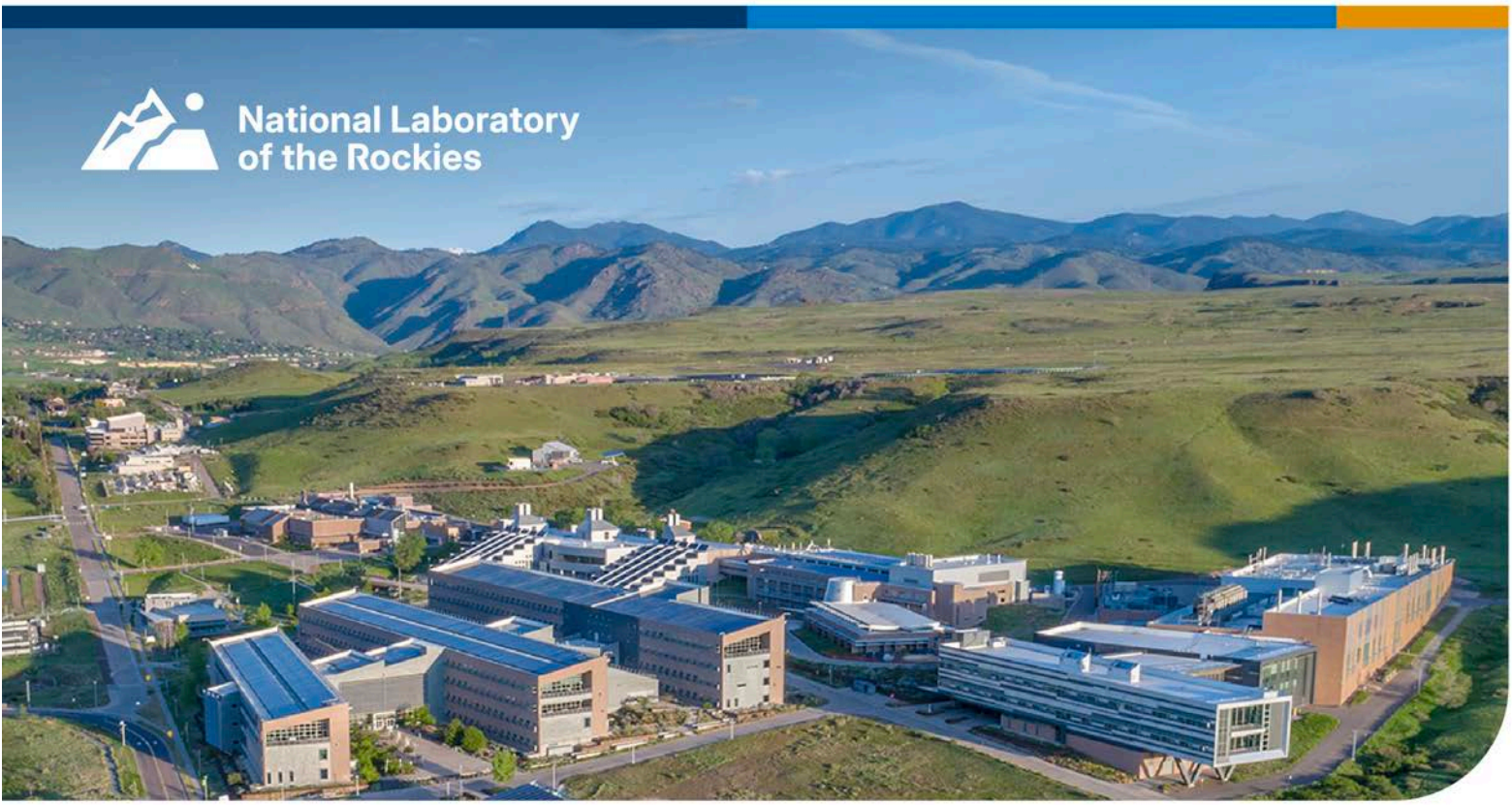

SuperLab 2.0 Showcase: Connecting Five Labs to Tackle Grid Complexity and Unlock Unique Grid Asset Potential

Rob Hovsapian,[1] Sanjeev Pannala,[2] Cliff Loughmiller,[3] Doug Black,[4] Nicolas Gurule,[5] David Tucker,[6] and Andrew Wiedlea[7]

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6 National Energy Technology Laboratory
7 Energy Sciences Network, Office of Science

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National Laboratory of the Rockies

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Office of Nuclear Energy
Hydrocarbons and Geothermal Energy Office

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List of Acronyms

ARIES	Advanced Research on Integrated Energy Systems
BESS	Battery energy storage system
CHIL	Controller hardware-in-loop
DCFC	DC fast charger
DER	Distributed energy resource
DOE	U.S. Department of Energy
DRTS	Digital real-time simulator
ESnet	Energy Sciences Network
EV	Electric vehicle
GT	Gas turbine
GTNET	Gigabit transceiver network (card)
HTE	High-temperature electrolyzer
INL	Idaho National Laboratory
ISA	Interconnection Security Agreement
LBNL	Lawrence Berkeley National Laboratory
LTE	Low-temperature electrolyzer
NETL	National Energy Technology Laboratory
NLR	National Laboratory of the Rockies
OSCARS	On-Demand Secure Circuits and Advance Reservation System
PHIL	Power hardware-in-loop
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaics
Sandia (SNL)	Sandia National Laboratories
SMR	Small modular reactor
SOEC	Solid oxide electrolyzer cell
SOFC	Solid oxide fuel cell

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Executive Summary

SuperLab 2.0 (a five-lab demonstration) is a collaborative, national-scale experiment showcasing the coordination of geographically distributed energy assets in real time. The demonstration integrates 25 physical and digital assets, spanning wind, photovoltaics, batteries, electrolyzers, DC fast chargers, microgrid controllers, building automation systems, small modular reactors, control centers, and gas turbines, across five U.S. Department of Energy (DOE) national laboratories: National Laboratory of the Rockies (NLR), Idaho National Laboratory, National Energy Technology Laboratory, Lawrence Berkeley National Laboratory, and Sandia National Laboratories. These assets are unified using Energy Sciences Network (ESnet), a low-latency, high-performance DOE network, and are controlled via a centralized energy controller hosted at NLR's Advanced Research on Integrated Energy Systems facility. The demonstration validates the ability to stress-test hybrid energy systems under dynamic scenarios to de-risk advanced control strategies for greater resilience and flexibility.

SuperLab 2.0 showcased a major advancement in federated national laboratory collaboration, enabling real-time, cross-laboratory experimentation to coordinate geographically dispersed distributed energy resources using various communication protocols and networks. SuperLab 2.0 built on previous demonstrations conducted between NLR and Pacific Northwest National Laboratory and between NLR and Idaho National Laboratory to connect diverse assets such as distant protection devices, a small modular reactor simulator, and a high-temperature electrolyzer. Previous demonstrations were based on a single connection between two labs with minimal coordination challenges. The five-lab demonstration—which included a centralized controller, distributed test beds across different geographical locations, and use of protocols-based communication—represents a scenario closer to real-world grid operations that coordinate resources across a region to meet system needs. This experiment studied how local distributed energy resource controllers interact with a centralized energy controller during normal and abnormal events to maintain reliability.

The SuperLab team across the five labs implemented a notional power system model equivalent to transmission and distribution lines, represented by the data networks interconnecting the labs. Each lab continuously exchanged local parameters (such as real and reactive power) from its controller hardware-in-the-loop (CHIL) and power hardware-in-the-loop (PHIL) assets through a centralized energy controller at NLR, enabling real-time interaction and coordination across sites. By leveraging ESnet as the communication backbone, the team successfully operated the distributed assets as a unified power system, with each bus represented by a different laboratory. This setup mirrors how assets interact in real-world power systems across dispersed locations with various protocols and latencies. At each lab site, assets were operated using their own local controllers, which were coordinated through an overarching operation and control layer of centralized energy controller, equivalent to how an energy management system orchestrates assets across a regional or national grid.

SuperLab's federated connectivity utilized a digital real-time simulator type of gateway to connect CHIL and PHIL assets between labs. To enable this federated connection through ESnet, a deterministic network was established where latency variations were consistent. This

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consistency allowed the development of digital filters for the power system assets across CHIL and PHIL interfaces to avoid unstable and unreliable grid conditions.

This report provides an overview of the cross-laboratory configuration and offers insights into interconnecting geographically distributed research assets to test them as if they were co-located. The experiment represents a step toward linking nine DOE national laboratories, enabling nation-wide simulations that can address utility-driven challenges with grid resilience, flexibility, and modernization.

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1 Introduction

SuperLab began in 2017 with eight participating laboratories from national labs and universities across two continents, leveraging digital real-time simulator (DRTS) systems connected over the internet for pioneering energy system demonstrations. While the early demonstration proved successful in asset integration via virtual private networks, it also revealed significant latency challenges caused by geographic distances and variable delays. To overcome this, the National Laboratory of the Rockies (NLR) established connections using the U.S. Department of Energy's (DOE's) Energy Sciences Network (ESnet), drastically reducing latency and enhancing the reliability of simulations. In December 2021 NLR researchers, Pacific Northwest National Laboratory (PNNL) researchers, and ESnet staff collaborated to demonstrate this enhanced capability during a live microgrid experiment in Cordova, Alaska. Building on this success, NLR expanded efforts to demonstrate hybrid energy systems that combined diverse energy resources, including variable generation and nuclear energy, that can be optimized in response to grid conditions to support reliability. These milestones led to the formalization of SuperLab 2.0, which connected five national laboratories—NLR, Idaho National Laboratory (INL), Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratories (Sandia), and National Energy Technology Laboratory (NETL)—through ESnet to explore solutions to enhance grid reliability. SuperLab 2.0 primarily focused on coordinating the operation of geographically dispersed distributed energy resources (DERs) and loads such as electric vehicle (EV) loads, thermal loads, and storage systems.

The primary goal of SuperLab 2.0 was to develop a control platform that emulates the basic functionality of a grid control center. This platform was designed to enable real-time communication, control, and optimal coordination of emerging grid scenarios (e.g., mixed energy resources and loads). It facilitated the coordination of diverse energy resources and loads, including microgrids, small modular reactors (SMRs), building loads, DCFC, and hybrid energy plants, particularly in response to system disturbances.

SuperLab 2.0 showcased a complex simulation of diverse assets responding to grid conditions, leveraging a notional power system model and integrating geographically distributed assets across five labs. These assets were real generation sources and loads, equipped with local energy controllers and power conversion systems, that interacted with DRTS models, were digitally scaled in a DRTS environment, and communicated with centralized energy controllers operating a notional power system at NLR.

A communication architecture was established to enable seamless data exchange and coordinated operation across all participating laboratories. The system incorporated a combination of legacy communication protocols like TCP/IP, UDP, Modbus, and DNP3 to ensure data exchange among diverse assets and platforms. Each laboratory operated its DRTS at a time step of 50 microseconds, allowing high-fidelity simulation of transient dynamics. Local energy controllers at each site continuously exchanged equivalent P–Q (real and reactive power) information every few milliseconds, maintaining synchronization across the distributed network.

These local controllers interacted with a centralized energy controller hosted at NLR, which dispatched operational commands to the emulated grid platform. The centralized energy controller coordinated the distributed assets in real time, leveraging ESnet to continuously transmit energy status updates. This configuration enabled accurate execution of setpoints and stable system response under both normal and

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abnormal grid conditions, effectively demonstrating the coordinated operation of geographically dispersed assets as a unified, high-fidelity power system.

Comprehensive details of the SuperLab 2.0 setup are provided in the following sections:

Section 2: Resource coordination architecture

Section 3: Rationale for laboratory asset selection

Section 4: ESnet integration and network communication setup

Section 5: Operational scenario configurations and demonstration results

Sections 6 & 7: Key findings, insights, and lessons learned.

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2 Resource Coordination

To support the SuperLab 2.0 five-lab demonstration project, NLR implemented a centralized energy controller hosted at the Advanced Research on Integrated Energy Systems (ARIES) facility. Logical decisions were made as predefined control actions in response to the grid conditions explored in the demonstration.

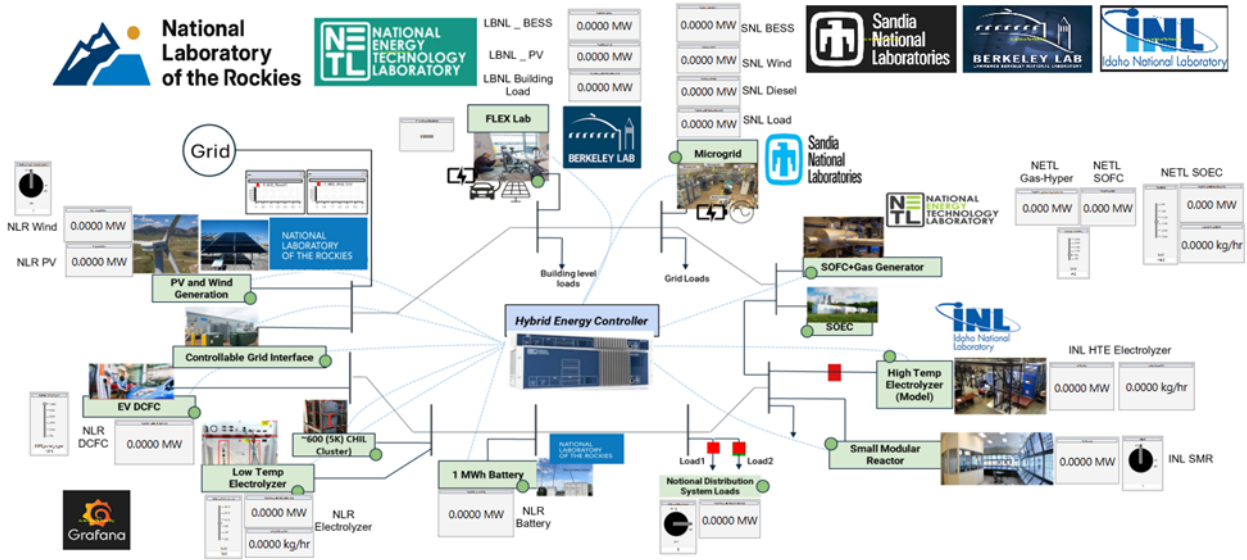

Figure 1. A notional power system network representing five-lab connections.

The centralized controller functioned as the operational hub for distributed assets across five national laboratories integrated into a unified energy system connected to a notional 500-MW power grid network. Leveraging the DRTS platform, the NLR team developed a digital twin that emulated realistic grid conditions, enabling the virtual coordination of DERs, thermal generators, hydrogen systems, microgrids, and diverse load profiles as if they were connected on a single regional network, as shown in Figure 1. Importantly, the simulation platform maintained a fixed, synchronized communication rate among all assets, closely mirroring the deterministic data exchange patterns observed in actual transmission and distribution networks.

The ARIES DRTS platform was equipped with outfacing network interface cards, such as GTNETx2 simulator network interface cards from RTDS Technologies, which supports various protocols such as SKT (TCP/UDP), Modbus, DNP, SV, and GOOSE, to interface with other national laboratory assets. This enabled seamless, real-time communication with the assets hosted at each national laboratory. Standardized communication protocols, including Modbus and TCP/UDP, were implemented over secured, deterministic IP channels established through ESnet. This network architecture ensured secure, low-latency, and reliable data transfer between geographically dispersed sites and NLR, enabling local controllers at each laboratory to interact dynamically with the centralized energy controller. The next section details 25 assets integrated from each participating laboratory, representing a diverse set of energy resources that can reflect the complexities of a modern electric grid.

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3 Laboratory Assets

Each lab's assets and capabilities in SuperLab 2.0 were selected based on the lab's domain expertise, available physical and emulated infrastructure, and their ability to interface with the centralized energy controller hosted at NLR. The NLR has one of the largest DRTS environments in the DOE national laboratory network. The facility includes 27 DRTS racks (82 RTDS cores, 31 Opal-RT cores, and 7 Typhoon hardware-in-the-loop platforms) to enable regional grid-scale electromagnetic transient simulation. The lab's hardware also includes over 5,000 Internet of Things CHIL controllers, 44 real-time CHIL Kria boards, 12 linear amplifiers (15 kW each), and 200 next-generation advanced metering infrastructure meters, enabling hardware-level experimentation with AC/DC distributed grid automation and controls, protection schemes, communication architectures, AI-driven model training, testing, and other grid applications.

Moreover, NLR leveraged its ARIES assets for SuperLab 2.0, including a high-fidelity test bed that integrates a 1.5-MW wind turbine, two photovoltaics (PV) systems totaling 3 MW, a 1-MWh lithium-ion battery energy storage system (BESS), a 0.8-MW DCFC, and a 1-MW low-temperature electrolyzer (LTE) operating in a PHIL and CHIL configuration. All assets are interconnected via a 7-MVA controllable grid interface, enabling real-time multi-node control and synchronized interlaboratory operations. These assets were chosen to represent DERs and grid-edge resources such as inverter-based resources, storage, and hydrogen production systems. They were integrated into the power system network in the RTDS/RSCAD simulation to support fast control and dispatch via GTNET interfaces. Within the overarching control architecture, NLR hosts the central energy controller at its ARIES facility, which communicates with all labs over ESnet using deterministic low-latency channels. Locally, NLR assets operate under CHIL and PHIL configurations and respond to setpoints in real time. Through digital scaling, NLR's assets represent 61 MW of wind, 79 MW of PV, 20 MW of LTE, 7 MW of DC fast charging, and a 50-MWh battery system. These scaling values were selected to emulate the behavior of a large DER cluster, with power levels reflecting real-world scenarios such as feeder-scale solar, depot-scale EV charging, and utility-scale battery dispatch.

At INL's Human System Simulation Laboratory, the experiment integrates an SMR with high-temperature electrolyzer (HTE) models to explore flexible nuclear/hydrogen hybrid operations. The SMR, modeled for up to 300 MW of output, can ramp down to 50% capacity in 10 minutes with a 1.05-MW/s ramp rate. Paired with a 25-kW HTE model for efficient "pink hydrogen[1]" production, the system is digitally scaled to 220 MW for the SMR and 100 MW for the HTE, enabling real-time coordination between nuclear power generation and hydrogen production. These assets were chosen for their relevance in modeling next-generation hybrid nuclear/hydrogen systems, offering dispatchable baseload power and scalable hydrogen output. INL's capabilities were tied together using UDP, allowing seamless integration with the centralized energy controller at NLR. Within the overarching control scheme, INL operates under a CHIL configuration, receiving dispatch instructions from NLR and responding with real-time simulation data. The power scaling, 220 MW for SMR and 100 MW for HTE, was chosen by anticipated commercial deployment targets and the need to realistically simulate regional-scale flexible generation and hydrogen co-production strategies.

[1] pink hydrogen refers to hydrogen produced through water electrolysis powered by nuclear-generated electricity (and, where applicable, nuclear heat), resulting in low-carbon and high-efficiency hydrogen production.

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NETL's assets combine a stand-alone 120-kW gas turbine with a solid oxide fuel cell (SOFC)–gas turbine (GT) hybrid system, connected to a 120-kVA load bank for dynamic stability analysis. The SOFC-GT hybrid achieves 70% fuel-to-electricity efficiency with a 50% load turn-down capability in under 10 seconds, operating on natural gas or hydrogen. A solid oxide electrolyzer cell (SOEC)-GT hybrid system also serves as a controllable load optimized for high-efficiency hydrogen production. These assets were selected to study high-efficiency fuel-hydrogen-electricity integration and were tied together through a co-simulation environment in Opal-RT where NETL assets interface directly with the centralized controller at NLR using TCP/IP communication protocols. The lab operates within the SuperLab 2.0 architecture under a PHIL configuration, receiving setpoints and sending telemetry in real time. Power values were scaled to a 30-MW SOFC-GT, a 30-MW SOEC hydrogen production system, and a 30-MW dynamic load, representing modular distributed power systems capable of flexible peaking support or grid-following operations. These values reflect commercially relevant scales and allow accurate modeling of start-up dynamics, load shifts, and hydrogen response curves.

At LBNL, SuperLab 2.0 connected building-level assets, including controllable heating, ventilating, and air-conditioning systems; lighting; plug loads; and building envelope controls. Occupancy sensor data informs dynamic load-shedding strategies, while behind-the-meter DERs such as three Tesla Powerwalls, a bidirectional Nissan Leaf EV, and three SolarEdge inverters support managed charging and discharging. These capabilities were chosen to emulate smart building-to-grid interactions and were tied together through local automation controllers that communicated with NLR's central energy controller via Modbus TCP. Within the overarching architecture, LBNL functions as a demand flexibility node, dynamically shifting loads and DER behavior based on real-time system needs. The total digital scale—1 MW of PV, 2.5 MW of BESS and EVs, and 3 MW of building loads—was upscaled to a 30-MW combined generation and 30-MW building load system, simulating a large commercial facility or campus-scale net load center. This scaling allows LBNL to demonstrate how building DERs can contribute to grid stability and load balancing under coordinated control.

At Sandia's Distributed Energy Technologies Laboratory, SuperLab 2.0 integrated variable generation and non-variable generation assets into a microgrid managed by an advanced grid controller. The lab features a 0.9-MW wind turbine scaled to 1 MW, a 0.075-MW BESS scaled to 28 MW, and a 2-MW diesel generator scaled to 1 MW for resilient backup. Additionally, a modeled 0.6-MW load (i.e., mixed load representing residential and industrial customers) is scaled to 30 MW. These assets were selected to represent a black-start-capable microgrid with diverse generation types and fast-responding storage. They are tied together via Sandia's microgrid controller and integrated into the distributed energy system through Modbus-based communication and real-time data exchange over ESnet. Within the control architecture, Sandia operates as an autonomous microgrid node capable of both grid-tied and islanded operation modes. The digital scaling of assets—28-MW BESS, 30-MW load, and 9-MW wind—was intended to mimic critical microgrid infrastructure and stress-test high-penetration inverter-based systems under grid events such as frequency dips or voltage instability.

Together, these asset integrations across five national laboratories, enabled through low-latency ESnet communication, real-time CHIL/PHIL interfaces, and centralized energy control at NLR, represent an advancement in modeling and simulating distributed and hybrid energy systems under various grid scenarios. The deliberate scaling of assets ensures each lab meaningfully contributes to realistic simulations of 500 MW of distributed generation and 468 MW of dynamic load, allowing the system to respond to grid disruptions and evaluate future grid strategies with high fidelity. The detailed breakdown of assets by lab is shown in Table 1.

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Table 1. Summary of Laboratory Assets, Scaling, and Communication Protocols in SuperLab 2.0

Lab	Assets connected	Selection Criteria	Scaling	Communication Protocol
NLR	PV (3 MW), Wind (1.5 MW), BESS (1 MWh), EV DCFC, LTE	Represents DER clusters, grid-edge flexibility, hydrogen integration	PV scaled to 79 MW, BESS to 50 MWh, DCFC to 7 MW, LTE to 20 MW	UDP, Modbus,TCP/IP
INL	SMR (300-MW model), High-Temp Electrolyzer (25 kW)	Studies nuclear/hydrogen co-production	SMR scaled to 220 MW, HTE to 100 MW	UDP
NETL	SOFC-GT Hybrid, SOEC, Gas Turbine	Simulates integrated fuel-hydrogen power plants	All scaled to 30 MW each	TCP/IP
LBNL	Building loads, Powerwalls, PV, EVs	Focus on demand-side flexibility and Demand response coordination	Load scaled to 30 MW, generation to 30 MW	Modbus
Sandia (SNL)	Wind, Diesel, BESS	Validates microgrid resilience under grid islanding and storage response	Wind scaled to 9 MW, BESS to 28 MW, load to 30 MW	Modbus

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4 Connectivity via DOE Office of Science's ESnet

The initial SuperLab connection successfully linked national laboratories across vast distances, pioneering a new era of collaborative energy research. However, this early achievement came with a significant challenge: latency. In the first SuperLab experiment, while asset integration across geographically separated labs was technically possible, the unpredictable and variable latency in data transfer over standard internet connections introduced jittering effects. These latency issues made coordinated asset control difficult and, at times, unrealistic compared to actual energy system operations. This problem was particularly critical in dynamic grid environments, where generation and load conditions fluctuate rapidly, requiring precise and timely control within a few cycles on the order of 100–500 ms, which can capture the behavior of fault scenarios, loss-of-load events, and loss-of-generation events. The issue was clearly demonstrated in an early NLR-INL SuperLab 1.0 demonstration with latency measurements of maximum 369 ms, minimum 20 ms, average 27.15 ms, and with a variance of 11.5 ms, as shown in Figure 2. Such wide-ranging and unpredictable latencies severely impacted the accuracy and reliability of experiments, making it impossible to truly replicate real-world grid behavior.

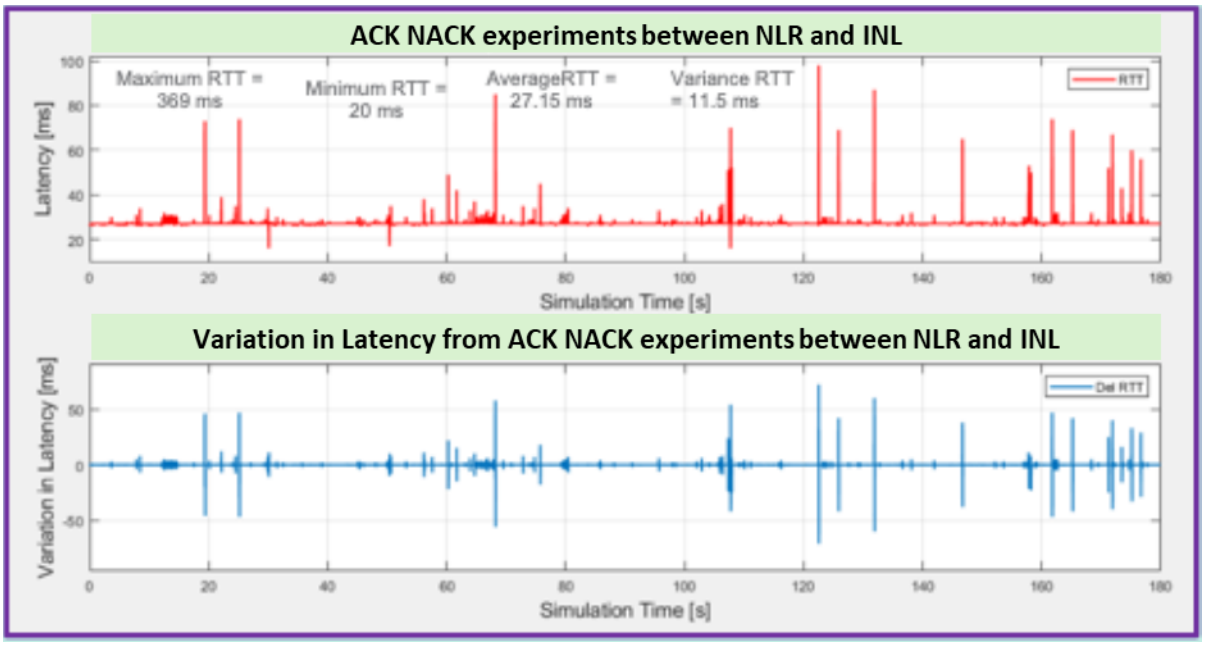

Figure 2. Latency measurements in SuperLab 1.0 demonstration between NLR and INL.

Recognizing the need for a robust solution, the team set out to find a way to correct these latency challenges and enable more realistic, synchronized experiments. Their search led to the DOE's ESnet—a high-performance, dedicated scientific network. ESnet, renowned for supporting critical global scientific endeavors such as the Large Hadron Collider, offered the stability and speed necessary for SuperLab's goals. When ESnet was paired with the On-Demand Secure Circuits and Advance Reservation System (OSCARS)—a tool for reserving high-speed network resources—the team could ensure consistent, low-latency communication during experiments.

This approach led NLR to reestablish SuperLab connections among geographically distributed labs via ESnet (Figure 3). Consistent, deterministic communication with predictable latency, enhanced further by

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perfSONAR (performance Service-Oriented Network Monitoring Architecture), which is a network measurement toolkit designed to provide federated coverage of paths and help to establish end-to-end usage expectations and monitoring system at each site. This led the researchers to fully understand network performance at each lab site and track down delays and packet drops behind each site's network. Each lab's IT support was able to resolve issues with help from the ESnet team.

Figure 3. SuperLab 2.0 showcase demonstrating five national laboratories working as one integrated energy system.

ESnet integration enabled the connection between PNNL and NLR to dramatically improve in 2023 with latency parameters dropping to a maximum of 24.2 ms, a minimum of 23.6 ms, an average of 23.90 ms, and a low variance of 0.02 ms. Results are shown in Figure 4. This reliable, stable communication across national laboratories was critical for enabling accurate, synchronized experiments over large distances.

Variance in latency was mitigated by establishing local filters within the notional power system running in a DRTS environment at NLR and compensated parameters utilized in dispatching commands from the centralized energy controller.

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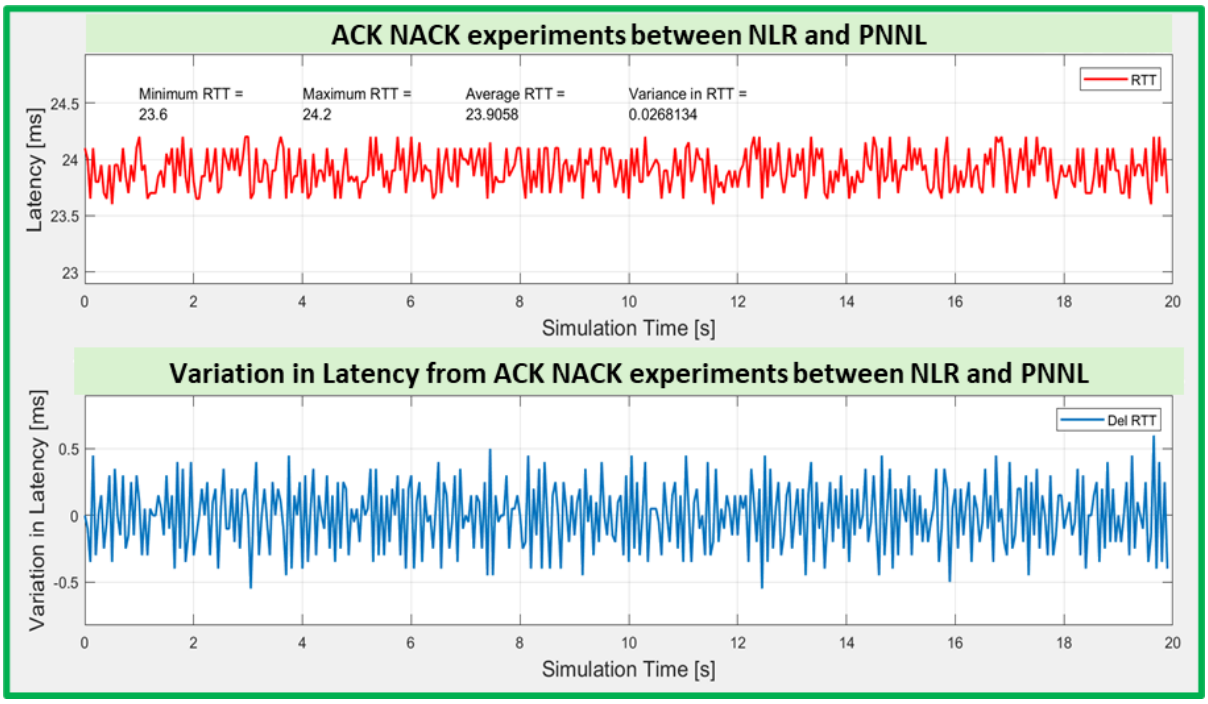

Figure 4. Latency measurements in lab connection between NLR and PNNL.

The improvements in network performance reduced variability in the connections to make it more deterministic for real-time grid emulations within DRTS, enabling high-fidelity simulations at fixed time steps as low as 50 µs for dynamic, real-time experimentation locally at each lab site. This setup allowed simulation of complex grid scenarios involving mixed energy resources, including load and generation fluctuations, across regional grids. It also facilitated the evaluation of how well centralized grid controllers can coordinate with distributed assets to meet dynamic operational needs during unexpected grid events. Furthermore, SuperLab 2.0 supports the analysis of fast transients such as inverter responses and frequency excursions with local event resolution on the order of microseconds and end-to-end control coordination within 25–50 ms.

One of the key challenges encountered during the five-lab demonstration was the integration of multiple DRTS platforms (RTDS, OPAL-RT, and Typhoon) in use across the participating laboratories. Each of these platform's interfaces differently with CHIL and PHIL assets, creating interoperability and synchronization challenges. To address this, the team used legacy communication protocols to establish standardized interfaces between each lab's local controllers and the centralized controller at NLR. This approach ensured consistent data exchange and fixed communication intervals across all DRTS platforms, as detailed in Section 5.

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5 Demonstration of Use Cases

After establishing the unified simulation environment through ESnet with the centralized energy controller at NLR's ARIES facility, as shown in Figure 5, the project team planned a SuperLab 2.0 demonstration to showcase the value and potential of an integrated energy system under realistic operating conditions. This demonstration aimed to highlight the system's ability to address key challenges faced by utilities, including real-time coordination of DERs, dynamic load balancing, and grid resilience during extreme events. It modeled three scenarios that reflect critical situations ranging from abrupt spikes in electricity demand to significant losses in electrical load that have historically challenged utility operators and grid stability.

The key challenge was replicating a real-world utility environment while leveraging geographically distributed national laboratory grid assets. The team developed a notional power system model based on the standard IEEE 14-bus system, which was modified to integrate each lab's physical and simulated assets at designated bus locations. Each lab operated its assets through local controllers connected to their respective DRTS platforms. These platforms communicated in real time with a centralized DRTS environment hosted at NLR, where all buses were combined into a single, unified power system model. The centralized energy controller at NLR dispatched setpoints to each local controller through the DRTS interfaces via dedicated ESnet connections, enabling coordinated operation across all sites. This architecture allowed geographically distributed assets—spanning multiple national laboratories—to interact dynamically as part of a single, integrated power system, effectively demonstrating large-scale coordination across diverse hardware and simulation environments. It also addressed challenges such as integrating heterogeneous assets across multiple laboratory sites; co-optimizing electricity, thermal generation/load, and hydrogen systems; and ensuring interoperability across various protocols and control platforms during different scenarios such as sudden load surges, generation intermittency, and demand-side flexibility. SuperLab 2.0 demonstrated how the electric utility industry can leverage a scalable, low-latency, multi-lab capability to study grid stability, flexibility, and operational reliability in increasingly complex conditions with centralized energy controllers.

5.1 Scenario 1: Blue Sky Scenario With Inverter-Based Resources

This scenario represented **a steady-state operating condition** under high penetration of DERs. It is designed to emulate a typical day (i.e., "blue sky" operation) in a power system where inverter-based resources and flexible assets must be managed in a coordinated and balanced manner. The goal was to baseline performance and system coordination under normal conditions to establish a reference point to evaluate against more extreme or disruptive scenarios.

The response actions across all participating labs in this scenario were pre-scripted within the centralized energy controller at NLR to ensure a smooth demonstration within the limited time window. Although the controller executed the sequence in real time, this pre-scripted approach was used only for this demonstration and can be replaced with fully dynamic, real-time operation for future control center applications. While the overarching control logic and setpoints were executed centrally in real time, each lab's local controllers operated accordingly to carry out asset-level responses, such as dispatching gas turbines, SMRs, and BESS or curtailing loads based on received commands. This approach mimics real-world energy management system interactions with distributed control systems. The run-time window of SuperLab 2.0 driven by the hybrid energy controller is shown in Figure 6 in Section 5.4.

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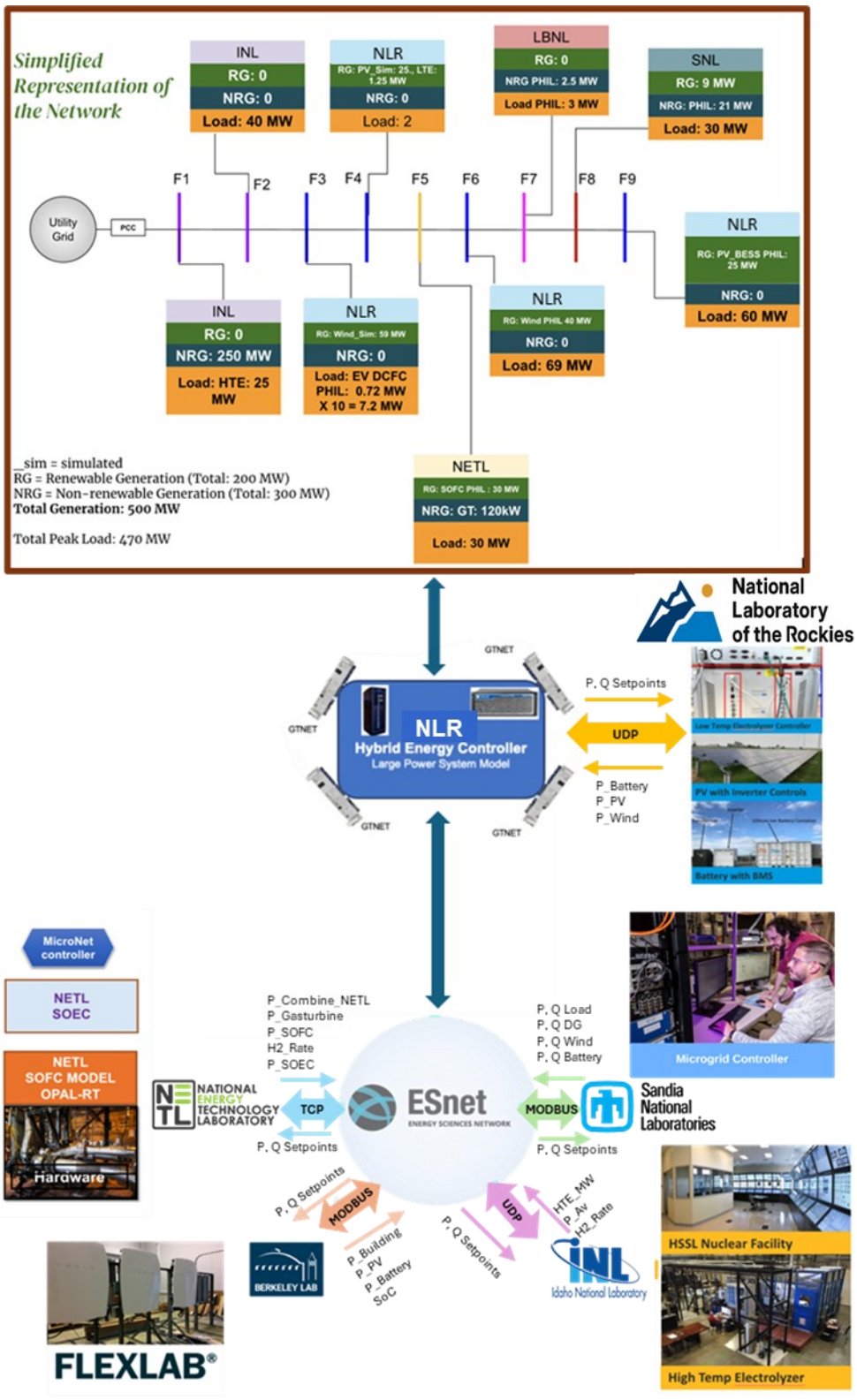

Figure 5. SuperLab 2.0 architecture showing cross-lab asset integration via ESnet with centralized control from NLR's Energy Controller.

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In the blue sky scenario, each lab operated under normal, steady-state conditions while maintaining active contributions to the system. At NLR, the centralized energy controller dispatched commands so that all loads were turned on to 50%, with solar PV, BESS, and wind generation actively feeding the grid, and the DCFC operated at 100% load (Figure 7, Blue Sky Scenario). The centralized controller also sent a signal to INL to keep the HTE running while operating the SMR at 45% capacity, with flexibility to direct the produced thermal energy toward industrial applications or electrical generation (Figure 8, Blue Sky Scenario). The central controller directed LBNL to maintain BESS at 0 MW, while optimizing the site's net load consumption from the utility to reduce costs and improve energy efficiency (Figure 9, Blue Sky Scenario). The centralized controller sent a signal to Sandia to maintain a constant 26 MW load along with a BESS discharge setpoint of 3.5 MW (Figure 10, Blue Sky Scenario). Finally, at NETL, the SOFC remained online (2 MW) per the signal sent from the centralized controller, the gas generator was on standby at 4 MW, and the SOEC was loaded at 16 MW (Figure 11, Blue Sky Scenario).

5.2 Scenario 2: Sudden Load Increase (Inspired by 2021 Texas Winter Event)

This scenario reflected real-world emergency conditions, such as the February 2021 Texas power crisis, simulating **a sharp and sudden rise** in power demand. To maintain equilibrium, generation must quickly ramp up when the load increases suddenly. The SuperLab 2.0 project demonstrated how a diverse mix of assets, such as batteries, SMRs, thermal generation, and EV charging infrastructure, can coordinate through a centralized controller to close the demand gap while maintaining voltage and frequency stability. Like the Blue Sky scenario, the control actions were programmed into the centralized energy controller but executed in real time. The control system sent synchronized setpoints to each lab, with local control loops managing device-level interactions and responses. At NLR, regular loads increased to 100% capacity, with an additional 125 MW of central load. To quickly compensate for this surge in demand, the centralized energy controller sent a signal to BESS to dispatch power rapidly, which was reflected in a visible rise in BESS output. Meanwhile, DCFC EV loads were curtailed by 50%, reducing EV charging demand to approximately 4.55 MW (Figure 7, Texas Winter Event). The central energy controller sent commands to INL to turn OFF HTE to prioritize essential loads, while the SMR ramped up its output to meet the increased power requirements (Figure 8, Texas Winter Event). LBNL decreased building loads power consumption and ramped up BESS power to provide additional support to the grid as directed by the central controller (Figure 9, Texas Winter Event). The centralized energy controller sent signals to the microgrid at Sandia to increase generation by 80%, allowing the BESS to push significantly more power, ramping from 3 MW to 24 MW, into the nominal power grid to stabilize the system (Figure 10, Texas Winter Event). In the Sandia microgrid, wind generation and the diesel generator were not available during this time. NETL ramped up its gas turbine, increasing generation from the SOFC, and placed its gas generator on active standby to meet backup needs per commands received from centralized controller. Additionally, the SOEC reduced its load dramatically from 15.5 MW (50%) to just 2 MW (7%), freeing up further capacity for critical grid operations (Figure 11, Texas Winter Event).

5.3 Scenario 3: Sudden Load Drop (Inspired by 2003 East Coast Blackout)

This type of scenario simulated a cascading failure similar to the 2003 historic East Coast blackout by simulating **a sudden and unexpected drop** in electricity demand. If such occurrences are not dealt with right away, they may cause instability throughout the system, potentially leading to a regional blackout. The SuperLab 2.0 project showcased how fast-responding assets, like batteries, fuel cells, electrolyzers,

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and controllable loads, can absorb excess energy and stop frequency overshoots, preventing grid collapse. The response actions across all participating labs in this scenario were programmed within the centralized energy controller at NLR. While the overarching control logic and setpoints were executed centrally, each lab's local controllers operated accordingly to carry out asset-level responses.

At NLR, the centralized load was reduced by 50%, corresponding to a 125-MW load drop. To balance the surplus of available generation, the centralized energy controller sent a signal to LTE to ramp up to 100% operation, producing up to 20 MW of green hydrogen, while DCFC EV charging was simultaneously increased to 100%, bringing the DCFC to full-rated capacity (7 MW) to absorb excess power (Figure 7, East Coast Blackout). The centralized energy controller sent a signal to INL to respond by turning on its HTE while the SMR remained active but gradually ramped down, effectively shifting some of the reactor's output into hydrogen production (pink hydrogen) for storage (Figure 8, East Coast Blackout). The centralized controller sent signals to LBNL to increase the building loads to 100% by boosting HVAC system usage and increasing charging rates to the site's BESS, thus raising electricity consumption to match the available supply (Figure 9, East Coast Blackout). Sandia decreased the microgrid's export power to just 10%, and the BESS was shifted into a charging mode, helping to absorb excess generation within the microgrid and stored energy for future peak demand periods as commanded by the central controller (Figure 10, East Coast Blackout). Finally, the centralized energy controller directed NETL through command signals to increase its SOEC load to 100%, further utilizing surplus grid power for hydrogen production and maintaining system balance during the load drop event (Figure 11, East Coast Blackout).

5.4 SuperLab 2.0 Power Output Result from Each Laboratory

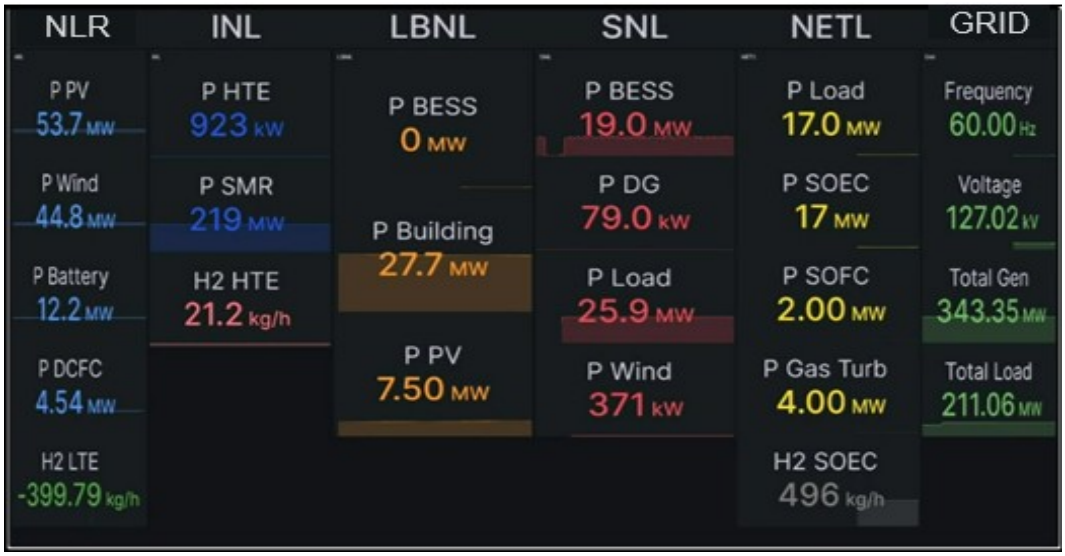

Figure 6. Run-time window of SuperLab 2.0 driven hybrid energy grid.

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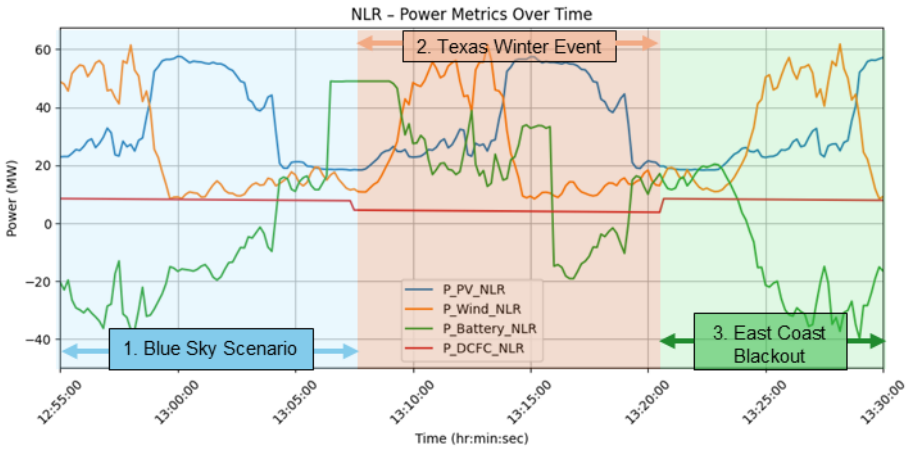

Figure 7. NLR power profiles for PV, wind, battery, and DCFC during different scenarios.

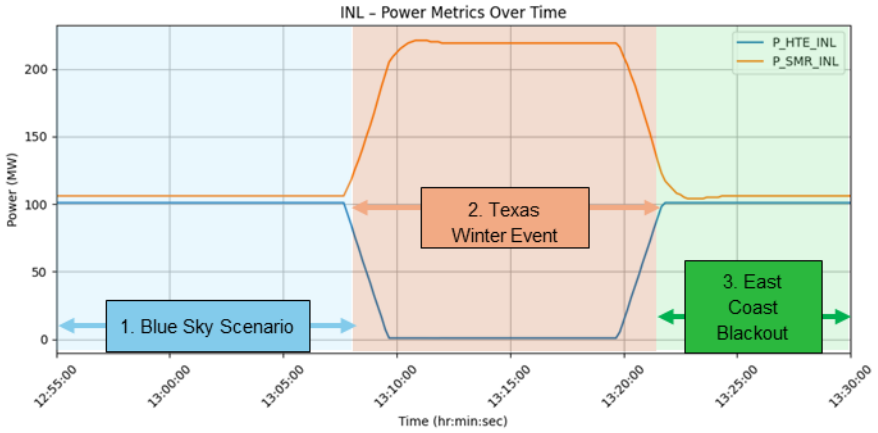

Figure 8. INL power profiles for HTE and SMR during different scenarios.

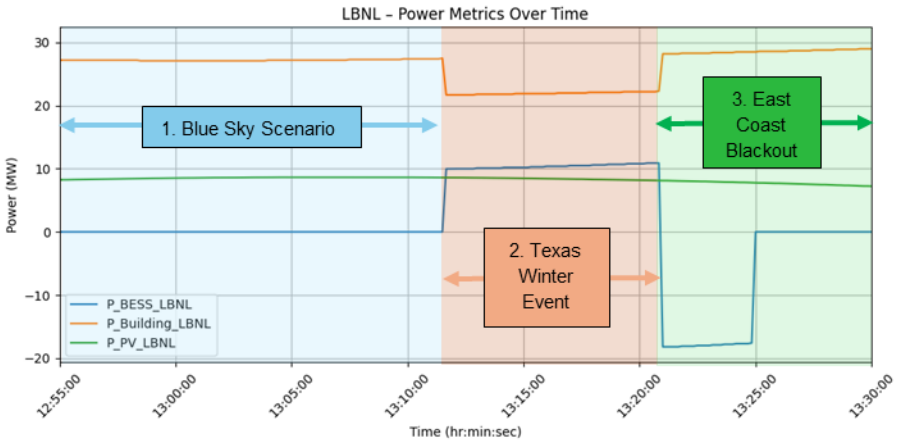

Figure 9. LBNL power profiles for BESS, building load, and PV during different scenarios.

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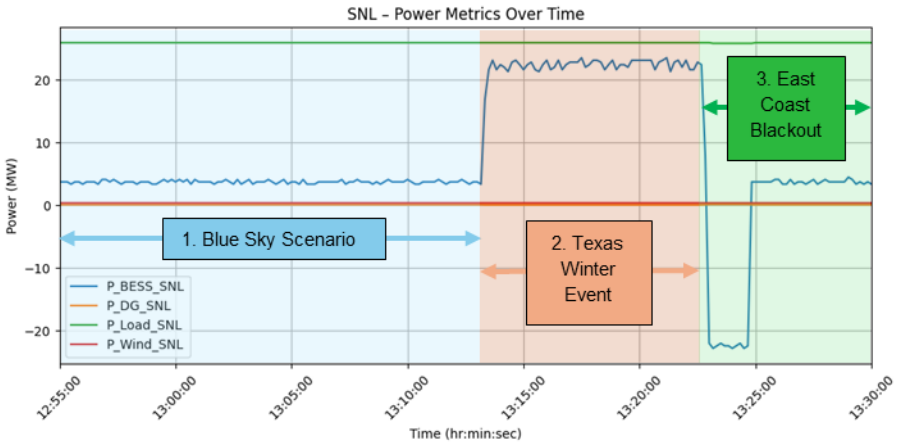

Figure 10. Sandia power profiles for BESS, diesel generator, load, and wind during different scenarios.

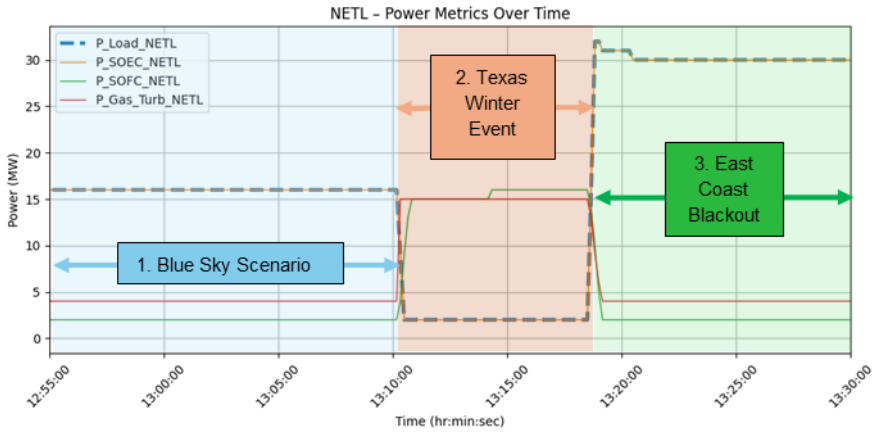

Figure 11. NETL power profiles for load, SOEC, SOFC, and gas turbine during different scenarios.

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6 Key Findings From Five-Lab Demonstration

The SuperLab 2.0 five-lab demonstration highlighted advancements in connecting geographically distributed energy assets into a cohesive, real-time, unified energy system. A major finding was the critical importance of **consistent and deterministic communication** between laboratories to enable both local and centralized filter compensation, which are essential for nullifying parameter offsets and maintaining time-synchronized asset control across each lab and the centralized energy controller at NLR. In the initial SuperLab 1.0 experiment, significant latency and jitter up to 369 ms introduced inaccuracies and made synchronized control of dynamic energy resources nearly impossible to induce fault-driven response. These delays compromised the realistic integration of distributed assets and stability of the experiments, especially during scenarios simulating fluctuating grid conditions in real time. The new information learned from the five-lab demonstration includes the interaction of various timescale devices such as the gas turbine at NETL, SMR command and control at INL, hydrogen electrolyzer and BESS at NLR, DC microgrid at Sandia, and building management at LBNL as if they were in a real-world setting, facilitated by ESnet. ESnet served as the network equivalent to those connections, with all real-time interactions occurring at the local labs while the ESnet connection mimicked the transmission/distribution lines. This setup is as close to a real-world environment as possible, capturing the CHIL and PHIL physics interactions. Although it does not capture real-world physics entirely, it is much more realistic than simple simulations.

The integration of ESnet and the OSCARS circuit reservation system proved transformative by transitioning away from standard internet connections to high-speed, dedicated scientific networks. This brought real-world fidelity to the experiments, allowing distributed laboratories to function as if they were side-by-side in a real grid environment, a critical advancement in modeling transmission and distribution operations under dynamic conditions. With ESnet, we were able to achieve more deterministic connections, and utilizing ESnet's Science Demilitarized Zone (DMZ) approach ensured that the connection latency remained consistent. This determinism allowed researchers to predict computational steps ahead or behind specific points, leading to the development of more sophisticated computational filters.

A key administrative best practice identified during the project was the standardization of Interconnection Security Agreements (ISAs). By making ISAs generic for all future power and energy asset remote connectivity standards, we have simplified the process and accelerated agreement approvals. This approach is crucial for any laboratories looking to connect seamlessly and effectively in the future. However, there is room for improvement. The ESnet team and the SuperLab team are currently working to make the ISAs not only generic but also multiyear, ensuring they are sustainable and more efficient for future projects. More work is needed to fully accomplish this goal, but the ongoing efforts are a significant step toward streamlining the administrative process and fostering smoother collaborations for remote connectivity.

Another key finding was that, in comparison to traditional modeling and simulation, leveraging synchronized, high-fidelity asset control connections using CHIL and PHIL with actual assets enables more realistic and actionable insights on grid asset interactions. This approach provides a higher level of fidelity and realism, making the findings more applicable to real-world scenarios and allowing researchers to better understand and optimize the dynamics of grid asset behavior. Assets from five national labs (NLR, INL, LBNL, Sandia, and NETL) were scaled digitally and coordinated across ESnet, simulating integrated energy systems that included wind, solar PV, BESS, SMRs, HTE, gas

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turbines, fuel cells, microgrids, EV chargers, and building-level controllable loads. This created the ability to study complex behaviors such as flexible nuclear/hydrogen operations, electrical-thermal coordination, building-to-grid interactions, and grid-forming inverter control under grid event scenarios.

The SuperLab 2.0 demonstration was positively received by utility stakeholders, with several participants inquiring about how utilities can actively engage in addressing challenges specific to their day-to-day operations. Utility feedback was collected during and following the demonstration, highlighting the significant interest in SuperLab 2.0's potential to de-risk the deployment of emerging grid technologies. Industry representatives emphasized this benefit during the demonstration. Future utility engagement will be pursued with the approval of DOE program managers to ensure coordinated and effective collaboration.

By creating a virtual yet highly realistic environment through SuperLab 2.0, researchers, industry partners, and utilities can address modern grid challenges without duplicating infrastructure investments. SuperLab 2.0 fosters collaborative innovation, validates new operational strategies, and enables scenario-based stress-testing of integrated energy systems.

In essence, **the SuperLab 2.0 project validated that geographically distributed yet synchronized assets and a virtual grid** can serve as a platform to address evolving energy challenges **without the limitations of physical proximity.**

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7 Conclusion

The SuperLab 2.0 project validated a scalable and replicable framework for de-risking new grid technologies and distributed energy systems without the need for massive physical infrastructure investments. It demonstrated that geographically distributed laboratories could operate as a cohesive integrated energy system under real-world grid dynamics, enabling complex system-level interactions that can support future energy resilience strategies.

SuperLab 2.0 expanded on the initial SuperLab demonstration to integrate diverse energy resources from five national laboratories. This demonstration presented a **model for operating geographically dispersed assets** under a unified grid condition, replicating complex interdependencies of real-world systems.

By leveraging DRTS and communication networks that operate at the same speed as those used in CHIL/PHIL setups, we were able to closely replicate real-world environments. This includes interactions between connected grid assets and real communication protocols. The result is a more realistic emulation, capturing power system dynamics at 50-µs resolution and communication delays that closely mirror real-world conditions.

By achieving consistent and deterministic communication alongside synchronized asset control, SuperLab 2.0 opens new avenues for collaboration among national laboratories, utilities, and industry stakeholders. This platform can accelerate technology validation, facilitate the integration of diverse and distributed energy resources, and foster robust solutions for extreme weather events and grid contingencies.

To further broaden its impact, SuperLab 2.0 plans to **integrate additional national laboratories** specializing in high-performance computing, next-generation power conversion technologies, and innovative grid-edge applications. Future development will also prioritize strong utility collaboration frameworks, deploy targeted grid validation campaigns, and build a national repository of validated control strategies for modern grid operations.

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