic area in which the operation of Bulk Power System components is synchronized such that the failure of one or more of such components may adversely affect the ability of the operators of other components within the system to maintain Reliable Operation of the Facilities within their control. When capitalized, any one of the four major electric system networks in North America: Eastern, Western, ERCOT and Quebec.

Network Resource Interconnection Service - Interconnection Service that allows the Interconnection Customer to connect its Generating Facility to the Transmission Provider's Transmission System and be deliverable during severe grid conditions, such that the generator can be designated as a capacity resource and contribute to resource adequacy requirements.

Reliable Operation - Operating the elements of the [Bulk-Power System] within equipment and electric system thermal, voltage, and stability limits so that instability, uncontrolled separation, or cascading failures of such system will not occur as a result of a sudden disturbance, including a cybersecurity incident, or unanticipated failure of system elements.

Resource Adequacy - The ability of supply-side and demand-side resources to meet the aggregate electrical demand (including losses).

Stranded Asset - A stranded asset is an asset that loses value or becomes a liability before the end of its expected economic life. This can happen due to a variety of factors, including unanticipated write-downs, devaluations, or conversion to liabilities.

System Operator - An individual at a Control Center of a Balancing Authority, Transmission Operator, or Reliability Coordinator, who operates or directs the operation of the BES in Real-time.

Transmission - An interconnected group of lines and associated equipment for the movement or transfer of electric energy between points of supply and points at which it is transformed for delivery to customers or is delivered to other electric systems.

Transmission Operator - The entity responsible for the reliability of its "local" transmission system, and that operates or directs the operations of the transmission Facilities.

Transmission Owner - The entity that owns and maintains transmission Facilities.

Transmission Planner - The entity that develops a long-term (generally one year and beyond) plan for the reliability of the interconnected bulk electric transmission systems within its portion of the Planning Authority area.

Transmission Provider - The entity that administers the transmission network, referencing both ISOs/RTOs and non-ISO Balancing authorities in this document. Could encompass system operator, transmission operator, and transmission planning roles.

Vehicle to Grid (V2G) - The general operating case where electric vehicles not only charge their onboard batteries but can also supply energy back to the power grid by discharging them.