EPRI

TECHNICAL BRIEF

Offshore Wind Black-Start Feasibility Framework for System Restoration Planning

LIST OF ACRONYMS

BESS	Battery Energy Storage System
CVOW	Coastal Virginia Offshore Wind
EMT	Electromagnetic transient
F/P	frequency droop control
GFL	Grid following inverter
GFM	Grid Forming inverters
GW	Gigawatts
HIL	Hardware in the Loop
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
MW	Megawatts
NERC	North American Electric Reliability Corporation
PM	Permanent Magnet
POI	Point of Interconnection
RMS	root mean square
STATCOM	static synchronous compensator
V/Q	the voltage droop control

EXECUTIVE SUMMARY

This report emphasizes the importance of adapting black-start and restoration strategies to accommodate the evolving generation mix, particularly with the integration of large offshore wind farms. These wind farms, with their high-capacity factors, are seen as potential candidates for providing restoration services in future power systems dominated by inverter-based resources. The literature review highlights the requirements for black-start resources, including self-start capability, voltage and frequency maintenance, and fault current contribution. It also discusses the challenges and potential solutions for integrating offshore wind farms into black-start plans, such as the use of grid forming inverters and soft-energization techniques.

Dominion Energy's black-start restoration plan, developed in collaboration with PJM Interconnection and adjacent utilities, is detailed next. The plan includes multiple restoration paths involving black start generating units, cranking paths, and critical loads. The objective is to form core islands

ACKNOWLEDGMENTS

This material is based upon work supported by the National Offshore Wind Research and Development Consortium ("Consortium") Massachussets, Maryland and New Jersey Neither the Consortium or the Funders, nor any of their directors, officers or employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Consortium or the Funders. The Consortium and the Funders have not reviewed this report and the views and opinions of authors expressed herein do not necessarily state or reflect those of the Consortium or the Funders. This material is based upon work supported by the National Offshore Wind Research and Development Consortium, under award titled - Offshore Wind Black-Start Feasibility Framework for System Restoration Planning, under agreement number 303.

that can be synchronized to restore the power system. The research will also identify key metrics and parameters for black-start, which will be used to develop a generalized framework for integrating the Coastal Virginia Offshore Wind (CVOW) project into existing restoration paths.

The data gathering and model development section describes the collection of system and generic model data, including wind turbine models, electrical infrastructure, and control systems for inverters. It also covers HVDC system modeling and the onshore transmission system model for Dominion Energy. The study methodologies and analysis section outline the development of study scenarios and performance evaluation criteria. These scenarios will assess the offshore wind farm's ability to meet real and reactive power requirements, maintain stability, and ride through voltage and frequency events during the restoration process.

Finally, the report details the performance metrics to be developed based on the study scenarios. These include system strength metrics, real and reactive power capability, dynamic reserve, steady state voltage level, frequency regulation, system stability, transient and low order harmonic resonant overvoltages, inrush current, and protection adequacy. The technical approach and assumptions section discusses the assumptions for wind farm availability, HVDC system operation, and onshore grid conditions. The report concludes with a description of the RMS, EMT, and HIL studies to be performed for black-start analysis and cranking path evaluations, as well as the analysis of study results.

INTRODUCTION

This work entails the development of a generalized black-start framework which can be used on a system-wide basis in identifying the areas of the network that are most suitable for restoration with offshore wind under a range of different operational and contingency scenarios. This project intends to validate the methods by performing the detailed black start engineering studies with the reference system being the Coastal Virginia Offshore Wind (CVOW) commercial site and associated onshore transmission network. Further, it is envisaged that part of the core outputs of this project will identify advanced inverter control (e.g. grid forming) strategies needed to integrate the offshore wind farm in restoration plans including providing black-start services and develop easy to use metrics for system operators to use during restoration activities involving offshore wind.

The goal of this inception report is to establish a comprehensive basis for conducting the analysis and set clear expectations for all stakeholders involved. This report summarizes the background work related to black-start, wind turbine controls, and current practices related to system restoration. It identifies key system components involved in black-start operations and determines the boundaries of the study in terms of geographical area and interconnected systems. It further describes the transmission system to offshore wind farm interconnection study area, as well as the key metrics for black starting. An outline of data requirements and sources, and an explanation of the analytical approaches to be employed for the engineering studies are discussed. This report presents the proposed methodology for conducting the studies, outlining the scenarios to be analyzed. The technical approaches and metrics for success criteria to the engineering studies are further enumerated.

LITERATURE REVIEW

Black-Start Review

To maintain credible black-start and restoration strategies that deliver resilience with high likelihood of restoring normal operations quickly after widespread outages, the plans must be adapted to keep up with the pace of changes in generation mix. With many large offshore wind farms are becoming operational across the world, these installations have recorded reasonable capacity factors that may qualify them to be considered as candidates for delivering restoration services for power systems with high penetration of inverter-based resources.

During black-start and system restoration, generation resources are required to swiftly self-start, energize transmission network, provide offsite supplies to critical transmission connected customers with either special safety requirements or are vital for the modern society, startup other generation resources required to develop restoration islands, and build up the system recovery through restoration island resynchronization. To enable such capability, the resources must be able to energize large transmission elements, maintain the key electrical parameters like voltage and frequency within certain ranges whilst energizing large blocks of load. Other less obvious requirements include fault current contribution to maintain protection adequacy, development of a sufficiently stiff island to maintain power quality and limit unwanted interactions.

Wind Turbine, Grid Forming Inverters, Controls

Offshore wind farms have large installed capacities and high availability factors giving them an advantage over other renewable resources like PV and onshore wind farm installations. However, offshore wind farm interconnections with the bulk transmission grid tend to be more complex, making their integration in black-start and early restoration plans challenging.

At the time of writing, no wind turbine OEM offers a black-start capable solution as part of their commercial portfolio. However, extensive testing has been performed, including successful live demonstration trials that involved startup of onshore wind farms without offsite supplies provided, energization of large transformers and high voltage transmission circuits, load pickup and synchronization with the rest of the transmission system. The type of onshore wind turbines involved in the testing share similar characteristics with the large wind turbine generators utilized for offshore wind farm installations. The grid forming version successfully tested is referred to as Virtual Synchronous Machine, but several alternative grid forming algorithms are possible and have been tested for other inverter-based resources like battery energy storage systems.

The proposed offshore wind turbine start-up involves utilization of an uninterruptible power supply type of solution housed in the nacelle that allows the wind turbine generators to start, harvest the power from the wind, and idle while awaiting for additional load. Alternative solutions could include centralized supplies housed on the offshore platform or even at the onshore substation.

The main challenges for offshore installations are the size and the complexity of the offshore transmission networks, which include long inter-array cabling networks, transmission export cabling and large power transformers. These can introduce concerns related to the capability of the offshore wind turbines to develop a sufficiently stiff island that allows direct energization of the offshore transmission system critical elements.

An alternative approach that aims to limit energization switching transients could employ soft-energization techniques to gradually build up the voltage across a period of time. But this will require a specific design with interlocking that allows the offshore system internal system to be switched in a certain configuration and protection functions and settings that are not preventing such energization approach whilst still protecting the assets. Further, this requires a controlled ramp up of voltage/frequency from the turbine level controls. Special consideration must be given to potential resonant conditions developed in certain configurations that combine extensive networks of cables, power transformers and very limited to no load.

Grid forming controls that would allow for self-start and energization of transmission circuits are now available from OEMs. However, these controls also depend on having an energy source being present. While these controls are available for small signal response and characteristics, there are still quite a bit of research to be done for ensure suitable response during faults.

Current Practices and Standards Related to Black-Start

The existing black-start and restoration plans of utilities do not rely on initial contribution from wind farms, or any other inverter-based resources. Some entities will consider integrating support from wind farms once stable islands are developed whilst more risk averse utilities will only return wind farms to service when the power system reverts to normal operation. The traditional black-start and restoration strategies are expected to be challenged in areas where the plans are reliant on thermal power plants planned to be decommissioned in the near future.

Regulators and utilities around the world have established restoration standards that set how much load and how fast should it be restored at certain stages during restoration. Some are legally binding, others are setting the expectations and intended to define the targets the system operators should work against when determining the number of capable resources to be procured and how these should be geographically distributed.

SYSTEM STUDY OVERVIEW

The Coastal Virginia Offshore Wind (CVOW) project is an offshore wind energy initiative designed to deliver clean, renewable energy for Virginia. The project will consist of 176 Siemens Gamesa 14-222 DD wind turbines, each with a capacity of up to 15 MW, yielding a total project capacity of 2.64 GW. The electric energy converted from wind will be transmitted to three offshore collector substations via the 66 kV inter-array cables with a total length of up to 300 miles and each offshore collector substation will have a capacity of 880 MW.

At the offshore substation, the power generated by the wind turbine generators will be transformed to 230 kV before transmitting to the onshore electricity infrastructure. Each offshore substation will contain three main transformers and four auxiliary transformers for other facilities such as heating and ventilation systems, low voltage distribution, diesel generators, etc. Three 3-core aluminum-conductor 230 kV subsea cables with lengths between 60 and 80 km will be used to transmit the power from each of the three offshore substations to the cable landing location in Virginia Beach and the complete project will have a total of nine subsea export cables.

Power will be transmitted from the cable landing location to a switching station south of Harpers Road or Princess Anne Road, in Virginia Beach via the onshore export cables which will comprise of 27 single-phase 230 kV cables buried underground within a dedicated cable route. The onshore switching station would serve as a transition point where the power transmitted through twenty-seven 230-kV onshore export cables coming from the cable landing location would be collected to three 230-kV interconnection overhead lines that connect to the expanded onshore substation at Fentress, to be finally stepped up to 500 kV.

Figure 1. Illustration showing the proposed location of the Costal Virginia Offshore Wind (CVOW) offshore wind farm (Ref. https://coastalvawind.com/about-offshore-wind/delivering-wind-power.aspx)

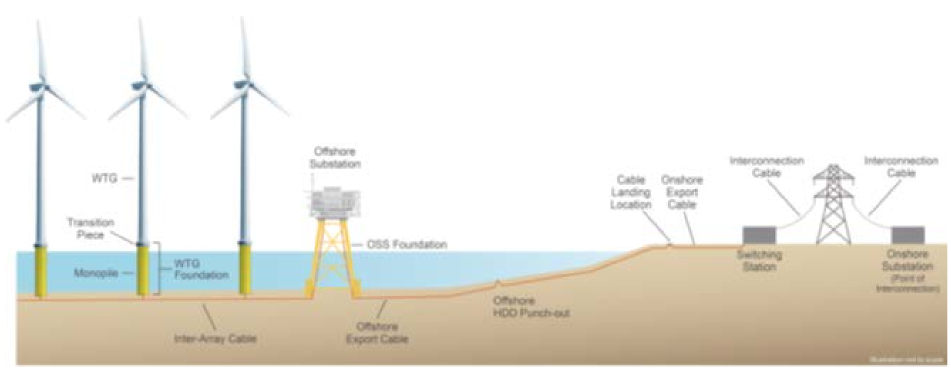

Figure 2. A simplified diagram showing the transmission interface connection to the planned offshore wind farm

The Dominion Energy's electricity transmission network includes approximately 6,600 miles of transmission lines operating at various voltage levels including 500 kV, 230 kV, 138 kV, 115 kV and 69 kV.

Overview of Dominion Energy Black-Start Restoration Approaches

Dominion Energy's black-start restoration plan is developed in cooperation with PJM Interconnection and adjacent utilities, ensuring compliance with NERC's system restoration standards. A black start restoration plan usually includes several restoration paths that involve black start generating units, designated cranking paths, and various critical loads. Black start units are required to perform a self-start from onsite fuel/energy reserve to establish and maintain the required voltage and frequency, after which it will proceed to energize the designated cranking paths to reach other major power plants, with the aim of forming a core island of generation and load. Figure 2 shows the major restoration paths in Dominion Energy's system restoration path. There are two primary paths to the nuclear power plants in the region and additional cranking paths are energized to start up other large power stations. After these paths are energized, three core islands will be established. The final synchronization is performed between the islands after successful establishment of each core island. After synchronization, the energization of other power plants, loads, and transmission network will support the energization of additional interconnections.

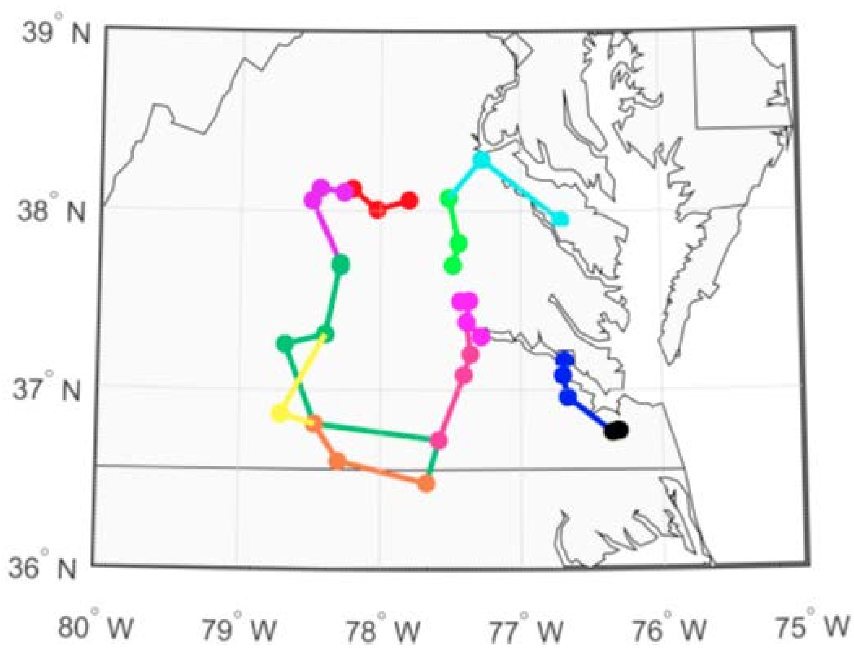

Figure 3. *An illustration of the cranking paths and core islands, where the CVOW project will be connected near the southeast core island indicated in black and blue.*

Ref. Y. Wang, H. Chou, R. Sun, W. Ju, C. Mishra and K. Thomas, "Dynamic study of Dominion's system restoration plan in RTDS," 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2019, pp. 1-5, doi: 10.1109/ISGT.2019.8791601

Identification of Key Metrics and Parameters for Black-Start

Models of Dominion Energy's transmission network and the CVOW wind farm will be utilized to run studies required to develop planning and operational strategies to integrate the offshore wind farm in existing restoration paths. Based on the studies conducted, key metrics and parameters will be identified which will be included in the generalized framework that can be used on a system wide level to identify the optimal restoration objectives that the offshore wind farm can support in a given point-of-connection (POI). Key metrics such as voltage transient levels and recovery durations to be allowed upon pick up of load would be considered. Other metrics include frequency recovery criteria, and fault withstand capability.

Data Gathering and Model Development

Below is a summary of the system and generic model data collection, model development and requirements for various study types.

Wind Turbine Models

Wind turbine model used for the EMT study will be based on the generic model available from a software vendor (PSCAD) which has been modified to include grid forming capability. The model is based on Type-4 wind turbine generator and it consists of both the mechanical and electrical system to simulate fundamental wind turbine behavior. The mechanical system models the wind turbine and the pitch angle controller, essentially converting the wind speed input into mechanical power input (mechanical torque) that feeds into a permanent magnet (PM) machine.

The electrical system models the permanent magnet machine and the AC-DC-AC conversion:

1. Grid-side converter and controls
2. Machine-side converter and controls
3. DC-link chopper protection
4. Low pass filters
5. Transformer
6. Scaling component

Two types of converter models are available, i.e. the detailed 'switch level' model and the average model. The model detail will be adjusted based on specific study objectives to ensure the model is sufficient.

The machine-side controller will monitor and control DC voltage and the AC voltage at the terminal of the PM machine. The grid-side controller will control the active and reactive power through the frequency droop control (F/P) and the voltage droop control (V/Q), respectively.

Electrical Infrastructure

The model of offshore wind farm, collection system, and offshore substation will be developed. If detailed information is not available for the project, typical generic parameters will be derived from public information to develop the 66 kV inter-array cabling system, taking into account the number of WTG per string and representative layouts already in operation for similar installations.

Similarly, the offshore power transformers will be represented taking into consideration technology limitations, thermal limits, fault level at the 66 kV side, and typical solutions utilized on similar offshore wind installations.

A preliminary discussion with Dominion or assessment will be conducted to determine the size of the offshore shunt reactor units required given the amount of 230 kV export cabling and landfall conditions.

The type of 230 kV export cables will be either obtain from Dominion if available, otherwise the cable type and cross-sectional area can be estimated for typical seabed conditions, cable length, reactive compensation scheme, and the power transfer required.

Onshore Transmission System Model for Dominion Energy

The onshore substation is an expansion of the existing Fentress Substation and will generally comprise the main power transformer units, static and dynamic reactive compensation devices, and harmonic filtering solutions. The design of these key components is determined by the local system conditions, size of the offshore wind farm, and the performance specifications set by the onshore transmission entity tasked to evaluate the grid compliance. The onshore substation is located roughly 25 km from the offshore cable landing point and the interconnection between the two is a mix of single core underground cables and overhead transmission lines that will be modelled accordingly.

Study Methodologies and Analysis

Scenario Development and Performance Evaluation Criteria

Study scenarios will be further refined and expanded based on the network restoration paths feasible for the project. Study scenarios shall be developed to evaluate the following criteria:

- Can the offshore wind farm meet the real and reactive power requirement throughout the restoration process?
- Can the offshore wind farm maintain stable operation throughout the restoration process?
- Can the offshore wind farm ride through voltage and frequency events during the restoration process?
- Are there any transient and temporary overvoltages generated due to the restoration process that may jeopardize the restoration process or cause potential negative impact to the plant or the transmission network?
- Can the offshore wind farm and the transmission network protect itself in the event of a fault?
- Can the offshore wind farm pick up any critical loads along the cranking paths?
- Can the offshore wind farm start up and supply power to the auxiliary loads required for the next available power plant?
- Can the offshore wind farm maintain stability while operating with the next available power plant?
- Can the power island that has been started up from the offshore wind farm synchronize with another power island?

The following initial scenarios/contingencies will be considered for the steady state and dynamic analysis:

- Black-start restoration with the Grid Forming (GFM) wind farm at 100% available capacity.
- Black-start restoration with the Grid Forming (GFM) wind farm at 66% (two-third) available capacity.
- Black-start restoration with the Grid Forming (GFM) wind farm at 33% (one third) available capacity.
- Load pick-up along the cranking paths.
- Loss of the largest generator once a power island is formed.
- Fault on the power island resulting in network separation.
- Synchronization of two power islands – One power island started off from the wind farm and the other started off from the next available black start unit in the network.
- Black start restoration with Grid following (GFL) wind farm and a Grid Forming (GFM) energy storage system.

The following energization steps shall be considered for the EMT analysis:

- Energization of 66/230 kV step-up transformers at the offshore substation.
- Energization of 230 kV offshore subsea cables and onshore export cables.
- Energization of the shunt reactors and main power transformers at the onshore switching station.
- Energization of 230 kV overhead lines/cables to reach the onshore substation (POI) at Fentress.
- Energization of 230/500 kV transformers at the onshore substation.
- Line energization along the cranking path.
- Transformer energization along the cranking path.
- Largest load pick-up along the cranking path.
- Largest auxiliary load pick-up at the next big power plant.

Performance Metrics

Based on the study scenarios developed together with the black start restoration paths, the following performance metrics shall be developed:

- System strength metrics – This will be developed using the Grid Strength Assessment Tool (GSAT) and an index developed by EPRI to identify potential converter control interactions and oscillatory issues in a low short-circuit environment.

- Real and reactive power capability – The minimum real and reactive power requirements for the black start restoration process will be determined. These shall not exceed the wind farm steady state and transient stability capabilities.
- Dynamic reserve – The wind farm shall have enough dynamic reserve to allow system to survive the loss of the largest energy contingency for the following two conditions:
  - With the full cranking path energized before reaching the next available power plant.
  - After forming the power island with another power plant.
- Steady state voltage level – The offshore wind farm ability to regulate the voltage at the POI to within the acceptable operating limits for each energization step. The steady state voltages along the cranking paths will be determined along with the voltage step increase for each energization step. These shall be maintained within the steady state operation limits.
- Frequency regulation – Frequency deviations during load acceptance and sudden loss of the largest energy resource with be determined. The wind farm shall be able to regulate frequency of the cranking path or power island to within the acceptable operating limits.
- System stability – The offshore wind farm can ride through and maintain stable operation for the following events:
  - Line energization
  - Cable energization
  - Transformer energization
  - Load pick-up
  - Loss of largest active power source
  - Loss of largest reactive power source
- Transient and low order harmonic resonant overvoltages – Overvoltages due to each energization step will be determined. These shall not exceed the standard insulation level or cause any adverse impact to the continuous operation of the wind farm and the network assets.
- Inrush current – The offshore wind farm can meet the transformer inrush current requirement without causing the inverter protection to be activated.
- Protection adequacy – performance of the existing protection of transmission grid in proximity to the POI will be evaluated in the configuration with the OWF being the only source of short-circuit current contribution in the island, concerns will be highlighted and mitigation solutions recommended.
- Control system effectiveness - collaboration between the transmission system, wind power plant controller, wind turbine generator controllers, reactive power compensation controls, and system protection devices shall be determined to maintain system security and support energization of the cranking path.

Technical Approach and Assumptions

Wind farm assumptions: wind availability, turbine control, etc.

Power system disturbance leading to a wide area blackout is a rare occurrence, therefore it is extremely difficult to determine the most accurate wind condition during which a blackout would occur. For this reason, the study will consider wind farm availability at different level, i.e at 100%, 66% and 33% capacity. The wind speed variation and turbine mechanical control will not be considered in the study. An equivalent representation of the wind farm array cable system will be derived and used in modelling the offshore wind farm for the study. The windfarm AC-DC-AC converters and its associated components as well its controller design and the GFM/GFL control strategy will be developed based on generic approach.

Onshore grid assumptions: grid topology, grid conditions, interconnection standard adherence

The on-shore electrical power transmission grid of the Dominion Energy will be used for the study. Technical data of the on-shore transmission network, grid topology and conditions assumed during the black start restoration will be based on information provided by Dominion Energy.

RMS, EMT and HIL Studies for Black-Start Analysis and Cranking Path Evaluations

Steady state analysis will be performed to assess active and reactive power requirement for the wind farm to perform a black-start restoration of the onshore transmission network and ensure that the load-generation balance and required operation limits (voltages and power flows) are met for each step.

Positive sequence RMS dynamic simulations will be performed to evaluate the requirement, including the sizing of auxiliary resources such as STATCOMs and BESS, for the offshore wind to maintain voltage and frequency stability during black-start restoration.

EMT simulations and analysis shall be performed to assess the system stability and integrity during early stages of the restoration due to phenomena such as:

- Non-linearities associated with transformer saturation characteristics and surge arresters.
- Low-order harmonics due to transformer energization and the potential for excessive over voltages due to the excitation of harmonic resonances.
- Resonance points created by subsea HVAC cabling, compensation reactors, and transformers.
- Interactions between primary power system components and protective relays, such as over-current conditions, over-voltage protection, and zero-cross miss phenomena.
- Inverter stability, control interactions, and parameter tuning.

Real-time HIL simulations will be set up for the restoration paths with the primary objective of verification of the performance of protection system.

Analysis of Studies Results

The analysis of the study results will be utilized to create specific and actionable metrics needed to implement offshore wind in system restoration strategies. Understanding the limitations of the offshore wind farm and the resource available will provide the data needed to define the metrics. Study assumptions will be evaluated against the results to identify any specific sensitivities of the study that should be investigated further in additional applications.

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

EPRI CONTACT

MOBOLAJI BELLO, *Technical Leader II*
865.340.2468, mbello@epri.com

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

3002031347 **November 2024**

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • www.epri.com