NREL

Transforming ENERGY

ARIES

Advanced Research on Integrated Energy Systems Research Plan

ARIES Advanced Research on Integrated Energy Systems Research Plan

Jennifer Kurtz and Rob Hovsapian

National Renewable Energy Laboratory

Suggested Citation
Kurtz, Jennifer and Rob Hovsapian. 2021. *ARIES Advanced Research on Integrated Energy Systems Research Plan*. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/81475.pdf

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP- 5C00-81475
December 2021

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

List of Acronyms

AC	alternating current
ARIES	Advanced Research on Integrated Energy Systems
CHIL	controller-hardware-in-the-loop
DC	direct current
DER	distributed energy resource
DOE	U.S. Department of Energy
DRTS	digital real-time simulators
ESIF	Energy Systems Integration Facility
EV	electric vehicle
HERTH	Hybrid Energy Real-Time Emulation Hub
HES	hybrid energy system
HIL	hardware-in-the-loop
HVDC	high-voltage direct current
IESS	Integrated Energy Systems at Scale
MVDC	medium-voltage direct current
NREL	National Renewable Energy Laboratory
PHIL	power-hardware-in-the-loop
PV	photovoltaic
R&D	research and development

Table of Contents

List of Figures

List of Tables

Introduction

The energy system that underlies our economy, our security, our relationship to the environment, and our daily lives is changing like never before. Amid this energy transformation, we have an opportunity to act now and advance the research that will lead to the best possible energy system for the future—affordable, flexible, clean, secure, resilient, and reliable.

During the past century, our energy infrastructure has evolved from an architecture of large, centralized power generation and control to a hybrid system that incorporates a variety of distributed energy resources (DERs) near the grid edge. At the same time, the electric grid is becoming increasingly interdependent on other infrastructures, such as natural gas, transportation, water, and telecommunications. Now, research and development (R&D) are needed at the frontiers of distributed management, wide-scale integration, and real-time system optimization.

The actions we take to modernize our energy infrastructure must address the fundamental challenges of integrated energy systems at scale:

- Managing variability in the *physical size* of new energy technologies being added to the energy system
- Controlling *large numbers* (millions to tens of millions) of interconnected devices
- Integrating *multiple diverse technologies* that have not previously worked together.

Although these challenges are significant, they also create enormous potential. With the visionary research platform Advanced Research on Integrated Energy Systems (ARIES), the National Renewable Energy Laboratory (NREL) will show how current challenges advance future innovations.

ARIES creates an environment to address the challenges of integrated energy systems at scale in the areas of energy storage, power electronics, hybrid energy systems (HES), future energy infrastructure, and cybersecurity—five research areas of critical importance in the scale-up from hundreds to millions of interconnected devices (Figure 1). This research plan describes the research platform, objectives, outcomes, and capital investment needs of ARIES.

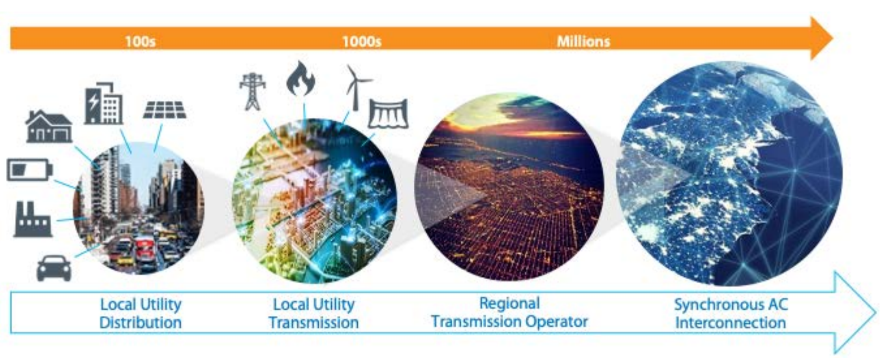

Figure 1. Millions of interconnected devices at multiple scales

1 A Research Platform to Support a Rapidly Evolving, Interdependent Energy System

To anticipate the evolution of our energy system, we need to get ahead of it. The ARIES platform allows us to prepare for and project what a full-scale energy transformation could look like. ARIES is a capability to explore new connections among ever-changing technologies and overlapping energy domains. With its proposed size and versatility, ARIES will be a key platform to ensure that our nation's energy system remains secure, stable, efficient, and effective at all scales.

Only a capability that investigates system behavior at multiple scales can show the impact of new technologies and trends in the industry. At the grid edge—where consumers connect to the electric grid—vast sensor arrays, high-speed networks, and advanced communications are creating a dynamic space where energy is not only passively consumed but also generated, stored, managed, and traded.

Further, at multiple scales, cost-competitive renewables are providing an increasing share of the energy mix, replacing a small number of large, dispatchable, inertial-based generation sources with many smaller power electronics-based sources, which are largely nondispatchable. In addition to these changes to the electric power system, we expect continued adoption of electric vehicles (EVs), smart energy management systems, and the electrification of heating/cooling systems in residential and commercial buildings. Together, we foresee the emergence of new energy systems, where infrastructures that once operated independently, such as electricity and transportation, overlap and are interdependent.

These new integrated energy systems will operate differently than they ever have. With preparation, we can incorporate new technologies with increased flexibility and coordination and with increased resilience to withstand and recover from natural disasters as well as cyber- and physical attacks. The costs of not preparing, however, could be damaging to utilities, customers, infrastructure, and industry.

Addressing changes to the energy system will require investment in a new national capability—an ability to conduct integrated research at the interface between distribution and bulk power systems, complemented with the development of new technologies and control techniques, advanced sensing and data analytics, and more sophisticated models and validation techniques.

The research objectives of ARIES are framed around the following integration needs and opportunities:

- **Increased penetrations of low-cost variable generation and storage**: Low-cost energy sources (e.g., natural gas, wind, and solar) are leading new capacity additions on the U.S. grid—in both the bulk and distribution systems. In traditional centralized generation, flexible generators ramp up or down in response to changing demand and use their inertia to manage grid stability. Variable power sources, however, such as wind and solar, are not entirely dispatchable (i.e., generation that can be controlled to follow load) and predictable; therefore, supply and demand profiles do not always align, causing curtailments or negative pricing. Currently, there is poor visibility upstream and downstream of the substation and few integrated controls of bidirectional power flows. Increased visibility and controls could improve situational awareness and grid operations, potentially improving the affordability of services (i.e., energy, capacity, ancillary). As increasing amounts of low-cost wind and solar are added to the electric grid, and as some baseload plants are retiring, the relative level of variable generation increases. This, plus the addition of more low-cost storage and the offset of electricity growth resulting from progress in energy efficiency, is changing the balance of energy, capacity, and ancillary services that is required in many grid operating regions and thus affects the future affordability, reliability, and resilience of the energy system.

- **Increased power electronics-based management and controls**: Households, businesses, and utilities are constantly installing new devices (e.g., EV chargers, rooftop solar, energy storage, and smart appliances) on the grid. As the number of these new devices increases to the millions, new solutions and capabilities are needed to optimize distribution power system management. The ability to handle communications with this large number of devices and the resulting big data also become a challenge in managing the electric grid. In an optimal system, there would be reliable communications and visibility between the bulk power and distribution system sides to maintain overall grid equilibrium and to maximize asset utilization; thus, seamless power flow, communications, and data management between the distribution and bulk power systems would create more real-time options for operating decisions that can benefit both customer preferences and grid stability. The multitude of devices and new solar and wind power plants on both the distribution and bulk power system sides will interface through power electronics that can improve stability and provide controllable interfaces between devices and subsystems, but it will not be enough to manage power flows or dampen instabilities by speeding up or slowing down synchronous generating devices; therefore, controls and integration strategies for high penetrations of power electronics-based devices need to be developed.
- **Hybridization of energy systems**: Unknown interdependencies within HES—systems at the intersection of domains such as the electric grid, electrified transportation, and fuels—present a challenge for the grid. Among these systems, a mix of technologies, generation types, and control strategies adds complexity to their integration. HES exist as either intentional integrations of new generation and storage or by virtue of individual technologies combined in a new control architecture (e.g., in microgrids). To de-risk hybridization, we need to study power-to-X (where X = molecules, hydrogen, heat, etc.), controllable loads (e.g., EVs, buildings, and industrial loads), and multi-timescale control strategies. The challenges of interdependencies can be managed by including at-scale interactions of generation, storage, advanced controls, and cybersecurity in HES both during the integration and planning stages.
- **Cyber-secure control strategies**: As singular bulk generators are replaced by millions of distributed wind power plants, photovoltaic (PV) systems, and storage systems, and as home, commercial buildings, and industrial facilities start to manage DERs by shaving, shifting, and modulating loads, reliance on vulnerable communications and control systems is increasing. Diffuse communications and control systems throughout the bulk power system and at the grid edge present more vulnerabilities than the current hierarchical system; however, the massive increase in the localized sensing and control of these systems can enable automated identification and response to cyber or physical

disruptions. Changing from a reactive defense by hardening cybersecurity to one of proactive defense by automating identification and response will begin shifting the paradigm of how we defend our energy systems. The magnitude and importance of these challenges cannot be overstated: The continued security and economic growth of the United States depend on it. These fast-moving technological and operational challenges along with increasing cyber threats require immediate and sustained action.

These integration challenges are the most relevant topics to energy research, yet there is currently no research platform anywhere in the world that can support research at the scale and versatility necessary to understand their future impacts. *Existing platforms can interconnect a few hundred devices at once, but none can successfully emulate the number of devices (>10^4) that will be connected to the grid in the next 3 years.* This lack of scale in experimentation will severely limit the ability to integrate new technologies into either distribution or transmission power systems.

With ARIES, we have the opportunity to develop and evaluate new technologies in a holistic, integrated energy system, for the first time, and at a moment when such a capability is most needed.

1.1 What Is ARIES?

ARIES is a research platform designed to de-risk, optimize, and secure current energy systems and to provide insight into the design, scale-up, and operation of future energy systems. ARIES is a unique asset to the U.S. Department of Energy (DOE) national laboratory complex that integrates real equipment and devices, emulated devices, hardware-in-the-loop (HIL) experiments, high-performance computing, and assets at other national laboratories to allow full experimentation of integrated energy systems at a scale that replicates the real world. Because the electric grid is the central enabler for most real-world integrated energy systems, ARIES is built around an integrated electric grid research environment. ARIES research also includes energy conversion infrastructure, such as power-to-X, to evaluate the value streams in accordance with energy applications or use cases that combine several energy technologies.

The ARIES platform (Figure 2) will leverage existing capabilities at NREL's Energy Systems Integration Facility (ESIF) and the Integrated Energy Systems at Scale (IESS) capabilities at NREL's Flatirons Campus and expand these capabilities through new investments to answer research questions for at-scale integration of energy systems and technologies. The ARIES platform will support and interconnect multiprogram research being conducted at the ESIF, IESS, and a virtual emulation environment that uses advanced computing and digital real-time simulators (DRTS) for power-hardware-in-the-loop (PHIL) and controller-hardware-in-the-loop (CHIL). This high-fidelity emulation and HIL platform can reduce uncertainties and assumptions on individual component and system technical performance and provide more consistent results for analysis and planning. A 100-Gbps fiber-optic link will interconnect the physical sites and virtual capability along with external connections to other national laboratories and research partners.

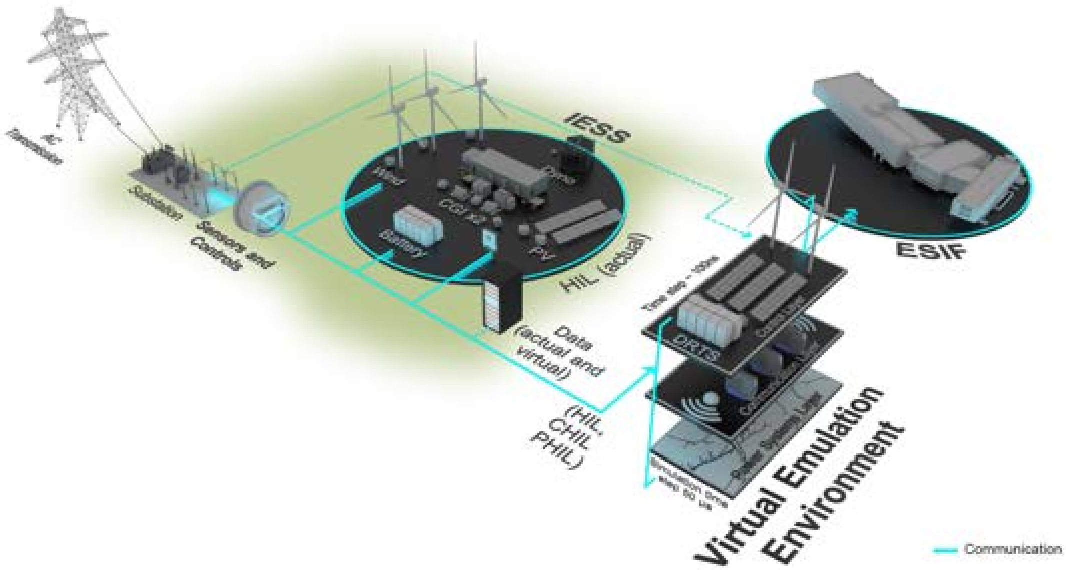

Figure 2. Conceptual layout of ARIES interconnecting the ESIF, IESS at the Flatirons Campus, and the virtual emulation environment

The high-speed exchange of power and communications will allow researchers to link assets at both sites and emulate millions of devices in a virtual environment. The unprecedented scale of this research network will make it possible to explore breakthrough topics at the frontier of energy systems.

Research at the ESIF can go up to 2 MW, which covers customer-level and distribution-size experiments. The IESS will allow for research at the 20-MW scale and beyond, representing the interface between the distribution and bulk power system levels. Using a state-of-the art, high-speed network as the backbone, this new capability will create solutions that optimize the integration of renewables, buildings, energy storage, and transportation. A summary of some ARIES device and system attributes can be grouped into fast and slow timescales (Table 1). The virtual environment applies to all scales.

The fast-timescale processes—which include power system stability, fast resilience services, and device/system performance under faults—are best characterized with colocated hardware, but larger systems can be characterized with PHIL. At the bulk power system size, simulations leveraging high-fidelity hardware characterization with CHIL are appropriate. The slow-timescale attributes, which include load/generation balancing and slow resilience services, can leverage both local and remote hardware to assemble complex experiments with distributed resources.

Table 1. ARIES Hardware-Based Research Scale Summary

Hardware-Based ARIES Research Space	Device Level <10 MW	Microgrid 0.1 MW–20 MW	Small Power System 20 MW–100 MW	Bulk Power System >100 MW
Fast timescale (>1 Hz): • Power system stability • Fast resilience services • Device/system fault performance	Yes—full-scale hardware characterization and PHIL	Yes—full-scale hardware characterization and PHIL	• Yes—hardware characterization for simulation • Local PHIL for small power systems	Yes—high-fidelity hardware characterization and CHIL for simulation
Slow timescale (<1 Hz): • Load generation balancing • Slow resilience services	Yes—full-scale hardware characterization and PHIL	Yes—full-scale hardware characterization and PHIL	• Yes—hardware characterization for simulation • Remote PHIL	Yes—high-fidelity hardware characterization and CHIL for simulation

The ARIES research platform is designed to adapt to the rapid pace of innovation in the energy sector. If new advances in one area upend the viability of certain technologies or cause them to flourish, ARIES is flexible enough to accommodate these changes.

Flexibility is achieved through a combination of at-scale hardware, emulation, research platform interface/interconnect design, and advanced computing. Likewise, the platform is agnostic to technologies and can connect with multiple types of generation, storage, conversion devices, or related combinations of technologies. ARIES was specifically designed to answer the most important changes that face the industry, researchers, and DOE. Other significant challenges for future integrated energy systems are addressed in the five primary research areas within the ARIES platform (Figure 3).

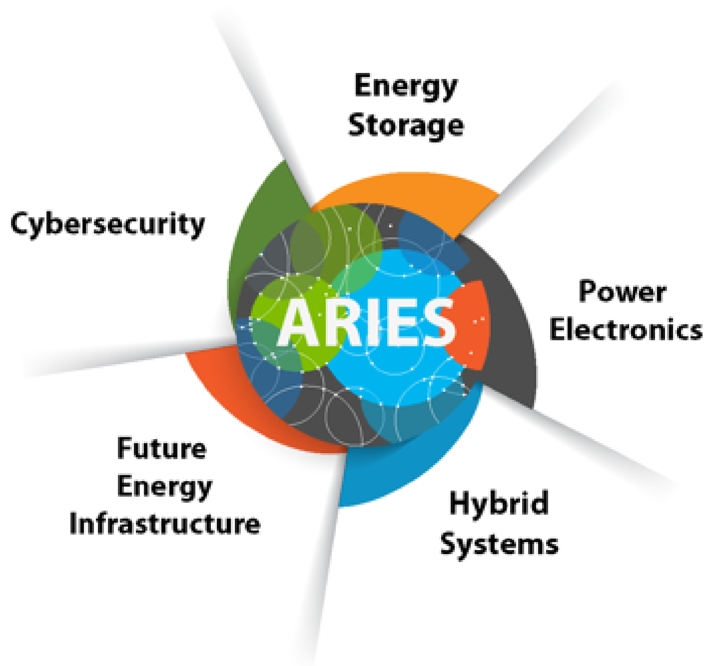

Figure 3. ARIES research areas

Future energy systems will not be affected by one topic or technology in particular, but, without exception, they will be affected by a combination of changes. Preparation will require an outlook of operations at distinct timescales and physical scales, and it will require using a new suite of technologies and resources. The vision of ARIES is to integrate diverse research areas in the laboratory to accurately reflect the interconnection that happens outside the laboratory.

ARIES, through work with each DOE Office of Energy Efficiency and Renewable Energy office and stakeholders, provides a crosscutting portfolio of R&D tools and approaches. This will allow researchers, entrepreneurs, utilities, and other stakeholders the ability to resolve the technical, operational, and financial risks of the large-scale integration that the ARIES platform will address. The ARIES impact will be through effective collaboration with DOE and a diverse set of stakeholders to ensure that relevant research is conducted to address the R&D integration challenges. Research and experiments using ARIES will provide data and information to multiple stakeholders involved in the planning and operations of the electric grid and other energy infrastructures.

In the following sections, we present each research area of ARIES, and we describe how they are integrated within the ARIES research platform.

2 ARIES Research Areas

ARIES creates a research space that unites capabilities across technology areas and explores operations on realistic, integrated systems. Only through evaluations and understanding the interdependencies among these areas is it possible to fully optimize integrated energy systems. The five research areas that are studied collectively within ARIES are:

- Energy storage
- Power electronics
- Hybrid energy systems
- Future energy infrastructure
- Cybersecurity.

Note that these research areas, though detailed individually, are highly interconnected within ARIES. That dependence of one research area on one another is critical and unique to address the three fundamental ARIES challenges. Each research area is summarized, along with the area's challenges, research goals, and possible research and capability outcomes. Each research area addresses the fundamental ARIES challenges and also has a set of unique research requirements needed to achieve integrated energy systems research across many conditions.

2.1 Energy Storage

Energy storage is a hot spot of innovation and is essential as a resource for stability and energy savings at every scale. The ARIES research platform can validate the multiple applications of energy storage using real hardware—from wind turbines to utility-scale batteries—and with real-time controls.

2.1.1 Challenge

Energy storage is critical to realizing both a flexible, resilient electric grid and a modern, affordable transportation system powered by a diverse suite of energy resources. Improvements are required in bidirectional electrical energy storage and other technologies to increase the flexibility of energy supply and demand, to minimize or eliminate demand charges, to manage power delivery from the electric grid, and to mitigate adverse distribution-level impacts. Further, R&D will drive advancements in the integration and control of DERs and improve the integration of many different loads that must interface with energy storage systems.

Because of the complexity of the evolving energy system, it is critical to address storage challenges from a system-level rather than a technology-specific perspective. Investing in and developing new research capabilities are essential to creating and sustaining global leadership in energy storage utilization and exports, ensuring a secure domestic manufacturing supply chain that is independent of foreign sources of critical materials.

2.1.2 Research

Many new storage technologies need to be validated at scale if they are to be part of a reliable and integrated solution. These new technologies span novel battery chemistries, innovative thermal storage systems, innovative energy conversion technologies (e.g., electrolyzers producing hydrogen), pumped storage hydropower, and others. Energy storage at ARIES will focus on high-energy and high-power storage systems spanning a range of storage duration, energy types, and power capacity.

One unique aspect of ARIES will be the direct coupling of multiple at-scale energy storage technologies (e.g., batteries-plus-thermal, batteries-plus-hydrogen) while integrated with a range of power generation options and power levels. Insights from these experiments will support essential research toward characterizing and validating system models and control algorithms, and it will help identify research targets.

The ARIES research platform will be used to characterize transient and steady-state behavior, performance, scaling challenges, and failure mechanisms that are expected to change as technologies graduate from the laboratory to the multimegawatt level. Interfaces and physical size can both have significant impacts on operation, failure modes, heat dissipation, device degradation, and optimal performance. The energy storage research area will address the three fundamental ARIES challenges by focusing on integrated energy storage at scale for:

- Electric grid modernization, reliability, and resilience
- Sustainable mobility
- Flexibility for a diverse and secure, all-of-the-above electricity generation portfolio
- Enhanced economic competitiveness for remote communities and targeted microgrid solutions.

2.1.3 Outcomes

Outcomes of the ARIES energy storage effort will set new benchmarks for efficiency and capacity of several specific applications of energy storage. In the near term, ARIES will address the safety hurdles of blending hydrogen into the natural gas infrastructure by studying the effects on material capability and infrastructure leaks for up to 50% hydrogen blends.

Later-term outcomes will accelerate the development of midsized behind-the-meter storage solutions that are free of critical materials, validate the economic viability of hydrogen produced via renewably powered electrolysis, and validate cost-effective methods for improved heat transfer and thermal energy storage.

2.2 Power Electronics

Power electronics create a new degree of control on the grid. If we can understand such devices and optimize their behavior, we can truly unlock their potential value for resilience and efficiency. The most urgent topics in power electronics involve their deployment at scale and integrated. These are the capabilities that ARIES brings to power electronics research.

2.2.1 Challenge

The use of power electronics within the energy system continues to increase, and current grid modernization efforts will perpetuate this trend. Renewable generation from wind and solar, for example, are driving growth in power electronics, which interface renewable energy to the grid and convert direct current (DC) to alternating current (AC), and vice versa, of the local power system. Battery energy storage systems and EVs supplying vehicle-to-grid services require similar interfaces but with bidirectional capability. Further, modern electrical loads are increasingly power electronics-based, including variable-frequency motor drives, EV chargers, solid-state lighting, and general electronic loads (e.g., televisions and computers). At a larger scale, the grid also contains multiple high-power power electronics-based elements, such as high-voltage DC (HVDC) transmission and flexible AC transmission systems, and it will eventually include solid-state transformers and asynchronous grid interconnection devices.

2.2.2 Research

ARIES R&D in power electronics will develop solutions to integrate increasingly higher levels of power electronics-enabled generation, storage, and loads into the power system as it evolves from the current, largely synchronous, machine-based system to a future system that uses power electronics interfaces to support flexible and resilient operation. The opportunities and challenges to be addressed by this research area include, but are not limited to:

- Developing a better understanding of the limits of grid-following power electronics-interfaced generation and developing power electronics controls to increase these limits to enable higher levels of renewable generation
- Improving grid resilience via the development of black-start-capable power electronics-interfaced generators and loads
- Addressing fundamental differences between power electronics-interfaced equipment and synchronous machines in terms of fault response to improve overall system protection performance and to improve system reliability and resilience
- Integrating, using, and developing new power electronics technologies—such as wide-bandgap semiconductor devices, converter architectures, energy storage elements, and thermal management techniques—to continue enabling power electronics-grid interfaces to increase in functionality while maintaining or reducing overall cost.

Power electronics-based grid interfaces are becoming the predominant way for generation sources and loads to connect to the electric grid. Power electronics research will cover the three fundamental ARIES challenges by:

- Advancing grid operations with very high levels of power electronics-interfaced generation and load
- Developing and integrating new power electronics technologies that are designed specifically for utilization in future grid applications.

2.2.3 Outcomes

Power electronics research using ARIES will develop and characterize power devices at a scale that is meaningful to the power system industry (e.g., transmission and distribution scales). This research will specifically enable low-risk PV interconnection in grids that risk stability impacts from distributed solar; and it will prototype and evaluate new technologies, such wide-bandgap power electronics, and their impact on the grid.

2.3 Hybrid Energy Systems

A hybrid combination of energy technologies requires that we understand the integration of such systems—both their management at a multiple scales and their controls. The ARIES research platform is uniquely able to reproduce the diverse timescales, physical scales, and technologies that comprise HES.

2.3.1 Challenge

HES are defined as the integration and coordinated operation of generation, energy storage, energy conversion, and controls. HES research is needed to understand the effects that various parts of energy systems can cause on one another as an integrated system. There are predicted benefits of creating multi-technology HES, which are fully quantified in terms of generation cost, system reliability, and operational flexibility. Overcoming the challenges to arrive at HES will drive more research and innovation in individual technologies and the development of HES operational strategies.

A major challenge of highly distributed systems is the large number of controllable technologies and the variety of devices. It is conceivable that a large metropolitan area could have more than 10 million controllable assets. As generation and storage become increasingly large and distributed, we will require new techniques to optimize and control the emerging energy system. Current approaches in distributed and online optimization, adaptive control, and machine learning are becoming increasingly inadequate in high-dimensional regimes (e.g., multiple hierarchical scales, multiple energy domains, and varying temporal dimensions).

2.3.2 Research

HES research is needed to optimize both individual components and entire systems by evaluating performance and developing the necessary science and technology to realize HES. ARIES research encompasses system-level advanced controls and power electronics that are needed to fully optimize these systems. Research in HES advances the foundational science for the real-time monitoring, optimization, and control of large-scale energy systems, which are governed by complex physical, behavioral, and computational interdependencies at multiple spatial-temporal scales. The research will develop a rigorous mathematical underpinning that offers a common and powerful analytic framework for modeling, computation, communications, optimization, and control.

These frameworks will be heavily interdependent on data analytics to improve run times and complex system simulations to express, discover, and address new principles and phenomena and to validate the performance of existing frameworks. Simulating highly complex systems with distributed controls across 10 million individually controllable devices will require integrated high-performance computing, DRTS, and PHIL to gather statistics, gain confidence, and optimize the system.

The Hybrid Energy Real-Time Emulation Hub (HERTH) will be developed for connectivity between various HIL and CHIL devices (up to 100, eventually increasing to more than 10,000) and emulated devices in real-time environments to demonstrate the dynamic and transient interaction of HES. This research area addresses all three ARIES challenges by focusing on the following key priorities:

- Optimizing the hybridization of multi-technology energy systems under multi-timescale dynamics and interdependencies
- Understanding the effects that various parts of HES can cause on one another

- Quantifying the benefits of such multi-technology hybrid systems in terms of cost, system reliability, and flexibility.

2.3.3 Outcomes

Following these research priorities, HERTH will enable a near-real-world environment that uses high-fidelity, physics-based, real-time models alongside characterized data and at-scale HIL experiments. HERTH will specifically allow NREL to eventually demonstrate the integration of renewables with storage and power-to-X at 10,000 nodes between NREL's campuses and other national laboratory assets. This scale of simulation will support the complete evaluation of controls, optimization, and data analytics that will characterize future power systems.

2.4 Future Energy Infrastructure

Energy infrastructure is affected at every scale by modern technologies and system growth. The improvements to energy infrastructure will impact transmission and distribution networks for generations to come. ARIES creates the scale and flexibility needed to study the exchange of energy at a size, integration, and degree of fidelity that has never been achieved.

2.4.1 Challenge

Transmission and delivery networks must advance to cost-effectively integrate higher levels of renewable generation and to achieve targeted levels of reliability, resilience, flexibility, security, and control. The ARIES future energy infrastructure capabilities support advanced science research and technology innovation for next-generation energy infrastructure solutions. Transmission and delivery networks are the backbone that create value in all sectors of the energy systems of the future—the power sector, transportation sector, building sector, and industrial sector, all of which rely on advanced transmission and delivery networks.

The future energy infrastructure will have two primary systems that will help achieve the optimized value of future energy systems: (1) advanced electricity infrastructures that address the delivery, management, and control of electricity across the bulk and distribution systems; and (2) advanced fuels infrastructure that will address the management and control of the delivery of fuels of all types, including natural gas, petroleum fuels, hydrogen, and other renewable fuels. The key challenge of both systems is the optimized value of the management, controls, and delivery designs given the rapidly evolving transformation of generation mix, storage, and conversion technologies.

2.4.2 Research

ARIES research in future energy infrastructure advances delivery platform designs, equipment designs, and management systems to support optimized delivery and control. Future energy infrastructure research at ARIES will specifically address advances to:

- Transmission grid designs, such as HVDC, medium-voltage DC (MVDC), and microgrid designs
- Delivery and control equipment, such as substation, transformer, and power quality management devices

- Management and control systems, such as power control systems, two-way control systems, communications, high-fidelity sensor instrumentations, and power quality control and management systems.

Distribution and transmission networks are each advancing to cost-effectively integrate higher levels of renewable generation. The key challenge for each will be achieving targeted grid reliability, resilience, flexibility, and security levels with evolving requirements in a fiscally responsible way. For these networks, research is needed into the next generation of (1) substation and transformer technologies and designs; (2) protection technologies; (3) grid sensors, measurements, and communications; and (4) control interfaces and management systems.

Future energy infrastructure research will also address infrastructure for advanced fuels, supporting the ARIES focus of integrating diverse technologies that have not previously worked together. This research concerns the management and control of the delivery of fuels such as hydrogen, methane, other renewable fuels (e.g., octane for marine and aviation), and fossil fuels to create the most cost-effective, highly configurable energy system.

2.4.3 Outcomes

The expected outcomes of the future energy infrastructure include the full implementation of a 19.9-MW controllable grid interface facility. The controllable grid interface will enable research on a full range of power delivery, management, and control equipment, and it will thereby support other ARIES research areas.

The combined capabilities of the future energy infrastructure with other ARIES assets will provide a platform to connect medium- and high-voltage hardware and to study system designs that span microgrids, synchronous generators, and electrolyzes for hydrogen fuel production. This research will help us understand the impacts and opportunities of high-penetration inverter-based grids, such as black starts and protection techniques.

2.5 Cybersecurity

The modernizing grid is a "system of systems" that brings together dissimilar forms of energy generation, load management, control networks, and communication platforms. In this system of systems, advances in device and network security are necessary but insufficient. Cybersecurity research must also close the system-level security gaps that inevitably emerge when so many hardware and software devices are brought into harmonious operation.

2.5.1 Challenge

The grid is transitioning from centralized, bulk generation to large numbers of distributed generation (wind, solar, etc.) and storage resources. Simultaneously, loads are becoming dispatchable through shaving, shifting, and modulating. These changes increase reliance on communications and control systems, which introduce new vulnerabilities to the system overall.

From these changes, ARIES has identified several challenges specific to cybersecurity:

- **Managing system complexity:** The scale and diversity of devices and energy technologies will result in an explosion of complexity. As system complexity increases, security becomes more difficult.

- **Ensuring security for large numbers of networked grid edge devices:** The large number of grid edge devices spread throughout a wide geographic area creates an enormous attack surface.
- **Providing real-time incident response:** In the event of a successful cyberattack, the system and system operators must mount a rapid, effective response to contain intrusion, minimize damage, and recover full system function.

2.5.2 Research

To address these cybersecurity challenges, ARIES has identified three broad programs of initial cybersecurity research:

- Proactive defense and automated response: Move beyond traditional cybersecurity hardening to automated detection, response, and endurance, leveraging NREL research's into autonomous energy systems.
- Improved situational awareness for cybersecurity: This will aid both manual responses and the monitoring of automated responses during rapidly unfolding cyber events.
- Communications innovation: Connect and control consumer-owned DERs and geographically dispersed bulk power resources more securely than current approaches, and assess the operational effectiveness and the security of new communication platforms.

2.5.3 Outcomes

In the near term, cybersecurity research under ARIES will build out an experimentation platform for the cybersecurity of communications and control, including advanced resources for visualization, monitoring, and data processing. This capability will then be incorporated with outcomes from other ARIES technical areas, with the ability to create digital twins for clusters of physical devices (e.g., PV plants, wind power plants, bulk storage facilities) and to use machine learning to detect attacks by comparing the digital twin state with actual physical systems. This research area will also implement a research distribution grid controlled and secured through 5G communications technologies.

3 ARIES Collaborations

Collaborations with other national labs and their existing capabilities will create an opportunity for a richer set of research experiments, results, analysis, and mining of data. Real-time interconnectivity among multiple DRTS at several U.S. national laboratories has proven to be valuable in the past. Multidisciplinary experiments have also been successful in leveraging energy assets at different DOE national labs. Specifically, the Energy Sciences Network, a closed-loop communications network among the national labs, could be used for synchronized ARIES research (see Figure 4).

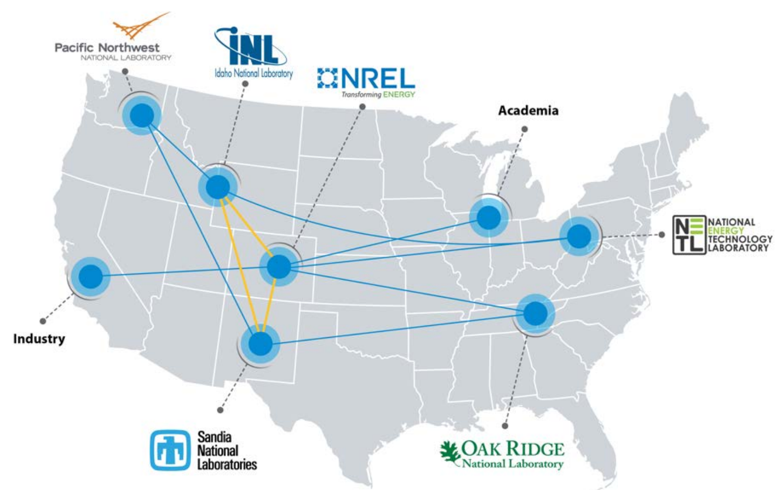

Figure 4. Proposed ARIES real-time connectivity between U.S. national laboratories

An example of an early cross-laboratory research collaboration with ARIES is the DOE Office of Electricity's Grid Storage Launchpad, located at Pacific Northwest National Laboratory. The collaboration of research within the Grid Storage Launchpad and ARIES provides holistic research capabilities for many types and scales of energy storage technologies. Research ideas include, but are not limited to, the definition of critical requirements, modeling and emulation, and the science of safety for energy storage technologies.

Research partnerships with industry are also valuable to ARIES research. A request for information was released in early 2018 to solicit feedback from industry, academia, research laboratories, government agencies, and other stakeholders on energy-efficiency and renewable energy R&D. The information formed an important foundation for the ARIES research platform.

Another request for information was open from February 11, 2020, through March 13, 2020, to ensure that the proposed ARIES research platform aligns with industry needs and priorities. Fourteen stakeholders responded to the request for information with varied feedback based on the wide range of respondents and reinforced the need for the ARIES research areas and at-scale capabilities. One common thread of the response was a need to address the scale-up of a wide range of energy technologies. Other common themes were research needs for interconnection, performance capabilities, central and distributed energy management, novel operating conditions, and the validation of energy technologies.

4 ARIES Research Capability Investments

A state-of-the-art research platform at a relevant scale, integration, and controllability is necessary to achieve the ARIES research vision. This section discusses the research equipment and infrastructure upgrades needed for ARIES research. The process for determining the capability investment list started with energy system experts, DOE and industry engagement, and current research experience. Each research area team completed many iterations of discussion on the research options and possible impacts for addressing the ARIES challenges. Possible stakeholders (DOE, industry, and academics) were another important factor in the determination of priority research options and the accompanying capabilities required. The ARIES team gathered research challenges and outcomes per research area, which were ultimately selected to inform and drive the capability investment requests summarized here.

The required equipment is organized first by the primary research area (Table 2) and second by the implementation phase. The estimated capability investment, spanning 5 years, includes the design, installation, and commissioning needed for the capability to be research ready. The capability investment request also includes the infrastructure needed to site, interconnect, and monitor the technologies.

Table 2. Five-Year Capability Investment Summary by Research Area

Research Area	General Objective	Equipment Required
Energy storage	Advance energy storage technologies based on a systems perspective to ensure a flexible, resilient energy system with increasing demand for multiple energy types	Batteries; hydrogen production, compression, and storage; hot and cold thermal storage, mechanical storage; highly integrated controllable loads; methanol; and carbon dioxide utilization
Power electronics	Develop solutions to integrate increasingly higher levels of power electronics-enabled generation, storage, and loads in the power system and new power electronics technologies	Power electronics grid interface platform, advanced power electronics technology proving ground, controllable load interfaces, prototypes, devices, 2-MVA PV inverter, 2-MVA synchronous generator, variable series/parallel impedance emulator
HES	Understand and predict the performance of large, integrated systems for optimization, monitoring, and control informed by scientific understanding or complex physical, behavioral, and computational interdependencies at various spatial-temporal scales	HERTH and distributed control prototypes; digital real-time communication, emulation, controls, and upgrades for 10K nodes and 1K device controllers; data acquisition, visualization, and technology-ready interconnection platforms

Research Area	General Objective	Equipment Required
Future energy infrastructure	Optimize the value of management, controls, and delivery designs for energy infrastructure that can adapt to a rapidly evolving energy system	Optical sensors, precision time measurements, 34.5-kV grid infrastructure, data integration, MVDC research platform, and substation device research platform
Cybersecurity	Automate the identification and response to cyber threats for existing and future energy systems	Digital twins; cyber research distribution grid, controls, and communications; and security prototypes for distributed grids

The new capability investments described so far have focused on ARIES investments primarily located at the IESS. The capability investment for the ESIF is equally critical for ARIES research. Those investments, spanning 5 years, are summarized in Table 3.

Table 3. ESIF Future Energy Infrastructure 5-Year Capability Investment Estimates

General Objectives	Investments
Development of energy system and grid cyber-physical security for a secure and efficient automated energy grid	Cyber technology lab, network research layer for labs, network security and encryption components and add-on devices, network discovery, analysis and machine learning tool sets
Advancement of key modern grid technologies for grid edge autonomy, DERs, microgrids, and distribution technologies	Combined heat-and-power and diesel gensets, battery energy storage, inverter, medium-voltage indoor power electronics test arena, advanced distribution management system, distributed energy resource management system, hundreds of grid edge devices, microgrid controller environment, medium-voltage sensors, fault research setup, AC and DC Emulators, RTDS Opal-RT real time simulators
Integration of electric and grid-interactive mobility technologies with the grid, energy storage, and buildings	DC distribution for extreme-fast-charging station at the Medium-Voltage Outdoor Test Area, research EVs, DC distribution 1600-A research electrical distribution bus, extreme-fast-charging station upgrades
Modernization of residential and commercial buildings by developing controls, storage, and interactive systems to increase efficiency and thermal integration/storage	Research chiller for combined head and power, environmental chamber upgrades, molten salt thermal storage, remote terminal unit support Infrastructure and building automation controllers, cold thermal storage

General Objectives	Investments
Development of advanced fuels and hydrogen systems for energy systems integration and electrons-to-molecules conversion advancement	Hydrogen pad expansion, hydrogen supervisory controls and data acquisition system controls upgrade, renewable natural gas/mixing distribution and storage, hydrogen fueling dispenser upgrades, supercritical carbon dioxide and capture
Research and methodology development for resilience science and engineering applied to energy systems, devices, and electric grid hardening	Integrated networking communications and controls, local-area network real-time emulation platform, complex system behavior emulation and visualization engine
Integrated research readiness	Collaborative visualization room, ESIF data acquisition and research data systems, modernization of the ESIF data acquisition system and harmonization with IESS systems

All these capabilities cross multiple research areas. Successful execution of ARIES research requires that the capabilities are closely designed, managed, and maintained. Figure 5 shows a summary of the required interconnections of equipment among research areas and phases. Research in one area is expecting to use capabilities in another area, indicated with a gray line and arrow. As the ARIES research progress, so will the interdependencies among research areas and capabilities, shown by the increase in connection lines for research in phases 2 and 3. This is an intentional design to address highly integrated energy system challenges.

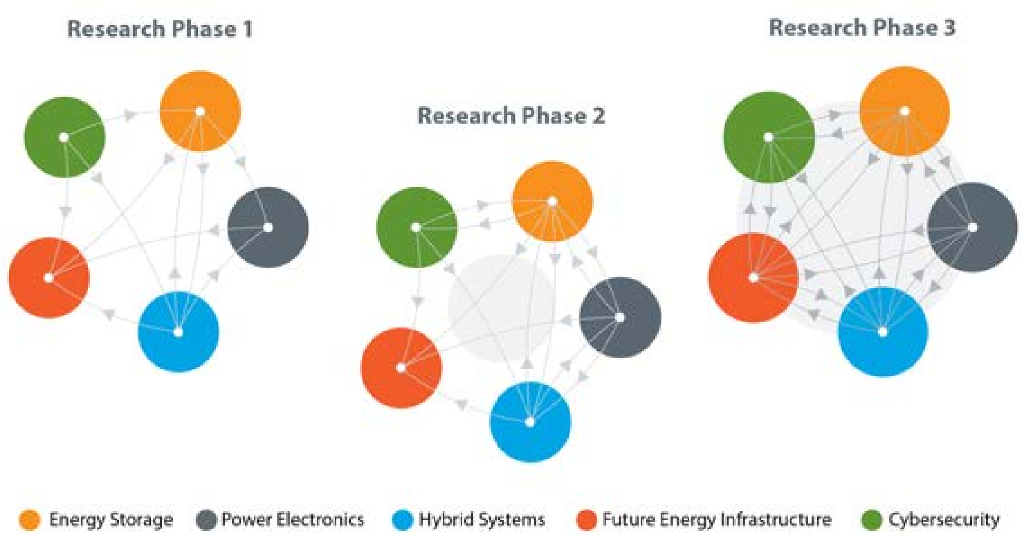

Figure 5. ARIES research interdependencies to capabilities by phase

5 Next Steps

The ARIES research plan will evolve based on changes with integrated energy systems and technologies. The team will continue to explore research collaborations and incorporate feedback from stakeholders. Near-term next steps include the ARIES stewardship plan, research prioritization, execution of research, and R&D of the ARIES capabilities.