SAND2026-21435PE

Virtual Webinar:

Distributed Wind Interconnection Standards (DWIS)

A Review of the Current Landscape of Distributed Wind Interconnection Standards

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Sandia Introduction

Previous DW Work at Sandia National Laboratories

Sandia National Laboratories has expertise, experience, and ongoing efforts in distributed wind energy interconnection topics.

Standards

- Participation in RAISE[1] (review of interconnection challenges for rural DW[2] generators)
- Leadership in IEEE 1547 standards working groups and ongoing revisions, including:
  - P1547[3], P1547.1[4], P1547.4[5]

Stakeholder Engagement

- Participation in annual DWEA[6] meeting
- Consistent communication with DWEA members

Equipment Performance Testing

- Commercial inverter performance testing
- PHIL[7] testing
- Development and testing of DERMS[8] controller utilizing RL[9]

[1] **RAISE:** Rural and Agricultural Income and Savings from Renewable Energy (USDA and DOE program);
[2] **DW:** distributed wind;
[3] **IEEE P1547:** Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces;
[4] **P1547.1:** Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces;
[5] **P1547.4:** Guide for Design, Operation, Integration and Interoperabililty of Intentional Electric Power Systems Islands;
[6] **DWEA:** Distributed Wind Energy Association;
[7] **PHIL:** power hardware-in-the-loop;
[8] **DERMS:** distributed energy resource management system;
[9] **RL:** reinforcement learning

Recently-Published Sandia Reports

https://doi.org/10.2172/3018760
https://doi.org/10.2172/3013880

Report Objectives:

A Review of Distributed Wind Interconnection Technology and Standards

- Describe unique technical characteristics of wind energy power converters
- Identify current challenges in complying with existing standards
- Propose recommendations for addressing challenges to improve DW project outcomes

Regulatory and Technical Challenges and Barriers to Adoption of Distributed Wind Energy in Agricultural Settings

- Contextualize the DW landscape in agricultural settings for the RAISE[1] initiative
- Highlight challenges, barriers to adoption, and opportunities for rural and agricultural DW development

[1] **RAISE:** Rural and Agricultural Income and Savings from Renewable Energy (USDA and DOE program)

Background

Motivation for DW Interconnection Standard Deep-Dive

- Authorities having jurisdiction over grid distribution infrastructure may adopt standard requirements
  - **IEEE 1547-2018:** *Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*
  - **IEEE 1547.1-2020:** *IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces*
  - **UL 1741 (and Supplement A and B):** *Standards for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources*
  - **UL 3141:** *Outline of Investigation for Power Control Systems*
- Designing and commercializing compliant/certified wind energy generator inverters can be **costly** and **time-consuming**
  - These challenges result in a perceived **market risk** and slowed development of wind turbine inverters that can be used for interconnected generation projects

The current regulatory and market landscape presents barriers for development of interconnected distributed wind projects.

Purpose of DER Interconnection and Interoperability Standards

- Standard performance specifications ensure that fielded DER equipment and system will operate and communicate as anticipated
- Involves inspecting “corner cases” that could lead to unexpected device behavior
- Serves multiple stakeholders:
  - Vendors can know their equipment will function as designed
  - Sets minimum technical capability and performance requirements for interconnection with the grid

Standardized performance and certification criteria can ensure **safe** and **consistent operation** of distributed energy resource systems **interconnected** with the main grid.

* **DER:** distributed energy resource

General Stakeholder Responsibility Framework for Interconnection Projects

Standards Publishers

- IEEE (e.g., IEEE 1547-2018, IEEE 1547.1-2020)
- UL (e.g., UL 1741 SA and SB)

- Develop standards for DER system and interconnection equipment performance
- Iterate on and update standards

Grid Infrastructure Owner-Operators

- Utilities (IOUs[3], co-operatives/co-ops, municipal utilities)

- Enforce regulations for equipment under their purview
- Ensure compliance of new interconnected DER projects with set regulations
- Provide feedback to regulatory agencies

Regulatory Agencies

- Federal (e.g., FERC[1])
- State (e.g., PUCs[2])
- Municipal
- Co-operative boards

- Adopt standards as regulation
- Enforce regulation
- Delegate regulation enforcement to grid infrastructure owner-operators
- Address feedback from stakeholders through regulation updates as necessary

DW Industry

- Product manufacturers and OEMs[5] (e.g., Bergey, Foundation Windpower)
- DW project developers

- Ensure compliance of products with relevant performance and certification standards
- Provide feedback to regulatory agencies, standards publishers, and grid infrastructure owner-operators

[1] **FERC:** Federal Energy Regulatory Commission
[2] **PUC:** Public Utilities Commission
[3] **IOU:** investor-owned utility
[4] **SMJU:** small and multi-jurisdictional utilities
[5] **OEM:** original equipment manufacturer

IEEE 1547 Standard Series

IEEE 1547-2018:

- Specifies standard capabilities of DER systems
- Allowable **voltage** and **frequency** ranges for entering service
- Reactive and active **power control**
- Parameter limits for **synchronization**
- **Unintentional islanding** protection
  - System must detect UI formation and trip within 2 seconds

IEEE 1547.1-2020:

- Provides specific test procedures and methods to meet performance requirements in IEEE 1547-2018
  - E.g., test methods and circuit configurations for voltage and frequency trip confirmation
- **Type tests**: testing for functionality
- **Production tests**: testing for consistency in manufacturing of products
- **Commissioning tests**: testing for correct installation, configuration, and interaction of DER unit and interconnected equipment with the grid
- **Periodic interconnection tests**: repeating parts of commissioning tests as part of ongoing monitoring

The IEEE 1547 series contains performance criteria and tests for **interconnected** and **interoperated** DER systems.

UL 1741 Standard

- Supplements IEEE 1547
  - Adds detail to test methods and procedures in IEEE 1547
  - Includes **certification** for interconnection devices to achieve DER system standards prescribed in IEEE 1547
- Included topics:
  - Physical and electrical construction
  - Performance requirements and testing
  - Rating
  - Manufacturing tests
  - Production tests
- Applicable equipment includes:
  - Generic inverters/converters
  - Charge controllers
  - AC modules and PV modules with integrated electronics
  - Rapid shutdown equipment
  - Interconnection equipment for rotating generation

UL 1741 supplements and provides detail for the IEEE 1547 tests.

The UL 1741 **certification** for **interconnection devices** allows **tested devices** to achieve criteria set in the IEEE 1547 standards.

UL 1741 Supplements

Supplement A

- Published in 2016 after UL 1741 Edition 1 publication
- Contains **performance tests** for various capabilities
  - Anti-islanding and UI protection
  - Low and high voltage ride-through
  - Low and high frequency ride-through
  - Normal and soft start ramp rate
  - Volt-var mode

Supplement B

- Published in 2021 with UL 1741 Edition 3 publication
- Contains updated type tests and **advanced grid functionality**
  - Temperature stability
  - Response to voltage or frequency disturbances
  - Voltage phase-angle change ride-through test
  - Interconnection integrity tests
  - Unintentional islanding confirmation
  - Voltage regulation
  - Frequency support
  - Prioritization of DER response
  - Limitation of overvoltage contribution
  - Interoperability tests

Practical Application of Standards to DW

AHJs[1] can adopt compliance of standards as requirements for DER developers intending to interconnect projects to the distribution grid.

California Public Utilities Commission developed **California Rule 21** (Interconnection Tariff):

Technology-Agnostic

Generally applies to DERs

Generic

Provides general requirements for IOUs to adapt and specify for their own systems

Examples of Included Requirements:

Device Capability Requirements

Encourages (but does not require) replacement of already installed non-smart inverters at end-of-life with smart inverters

Requirements for new inverters continue to be updated in accordance with standards publications

- Before 2016: Inverters needed to be IEEE 1547-compliant
- 2016-2022: Inverters needed to be "smart" and UL 1741 SA-certified
- After 2022: Inverters need to be "smart" and UL 1741 SB-certified

Affordability Considerations

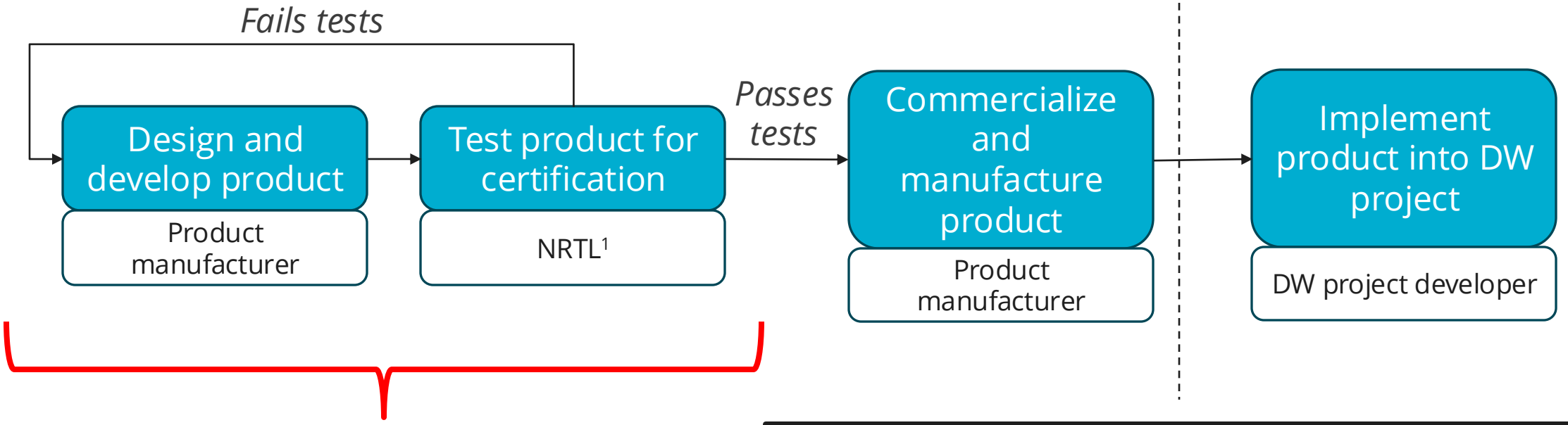
Initiated efforts like cost envelope studies across utilities to improve feasibility and affordability of interconnection projects

Transparency Improvements

Required utilities to host workshops for current and prospective interconnection customers to understand application processes

[1] **AHJ:** authorities having jurisdiction

Process for Developing and Commercializing a DER Inverter or Converter



Bottleneck created by costly and time-consuming testing process →

Manufacturers often end up:

1) Focusing on more currently financially viable options
   - E.g., solar products
2) Not having resources to pursue DW product commercialization
   - E.g., infrastructure, personnel, financial ability

[1] **NRTL:** Nationally Recognized Testing Laboratory

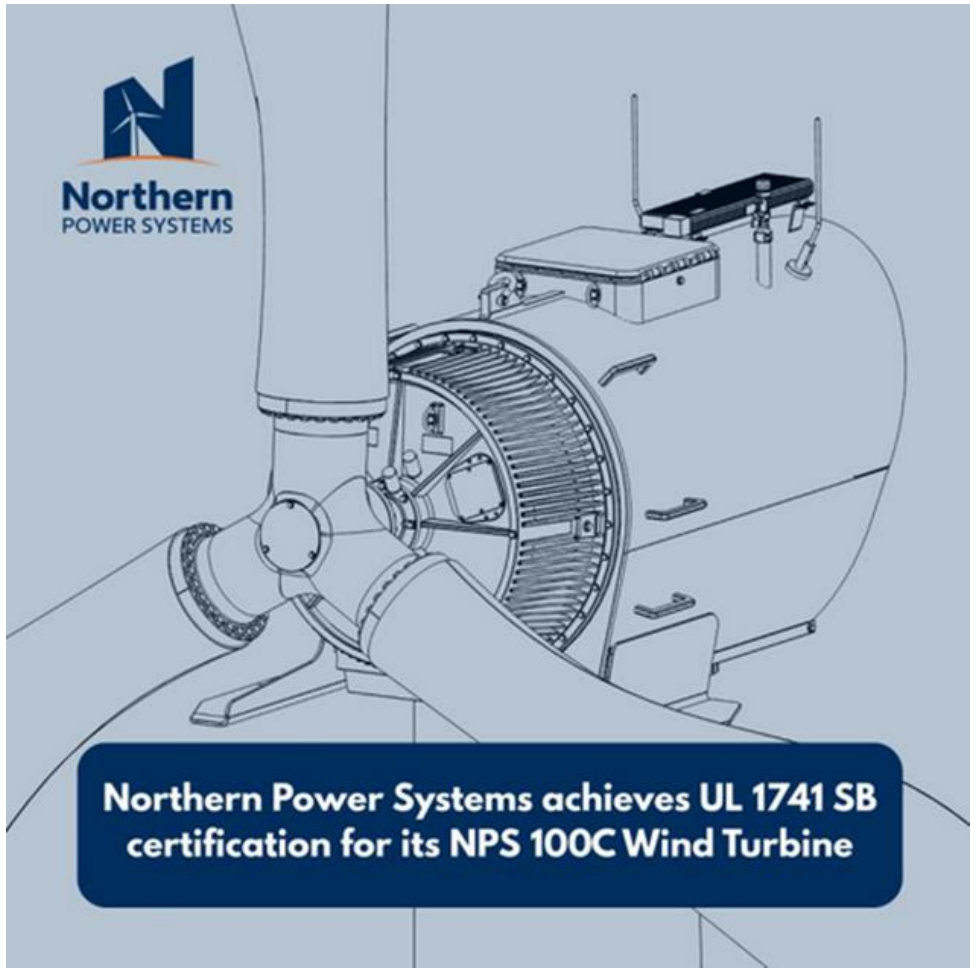
Example of Previously Commercial Certified Wind Turbine Inverter

SMA America Windy Boy 5000-US, 6000-US, 7000-US, 8000-US

- UL 1741 certified at the time of availability (2003-2013)
  - Not necessarily certified with current or future versions of standards
- Operated over a range of voltages (208–277 V)
- Served a range of DC power inputs (5.3–8.6 kW) and with a range of AC power outputs (50–80 kW)
- **Not manufactured or sold anymore**
  - DW is more expensive than solar, so solar is currently a generally more financially viable option
  - SMA discontinued this product and exited the small wind energy market to pursue more profitable industries

Ongoing DW Interconnection Device Development and Certification Activities

Northern Power Systems obtained UL 1741 SB certification for the NPS 100C wind turbine power converter on February 3, 2026.



Current Challenges and Efforts

Engagement and Outreach Efforts

We interviewed industry stakeholders* at the 2025 Distributed Wind Energy Association (DWEA) meeting to understand pain points associated with interconnected DW project development.

- DWEA
- Bergey Windpower Co.
- Northern Power Systems
- Buffalo Renewables Inc.
- Windurance
- Matric Group
- RE Innovations
- Xflow Energy

1. What are the main challenges you face in your distributed wind products or research?
2. What distributed wind energy technologies are most important to enabling safe and reliable growth of distributed wind interconnection with other DERS and electric power systems?
3. What research opportunities are there to better integrate distributed wind with battery storage and PV solar?
4. What parts of the IEEE 1547 and 1547.1 standards are difficult to meet or add significant cost to your product?
5. What recommendations would you make for improving the IEEE 1547 and 1547.1 standards to better accommodate distributed wind energy systems?

* Understanding perspectives of other stakeholders (e.g., utilities, regulators) will be prioritized in future work.

Stakeholder Feedback Highlights

1. Developing wind energy generator interconnection devices compliant with technology-agnostic standards can be **technically difficult**

2. One major barrier is achieving compliance with IEEE 1547 and UL 1741 standards **increases costs** of new products, sometimes prohibitively for the manufacturer and/or DW project developers

3. DW manufacturers perceive a **market risk** from these factors, slowing development and commercialization of compliant devices

Potential Technical Challenges for DW Interconnection Devices In Achieving Performance Standards

- Wind turbines have variable active and reactive power because of the characteristics of wind
  - Generally difficult to maintain control over setpoints (e.g., power, voltage)
- Wind energy systems have high inertia
  - Meeting interconnection requirements for rapid power adjustment adds cost and complexity to the DW interconnection system
    - E.g., for under/over voltage and frequency scenarios
  - Established power ramp rate requirements may necessitate specific control capabilities
- In some cases, an isolated device may pass some UL 1741 tests that a field-installed DW system may fail
  - E.g., voltage-active power modes
- IEEE 1547.1 explicitly refers to some devices:
  - Distributed wind
  - Induction machines
  - Double-fed induction machines
  - In some cases, requirements for induction machines are the same as synchronous machines – may lead to technical challenges

Regulatory and Economic Challenges of DW Interconnection

Barriers to market entry for certified wind turbine power converter devices:

Costly

- Several hundred thousand dollars
- Wind energy interconnection devices tend to be more expensive than their solar counterparts

Time-Consuming

- Long turnaround times (3-6 months)

Outsourced

- There are not currently sufficient testing platforms for manufacturers to conduct in-house testing before officially applying for certification

Small Market Size

- Chicken-and-egg issue → market and investment/support are small

Impacts on DW device manufacturers:

Small Manufacturers

May not have the resources (time, money, personnel) to support certification process

Large Manufacturers

May prefer to pursue more profitable products/industries

E.g., SMA America discontinued its (then-certified) Windy Boy™ inverter to focus on solar inverters

There are no commercially available wind inverters that are certified to the current UL 1741 SB standard.

Proposed Paths Forward

Proposed Paths Forward for Removing Barriers to Adoption (1)

Responsible Stakeholder	Potential Actions	Remarks
Standards publishers (IEEE, UL)	• Clarify practical application of existing standards to DW systems (e.g., if certified solar inverters have a streamlined/accelerated certification process for use with wind energy systems) • Codify exemptions from specific standard criteria for small DW projects (e.g., in an addition UL 1741 supplement or a distinct standard)	• Standards publishers would need ample evidence showing that wind energy systems would interconnect and interoperate as "good citizens of the grid" without the current requirements and certifications
AHJs (regulators, utilities)	• Provide guidance and research support (e.g., working groups) to address DW interconnection pain points • Require previous standards and adopt UL 1741 SB standards for wind once the wind energy power electronics market catches up to the current requirements • Explore and allow alternatives to specifically costly requirements (e.g., PG&E DTT requirement) • Offer non-technical solutions (e.g., insurance as an anti-islanding mitigation)	• AHJs and grid infrastructure owner-operators would potentially not be motivated to make requirements less strict or less updated from the already-adopted requirements • AHJs likely have electrical reliability, safety, and risk (e.g., financial) as priorities

Proposed Paths Forward for Removing Barriers to Adoption (2)

Responsible Stakeholder	Potential Actions	Remarks
Research institutions (national laboratories, private companies)	• Understand holistic landscape and stakeholder perspectives for DW interconnection (e.g., specific tests that are challenging to pass, and reasons for test failures) • Provide services for testing commercial power electronics equipment to IEEE 1547 and UL 1741 criteria • Develop and refine testing platforms so manufacturers can conduct in-house testing and iteration before undergoing the certification process	• Research institutions may have more bandwidth than other stakeholders to complete this work, especially with sponsor (e.g., Department of Energy) support • Research institutions are responsible for providing unbiased recommendations to facilitate advancement of DW interconnection
DW industry stakeholders (turbine and electronics developers, testers, integrators, maintainers)	• Work with standards publishers, AHJs, and research institutions to communicate barriers to DW interconnection • Conduct research as able (e.g., use of wind energy inputs with solar-certified inverters)	• DW industry stakeholders have time, money, and personnel/effort constraints • DW industry stakeholders likely prioritize economic opportunity of product development and commercialization

Ongoing and Planned Efforts

Ongoing Efforts Related to California Rule 21 Unintentional Islanding Requirements

CPUC requires UI[1] protection through Rule 21.

Utilities implement the requirement in their own Rule 21 tariffs.

Example:
PG&E requires ROI[2] study

Systems that fail the study must install DTT[3]

ROI and DTT is often **prohibitively costly** for project developers

Recent and Ongoing Efforts by CPUC to Address Concerns of DW Industry

UIWG[4]

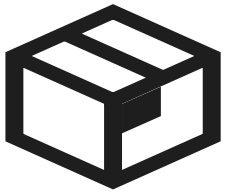
- Established by CPUC[5] in 2021
- Published final report in 2023 with findings
  - Included initial research into potential **DTT alternatives**

Rule 21 Proceeding R.25-08-004

- Opened in August 2025
- DW developers (e.g., DWEA[6] members) expressed ongoing challenges
  - DTT requirements for UI mitigation are costly
  - UL 1741 SB certification rule requires development of **bespoke wind energy inverters** (**costly and time-consuming**)

[1] **UI:** unintentional islanding
[2] **ROI:** Risk of Islanding
[3] **DTT:** direct transfer trip
[4] **UIWG:** Unintentional Islanding Working Group
[5] **CPUC:** California Public Utilities Commission
[6] **DWEA:** Distributed Wind Energy Association

Ongoing Research Efforts Supporting DW Interconnection and Interoperability



Product Testing

- Sandia conducts PHIL[1] testing of inverters in DETL[2]

Testing Platform Development

- **SVP**[3]: open-source, Sandia-developed tool for PHIL testing
  - *Well-developed for solar systems*
  - *Testing platform for wind energy is ongoing*
- **LabTest**: commercially available, DER Security Corp-developed tool for IEEE 1547 and UL 1741 SB testing
- *Recently (early 2025) updated to certify wind energy systems to UL 1741 SB*

Regulatory Landscape Review

- Sandia reviews IEEE 1547 and UL 1741 standards, focusing on pain points in DW
  - Future work will incorporate utility and regulator perspectives
  - Sandia will continue to be in contact with DW industry stakeholders (e.g., DWEA)

[1] **PHIL:** power hardware-in-the-loop
[2] **DETL:** Distributed Energy Technology Laboratory
[3] **SVP:** System Validation Platform

Planned Sandia Efforts

- Stakeholder engagement with **utilities** and **regulators**
  - Focus on needs and challenges from multiple stakeholder perspectives
- Review and comparison of individual state-level regulatory structures regarding DW and IEEE 1547-2018 adoption
  - California, Texas, Oklahoma, Michigan, Alaska, potentially New York and Massachusetts
    - Covering multiple regions of the country, statuses of IEEE 1547-2018 adoption, and current total installed DW capacities
- Review of international standards, including:
  - IEC 61400: Wind Turbine Generator Systems
  - IEC 61850: Communication Networks & Systems for Power Utility Automation
  - IEC 62351: Power Systems Management and Associated Information Exchange
  - IEC TS 62786: Distributed Energy Resources Connection with the Grid

Conclusions

Conclusions

DW projects may be stalled or rejected because of the use of interconnection equipment not compliant/certified to IEEE 1547-2018, IEEE.1-2020, UL 1741 SB.

Many DW product manufacturers find development of certified products to be prohibitively costly, time-consuming, and fast-paced.

Engagement from a combination of stakeholders can provide opportunities to promote improved DW product commercialization and DW implementation outcomes.

Thank You

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Additional Slides

Resources

Referenced Standards

- “IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.” Institute of Electrical and Electronics Engineers, Apr. 06, 2018. [Online]. Available: https://standards.ieee.org/ieee/1547/5915/
- "IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces.” IEEE 1547.1-2020, May 21, 2020. Accessed: Nov. 12, 2025. [Online]. Available: https://standards.ieee.org/ieee/1547.1/6039/
- “Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources.” Underwriters’ Laboratories, Oct. 23, 2024. [Online]. Available: https://www.shopulstandards.com/ProductDetail.aspx?productId=UL1741_3_S_20210928

Past Sandia Research

- S. R. Kamala, J. Choi, and R. Darbali-Zamora, “Unintentional Islanding Detection for Type-I Wind Turbine Generators Using Feeder Protection Relays: A Hardware-in-the-Loop Test,” in 2024 56th North American Power Symposium (NAPS), Oct. 2024, pp. 1–6. doi: 10.1109/NAPS61145.2024.10741658
- R. Darbali-Zamora, J. Johnson, N. S. Gurule, M. J. Reno, N. Ninad, and E. Apablaza-Arancibia, “Evaluation of Photovoltaic Inverters Under Balanced and Unbalanced Voltage Phase Angle Jump Conditions,” in 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), Aug. 2020, pp. 1562–1569. doi: 10.1109/PVSC45281.2020.9300604
- M. S. Louie and R. Darbali-Zamora, “Regulatory and Technical Challenges and Barriers to Adoption of Distributed Wind Energy in Agricultural Settings,” Sandia National Laboratories, Publication in Progress.

Tools

- DER Security Corp LabTest tool webpage: https://dersec.io/dersec-labtest/
- Sandia Resilient Energy and Distributed Systems Integration tools webpage: https://energy.sandia.gov/programs/electric-grid/resilient-energy-and-distributed-systems-integration/

Timeline for Rollout of IEEE 1547-2018 Compliant DER