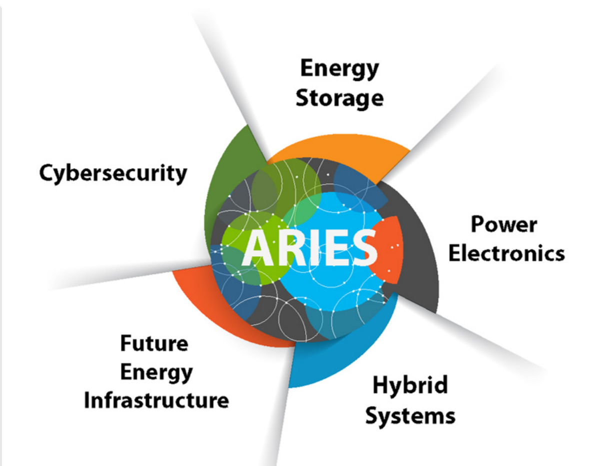
NREL
Transforming ENERGY

ESnet
ENERGY SCIENCES NETWORK

ARIES Network Requirements Review

May 2021



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DOE Office of Energy Efficiency and Renewable Energy, DOE Office of Science
Energy Sciences Network (ESnet)

ESnet is funded by the US Department of Energy, Office of Science, Office of Advanced Scientific Computing Research. Carol Hawk is the ESnet Program Manager

ESnet is operated by Lawrence Berkeley National Laboratory (Berkeley Lab), which is operated by the University of California for the US Department of Energy under contract DE-AC02-05CH11231.

This work was supported by the Directors of the Office of Science, Office of Advanced Scientific Computing Research, Facilities Division, and the Office of Energy Efficiency and Renewable Energy.

This is LBNL report number LBNL-2001476[1].

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Cover Images:
Advanced Research on Integrated Energy Systems (ARIES)

[1] https://escholarship.org/uc/item/5x5563kx

22-SN-35034

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1 Executive Summary

About ESnet

The Energy Sciences Network (ESnet) is the high-performance network user facility for the US Department of Energy (DOE) Office of Science (SC) and delivers highly reliable data transport capabilities optimized for the requirements of data-intensive science. In essence, ESnet is the circulatory system that enables the DOE science mission by connecting all of its laboratories and facilities in the US and abroad. ESnet is funded and stewarded by the Advanced Scientific Computing Research (ASCR) program and managed and operated by the Scientific Networking Division at Lawrence Berkeley National Laboratory (LBNL). ESnet is widely regarded as a global leader in the research and education networking community.

ESnet interconnects DOE national laboratories, user facilities, and major experiments so that scientists can use remote instruments and computing resources as well as share data with collaborators, transfer large data sets, and access distributed data repositories. ESnet is specifically built to provide a range of network services tailored to meet the unique requirements of the DOE's data-intensive science.

In short, ESnet's mission is to enable and accelerate scientific discovery by delivering unparalleled network infrastructure, capabilities, and tools. ESnet's vision is summarized by these three points:

1. Scientific progress will be completely unconstrained by the physical location of instruments, people, computational resources, or data.
2. Collaborations at every scale, in every domain, will have the information and tools they need to achieve maximum benefit from scientific facilities, global networks, and emerging network capabilities.
3. ESnet will foster the partnerships and pioneer the technologies necessary to ensure that these transformations occur.

Requirements Review Purpose and Process

ESnet and ASCR use requirements reviews to discuss and analyze current and planned science use cases and anticipated data output of a particular program, user facility, or project to inform ESnet's strategic planning, including network operations, capacity upgrades, and other service investments. A requirements review comprehensively surveys major science stakeholders' plans and processes in order to investigate data management requirements over the next 5–10 years. Questions crafted to explore this space include the following:

- How, and where, will new data be analyzed and used?
- How will the process of doing science change over the next 5–10 years?
- How will changes to the underlying hardware and software technologies influence scientific discovery?

Requirements reviews help ensure that key stakeholders have a common understanding of the issues and the actions that ESnet may need to undertake to offer solutions. The ESnet Science Engagement Team leads the effort and relies on collaboration from other ESnet teams: Software Engineering, Network Engineering, and Network Security. This team meets with each individual program office within the DOE SC every three years, with intermediate updates scheduled every off year. ESnet collaborates with the relevant program managers to identify the appropriate principal investigators, and their information technology partners, to participate in the review process. ESnet organizes, convenes, executes, and shares the outcomes of the review with all stakeholders.

This Review

On May 1, 2021, ESnet and the DOE Office of Energy Efficiency and Renewable Energy (EERE), organized an ESnet requirements review of the ARIES (Advanced Research on Integrated Energy Systems) platform. Preparation for this event included identification of key stakeholders to the process: program and facility management, research groups, technology providers, and a number of external observers. These individuals were asked to prepare formal case study documents in order to build a complete understanding of the current, near-term, and long-term status, expectations, and processes that will support the science going forward.

Key Findings

Several key findings emerged from the review in three major categories:

- Experimental facilities.
- Instrumentation and experimental resources.
- Network design, implementation, and operation.

These findings can be summarized as:

1. The National Renewable Energy Laboratory's (NREL) research platform for Advanced Research on Integration Energy Systems (ARIES) creates an environment to address integrated energy systems at scale challenges in the areas of energy storage, power electronics, hybrid energy systems, future energy infrastructure, and cybersecurity. The primary site will be NREL and other labs participating in ARIES related research (connected via ESnet) are Idaho National Laboratory (INL), National Energy Technology Laboratory (NETL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL).
2. ARIES-related research may involve these additional laboratories, including expertise and unique research assets to address energy system research at scales impractical to be addressed by any one laboratory.

3. Multiple assets exist throughout the ARIES program and at the collaborating sites. These include energy systems hardware, digital real time simulations, cluster and high performance computing (HPC) resources, control systems, and a number of other experimental resources.
4. The success of ARIES depends on establishing stable and predictable network connectivity between the participating sites.
5. ARIES network requirements are different from data-intensive experimentation. Bandwidth capabilities are not a concern, given that the instrumentation being used for experimentation will not produce large data files that require transfer to remote locations.
6. Stability and deterministic behavior are more important than bandwidth, as the crucial aspect for this work is "virtual proximity" - the time sensitive exchange of command and control information to allow disparate research assets to be federated and operate as if in the same room. Steps must be taken to characterize and understand the behavior during experimentation.
7. A keen understanding of latency and jitter is a requirement, given that experimental success relies on being able to understand these behaviors during analysis.
8. ESnet and ARIES are currently collaborating on the use of perfSONAR and Globus to characterize, monitor, and evaluate the network environment.

Opportunities

Several opportunities emerged from the review that relate to the near-term, long-term, and mission-critical goals of ARIES. These can be summarized as follows:

- ESnet will support NREL as needed in its outreach to INL, NETL, ORNL, PNNL, and SNL to raise awareness of the ARIES project and the immediate technical requirements and scientific milestones. This should include engagement of respective ESnet site coordinators at each site, along with ARIES technical staff.
- NREL will collaborate with ESnet to request the establishment of an initial set of On-Demand Secure Circuits and Advance Reservation System (OSCARS) circuits between NREL and the other ARIES sites to support operational trials. NREL will engage with other ARIES participants at INL, NETL, ORNL, PNNL, and SNL to establish memorandums of understanding (MOUs) for network traffic, since the connectivity may need to bypass cybersecurity profiles at a number of sites.
- ESnet will collaborate with ARIES sites to formulate a plan for testing initial OSCARS circuits between collaborating sites. Once established, this service will be used for the ARIES controls network, and must be validated against requirements for latency, jitter, traversed path, bandwidth, and other metrics that were determined by the system design.

- NREL will collaborate with ESnet to evaluate the technical requirements for potential longer-term OSCARS operation to support ARIES. This includes specifications for the ongoing stability of network metrics, inquiry into available application programming interfaces (APIs), ways that NREL can prepare for failure scenarios, and mechanisms that can be used to deliver network security functionality.

- ESnet and NREL will collaborate on the discussion of a framework for developing and enhancing the ARIES network environment in the future. Requirements may include developing Science DMZ infrastructure, network monitoring, and network security where necessary.
- ESnet and NREL will collaborate to develop a model, or design pattern, for connecting additional ARIES sites and services. Initial designs will originate from NREL. Future designs could resemble more of a mesh of connections.
- The aforementioned ESnet networking support will aid NREL for a series of demonstrations of ARIES capabilities for DOE EERE. Preparation for these activities began in August of 2021, and future events will occur on a roughly six-month cadence culminating in an at-scale demonstration at the end of FY2023.

2 Review Findings

The requirements review process helps to identify important facts and opportunities. The following sections outline a set of findings that summarize important information gathered during the review discussions. These findings are organized by topic area for simplicity, and adhere to these common themes:

- Experimental facilities.
- Instrumentation and experimental resources.
- Network design, implementation, and operation.

2.1 Experimental Facilities

- The ARIES platform will consist of resources deployed at a number of locations when complete. Up to five participating sites will connect to NREL over ESnet: INL, NETL, ORNL, PNNL, and SNL. These will be connected in phases through the end of the experimentation in 2023.
- The success of ARIES depends on establishing stable and predictable network connectivity between NREL and the other participating sites. ESnet is an available resource to each of the ARIES sites. In the near to medium term, experimental components will be located at the four participating sites.
- The ARIES platform may expand beyond the core locations as the results from the early experimentation help to guide future expansion to other use cases.

2.2 Instrumentation and Experimental Resources

- Multiple, significant, and complex assets exist throughout the ARIES platform at the collaborating sites. These include energy systems hardware (energy generation, energy storage, etc.), cluster and HPC resources for simulations and digital twins, control systems, and a number of other experimental resources.
- As each resource is integrated into the ARIES environment, functions such as operational telemetry, control, cybersecurity, and ongoing operational monitoring will be performed remotely using networking components.
- The multi-site nature of ARIES drives a requirement to design, create, and operate a "controls" network that is able to provide virtual proximity for the different ARIES assets and capabilities at the collaborating ARIES locations.
- Stability and deterministic behavior are more important than bandwidth for the controls network, and steps must be taken to characterize and understand the behavior during experimentation. This will entail understanding latency and jitter, such that the captured telemetry from each device can be characterized accurately. Bandwidth requirements are expected to be minimal (e.g., 1 Gbps to start).

- In the event of an underlying failure to the network infrastructure, it is desirable to enable notification and predict the resulting behavior during a failure scenario. For instance, a total loss of connectivity can be accounted for, but a network change that results in increased latency may result in higher than expected experimental error into the experimental observations.

2.3 Network Design, Implementation, and Operation

- The distributed nature of the ARIES platform requires networking to be a core functionality to ensure experimental success.
- In the near term, ARIES requires a stable, deterministic distributed network, which interconnects components at the collaborating sites, as well as the ability to back up data sets over the network. Bandwidth requirements to support ARIES are minimal, with 1 Gbps expected during pilot phases to establish data flow expectations.
- In the medium (two- to five-year) term, the ARIES platform will need multiple network-centric capabilities, including a distributed controls network, remote visualization capabilities, and the integration of computing/digital twin capabilities with the experiment environment.
- In the medium (two- to five-year) term, network security for the ARIES control network will be explored using a variety of security approaches. These may include encryption and intrusion detection systems. NREL will collaborate with ESnet to understand the impacts of these on network behavior.
- In the future, ARIES may add additional sites beyond the current four locations, and more connected resources at each site.
- ARIES network requirements are different from data-intensive experimentation. Bandwidth capabilities are not a concern, given that the instrumentation being used for experimentation will not produce large data files that require transfer to remote locations.
- The ARIES platform has specific needs for deterministic behavior, low jitter, and network transparency regarding performance and operational status. The experimental instruments will frequently transmit small amounts of data that must be recorded, and this information often has time-sensitive implications during operation. ARIES will collaborate with ESnet to understand what forms of service level guarantees are available, along with any telemetry that can aid in experimental operation.
- NREL is considering using ESnet's OSCARS virtual circuit service as a solution for the ARIES distributed controls network. This use case would allow all of the participating sites (INL, NREL, NETL, ORNL, PNNL, and SNL) to leverage their existing ESnet connections to create a logical overlay. Initial design of this would have NREL operating as the central location, with others connected to it (e.g., a "star" paradigm). Once in place, this would facilitate a site by site, and platform-wide, set of policies for operation and security.

- NREL will engage with other ARIES participants at INL, NETL, ORNL, PNNL, and SNL to establish MOUs for network traffic, since the connectivity via OSCARS may need to bypass cybersecurity profiles at a number of sites.
- Section 5.9 of the case study provides a list of design considerations. While this list may not be exhaustive, it serves as a foundation for scoping the parameter space of the design collaboration.
- ESnet and NREL are currently collaborating on the use of perfSONAR to characterize and monitor the existing network environment for ARIES for both Science DMZ and enterprise network deployments. Future testing will be done across the overlay controls network using domain-specific tools, along with perfSONAR.
- ESnet and NREL are currently collaborating on the use of Globus to participate in the Data Mobility Exhibition (DME).

3 Review Action Items

ESnet recorded a set of opportunities from this May 2021 review that relate to two event horizons for ARIES operation. These are:

- Near-term planning.
- Strategic planning.

As of May 2021, NREL was expected to undertake a series of progressively larger capabilities demonstrations for DOE EERE leadership starting in August of 2021 as a part of a performance evaluation and measurement plan (PEMP). These internal demonstrations will occur roughly every six months, with an at-scale demonstration at the end of FY2023 as a major milestone in the ARIES project's PEMP. Opportunities related to this event will be tracked separately from the planning goals.

3.1 Near-Term Planning

- The ESnet Science Engagement Team will brief ESnet's program management, leadership, and the Network Engineering Group on the findings and opportunities from the ARIES review.
- ESnet site coordinators (ESnet Site Coordinators Committee [ESCC] members) for INL, NETL, NREL, ORNL, PNNL, and SNL should be immediately engaged alongside their ESnet site ambassadors to raise awareness of the ARIES project, and of the pending technical requirements and scientific milestones, including how to request network services to support demonstrations and ongoing operation.
- INL, NETL, NREL, ORNL, PNNL, and SNL will work with ESnet to request an initial set of OSCARS circuits to support ARIES experimentation. Each circuit will link NREL to the other sites, and will consume 1 Gbps of bandwidth to start. Once this request is established with ESnet engineering, an initial design of service will come from consultations with ESnet Networking Engineering and ESCC members from the involved sites. These experiences will inform the strategic design efforts.
- Consultations should include a plan for testing the initial OSCARS circuits for the controls network, using either the perfSONAR network measurement framework or the proposed ARIES controls software. Testing should include latency, jitter, path, bandwidth, and other metrics, as determined by the design.
- Consultations should also include an evaluation of the technical requirements for ongoing OSCARS operation. This includes specifications for the ongoing stability of network metrics (e.g., jitter, latency, traversed path), available APIs, and ways that NREL can prepare for failure scenarios.

3.2 Strategic Longer-Term Planning

- ESnet and NREL will collaborate to discuss a framework for enhancing the ARIES network environment. This could include multiple elements, including plans for adding additional network services (e.g., support for remote visualization) and incorporating computing (e.g., cluster, HPC, high-throughput computing) resources. These may become part of the distributed controls network or use other ESnet network services.
- 5G discussions are also underway to test how to connect remote parts of the NREL campus and ARIES instruments that are not reachable by fiber.
- ESnet and NREL will collaborate on potential models that could support wide-area use cases for ARIES. These discussions could allow for the adoption of a Science DMZ model for data movement and network security.
- ESnet and NREL will develop a model, or design pattern, for connecting additional sites and services to the ARIES environment.
- ESnet and NREL will collaborate on a number of network security approaches. These may include encryption and intrusion detection systems. These deployments will be measured against network performance to understand what impacts they may have on operation.

3.3 ARIES Demonstrations

NREL is undertaking a series of progressively larger capabilities demonstrations for DOE EERE leadership. These demonstrations gradually add more capability roughly every six months, and as of May 2021 had an expected start date of August 2021. An at-scale production demonstration is planned for the end of FY2023. The goal of these demonstrations is to show the site-to-site connectivity, and the ability to add incrementally larger numbers of devices at each of the sites.

ESnet's role in the demonstrations is to provide the OSCARS circuits facilitating NREL-to-site communication. Local connectivity (e.g., connecting devices at each site) is the responsibility of ARIES. As of May 2021, the expectation was that:

- NREL would establish a working group with representatives from the five sites and ESnet to work out the specifics of these demonstrations.
- August 2021 demonstration: ARIES would be tested between NREL and one of the collaborating sites using a prototype version of the experimental backplane over ESnet. The goal is to show communication for a small number of connected devices across the shared network.
- FY22 demonstration 1: ARIES capabilities demonstrated for three connected sites (NREL add two others) using the shared overlay network and a small number of connected devices at each.
- FY22 demonstration 2: ARIES capabilities demonstrated for five connected sites and a total of 100 connected devices. The increase in connected devices will not affect ESnet support of the activity. Results of the tests will help to

validate the remaining larger demonstrations and may require revisiting the overlay configuration.

- FY23 demonstration 3: ARIES capabilities demonstrated for five connected sites and a total of 1,000 connected devices.
- Final FY23 demonstration for the DOE: at-scale ARIES operation of five collaborating sites and 10,000 devices total.

4 Requirements Review Structure

Requirements reviews are a critical part of a process to understand and analyze current and planned science use cases across the DOE SC. This is done by eliciting and documenting the anticipated data outputs and workflows of a particular program, user facility, or project to better inform strategic planning activities. These include, but are not limited to, network operations, capacity upgrades, and other service investments for ESnet, as well as a complete and holistic understanding of science drivers and requirements for the program offices.

The requirements review is designed to be an in-person event; however, the COVID-19 pandemic has changed the process to operate virtually and asynchronously for several aspects. The review is a highly conversational process through which all participants gain shared insight into the salient data management challenges of the subject program/facility/project. Requirements reviews help ensure that key stakeholders have a common understanding of the issues and the potential actions that can be taken in the coming years.

4.1 Background

Through a case study methodology, the review provides ESnet with information about:

- Existing and planned data-intensive science experiments and/or user facilities, including the geographical locations of experimental site(s), computing resource(s), data storage, and research collaborator(s).
- The "process of science" for each experiment/facility project, including the goals of the project and how experiments are performed and/or how the facility is used. This description includes information on the systems and tools used to analyze, transfer, and store the data produced.
- Current and anticipated data output on near- and long-term timescales.
- Timeline(s) for building, operating, and decommissioning of experiments, to the degree these are known.
- Existing and planned network resources, usage, and "pain points" or bottlenecks in transferring or productively using the data produced by the science.

4.2 Case Study Methodology

The case study template and methodology are designed to provide stakeholders with the following information:

- Identification and analysis of any data management gaps and/or network bottlenecks that are barriers to achieving the scientific goals.
- A forecast of capacity/bandwidth needs by area of science, particularly in geographic regions where data production/consumption is anticipated to increase or decrease.

- A survey of the data management needs, challenges, and capability gaps that could inform strategic investments in solutions.

The case study format seeks a network-centric narrative describing the science, instruments, and facilities currently used or anticipated for future programs; the network services needed; and how the network will be used over three timescales: the near term (immediately and up to two years in the future); the medium term (two to five years in the future); and the long term (greater than five years in the future).

The case study template has the following sections:

Science Background: a brief description of the scientific research performed or supported, the high-level context, goals, stakeholders, and outcomes. The section includes a brief overview of the data life cycle and how scientific components from the target use case are involved.

Collaborators: aims to capture the breadth of the science collaborations involved in an experiment or facility focusing on geographic locations and how data sets are created, shared, computed, and stored.

Instruments and Facilities: a description of the instruments and facilities used, including any plans for major upgrades, new facilities, or similar changes. When applicable, descriptions of the instrument or facility's compute, storage, and network capabilities are included. An overview of the composition of the data sets produced by the instrument or facility (e.g., file size, number of files, number of directories, total dataset size) is also included.

Process of Science: documentation on the way in which the instruments and facilities are and will be used for knowledge discovery, emphasizing the role of networking in enabling the science (where applicable). This should include descriptions of the science workflows, methods for data analysis and data reduction, and the integration of experimental data with simulation data or other use cases.

Remote Science Activities: use of any remote instruments or resources used in the process of science and how this work affects or may affect the network. This could include any connections to or between instruments, facilities, people, or data at different sites.

Software Infrastructure: discussion of the tools that perform tasks, such as data source management (local and remote), data-sharing infrastructure, data-movement tools, processing pipelines, collaboration software, etc.

Network and Data Architecture: what is the network architecture and bandwidth for the facility and/or laboratory and/or campus? The section includes detailed descriptions of the various network layers' (local area network (LAN), metropolitan area network, and wide area network [WAN]) capabilities that connect the science experiment/facility/data source to external resources and collaborators.

Cloud Services: if applicable, cloud services that are in use or planned for use in data analysis, storage, computing, or other purposes.

Data-Related Resource Constraints: any current or anticipated future constraints that affect productivity, such as insufficient data transfer performance, insufficient storage system space or performance, difficulty finding or accessing data in community data repositories, or unmet computing needs.

Outstanding Issues: an open-ended section where any relevant discussion on challenges, barriers, or concerns that are not discussed elsewhere in the case study can be addressed by ESnet.

5 ARIES Platform

5.1 Science Background

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 advance the research that will lead to the best possible energy systems. Some of the most important and consequential research challenges to advancing the energy economy are at the *system level*. A research platform is needed to support development and demonstration at this level, while simulating and encouraging scaling toward real-world application of this research.

Over 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 resources of different sizes and capabilities near the edge of the grid. At the same time, the power grid is becoming increasingly interdependent with other infrastructures like natural gas, transportation, water, and telecommunications. Research and developments are now needed at the frontiers of *distributed management*, *at-scale integration*, and *real-time system optimization*.

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

- 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.

To address this, ARIES was developed by NREL in partnership with the DOE's Office of EERE. ARIES is a unique research platform for the scientific community and industry. It is designed to support the transition to a modern energy system that is clean, secure, resilient, reliable, and affordable. ARIES will help the nation explore the possibilities of tomorrow's energy systems while addressing the realities of complexity and scale. Rather than evaluating new clean energy and energy efficiency technologies in silos, ARIES expands the research view to take in the full picture, from consumers to distribution to transmission. This unprecedented perspective brings opportunities and risks to the surface in the spaces where sectors like transportation, communications, and the electric grid meet.

Modernizing our energy infrastructure will require new approaches to some fundamental challenges. These include coordinating many different types and sizes of energy technologies, securely controlling tens of millions of devices, and integrating diverse technologies with high amounts of renewable generation.

ARIES's core capabilities to address these challenges include:

- **Unparalleled research equipment** to support integrated energy and clean transportation research, analysis, modeling, and hardware experiments.
- **Interconnected grid-scale devices and distributed energy** resources for high-fidelity experimentation.
- **The ability to create, prove, and validate complex energy systems** by interconnecting hardware and software capabilities that imitate varied renewable energy configurations and solutions for energy and transportation systems.
- **An 8-petaflop high-performance computer** to break through existing limitations and achieve metropolitan- and regional-scale research resolution.
- **A team of national laboratory experts** with a depth and breadth of knowledge in energy systems integration and clean energy innovation at the leading edge nationally and internationally.

The ARIES platform is built to create, prove, and validate complex energy systems with the ability to plug and play different technologies into a flexible and scalable core integrated system. This makes it possible to pivot and stay ahead of the rapidly evolving energy sector. ARIES was designed around five research areas of critical importance where knowledge gaps that must be further explored exist:

- **Energy storage**: balance variable renewable generation and demand.
- **Power electronics**: control and integrate rapidly increasing electronics-based technologies.
- **Hybridization**: achieve enhanced coordinated capabilities beyond isolated technologies.
- **Infrastructure**: adapt existing energy infrastructure for safety, monitoring, and controls.
- **Cybersecurity**: secure operations to prevent disruption, damage, and loss of functionality.

The ARIES platform will provide a virtual emulation environment that uses advanced computing and digital real-time simulators. ARIES will help researchers address the challenges of integrated energy systems at scale in the areas of energy storage, power electronics, hybrid energy systems, future energy infrastructure, and cybersecurity: five research areas of critical importance as devices scale up from the hundreds to millions.

5.2 Collaborators

The ARIES platform is designed to facilitate the deployment of physical resources and have them linked to a common communication backplane capable of collecting observational data and providing core services, such as computing and storage. In this environment, collaborations will be tightly integrated with the platform, and most, if not all, communication and data transmission will remain within the system. The following sections outline some of the factors surrounding the collaboration space, and will be expanded over time as the platform is deployed and expanded.

5.2.1 NREL Researchers

The core constituency for the ARIES platform will be the researchers at NREL. This constituency will be responsible for operation and maintenance of a number of the technologies and services deployed. A critical observational result of ARIES will be the behavior of these devices from within the system itself, captured as control messages from the communication network. Over time, these small messages will be collected and stored so that their interactions can be studied and replayed.

Data transmission requirements are on the order of kilobytes to megabytes, and may approach gigabyte sizes over many years. Data storage and transmission are not expected to be immediate problems. However, there is concern regarding the ability to accurately capture the results over time as the control packets may be generated on a microsecond basis from each participating hardware component.

These data sets will reside at NREL primarily. Linked facilities (see Section 2.2) may collect and store data for resident hardware components locally or utilize NREL storage. The size and frequency requirements are expected to be similar. Linked facilities may pose a challenge due to the latency behaviors they import during experimentation, and it will be critical for NREL researchers to characterize and understand this when performing observations and calculations.

5.2.2 DOE National Laboratories and Facilities

ARIES has the potential to collaborate with other facilities located at several DOE laboratories. These facilities are in different physical locations, and are all connected via ESnet. The initial set of potentially connected sites includes:

- INL
- ORNL
- PNNL

Other sites, such as NETL and SNL, may participate near the end of the experiment in 2023, but have not fully committed as of the writing of this report.

A stable network to interconnect these facilities is viewed as a mission-critical requirement for ARIES, particularly with regards to being able to tightly control the network behavioral metrics (e.g., latency and utilization), along with usage policies and physical interconnections to affiliated components at the partner facilities. The following sections discuss some of the proposed research and collaboration requirements for each.

5.2.2.1 INL

INL has cutting-edge software and laboratory assets associated with nuclear and other clean energy generation and utilization. Coupled real-time simulations via interconnection with INL can enable a holistic inclusion of integrated energy systems. It can also enable an increase in real-time simulation capacity, thermal loops representing nuclear plants, microgrids, electric vehicle (EV) charging stations, and other clean energy assets. Data coupling and software co-simulation of nuclear station models with NREL and other lab assets is essential to enable future integrated energy systems (IES).

5.2.2.2 ORNL

ORNL has several laboratory assets as hardware that can enable key pillars of IES, including a medium voltage direct current hardware setup, grid interface controllers, advanced power electronic converters, and advanced EV charging infrastructure. ORNL also has advanced 1 MW hardware-in-the-loop (HIL) capability that allows the interface of clean energy and transportation-related lab assets that can be coupled and utilized.

5.2.2.3 PNNL

PNNL has a host of hardware-based lab assets, including advanced buildings, EV charging stations, distribution and transmission level controls, etc. One of the salient facilities that PNNL operates is its cybersecurity test bed, which allows the study and control of risks associated with energy systems and assets. This will enable the addition of several dimensions of the hardware-based research as a part of the ARIES platform.

5.3 Instruments and Facilities

Some of the most important and consequential research challenges to advancing the energy economy are at the system level. However, the broader impacts of wide-scale deployment and operation remain considerable issues. The ARIES platform will support development and demonstration at the system level, while scaling to real-world applications. Developing technologies within narrowly constrained environments (e.g., silos) often prevents this broader view. A primary goal for ARIES is to enable the transition to a modern energy system, and this will be accomplished through mirroring the complexity and scale of real energy systems.

Factors such as consumers, industries, and utilities are considered to uncover opportunities and risks in the spaces where energy technologies and sectors, including transportation, buildings, and the electric grid, meet. ARIES will require thought and design toward new approaches to some fundamental challenges. These include coordinating many different types and sizes of energy technologies, securely controlling tens of millions of devices, and integrating diverse technologies with high amounts of renewable generation.

ARIES can be viewed as an at-scale opportunity to deploy hardware, software, and services, with built-in capabilities to measure, monitor, and evaluate their effectiveness. The underlying network connectivity is a critical conduit to this system, as it provides a fundamental backplane between these independent resources, their monitoring systems, computational capabilities, and the human users controlling their operation. The following sections discuss the trajectory of these systems over the next several years of design, implementation, and operation.

5.3.1 Present

The ARIES program provides mechanisms to perform experimentation for power, energy, and transportation systems. This is accomplished by facilitating access and ability to stage distributed, but coupled, real-time simulations of hardware, software control systems, and the ability to inject various forms of stimulus into experimental scenarios, all occurring across a distributed environment that spans different facilities linked through a communication network.

A power grid simulator is a programmable alternating current (AC) power supply capable of emulating varying power grid conditions to facilitate the testing of equipment at megawatt scales (NREL supports a 7 MW capability). This environment is then used to evaluate HIL types of designs: a common paradigm that attempts to seamlessly integrate physical hardware and software models in a single closed-loop simulation at full power. By using software to simulate the actual electric distribution circuit, HIL testing ensures new, innovative hardware works with the utility system at actual load levels before it is integrated into the system. Researchers can mirror real-world conditions and evaluate complex interconnection scenarios in a controlled laboratory setting—posing no risk to electric utilities or their customers.

HIL testing is designed to evaluate the physical components (e.g., sensors, actuators, mechanical components) and how they interact with the accompanying electronic control units and software before final integration and deployment. Most digital real-time simulator (DRTS) environments are coupled to a set of physical assets to support the HIL type of experimentation. Examples that ARIES envisions include, but are not limited to:

- Wind turbines.
- Behind-the-meter-storage, including batteries.
- Photovoltaic (PV) systems (i.e., solar power).
- EV charging stations.
- Electrolyzer systems (e.g., systems to break water into hydrogen and oxygen components through electrolysis).

ARIES expands these ideas by linking facilities through network connectivity, which enables a broader view of behaviors and simulation opportunities. Large-scale DRTS, as well as the HIL physical components, can be located at different national laboratories around the country. Participants will include resources at NREL, as well as others that may be located primarily at INL, NETL, ORNL, PNNL, and SNL.

ARIES as a whole will be populated with an advanced set of DRTS and HIL capabilities at any given point in time. Data exchanged in near real-time between the different laboratories will lead to a coupling of assets and simulations to enable addressing larger challenges facing the energy and transportation systems.

5.3.2 Two to Five Years

A number of upgrades to core systems will occur during this time window. Of particular note is that the grid simulator at NREL will be expanded to a unique 20 MW asset which will facilitate performing HIL of all components of hybrid energy systems. This upgrade will increase the total testing capacity for HIL instruments, along with encouraging deployment of instruments that can support more advanced capabilities.

Almost all other assets at ARIES will also progressively increase and be of higher ratings during this time period, and the possibility exists that partner sites may see expansion as well. It is unknown if additional sites will be added to the ARIES platform during this time window.

5.3.3 Beyond Five Years

It is expected that the ARIES environment will become more "plug and play," meaning that the incorporation of new instruments and capabilities will become more commonplace. It is also expected that remote HIL (e.g., remote utilization of assets, enhanced collaboration between researchers) will be available, and help solve advanced challenges and barriers facing the energy systems. With ease of use will come greater research and development activities that can be performed jointly between research groups located around the world.

It is expected that other assets at ARIES will also progressively increase and be of higher power and capability ratings during this time, and the possibility exists that partner sites may see expansion as well. Whether additional sites will be added to the ARIES platform during this time is unknown.

5.4 Process of Science

ARIES will unite research capabilities at multiple scales, and across sectors, to create a platform for understanding the full impact of energy systems' integration. ARIES addresses the risks and opportunities across five research areas:

- **Energy storage**. ARIES connects multiple individual energy storage applications with a system-level perspective. The coupling of at-scale storage technologies will support validating and scaling energy system models and controls.
- **Power electronics**. ARIES helps address differences between power electronic-based equipment and traditional devices, and the limits that must be overcome to enable higher levels of renewable generation as research and development (R&D) works to establish a future grid with resilient and flexible operation.
- **Hybrid energy systems**. ARIES can reproduce the diverse timescales, physical scales, and technologies of hybrid energy systems. This is done via a near real-world environment with high-fidelity, physics-based, real-time models that facilitate the connection between hundreds of real hardware devices and tens of millions of simulated devices.
- **Future energy infrastructure.** This research area concerns transmission and delivery networks for a variety of advanced fuel types and infrastructures, which undergird the power, transportation, buildings, and industrial sectors. ARIES will enable testing on grid designs that span microgrids up to high-voltage direct current transmission grids and on management and control systems that optimally integrate power delivery for diverse fuel and technology types.
- **Cybersecurity**. ARIES helps close the system-level security gaps that emerge from distinct hardware and software becoming integrated. The ARIES platform involves visualization, monitoring, and data processing for ARIES research assets and the connections between them. By creating a digital twin of research hardware clusters, ARIES has the ability to simulate and detect attacks on communications and control systems that are still evolving, with an effect of reducing overall vulnerabilities in energy systems.

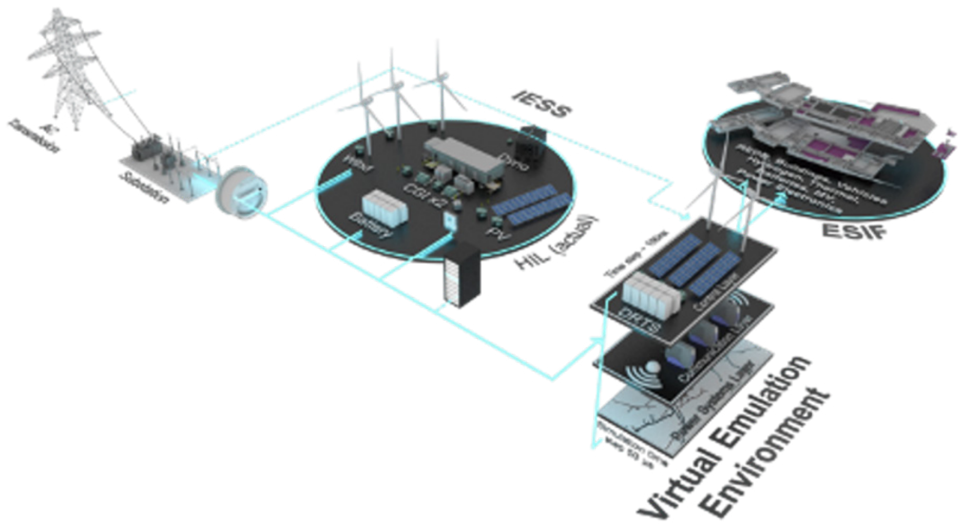

Figure 1: Conceptual layout of ARIES interconnecting the Energy Systems Integration Facility (ESIF), IESS at Flatirons Campus, and the virtual emulation environment

As shown in Figure 1, ARIES will be constructed using resources within the NREL campus environment, but also affiliated national laboratories linked via ESnet nationally, and the Bi-State Optical Network (BiSON) operated by the Front Range GigaPop (FRGP). Resources will be deployed at the participating facilities, and linked together via this underlying network control plane. The network is a critical component of ARIES, as it serves as the mechanism to transport operational telemetry from DRTS and HIL testing across the available power grid environment. Large-scale simulation to evaluate operational soundness in the core research areas will require this connectivity.

5.4.1 Present

A critical requirement during this time quanta is establishing a common communication plane between the distributed resources. NREL will collaborate with participants INL, NETL, ORNL, PNNL, and SNL via ARIES as large-scale DRTS are designed to evaluate HIL components. This near real-time environment and its performance are fundamental to the quality of experiments and simulations that can be performed. ESnet will become a critical controls network and experimental backplane for the overall success of this project.

Research on power, energy, and transportation systems will generate data that is relevant and reproducible, all of which will be shared between the participating laboratories. Relevance of the information that is transmitted is determined by physical infrastructure-based coupling parameters that are required for performing synchronized real-time simulations and HIL. Most of the DRTS assume geographical distribution; thus the network is a common and expected resource at all times.

Synchronization between resources is critical. Thus the underlying network must be stable, predictable, and resilient to failure scenarios that will be carefully monitored and tracked over time.

Any data transmitted from the DRTS and HIL testing will be curated and utilized locally to NREL. Typically, this data takes the form of information regarding a certain aspect of hardware setup or of the real-time simulation. The size and quantity of the data have yet to be determined, but typically take the form of time-based observations for a number of metrics that could grow to MB and GB sizes for a given simulation.

For example, if two laboratories are working on remotely characterizing a wind turbine and coupling it to a power grid simulation, then boundary layer conditions will be exchanged during this operation. The network will become a critical component that facilitates synchronization as well as data exchange. Other factors, such as physical phenomenon (internally or externally monitored), may also be incorporated into the gathered data set, which could increase in a greater utilization of remote assets.

5.4.2 Two to Five Years

The connectivity between distributed resources will become more critical as the sophistication of DRTS and HIL components increases. The volume of research data may increase during this time window. It is also expected that the number of connected devices, as well as the number of sites involved in the experimentation, could expand. Early experiences on ARIES will influence some of the future directions for the platform, but it is assumed that the network will remain critical throughout.

ARIES's advancement will enable solving greater challenges that face energy and transportation systems. Thus the coupling between geographically distant assets and simulators will encourage collaboration and facilitate greater cooperation.

5.4.3 Beyond Five Years

Specifics during this time quanta are unknown, beyond the expectation of more sophisticated simulations and hardware. Partner sites could grow during this time, which would place additional requirements on the network infrastructure to support more facilities, but should not require enhanced capacity.

5.5 Remote Science Activities

NREL as the lead institution will house the core components of the ARIES platform (e.g., computing and storage to support DRTS, some HIL deployments, and connectivity to ESnet via BiSON). Given the collaborative nature of the project, additional resources will be engaged remotely that reside at the primary participants INL, NETL, ORNL, PNNL, and SNL. Collaboration will be facilitated by the networking connectivity aspects, and each laboratory will have different policies and methods for accessing ARIES through this shared resource.

5.5.1 Present

The NREL-led platform that facilitates a plug and play approach for real-time interconnectivity will be deployed. This platform will enable several capabilities, such as synchronizing DRTS, HIL at remote sites, data transmission quality, visualization, data storage, etc. It will also enable both real-time and non-real-time functions that allow geographically distributed real-time simulations. Assets such as the real-time simulators, as well as the physical hardware components that include microgrid controllers, EV chargers, wind turbines, batteries, electrolyzers, supercapacitors, etc., will be remotely coupled to the real-time simulations.

All of the assets are designed to serve in their normal functional roles, as if they were connected to the standard electric grid. However, ARIES allows for a higher level of telemetry and control, wherein the performance of each device can help augment larger simulation and hardware-based studies. For example, a local HIL of a PV panel can be coupled with a remotely located battery for studying advanced algorithms to provide firming capacity. Data servers located within the ARIES infrastructure will hold collected interface data and prime simulation information as the distributed real-time simulation progresses over time.

The most important factor that will enable the success of this R&D is the data stream being coupled directly to the real-time simulators and ensuring coupling. Other physical assets required for this include networking devices, such as routers and connection boxes, for enabling communication. Given the fully distributed nature of some of the more advanced simulations that are expected over time, the network is a critical resource for success.

5.5.2 Two to Five Years

As DRTS and remote-HIL fields mature, and ARIES gains experience from operation, the application space will flourish. Visualization is a key aspect of performing these simulations and is also expected to advance over this time period. The underlying network infrastructure will see dual roles as the distributed controls network, but also as a conduit to facilitate observation and visualization of results.

5.5.3 Beyond Five Years

Little is known for this time quanta beyond the need to manage larger and more complex simulations over time. Capabilities and capacities will increase, pushing the boundary of what is possible for the hardware and software. The network is expected to remain a critical aspect for success.

5.6 Software Infrastructure

The software landscape that ARIES will use is still being defined. The primary use cases for the research (e.g., enabling DRTS) must be able to accurately map and control large-scale real-time simulations and HIL that span different facilities. Consideration must be given to the rich environment of hardware, along with the distributed nature of the deployment. To this end, a number of tools (open source and commercial) are being considered.

5.6.1 Present

The project will utilize an NREL-built tool that enables all the major real-time and off-line functions associated with the geographically distributed real-time simulations. In the past, an open-source tool, VILLASframework[1], was used to perform a seven-site demonstration based on distributed real-time simulations and remote HIL. VILLAS, an open-source platform, attempted to couple existing real-time simulators into clusters through the Internet. This co-simulation framework works on interfacing participating simulators with each other.

ARIES will have a secured, next-generation, and significantly advanced tool that enables synchronization of real-time simulators across long geographical distances. This secure and reliable DOE NREL tool will allow all the necessary functionalities for conducting distributed real-time simulations to be built, tested, and deployed. This tool will have several of the capabilities to synchronize, maintain, and troubleshoot remote connectivity between facilities that will populate ARIES. Accuracy of data transmission, delay compensation mechanisms, data loss protocols, connectivity performance, etc. will be fundamental capabilities of this tool. It will also have the ability to maintain storage for key parameters associated with experiments and hardware assets involved. Visualization of underlying hardware and experiments, and the ability to conduct some file transfer activities (e.g., backing up data gathered via experimentation) will be key features. The tool will be consistent with the interconnection policies and agreements so that, once agreed on and deployed, it will enable seamless coupling of energy system and transportation assets across the ARIES participants.

Concern remains about the tool's ability to deal with some aspects of connectivity between facilities during operation. Some DRTS will require the use of virtual private network tunnels to allow support staff to maintain connectivity or transfer information. It is desirable to facilitate backups (or large-scale data dumps) in parallel during a simulation.

1 https://www.fein-aachen.org/projects/villas-framework

5.6.2 Two to Five Years

Newer tools and simulation platforms that offer integration with high-performance computational resources will be added over time. Present-day designs include a cluster to support DRTS activities. With more capabilities comes the ability to unlock a host of extremely high-profile data processing, analysis, and visualization capabilities for the future.

5.6.3 Beyond Five Years

Operational experience from the prior time quanta will guide some of the future choices for software. The behavior in distributed environments, as the complexity of the hardware and data produced increases, may influence future requirements.

5.7 Network and Data Architecture

NREL's ARIES research platform will ultimately connect to INL, NETL, ORNL, PNNL, and SNL. For the sake of this case study, the main components at NREL are described. The current generation of networks is based on a hierarchical design that supports the campus. Additional components to support the plug and play aspects of HIL, and support DRTS requirements, are being designed.

5.7.1 Present

The hierarchical design of the network can be seen in Figure 2. Firewall pairs are used on each campus to isolate SCADA, CRADA, and other networks requiring remote vendor access. WAN connectivity is provided by ESnet using a 100 G primary and a 10 G backup connection over a fiber-optic transport provided by BiSON.

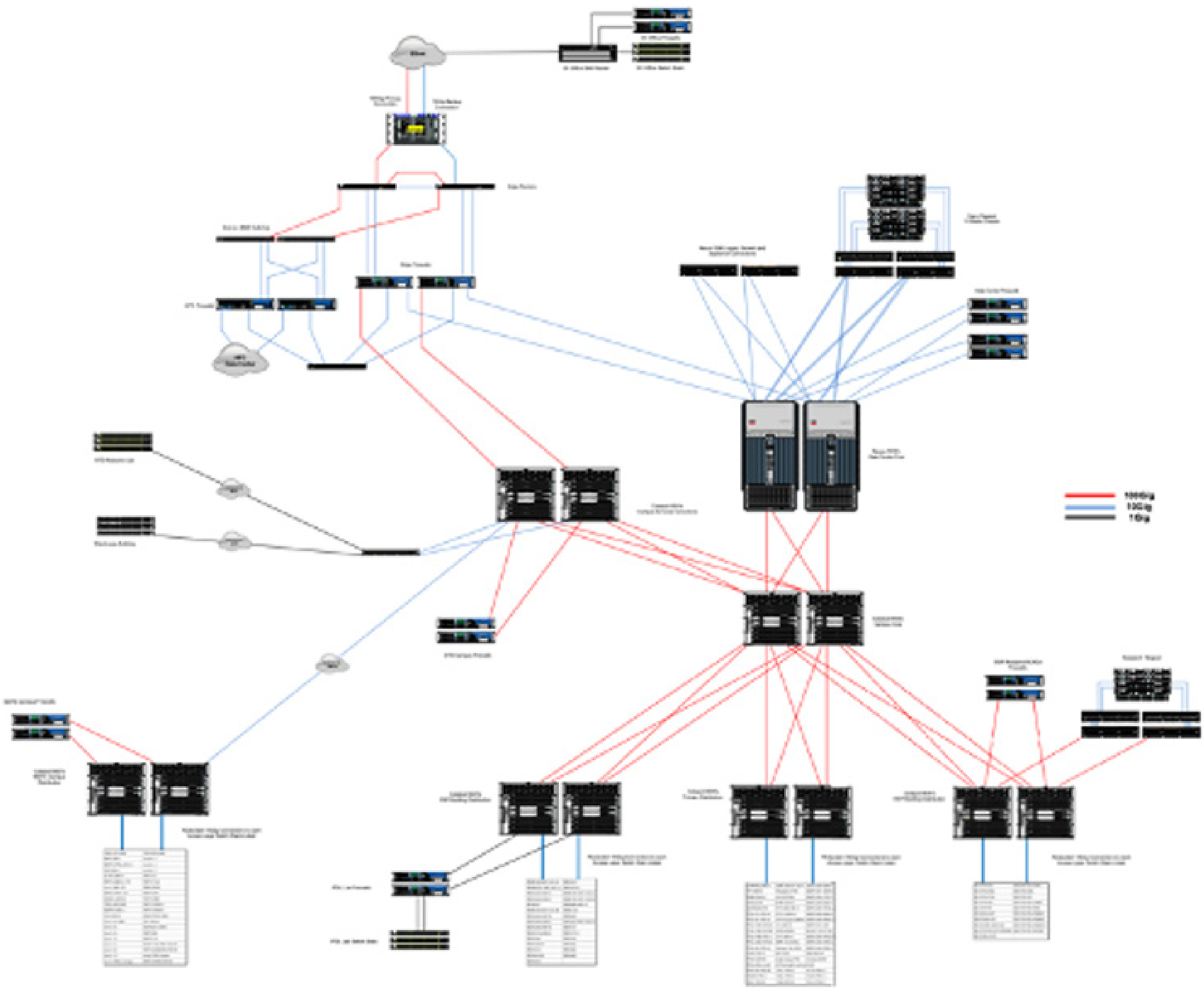

Figure 2: NREL campus network

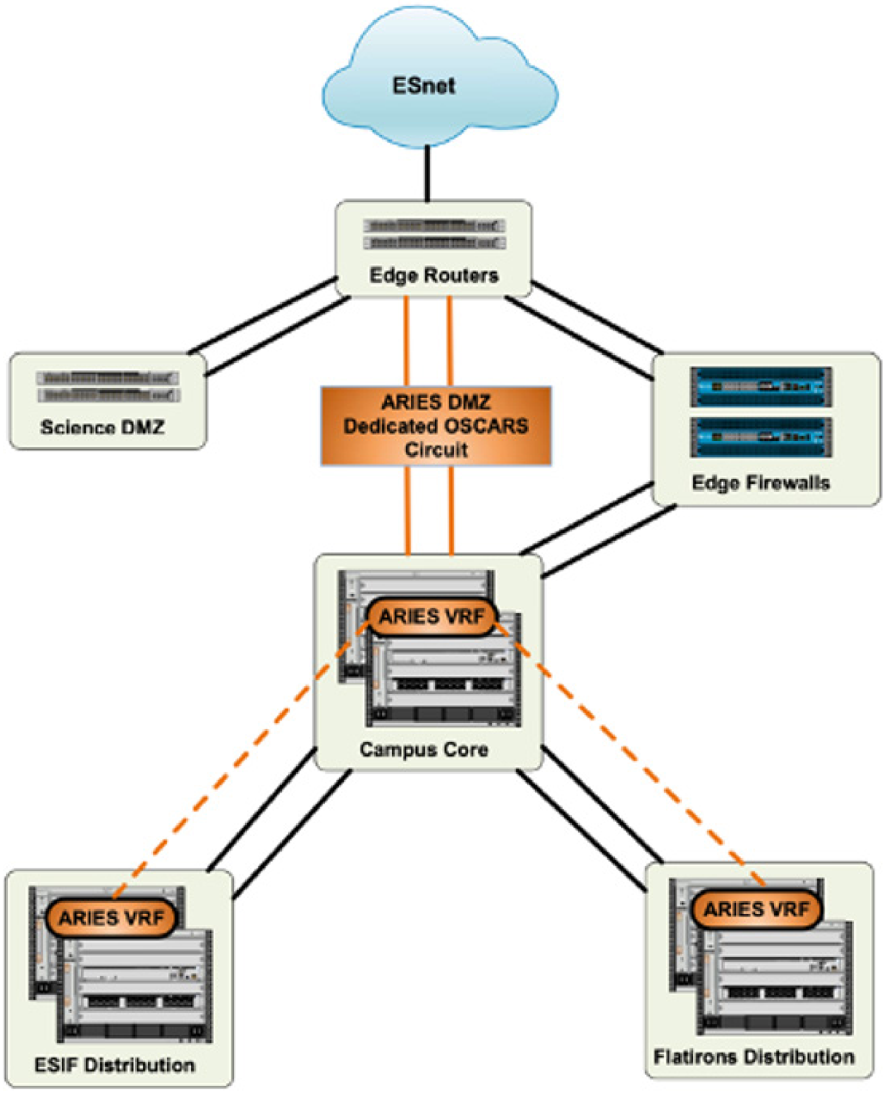

Figure 3: ARIES-high level design

NREL is working with BiSON to install redundant 100 G connections between the Flatirons and South Table Mountain campuses to support ARIES research. ARIES research is a combination of experiments located at the Flatirons campus and the ESIF (Energy Systems Integration Facility) building located on the South Table Mountain campus. The 100 G connections will connect Flatirons to the South Table Mountain campus core switches, providing equal access to ESnet and the ESIF building.

Figure 3 shows a high-level design of how potentially ESnet-provided virtual circuits (e.g., OSCARS) could be utilized to link virtual routing and forwarding (VRF) configurations around the NREL campus. A similar design could be implemented to link other facilities (e.g., participating labs at INL, NETL, ORNL, PNNL, and SNL).

5.7.2 Two to Five Years

Operational experience from ARIES demonstrations and trials will help to solidify design choices. Factors such as the security profiles for sites that are linked via virtual circuits will be carefully considered, along with the implications in using security devices that may affect performance. NREL continues to work with ESnet on perfSONAR characterization (see Figure 4) of performance between facilities, and this is expected to continue during wide-scale deployment and operation.

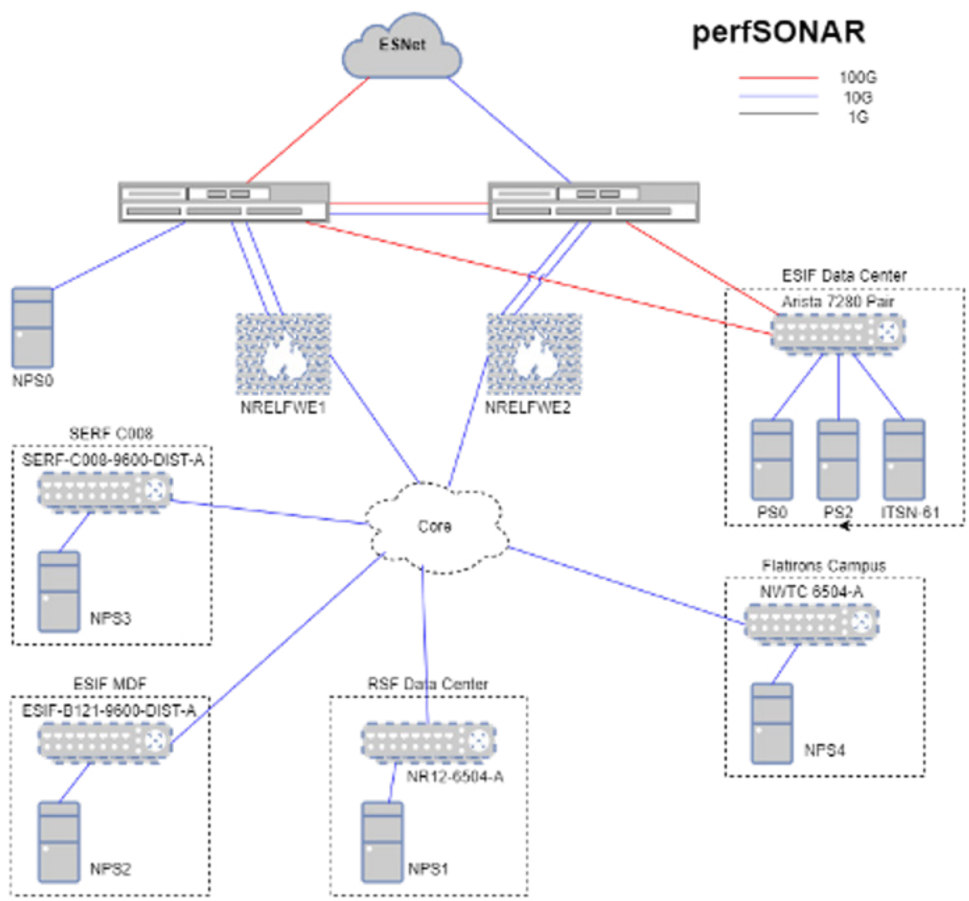

Figure 4: perfSONAR testing at NREL

5.7.3 Beyond Five Years

Upgrades to support key components (facilities, security, computation) are expected during this time, and may require changes to the network configuration. Longer-term experience with the use of VRFs and virtual overlays will also influence changes to the overall profile of the networking.

5.8 Cloud Services

Cloud services are not currently a factor for ARIES, and all aspects of computation and storage will come from within the proposed system. Future-facing requirements that may require integration with national-scale resources (e.g., access to distributed sensor networks or repositories of data such as weather) may require the ability to integrate cloud access. NREL will evaluate the requirements over time, as more becomes known about future HIL testing and requirements that may integrate with clouds.

5.9 Data-Related Resource Constraints

The ARIES control network must be designed with several mission-critical considerations. These include:

1. The ability to securely link the facilities that are participating in ARIES. The participants (including INL, NETL, NREL, ORNL, PNNL, and SNL) are connected via ESnet, which will serve as the backplane that facilitates communication. Further demarcation of experimental traffic is suggested to be provided by virtual connectivity (e.g., through OSCARS-provisioned connectivity) between the sites. This segregation of traffic from that of the general-purpose Internet will allow for a more fine-grained application of security policy.
2. Deterministic network metrics, in particular known latency and minimized jitter between facilities. It is critical that the latency between facilities be known as a priority, as it will be used to configure design aspects of DRTS. During a simulation, the latency should not change, or it runs the risk of interfering with the measurement and synchronization of HIL behaviors.
3. In the event of a network failure, mitigations must be in place to "fail cleanly," meaning that the logical connectivity is better to fail completely versus trying to re-establish connectivity that may result in altered latency behavior. For example, if a link on ESnet carrying ARIES traffic were to fail, instead of routing the logical circuit around this failure, it is better to not offer connectivity as the change in latency could severely affect experimental results. NREL will work with ESnet engineering to understand these requirements, so that any virtual overlay (e.g., one provided via OSCARS) can be properly implemented and configured to experimental needs.
4. Understanding the impacts of network devices (routers, switches, and firewalls) and being able to accurately map and understand these metrics with measurement tools like perfSONAR.
5. Defining sensible security policies that facilitate an open environment between facilities, while still protecting the hardware being evaluated and measured from external risks.

5.10 Outstanding Issues

Beyond the technical issues described in Section 5.9 for the design and operation of the ARIES control network, several issues remain to be addressed to facilitate full experimental operation. These include:

1. NREL and ESnet are discussing the project, and its technical requirements, to understand the potential costs, barriers to implementation, and other service-level agreements that may need to be in place between the facilities. These discussions will take place between DOE SC and EERE.
2. NREL and other partners in ARIES (a list that presently includes INL, NETL, ORNL, PNNL, and SNL) will need to understand the optimization requirements for LAN and WAN operations, and how these postures could affect operational soundness. For instance, if a local network is not well characterized and has several layers of routing, switching, or security that must be traversed, what will be the overall impacts to the network performance (e.g., increased latency, unpredictable jitter, etc.)?
3. How will ARIES receive notification of network status when an event occurs? There are traditional means (e.g., network operations center communications) that can be sent when ESnet operations staff notices an underlying problem. ARIES may explore other possibilities, to better understand and characterize the behavior and status of the network. This could include access to APIs that may be available from ESnet (e.g., ESnet6 services, OSCARS), or by installing monitoring systems to proactively report when problems are sensed.

List of Abbreviations

AC	alternating current
API	application programming interface
ARIES	Advanced Research on Integrated Energy Systems
ASCR	Advanced Scientific Computing Research
BiSON	Bi-State Optical Network
DME	Data Mobility Exhibition
DOE SC	DOE Office of Science
DOE	Department of Energy
DRTS	digital real-time simulators
EERE	Energy Efficiency and Renewable Energy
ESCC	ESnet Site Coordinators Committee
ESIF	Energy Systems Integration Facility
EV	electric vehicle
FRGP	Front Range GigaPop
HIL	hardware-in-the-loop
HPC	high-performance computing
IES	integrated energy systems
INL	Idaho National Laboratory
LAN	local area network
LBNL	Lawrence Berkeley National Laboratory
MOU	memorandum of understanding
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
OSCARS	On-Demand Secure Circuits and Advance Reservation System
PEMP	performance evaluation and measurement plan
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
R&D	research and development
SNL	Sandia National Laboratories
VRF	virtual routing and forwarding
WAN	wide area network