Planning Roadmap for DER Integration in India: Industry Best Practices and Resource Guide

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National Renewable Energy Laboratory

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Disclaimer

The standards, guidance documents, and further reading resources provided in this document represent a noncomprehensive list of resources to aid in distributed energy resource (DER) integration activities. These documents and standards are subject to future revisions, secessions, or becoming obsolete as the industry evolves. It is critical users of this guide research the current state of the art in addition to the resources provided herein. This document does not mean to prescribe any of the following standards as the best-suited standards for any users of this document, nor does it serve as a replacement for the guidance and wording within those standards.

List of Acronyms

AC	alternating current
BES	battery energy storage
BIS	Bureau of Indian Standards
BPS	bulk power system
BTM	behind the meter
CEA	Central Electric Authority
CSIP	Common Smart Inverter Profile
DC	direct current
DER	distributed energy resource
DERMS	distributed energy resource management system
DISCOM	distribution company
DNP3	Distributed Network Protocol 3
DOE	U.S. Department of Energy
EV	electric vehicle
FERC	Federal Energy Regulatory Commission
GW	gigawatt
Hz	hertz
IDP	integrated distribution planning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IREC	Interstate Renewable Energy Council
kV	kilovolt
kVA	kilovolt ampere
kW	kilowatt
MW	megawatt
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PUC	Public Utilities Commission
PV	photovoltaic
SCADA	supervisory control and data acquisition
SEP	Smart Energy Profile
SGIA	Small Generator Interconnection Agreement
SGIP	Small Generator Interconnection Procedures
T&D	transmission and distribution
VAR	volt ampere reactive

Executive Summary

Widespread, global adoption of distributed energy resources (DERs) represents a fundamental shift in the power sector, driven largely by policy changes, evolving customer expectations, and decarbonization efforts. Navigating this rapidly evolving landscape while maintaining the safety, reliability, and affordability of our energy systems is a significant challenge for utilities, regulators, original equipment manufacturers (OEMs), and even customers. As installed DER capacity increasingly makes up a significant portion of our energy systems, careful planning and management of the grid edge and DER integration is paramount. Developing sound DER integration practices and procedures is a multifaceted exercise that generally scales in complexity with the anticipated levels of DER adoption. Within the broad definition of DER integration are several key development areas including interconnection standards and grid codes; equipment testing and certification; interoperability and cybersecurity; interconnection procedures; and advanced forecasting, planning, and DER management. India has already seen significant growth in DER adoption and has stated goals for continued growth in this sector; this has prompted the need for a holistic approach to DER integration and planning as well as key consideration of these five development areas.

1. **Interconnection standards and grid codes:** The adoption or development of sound interconnection, testing, and cybersecurity standards provides baseline requirements for the performance, operation, testing, safety, and maintenance of DERs, creating uniformity and industry confidence in DER performance and streamlining the overall DER integration process.

2. **Equipment testing and certification:** Creating national, or leveraging international, accredited testing facilities to conduct testing and certification procedures ensures locally available DER equipment is technically capable of meeting requirements, as prescribed in applicable standards. DER commissioning, verification, and monitoring provide necessary visibility for utility planners and system operators to prevent misconfigurations or suboptimal DER performance.

3. **Interoperability and cybersecurity:** Enabling operational remote visibility and control of behind-the-meter DERs through communications and interoperability requirements provides utilities with visibility of disaggregated load and can alleviate challenges that come with load masking in forecasting and planning efforts. An increase in internet-connected, remote-accessible third-party-owned and -operated devices connected to the distribution system is also expanding the potential attack surface for cyber criminals. Cross-organizational cybersecurity (e.g., including utilities, OEMs, aggregators, customers, etc.) will become central to system-wide cybersecurity for power systems in a high-DER, clean energy future.

4. **Interconnection procedures:** Developing appropriate, streamlined interconnection screening procedures ensures DERs can interconnect quickly and without negative impacts to system reliability, safety, or system operations. DER grid impacts can take a variety of forms and the associated interconnection screens can range from simple heuristics to complex power-flow studies.

5. **Advanced forecasting, planning, and DER management:** The dynamic nature of DERs and the uncertainty in future adoption levels can strain legacy system planning structures. Bottom-up customer adoption modeling, scenario-based planning, and integrated distribution planning (IDP) all present important opportunities for utilities to make informed investment decisions amid mounting uncertainty.

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1 Introduction

Navigating a rapidly evolving industry while ensuring the reliable, safe integration of distributed energy resources (DERs) presents a significant challenge for many stakeholders. With the ubiquity of advanced inverters, increasingly significant system impacts of DERs, and newly revised DER standards (e.g., Institute of Electrical and Electronics Engineers (IEEE) 1547-2018 [1]), streamlined processes, collective understanding of key issues, and development of new tools, facilities, and planning frameworks are critical to the success of India's clean energy goals. India has already seen significant growth of DERs, as shown in Figure 1, with nearly 13 gigawatts (GW) of installed rooftop capacity in 2024 [2], and a stated target of 40 GW [3]. With the potential for DERs to comprise a significant portion of the country's generation capacity, it is crucial to consider appropriate behaviors and technical requirements for these grid-edge resources to ensure they support the bulk energy system and distribution system reliability.

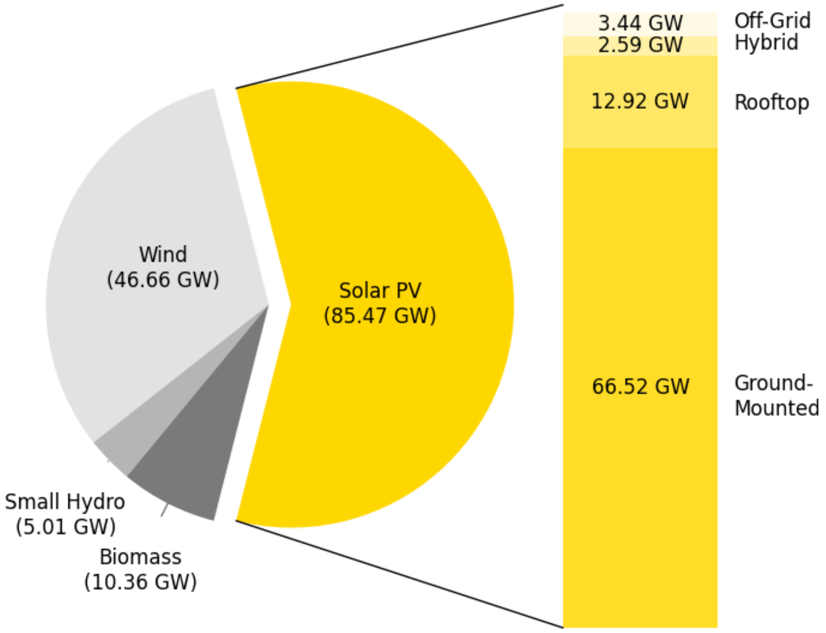

Figure 1. Installed renewable energy capacity in India in 2024

This report outlines key concepts and best practices related to DER integration. Though not comprehensive, it may serve as a starting point for India's broader energy goals and highlights critical development areas for consideration by policymakers, regulators, utilities, and equipment manufacturers. One should note significant emphasis is placed on the adoption and implementation of IEEE 1547-2018 [4] and other U.S.-based standards, guidance documents, utility best practices, though other commonly used international standards are included for further reading within this report. Though the implementation of these standards in the U.S.-context provides valuable case studies and lessons learned, this report does not intend to prescribe these standards as the best suited for international adoption, including within India. As such, readers of this report in *any* jurisdiction should assess the local suitability of this guidance to the local power systems and broader energy sector.

India’s Bureau of Indian Standards (BIS) recently formally adopted IEEE 1547-2018 [5]. Following this milestone, there are myriad further steps to implement this and related standards. The following sections outline key decision points, technical concepts, emerging industry best practices, and resource guides to aid in this process. The five development areas in Figure 2 each represent, in no particular order, key considerations for successful DER integration.

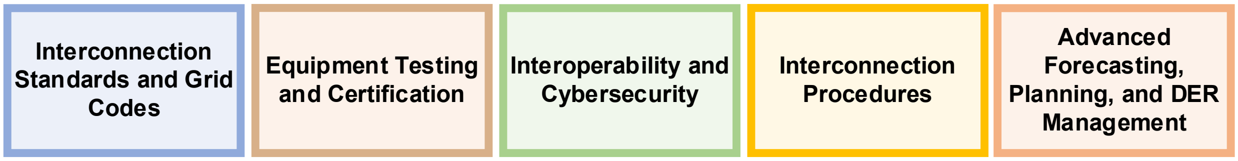

Figure 2. Development areas for DER integration

2 Evolution of Advanced Distributed Energy Resource Integration

DER integration is a multifaceted exercise that generally scales in complexity with the anticipated levels of DER adoption. The strategy map shown in Figure 3 provides an overarching view of the myriad tasks related to DER integration, illustrating the five development areas, key subtasks, and process interdependencies. The mapping of subtasks illustrates *one* possible pathway for successful DER integration, though this is by no means the *only* pathway. The depiction is not meant to be prescriptive. Many of the concepts outlined are representative of the industry cutting edge, and complete implementation of this roadmap in its entirety is still largely nascent in today's industry. Nonetheless, we believe these best practices can provide key objectives for stakeholders to consider in their DER integration and grid modernization pursuits.

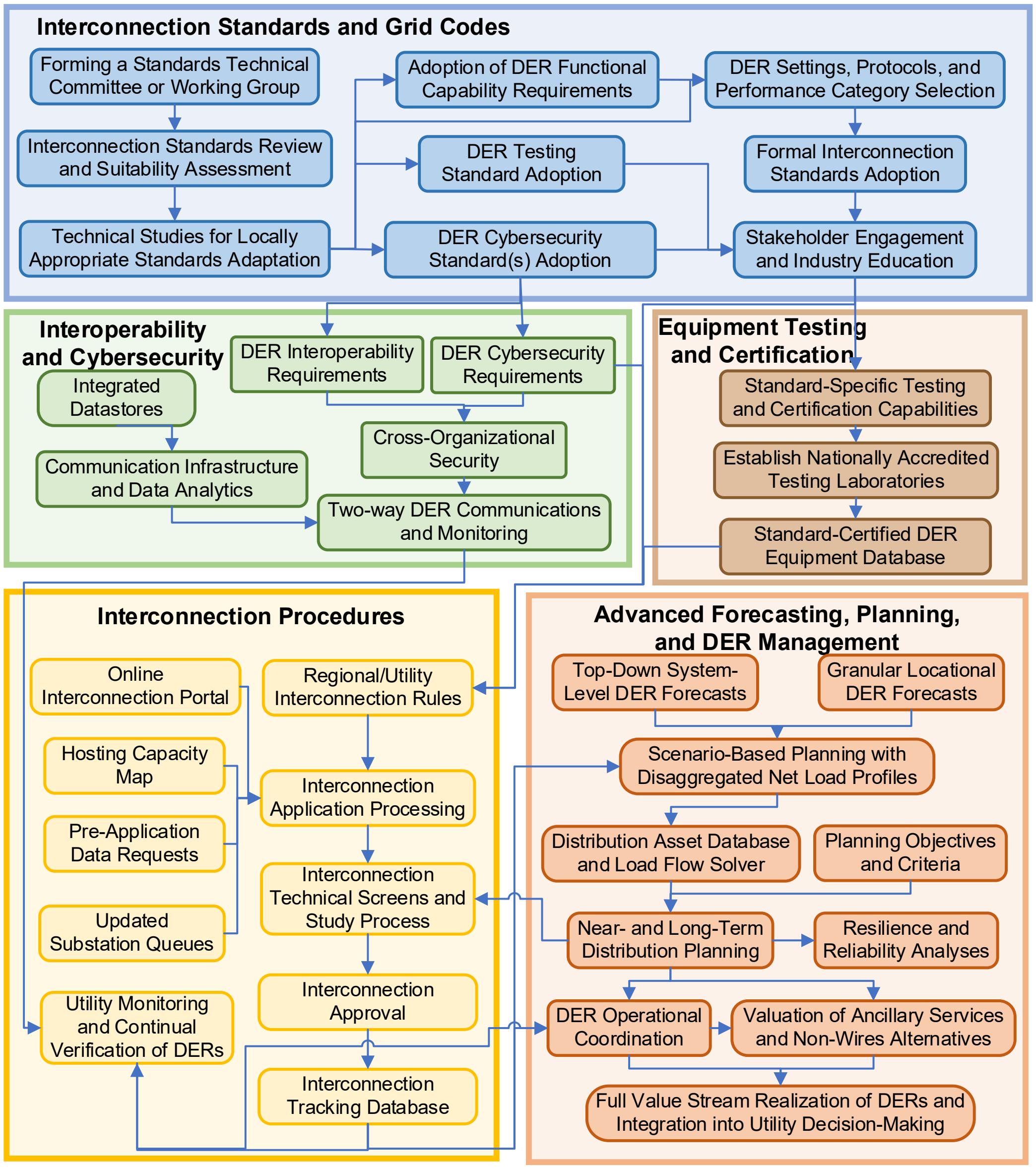

Figure 3: DER integration strategy map and process interdependencies

3 Interconnection Standards and Grid Codes

Standards provide baseline requirements for the performance, operation, testing, safety, and maintenance of DERs. Adoption of standards can improve the overall DER interconnection process by setting out clear requirements that can help streamline manufacturing, testing, certification, and installation practices. Standardization across multiple distribution jurisdictions can provide uniformity in DER performance and grid support functionalities across larger transmission systems, enabling higher confidence from grid operators that DERs in all regions of their system will perform as expected. This uniformity in configurations and settings can also improve the accuracy of grid modeling efforts, simplify monitoring and verification practices, and inform future customer program development.

Key Considerations for Standards Adoption/Adaptation

Character of service: Critical evaluation of the design and operating characteristics of the local electric power system and how proposed DER functionalities and settings may affect system performance and reliability.

Performance function selection: The selection of DER functionalities such as voltage/frequency ride-through to ensure BPS stability or voltage support for decentralized distribution-level voltage regulation.

Performance category selection: Based on the type of DERs and the level of DER penetration, IEEE 1547-2018 designates categories for DER performance under both normal and abnormal conditions.

DER settings selection: Assigning default settings in IEEE 1547-2018, settings within the allowable ranges, or making country-specific amendments (e.g., conversion to 50 Hz or referencing local voltage standards) to accommodate local grid conditions.

Early adoption: Early implementation of standards prior to significant DER adoption to prevent costly retrofit efforts in the future.

Central regulators and/or standards agencies, such as BIS, may choose to form a standards technical committee or working group to conduct initial suitability assessments of existing interconnection standards and prescribe or recommend the standard on the national scale, whereas state and local agencies such as state regulators and/or distribution companies (DISCOMS) can integrate these requirements into their interconnection rules and grid codes as appropriate or as required. Adopting an existing international interconnection standard, such as IEEE 1547-2018, must be done with careful consideration of the local operating conditions and underlying assumptions of the chosen standard. Recognizing the fundamental U.S. focus of some IEEE standards (i.e., a 60-hertz [Hz] base frequency; references to North American reliability grid codes and standards; and the influences of studies of large, interconnected power systems as exist in North America) can aid in developing locally appropriate grid codes. Defining a character of service for local power systems—including typical normal and abnormal operating ranges for voltage and frequency, utility preferences for DER performance, bulk power system (BPS) reliability requirements, and other nuances of the local systems and markets—can inform decisions about selecting required DER functions, IEEE-1547 performance categories, and DER settings [5]. These decisions should be made with a diverse group of stakeholders to adequately represent the interests and system requirements of the BPS and the distribution system. Inappropriate selection of DER settings or delayed adoption of standards can result in costly mistakes or require retroactive solutions. Valuable lessons can be learned from the notable "50.2-Hz Problem" experienced in Europe almost 2 decades ago [6], during which a widespread retrofit of inverters with inappropriately sensitive overfrequency trip thresholds was required. Thus, it is critical that regional adopters of the standard conduct technical studies for a locally appropriate implementation and consider future DER penetration and potential BPS impacts. Initially, incremental steps can be taken, such as the adoption of DER functional capability requirements (i.e., the *ability* to ride through disturbances or provide active voltage regulation), with settings and performance category decisions to follow.

4 Equipment Testing, Certification, and Verification

Locally available DER equipment must be technically capable of meeting the requirements set forth within the implemented interconnection standards. Jurisdictions may opt to rely on nationally accredited testing laboratories where available, international certifications, or original equipment manufacturer (OEM) self-certification where deemed sufficient. Utilities may opt to require standard-certified DER equipment as a prerequisite to interconnection to increase efficiency in the interconnection process and instill confidence in equipment capabilities. For example, Underwriter's Laboratory (UL) standard UL 1741 [7] is harmonized with IEEE 1547-2018 and the accompanying IEEE testing standard 1547.1-2020 [8]. Some utilities already require UL 1741 certification for interconnecting DER equipment. An inverter's anti-islanding functionality, for example, is a key capability required for DERs, which may be verified using the procedures outlined in IEEE 1547.1-2020 and UL 1741. Additionally, good installation and electrical safety practices are paramount in any DER or electrical system. In the U.S., the National Fire Protection Association (NFPA) codifies many of these requirements in the National Electric Code (NEC) [9].

Equipment Testing Categories in IEEE 1547.1-2020

Type tests: Testing of the manufactured devices to verify they can meet the requirements of IEEE 1547-2018, including responses to grid disturbances and faults, voltage and frequency support, and priority of responses.

Interoperability tests: Testing of the local DER communication interface to verify communication criteria are met and all relevant data associated with DER interoperability are exchanged and acted on properly.

Production tests: Testing done by the manufacturer on every unit of DER equipment prior to shipment.

DER evaluations: "Desk studies" and as-built/on-site installation evaluations to verify DER designs meet IEEE 1547-2018 requirements as well as correct installation and configuration of DER components according to design documents.

Commissioning tests: May include performing visual inspections of components and connections, conducting tests of key functions, and verifying the installed combination of DER equipment can collectively meet IEEE 1547-2018 requirements at the reference point of applicability.

Periodic interconnection tests: Periodic tests to reverify the DER still meets the requirements of IEEE 1547-2018 and agreed to within interconnection agreement documents.

Jurisdictions should strive to build collective understanding among all involved stakeholders well in advance of enforcing any new standards or testing requirements. Enforcing compliance with a standard prior to the availability of certified equipment may complicate interconnection procedures and strain manufacturers and local developers. Once sufficient testing protocols and resources are in place, the use of a regional or countrywide certification database to list approved devices can increase interconnection efficiency and streamline certification efforts. The California Energy Commission maintains the Solar Equipment Lists [10] to include DER equipment like PV modules, inverters, meters, and batteries that meet certain safety and performance standards.

Established nationally accredited testing facilities may still require additional testing equipment, personnel, and/or training to perform DER equipment testing aligned with a chosen testing standard. Testing to IEEE 1547.1-2020, for example, requires several pieces of specialized equipment including a digital oscilloscope, power analyzer, current and voltage sensors, a photovoltaic/battery simulator, a grid simulator, load banks, a real-time simulator, breakers/switches, transformers, and computer-inverter communications.

In addition to equipment testing and certification, commissioning and verification processes are equally critical and also represent a challenge for many utilities. There is a need to ensure as-built installations are verified in the field to have the correct equipment, programmed functionalities, and settings as were studied during earlier stages of the interconnection process. Intentional or inadvertent changes to the studied parameters at a later date should also be identified through periodic tests and/or remote monitoring. As DER growth accelerates, performing in-person witness tests and periodic verification of every interconnection becomes intractable—particularly for large numbers of small-scale installations—highlighting the value of telemetry and interoperability requirements. Specified system size thresholds for when these requirements are enforced can aid in maximizing the benefits of these advanced capabilities and minimizing the costs. At the bulk-system scale, multiple recent grid disturbances in the United States have shown systemic grid support performance issues in some large-scale inverter-based generating assets, resulting in the unintended loss of significant generating capacity. These events were partially the result of as-installed inverter control settings not matching the as-studied settings [11]. As such, avoiding misconfigurations in installed devices or subsequent settings changes through commissioning procedures and continuous verification practices is paramount, especially for large-scale assets or large aggregations of small-scale assets. Lastly, developing clear end-of-life or replacement requirements and procedures for existing DERs is also a best practice to ensure desired DER performance throughout the lifespan of a generating asset.

5 Interoperability and Cybersecurity

As DER adoption grows, having operational visibility of DER performance can be invaluable for understanding disaggregated load and avoiding the challenges that come with load masking in forecasting and planning. DER communications with utility systems (i.e., with distribution management systems) are still a largely nascent capability, especially for smaller-scale DERs given the significant added costs of communications equipment and/or DER sub-metering (i.e., metering beyond the utility billing meter). In charting the potential evolution of communication with DERs, early protocols may be used to simply communicate DER settings and utility-required profiles [12]. Later protocols may be used for one-way data exchange to provide utilities with performance data (e.g., real and reactive power production, inverter voltage measurements, and so on) that can be used for net load disaggregation, performance measurement, and verification of DER grid support. Two-way communication may one day enable distributed energy resource management systems (DERMS), which can be established using either vendor cloud controls or DER gateway devices and enable aggregation and control of large populations of DERs.

DER Information Categories (as defined in IEEE 1547-2018)

Nameplate information: As-built characteristics of the DER, including active power rating, specified power factor, and normal/abnormal operating performance category (read-only).

Configuration information: As-configured values indicative of the present ability of the DER to perform functions or any changes to the nameplate values using a local device setting change (read/write).

Monitoring information: Present operating conditions of the DER, including active power output, phase voltages, and connection status (read-only).

Management information: Information used to update functional and modal settings of the DER (read/write).

IEEE 1547-2018 provides guidance on DER interoperability requirements, information exchange, and communication protocols for DERs along with protocol-specific requirements for each of the three included protocols (IEEE 2030.5-2013/SEP2.0, IEEE Std 1815/DNP3, and SunSpec Modbus). The standard includes approximately 100 parameters for DERs. Standardized data formats can facilitate accurate data transfer among many parties and ensure data are human- or machine-readable without ambiguity [13]. Early decisions regarding which protocol to use, which DERs will require advanced telemetry, what data to collect and store, and future use cases will all play a role in regulatory processes and long-term planning approaches for DER integration. Care should be taken to consider future use cases and balance these with cost considerations for both developers and utilities to install infrastructure and implement advanced analytics or management tools. Though there will always be some amount of uncertainty in long-term planning, forward thinking at early stages of DER adoption can help avoid inadequate DER service provision and functionality, reducing the risk of stranded assets or requiring retrofits of legacy installations.

Communication Protocols (as listed in IEEE 1547-2018)

IEEE 2030.5-2013 or the Smart Energy Profile (SEP) 2.0 provides guidance for communication among consumer devices, home area networks, and smart grid infrastructure.

IEEE Std 1815 or the Distributed Network Protocol (DNP3) is most commonly used with utility automation systems—i.e., supervisory control and data acquisition (SCADA)—to communicate between control centers and field remote terminal units.

SunSpec Modbus uses the Modbus protocol to facilitate communication between various components in DER systems by defining a common language and data model, ensuring integration and information exchange between different manufacturers' products.

Though streamlined read-write access to DER data can benefit myriad planning and operational challenges, the increased adoption of internet-connected, remote-accessible, grid-interactive devices presents new cybersecurity risks for utilities, developers, and even consumers. The expanding cyber-attack surface coupled with new third-party involvement with daily utility operations creates new pathways for hackers to inflict harm on our energy systems. Should malicious actors gain access to these systems, breaches of customer privacy or disruption of utility distribution or BPS operations could occur [14]. Even advanced DER functionalities prescribed in IEEE 1547-2018 could be used in a harmful manner. Attackers may attempt to alter inverter settings, trip off large assets (or large aggregations of small assets) or create system instabilities through rapid alterations of DER operating behaviors (e.g., issuing malicious dispatch commands to several DERs). The list of potential attack methods and vectors is constantly evolving. By the time a given cyber solution is fully implemented, it may already be obsolete.

To mitigate cybersecurity risks, the concurrent adoption of DER cybersecurity standards and accompanying cyber-specific testing standards is a critical consideration for emerging DER markets. IEEE 1547.3-2023, for example, provides in-depth guidance for energy system security, referencing myriad existing cybersecurity standards and frameworks. A key challenge addressed by the standard—largely unique to DERs and future power systems—is the need for cross-organizational security enabling the secure transfer of data, control signals, and customer information across utility and nonutility (e.g., aggregators, installers, communications company) parties. As power systems become increasingly complex and dynamic, securing communications among more stakeholders introduces new challenges. Each organization may have different risks, equipment, and operating procedures, requiring varying approaches to cybersecurity.

6 Interconnection Procedures

Interconnection is the process in which utilities study, design if necessary, decide on the grid connection of, and commission DER applications. Interconnection screens have been used by utilities to filter and accept grid connection based on the proposed interconnection passing engineering acceptance criteria. Appropriate heuristics-based screens can avoid the need for planning engineers to manually study all interconnection applications in detail. The creation of current, clear, publicly available regional interconnection rules and procedures can streamline the interconnection process, reduce congestion of interconnection queues, ensure applicable standards are followed, and allow the tailoring of standard requirements to individual utilities as needed. DER grid support functions, utility-required control parameter profiles, or interconnection study processes can be defined in these interconnection requirements. Utilities have opportunities to develop protocols for processing interconnection applications in a streamlined manner. These may include creating online application portals, publicly available hosting capacity maps, publicly available interconnection queues or allowing preapplication data requests to reduce the number of nonviable interconnection requests.

Interconnection Best Practices

Application templates and/or online application portals can improve workflow efficiency, guide users through the interconnection process, enable the storage of legacy interconnection data in a centralized database, provide ease of access to utility sample interconnection documents, and ensure the completeness of information collected.

Preapplication data requests and/or hosting capacity maps can reduce the number of unsuccessful interconnection requests by steering applicants toward more robust circuits of the distribution network.

Updated substation queues can improve utility/developer relations, effectively communicate any potential study delays or queue congestion, and allow grouped studies of multiple interconnections for improved screening efficiency and the possible cost sharing among developers.

Continuous stakeholder engagement can include developer trainings, gathering of industry feedback, process refinement, and communication of changes and updates to requirements and procedures as needed.

The Federal Energy Regulatory Commission (FERC) has compiled best practices documents—the Small Generator Interconnection Agreement (SGIA) and Small Generator Interconnection Procedures (SGIP)—outlining both the contractual agreements and the technical screening procedures required for interconnecting distributed generation (defined as under 20 megawatts [MW]) [15], [16]. These documents provide a robust foundation on which to build interconnection rules and procedures if tailored to the nuances of a given jurisdiction or utility along with useful example templates for applications and agreements. The SGIP provides a tiered approach to studying the grid impacts of DER interconnections, scaling the level of technical scrutiny to the likelihood of adverse grid impacts based on high-level heuristics (i.e., DER nameplate power, certified or noncertified equipment, voltage class, circuit location, or violations of more basic screening thresholds). This allows more efficient application processing, concentrating the bulk of the engineering analysis on the most impactful interconnections. In addition, the Interstate Renewable Energy Council's (IREC's) 2023 Model Interconnection Procedures [17] propose some minor changes to the existing SGIP, including select advanced functionalities and considerations for the interconnection of storage systems and zero- or limited-export systems.

FERC SGIP Key Concepts and Procedures

Certification criteria are used to classify "certified" small generating facilities eligible for expedited review if they have been tested by a Nationally Recognized Testing Laboratory in accordance with relevant industry standards and certified, among several other requirements.

Preapplication reports are informal requests for nonbinding information on the high-level feasibility of interconnection at a given site, including several pieces of nonconfidential system information to inform customer decisions and reduce the likelihood of nonviable interconnections. Full interconnection reviews are still required.

Queue positions are assigned based on a timestamped interconnection request and are used to determine the cost responsibilities for required system upgrades.

The 10-kilowatt (kW) inverter process is a simplified interconnection process for small (<10 kW) interconnection requests with established timelines, application materials, and technical requirements (i.e., UL 1741 listed equipment).

Fast-track process eligibility is determined based on the generator type, size, and interconnection voltage; site location; and certification criteria. Fast-track process screens are mostly high-level, heuristic technical screens to determine the need for additional, detailed studies.

Supplemental review includes additional studies assessing items such as DER-to-minimum-daytime-load ratio, impacts to system voltage, harmonics, and safety and reliability if a request fails the fast-track process.

The study process is used for requests of 2–20 MW in size, those that use noncertified equipment, or those that did not pass the fast-track process and can include the three screens that follow.

A feasibility study is part of the study process and identifies adverse system impacts resulting from the proposed interconnection, including exceeding circuit breaker capacity, voltage violations, grounding requirements, system protection, and a nonbinding estimate of necessary upgrade costs.

A system impact study is part of the study process and, based on the results of the feasibility study, further evaluates the impacts of the proposed interconnection and determines if there is a need for a transmission system impact study. A system impact study may include any of the following analysis topics as well as an indication of cost and time frame for upgrades to be implemented: short-circuit study, system stability, power flow study, voltage drop and flicker, protection coordination, operational flexibility, and grounding requirements.

A facilities study specifies the costs to design and implement the required system upgrades identified in the system impact study.

Interconnection technical screens should be able to filter for applications that will result in adverse grid impacts and allow the necessary stakeholders to take the appropriate mitigations following more detailed technical studies. In general, interconnection screens can cover the following categories of system impacts: thermal overloads, voltage regulation, system protection, operational flexibility, cybersecurity, and bulk system impacts.

Thermal overloads resulting from DERs may require upsizing transformers, reconductoring, adding and configuring protective devices, or reducing the proposed system size. Screens to fast-track interconnections that avoid violating network limits can often be performed with limited modeling tools, comparing equipment ratings to the maximum amount of aggregated generation the asset may encounter.

DER-induced voltage impacts can take multiple forms. A current source injecting power into the grid will generally raise system voltages, with the greatest impact at the DER inverter AC terminals. For distributed generation, voltage rise is typically more pronounced during times of low load and high generation (e.g., minimum daytime load). Overvoltages may also result from DER located near (on the load side) a utility-owned voltage regulation device such as a substation load-tap changer or a line regulator. If improperly configured, DERs operating at a nonunity power factor or with active voltage regulation capabilities may also interact with utility-owned voltage management systems. Performing time-series load flow studies using accurate feeder models is among the most comprehensive ways to assess these effects, though simpler calculations may be acceptable for smaller systems, given the reduced potential for adverse grid impacts.

At high levels of DER adoption, distribution system protection may also be impacted. Screens to evaluate protection impacts such as exceeding device interrupting ratings, protection miscoordination, reverse power flow, or line worker safety may be needed. In some cases, changes to system protection schemes may be warranted such as enabling or installing advanced protection functions like voltage supervisory reclosing, ground fault overvoltage protection, reverse trip blocking, noninverter-based open-phase detection, additional protective devices to improve sensitivity, or even non-time-overcurrent-based distribution protection. Conducting short-circuit and coordination studies (or electromagnetic transient simulations in select cases) to assess the effectiveness of current protection systems is a critical step to ensure the safe, reliable operation of distribution systems.

Should interconnecting DERs limit a utility's operational flexibility (i.e., the ability to freely conduct switching procedures for outage restoration or construction), further studies may be warranted or additional devices to disconnect DERs when needed may be required. Careful consideration for both nominal and N-1 (and N-2 if applicable) circuit topologies and equipment ratings is critical to avoid detrimental effects to system reliability and safety during routine switching procedures. Assessing DER impacts on multiple system configurations can significantly increase the workload for performing detailed system impact studies. Though largely nascent in the industry, partial or full automation of these studies [18] can enable more comprehensive impact assessments by studying multiple realistic scenarios in an efficient manner.

At low levels of DER uptake (relative to total bulk system generation), the detrimental effects on the bulk energy system from the sudden loss (or rapid change in output) of distributed generation are likely to be minimal. Early versions of interconnection standards (i.e., IEEE 1547-2003) reflected this presumption, including few provisions to protect bulk system stability from a DER standpoint. As the industry has accelerated, the realization that DERs can have nonnegligible or even substantial responsibility for the reliable operation of the overall BPS demanded new interconnection practices. The sudden widespread loss of distributed generation, for example, can create system instabilities, exacerbate grid events, and impact overall system power quality. Incorporating critical grid functions, such as voltage and frequency ride-through, into interconnection reviews early in the process can save significant costs, time, and risk down the road (e.g., the 50.2-Hz problem).

7 Advanced Forecasting, Planning, and Distributed Energy Resource Management

Incorporating DERs into load forecasting and planning exercises is critical given the potential impacts on net load and future grid investments. Over- or underestimating future DERs risks mismatched grid investments relative to future needs. Long-term forecasted DER adoption could impact other utility and regulatory decisions related to tariff design, DER program design, interconnection requirements, grid support functions, integrated resource planning, or other investments in planning and operations. Absent significant DER adoption, most utilities employ deterministic load forecasting, using current system peak demand and extrapolated growth rates to determine future loads, typically on a 5- to 10-year time horizon. In the face of growing DERs, utilities may elect to use probabilistic forecasts—including known uncertainties in adoption rates, weather, or future policy changes—or scenario analysis to assess the impacts of various possible levels of future DER growth. Incorporating DER growth into these forecasts requires appreciably more inputs and sophisticated modeling.

Integrated Distribution Planning Key Components

Forecasting elements must evolve by increasing locational and temporal granularity and by integrating DERs and evolving load characteristics.

Optimized grid solutions may begin to take new forms rather than simple poles-and-wires-type upgrades of the past. Nontraditional solutions such as managed electric vehicle (EV) charging, behind-the-meter (BTM) battery storage, or building thermal storage (i.e., smart thermostats) may be evaluated for cost-effectiveness in an integrated distributed planning (IDP) framework.

Bulk-Distribution integration and coordination is needed to replace previously siloed planning processes across these areas. Coordination of resources and planning objectives across transmission, generation, and distribution promotes more holistic energy system planning and total system optimization.

New forecasting methods largely fall into two categories: top-down and bottom-up. Top-down system-level DER forecasts largely focus on the system as a whole, not accounting for geographic heterogeneity and using predictive factors that include historical adoption rates, program incentive targets, policy goals, and engineering judgment. In contrast, bottom-up, granular, locational DER forecasts—such as customer adoption models—analyze the customer, assessing their individual proclivity to adopt a given technology considering a wide range of inputs. Customer adoption models rely on factors such as historical location-specific adoption rates, locational solar resources, economic and demographic trends, and customer behavior models [19]. Having accurate DER forecasts allows utilities to conduct scenario-based planning with disaggregated net load profiles, highlighting the distinct impacts from load or DER growth and allowing the tailoring of grid solutions. Developing near- and long-term planning procedures that incorporate DER forecasts is paramount to understanding the increasingly complex and dynamic operations of distribution systems. For instance, accurately quantifying the energy contributions from distributed generation is a key requirement for resilience and reliability analysis, contingency planning, and integrated resource planning at the bulk system level.

DER submetering to improve the visibility of DER performance for advanced planning comes at a significant cost, with potentially uncertain benefits given that most DERs monitor their own production but, at present, typically do not share these data with the utility [20]. Absent dedicated DER submetering and/or real-time telemetry, physics-based solar-resource modeling using accurate DER configuration and nameplate information may still be able to provide sufficient estimates of solar production for these purposes. Uncertainties in this approach depend largely on the modeling rigor and integrity of data input.

Key Considerations for Indian Stakeholders

Ministry of Power

— Broad stakeholder engagement is critical in developing locally appropriate DER integration pathways. Eliciting input from a variety of energy industry players can build consensus and foster collective understanding of key issues.

— Early adoption of critical standards is key to avoid costly retrofits in the future.

Bureau of Indian Standards (BIS)

— Careful consideration of existing standards—international or domestic—and selecting those most suitable to India's power systems.

Central Electric Authority (CEA)

— Selecting performance categories and settings for BPS-level grid support functions, specifying which parameters and requirements are necessary for BPS reliability and stability and which may be adjusted to the utility's preference.

— Ensuring proper coordination of DER response with related BPS functions.

Distribution companies (DISCOMs)

— Integration of DERs into existing planning structures can improve the overall efficiency and effectiveness of DER interconnection and planning.

National Accreditation Board for Testing and Calibration Laboratories

— There may be additional testing equipment, personnel training, or software requirements for laboratories that plan to begin testing to new DER standards.

Managing the increasing complexity of distribution planning amidst emerging technologies, clean-energy goals, increasing transmission-distribution-generation interactions, and evolving customer behaviors and expectations creates vast new challenges for utilities which are straining existing siloed planning departments and utility operations. Integrated distribution planning (IDP) represents a unified, objective-driven framework for developing holistic planning and grid investment strategies and enabling the continued reliable integration of grid-edge technologies. IDP places significant focus on transmission and distribution (T&D) coordination and harmonizing these previously siloed planning objectives, forecasts, and investment decisions. Objectives within an IDP framework focus on a wider range of criteria including decarbonization, energy resilience, environmental justice, consumer market interactions (i.e., FERC 2222), and overall complexity management. For example, creating new analysis capabilities to provide valuation of DER ancillary services can enable nonwires-alternative programs to provide enhanced reliability and decarbonization progress. IDP may include new technical functionalities as well, driven by a need for innovative solutions and emerging technologies that include smart metering, new communication architectures, DER operational coordination, or advanced distribution management systems and DERMS software suites. Ultimately, IDP is a path for utilities to fully integrate DERs (among other grid modernization strategies) into decision-making processes and optimize future investments.

8 Conclusions and Considerations in the Indian Context

A holistic approach to DER integration, including critical focus areas such as standards adoption, interoperability and cybersecurity, testing, interconnection screening, and integrated system planning, represents a monumental challenge for the many involved stakeholders. It is important to note although the approaches detailed within this report represent some of the established industry best practices, much of this space is largely nascent. Case studies of jurisdictions that have implemented the entirety of these practices, at the time of this writing, do not exist. As such, these practices are liable to evolve alongside the industry.

India's significant levels of existing and forecasted DER adoption present clear challenges to the industry and require a proactive approach to ensure the sound integration of these new technologies. Indian stakeholders from government, regulatory, and industry spaces can benefit from continued coordination and the formation of diverse technical committees to address these challenges.

9 Resource Guide: Relevant Standards and Guidance

Tables 1–5 correspond to each of the focus areas detailed previously and provide resources pertinent to DER integration, listed alphabetically. Much of the focus is placed on standards—both domestic to the United States and international—to assemble some of the more well-known or industry-leading standards within each focus area. It is important to note the following descriptions are only high-level summaries and may not be fully representative of the contents of each standard because several are paywall-protected resources. Several of these resources also may apply to more than one development area. It is important readers of this report rely on the language within each document referenced. Because of the dynamic and highly heterogenous nature of the industry, the lists in the tables are not comprehensive and are subject to change with time. Nonetheless, we hope at a minimum these resources can function as an introduction to each of these topics and emphasize the time and resources required to adequately address emerging challenges.

Table 1. Resource Guide: Interconnection Standards and Grid Codes

Interconnection Standards and Grid Codes	
CEA REGD. No. D. L.-33004/99 – 2013 [21]	*Technical Standards for Connectivity of Distributed Generation Resources*: India's current interconnection standard for distributed generation, issued by the Central Electric Authority (CEA) in 2013.
CSA C22.3 No. 9 – 2020 [22]	*Interconnection of Distributed Energy Resources and Electricity Supply Systems*: Issued under Part III of the Canadian Electric Code, outlining requirements for DER interconnection (<50-kilovolt [kV] interconnections) and DER equipment testing and certification.
EN 50549 – 2019 [23], [24]	*Requirements for Generating Plants to be Connected in Parallel with Distribution Networks*: European standard providing requirements for generating plants connected at low- or medium-voltage distribution networks and serving as a technical reference for functionalities defined in the European Network Code's Requirements for Generators.
IEC 61727 – 2004 [25]	*Photovoltaic (PV) systems - Characteristics of the utility interface*: International interconnection standard for PV systems under 10 kilovolts-ampere (kVA) in size.
IEC TS 62786 – 2017 [26]	*Distributed energy resources connection with the grid:* An IEC Technical Specification providing the principles and technical requirements for DER interconnections.
IEEE NESC – 2023 [27]	*National Electrical Safety Code:* Updated by IEEE every 5 years, this sets rules for ensuring worker and public safety and defines rules for the construction, installation, operation, and maintenance of electric infrastructure, communications, and related equipment.
IEEE Std 1547 "Family of Standards" [4], [8], [28], [29], [30], [31], [32], [33], [34]	*IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*: IEEE's suite of DER interconnection standards and guides, with the benchmark standard being IEEE 1547-2018. Accompanying standards and guides include testing procedures, impact studies, energy storage interconnections, and cybersecurity.
IEEE Std 2030.7-2017 [35]	*IEEE Standard for the Specification of Microgrid Controllers*: Standard providing interconnection and technical specifications and requirements for

Interconnection Standards and Grid Codes	
	microgrid controllers or microgrid energy management systems, including guidance for both islanded operation and grid-connected operation.
IEEE Std 2800 – 2022 [36]	*IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems*: IEEE's interconnection standard pertaining to bulk power system interconnection of inverter-based resources.
NFPA 70 NEC – 2023 [9]	*National Electric Code:* From the National Fire Protection Association (NFPA), the National Electric Code is revised every 3 years and codifies requirements for safe electrical installations.
NZ/AUS 4777.2 – 2020 [37]	*Grid connection of energy systems via inverters, Part 2: Inverter requirements*: Australian standard that specifies the performance requirements for inverters interconnected at low voltage and the required testing procedures.
VDE-AR-N 4105 – 2018 [38]	*Power Generating Plants Connected to the Low-voltage Network*: German interconnection standard for low-voltage interconnections.
VDE-AR-N 4110 – 2023 [39]	*Technical requirements for the connection and operation of customer installations to the medium-voltage network*: German interconnection standard for medium-voltage interconnections.
VDE-AR-N 4120 – 2018 [40]	*Technical Connection Rules for High Voltage*: German interconnection standard for high-voltage interconnections.

Further Reading: IREC: Decisions Options Matrix for IEEE 1547-2018 Adoption [41]; National Renewable Energy Laboratory (NREL): Interconnection of Distributed Energy Resources in the Indian Context: IEEE 1547-2018 Adaptation for Locally Appropriate Grid Code Development [5]; Advanced Inverter Interactions With Electric Grids [42]; NREL: IEEE 1547-2018 Resources [43]; NREL: Research Roadmap on Grid-Forming Inverters [44]

Table 2. Resource Guide: Equipment Testing and Certification

Equipment Testing and Certification	
ANSI/UL 1741 – 2023 [7]	*Inverters, Converters, Controllers, and Interconnection System Equipment for Use With Distributed Energy Resources*: A product safety standard covering the testing and certification of advanced inverters used for grid-connected systems as defined in IEEE 1547.
CAN/CSA C22.2 No. 107.1 – 2021 [45]	*Power Conversion Equipment*: Issued by the CSA Group and part of the Canadian Electrical Code, this provides testing and certification for power converters.
CAN/CSA 22.2 No. 330 – 2023 [46]	*Photovoltaic rapid shutdown systems*: Establishes provisions for rapid shutdown PV systems and is to be used in conjunction with CAN/CSA C22.2 No 107.1-2021.
IEC 62109 [47], [48], [49]	*Safety of power converters for use in photovoltaic power systems:* A multi-part international standard covering safe use of power converters with photovoltaics.
IEC 62116 – 2014 [50]	*Utility-interconnected Photovoltaic Inverters - Test Procedure of Islanding Prevention Measures*: Outlines testing procedures for anti-islanding performance for grid-connected PV systems.
IEC 62446 [51], [52], [53]	*Photovoltaic (PV) systems - Requirements for Testing, Documentation, and Maintenance*: A multi-part standard that defines the required information exchanges and documentation between the commissioning entity and the

Equipment Testing and Certification	
	customer for the installation of a grid-connected PV system as well as the necessary commissioning testing, inspection criteria, documentation, and maintenance to ensure a safe installation and sound interconnection.
IEC 61215 [54], [55]	*Terrestrial photovoltaic (PV) modules - Design qualification and type approval:* A two-part standard describing environmental stress tests and test procedures to assess whether a module can withstand prolonged outdoor exposure.
IEC 61730 – 2023 [56], [57]	*Photovoltaic (PV) module safety qualification:* A two-part standard that specifies the construction requirements and test requirements for PV modules to prevent electrical shock, fire hazards, and personal injury. UL 61730-1 [58] and UL 61730-2 [59] are harmonized with IEC 61730 but with slight differences for NEC compliance.
IEC 62477 [60], [61]	*Safety requirements for power electronic converter systems and equipment:* A two-part safety standard for power electronic converter systems and equipment with working voltages up to 1,500 VDC or 1,000 VAC, specifying requirements for protection against electric shock, energy-related hazards, fire, and mechanical and chemical hazards.
IEC 60068 [62], [63], [64]	*Environmental testing*: Multi-part standard to assess the environmental robustness of a wide variety of electronic equipment, including solar PV system components.
IEEE 1547.1 – 2020 [8]	*IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces*: Accompanying testing standard to IEEE 1547-2018 outlining the type, production, commissioning, and periodic tests to ensure interconnecting DERs are compliant with IEEE 1547-2018.
SunSpec CSIP [65], [66]	*The SunSpec Common Smart Inverter Profile (CSIP)*: A protocol and certification developed by the SunSpec Alliance in response to California Rule 21 (where it is listed as a requirement). It defines the communication interface for smart inverters to ensure compliance with grid interconnection requirements.
UL1699B – 2021 [67]	*Photovoltaic (PV) DC Arc-Fault Circuit Protection*: Used primarily in the United States, it sets guidelines for PV direct current (DC) arc-fault circuit protection. This standard is applied to evaluate the arc-fault detection and interruption capabilities of PV equipment. It addresses the safety concerns related to electrical fires by requiring arc-fault protection measures.

Table 3. Resource Guide: Interoperability and Cybersecurity

Interoperability and Cybersecurity	
ASHRAE 135 – 2020[1] [68]	*BACNET™ — A Data Communication Protocol for Building Automation and Control Networks*: Defines a building automation and control networking protocol for applications such as heating, ventilation, and air conditioning; fire safety; energy management; lighting; physical access; and elevators.
ASHRAE 201 – 2020[1] [69]	*Facility Smart Grid Information Model*: Provides an object-oriented information model to manage loads and generation in coordination with a utility smart grid.
EPRI Common File Format v 2.0 – 2022 [13]	*EPRI Common File Format v 2.0*: A file formatting guidance document, developed in alignment with IEEE 1547.1-2020, to standardize the exchange and formatting of DER configuration data and settings.
IEC 61850-7-420 – 2021 [70]	*Communication networks and systems for power utility automation - Part 7-420: Basic communication structure - Distributed energy resources and distribution automation logical nodes:* Provides DER information models to be used with the IEC 61850 communication protocol and distribution automation systems including full support of the advanced functionalities in IEEE 1547, EN 50549, and IEC 62786.
IEC 60870-5-101 – 2015[1] [71] **IEC 60870-5-104 – 2016[1] [72]**	*Telecontrol equipment and systems - Part 5-101: Transmission protocols - Companion standard for basic telecontrol tasks*: Provides the communication profile and interoperability for telecontrol communications sent between central telecontrol stations and distributed outstations for the automation of electric power systems. *Telecontrol equipment and systems - Part 5-104: Transmission protocols - Network access for IEC 60870-5-101 using standard transport profiles*: Expands upon 60870-5-101 to obtain network access using standard transport profiles. It is used for monitoring and controlling geographically dispersed processes.
IEC 61724 [73], [74], [75]	*Photovoltaic System Performance*: Multipart standard outlining the monitoring of PV system characteristics, including in-plane irradiance, system output, and the exchange and analysis of monitored data.
IEC 61968-5-2020[1] [76]	*Application integration at electric utilities - System interfaces for distribution management - Part 5: Distributed energy optimization*: Defines an interface architecture for power system management focusing on distribution management processes.
IEEE 1547.3 – 2023 [29]	*IEEE Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems*: Establishes protocols for communication between DERs and utility control systems, ensuring integration and coordination. In the context of DER applications, compliance with IEEE 1547.3 is essential for facilitating effective two-way communication, control, and monitoring between utility systems and DERs.
IEEE 2030.2 – 2015[1] [77]	*IEEE guide for the interoperability of energy storage systems with electric power infrastructure*: Framework for identifying and organizing interconnection information for energy storage systems, including functionality for frequency regulation, volt/VAR, renewable integration, substations, DER services, and microgrid implementation.

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[1] Detailed in 1547.3-2023 Annex C [29]

Interoperability and Cybersecurity	
LonTalk Stack[1] [78]	*LonTalk Stack*: Developed by Echelon Corporation to allow for the control networking interface from ISO/IEC 14908 to be added to any product with a microprocessor, microcontroller, or embedded processor.
NERC CIP[2] [79]	*Critical Infrastructure Protection*: Focused on the security of the bulk energy system. Given the potential bulk system implications from large aggregations of DERs, the standard is worth reviewing for DER cyber considerations.
NIST CSF – 2024[3] [80]	*NIST Cybersecurity Framework*: Cybersecurity policy framework to allow entities to identify their cyber assets, prevent and detect cyber events, and recover from those that occur.
OPC UA – 2008[1] [81]	*Open Platform Communications United Architecture*: Manufacturer-agnostic data exchange standard for machine-to-machine industrial automation communications.
OpenADR 2.0-3.0[1] [82]	*Open Automated Demand Response*: Optimization for demand response actions including load shedding, load shifting, and providing continuous dynamic price signals for use in demand response applications.
Open FMB - 2016[1] [83]	*Field Message Bus*: Developed by Duke Energy, Coalition of the Willing, and the NIST-led Smart Grid Interoperability Panel and ratified by the North American Energy Standards Board, this allows for grid edge interoperability and distributed intelligence by enabling node-to-node communications.

Further Reading: California Public Utilities Commission (PUC): Distributed Resource Plan [84]; NREL: Certification Procedures for Data and Communications Security of Distributed Energy Resources [85]; U.S. Department of Energy (DOE): GMLC Survey of Distributed Energy Resource Interconnection and Interoperability Standards [86]; Sandia: Cyber Security Primer for DER Vendors, Aggregators, and Grid Operators [87]; NREL: Distributed Energy Resource Cybersecurity Framework Best Practices [88]; DOE: Roadmap for Wind Cybersecurity [89]; Idaho National Laboratory: Cybersecurity Guide for Distributed Wind [90]

Table 4. Resource Guide: Interconnection Procedures

Interconnection Procedures	
FERC SGIA – 2023 [15]	*Small Generator Interconnection Application*: Outlines the contractual agreements and application materials for interconnecting generators under 20 MW.
FERC SGIP – 2023 [16]	*Small Generator Interconnection Procedures*: Outlines the technical screening procedures necessary for interconnecting generators under 20 MW.
IEEE 1547.7 – 2013 [32]	*IEEE Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection*: Provides criteria, scope, and extent for engineering studies of the impact of DERs on a distribution system.
IEEE 1547.9 – 2022 [33]	*IEEE Guide for Using IEEE Std 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems*: Provides additional guidance and considerations for interconnecting energy storage DERs beyond what is included within the IEEE 1547-2018 base standard.

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[2] Detailed in 1547.3-2023 Annex D [29]

[3] Detailed in 1547.3-2023 Annex E [29]

Interconnection Procedures	
IREC BATRIES Toolkit [91]	*BATRIES Toolkit - The Toolkit and Guidance for the Interconnection of Energy Storage and Solar-Plus-Storage*: Provides DER interconnection guidance specific to energy storage systems or solar-plus-storage systems.
IREC Model Interconnection Procedures – 2023 [17]	*Model Interconnection Procedures*: Provides additional screening guidance and incorporation of select advanced functionalities, flexible interconnection, and considerations for battery energy storage.
SAND2012-1365 [92]	*Suggested Guidelines for Assessment of Distributed Generation Unintentional Islanding Risk*: Sandia National Laboratories' guidance for evaluating the relative risk of an unintentional island formation based on a series of screens.

Further Reading: California PUC: Rule 21 [93]; Hawaiian Electric: Rule 14H [94]; IREC: Freeing the Grid [95]; New Mexico PRC: Rule 17.9.568 [96]

Table 5. Resource Guide: Advanced Forecasting, Planning, and DER Management

Advanced Forecasting, Planning, and DER Management	
DOE DSPx – 2020 [97], [98], [99], [100]	*Modern Distribution Grid*: A four-part series providing a holistic, transparent, multi-objective and performance-driven decision framework to inform investment decisions and grid modernization initiatives. The four parts address key functional requirements for future grids, technology maturity assessments to achieve those functional requirements, a decision guide for implementation of functionalities, and overall grid modernization strategy and implementation.
IEEE 2030.11-2021 [101]	*IEEE Guide for Distributed Energy Resources Management Systems (DERMS) Functional Specification*: Guidance document on the functional implementation of a DER management system, including interoperability requirements, transmission and distribution coordination, and communication and information infrastructure requirements.
NARUC Comprehensive Planning Library [102]	*NARUC Comprehensive Planning Library*: An online resource guide related to comprehensive electricity planning, including topics related to data access, ratemaking, distribution system planning, emerging distribution system planning practices, forecasting, grid modernization, planning coordination, planning criteria, procurement strategies, resilience, rural DER integration, scenario and risk analysis, solution evaluation, stakeholder engagement, and utility best practices for integrated planning.
PNNL Grid Architecture [103]	*Grid Architecture*: Provides a theoretical framework using a combination of system architecture, network theory, control engineering, and software architecture to conceptualize and manage a hyper-complex grid of the future.

Further Reading: U.S. DOE: Duke Energy's Integrated System and Operations Planning: A comparative analysis of integrated planning practices [104]; Xcel Energy: Integrated Distribution Plan [105]; Smart Electric Power Alliance: Integrated Distribution Planning: a Framework for the Future [106]; Grid Architecture: A Core Discipline for Grid Modernization [107]; NREL: Distribution Capacity Expansion Planning: Current Practice, Opportunities, and Decision Support [108]; International Renewable Energy Agency: Aggregators Innovation Landscape Brief [109]; NREL: A Primer on FERC Order No. 2222: Insights for International Power Systems [110]; DOE: The Pathway to Virtual Power Plants Commercial Liftoff [111]

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