INL/EXT-20-61115
Revision 0

Integrated Energy Systems Program Management Plan

December | 2020

Rebecca Onuschak
Department of Energy, Office of Nuclear Energy

Shannon Bragg-Sitton
Idaho National Laboratory

IES
Integrated Energy Systems

INL/EXT-20-61115
Revision 0

Integrated Energy Systems Program Management Plan

Rebecca Onuschak
Department of Energy, Office of Nuclear Energy

Shannon Bragg-Sitton
Idaho National Laboratory

Error! Reference source not found.

Idaho National Laboratory
Integrated Energy Systems
Idaho Falls, Idaho 83415

http://www.ies.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Science
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

Integrated Energy Systems
Program Management Plan

INL/EXT-20-61115

December 2020

Prepared by:

Rebecca Onuschak IES Program Manager, DOE/NE-51	Date
Shannon M. Bragg-Sitton IES National Technical Director, INL	Date

Concurrence:

Melissa Bates Acting Capabilities Team Manager, DOE/NE-51	Date
Suibel Schuppner Director, DOE/NE-51	Date

Page intentionally left blank

CONTENTS

FIGURES

TABLES

ACRONYMS

AI	artificial intelligence
ANL	Argonne National Laboratory
ARD	Advanced Reactor Development
CEM	capacity expansion models
CHP	chemical heat pumps
CIE	cyber informed engineering
CNEWG	Civil Nuclear Energy Working Group
CSP	concentrated solar power
CTD	Crosscutting Technology Development
DAS	Deputy Assistant Secretary
DETAIL	Dynamic Energy Transport and Integration Laboratory
DOE	Department of Energy
DRTS	digital real-time simulator
DSS	dynamic system scaling
EERE	Energy Efficiency and Renewable Energy
EPRI	Electric Power Research Institute
ESL	Energy Systems Laboratory
FASTR	Facility to Alleviate Salt Technology Risks
FOA	funding opportunity announcement
FY	fiscal year
HFTO	Hydrogen and Fuel Cell Technologies Office
HIL	hardware-in-the-Loop
HTE	high-temperature electrolysis
HTGR	high-temperature gas reactor
HTTR	high-Temperature Test Reactor
IES	Integrated Energy Systems
INL	Idaho National Laboratory
IPL	Integrated Priority list
JAEA	Japanese Atomic Energy Agency
LFR	lead-cooled fast reactor
LWR	light-water reactor
LWRS	Light Water Reactor Sustainability
MAGNET	Microreactor agile nonnuclear test

NE	DOE Office of Nuclear Energy
NEI	Nuclear Energy Institute
NE-4	Nuclear Fuel Cycle and Supply Chain
NE-5	Office of Nuclear Reactor Fleet and Advanced Reactor Deployment
NEUP	Nuclear Energy University Program
NHES	Nuclear Hybrid Energy Systems
NREL	National Renewable Energy Laboratory
NRIC	National Reactor Innovation Center
NTD	national technical director
ORNL	Oak Ridge National Laboratory
OSTI	Office of Scientific and Technical Information
PICS:NE	Program Information Collection System: Nuclear Energy
PPBE	Planning, Programming, Budgeting and Execution
RD&D	research, development and demonstration
SBIR	Small Business Innovative Research
SMR	small modular reactor
TAL	technical area lead
TEDS	Thermal Energy Distribution System
TES	thermal energy storage
TRL	technology readiness level

Integrated Energy Systems Program Management Plan

1. Introduction

In 2012, the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) initiated the Nuclear Energy Enabling Technology Program, which includes the Crosscutting Technology Development (CTD) portfolio of subprograms, to conduct research, development, and demonstration (RD&D) to support existing, new, and advanced reactor designs and fuel cycle technologies.

This program plan describes the Integrated Energy Systems (IES) Program, an element of the CTD portfolio since 2016 that seeks to improve the economic competitiveness, efficiency, and environmental performance of nuclear energy systems by expanding their potential application space beyond electricity and optimizing their utilization in the context of the larger U.S. electric and nonelectric energy system.

1.1 Program Motivation

Although the use of renewable and low-carbon energy sources has been steadily increasing, an unintended result has been to drive nuclear energy out of the market in some regions, limiting the overall impacts of these new energy sources on total carbon reduction (International Energy Agency 2019). Low-cost renewable generation, primarily from variable sources such as solar and wind, drives down the price of electricity while these resources are available, challenging the ability of providers, such as nuclear plants, to provide needed baseload capacity.

The IES Program aims to maximize the efficient application of nuclear energy resources across all energy sectors. Maximizing the production of low-emission energy requires a continued increase in the use of variable renewable energy sources, coupled with increased flexibility in nuclear energy generation to allow nuclear plants to thrive economically even while supporting variable grid demand. A key mechanism for implementing such flexibility would be to use excess heat and electricity (available at times of low net electricity demand[a]) for hydrogen production, water desalination, or other industrial processes. IES are cooperatively controlled systems that dynamically apportion thermal or electrical energy to provide responsive generation to the power grid. They are composed of multiple subsystems, which may or may not be geographically collocated, including multiple generation sources (e.g., nuclear heat generation, renewable generation, fossil generation with carbon capture), a turbine that converts thermal energy to electricity, and one or more industrial processes that utilize heat or power from the energy sources to produce a commodity-scale product. Additional subsystems that provide small-scale thermal, electrical, or chemical storage may be included within the system architecture to better manage energy within the system boundary and with the grid. There are three major implementation approaches to IES[b], each requiring somewhat different considerations for commercial viability:

- *Tightly Coupled IES* (Figure 1) – Multiple generation sources (e.g., nuclear, renewable, fossil), energy storage, and industrial process(es) are directly integrated behind the grid (thermally and electrically) and co-controlled, such that there is a single connection point to the grid and a single financial entity managing the IES (i.e., economic performance of the IES is optimized for the integrated system rather than for each subsystem independently).

[a] Net demand is the remaining demand that must be met by conventional dispatchable generation sources after variable generation is subtracted from the total electricity demand. Variable renewable generation generally is not curtailed as a means of managing overproduction.

[b] Topping heat may or may not be necessary for intermediate and high temperature processes as a function of the outlet temperature of the selected nuclear reactor technology. Note that, depending on the supported industrial processes and secondary products, chemical energy storage may also be added to this system configuration to further increase its operational flexibility.

- *Thermally Coupled IES* (Figure 2) – Subsystems may have more than one connection to the same grid balancing area and may not be collocated; however, the generation subsystems are co-controlled to provide electricity and ancillary services to the grid. These systems have more than one connection point to the grid but are managed by a single financial entity.
- *Loosely Coupled, Electricity-Only IES* (Figure 3) – This configuration is controlled in a similar fashion to the thermally coupled system, but generators would only be electrically coupled to industrial energy users (no direct thermal coupling of subsystems). This scenario allows the management of the electricity produced within the system prior to the grid connection. These systems may have more than one connection point to the grid but are managed by one financial entity.

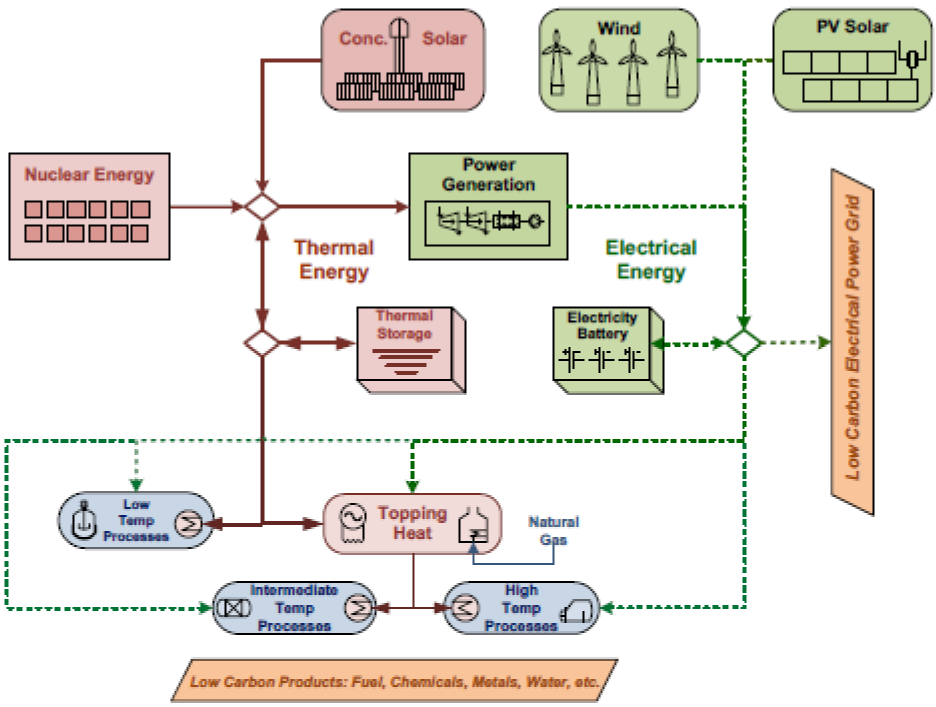

Figure 1. General architecture for a tightly coupled IES, from (Bragg-Sitton, et al. 2020).

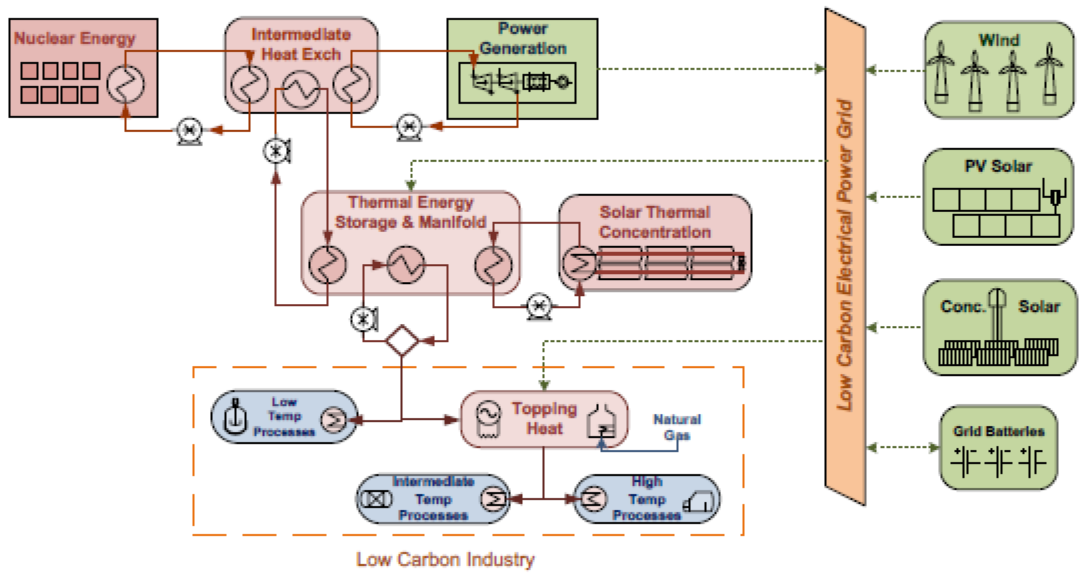

Figure 2. General architecture for a thermally coupled IES, from (Bragg-Sitton, et al. 2020).

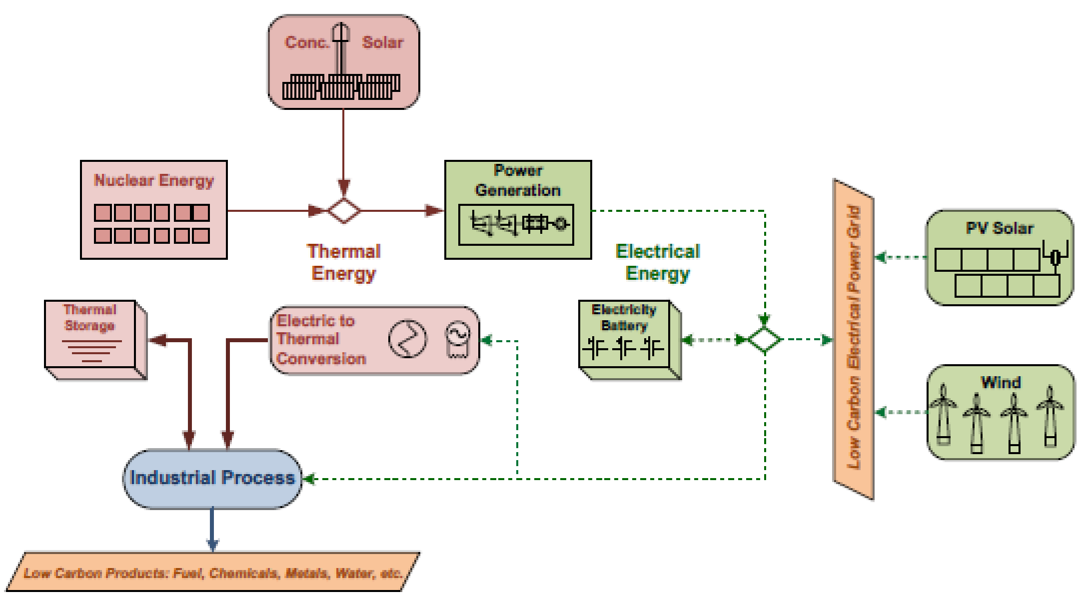

Figure 3. General architecture for a loosely coupled IES, from (Bragg-Sitton, et al. 2020).

The current implementation state and challenges to the implementation of the different classes of IES are described in more detail in the *Integrated Energy Systems 2020 Roadmap* (Bragg-Sitton, et al. 2020).

1.2 Vision, Mission, and Linkage to NE Strategic Objectives

The IES program vision and mission are as follows:

> **Vision**: A robust and economically viable fleet of light-water and advanced nuclear reactors available to support U.S. clean baseload electricity needs, while also operating flexibly to support a broad range of nonelectric products and grid services.
>
> **Mission**: Maximize energy utilization, generator profitability, and grid reliability and resilience through novel systems integration and process design, using nuclear energy resources across all energy sectors in coordination with other generators on the grid.

The current program focus is on developing tools and technologies that will lead to the demonstration of multiple integrated energy systems with a clear path towards commercialization. Timelines for demonstration follow the associated reactor concepts and designs (see Appendix A for estimated timelines from (Bragg-Sitton, et al. 2020)). Concepts to support the current fleet are focused on immediate applications, whereas concepts for small modular reactors (SMRs) and for advanced, non-light-water reactors target the five-to-fifteen-year window. Some RD&D products originating in this program have already been transitioned into the Light Water Reactor Sustainability (LWRS) Program, which is leading demonstration projects at existing nuclear plants. As SMR and non-LWR projects mature, these are also expected to be transitioned to other programs for demonstration and commercialization support.

Table 1 describes the general linkages of the IES Program to the Goals, Objectives, and Performance Indicators in the Office of Nuclear Energy's 2020 Strategic Plan (Office of Nuclear Energy draft). The IES Program continues to investigate means of expanding the capability of existing nuclear plants to participate in markets beyond electricity, as part of the NE strategy for ensuring their continued operation. The program has already supported the demonstration of a scalable hydrogen plant through the development and application of modeling tools to establish their business case and to support technical planning. Achieving the specific performance indicator is now the responsibility of the LWRS Program. IES also supports expanding market opportunities for a diverse variety of next-generation reactors. The Program is actively engaged with the National Reactor Innovation Center (NRIC) to ensure that modeling, simulation, and experimental needs are in place to support demonstrating an IES using an advanced, non-LWR by 2027.

Table 1. Linkage to Office of Nuclear Energy Strategic Goals.

Goals	Objectives	Performance Indicators
Enable continued operation of existing U.S. nuclear reactors.	Develop technologies that reduce operating costs.	By 2022, demonstrate a scalable hydrogen generation pilot plant.
	Expand to markets beyond electricity.	By 2023, pilot a digital safety system in an operating plant.
		By 2023, begin replacing existing fuel in U.S. commercial reactors with accident tolerant fuel.
	Provide scientific basis for continued operation of existing plants.	By 2026, license accident tolerant fuel to operate for an extended period of time in the reactor core.
Enable deployment of advanced nuclear reactors.	Reduce risk and time needed to deploy advanced nuclear technology.	By 2024, demonstrate and test a fueled microreactor core fabricated by advanced manufacturing techniques.
		By 2025, enable demonstration of a commercial U.S. microreactor.
	Develop reactors that expand market opportunities for nuclear energy.	By 2026, enable operation of the first commercial U.S. small modular reactor.
		By 2027, demonstrate operation of a nuclear-renewable hybrid energy system.
	Support a diversity of designs that improve resource utilization.	By 2028, demonstrate two U.S. advanced reactor designs through cost-shared partnerships with industry.
		By 2035, demonstrate at least two additional advanced reactor designs through partnerships with industry.

*Shaded cells highlight specific objectives and performance indicators supported by the IES Program.

Specific, multiyear objectives of the IES program focus on enhancing simulation and analysis capabilities, validating those capabilities via experimental systems, and demonstrating IES technologies. These objectives fit within the IES technical areas described in Section 1.4 and include the following:

- FY 2021—begin operation of the electrically heated thermal energy distribution system (TEDS) and validate the thermocline energy storage system transient behavior.
- FY 2021—demonstrate a thermal and electrical linkage to hydrogen production through the integration of TEDS to a collocated hydrogen production skid.
- FY 2022—install a heat exchanger to thermally integrate the microreactor agile nonnuclear test bed (MAGNET) to TEDS to further enhance the experimental capability to emulate thermal energy input from a nuclear subsystem.
- FY 2023—establish a reference capability to validate current practices in valuing nuclear energy in the energy market.
- FY 2023—deliver a "plug-and-play" flexible simulation ecosystem for industry applications, representing multiple energy input and use technologies, with a graphical user interface to allow broad use by laboratory and academic researchers and private industry.
- FY 2024—demonstrate a broad experimental capability that can emulate a large-scale, multisystem IES that incorporates both real and virtual elements. This capability will provide realistic information on the characteristics and performance of complex integrated systems operating with the electric grid before initiating the significant investment required to deploy them in the commercial marketplace.
- FY 2026—in collaboration with the NRIC, perform modeling, simulations, and experiments to support the inclusion of an IES with an advanced reactor demonstration.

1.3 Challenges

The *Integrated Energy Systems 2020 Roadmap* (Bragg-Sitton, et al. 2020) describes the challenges to the commercial implementation of IES, without regard to the roles and responsibilities of various programs and entities in addressing them. This section summarizes those challenges, while Section 1.4 describes the IES Program's approach to conducting RD&D to facilitate a commercialization pipeline. The challenges are generally categorized as technology availability, market competitiveness, regulations and licensing, and nuclear insurance.

Technology availability encompasses the technical readiness of IES component systems at scale and the technologies required to integrate them. In many cases, the component systems being considered are commercially available as independent systems, but they have not been coupled with nuclear energy systems. In such cases, the primary gaps associated with IES commercial deployment are associated with integration needs: heat exchangers, intermediate loops, thermal energy storage systems, and approaches to effectively couple technologies, such as heat augmentation to thermodynamically match the energy generation resource to the energy use technology. Appropriate control systems to efficiently operate multi-application energy systems must also be demonstrated. To maximize the potential value of advanced nuclear systems for some applications, component system technologies may also need to be matured or scaled, such as by developing commercial-scale processes to take advantage of higher-temperature heat.

A clear understanding of market competitiveness is required to bring technologies across the "valley of death" illustrated in Figure 4. As technologies mature beyond the early stages typically supported by academia and government laboratories, assurance of potential market viability is needed to secure private investment. IES are intended to operate across multiple markets (e.g., electricity, heat, hydrogen, chemicals, water), each of which is complex, evolving, and uncertain. Sophisticated tools are required to estimate system capital and operating costs, current markets, future potential markets, and sensitivities at a level sufficient to support commercial investment. Certainty of costs and revenues allows private investors to move a technology across the valley of death, sustained by the promise of future returns.

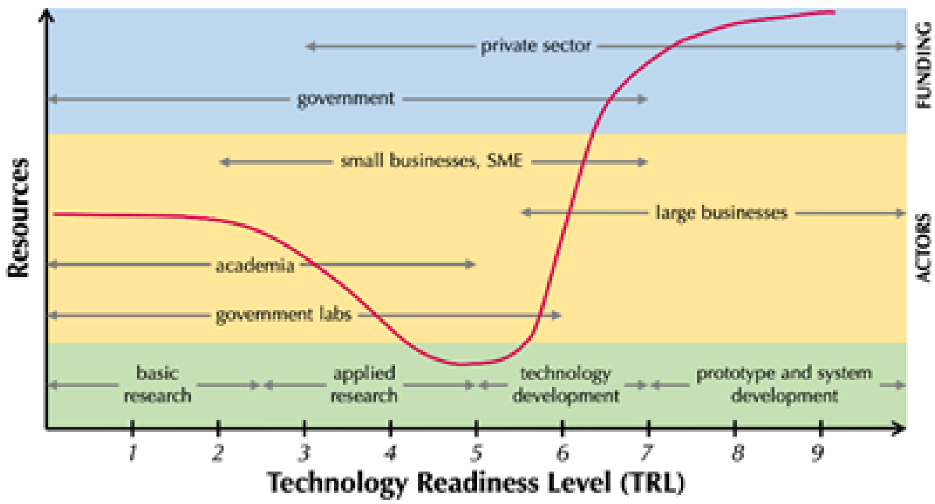

Figure 4. Resource availability as a function of technology maturation. The central depression between TRL 3 and 6, where few resources are available, is known as the technology valley of death (figure and caption from (Bragg-Sitton, et al. 2020), cited there as adapted from (Hensen, Loonen and Archontiki 2015)).

The challenges described for regulations, licensing, and nuclear insurance are related to the unique aspects of designing, constructing, and operating IES that include nuclear power systems. While the Nuclear Regulatory Commission focuses on the nuclear island, deployment of nuclear reactors within an IES configuration may require additional regulatory consideration in cases of potential interaction between the nuclear and nonnuclear systems. Operators of the nonnuclear subsystems operating in an IES may, depending on their nature and location, need to consider nuclear regulatory aspects not otherwise part of their business models or experience base, such as avoiding impacts to nuclear operations and participating in nuclear-related emergency response planning. Development and operation of a nuclear site in the U.S. also requires that the operating company obtain insurance for the site during construction and for the operating facility. As the IES configuration is outside of the standard scope of nuclear power plant operation, the structure of the insurance coverage and the associated insurance premiums are anticipated to be somewhat different than for a currently operating plant. Preliminary investigation of the anticipated insurance requirements for an operational facility should be conducted with industry collaboration during the laboratory testing, scale-up, and system refinement to ensure that there will be no significant roadblocks to the commercialization of the proposed IES.

1.4 Research Approach

The challenges to IES implementation can only be met through the combined effort of government, academia, and industry. The IES program has approached these challenges by considering the pathway from concept to deployment of any proposed IES solution and identifying the areas where federally supported RD&D is most appropriate. In general, these are selected based on early technology state (such that private investment would be unlikely due to a high level of risk or duration to return on investment), breadth of potential applicability, and complexity of the RD&D need. These stages and program roles are summarized in Table 2.

Table 2. Program Roles in Stages of Technology Development.

Development Stage	**Activity**	**NE IES Program Roles**
Analytical Assessment of Merit	Determine whether a concept is appropriate for further development based on technical, financial, environmental, and policy factors.	Coordinate stakeholder input and develop and publish consensus metrics, performance goals, and optimization constraints. Provide analytical tools and services to perform or support concept assessments.
Lab-Scale Testing	Perform bench-scale, subsystem-level, and integrated multisystem level testing of components, subsystems, and integration technologies.	Provide capability (e.g., facilities, technologies, and expertise) and services to conduct testing not available in the private sector for innovative technologies and IES solutions. Provide high-fidelity, dynamic simulation and analysis environment, operating over multiple timescales, to evaluate IES solutions in the context of the broader energy system.
Nuclear System Demonstration	Demonstrate IES at a nuclear facility to increase the Technology Readiness Level (TRL), primarily of interface hardware, control systems, operational methods, and the integrated system as a whole, as a key precursor to licensing and commercial deployment.	These activities are led by implementing programs outside IES. This may include NE programs, such as LWRS (to date), with the future scope expected to include SMR and non-LWR reactor demonstration efforts, and it may also include non-NE programs, such as programs funded via the DOE Office of Energy Efficiency and Renewable Energy (EERE) (e.g., for hydrogen production or other energy use technologies). IES retains a support role, providing experimental and analytical support as requested by the lead program and industry partner(s) and using data obtained to validate and improve IES tools.

The IES program explores and develops concepts before they have achieved readiness for pilot-scale demonstrations and provides analytical and experimental support for more mature concepts being considered for such demonstrations. In order to maximize the potential for the commercial application of IES RD&D products, the program maintains close coordination with industry stakeholders, as described in the summary of stakeholder engagement activities (Bragg-Sitton and Boardman 2019). As technologies transition to other NE programs or to industry for demonstration and larger scale commercial use, the IES program maintains relationships with these programs in order to record lessons learned and to validate IES tools and methods being used to support the advancement of other concepts.

The IES program scope is divided into three broad technical areas, which will be discussed further in later sections, with economic analysis currently managed as a subset to system simulation:

- ***System Simulation***. Develop and exercise an ecosystem for modeling, analysis, and optimization of IES that can accommodate various reactor types, renewable technologies, energy storage, and energy users.
- ***Economic Analysis.*** Establish a reference capability to validate current practices in valuing nuclear energy in the energy markets (electric and nonelectric).
- ***Experimental Evaluation***. Establish and operate a fully functional and diverse nonnuclear facility for model validation and initial technology demonstration.

2. Program Implementation

The CTD IES program conducts RD&D to address identified gaps by engaging with expertise and utilizing facilities at the DOE national laboratories and via partnership with academia and industry. The multidisciplinary nature of IES requires this work to be coordinated with a range of programs and activities across the DOE offices and DOE laboratory complex.

2.1 Relationship to Other Programs

Like other CTD elements, the IES program performs RD&D applicable across a range of technologies, encompassing both the current and future fleet of nuclear energy systems. The program team interfaces with a number of other NE programs to ensure that:

1) IES-developed tools and technologies will meet the highest-priority needs of end users with appropriate timing
2) IES-related work, within the CTD program, other NE programs, and programs managed by other DOE offices, is not duplicative of other efforts underway or already completed within NE or elsewhere (i.e., this program ensures awareness of the current state of practice).

Specific NE-5 programs that are or will be supported in this manner include LWRS, SMRs, and Advanced Reactor Development (ARD). For the latter, working-level interactions are expected to occur at the subprogram level, as the IES Program explores the needs of the various ARD-supported reactor types (e.g., molten-salt, liquid-metal, gas-cooled, microreactors). Because the IES program's primary mission is advancing technology concepts to demonstration, the IES Program also coordinates closely with both LWRS and with NRIC on IES RD&D plans that could lead to demonstration opportunities. The System Analysis and Integration Campaign under NE-4 (Nuclear Fuel Cycle and Supply Chain) similarly conducts analysis related to nuclear energy system technical and economic viability and long-range energy system planning that is necessarily coordinated with IES.

Although the other CTD program elements are closely interlinked and often must coordinate very closely with one another to provide related technologies, the IES program element is more distinct. The IES program and other CTD program elements maintain mutual awareness of their ongoing work, and the IES program will leverage the CTD expertise in advanced sensors and instrumentation, cybersecurity, advanced manufacturing, and machine learning and artificial intelligence, as needed to support specific IES concepts. While such technical support will be important for the IES program, the technologies being developed by these programs are not closely coupled to IES outcomes at this time.

The IES objectives and approach are not unique to nuclear applications. The broad outcomes that can be achieved by the "system of systems" optimization within the energy sector are also being examined and developed by other programs, including those supporting other types of electricity generation, efficiency of electric and nonelectric energy applications, and improvements to energy storage, transmission and distribution. To foster interoffice cooperation and coordination in this area, DOE and its national laboratories have established several related initiatives that the IES program supports, either through representation, jointly funded projects, or both. At the time of this writing, these include the Grid Modernization Initiative (U.S. Department of Energy n.d. b), the Energy Storage Grand Challenge (U.S. Department of Energy n.d. a), the Water Security Grand Challenge (U.S. Department of Energy n.d. f), the Applied Energy Tri-Laboratory Initiative (Arent, et al. 2018), and the Hybrid Energy Systems Working Group, an informal federal staff team identifying areas of potential RD&D coordination across DOE offices. Specific collaboration between the CTD IES program and the DOE-EERE Hydrogen and Fuel Cell Technologies Office (HFTO, formerly the Fuel Cell Technologies Office) has also been established to advance analysis and demonstration of nuclear-driven hydrogen generation via electrolysis. This collaboration has led to joint publications and partnership on the current fleet LWR-hydrogen demonstration projects (initiated via IES, but now managed by LWRS).

2.2 Stakeholder Engagement

The IES program formally documents its process for stakeholder engagement and the status and results of those efforts in an annually updated report (Bragg-Sitton and Boardman 2019). These efforts, primarily led by the INL national technical director (NTD) or her designee, include:

- engaging with industry groups, such as the Electric Power Research Institute (EPRI) and the Nuclear Energy Institute (NEI), to ensure a mutual understanding of industry needs and program RD&D results
- soliciting input from industry advisory groups (one each for the current fleet and future reactors) on the technical gaps for IES implementation
- coordinating efforts with related NE and other DOE programs and national laboratories
- supporting longer range RD&D being conducted in collaboration with academia
- participating in international cooperative research and information-sharing efforts organized through NE.

2.3 Research Organization

The IES program accomplishes its goals through a combination of directed and competitive research projects, including work conducted by national laboratories, academia, and industry.

2.3.1 Directed Research

Directed research includes IES RD&D activities for which the most appropriate means of meeting program objectives is to apply the unique capabilities of the DOE national laboratories. These activities are not selected competitively but are selected through the formal review of an annual Integrated Priority List (IPL). The IPL is prepared by the NTD and formally reviewed through the annual NE Planning, Programming, Budgeting, and Evaluation (PPBE) process. Because this set of processes is common across the Office of Nuclear Reactor Fleet and Advanced Reactor Deployment (NE-5), it is not described in detail in this document. At the time of this writing, this process is not contained in a single source document, but recent process documentation that supported the preparation and approval of this plan are included in the references (Caponiti 2020). Additional information documenting the scope, work breakdown structures, budgets, detailed milestones and related approvals is contained in NE's electronic program management system, known as the Program Information Collection System: Nuclear Energy (PICS:NE).

All three major program RD&D areas (system simulation, economic analysis, and experimental validation) are included in the directed research portion of the program. INL has developed a modeling and simulation platform, with the additional support of researchers at Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL), that has been used to support numerous studies assessing the technical and economic viability of various IES concepts. This system is currently being enhanced to include a graphical user interface and being released as an open-source tool available for use beyond the national laboratory team, such as by academia and industry. The timeline for availability of these tools is summarized in the high-level milestones provided in Section 1.2 and is in alignment with the needs associated with the timelines provided in Appendix A. For additional details, see (Bragg-Sitton, et al. 2020).

The economic analysis mission was formally added to the IES program in FY 2020 as a key component of the system simulation activities, although economic analysis for specific IES configurations has been a component of system analysis from the start of the IES program work. Although the economic analyses to be conducted are not limited to IES, the objectives and needed technical capabilities are closely related and complementary to the other program activities. The objective of this set of activities is to encourage the accurate and consistent representation of nuclear energy, particularly advanced nuclear energy technologies, in the tool sets currently used for a variety of energy modeling applications. This broader economic analysis component has been initiated with a single project that will investigate several such tools applied for studies of capacity expansion options, documenting the similarities and differences in how nuclear energy is represented within each of the tools and comparing how these assumptions and methods affect results obtained from the tools.

The IES program conducts its experimental activities primarily within the Energy Systems Laboratory (ESL) at INL. The main set of capabilities developed and used by the program is known as the Dynamic Energy Transport and Integration Laboratory (DETAIL), which can demonstrate the real-time integration of multiple subsystems, including:

- electrically emulated nuclear energy input
- renewable energy inputs
- electrical grid (digital real-time simulator [DRTS], microgrid test bed)
- thermal and electrical energy storage
- energy delivery to an end user
- industrial processes.

Within DETAIL, the TEDS has been constructed and is currently being commissioned to emulate thermal energy generation, initially using a controllable heater element, thermal energy storage, and distribution of thermal energy to the generation of electrical power or use in producing nonelectrical commodities (e.g., hydrogen). TEDS began commissioning in December 2020 and will complete shakedown testing in January 2021. Many of the subsystems incorporated in DETAIL are funded by other DOE programs, including LWRS, Microreactor, and EERE HFTO, but they are or will be interconnected to achieve the goals established for demonstration and operation of integrated energy system configurations, as reflected in the milestones listed in Section 1.2.

As noted in Section 1.2, multiyear objectives have been established for IES. In many cases, the accomplishment of these objectives requires direct coordination with other DOE programs that are responsible for hardware installation (e.g., MAGNET, hydrogen electrolysis). Key near-term IES program milestones support the achievement of the timelines summarized in Appendix A. These include:

- FY 2023—deliver a “plug-and-play” flexible simulation ecosystem for industry applications, with a graphical user interface to allow broad use by laboratory and academic researchers and private industry
    - Dynamic representation of multiple energy generation and use technologies
    - Application of technical constraints, and evaluation of both technical and economic performance

    - Optimization driven by regional data, such as time-dependent data for renewable generation, grid demand, and grid pricing
- FY 2024—demonstrate an experimental capability that can emulate a large-scale, multisystem IES that incorporates both real and virtual elements.
    - Local subsystems will include an electrically heated reactor emulator, high-temperature electrolysis for hydrogen generation, and energy storage
    - Remote systems may include facilities at partner laboratories, such as wind generation and low temperature electrolysis
    - Virtual systems may include the emulation of multiple variable loads and will be used to emulate nuclear reactor dynamics
    - This capability can provide realistic information on the emergent characteristics and performance of these complex systems operating with the electric grid before initiating the significant investment required to deploy them in the commercial marketplace.
- FY 2026—in collaboration with NRIC, perform modeling, simulations, and experiments to support the inclusion of an IES with an advanced reactor demonstration.

A complete list of current-year directed work projects is included in Appendix B.

2.3.2 Competitive Research

In addition to the directed research described Section 2.3.1, the IES Program also pursues its objectives through NE and DOE competitive opportunities. These currently include the Nuclear Energy University Program (NEUP) (U.S. Department of Energy n.d. c), the Small Business Innovative Research (SBIR) Program (U.S. Department of Energy n.d. d), and the NE Funding Opportunity Announcement (FOA), and the U.S. Industry Opportunities for Advanced Nuclear Technology Development (also known as the industry FOA) (U.S. Department of Energy n.d. e).

NEUP is an NE-specific program that uses competitively selected, university-led research to advance program objectives. It is imperative that program leads consider benefits to long-range goals when identifying scope for university projects, recognizing that the work will take approximately one year to be awarded and an additional three years to be completed. For IES, the program elements best suited to university-led research may include conceiving and analyzing IES configurations and applications, developing and exercising modeling tools and techniques, integrating new models into the INL modeling and analysis ecosystem, developing interface technologies, and developing nonelectric end-use technologies, in cases where such technology development would enable or enhance the ability of that end-use to take advantage of unique capabilities of advanced nuclear power systems. Within the NEUP call, the IES section explicitly requires that proposals utilize the simulation and analysis platform under development at the national laboratories or that any developed models can later be easily integrated into this platform, to ensure that the resulting output from each of the projects can be utilized by the broader program. A list of previously awarded IES NEUP projects is included in Appendix C; the IES program awarded its first NEUP projects in FY 2018. University principal investigators and their project teams are engaged in regular meetings (e.g., monthly) with laboratory program staff to provide intermediate guidance on project direction and to ensure that the university developed models, analysis approaches, data, etc. can be integrated into the main program as early as possible.

The SBIR program is a DOE-wide effort managed by the Office of Science, engaging small businesses to apply technology innovations to the advancement of DOE missions. For IES, the areas where small business is currently poised to engage are primarily related to developing interface technologies and control systems. As with NEUP, end-use technologies are also of interest if the proposed technologies enable an IES to take advantage of specific advanced reactor features or capabilities in ways that current technologies cannot. As IESs progress into more widespread use, it is also anticipated that small businesses may develop and offer software solutions to support their operation. A list of previously awarded IES SBIR projects is included in Appendix C; the IES program made its first SBIR award in FY 2020.

The industry FOA is an opportunity managed by NE, supporting industry-led activities that advance nuclear innovations toward near-term commercial deployment. Unlike the SBIR program, this opportunity is open to U.S. businesses of any size. Applicants may also propose projects over a far wider range of funding levels. Although this opportunity includes the possibility of IES development, the IES program has not funded any selected projects under the NE FOA to date. The IES-relevant projects that have been initiated so far through the industry FOA have been nuclear demonstration projects that support hydrogen production by low temperature and high-temperature electrolysis at current fleet LWR plants, funded and led by the LWRS program in collaboration with an industry consortium (i.e., Energy Harbor, Xcel Energy, Arizona Public Service). However, the IES program has contributed to an FY 2019 FOA awarded by the DOE Office of Energy Efficiency and Renewable Energy (DOE-EERE) Fuel Cell Technology Office (recently renamed to the Hydrogen and Fuel Cell Technology Office), via EERE-NE collaboration for hydrogen production (the IES program provided 50% of the DOE cost share). This award will result in the demonstration of hydrogen production technology at an Exelon nuclear plant in accordance with the LWR-IES goals and timeline summarized in Appendix A; hence, it is now managed from the NE side by the LWRS program.

3. Program Management

This section describes, in general terms, the approach to planning, authorizing, and managing the IES program work. IES is a subprogram that follows general processes common across NE-5 for many program management functions. This plan describes these common processes only at a high level, focusing instead on elements unique to IES implementation.

3.1 Organizational Structure

The IES program is led by INL, and has a structure as depicted in Figure 5. The NTD is supported by a technical area lead (TAL) for each major research component and by a TAL for the work at each supporting national laboratory.

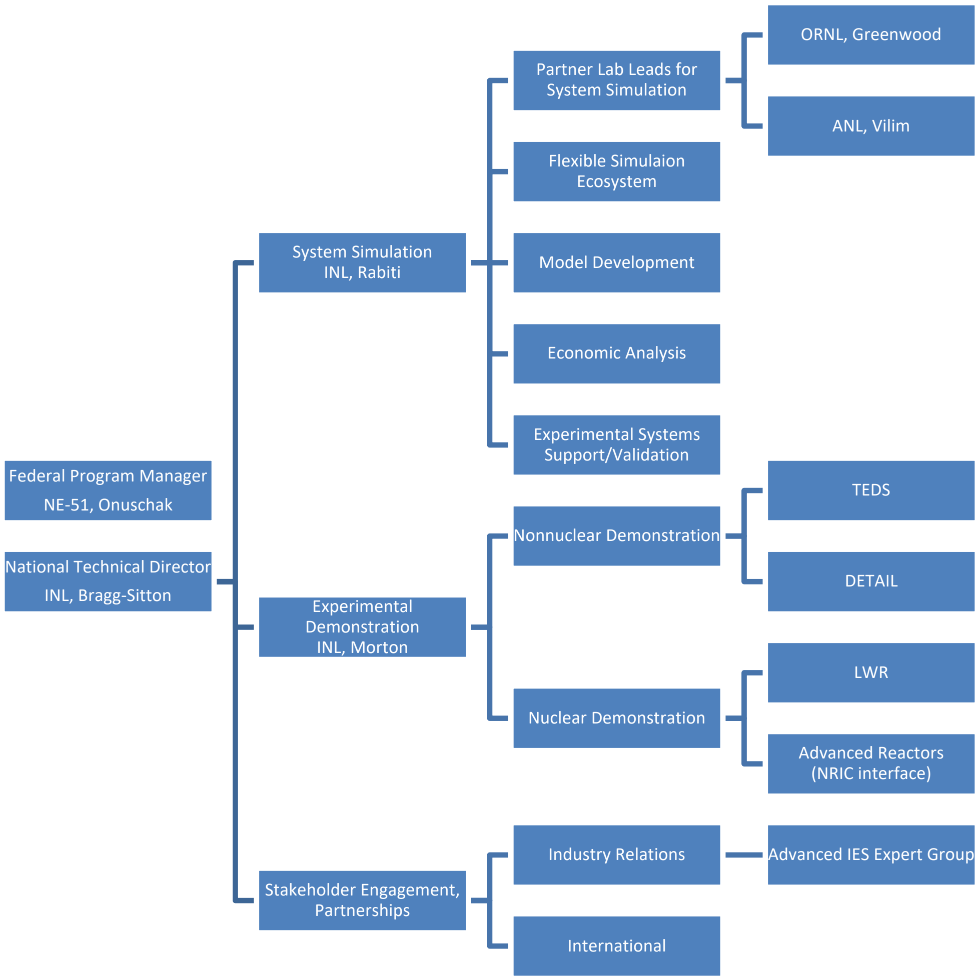

Figure 5. IES Organizational Structure.

3.2 Roles and Responsibilities

The DOE program manager is responsible for working with NE management to ensure that the IES program is aligned with DOE and NE priorities, for obtaining the resources required to carry out its objectives, and for providing federal oversight of the work, in coordination with appropriately authorized contract oversight personnel at the DOE Idaho Operations Office. Key roles and responsibilities of the DOE Program Manager include:

- Working with the NTD to prepare and update program planning documents
- Coordinating with the NTD as appropriate, preparing budgets and supporting documentation as part of the annual appropriations process
- Approving work plans as they are progressively elaborated in advance of each fiscal year and as they are modified
- Providing funding and work authorizations to the national laboratories
- Working with the NTD to prepare scopes for competitive RD&D solicitations and to select and monitor resulting awards
- Providing federal oversight for all program work at national laboratories and other institutions and

- Representing the program in agency-level working groups and collaborative RD&D efforts.

The NTD provides the technical leadership of the IES program, ensuring that both elements conducted at the national laboratories and through competitive awards form a cohesive set of progress toward the program's goals. The NTD is also responsible for the integrated programmatic management of all activities conducted at INL and the other national laboratories. Key responsibilities of the NTD include:

- Maintaining knowledge of elements across the NE RD&D portfolio that are relevant to the IES program and establishing routine coordination across NE.
- Working with the DOE program manager to prepare and maintain program plans and technology roadmaps to guide RD&D prioritization.
- Serving as the program's primary technical representative to industry working groups, international collaboration structures, regulators, and other stakeholders.
- Establishing annual and multiyear budgets, integrated priority lists, and work plans in coordination with the NE program manager and the TALs.
- Maintaining oversight and accountability for program execution, in coordination with the TALs; serving as the primary interface to NE for program reporting and change control. This includes maintaining cognizance of cost, schedule, and technical performance status, participating in scheduled program reviews and personally reviewing and approving all program content provided in PICS:NE.
- Providing technical leadership and support for competitively awarded IES projects. This includes developing language for annual solicitations, participating in informational webinars, performing relevancy reviews and recommending technical reviewers for proposals, monitoring and evaluating resulting awards, and proposing pathways for continued development of the most promising work.
- Serving as the primary technical resource for NE programs requiring input on program-related matters. This may include such things as providing technical input to communications products or advice on the current technical state of practice.

TALs support the NTD by providing direct management of portions of the program scope. The TALs are primarily responsible for initial definition and execution of the technical work under each of the defined work packages in the directed research areas summarized in Appendix B. The TALs are additionally assigned to coordinate integration of competitive research projects (summarized in Appendix C) with the laboratory-led research scope. As appropriate and requested, they or their staff may also serve as subject matter experts on Integrated Project Teams for demonstration projects or similar large-scale activities for which multidisciplinary technical support is beneficial.

3.3 Planning, Programming, Budgeting, and Execution Processes

IES participates in PPBE processes coordinated at the NE-5 level and is not responsible for developing or managing its own PPBE processes. From the perspective of a subprogram such as IES, planning, programming, and budgeting are not distinct processes but are managed in an integrated fashion. The NE execution process is supported by IES through the work authorization, reporting, and oversight processes described in Section 3.4.

Like all DOE programs, NE budgets are prepared two years prior to each FY, with planning refined as government-wide budgets are announced and appropriations are approved by Congress. The IES program prepares and submits its plans to support these process inputs in accordance with NE direction. It is not necessary for the purposes of this plan to describe these processes in depth; instead, key processes conducted prior to the start of each FY that are directly used to prioritize IES work will be summarized.

Early each summer, an NE-5 strategic planning meeting is conducted, inclusive of all NE-5 programs, to ensure that the deputy assistant secretary (DAS) approves of all multiyear program goals and plans, that these are aligned with the NE Strategic Plan, and that there is appropriate coordination among programs to ensure that cross-program goals are appropriately resourced and that there is no duplication. Feedback from this meeting is incorporated by programs as they prepare for a follow-on meeting just before the start of each FY, where attention is focused on single-year planning. IPLs for the upcoming FY, prepared by the NTDs and coordinated with DOE program managers, are reviewed against the organizational goals and anticipated budgets, and adjustments are directed by the DAS as needed. After this meeting, the NTD begins to prepare work packages for DOE program manager approval, and the program proceeds to the budget execution phase, as described in Section 3.4.

3.4 Work Authorization, Reporting, and Oversight

NE uses an automated system, PICS:NE, to document and authorize work scopes; provide formal guidance; track technical, cost, and schedule performance; collect deliverable documents and provide formally documented government approvals, such as for scope changes, documents requiring approval, and performance evaluations for work elements that require it. Because these processes are common to all NE-5 programs, they will only be summarized here.

TALs include all of the work described in the approved IPL in PICS work packages to be approved by the NTD and the DOE program manager. Each work package describes, at an agreed-upon level of detail, work to be performed, milestones, deliverables, and a time-phased budget. Once baselined, changes to work packages require a Baseline Change Proposal, with approval levels in accordance with predefined change thresholds. Work packages are also established for each competitively awarded project, but these are not managed directly by the NTD.

As work progresses, each TAL (for national laboratory work) or each principal investigator (for competitively awarded projects) submits performance information on a required schedule (monthly or quarterly). Performance is monitored by the DOE program manager, with adjustments to work scope or funding as necessary, within authorized levels. Issues requiring NE management attention or intervention are elevated as needed by the DOE program manager. For competitively awarded grants under the NEUP program, an assigned TAL, the NTD, and the DOE program manager provide formal evaluations in PICS quarterly, at the project midpoint, and on project completion. These are used not only to document award performance but to consider appropriate next steps for the RD&D conducted at universities in conjunction with the IES program.

NE-5 conducts reviews of its portfolio at least quarterly, at which time the performance information is provided for each program, including IES. At these reviews, the IES NTD provides technical, cost, and schedule status information for all IES program work, whether led by INL, the other national laboratories, or other institutions.

4. Program Success Metrics

The IES program uses a number of metrics to evaluate its performance and effectiveness. Performance metrics are used to measure the extent to which the program is achieving its agreed-upon baseline goals, within its established budget and schedule. For performance metrics, specific quantitative targets are established in advance of the work and monitored as the work progresses. Effectiveness measures, in contrast, are designed to evaluate the extent to which the program, regardless of its performance toward its baseline, is achieving the benefits for which it was established. For the IES program, effectiveness metrics are evaluated as the work progresses, without using preestablished target values. The primary purpose of the IES program is to provide the information and tools that support industry movement toward the use of IES in nuclear energy systems, to improve economic competitiveness of nuclear energy, and to improve the environmental performance or resiliency of the integrated system. The most important success indicators are the initiation of pilot demonstration projects based on IES program work and the progression of those projects toward larger implementations as the pilot efforts validate the IES program's assessments. However, because these are not expected to be frequent events, interim metrics are used to assess progress toward demonstrations, such as industry sponsorship or partnership in IES analytical and experimental studies, the transition of work products into other NE programs, the approval of software and analysis tools to be made available as open-source, peer-reviewed publications, the internal and external recognition of program outcomes, and any potential patent applications.

4.1 Performance Measurement

The IES program establishes its multiyear goals and decomposes them into annual baselines as described in Section 3.3. Similarly, the work is authorized and monitored according to standard NE processes, described in Section 3.4. Expectations for successful program performance are established by NE management and may change, superseding this plan. At the time of this writing, programs are considered to have successful performance if:

- All Level 2 milestones are met on time and within budget, as defined in the original or an appropriately approved modified baseline
- All Level 3 milestones, as defined in the original or approved adjusted baseline, are achieved within the program's total fiscal year budget, even if delayed
- All deliverable reports are received on time, and accepted and published to the Office of Scientific and Technical Information (OSTI), as appropriate, within 2 months of original submission, following full approval by the publishing laboratory for the lead author and the DOE program manager
    - Exceptions to the OSTI submission time frame may be considered on a case-by-case basis, for reports containing sensitive information or requiring external review before publication (e.g., reports prepared in partnership with industry or requiring external stakeholder review)
    - Lower-level milestones that provide progress toward an activity that will later be incorporated into a higher-level milestone report are not required to be submitted to OSTI.

4.2 Effectiveness Measurement

The IES program conducts its own reviews and participates in NE-5 portfolio reviews as described in Section 3.4. Although specific targets are not established in each of these areas, the following effectiveness measures will be included in all such reviews, to the extent appropriate to the review's purpose:

- IES pilot and demonstration projects, led by NE or others, including 1) the direct or indirect contributions made by the IES program; 2) any continuing role of the program or plans to obtain validation data from the project; and 3) the results of any program validation efforts performed using information already obtained from the pilot project
- Industry sponsorship or partnership in IES modeling or experimental tasks
- Transition of work from the IES program to other NE programs to advance it toward implementation
- Peer-reviewed publications and conference presentations
- Approval of software and analysis tools to become open source
- Patent applications planned or in progress and
- Awards and external recognition for the program's outcomes or key staff contributions to the field.

All such reviews will include formal feedback from NE management with an assessment of the program's effectiveness and any concerns or suggested changes. These will be used to adjust future program planning efforts in accordance with the processes described in Section 3.3 or to inform more immediate program changes as appropriate.

5. References

Arent, Douglas, Peter Balash, Richard Boardman, Shannon Bragg-Sitton, Jill Engel-Cox, David Miller, and Mark Ruth. 2018. *Summary Report of the Tri-Lab Workshop on R&D Pathways for Future Energy Systems.* Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72926.pdf.

Bragg-Sitton, Shannon M, Cristian Rabiti, James O'Brien, T.J. Morton, Richard Boardman, SuJong Yoon, JunSoo Yoo, Konor L Frick, M Scott Greenwood, and Richard Vilim. 2020. *Integrated Energy Systems: 2020 Roadmap.* Idaho Falls, ID: Idaho National Laboratory.

Bragg-Sitton, Shannon, and Richard Boardman. 2019. *Integrated Energy Systems: FY19 Stakeholder Engagement and International Activities.* Idaho Falls, ID: Idaho National Laboratory.

Caponiti, A. 2020. "NE-5 Fiscal Year 2021 Program Planning Meeting Guidance." August.

Hensen, J.L.M., R.C.G.M. Loonen, and M. Archontiki. 2015. "Using Building Simulation for Moving Innovations across the Valley of Death." *REHVA Journal* 52 (3): 58-62.

International Energy Agency. 2019. "Nuclear Power in a Clean Energy System." May.

Office of Nuclear Energy. draft. *DOE Office of Nuclear Energy Strategic Plan.* Washington, DC: US Department of Energy.

U.S. Department of Energy. n.d. a. *Energy Storage Grand Challenge.* Accessed December 2020. https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge.

—. n.d. b. *Grid Modernization Initiative.* Accessed December 2020. https://www.energy.gov/grid-modernization-initiative.

—. n.d. c. *Nuclear Energy University Program.* Accessed December 2020. https://neup.inl.gov/SitePages/Home.aspx.

—. n.d. d. *Small Business Innovation Research and Small Business Technology Transfer.* Accessed December 2020. https://www.energy.gov/science/sbir/small-business-innovation-research-and-small-business-technology-transfer.

—. n.d. e. *U.S. Industry Opportunities for Advanced Nuclear Technology Development.* Accessed December 2020. https://www.energy.gov/ne/initiatives/funding-opportunities#:~:text=U.S.%20Industry%20Opportunities%20for%20Advanced%20Nuclear%20Technology%20Development%20(Industry%20FOA)&text=The%20U.S.%20Department%20of%20Energy,advance%20nuclear%20power%20in%20Americ.

—. n.d. f. *Water Security Grand Challenge.* Accessed December 2020. https://www.energy.gov/water-security-grand-challenge/water-security-grand-challenge.

Appendix A
Timelines for IES Development and Demonstration

Timelines associated with the deployment of IES were summarized in (Bragg-Sitton, et al. 2020). Current fleet demonstrations, particularly those adopting electrical integration approaches, can be conducted within the relative near term, while thermally integrated IES will require a longer design and development timeline as well as associated safety reviews and licensing. The notional timelines for LWR integration is provided in Figure 6, noting options for both electrical and thermal integration. Novel IES incorporating SMRs and other advanced reactors will have more protracted development timelines reflective of their current development stage, as estimated in Figure 7 and Figure 8.

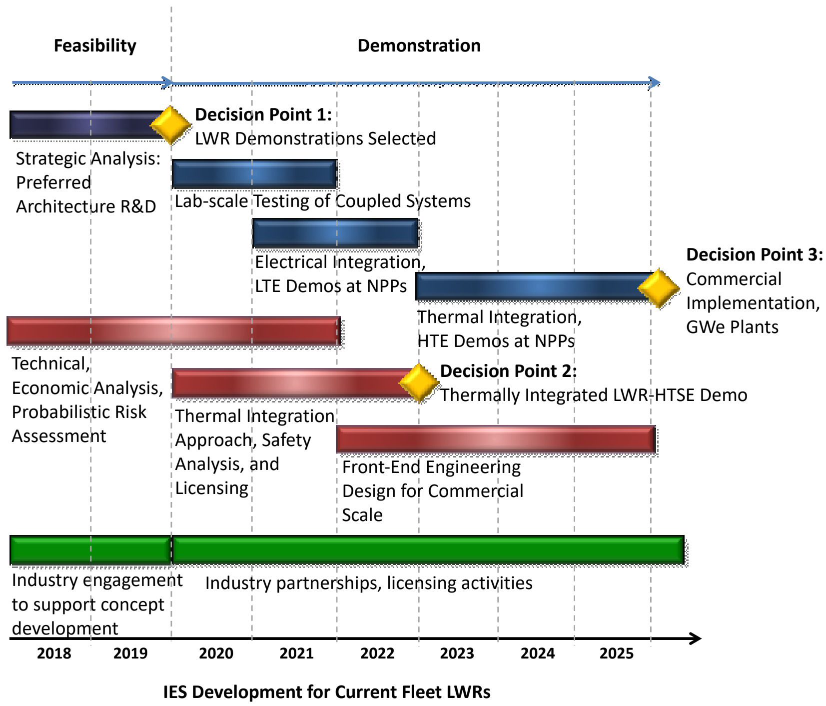

Figure 6. Notional IES deployment timeline for current fleet LWRs.

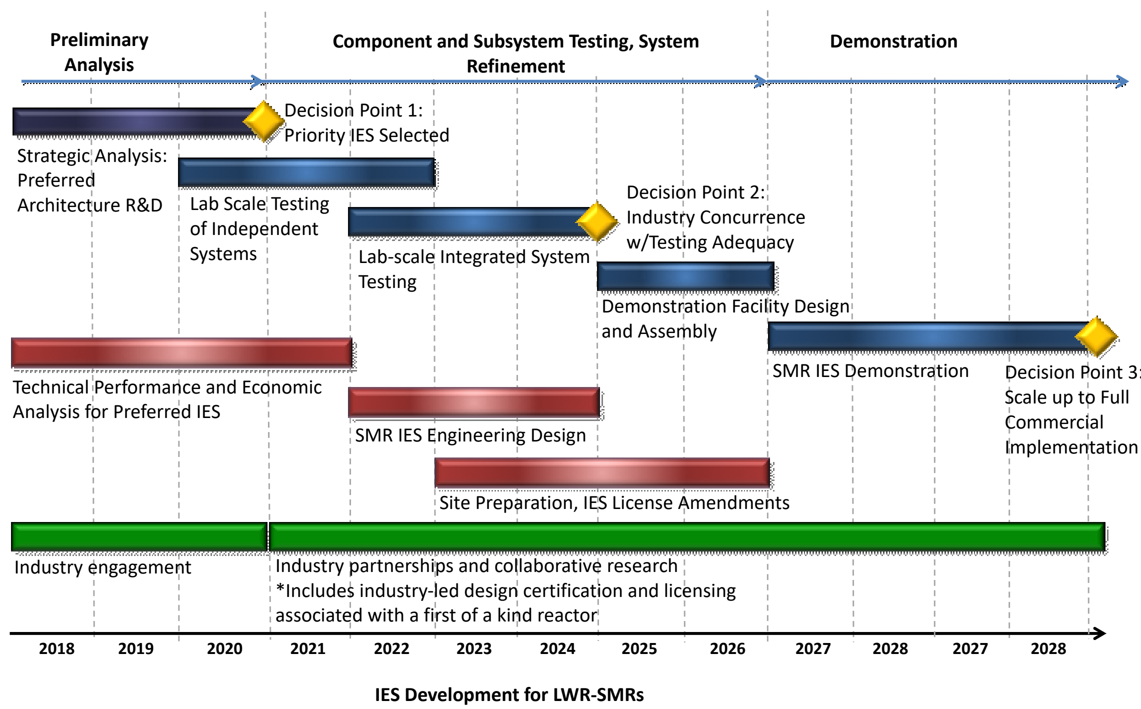

Figure 7. Notional IES deployment timeline for LWR SMRs based on the currently published schedules for commercial SMR deployment.

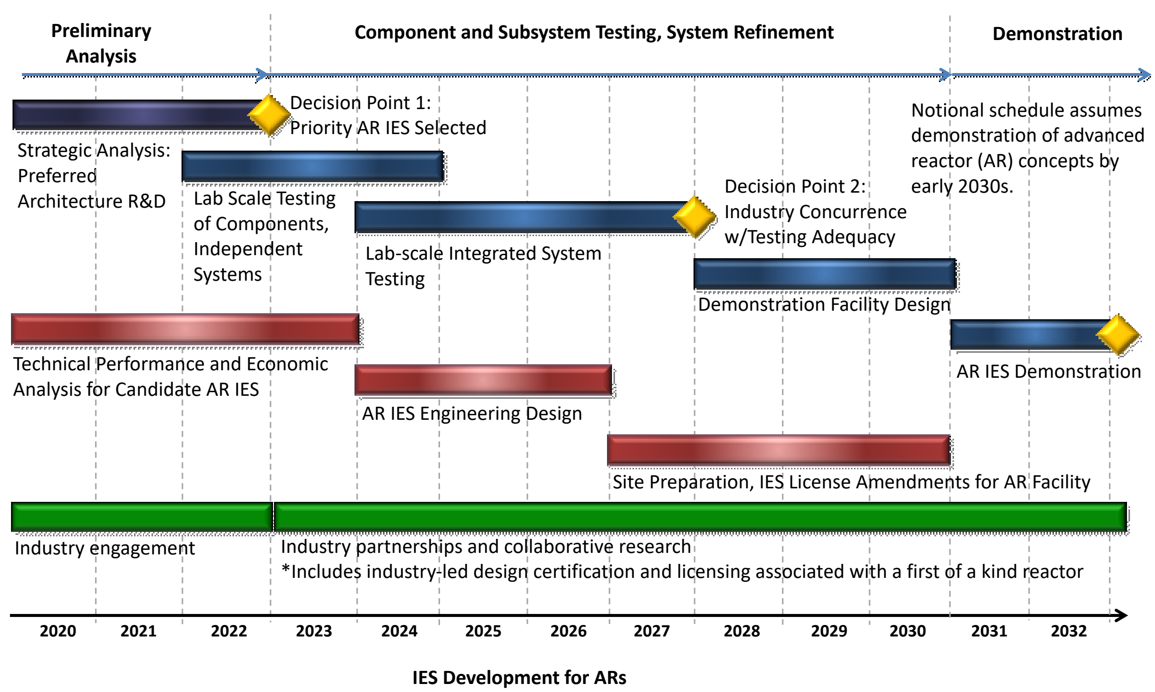

Figure 8. Notional IES deployment timeline for advanced reactors. The start date of 2020 reflects large-scale advanced reactors. Microreactors may be demonstrated on a shorter timeline and could include IES applications.

Appendix B
Current IES Directed Projects

The directed IES research is defined in PICS:NE under three main control accounts, each of which include a subset of work packages to manage this work. The high-level scope for the FY2021 work packages is included below, along with associated milestones.

Control Accounts

1. Program Management, Integration, Stakeholder Engagement (PMIS)
   - CT-21IN120101: IES Program Management & Stakeholder Engagement
2. System Simulation (SS)
   - CT-21IN120201: System Simulation Management & Support
   - CT-21IN120202: Flexible Simulation Ecosystem
   - CT-21IN120203: University Support for Framework Development
   - CT-21IN120204: Simulation of Experimental Applications with Validation
   - CT-21AN120205: Simulation Ecosystem Control System Development (ANL)
   - CT-21OR120206: IES Simulation Support – ORNL
   - CT-21IN120207: Real-Time Optimization/Digital Twin
   - CT-21IN120208: Dynamic Component Models
   - CT-21IN120209: Model Intercomparison (EPRI)
3. Experimental Systems Development & Testing (ESDT)
   - CT-21IN120301: Thermal Energy Distribution System
   - CT-21IN120302: Dynamic Energy Transport and Integration Laboratory Connectivity
   - CT-21IN120303: Advanced Reactor IES Platform (NRIC)

Program Management, Integration, & Stakeholder Engagement (PMIS)

The program management control account is enacted via a single work package that included activities for the overall management of program activities, stakeholder engagement, and international collaborations. The scope for each of these activities is summarized below.

Activity 1.a – Program management
Manage all IES program activities. Coordinate collaborative activities with the National Renewable Energy Laboratory (NREL, funded via DOE-EERE). Participate in industry activities related to options for the flexible operation of nuclear power plants, including EPRI-sponsored technical advisory groups, IAEA technical meetings and committees, and Nuclear Energy Agency expert groups. Fulfill the DOE-NE–EERE partnership through frequent meetings with EERE Vehicles, Renewable, Energy Efficiency, and Strategic Programs Offices, with special attention on H2@Scale.

Activity 1.b – Stakeholder engagement
Engage industry and other potential stakeholders, with specific attention given to the Advanced IES Expert Group established in 2020. The expert group includes the engagement of advanced reactor developers and will be extended to energy end users, with a goal of establishing relevant industry partnerships.

Activity 1.c – International collaborations
Coordinate international bilateral activities and collaborate with NE-6 on the Nuclear Innovation: Clean Energy Future (NICE Future) initiative under the Clean Energy Ministerial (funded via NE-6). Continue coordination of bilateral activities with India and Japan under the Civil Nuclear Energy Working Groups. Establish relevant new collaborations.

System Simulation (SS)

The SS control account is led by INL, with work being conducted at INL, ORNL, and ANL and additional work subcontracted, as necessary. In FY 2021, this includes a total of nine work packages. The scope for each of these work packages and activities is summarized below.

CT-21IN120201: System Simulation Management & Support
This work package supports the management and integration of all system simulation activities across the three laboratories and subcontractors. It also provides funding to annual software license support and a share of the costs to maintain the RAVEN repository (split across programs that use RAVEN).

Activity 1.a – Management and coordination of all simulation activities.
Integration of partner activities (lab, industry, academia). User support for analysis tools. Coordination of cyber security activities. Software licenses. Publications management for simulation activities. Coordination with modeling and simulation activities with the National Renewable Energy Laboratory (NREL, funded via DOE-EERE), National Energy Technology Laboratory, Grid Modernization Initiative, and Hybrid Energy Systems Task Force (EERE front office initiative). In FY 2021, this activity will also include the management of CINR and NEUPs.

Activity 1.b – General license support for Modelica, repository support for RAVEN.
Provide funding to support commercial software license fees and the relative IES fraction of support to maintain the RAVEN repository.

Activity 1.c – Overview of cyber security requirements for IES.
Integrated energy systems components, to maximize their efficiency, need to be co-controlled and aware of the electrical grid demand in real time. A natural question that arises is if this situation creates a unique cyber sensitive scenario outside of the one historically considered in these applications. This work will provide an initial assessment of the cyber needs of IES and indicate if they possibly represent a gap under the current state of the art.

Activity 1.d – Initiate cooperation with industry to develop pilot use case(s).
Seek a possible priority end-use case with support from the Advanced IES Industry Expert Group and, if identified, develop a conceptual framework for a value analysis of the IES business case. If a suitable high-priority end user is not identified, a possible user case is selected, and the framework for the value assessment defined.

CT-21IN120202: Flexible Simulation Ecosystem

Activity 2.a – Flexible modeling ecosystem
Modeling and simulation infrastructure enhancement to allow for a flexible simulation platform with "plug-and-play" capabilities. This is a unique capability not currently available in other platforms due to the application of the dynamic modeling language Modelica and planned integration with artificial intelligence (AI). The Modelica language allows the use of the FMI/FMU, which are precompiled templated modules representing a physical system. This approach allows intellectual property protection for any industrial partner while sharing the models. Second, the direct integration of RAVEN and Modelica allows researchers to explore the usage of AI to speed up simulation time. The goal of this activity is to develop the needed framework to deploy these capabilities.

In FY 2021, work will continue to develop a "plug-and-play" flexible simulation and optimization ecosystem to expand the capability of evaluating IES configurations having a wide variety of generation sources, storage technologies, and energy use pathways. It includes the work necessary to integrate or interface with the IDAES (NETL) platform or the SIIP (NREL) modeling platforms. Design and development of a graphical user interface will also be initiated.

The flexible ecosystem will support the inclusion of multiple generator types and energy use components, including energy storage. Hence, the contribution to energy storage research is counted as a fraction of the overall ecosystem development. Inclusion of these components will include the development of the appropriate interfaces and control approaches in the overall ecosystem structure.

Activity 2.b – Acquire and test IDAES framework and develop synergy strategy
The cooperation under the Grid Modernization Initiative and the Applied Energy Tri-Laboratory umbrellas requires a mutual understanding of capabilities and a common effort to identify gaps existing in the available computational modeling and analysis tools. This activity will support acquisition of the NETL IDAES (Design of Advanced Energy Systems) framework, simulation of a few test cases, and evaluation of SQA compatibility with RAVEN and the plugin system. Work will focus on determining both the potential overlap and uniqueness of the two different approaches and will propose a synergistic path forward. Given the current knowledge of the capabilities of IDAES, priority will be given to the assessment of the possibility to leverage the PRESCIENT tool. This would expand the current capabilities of the HERON/RAVEN framework so that it can simulate a larger section of the grid. This would allow the framework the capability to better capture grid feedback in the economic evaluation of IES.

Activity 2.c – U.S. market structure review
One of the key differentiating attributes for IES is the capability to act within the grid as a load response or equivalently as batteries. While qualitatively we know that this provides value to the grid, not all electricity markets reward these services. The work under this activity will review the different markets in the U.S. and generate a document that can be used as a reference to initiate a technoeconomic analysis in the context of one of the U.S. markets. The document will contain the market structure, the characteristics (e.g., ramp rate, duration) that are necessary to qualify for the market, and, if available, the location of historical data.

CT-21IN120203: University Support for Framework Development
This work package supports the engagement of experts in academia to develop specific simulation capabilities to support the development of the modeling and optimization ecosystem.

Activity 3.a – Purdue University
Enhancement of the analysis and optimization framework for robust economic. IES is currently performing a stochastic optimization, where the goal function to optimize is the mean of the relevant financial figure of merit. For some investors, instead of optimizing the mean, it may be preferred to choose a less optimal configuration that is less sensitive to the scenario uncertainties (e.g., capital cost, etc.). Implementing and improving this type of approach is the task goal.

Activity 3.b – Colorado School of Mines
FY 2020: Incorporation of process workflow to cover best practices to create synthetic data associated with renewable generation and electricity demand into the simulation framework.
FY 2021: Selection and analysis of an IES advanced reactor user case using IES workflow and tools.

Activity 3.c – George Washington University
FY 2020: Framework enhancement by the acceleration of stochastic optimization techniques.
FY 2021: Enhancement of optimization capabilities, low probability sampling for risk adverse optimization.

Activity 3.d – Coordination
Coordination of university activities and production of a final report integrating the activities' efforts. Note that individual subcontracts will produce reports to INL that will be rolled into the overarching M3 deliverable.

CT-21IN120204: IES Simulation of Experimental Applications with Validation
This work package supports the development of dynamic system scaling approaches to support experimental system design and analysis. The utilization of experimental systems to validate models is also included.

Activity 4.a – Dynamic system scaling
The coupling of one reactor module with a heat transfer loop to test the feasibility of heat extraction from a water-cooled small modular reactor (e.g., a NuScale plant) will require simulating the performance of the system in advance. The simulation must be capable of reproducing experimental results. Therefore, a set of representative experiments will need to be defined and used to validate the models against experimental results. The current activity will focus on developing the needed framework to use the dynamic system scaling (DSS) approach to perform the validation of the model. DSS is an advanced validation methodology that NuScale is already exploring and that it is suggesting for validation activities related to the hybridization of the NuScale SMR design. In FY 2021, the scope also includes completing the integration of a validation system with the regression system and software release.

Activity 4.b – Advanced reactor collaboration: JAEA
Continue the collaborative work initiated in FY 2019 with the Japanese Atomic Energy Agency (JAEA) defined under the Civil Nuclear Energy Working Group (CNEWG). CNEWG Task 6 was expanded in FY 2020 from a nuclear-only hybrid cogeneration (electricity/H2/heat) to include a renewable integration moving forward. The collaboration will be focused on the use of a high-temperature gas reactor (HTGR) for hydrogen production via the sulfur iodine process under development at JAEA. Analysis work will focus on future demonstrations using the JAEA High-Temperature Test Reactor (HTTR). This collaboration will support a greater mutual understanding of HTGRs and nuclear-hybrid systems through the joint experiment design, analysis, and comparison of results. Specific tasks include the design, modeling and simulation, and test planning. JAEA will assist INL in improving the model accuracy for HTTR-GT/H2,

revise the reactor physical design for renewable integration, and learn from the DOE Integrated Energy Systems Program renewable load models and economic analysis models. INL is supporting this effort using RELAP5-3D and Modelica. In FY 2021, the main activity will be the integration of JAEA plant models in the flexible ecosystem to perform a technoeconomic analysis.

Activity 4.c – TEDS facility Modelica model development and validation.
Develop a detailed dynamic model of the as-fabricated TEDS to support the experiment design and future system analysis. The model, initially developed in FY 2020, is written in the Modelica language to allow coupling with the overall modeling framework. As data becomes available via the TEDS operation (see CT-21IN120301), the model will be validated using experimental data and will be used to guide the development of the experimental test matrix for nominal and off-nominal conditions using DETAIL.

Activity 4.d – Develop technical plan and gap analysis for virtual and physical system integration
Develop a plan to enable improved linkage between simulation activities and experimental demonstration for IES.

CT-21IN120207: Real-Time Optimization and Digital Twin
This work package includes the scope to develop IES models and deploy real-time optimization via digital twin for advanced reactor pilot case study. Also included are the development of dynamic advanced reactor models integrated in the flexible modeling ecosystem for IES design and optimization.

Long-term goals include:
(FY 2024) Develop an IES model for a selected application and validate via nonnuclear test facilities.
(FY 2025) Deliver an online data acquisition system design to support digital twin deployment for IES demonstrations.

Activity 7.a – Initial assessment for digital twin development
Initiate design of the software infrastructure for a digital twin based in the available capabilities in the hybrid plug-and-play ecosystem. Perform gap analysis for determining software development and hardware needs. Development of a digital twin for experimental facilities will necessarily include energy storage components represented in the laboratory hardware.

CT-21IN120208: Dynamic Component Models
Activities under this work package will develop additional component models for incorporation into the IES framework. Identify and model thermal energy storage systems that may be relevant to integral pressurized water reactors or other advanced reactor applications. In collaboration with relevant EERE and FE programs, develop detailed dynamic models to represent coupled subsystems (e.g., industrial processes).

Activity 8.a – Energy storage models in Modelica
Development of energy storage physical models in Modelica for incorporation into the IES simulation ecosystem. Candidate thermal storage technologies include concrete energy storage, liquid air energy storage, or phase change materials. Such models will be based on the latest publicly available resources and will be built to allow the easy inclusion of proprietary models at a later time, if necessary. In addition, basic economic data will be defined and incorporated into the IES database for the selected energy storage system. The models will be created at two levels of fidelity: (1) A high-fidelity systems level model that will incorporate novel control strategies, pumping systems, and will be capable of discerning transients throughout the system and can be

directly coupled with other Modelica systems; and (2) a lower fidelity surrogate model written in python or another language that will be able to emulate large systemwide effects on an hourly time basis but will not include control strategies. These models can be directly integrated with HERON and RAVEN for technoeconomic optimization on an hourly time basis.
FY 2020 funding will support the development of concrete energy storage and phase change material models; FY 2021 allocation will further extend these models to include liquid air energy storage and geothermal storage. A low fidelity model V/HTGR model will also be developed to explore high-temperature storage options for future applications.

Activity 8.b – IES advanced reactor use case for carbon conversion
Define the markets to be addressed, both for the selected co-product and electricity. Perform a gap analysis with respect current capabilities and necessary capabilities to properly perform an economic evaluation of the carbon conversion use case (developed by the INL/NREL/NETL Tri-Lab Initiative) that would incorporate an advanced reactor. Determine if the acquisition of external software is necessary, frame the problem to perform an initial economic evaluation and, if necessary, complete software acquisition and training.

Case description: Heat and electricity from cost-competitive clean nuclear and renewable generators is used to convert the country's abundant coal resources into high-value materials, chemicals, and fuels.

CT-21AN120205: Argonne National Laboratory – IES Modeling and Simulation Support
Scope described within this work package is managed and conducted by ANL.

Activity 5.a – Validation and demonstration of control system functional capabilities within the IES plug-and-play simulation environment
Exercise a new plug-and-play control system capability to validate and demonstrate its capabilities. Individual modules in the new library will be invoked as part of an advanced control system design process whose objective is to meet multiple imposed process constraints, such as equipment temperatures and demand values for process outputs. The performance of the multi-input, multioutput solution will be compared to that of a classic control system with respect to the frequency of constraint violation and missed demand.

Activity 5.b – Development of energy storage: Cost models
Extend the cost models in RAVEN to include the additional economic flexibility of storing energy in a thermal storage unit.

Activity 5.c – Development of electrochemical battery model for plug-and-play ecosystem library
This work package supports the development of dynamic component models. A battery model is needed that exhibits discharge and charge cycle physical limitations for use in the ecosystem plug-and-play library.

Activity 5.d – Monitoring system design to support experimental system operation
This work package supports the development of real-time optimization and digital twins. A state observer (Kalman filter, virtual sensors) will be used to support the demonstration of experimental systems and their operation, which will include extension of monitoring capabilities beyond the available sensor set.

Activity 5.e – Control system design for multi-component IES, including storage with equipment operating constraints

This work package supports the development of the flexible modeling ecosystem. Address how to control for optimal systemwide economics given finite-capacity energy storage plants and other equipment operating constraints. Build on the FY 2020 reference governor approach.

Activity 5.f – Effort management
Funds to manage the work package and associated activities at ANL.

CT-21OR120206: Oak Ridge National Laboratory IES Simulation Support
Scope described within this work package is managed and conducted by ORNL.

Activity 6.a – Advanced nuclear reactor characterization for IES
One of the key goals of the IES is to assess the economic viability for advanced reactor based IES configurations. The landscape for advanced reactors is heterogenous, and several designs, with different heat profiles, are currently being studied. This work aims to perform a literature review of the current proposed systems and establish, for each type, a range of operational temperatures that can be used for coproduction, in addition to electricity. Moreover, depending on the type of secondary system selected in the plant design, the ramp rate at which the heat can be redirected from electricity production to heat utilization (and vice versa) will be characterized.

Activity 6.b – Advanced reactor models for system studies
This is a companion task to Activity 6a. This task would identify the most promising or representative reactors based on the Activity 6a study and create high-level models for use in the IES Modelica framework for use in the IES system study and optimization.

Activity 6.c – Digital reliability and operation twin of facility for IES exploration
This work package supports the development of the flexible modeling ecosystem. Demonstrate and mature the "plug-and-play" capability of the RAVEN reliability module plugin for technoeconomic analysis using an energy storage system. This work will identify a pertinent technology associated with an energy storage system that has sufficient available data to perform an in-depth reliability analysis. The identified technology or system will then be properly modeled to perform the analysis and mature the reliability tool for future applications.

Activity 6.d – Visualization
This task translates the Modelica-based system models to a representative 3D model to evaluate and illustrate physical and geospatial interactions among the different components and subsystems within a conceptual IES. The utility of this capability is to examine integrated system layouts, especially in the context of installing new systems in existing facilities. Further, different figures of merit or operational parameters can be displayed as part of an augmented reality visualization approach.

Activity 6.e – Uncertainty quantification high-low coupling using RAVEN and TRANSFORM
This work package supports dynamic component models. Develop, demonstrate, and mature RAVEN-based methodologies to perform complex analysis (i.e., uncertainty propagation) of high-low fidelity coupled simulations (i.e., VERA and Modelica/TRANSFORM) building on work performed in FY 2020.

Activity 6.f – Modelica-centric enabling software
This work package supports the Simulation for Experiment Support. In collaboration with the RAVEN MOOSE team, it will assist in the development of a regression and validation system for Modelica based on the INL-developed capabilities.

Activity 6.g – Physics-based model of FASTR for IES exploration
This work package supports the real-time optimization and digital twin. It will create a physics-based model of the Facility to Alleviate Salt Technology Risks (FASTR) experiment using the plug-and-play ecosystem. This facility is a high-profile facility highly pertinent to IES as it is tasked with maturing molten-salt applications, such as liquid-salt energy storage, salt applications, such as solar power facilities, and other advanced reactor technologies that may be crucial aspects of IESs.

Activity 6.h – Work package management
Funds to manage work package and associated activities at ORNL.

CT-21IN120209: Model Intercomparison Study
Capacity expansion models (CEMs) are important tools to inform strategies for meeting future electricity and energy needs under a range of policy, technology, and market conditions. However, CEMs vary significantly in their coverage, structure, and input assumptions. Understanding model differences and output drivers is important to improve model insights and impact. This work package will initiate a study to evaluate these differences and the impact of each modeling approach on the overall results, with a specific focus on nuclear systems.

Activity 9.a – Model intercomparison study
Work with the teams who own, update, and apply these models as well as subject matter experts to create a forum in which modelers and subject matter experts can discuss structure and coding assumptions and challenges to developing the models for future use. Specific study aims include:

- Understand how issues central to nuclear power plant operations and economics are modeled in CEMs
- Investigate how model structures and input assumptions impact projections for existing and advanced nuclear reactors
- Identify and prioritize areas for refining the representation of nuclear energy in CEMs
- Communicate findings to the research community and decision-makers

Work to be conducted via subcontract to EPRI and NREL. Additional contributions from the Environmental Protection Agency and the Energy Information Administration are at no cost to DOE.

Experimental Systems Development and Testing (ESDT)

The Experimental Systems Development and Testing control account is led by INL, with work being conducted at INL, in collaboration with other relevant DOE programs. In FY 2021, this includes a total of three work packages. The scope for each of these work packages and activities is summarized below.

CT-21IN120301: Thermal Energy Distribution System

Activity 1.a – Complete TEDS construction and commission system
Complete construction activities, commission system, finish insulation following leak checking, and deliver report with data from shakedown testing.

- Complete construction, fill with heat transfer oil
- Commission system
- Shakedown testing

Activity 1.b – TEDS preliminary operations

Operate TEDS through the complete test matrix to characterize system performance.

- Run system through complete operational test according to test matrix
- Develop validation data for thermocline energy storage performance
- Deliver externally releasable report detailing results

Activity 1.c – Design TEDS enhancements based on feedback from initial operations
Design system upgrades based on feedback from initial system operations and guidance from industry partners

- Revise system functional and operational requirements
- Revise system piping and instrumentation diagram
- Collaborate with INL engineering to deliver drawing and specification package
- Procure long-lead equipment for system enhancements

Activity 1.d – Thermal storage testing within the enhanced TEDS

- Develop and conduct a test matrix to fully characterize thermal storage with modified system
- Write test matrix document for external release

CT-21IN120302: Dynamic Energy Transport and Integration Laboratory Connectivity

Activity 2.a – Thermally integrate high-temperature electrolysis skid
Establish physical linkage to integrate TEDS to the high-temperature electrolysis (HTE) test facility for steam generation. Demonstrate thermally integrated operation and characterize the dynamic behavior of these thermally integrated systems. Note: the HTE hardware is supported via funding from EERE Hydrogen and Fuel Cell Technologies.

Activity 2.b – Thermally integrate MAGNET and TEDS
Design and construct the piping and heat exchanger required to thermally integrate TEDS and the Microreactor Agile Nonnuclear Experiment Testbed (MAGNET). Note: MAGNET hardware is supported via funding from the DOE-NE Microreactor program. FY 2021 work will continue efforts toward thermal integration. Activities include:

- Issuing functional and operating requirements for system integration
- Procuring GFE
- Awarding construction contract
- Demonstrating integrated operations, including energy storage components.

Activity 2.c – Program local controls and demonstrate integrated system operation within DETAIL
Develop and implement LabView programming for an integrated system operation within DETAIL

Activity 2.d – Demonstrate operation of DETAIL with expanded set of subsystems and integrated controls
Initiate the long-term operation of TEDS with collocated DETAIL systems. Test multiple operational conditions and configurations to include both steady-state and transient operations. Compare results to TEDS dynamic model for verification and validation.

CT-21IN120303: Advanced Reactor IES Platform

Activity 3.a – Deliver conceptual design for IES test platform

In collaboration with the National Reactor Innovation Center (NRIC), develop a conceptual design for an IES test platform for advanced reactor demonstrations. This activity only includes the design of the IES interface supporting multiple energy users (e.g., energy storage components, hydrogen, chemical production, water desalination).

- Develop conceptual design for IES platform
  - Preliminary piping and instrumentation diagram
  - Functional and operational requirements document
  - Generate engineering request
- Obtain quotes for government-furnished equipment for IES platform (e.g., HX, pumps, compressors)
- Initiate procurement of long-lead government-furnished equipment (GFE)

Appendix C
Current Competitive IES Awards

Nuclear Energy University Program

Each year, 20% of the budget for R&D programs in DOE-NE is allocated to university-led research. NEUP projects can include national laboratory and industry participants at up to 20% of the total budget, and they extend over a 3-year duration. It is imperative that the research scope be identified by the program leads that can be beneficial to achieving the long-range program goals, recognizing that the work will take approximately one year to be awarded and an additional three years to be completed. The IES program has developed scope in the annual NEUP awards since 2018. In doing so, the IES portion of the call requires that proposals utilize the simulation framework under development at the national laboratories or that any developed models can be later be easily integrated into this framework, to ensure that the resulting output from each of the projects can be utilized by the broader program. Additionally, regular meetings (nominally monthly) are established with the project teams to allow them to interface with the lab-based program from the start of the project. In this manner, intermediate guidance can be provided to ensure the maximum impact of the university-led R&D, and models, analysis approaches, data, etc. can be integrated into the main program as early as possible.

2018 Awards

Development of Nuclear Hybrid Energy Systems (NHES): Temperature Amplification through Chemical Heat Pumps for Industrial Applications (CFA-18-14963)

PI: Vivek Utgikar, University of Idaho
Collaborators: Brian M. Fronk, Oregon State University; Piyush Sabharwall, Idaho National Laboratory

Abstract:

Nuclear plants, historically designed for baseload electric power generation, are also increasingly expected to provide energy for nonpower process heat applications and deal with a fluctuating power demand. Chemical heat pumps (CHPs) can be the enabling technologies for the NHES by providing a temperature boost for the direct utilization of nuclear heat for industrial process applications.

The overall goal of the proposed research is to develop and demonstrate, through modeling and experimental investigations, the temperature amplification capabilities of a chemical heat pump system that can be coupled to a conventional or a near-term small modular reactor.

Specific objectives of the research are:

- To develop an integrated system model comprised of coupled submodels for individual components of the system
- To conduct experimental investigations on the system components to verify and validate the theoretical model and obtain data and system parameters for scale-up and design
- To demonstrate the technical feasibility of the proposed concept through experimental investigations on a bench-scale integrated system.

These objectives will be accomplished through the execution of three research tasks: the first task involves the development and validation of a dynamic model through the development of a detailed process flow diagram, followed by the development of preliminary, steady-state, thermodynamic submodels for the system components, and the integration of these submodels for the overall model of the system. The second task involves conducting detailed experimentation on component systems to obtain data and characteristic system parameters needed to verify and validate the model. The third task will involve developing an integrated system based on component data to prove the technical feasibility of the proposed concept for temperature amplification.

The expected outcomes of the research are: NHES architecture involving chemical heat pump mediated temperature amplification, increasing the industrial process applications of nuclear heat, the mathematical model describing the behavior of the dynamic behavior of NHES that can be integrated with the various modeling tools developed by DOE investigators, and experimental data that can be used for model verification and validation, as well as the scale-up and design of an integrated CHP-NHES. Research proposed herein thus supports the DOE missions in enhancing energy security and increasing the role of nuclear energy in the nation's energy system.

Modeling and Experimental Verification of Thermal Energy Storage Systems to Enable Load Following Capability for Nuclear Reactors (CFA-18-15602)

PI: Dr. Richard N. Christensen, University of Idaho
Collaborators: Dr. Matthew J. Memmott, Brigham Young University; Piyush Sabharwall, Idaho National Laboratory

Abstract:

The proposed work aims at integrating new thermal energy storage (TES) models developed in Modelica with ongoing nuclear–renewable hybrid energy systems (NRHES) modeling efforts, and perform optimization in RAVEN, to evaluate the economic potential and advantages of the new process designs over baseload electricity production. It also aims to scale, design, test, and optimize the TES systems to be later integrated with the Idaho National Laboratory's Dynamic Energy Transport and Integration Laboratory (DETAIL) for integrated systems testing.

Renewable energy penetration has increased over past few years and with the current DOE programs and SunShot efforts, the penetration would further increase. However, due to the intermittent nature of these energy sources, caused due to their dependence on geographical and weather conditions, instabilities in the grid and price fluctuations in the electricity market have also increased. Such instabilities can be overcome by implementing an NRHES. The NRHES is an integrated system comprised of a nuclear reactor, renewable energy source, and industrial processes that can simultaneously address the need for grid flexibility, greenhouse gas emission reductions, and optimal use of investment capital. In order to make the NRHES technology more attractive, it is herein proposed to couple the NRHES with a TES system, to which excess heat not demanded by the grid for electricity production can be allocated, for later use when there is high demand or a low renewable energy contribution.

The objective of this work is to evaluate the potential and economic benefits of advanced NRHES systems integrated with TES systems. The computational phase of this project will include the development of mathematical and physics-based models of TES systems, which could later be translated to Modelica and integrated with some of the existing NRHES components. The testing and optimization of these models will be conducted using RAVEN. A technoeconomic analysis will be performed to evaluate the compatibility of the newly formed integration of TES and NRHES, as well as to quantify its feasibility and economic benefits. The experimental aspect is more focused on the development of scaled TES systems, which will not only serve as verification for the models generated in Modelica, but also allow for integrated systems testing upon being integrated with the INL DETAIL.

The following deliverables are to be developed to quantify the potential of the integrated NRHES–TES system: (i) development of mathematical and physics-based models of TES systems; (ii) acquire thermophysical characteristics of molten salts; (iii) scale, design, and test TES systems; (iv) perform comparative analysis and verification based on experimental and modeling results; (v) integrate

developed models into existing NRHES models, and (vi) evaluate results and perform optimization of integrated systems.

The proposed study involves two universities and one national laboratory and will have a significant impact on undergraduate and graduate education and the training of postdoctoral researchers. This research will help develop the future workforce for the U.S. nuclear industry.

2019 Awards

Proactive Hybrid Nuclear with Load Forecasting (CFA-19-16879)

PI: John Hedengren, Brigham Young University
Collaborators: Matt Memmott, Brigham Young University; Kody Powell, University of Utah; Paul Talbot, Idaho National Laboratory

Abstract:

The main objective of the project is to improve the design and optimize the dispatch of nuclear hybrid energy systems (NHES) coupled with energy storage and to evaluate those systems for both economic benefit and technical feasibility. To do this, we propose an extension of the capabilities of RAVEN to include improved forecasting, dispatch optimization, and design optimization with a combination of new and proven methods. A new method is improved forecasting with blended machine learning that combines the latest advancements in data-driven modeling with physics-based elements. Inaccurate forecasts lead to suboptimal dispatch solutions and, in some cases, produce an outcome that is worse than using no forecast. The improved forecasting attempts to improve upon autoregressive moving average models that are used in the existing workflow. Another innovation of this project is the integration of two new tools with RAVEN. The first is the GEKKO Optimization Suite that is designed for the efficient dispatch of large-scale hybrid energy systems. GEKKO is proposed to replace the existing dispatch optimization method in RAVEN. GEKKO offers an interface to large-scale gradient-based optimizers that use warm-start methods, forecasts, and dynamic models to efficiently achieve a minimized effective levelized cost of electricity (eLCoE). The evaluation of the optimized eLCoE is performed many times as new unit capacities are generated by RAVEN, so it is important that this inner step is efficient and effective at finding the best solution. A second innovation is to determine novel nuclear designs that further improve the eLCoE. The integration of the nuclear design package OPTIONS is proposed as another extension of RAVEN capabilities. Two experimental studies will validate the software innovations. The first is a lab-scale energy storage system that emulates temperatures within the primary and secondary containment loops of a nuclear reactor. This experimental study is proposed to validate the models with phase changing materials to enable a large energy thermal storage. Industrial instrumentation and controls will be used to regulate the small-scale system. The hardware control system will be documented, and a data repository created as a benchmark test case for further development. The second experimental validation is proposed with a full-scale district energy system that includes thermal and electrical generation, energy storage, and demand profiles for campus-wide users. The RAVEN-enhanced tools will be tested over a one-year period to determine the improved eLCoE and validate the software for real-time use. As a final step, the improved RAVEN capabilities will be generalized for the optimal dispatch and design of other NHES concepts that may include nuclear integration with petroleum oil refining, natural gas reforming to produce hydrogen, ammonia or ammonia-based products, methanol, olefins, synthetic fuels, biomass conversion to biofuels, and reverse osmosis desalination. This project is critical to the nuclear energy program because it will provide an improved workflow for the design and operation of NHES. As a baseload power and heat source, nuclear is made adaptable to load changes through coupling with other systems. The proposed methods will allow reactor development teams to quickly run different scenarios, discovering improved options, and optimize the dispatch control of hybrid systems.

Multi-Timescale Nuclear–Renewable Hybrid Energy Systems Operations to Improve Electricity System Resilience, Reliability, and Economic Efficiency (CFA-19-17327)

PI: Jie Zhang, The University of Texas at Dallas
Collaborators: Pingfeng Wang, University of Illinois at Urbana–Champaign; Mark Ruth, National Renewable Energy Laboratory; Dylan Cutler, National Renewable Energy Laboratory

Abstract:

Nuclear and renewable energy sources are important to consider in the U.S. economy's evolution because both are clean, non-carbon-emitting energy sources. Advanced nuclear–renewable hybrid energy systems (N-R HESs) composed of nuclear and renewable energy sources, industrial energy users, and energy storage systems are being evaluated for their economic benefit and technical feasibility. N-R HESs have been proposed as a technology that can generate very low-carbon, dispatchable electricity and provide very low-carbon energy to industry at a lower cost than many other options.

Beyond classic energy-shifting services, N-R HESs may be able to provide a suite of services at finer timescales to promote a safer and more reliable integration of renewable energy resources. The overarching objective of this project is to develop a multi-timescale N-R HESs operations framework to provide different types of grid products. The benefits of two N-R HESs will be evaluated: (i) one with a nuclear reactor, wind power plant, an industry thermal user, and energy storage; and (ii) one with a nuclear reactor, solar power plant, an industry thermal user, and energy storage. We aim to model and analyze the capabilities of N-R HESs to provide power grid services at different operation timescales ranging from seconds to days, such as day-ahead unit commitment, flexible ramping (5–45 minutes), regulation reserves (1–5 minutes), and frequency response (less than seconds). This innovative, holistic, multi-timescale N-R HESs operations strategy is expected to improve electricity system resilience, reliability, and economic efficiency by exploring more benefits that accrue to both N-R HESs and other grid assets. The following four research thrusts will be investigated in this project:

- **Data-Driven Short-Term Load and Renewable Generation Forecasting:** This research thrust will pursue research activities to model and forecast the wind and solar power generation, load and netload (at different levels of aggregation) with high penetrations of renewables and distributed energy resources, and extreme ramping events in renewables and load and netload.
- **Short-Term Multi-Timescale N-R HES Operation:** The team will explore the market opportunities available for N-R HES to participate in energy and ancillary markets and develop optimal strategies for bidding N-R HES into the bulk grid or for industry thermal users.
- **N-R HES and Electricity Grid Resilience:** The team will develop a power system disruption management framework for the enhanced resilience of N-R HESs, which utilizes smart operational enhancement strategies, such as N-R HES control, storage, or curtail strategy, to minimize the negative impacts due to disruptive events, thereby improving the overall energy system reliability and resilience.
- **Hardware-in-the-Loop (HIL) Test:** The team will conduct the thermal-electrical HIL simulation and laboratory demonstration for the developed multi-timescale N-R HES operations control and disruption management platform in improving electricity system resilience, reliability, and economic efficiency.

2020 Awards

Creation of Multiple Effect Evaporator and Combined Cycle Modelica Modules, and Optimization of Potable Water Generation from Saltwater Sources (CFA-20-19216)

Co-PIs: Stephen Terry and J. Michael Doster, North Carolina State University
Collaborators: Konor Frick, Idaho Energy Laboratory

Abstract:

The goal of this research is to develop models of multiple effect evaporators and combined cycle gas turbine systems for use in the Modelica framework. The models will be capable of being implemented into larger models of grid independent or near independent energy parks located about military bases, large manufacturing facilities, and in small communities where freshwater is limited. The end goal being to create an energy park that can supply its own energy and water through small modular reactor nuclear systems or combined cycle gas turbine systems with brackish to brine water sources (i.e., groundwater or ocean water).

The models will link in the need for water for the generation of power to supply evaporative condensers in the Rankine cycle, as well as water needed by the community for domestic and specified industrial uses. The use of multiple effect evaporators, supplied with extraction steam from a Rankine cycle or from the heat recovery steam generator of a combined cycle plant, will be modeled and compared to the option of simply using a reverse osmosis system powered by the power cycles.

Integrated Solar & Nuclear Cogeneration of Electricity & Water using the sCO2 Cycle (CFA-20-19363)

Co-PIs: Ben Lindley, University of Wisconsin-Madison (UW)
Collaborators: Gregory Nellis, Mark Anderson, and Laura Albert, UW; Joshua McTigue, Ty Neises, and Michael Wagner, National Renewable Energy Laboratory; Cory Stansbury, Westinghouse Electric Company

Abstract:

We will design and model a nuclear + renewable integrated energy system (IES) for the cogeneration of cost-competitive electricity and clean water. We will also develop modeling tools that will allow IES to be simulated, providing a crucial toolset for present and future studies of this type. A conceptual design of IES is proposed, comprising the following components.

- Concentrated solar power (CSP) – compatible with thermal energy storage for dispatchability
- The supercritical CO_2 (sCO2) cycle – utilizes temperatures compatible with cogeneration of electricity and clean water as the outlet temperature is compatible with desalination
- Multi-effect distillation (MED) – for desalination as a cogeneration application while providing heat rejection from the sCO2 cycle without being a parasitic load on the power station
- Lead-cooled fast reactor (LFR) – leading U.S. advanced reactor technology that uses a sCO2 cycle, so it can be combined with the rest of the system efficiently.

The proposed IES has improved dispatchability compared to CSP and nuclear in isolation. The molten-salt thermal energy storage system connected to the CSP provides the capability to meet short-term changes in demand and frequency control, while the LFR is suitable for a longer term load follow. Synergies between the technologies may also allow for a reduction in component requirements. A reference configuration for the IES will be defined, considering technical and lifecycle aspects (cyber informed engineering [CIE], regulatory environment) and likely system cost. RAVEN/Modelica will be interfaced to the freely available and open-source System Adviser Model, developed at NREL. This capability will then be applied to the analysis of the proposed concept.

The project consists of the following tasks:

1. Develop the overall system concept, following a CIE Approach.
2. System modeling, including the integration of RAVEN/Modelica with NREL models.
3. System analysis, including optimized operational dispatch, CIE.
4. Market and market competitiveness analysis.

5. Sensitivity analysis. The analyses will be guided by the output of Task 4.
6. Conclusions and reporting.

This deliverables and outcomes of this project are:

1. Report on the feasibility and viability of the proposed IES. This supports wider deployment markets due to improved dispatchability and cogeneration capabilities.
2. An analysis framework and computational models, compatible with the existing RAVEN/Modelica ecosystem, which can be used for future studies.

Small Business Innovative Research

Each year, approximately 5% of the budget authority in each program is set aside for allocation to SBIRs. Although this allocation has been made each year since the IES Program was established, FY 2020 was the first year in which specific IES language was included in the SBIR call and a project was subsequently awarded. Additional IES-related projects are expected to be awarded in future years.

FY2020

Development of SiC-SiC Heat Exchangers for High-Temperature Heat Transfer

Company: Innovative Technologies International (Novatech)

Principle Investigator: John Malloy
Business Official: Anne Austin

Abstract:

Industrial process heat is used for a large variety of applications with different heat requirements and with temperature ranges covering a wide spectrum. Process temperatures range from 100 to 180°C for district heating and desalination to over 800°C for coal gasification and hydrogen production. Although concentrated solar power (CSP) systems can potentially provide much of the process heat needs, nuclear power systems are the best choice to minimize carbon release. Gen IV nuclear reactor technologies have advanced safety features that could limit the size of low-population zones to the actual plant site boundary, minimizing monitoring and evacuation planning that may discourage industrial users from locating adjacent to the power plants. The high operating temperatures of the Gen IV designs also make them able to support most industrial thermal processes. Yet, even when the industrial facilities are closer to the power plants, heat transfer can be difficult for high-temperature processes. Reliable, high-temperature, SiC composite heat exchangers are important contributors to IES feasibility. High-temperature heat transfer between power plants and collocated industrial facilities requires coolants like molten salts with high boiling temperatures and very low vapor pressures. While less reactive than most liquid metals, molten salts are very corrosive and are not compatible with many traditional metals, especially at very high temperatures. High nickel alloys, such as Haynes 230, offer short-term corrosion resistance, but these materials are very expensive and creep strength drops rapidly at the desired temperatures. Alternative materials and associated fabrication techniques are needed. Novatech will develop and demonstrate the feasibility of utilizing silicon carbide composites to fabricate robust, resilient heat exchangers that will effectively and efficiently integrate industrial energy users with high-temperature nuclear power plants. The technology already demonstrated by NovaTech has shown that SiC fiber wound SiC tubes are significantly more robust than simple SiC tubes and will retain their strength at high temperatures. SiC is also compatible with high-temperature liquid metals and molten salts. For this

project, we will build on our experience in the design of SiC composite components for nuclear reactors and solar thermal power plants.