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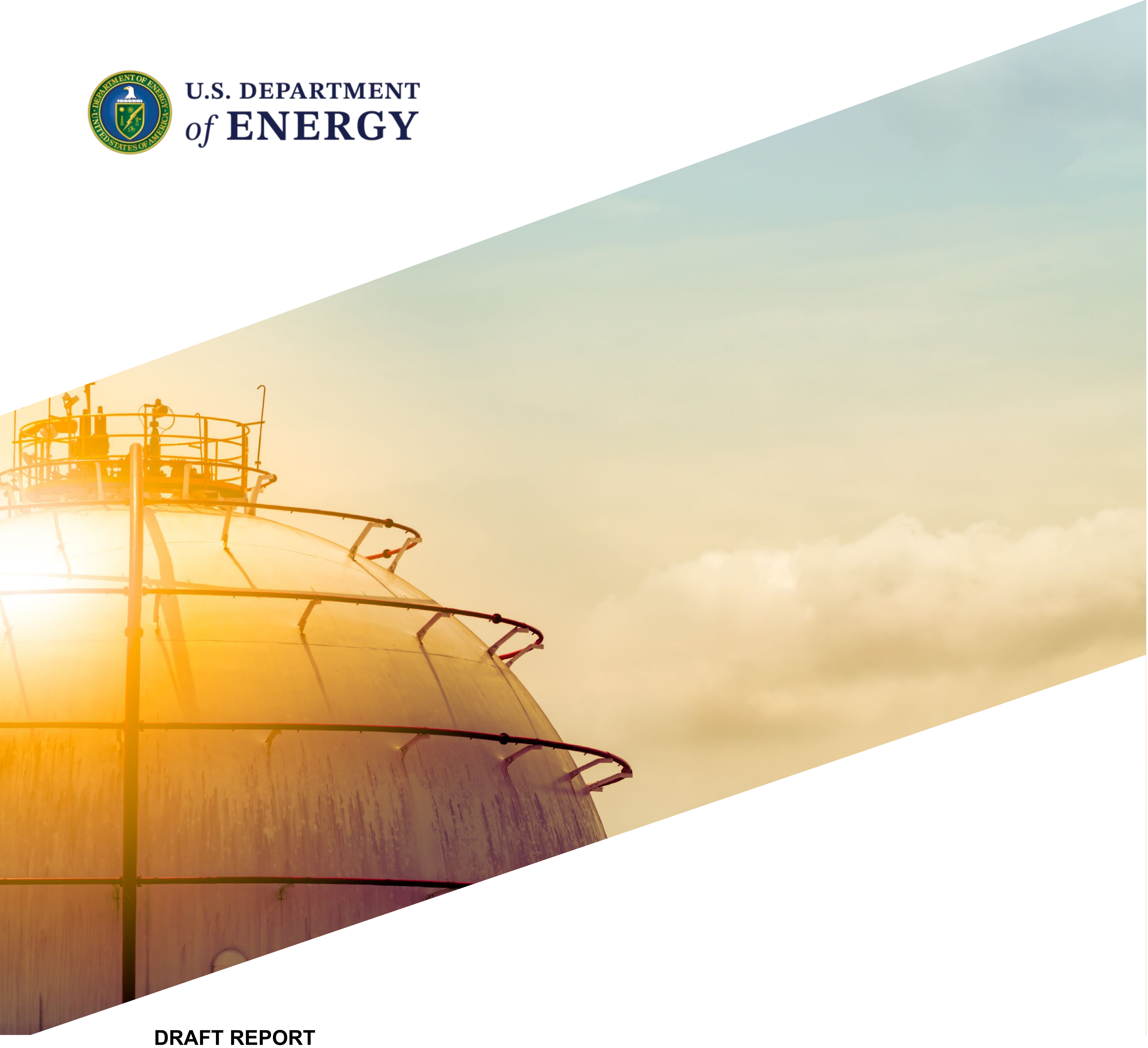

DRAFT REPORT

Microgrids R&D Strategic Plan

Topic 2 – T&D Co-simulation of Microgrid Impacts and Benefits

March 2026

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Original Authors

The authors of the original 2021 document that formed the basis for this iteration are:

Kevin P Schneider, Pacific Northwest National Laboratory (PNNL)

Karthikeyan Balasubramaniam, Argonne National Laboratory (ANL)

David Fobes, Los Alamos National Laboratory (LANL)

Alexandre Moreira, Lawrence Berkeley National Laboratory (LBNL)

Vaibhav Donde, Lawrence Livermore National Laboratory (LLNL)

Bryan Palmintier, National Laboratory of the Rockies (NLR)

Teja Kuruganti, Oak Ridge National Laboratory (ORNL)

Michael E Ropp, Sandia National Laboratories (SNL)

Chen-Ching Liu, Virginia Polytechnic Institute and State University

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Aftab Alam (California Independent System Operator), Anantha Narayanan (National Rural Electric Cooperative Association), Anjan Bose (Washington State University), Frances Bell (Kevala Analytics), and Song Zhang (Independent System Operator New England).

Revision Authors

The authors of the 2025 revision to the strategy document are:

Manuel Garcia, LANL

Philip Top, LLNL

Karthikeyan Balasubramaniam, ANL

Ryan Sun, LLNL

Adam Mate, LANL

List of Acronyms

AI	Artificial Intelligence
ANL	Argonne National Laboratory
BA	Balancing Authority
BPS	Bulk Power System
CHP	Combined Heat and Power
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EMT	Electromagnetic Transient
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
GMLC	Grid Modernization Laboratory Consortium
HELICS	Hierarchical Engine for Large-Scale Infrastructure Co-Simulation
ISO	Independent System Operator
LANL	Los Alamos National Laboratory
LEL	Large Electric Loads
LLNL	Lawrence Livermore National Laboratory
LMP	Locational Marginal Pricing
ML	Machine Learning
NAERM	North American Energy Resilience Model
OE	(U.S. DOE) Office of Electricity
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
QSTS	Quasi-Static Time Series
R&D	Research and Development

RD&D	Research, Development, and Deployment
RTO	Regional Transmission Organization
SMR	Small Modular (Nuclear) Reactor
T&D	Transmission & Distribution
TA	Technical Assistance

Executive Summary

The future electricity infrastructure of the United States is projected to have an abundance of distributed energy supply and demand assets. In this future, microgrids will be a fundamental building block in addressing the challenges of interoperability and scalability. They will operate in various control architectures to support bulk power system operations, achieve local economic and operational objectives, and support the critical end-use loads where the bulk power system is not available.

To this end, the DOE Microgrid R&D Program vision is to facilitate the microgrids to enable the nation to have (1) a more resilient and (2) more reliable and secure electricity infrastructure, which unlocks an (3) energy abundance to help modern industry and advanced applications flourish. These three enumerated strategic goals are developed in the context that the United States' electricity system is becoming more distributed in nature, and that disruptions to the electricity delivery system (EDS) are occurring more frequently and with greater severity.

The vision assumes an increasing need to provide reliable power to advanced applications like data centers running artificial intelligence algorithms and advanced mineral extraction operations. In that context, the Microgrid R&D program seeks to accomplish these three goals:

> Goal 1: Promote microgrids as a core solution for enhancing **resilience** of the EDS while supporting faster recovery of critical infrastructure during and after black sky events
>
> Goal 2: Ensure that microgrids serve as a driver to maintain a **reliable and secure** EDS by allowing important infrastructure to have consistently available alternative sources of power that can support the operations through both natural and man-made events.
>
> Goal 3: Use microgrids to enhance **energy abundance** by providing additional capacity through distributed energy supply and demand assets, as well as by providing necessary services and capabilities back to the bulk power system to help maintain consistent operations.

These goals additionally have cross-cutting topics of focus on designing dependable electric supply infrastructure and reducing economic inefficiencies using microgrid-integrated distributed energy supply and demand resources in both R&D and partnered demonstrations. This strategy document is one of nine prepared for the DOE Microgrid R&D program as part of the strategy development. The nine strategy documents focus on the following areas:

1. Program vision, objectives, and R&D targets in 5 years
2. **T&D co-simulation of microgrid impacts and benefits**
3. Building blocks for microgrids
4. Microgrids as a building block for the future grid
5. Advanced microgrid control and protection
6. Integrated models and tools for microgrid planning, designs, and operations
7. Small Nuclear Reactors in Future Microgrids
8. Artificial Intelligence and Machine Learning for Microgrid Applications
9. Enabling regulatory and business models for broad microgrid deployment

This strategy document covers Topic Area #2 and presents concepts for how co-simulation of transmission and distribution systems, as well as relevant supporting infrastructure like communications systems, can be used to support the DOE Microgrid R&D program vision, as outlined in the strategy document for Topic Area #1. Specifically, how microgrids, and networks of microgrids, will be fundamental building blocks for a future electrical infrastructure that is resilient, decarbonized, and is cost-effective/accessible for all stakeholders. The work proposed for the Microgrid R&D Program will leverage previous DOE investments in the form of existing tools such as the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) and the North American Energy Resilience Model (NAERM) extensively. Additionally, existing academic and industrial capabilities will be leveraged, and public/private partnerships formed as necessary. The material presented in this strategy document focuses on the development of co-simulation capabilities using existing platforms, including extensions to them, and does not recommend the development of new co-simulation platforms.

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1 Introduction

In the United States and its territories, electric generation is increasingly supplied from distributed energy supply resources. These trends are leading to a future power system with significant generation assets connected at the distribution level, resulting in complex architectures, operations, and regulatory structures. Microgrid technologies will be a key enabler for a future with high concentrations of local energy supply and demand resources, which may be aggregated to better coordinate with the transmission system. This includes enabling and unlocking additional capacity to help serve growing load demand, such enabling the interconnection of advanced data centers and mineral extraction projects. Additionally, the increasing occurrence of extreme weather events is placing greater operational pressures on transmission systems under conditions for which they were not designed. This is another opportunity for microgrids to support critical end-use loads by enabling portions of the distribution system to operate independently when the bulk power system (BPS) is not available.

These capabilities offer bottom-up flexibility and scalability to help transition to a future grid that is higher in resiliency, more reliable and secure, and offering greater energy abundance. To navigate the path to the future, simulation and analysis will be a key tool to understanding options, supporting decisions, and determining technical requirements. In particular, the co-simulation of transmission and distribution systems, as well as relevant supporting infrastructure like communication and transportation systems, will play an essential role in determining how microgrids can provide the fundamental controls and capabilities to support not only the critical end-use loads, but to also interact on a routine basis with the BPS.

Traditionally, the modeling of electric power systems has been divided along the lines of transmission systems and distribution systems (Bergen 1986)(Kersting 2018). In each of the simulation types, the other is treated as a boundary condition. Transmission-level simulations treat the individual distribution systems as aggregated load models, typically as simple constant power loads for steady state analysis and simplified static and/or dynamic models for transient stability analysis, and distribution-level simulations treat the bulk power system as an ideal stiff voltage source (Kundur 1994). While this approach was effective when distribution systems were passive actors and load growth was relatively static, the increasing concentration of distributed energy supply and demand assets, including large electrical customers, is increasing the interactions across the transmission and distribution (T&D) boundary. Microgrids can be deployed to help provide additional power capacity to a local grid to support a new data center exploring artificial intelligence algorithms, while those same microgrid-integrated local energy supply assets can provide necessary voltage support to help maintain the stable operation of the BPS during both normal operating conditions abnormal events.

In the 2010s, with the increasing deployment of distributed energy supply and demand assets, there was an increasing awareness of the need to model T&D systems in a coordinated simulation environment. By examining both transmission and distribution in a "co-simulation" environment, it is possible to examine the interdependencies of transmission and distribution systems while still capturing key features only seen with each at full resolution. Although transmission and distribution systems are both power systems, there were many barriers that posed challenges to combining the models and running co-simulations. These include:

1) For most applications, transmission systems are assumed to be electrically balanced and modeled using a single-phase representation. In contrast, most distribution modeling captures the inherent imbalance of North American systems using full three-phase representations. This also allows accurate modeling of single and double phase portions of the distribution system, such as laterals (Kersting 2018).
2) While the bulk power system of North America has three electrical interconnects, there are 36 balancing authorities (BAs) in the eastern interconnection, 34 in the western interconnect, and the Electric Reliability Council of Texas (ERCOT). Each of the BAs maintains its own power system models, with assumptions and representations for overlapping areas of connection.
3) According to the US Energy Information Administration (EIA), as of August 2019, there are 168 Investor Owned, 812 cooperative, and 1,958 public utility distribution companies (U.S. EIA 2019). Each of these companies maintain their own independent models, and in many cases may have missing or incomplete data or may include only asset management data rather than full electric models.
4) Different organizations conduct different levels of simulation and analysis.
5) Different organization use different software, each with its own modeling structure which are often not natively compatible.

While there were a number of early academic and research tools for conducting co-simulation of T&D, not all of these were practical for full scale analysis. Some of these early efforts combined, or "federated", existing tools (Anderson, Narayan, and El Gamal 2013)(Palensky et al. 2014)(Evans 2014), while others reformulated the entire simulation problem into a single environment (Marten et al. 2014)(Singhal and Hedman 2013). While the approaches that reformulated the entire simulation approach were mathematically innovative, they failed to leverage decades of research, development, and investment that existed in current tools; and also, often failed to address the data handling challenges of the different tools. Additionally, those co-simulation approaches that did use off-the-shelf simulation components were typically developed using custom connections that hampered utility and extensibility (Palmintier et al. May 2017)(Kelley et al. 2015)(Ciraci et al. 2014).

The most advanced co-simulation tool to date that leverages existing commercial investments is the DOE's Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS)(Palmintier et al. 2017)(Hardy et al. 2024). Consistent with DOE's effort to support, and not reproduce, industry capabilities, HELICS is designed to federate the capabilities of existing tools, both research and commercial. HELICS acts as the coordinator to enable simulations to be run in parallel and for information to be exchanged in a synchronized manner during the simulation run time. Specifically, time management and data transfer between the simulators is handled by HELICS. This allows different simulators to be run at different time resolution, if needed. These functionalities allow models that already exist at utilities to be used by HELICS, and combined with other simulations, including those that cross the T&D boundary (Hardy et al. 2024).

The purpose of this strategy document is to examine what T&D co-simulation capabilities will be necessary in the next 3-5 years to support the design and operation of microgrids and networked microgrids. Based on the current capabilities of the HELICS platform, the DOE Microgrid R&D program will not need to develop generalized co-simulation capabilities but will instead focus on how existing co-simulation capabilities can be used to identify/validate the utility and value of microgrids across the T&D boundary and other domains, including enhancements to individual simulation tools and corresponding interfaces for use in established co-simulation frameworks. Additionally, relevant supporting infrastructure like communications and transportation systems will be included as necessary to properly represent the range of operations necessary in a future power system where microgrids are a fundamental building block (Bhattarai et al. 2020)(Duan et al. 2020).

2 Vision for the Future

To achieve goals of increasing power system resilience, reliability, affordability, energy abundance, and economic efficiency, we envision using microgrids as a fundamental building block of system planning and operations. In this setting microgrids can operate in support of the BPS or independently from the BPS as necessary. In remote applications, microgrids may not be connected to any bulk power system, but there may still be multiple small microgrids that can interconnect. The degree to which distributed energy supply and demand assets are aggregated into microgrids, and networks of microgrids, depends on the needs and constraints of the end-users and access to technical capabilities, available resources, and mid and long-term planning considerations.

Within the next few years, the operations of microgrids will begin to transition from independent one-off deployments to coordinated systems that can interact with one another and support the BPS. As microgrids move to these more complicated operational scenarios, the control systems will evolve from traditional centralized systems to architectures with more distributed features to support the increasing number of distributed devices and mixed ownership modes. Enabling such future operations, including evaluating new control architectures, will require significant advancement of existing simulation capabilities and analysis processes. This Topic Area #2 whitepaper envisions a future where evolved simulation and analysis capabilities will be able to support examining the planning and operational issues of microgrids for both distribution and transmission systems. This includes a range of simulation capabilities from static power flow solutions to the more complex dynamic and transient simulations combined with multiple levels of control systems.

This strategy document outlines the required fundamental and applied capabilities so that planners and system operators will be able use advanced tools to answer the more complex questions related to microgrids. An example capability would be to examine the economic optimization of microgrids using locational marginal pricing (LMP) at both the transmission and distribution level while ensuring dynamic stability of the BPS. To do this, a number of individual technological developments are necessary.

Co-simulation capabilities will be essential to support the microgrid operations necessary to enable the transition to the future power system. To fully evaluate the technical and regulatory impacts of microgrid operations that span the T&D boundary, it will be necessary to move beyond static power system flow simulations. Specifically, it is expected that T&D co-simulations will need to support:

1) Power flow (steady-state)
2) Time-series, also referred to as Quasi-Static Time-Series (QSTS)
3) Electromechanical Dynamics (time-steps of approximately 1 millisecond)
4) Electromagnetic Dynamics (time-steps of approximately 1 microsecond)
5) Control and Protection

6) Techno-economic Optimization (production cost model type studies)
7) Coupling with other domains (communications, transportation, water, etc.)
8) Markets and pricing including consumer pricing, affordability, and behavior considerations)

Future co-simulation environments and workflows that can support all eight of these areas will be necessary to fully evaluate how microgrids will be most effective in supporting the nations electrical infrastructure. Accelerating towards these capabilities will be a focus of the Microgrid R&D Program.

3 Technology Developments and Enabling Technologies

Effective co-simulation of microgrid planning and operations across the T&D boundary will require leveraging existing DOE investments in co-simulation tools, leveraging existing industrial tools, coordinating with other DOE analysis efforts, and coordination with the other eight topic area strategy documents in this series. The central challenge of co-simulation lies in providing the ability to simultaneously utilize these capabilities in coordination with each other. This coordination is performed by co-simulation environments that interact with many different software tools. While co-simulation environments have existed in other domains for years, it is only in the past decade that power systems have begun to examine the issue. Existing commercial simulation packages have historically focused on either the transmission or distribution system, with the other treated as a boundary condition. To address these challenges, Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) was developed as a unified co-simulation framework funded by the Grid Modernization Laboratory Consortium (GMLC) to integrate diverse simulation tools across transmission and distribution domains (Palmintier et al. 2017).

In many cases, there are existing simulation tools that allow simulation of each system or subsystem individually, but these tools tend not to be compatible with one another, both in terms of data structures as well as simulation methodologies. HELICS is a co-simulation environment that that serves as the “glue” of co-simulation, focusing on issues such as time synchronization, memory management, data structures, and managing the various federates or simulation components. As used by HELICS, a federate can be an instance of software environment, a script or program that emulates a controller and/or function, hardware emulator, or any other component that could be included in the co-simulation environment. One of the greatest advantages of HELICS is that it is being developed as a “federate agnostic” environment. This means that instead of being optimized for one commercial product family, it is being designed to support the entire range of industry tools. While there is a cost for such broad support, the benefits of being accessible to all software platforms far outweigh them. More detail on the HELICS platform can be found online (HELICS n.d.).

While there are multiple co-simulation environments that have been developed, the Microgrid R&D Program will primarily use the HELICS framework. The DOE is investing in the HELICS co-simulation platform and, as such, the microgrid program will not develop parallel capabilities. Instead, the focus is on developing new capabilities for existing tools and/or extending their current capabilities. This could include, but not be limited to, the development of new co-simulation workflows and analysis, development of new device and controllers for existing federates, and the development of new federates. Where necessary, additional capabilities will be developed and committed into the open-source HELICS code so that the work has the greatest value. Because of the wide range of potential planning and operational scenarios that can be examined, this white paper will focus on the capabilities that should be developed, and how they can be used to address larger classes of problems.

The program will extensively leverage the existing capabilities of the North American Energy Resilience Model (NAERM), which conducts much of its work using HELICS. NAERM has focused on power flow and time-series work for traditional power systems and their interconnected infrastructures such as natural gas, transportation, and communication. Where the distribution system has been included, it has typically been treated as a passive actor, and therefore microgrid operations have not been examined. To this end, the efforts of NAERM and many other efforts using HELICS will be important for T&D co-simulation in the Microgrid R&D Program, but their capabilities will need to be extended. For example, building new controller models for microgrids to extend the analysis and workflows developed as part of NAERM to include scenarios where microgrids serve a fundamental role for aggregating large numbers of controllable devices. This example would build on the foundational work of NAERM that has co-simulated power flow studies and passive distribution system dynamics, using HELICS, to an example where microgrids are active control participants that interact with the bulk power system. Collections of individual microgrids as well as networks of microgrids would be included in this example.

It will be necessary to have the capability to fully model and understand the T&D boundary at the full range of time scales. This will require the use of existing co-simulation capabilities to build the use-cases and knowledge to examine co-simulation for a range of analyses, that include, but are not limited to:

- **Resource optimization:** to conduct optimizations that span from the transmission system to the end-use load.
- **Static power flow conditions:** to conduct power flow simulation that include large transmission systems with many individual distribution system models.
- **Dynamic simulations:** to conduct dynamic simulations that allow for dynamics at the distribution level to impact the transmission solutions, and vice versa.
- **Control and protection:** to examine control schemes for resilient operations and to determine if new protection schemes that span across T&D are necessary.
- **Market interactions:** to explore and refine the bid, price, and control interactions between ISOs and microgrids for energy and service provision.
- **Islanded and integrated simulations:** to enable a single co-simulation setup to seamlessly model the system as one large system or—without restarting—as multiple smaller islands, potentially up to thousands of individual microgrids.
- **Transitions among multiple timescales:** Transitions to/from islanded and integrated states during a longer duration simulation might also require heterogeneous timescales such as using quasi-static power flow for timeseries simulation and then shifting to use faster dynamic or transient simulation during these transitions.
- **Cyber-physical system co-simulations:** to integrate power system and communication network simulations, enabling the study of interactions between microgrids, control system and their supporting communication infrastructure.

- **Hardware-in-the-loop testbed integrations:** to incorporate real hardware devices (e.g., controllers, protection relays, inverters, and communication equipment) into T&D co-simulation environments, enabling validation of control strategies, protection schemes, and interoperability under realistic operating conditions.

A variety of existing tools can be used in the HELICS framework to perform the analyses above. Large BPS are studied using a variety of tools depending on the time scale of the phenomenon being studied. For power flow studies positive sequence simulators such as PSS/E, PSLF, or PowerWorld are widely used and are sufficiently accurate (Siemens n.d.)(General Electric n.d.)(PowerWorld Corporation n.d.). These tools also include dynamic simulators capable of accurately representing electromechanical dynamics typical of power systems supplied by large rotating machines during events such as load switching, system faults, and/or a loss of a generator. For large BPS, these dynamics typically have time constants on the order of seconds to tens of seconds, and the simulation tools used have optimized solvers that allow them to efficiently simulate systems with tens of thousands of nodes or more (). When electromagnetic phenomena such as capacitor switching are studied, electromagnetic transient (EMT) simulators such as PSCAD, EMTP-RV, or MATLAB/Simulink are used to study only a small portion of the affected system (tens to hundreds nodes), with the rest of the system being reduced, with methods such as a Thevenin equivalent comprised of a voltage source behind an impedance (PSCAD n.d.)(EMTP n.d.)(Mathworks n.d.). The voltage source may have some dynamic behaviors represented, but it is typically assumed that these dynamics are far slower than the electromagnetic phenomena being studied (Elizondo, Tuffner, and Schneider 2015). Furthermore, there has been limited prior work with HELICS on electromechanical dynamic simulations (Huang and Vittal 2017), with faster electromagnetic co-simulation only captured when HELICS is used to bridge QSTS simulations to real-time EMT simulations, but without exchanging the microsecond-scale EMT data among multiple federates, or in a few proof-of-concept simulations.

A variety of tools are used to simulate and study microgrids in the context of investment planning. Tools like HOMER are often used to perform adequacy planning (“sizing”) and preliminary economic optimization and feasibility studies (HOMER n.d.). When a microgrid is connected to the larger grid, typical distribution analysis tools can be used to study power flow, perform protection studies, and examine the impacts of microgrid on the circuits they are connected to (Duan et al. 2021). These tools include CYME, Synergi, WindMil, ETAP, and SKM, among several others (Cyme n.d.)(DNV n.d.)(Milsoft n.d.)(ETAP n.d.)(SKM n.d.). When the microgrid is operating autonomously, it is often necessary to use an EMT simulator like PSCAD or MATLAB/Simulink because: a) there is no “infinite bus”, so the frequency is no longer constant at 60.0 Hz and the power, energy and current limitations of the microgrid sources must be explicitly represented; and b) the time constants of microgrid responses to various phenomena tend to be on the order of milliseconds to seconds.

While the primary objective of T&D co-simulation for microgrids is to accurately model electrical behaviors across transmission and distribution boundaries, it is equally important to capture their reliance on communication networks. Cyber-physical system (CPS) co-simulation addresses this need by integrating power system and communication network models within a shared environment. Tools such as OPNET, ns-3, and OMNeT++ can be coupled with power system simulators via HELICS to evaluate the impacts of communication latency, data loss, or cyber events on microgrid monitoring, control, and protection (Hardy et al. 2024). In parallel, HIL testbeds embed real hardware components (e.g., controllers, relays, inverters, communication devices) into the simulation environment. Platforms like OPAL-RT, Typhoon HIL, and RTDS enable these devices to interact in real time with simulated power and communication networks. When combined with HELICS-based T&D co-simulation, CPS and HIL approaches provide a coordinated framework for assessing multi-domain interactions and validating control strategies, protection schemes, and interoperability under realistic operating conditions. This integration bridges the gap between simulation and field deployment, strengthening the ability to evaluate performance and resilience of future microgrid systems.

The future power grid will be comprised of a backbone BPS as well as networks of microgrids at the distribution level that must work together to maintain system security, stability, and reliability. This interconnected system may have the ability to spontaneously self-disassemble during major events into adaptive intentional islands and then self-assemble after the event (Schneider et al. 2020). A variety of tools exist that assist in analyzing the restoration process at the transmission and distribution levels separately. At the distribution level, PowerModelsONM.jl solves the restoration ordering optimization problem and integrates feasibility checks including checks on AC feasibility and quasi-steady state stability (Fobes, Nagarajan, and Bent 2022). These capabilities should be integrated to analyze the joint T&D system, potentially facilitating microgrids to perform black-start restoration in portions of the transmission system while coordinating with centralized restoration efforts.

4 Use-Case/Scenario Examples

These use-cases highlight how co-simulation of microgrid operations could be used in the next 3-5 years as part of a larger analysis strategy to support a more resilient, reliable, and lower cost electricity infrastructure. It is anticipated this would be through extending the current work of HELICS and NAERM so that microgrids are modeled as active control elements that interact with the bulk power system, distribution systems, and critical end-use loads. This will include individual microgrids, networks of microgrids, and a heterogenous collection of individual and networks of microgrids. This section is divided into three high level use-cases, each with individual scenarios providing specific examples of how co-simulation could be used to examine new microgrid planning considerations and operational strategies. The presented use-cases are qualitative in nature and are intended to show how T&D could be used to evaluate future microgrid operations. They represent the types of analysis that will need to be done in the future to provide context for how co-simulation needs to evolve to support microgrid operations. These use-cases do not specify the complete details of how co-simulation should be used; that is the role for future research projects.

For the various scenario descriptions below, the details are provided in two paragraphs. The first provides a qualitative description of the use-case, why co-simulation is needed, and how existing capabilities could be leveraged. The second describes the capabilities that are currently missing and what the benefits of filling these gaps might be.

4.1 Use-case #1: Networks of Microgrids Providing Bulk Grid Services During Normal Operations

A key characteristic of microgrids is their ability to integrate a range of devices and to coordinate them to provide operational flexibility. This operational flexibility will be essential for large numbers of distributed resources to support routine operations of the bulk power system. As an example, historically distributed resources have been part of the passive demand, perhaps with some of the larger industrial loads participating in infrequently used demand response or curtailment programs. Microgrids (and recent regulations) have the potential to enable demand-side resources to instead become key contributors to transmission-scale grid support services. As the nation's electrical infrastructure transitions to the vision described in Section 2, a substantially larger number of controllable resources at the distribution level will begin collaborating through various control systems and/or market structures. Co-simulation will allow researchers to examine various options for architectures, controls, and regulatory structures. The following use-cases provide examples where co-simulation could be used to characterize the capabilities and value of microgrids, and networks of microgrids.

4.1.1 Scenario #1.1: Microgrids to Support Bulk Power System Operations

The enhanced controllability of microgrids allows them to contribute more than electric power to the BPS. In fact, resources contained within microgrids may be able to provide basic operating functions of the BPS more cost effectively than central generating power plants, e.g. inverter-based resources can act quickly to provide frequency control and other fast acting ancillary services. The Federal Energy

Regulatory Commission (FERC) Order 2222 sets the foundation for local distributed resources and microgrids to participate in support of basic system operations (FERC 2222 n.d.). In this scenario, microgrids and networks of microgrids use their existing connections to the bulk power system to ensure a stable frequency and voltage during normal system operations. This is primary done through their participation in system-wide ancillary services. To evaluate operations under these conditions, it is necessary to conduct co-simulations to evaluate the effectiveness of the services provided by microgrids and to evaluate the impact, if any, to the distribution system. Existing co-simulation frameworks such as HELICS enable conducting full co-simulations of both power flow and dynamics (Duan et al. 2020), but microgrids have not been examined in any detail.

The simulation tools and interactions required for full-scale dynamic simulations that span both the transmission and distribution systems continue to face challenges related to scale and numerical issues. Numerical challenges within this context are primarily associated with the limitations posed by the simulator APIs which ultimately dictates the type of coupling protocol that can be employed at the T&D interface. Additionally, most optimization packages face challenges with the size of models appropriate for a complete T&D model, which can easily be in the range of millions of nodes, especially in a multi-period optimization (Wood and Wollenberg 1996).

4.1.2 Scenario #1.2: Protection Coordination

As microgrids become more prevalent in distribution systems, it will become increasingly necessary to examine the coordination of protection schemes between transmission and distribution. Independent protection mechanisms are present at the transmission level, in distribution, and in the individual generation sources, particularly power electronics-based sources with fast overcurrent and other internal protection. The ability to simulate all of these, over the same time and system-size scales, is key to ensuring coordination between the various protection schemes.

To properly coordinate protection of this combination of microgrid and bulk grid assets, it will be necessary to co-simulate the fault performance of both traditional resources and power electronic-based devices. This includes their local controls, the decision-making software of the microgrids, the electromechanical dynamics of segments of the bulk grid, and the communications systems they may use, and to do so over large areas of the grid containing hundreds of thousands of nodes. This co-simulation capability would facilitate a wide range of use-cases. One near-term example would be to allow power electronics manufacturers to ensure that their internal self-protection functions are properly coordinated with system-level needs in a range of different grid topology conditions to the greatest extent possible.

4.1.3 Scenario #1.3: Load Transfer to Support Transmission Overloads

Traditionally, distribution systems are viewed as points of aggregated load from the transmission systems perspective. As the capabilities of distributed resources continue to increase, and are aggregated by microgrids, there is need for a correspondingly higher level of observability and controllability for monitoring and control to allow distribution systems to be a resource to support transmission operations. This includes building a fundamental understanding for what level of observability and controllability are necessary for various planning and operational objectives. In this use-case, distribution systems contribute to the remedial control of the transmission system through load management. A line overload condition on the transmission system is alleviated by load transfer in the distribution systems that shifts loading from a substation to other substation(s) and/or by a microgrid operating to pick-up additional load. By doing so, the loading of the overloaded transmission line is reduced.

Co-simulation of transmission and distribution systems with microgrids is needed for this use-case (Li et al. 2014). The transmission system portion of the co-simulation determines the amount of load that needs to be moved from substations on the two sides of the overloaded line and allows computing sensitivity and boundary constraints. Distribution systems determine the load transfer on the distribution feeders to implement the new loading of substations. Reconfiguration of the distribution system is performed to identify the switching sequence for the feeders. Microgrids contribute to load transfer, reconfiguration, and control in coordination with the distribution grid, removing the transmission system operating constraint.

4.1.4 Scenario #1.4: Market Considerations for Normal Operations

The evolving structure of the U.S. electric grid, characterized by a large number of controllable resources in distribution systems, demands a better coordination between distribution-level markets and transmission-level wholesale markets. Traditionally, distributed generation and responsive loads, were passive elements with limited participation in system-wide operations. However, FERC Order 2222 mandates that aggregated controllable resources, including those within microgrids, be allowed to participate directly in wholesale markets operated by Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) (FERC 2222 n.d.). This policy milestone lays the regulatory foundation for distribution-connected resources to deliver grid services and for microgrids to act as aggregators of distributed resource capacity and flexibility. Transmission-distribution co-simulation platforms like HELICS can enable exploration of market integration scenarios by allowing simultaneous modeling of both transmission system operations and detailed distribution network behaviors, including microgrid control and price responsiveness (Palmintier et al. 2017).

To fully understand and unlock the potential value of microgrids in multi-layered markets, it is essential to simulate how microgrids bid into wholesale markets while responding to distribution-level constraints and incentives. Co-simulation frameworks must represent not only the physical interactions at the T&D interface but also the economic dynamics, such as how price signals influence dispatch, demand response, and the transition between grid-connected and islanded modes. A major challenge remains the lack of standardized software tools capable of modeling bid formation and real-time market participation by microgrids (Farivar et al. 2020). Future research must focus on integrating market simulation platforms with microgrid optimization tools, while ensuring interoperability via co-simulation. Doing so will help clarify the operational and economic impacts of increased participation of distributed controllable resources, reduce uncertainty at the Transmission System Operator-Distribution System Operator boundary, and will inform market designs that fairly value microgrid flexibility and resilience contributions.

4.2 Use-case #2: Networks of Microgrids Providing Bulk Grid Services During Abnormal Operations

During abnormal operations, distributed generation contained within microgrids provides the distribution system with the ability to assist the transmission system during abnormal operation, e.g. system level frequency or voltage instability. To that end, co-simulation will be essential in evaluating the architecture and controls for networks of microgrids to effectively support abnormal operations. This section provides three scenarios where co-simulation could be used to advance the utility and value of microgrids and networks of microgrids.

4.2.1 Scenario #2.1: Automated Control and Dynamic Simulation

Distributed generation must actively support the bulk transmission system during abnormal events that may cause dynamic instability on fast time scales of seconds or faster, such as frequency instabilities and voltage collapses. Importantly, these abnormal events are caused not only by intentional and natural threats, but also by necessary switching actions that occur during the restoration or reconfiguration process, e.g., cold-load pickup, see the following scenario. Simulating the ability for the distributed generation resources to support transmission system during these abnormal operations can best be accomplished with co-simulation. Existing co-simulation tools have the fundamental capabilities to simulate these events, but they do not have the necessary device models, e.g., inverter-based resources such as lithium-ion batteries.

Currently, the ability to model the advanced control functions of local distributed resources only resides in distribution level simulation tools. And for functions such as grid-following operations, these only exist in research packages such as OpenDSS and GridLAB-D (EPRI n.d.)(Du et al. 2020). To properly model the ability of microgrids to support the bulk power system during abnormal events, it will be necessary for co-simulation capabilities that allow for advanced controls operating in a range of architectures. When accomplished, co-simulation will allow for the evaluation of the various control systems that would enable this level of interaction. This would increase the benefit of microgrids, and networked microgrids.

4.2.2 Scenario #2.2: Optimal Restoration and Reconfiguration

Restoration and reconfiguration of networked microgrids involve switching operations that change the underlying structure of the power system. In both cases, future work must develop optimal decision-making tools to determine optimal switching actions taken during the restoration or reconfiguration process. Similar tools exist at the distribution level, but not at the combined T&D level (Fobes et al. 2022). For example, when subject to an extreme event that damages portions of the power system, a network of microgrids can reconfigure itself by switching breaker statuses of distribution lines and other distributed resources in a way that continues to serve maximal load. The optimal choice of switching is generally difficult to determine in a complex network of microgrids with substantial outages. Furthermore, the act of opening and closing breakers may cause dynamic stability issues. In this case, system-wide dynamic simulations, possibly electromechanical and/or electromagnetic, are necessary to evaluate system stability for new operating modes, and to evaluate switching operations.

In the context of restoration, the power system is initially in a dilapidated state following an extreme event with significant load loss where networked microgrids are operating as energized islands to withstand the extreme event that has transpired. In this case, microgrids may expand their energized island to restore the system faster than traditional methods that rely solely on the transmission network. In fact, microgrids located in distribution networks may be capable of restoring transmission services during the restoration process. However, there are many open questions that need to be answered about this type of operation including how to ensure voltage stability during restoration actions (switching and load-pickup) and system protection in the case of power flow reversal (most protection schemes in distribution systems are designed based on unidirectional power flow). Co-simulation offers the ability to answer these questions while leveraging existing capabilities, such as high-fidelity power flow simulators for either transmission or distribution, and HELICS to combine them.

4.2.3 Scenario #2.3: Market Considerations for Extreme Events

During the 2021 Texas winter storm, wholesale electricity prices reached the market cap of $9,000/MWh, leaving millions of consumers exposed to both prolonged outages and price shocks. Microgrids, through their ability to operate in islanded mode and leverage local distributed generation such as gas-powered generators, can mitigate both physical and economic risks by maintaining supply to critical loads without relying on volatile grid prices. This capability makes microgrids a critical tool for improving energy resilience and reliability, particularly for facilities such as hospitals, emergency shelters, and water infrastructure. As demonstrated in (Schneider et al. 2020), microgrids can support resilient operations by isolating themselves from the bulk power system and maintaining energy access during transmission outages. In doing so, they can reduce the social and economic harm during black sky events while supporting local autonomy and disaster preparedness.

Price volatility during extreme events also presents a strong economic signal that can drive microgrids to invest in price-responsive demand and generation capabilities. These include technologies such as flexible loads, behind-the-meter storage, and intelligent control systems that respond to real-time prices. By leveraging these assets, microgrids can provide grid services, optimize their participation in energy markets, and even export energy during peak conditions, thereby improving overall system efficiency and resilience. On (Parhizi, Khodaei, and Shahidehpour 2018), price-based dispatch and market-clearing models demonstrate how microgrids can shift from passive consumers to active market participants under emergency conditions. Furthermore, the use of co-simulation tools such as HELICS (Hardy et al. 2024) enable the analysis of how microgrids interact with transmission-level markets during extreme events, identifying optimal control strategies and pricing outcomes. These modeling capabilities will be essential to inform regulatory frameworks and system planning as microgrids scale and play an increasingly important role in mitigating the impacts of extreme weather events.

4.3 Use-case #3: Evaluation of Control Structures for Networked Microgrid Architectures

As more microgrids are deployed, there will be a variety of potential architectures for how they will interact with the bulk power system. In particular, it will be necessary to examine various potential control architectures from the perspective of both planning and operations. Both the transmission system and the distribution system deploy mixes of control architectures and control timescales. Microgrids can often have the individual device-level controls operating at subsecond time scales, but also have a central microgrid controller that is coordinating all controllable assets in the microgrid every few seconds. When the microgrid is connected to the larger power system, these two different control types and speeds are further interacting with controls on the bulk electric system. The interactions not only include the underlying physics of the power system, but also any communication channels between both the microgrid and the bulk electric system.

To evaluate the performance of such a complex control system, it is necessary to model not only the response of the system physics but also controller behavior, communications, and system-level decision-making. This requires different, complex models from different domains at both the transmission and distribution/microgrid level. Co-simulation is essential to design and evaluate the performance before deployment. This evaluation requires investigating control interactions with continuous systems (physical systems) and discrete systems (communication systems) at varying time scales. Additionally, networked microgrid systems are software-intensive and require modeling the software and computational optimization for evaluating the end-to-end performance. While individual tools for modeling the system behavior exist, there is a lack of methods and interfaces to integrate diverse set of simulators for trustworthy system-scale modeling with multi-scale dynamics. Transmission and distribution co-simulation, often over multiple domains like power systems and communications, is needed to ensure the stable and efficient operation of both the larger power system and any microgrids contributing/interacting with the system.

5 Research Targets and Goals for 3 to 5 Years

The challenge with defining program targets and goals is that co-simulation, as discussed in Section 2.0, exists for multiple simulation types, e.g., power flow/time-series, electromechanical, electromagnetic, and optimizations. To address this, this section will first examine the technical focus areas for co-simulation and then map the gaps of these to the program targets and goals.

5.1 Microgrid Co-simulation Technical Focus Areas

The technical focus for microgrid co-simulation over the next 3 to 5 years should focus on three specific areas:

- Area 1: Development of new workflows and analytics
- Area 2: Creation of new device models to support existing tools
- Area 3: Creation of new federate interfaces to support existing tools

Area 1 should focus on how to use co-simulation platforms to conduct specific microgrid analysis. The HELICS project does not target microgrids and instead focuses on developing the underlying framework that allows modeling tools to be brough together to conduct co-simulation. Co-simulation-based analysis currently requires significant effort in data management and post-simulation analysis. Future work in this area should focus on the overall workflow required to effectively assemble the unique needs for microgrids. This includes identifying the effective research and industry-oriented workflows tailored to microgrid-BPS interactions and ensuring that there is consistency between data and co-simulation models across the different simulation types. For example, the electromagnetic steady state solution should be consistent with the static power flow simulation. Additionally, there is a need to standardize both the input/output formats and develop template co-simulation cases for microgrid studies using HELICS. Common data schemas and naming conventions would streamline tool integration, reduce user burden, and improve reproducibility. This standardization would make HELICS and microgrid studies more accessible, consistent, and scalable for both research and industry use.

Area 2 should focus on the need for new device and controller models for co-simulation. While a range of device models already exist, few are currently able to handle the unique needs of microgrids, notably the ability to support islanded and grid-connected operations, to transition accurately between these modes, and consistently simulate these operations across the multiple timescales required. For example, many longer-duration simulations would be best enabled by models that can seamlessly transition between time-series analysis and dynamic or EMT simulations during transitions to/from islanded modes. In addition to device control models, it will be necessary to build a range of system level control models to represent the various levels of potential hierarchical control schemes that control microgrids. This can include, but not be limited to, controls for networks of collaborative microgrids, microgrids coordinating with centralized controllers, and Energy Management System/Distribution Management System coordination with distribution level microgrids. This area should be coordinated with Topic Area #6: "Integrated Models and Tools for Microgrid Planning, Designs, and Operations."

Area 3 should focus on integrating new federates for use in existing co-simulation platforms, specifically using HELICS. As previously discussed, federates for a co-simulation platform can take various forms ranging from a single instance of a controller in a Python script to a full-scale commercial simulation package. Although several tools have existing interfaces for co-simulation, the emerging standardized interfaces that enable true modularity do not cover microgrid use-cases. Identifying a common nomenclature, structure, and conventions for these interfaces to support microgrids is a key need. Also required is a library of off-the-shelf federates for common microgrid needs, such as microgrid controllers. Work in this area should develop the federates and corresponding interfaces necessary to conduct simulation and analysis that specifically supports future scenarios of several microgrids interacting with the bulk power system.

In each of the three areas, two key considerations will be the computational and data requirements. The computational capabilities of platforms such as HELICS will not be a focus of the Microgrid R&D Program because that will be driven by the larger DOE co-simulation agenda. However, the work in the Microgrid R&D Program should extend capabilities within existing platforms in a way that considers computational efficiency and does not replicate existing capabilities. Finally, work in the program should follow best practices of the specific platform and should support efforts to standardize within industry.

5.2 Co-simulation Current Status and Gaps

Currently, the technical capabilities of co-simulation vary depending on the type of simulation being conducted. As a result, the technical needs are expressed as a matrix, Table 1, with the axes being the three areas from Section 5.1, and the types of co-simulation. The data in Table 1 is based on a HELICS co-simulation capabilities using full-size interconnection-level models for the transmission system (e.g., Western Electricity Coordinating Council and Eastern Interconnect models), and multiple full-size distribution circuit models (e.g., unbalanced distribution circuits with 5,000+ nodes each).

Table 1. Current Technical Capabilities of Co-simulations for Microgrid-Bulk Interactions

	Power flow/ time-series	**Electromechanical**	**Electromagnetic**	**Optimization**
Workflows/ Analytics	Ongoing	Ongoing	Foundational	Preliminary
New Device Models	Preliminary	Preliminary	Foundational	Preliminary
New Federates	Ongoing	Ongoing	Foundational	Ongoing

The technical targets for co-simulation, which will support the Microgrid R&D Program Target and Goals for the next 3-5 years are:

- **3 years:** Develop templates and example interfaces to improve ease of integration for electromechanical and electromagnetic co-simulations to support planning and operations, with the necessary models and level of detail, to examine various architectures for how networks of microgrids would operate during normal and abnormal conditions at a variety of scales.
- **5 Years:** Develop the ability to setup, conduct, debug, and evaluate electromagnetic full-scale optimization, and multi-domain co-simulations to support planning and operations, with the necessary models and level of detail, to examine various architectures for networks of microgrids in the energy system in normal and abnormal conditions.

For these goals, all software and developed products would be released as open-source products to public repositories. Where appropriate, participation in recognized industry working groups and power system software development meetings should occur to help integrate the developed solutions into commercial/industrial software offerings.

5.3 Co-simulation Program Goals

While the previous section identified the technical goals of co-simulation capabilities, this section will outline the specific Microgrid R&D Program Target and Goals for the next 3-5 years. Specifically, it will combine the technical focus areas of Section 5.1 with the technical targets for co-simulation of Section 5.2, while referencing the use-case scenarios of Section 4.0.

5.3.1 Research Targets & Goals- 3 Years

Within the three-year timeframe, the Microgrid R&D program should focus on the ability to leverage existing time-series co-simulation capabilities and adapt them for microgrids. While also laying the foundation for electromechanical dynamics, electromagnetics, and optimization which include microgrids for planning and operations. Specific targets and goals include:

- Developing high-level controller models over aggregated resources and low-level controller models of individual edge devices that can support microgrid and networked microgrid operations.
- Ensuring that models are accessible and can be used by multiple types of simulators, e.g. creating software that interacts with HELICS. This includes the development of data formats that are common to all software related to co-simulation.
- Developing modeling and interfacing approaches to support transitions from one large grid simulation to multiple separate sub-grids and back within the same co-simulation.
- Enabling T&D co-simulation to interact with other simulation frameworks, for example, simulation of electricity markets and economics as well as simulation of the communication and metering infrastructure.

5.3.2 Research Targets & Goals- 5 Years

Within the five-year timeframe, the Microgrid R&D program should focus on expanding time-series capabilities to more complex multi-domain operations, implement electromechanical dynamic simulations at the system level, and continue building devices models and workflows for electromagnetic simulations and optimizations which include microgrids for planning and operations. Specific targets and goals include:

- Develop high-level controller models over aggregated resources that can support networked microgrid operations with respect to frequency and voltage control, during normal and transient conditions.
- Develop models for responsive/controllable edge devices. (e.g., inverters, variable frequency drives, solid state transformers, power electronics-based voltage regulation devices, electric vehicles, etc.)
- Enhanced support for separate vs. combined co-simulations to support mixed timestep simulations, such as the ability of both tools and interfaces to support using dynamic-scale simulation during transitions and as needed in islanded operations within an otherwise time-series-based co-simulation.
- Enhanced support for planning and operations tools to make decisions that account frameworks outside of T&D co-simulation, for example, simulation of electricity markets and economics as well as simulation of the communication and metering infrastructure.

6 Why Should DOE be Funding these Goals and Visions

Funding the examination of the future role of microgrids, via co-simulation, is ideally suited for DOE funding because it is building the foundation for future power system planning and operations that are currently not being explored by industry. With proper DOE investment, the industry will be better situated to support the future power visions, which is being driven by factors that typically move faster than the industry. This includes the development of analysis tools and capabilities, as well as the standards that are necessary for their broad industry adoption.

The current generation of industry tools is still focusing on their legacy client base and there are limited investments in the capabilities that will be needed to fully evaluate the range of potential microgrid operations. In particular, traditional tools are still examining either distribution or transmission with the other treated as a boundary condition. Based on past industry trends, once the utilities begin to “ask” for T&D co-simulation capabilities, it will take industry at least 3-5 years to develop these capabilities, during which time there will be competing approaches and standards. This provides DOE with a leadership opportunity.

By continuing to invest in technologies that integrate microgrid technologies into co-simulation platforms, DOE can ensure that ongoing efforts in the Microgrid R&D Program continue to contribute to the modernization of the nation’s electrical Infrastructure. Ensuring a more reliable, resilient, and cost effective critical electrical infrastructure for the nation.

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