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Nuclear-Renewable Hybrid Energy Systems: 2016 Technology Development Program Plan

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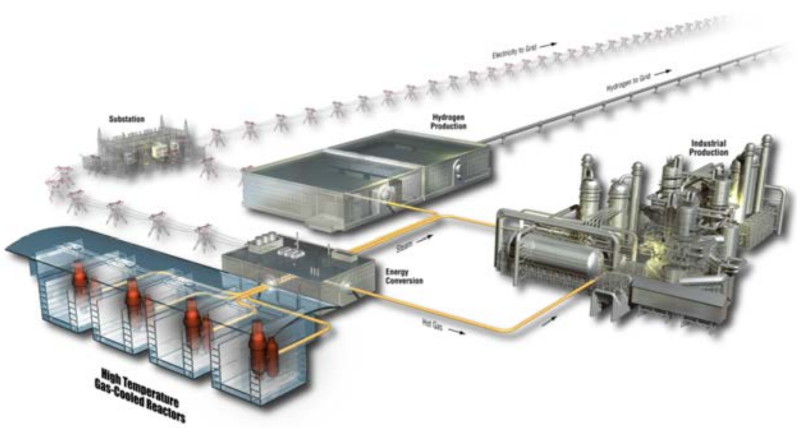

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EXECUTIVE SUMMARY

The United States is in the midst of an energy revolution, spurred by advancement of technology to produce unprecedented supplies of oil and natural gas. Simultaneously, there is an increasing concern for climate change attributed to greenhouse gas (GHG) emissions that, in large part, result from burning fossil fuels. An international consensus has concluded that the U.S. and other developed nations have an imperative to reduce GHG emissions to address these climate change concerns. The global desire to reduce GHG emissions has led to the development and deployment of clean energy resources and technologies, particularly renewable energy technologies, at a rapid rate.

At the same time, each of the major energy sectors—the electric grid, industrial manufacturing, transportation, and the residential/commercial consumers— is increasingly becoming linked through information and communications technologies, advanced modeling and simulation, and controls. Coordination of clean energy generation technologies through integrated hybrid energy systems, as defined below, has the potential to further revolutionize energy services at the system level by coordinating the exchange of energy currency among the energy sectors in a manner that optimizes financial efficiency (including capital investments), maximizes thermodynamic efficiency (through best use of exergy, which is the potential to use the available energy in producing energy services), reduces environmental impacts when clean energy inputs are maximized, and provides resources for grid management.

Rapid buildout of renewable technologies has been largely driven by local, state, and federal policies, such as renewable portfolio standards and production tax credits that incentivize investment in these generation sources. A foundational assumption within this program plan is that renewable technologies will continue to be major contributors to the future U.S. energy infrastructure. While increased use of clean renewable technologies will aid in achieving reduced GHG emissions, it also presents new challenges to grid management that must be addressed. These challenges primarily derive from the fundamental characteristics of variable renewable generators, such as wind and solar: non-dispatchability, variable production, and reduced electromechanical inertia.

This document presents a preliminary research and development (R&D) plan for detailed dynamic simulation and analysis of nuclear-renewable hybrid energy systems (N-R HES), coupled with integrated energy system design, component development, and integrated systems testing. N-R HES are cooperatively-controlled systems that dynamically apportion thermal and/or electrical energy to provide responsive generation to the power grid. They are comprised of multiple subsystems, which may or may not be geographically co-located:

- A nuclear heat generation source,
- A turbine that converts thermal energy to electricity,
- At least one renewable energy source, and
- An industrial process that utilizes heat and/or power from the energy sources to produce a commodity-scale product.

System options encompassed by the N-R HES program can be classified in three categories:

1. *Tightly Coupled HES*. Nuclear and renewable generation sources and the industrial process(es) are directly integrated behind the grid and co-controlled, such that there is a single connection point to the grid and a single financial entity managing the HES (i.e., profitability of the HES is optimized for the integrated system rather than for each system independently).
2. *Thermally Coupled HES.* Subsystems may have more than one connection to the same grid balancing area and may not be co-located; however, the nuclear and renewable subsystems are co-controlled to provide energy and ancillary services to the grid. This category includes thermally integrated

subsystems that are tightly coupled with the heat generation source; geographical location of the industrial process will be dependent on required heat quality, heat losses to the environment along the heat delivery system, and the required exclusion zone around the nuclear plant. These systems have more than one connection point to the grid but are managed by a single financial entity.

3. *Loosely Coupled, Electricity-Only HES.* This case configuration is controlled in a similar fashion to the thermally coupled system, but generators are only electrically coupled to industrial energy users (no direct thermal coupling of subsystems). This scenario allows management of the electricity produced within the system (e.g., from the nuclear plant via power conversion or renewable electricity generation) prior to the grid connection. Note, however, that the system may include electrical-to-thermal energy conversion equipment to provide thermal energy input to the industrial process(es). Such an option allows for potential retrofit of existing generation facilities with fewer regulatory challenges. These systems have more than one connection point to the grid but are managed by one financial entity.

For comparison, the *Base Case* includes nuclear and renewable power systems that are independently connected to the grid to provide electricity and an independent industrial process that draws electricity from the grid. This case does not involve any direct use of thermal energy from nuclear or renewable sources, but may derive thermal energy input from burning fossil fuels to drive the industrial process(es). This case describes current grid operations.

N-R HES are expected to provide significant benefits in minimizing cost and volatility of energy production while simultaneously providing low GHG emissions. Key benefits include:

- Provide dispatchable, flexible, and carbon-free electricity generation for the grid
- Provide synchronous electromechanical inertia to the grid
- Reduce the carbon footprint of the industrial sector
- Levelize and reduce energy costs (i.e., support stabilization of energy costs)
- Reduce energy system impact on water resources.

The ability to flexibly maneuver exergy produced by system resources can maximize profitability, minimize emissions, reliably provide electricity to the grid as needed, and provide clean energy for industrial processes. N-R HES eventually may lead to a broad energy economy that is less dependent on fossil fuels.

The U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) is currently investigating technical and economic viability for a range of possible N-R HES configuration options. Initial findings from two regional case studies for tightly coupled systems, which considered dynamic system operation, are encouraging. However, more analysis is necessary to fully characterize the N-R HES design configurations that are the most promising for near-term applications, and which may lead to the deployment of a variety of system options in the future. The relevance of N-R HES build-out in future energy markets is expected to be significant given the anticipated benefits of dispatchability, flexibility, real inertia for the grid, reduced carbon emissions beyond the electric generating sector, and stabilized energy costs. The technical, environmental, and economic evaluations performed for N-R HES concepts will be compared to alternative future energy infrastructures that could be capable of meeting the defined environmental, sustainability, and economic goals while maintaining grid resilience.

A concerted effort to define the constituent technology development needs for N-R HES is essential. This program plan outlines significant analysis efforts, including high-fidelity, dynamic modeling and simulation, which will guide the definition of hardware development and demonstration efforts that will be necessary to advance N-R HES. The general N-R HES architecture options are shown in Figures ES-1 to ES-3. Subsystems may be co-located and cooperatively controlled, or could be geographically dispersed depending on the technologies selected for coupling. Note that the fraction of renewable penetration within the system boundary and relative sizes of each subsystem will be a parameter in the optimization process. Hence, for the tightly coupled system, the renewable fraction could range from 0% (equivalent to nuclear cogeneration) to some maximum percentage based on the external boundary conditions for the grid balancing area. Regions having high renewable penetration within the balancing area may optimize to low or zero renewable components within the hybrid system.

This preliminary program plan outlines a technology development process for N-R HES that involves program planning and execution guidance relative to organizing the research team and execution of the necessary fundamental science, systems engineering, market analysis, and project execution to raise the Technology Readiness Level (TRL) of N-R HES components and interface technologies. The overall strategy for research, development, demonstration, and deployment is comprised of four phases. The first two phases are the focus of this program plan; these phases include DOE-led research activities necessary to mature integrated N-R HES technology through TRL 6. The final phases further demonstrate a prototype system under industrial leadership, or possibly through joint investment by DOE and industry. These phases are summarized as follows:

DOE Leadership:

Phase I: Preferred Architecture Research and Development

Phase II: Component and Subsystem Testing, Architecture Refinement and Integrated System Demonstration

Industrial Leadership or Joint Investment:

Phase III: Detailed Prototype Engineering Design

Phase IV: Prototype Construction and Testing

This program plan focuses on N-R HES configurations that could be demonstrated by 2030. This requirement entails integration of high-TRL subsystems and components; hence, the majority of the research effort is focused on the integration technologies, communications, and system control versus development of novel subsystem technologies. The resulting system will be designed to provide greater efficiency than provided by independent systems, yet be less susceptible to major consequences that could result from natural and manmade failures. Such a system could require development of some novel integration and control technologies. As a result of the constraint for near-term deployment, the program plan addresses integrated systems that utilize light water reactor (LWR) technology with an initial focus on small modular reactors (SMRs, defined by a unit size of <300 MWe), noting that temperature-boosting technologies may be required to achieve integration with some desirable industrial processes. Parallel DOE investment in the development of advanced reactor technologies, such as high-temperature gas-cooled and molten salt-cooled designs, will be tracked by the N-R HES program and could be considered in future updates to the HES program plan if they appear capable of meeting the desired N-R HES demonstration timeline. Note also that the described loosely coupled N-R HES architecture could be applicable to retrofit of some of the existing LWR fleet that are beginning to see requirements for increased flexibility as variable renewable penetration increases in their respective grid balancing areas.

Phase I of the N-R HES R&D begins with detailed evaluation of the driving factors motivating development of a novel, flexible energy system and definition of metrics associated with those factors; identification of system design options; and performance of detailed analysis of those options to support design optimization. Analysis activities will employ many existing tools, but will also require the development of new modeling and simulation tools to evaluate the dynamic behaviors of integrated energy systems and their interaction with the evolving grid. Advanced tools will be used to optimize the design configurations and to guide the development of optimized control systems. These analyses will result in identification of N-R HES architecture options, prioritization of those options, and optimization of the specific design configurations to meet both technical and economic performance requirements.

The ability to reliably and flexibly apportion energy within an N-R HES is dependent on the available technology. By identifying the component and subsystem requirements necessary for technically and economically viable system configurations and comparing those requirements to available technology options, gaps will be identified and targeted for development. The Phase I analysis process will identify these hardware development and testing needs, which will be further refined in Phase II as tests are conducted and models are validated and improved.

Phase II activities consist of establishing test facility infrastructure; testing components, subsystems, interconnections, and instrumentation; and demonstrating optimized integrated system control. The primary purpose of experimental work is to increase understanding of specific technologies and to provide validation data for the various models used in the integrated system analysis. Specific testing needs will be identified for the N-R HES architectures determined to be high-priority via the defined metrics. Technology development and testing that can support the needs of multiple N-R HES configurations will be prioritized early in the component and subsystem test series conducted in Phase II. These common technology areas include instrumentation and controls, interoperability systems and protocols, a small modular reactor for thermal energy generation (represented via nonnuclear, electrically heated simulator for laboratory testing), power conversion equipment, hardware interconnections, and thermal and electrical energy storage. This approach will ensure that the development needs for a larger number of the N-R HES configurations are addressed in early testing activities, allowing for a simplified transition among configuration options should the initially selected option be determined to be infeasible following more-detailed (higher fidelity) dynamic analyses.

Figure ES-4 provides a high-level overview of the preliminary timeline for R&D activities. Key decision points are shown in the timeline, offering multiple opportunities for refinement of the architecture design(s), or investigation of alternate energy system configurations, based on analysis and experimental results. The N-R HES program will focus on development of technologies that will be needed to make the high-priority, near-term system configurations successful. Many of the necessary components are commercially available or are being advanced through other research programs, but they must be demonstrated within the appropriate subsystem or fully integrated system to characterize the integrated system performance. The series of component and subsystem tests will provide characterization data for model improvement, provide model validation data, and address technical gaps, allowing the integrated system concept to mature toward commercial viability. This program plan and the associated development timeline will be reassessed and revised following the identification of high-priority candidate system architectures (selected based on metrics defined early in the analysis process), at the end of the Phase I strategic analysis activities, and periodically thereafter.

Focused R&D in N-R HES design, optimization, and testing for promising hybrid system architectures, coupled with development of technology options through complementary research programs, will enable a more efficient, environmentally sustainable energy sector in the future.

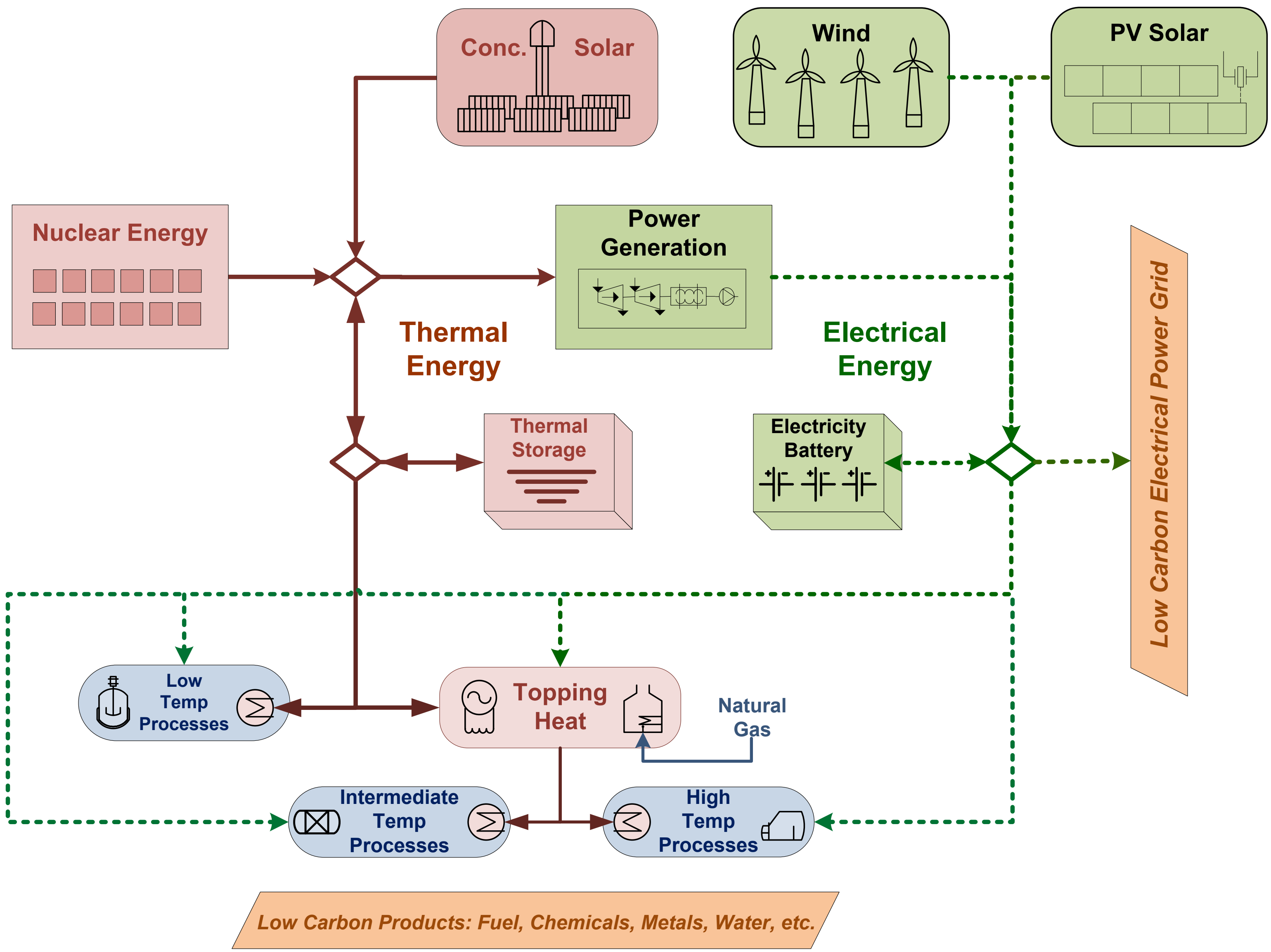

Figure ES-1. General architecture of a tightly coupled nuclear-renewable hybrid energy system, where the generation sources are integrated behind a single connection point to the grid and are managed by a single financial entity.

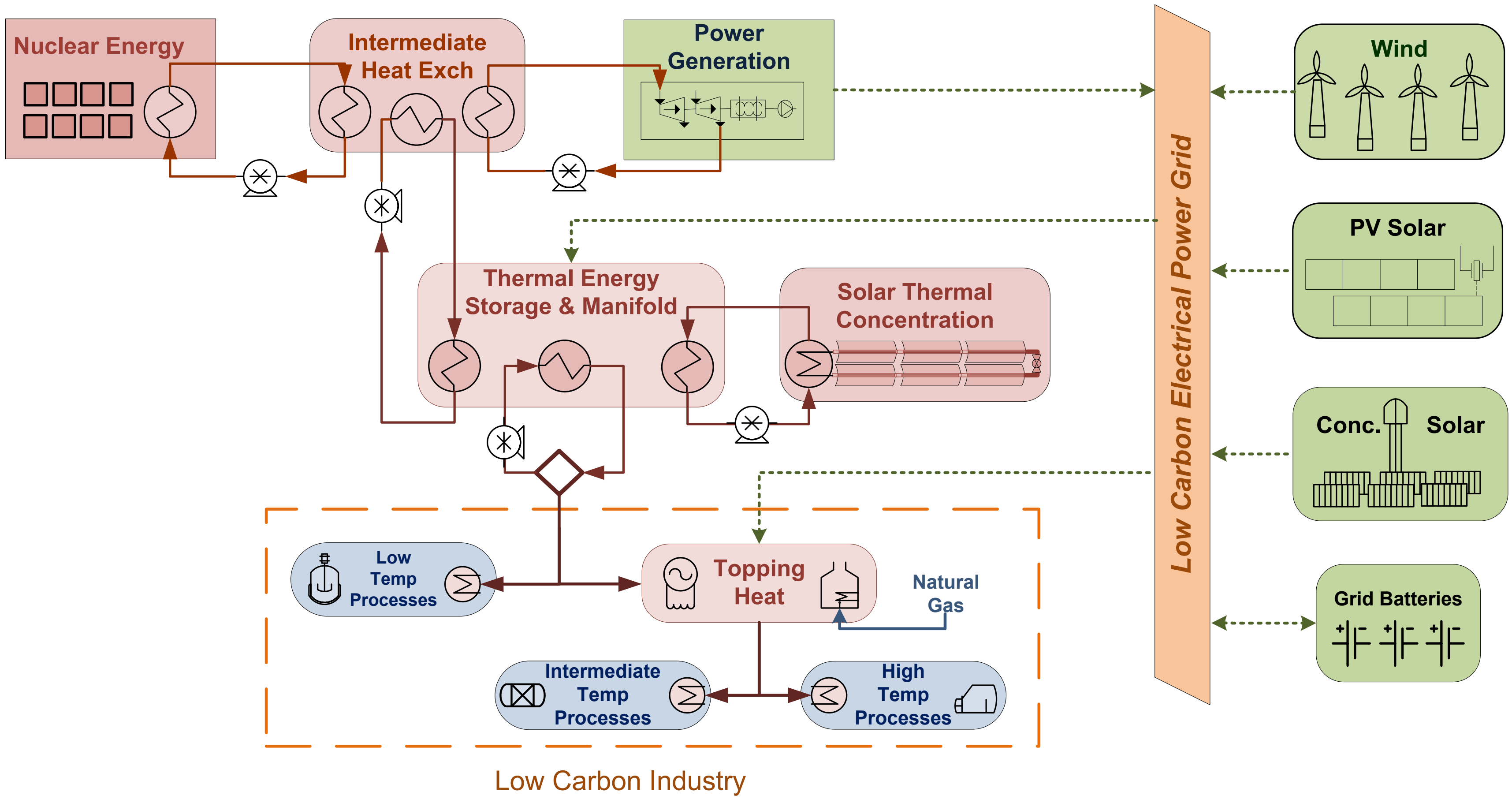

Figure ES-2. General architecture for a thermally coupled nuclear-renewable hybrid energy system, where the nuclear and renewable generation sources are co-controlled and managed by a single financial entity but may not be co-located. Note that all components shown may not be included in all system architectures.

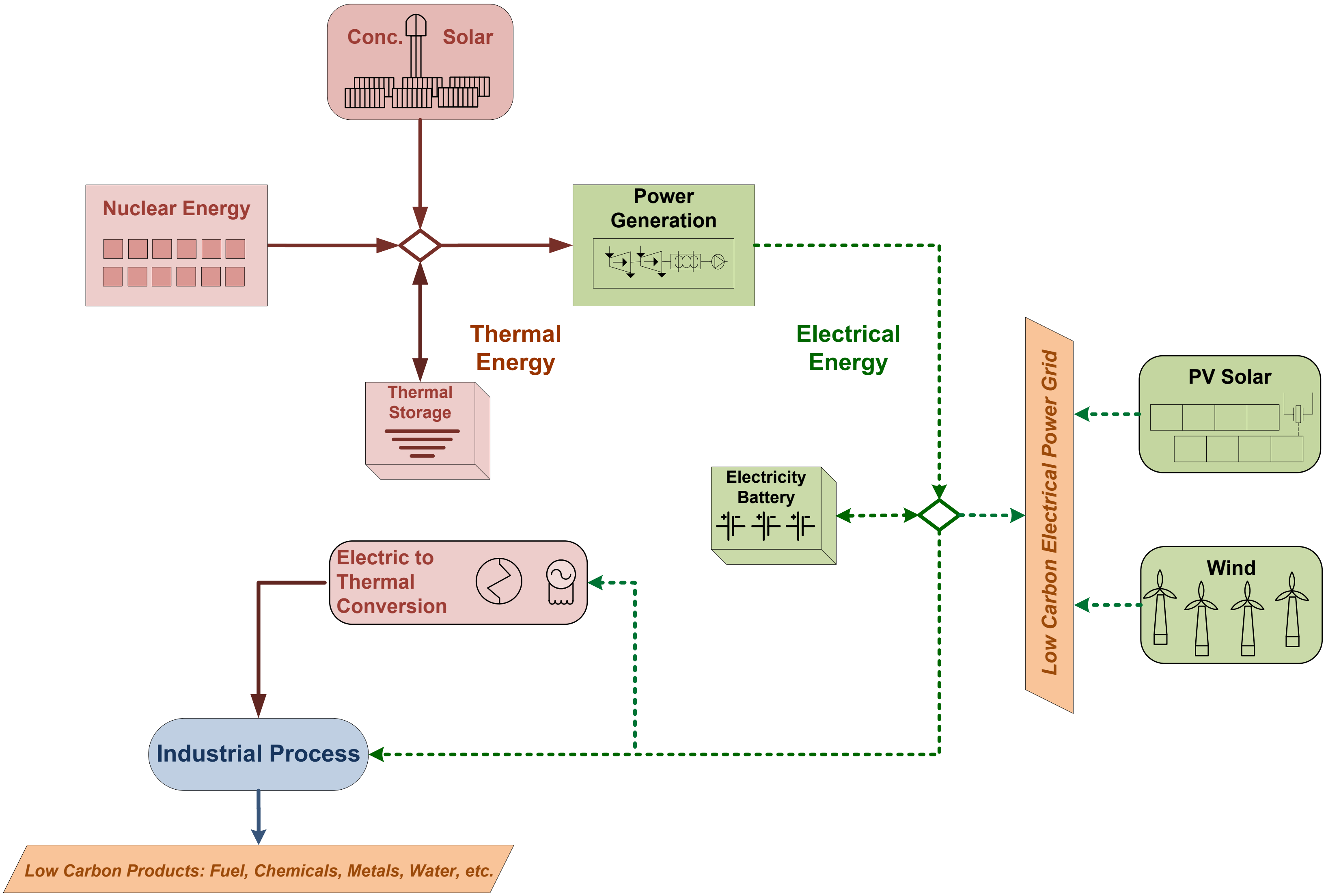

Figure ES-3. General architecture for a loosely coupled (electricity-only) nuclear-renewable hybrid energy system, where the generation sources are only electrically connected to the industrial process. Note that electrical-to-thermal energy conversion systems may be included to drive some processes.

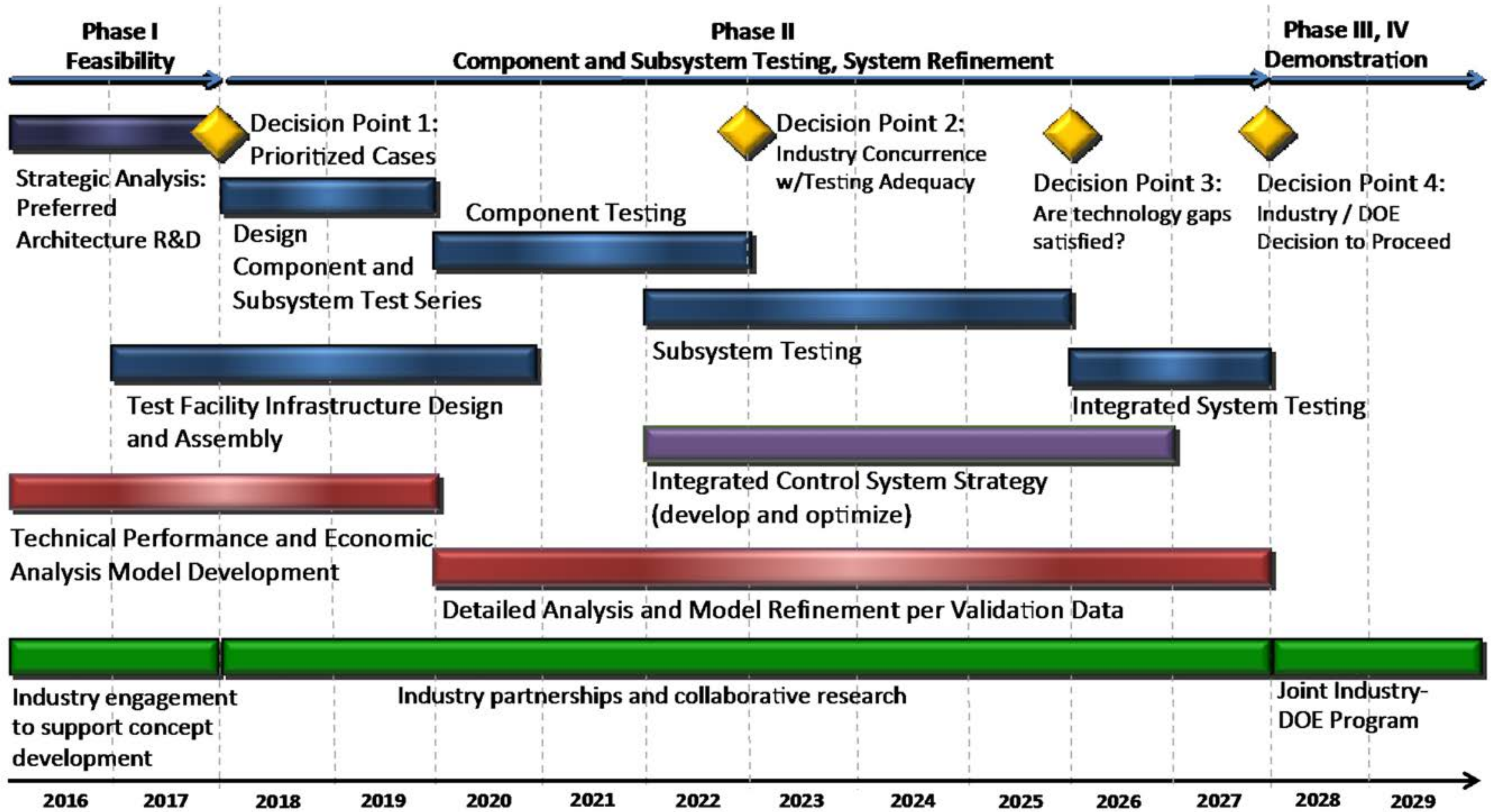

Figure ES-4. High-level timeline for N-R HES R&D activities.

CONTENTS

FIGURES

TABLES

ACRONYMS

AC	alternating current
ANI	American Nuclear Insurers
API	Application Programming Interface
ARPA-E	Advanced Research Projects Agency – Energy
ART	Advanced Reactor Technologies
ARTIST	Advanced Reactor Technology Integral System Test
CFD	Computation Fluid Dynamics
CFR	Code of Federal Regulations
CHiL	controller HiL
CHP	Combined Heat and Power
COL	combined operating license
DOD	U.S. Department of Defense
DOE	Department of Energy
DP	Decision Point
EERE	Energy Efficiency and Renewable Energy
EMT	ElectroMagnetic Transient
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
FACTS	flexible alternating current transmission system
FE	Fossil Energy
FERC	Federal Energy Regulatory Commissions
FIRES	Firebrick Resistance-Heated Energy Storage
FMEA	Failure Modes and Effects Analysis
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit
FOAK	First-of-a-Kind
FOM	figures of merit
GHG	Greenhouse Gas
HES	Hybrid Energy System
HiL	hardware-in-the-loop
HTSE	High Temperature Steam Electrolysis
I&C	instruments and controls

IAC	Industry Advisory Committee
INL	Idaho National Laboratory
IRP	integrated research project
ISO	Independent System Operator
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MIDC	Measurement and Instrumentation Data Center
MIT	Massachusetts Institute of Technology
MOOSE	Multiphysics Object Oriented Simulation Environment
N-R	Nuclear-Renewable
N-R HES	nuclear-renewable hybrid energy systems
NASA	National Aeronautics and Space Administration
NE	Nuclear Energy
NEAMS	Nuclear Energy Advanced Modeling & Simulation
NEIL	Nuclear Electric Insurance Limited
NERC	North American Electric Reliability Corporation
NEUP	Nuclear Energy University Program
NGNP	Next Generation Nuclear Plant
NPV	net present value
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NTD	National Technical Director
NUC	National Universities Consortium
OE	Office of Electricity Delivery and Energy Reliability
ORR	operational readiness review
PCU	power conversion unit
PEM	proton exchange membranes
PHiL	power HiL
PI	Principal Investigator
PIRT	Phenomena Identification and Ranking Table
PMU	phasor measurement units
PR	Principal Researcher
PRA	probabilistic risk assessment
PV	Photovoltaic
QA/QC	Quality Assurance/Quality Control

QAP	Quality Assurance Program
R&D	Research and Development
RAVEN	Reactor Analysis and Virtual control Environment
RO	reverse osmosis
RTDS	real time digital simulator
SAM	System Advisor Model
SMART	Strategic Management Analysis Requirements and Technology
SMR	small modular reactor
SSCs	structures, systems and components
T&FR	technical and functional requirements
T-S	temperature-entropy
TMY	typical meteorological year
TRL	Technology Readiness Level
V&V	validation and verification

Nuclear-Renewable Hybrid Energy Systems: 2016 Technology Development Program Plan

1. PROGRAM GOAL

This program plan defines the research and development (R&D) required for industrial-scale nuclear-renewable hybrid energy systems (N-R HES). Both renewable energy and nuclear energy are expected to become significant energy sources for all sectors in the near future because they reduce greenhouse gas (GHG) emissions and provide affordable, sustainable energy. N-R HES have the potential to expand those benefits to provide:

- Dispatchable, flexible, and carbon-free electricity generation for the grid
- Synchronous electromechanical inertia to the grid
- Reduced carbon footprint of the industrial sector
- Levelized and reduced energy costs (i.e., support stabilization of energy costs)
- Reduced energy system impact on water resources.

N-R HES are cooperatively-controlled systems that dynamically apportion thermal and/or electrical energy to provide responsive generation to the power grid. They are comprised of multiple subsystems, which may or may not be geographically co-located:

- A nuclear heat generation source,
- A turbine that converts thermal energy to electricity,
- At least one renewable energy source, and
- An industrial process that utilizes heat and/or power from the energy sources to produce a commodity-scale product.

Configuration options encompassed by the N-R HES program are described in Section 2. In all of the hybrid system architecture options, energy is dynamically apportioned to production of the industrial product, while simultaneously providing electricity to the grid to supply the net load. In some cases the industrial product may be an intermediate energy carrier, such as hydrogen, or an intermediate chemical feedstock, such as methanol. Additional subsystems that provide small-scale energy storage (thermal, electrical and/or chemical) may be included within the system boundary because they can act to buffer the dynamics between subsystems. This document presents a preliminary research and development plan for detailed dynamic simulation and analysis of N-R HES, coupled with integrated energy system design, component development, and integrated systems testing. However, the principles addressed herein may apply to hybridization of other primary heat generation sources, including coal and biomass power plants, natural gas combined-cycle units, and solar energy concentrating systems.

The primary program goal is to examine the viability of N-R HES through detailed technical performance analysis and, if determined to be viable, to establish the necessary science-based R&D capabilities to develop and demonstrate an N-R HES that has the potential to be demonstrated by 2030. To achieve this goal, state-of-the-art design, modeling, and optimization techniques for N-R HES will be developed with a focus on real-world opportunities and market drivers. A second goal is the development of enabling technologies necessary to connect and control subsystems within hybrid systems in a manner that achieves energy efficiency, provides grid stability, and is resilient to degrading effects. These technologies include dynamic heat exchangers and circulators, innovative mass conversion and transport operations, and new instrumentation and coordinated supervisory/automatic controls for large, complex systems with massive real-time data and communication networks among the energy markets and energy production/delivery agents. A third goal is involvement and support of key industries, energy resource holders, technology providers, electricity producers, and manufacturing industries through technology development, testing, and validation, such that these technologies will later commercialize under industry leadership. In the later development phases, industry partners will be responsible for obtaining appropriate licensing. Involvement from regulatory agencies (such as Federal Energy Regulatory Commission [FERC], Nuclear Regulatory Commission [NRC], and Environmental Protection Agency [EPA]) early in the design of N-R HES will be key to the successful development of these systems.

This program plan outlines a technology development process and involves program planning and execution guidance relative to organizing the research team and execution of the fundamental science, systems engineering, market analysis, and project execution through pilot-scale demonstration of a nonnuclear (electrically heated) integrated system (i.e., through Technology Readiness Level [TRL] 6).[1] Working through this development plan will greatly reduce the technical and financial risks of future commercial projects that deliver the promise of reliable, clean energy systems.

Involvement of research test centers or hubs at national laboratories, non-government research institutes such as the Electric Power Research Institute (EPRI), universities, and industry is an important aspect in accomplishing the planned work. As the N-R HES concept advances through the technology maturation process, cost sharing with industry will be needed to incentivize technology innovation and to accomplish the aggressive goals set out in this program plan. Efforts in public, industry, and government education are also essential to the ultimate commercialization and public acceptance of the technology.

In summary, N-R HES are a new paradigm in energy systems. This concept emerges from the projected changes in the U.S. electrical power system resulting from the increasing penetration of variable renewable generators on the grid and is enhanced by the development of small modular nuclear reactors. N-R HES could provide this class of reactors an economic opportunity to produce power, while simultaneously producing industrial products and providing a low-emission option for grid flexibility.

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1 TRL 6: Technology and system/subsystem demonstration at pilot scale in a representative environment.

2. N-R HES DEFINITION

N-R HES are cooperatively controlled systems that dynamically apportion thermal and/or electrical energy to provide responsive generation to the power grid. As discussed in Section 1, N-R HES include multiple subsystems, which may or may not be geographically co-located: a nuclear heat generation source, a turbine that converts thermal energy to electricity, at least one renewable energy source, and an industrial process that utilizes heat and/or power from the energy sources to produce a commodity-scale product.

In all of the hybrid system architecture options, energy is dynamically apportioned to production of the industrial product, while simultaneously providing electricity to the grid to supply the net load. Recognizing that the N-R HES subsystems would be managed by a single financial entity, this flexibility can be used to maximize overall system profitability (versus profitability of a single subsystem), ensuring that the system will be competitive within the broader energy market while simultaneously providing clean electricity to the grid. Additional subsystems that provide small-scale thermal, electrical, and/or chemical storage may be included within the N-R HES to buffer the dynamics between subsystems by providing an additional resource for energy management within the system boundary. N-R HES are innovative energy system options that can provide technical, economic, and environmental benefits versus electricity-only plant operations that are the current standard mode of operation. Anticipated benefits of N-R HES are detailed in Section 3.

2.1 Hybridization and Alternative Plant Configurations

This project focuses on the technical development needs of three types of hybrid energy systems. Three possible general N-R HES architectures in which nuclear energy is coordinated with variable renewable power generation are depicted in Figure 1 to Figure 3. These figures are intended to be representative only; all components shown may not be included in all system architectures. Moreover, some additional components may be necessary; for instance, some scenarios could entail conversion of stored electrical energy to heat to drive an industrial process. The relative size (i.e., power level) of each subsystem in the integrated system will be varied in the system design and analysis stage to establish an optimized configuration architecture for each use case. System options encompassed by the N-R HES program can be grouped in three general categories:

1. *Tightly Coupled HES*. Nuclear and renewable generation sources and the industrial process(es) are directly integrated behind the grid and co-controlled, such that there is a single connection point to the grid and a single financial entity managing the HES (i.e., profitability of the HES is optimized for the integrated system rather than for each system independently). See Figure 1.
2. *Thermally Coupled HES.* Subsystems may have more than one connection to the same grid balancing area and may not be co-located; however, the nuclear and renewable subsystems are co-controlled to provide energy and ancillary services to the grid. This category includes thermally integrated subsystems that are tightly coupled with the heat generation source; geographical location of the industrial process will be dependent on required heat quality, heat losses to the environment along the heat delivery system, and the required exclusion zone around the nuclear plant. These systems have more than one connection point to the grid but are managed by a single financial entity. See Figure 2.
3. *Loosely Coupled, Electricity-Only HES.* This configuration is controlled in a similar fashion to the thermally coupled system, but generators are only be electrically coupled to industrial energy users (no direct thermal coupling of subsystems). This scenario allows management of the electricity produced within the system (e.g., from the nuclear plant via power conversion or renewable electricity generation) prior to the grid connection; however, note that the system may include electrical-to-thermal energy conversion equipment to provide thermal energy input to the industrial process(es). Such an option allows for potential retrofit of existing generation facilities with fewer

regulatory challenges. These systems have more than one connection point to the grid but are managed by one financial entity. See Figure 3.

For comparison, the *Base Case* includes nuclear and renewable power systems that are independently connected to the grid to provide electricity, and an independent industrial process that draws electricity from the grid. This case does not involve any direct use of thermal energy from nuclear or renewable sources, but may derive thermal energy input from burning fossil fuels to drive the industrial process. This case describes current grid operations.

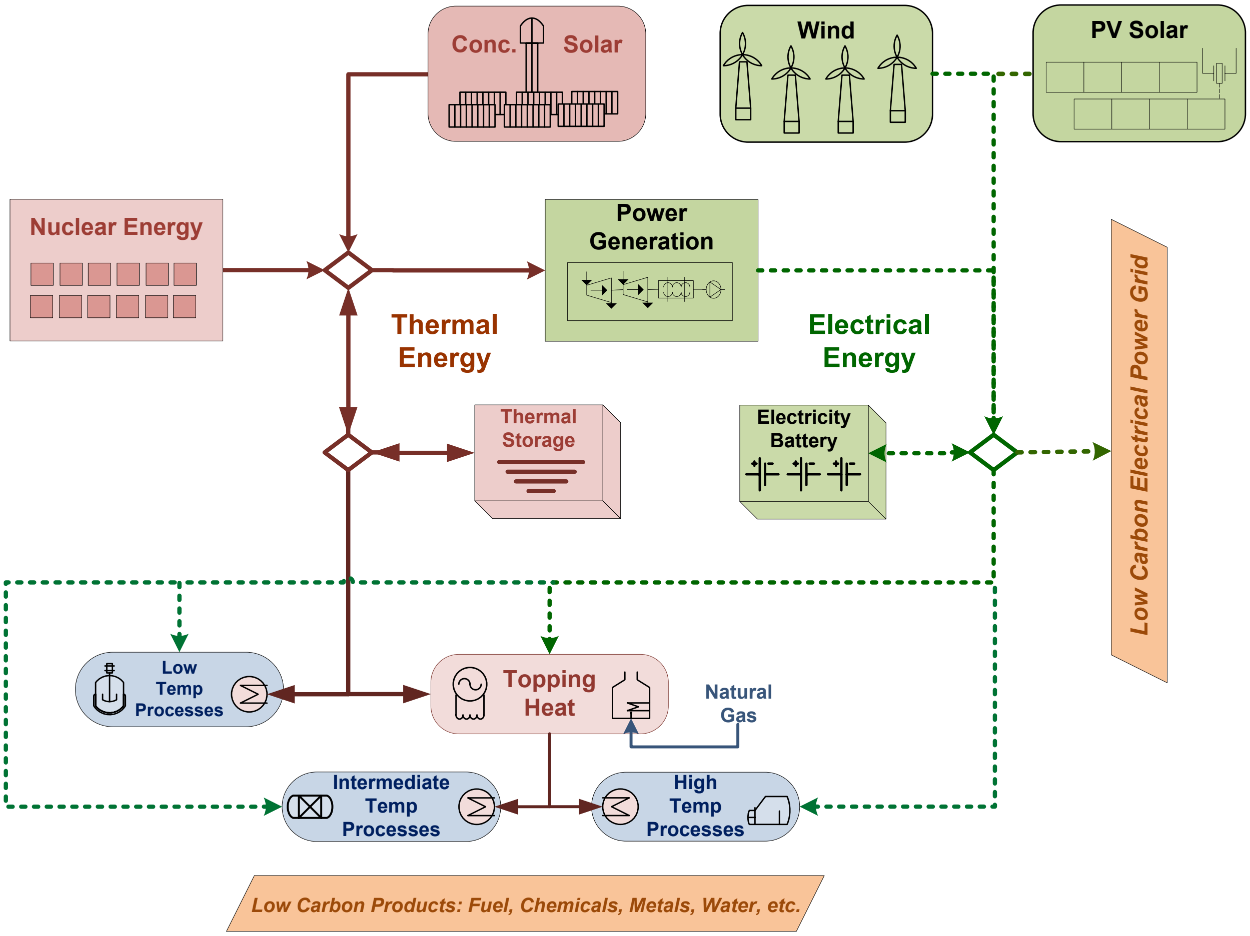

Figure 1. General architecture for a tightly coupled nuclear-renewable hybrid energy system, where the generation sources are integrated behind a single connection point to the grid and are managed by a single financial entity.

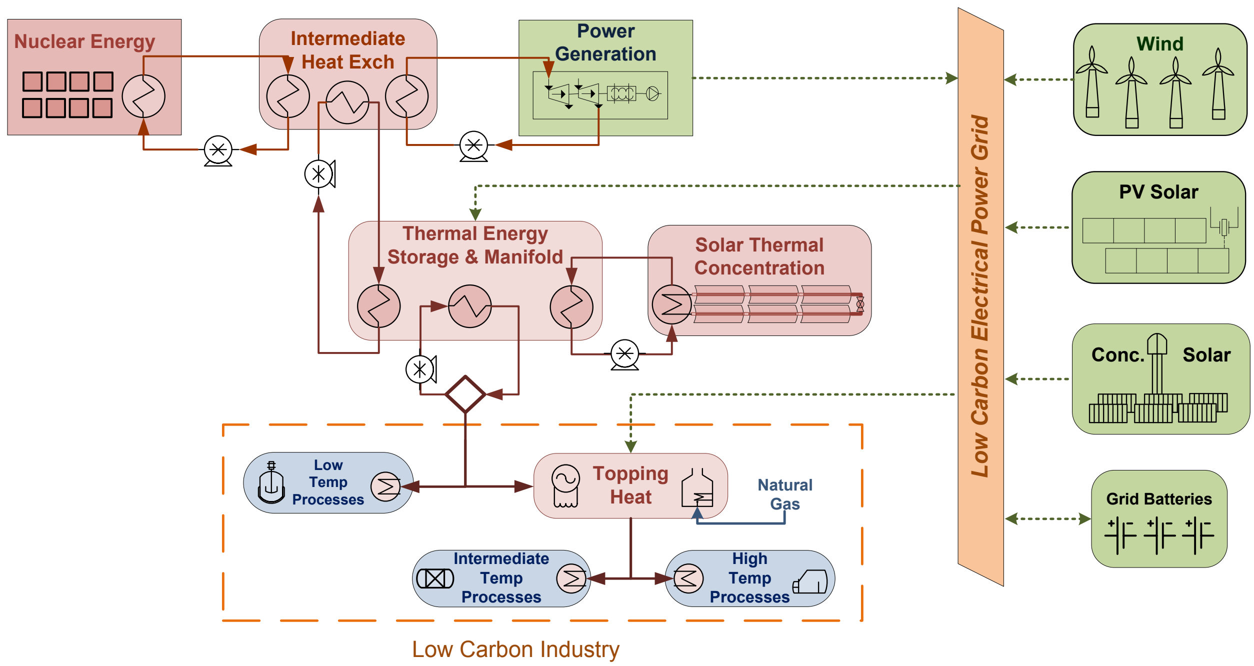

Figure 2. General architecture for a thermally coupled nuclear-renewable hybrid energy system, where the nuclear and renewable generation sources are co-controlled and managed by a single financial entity but may not be co-located.

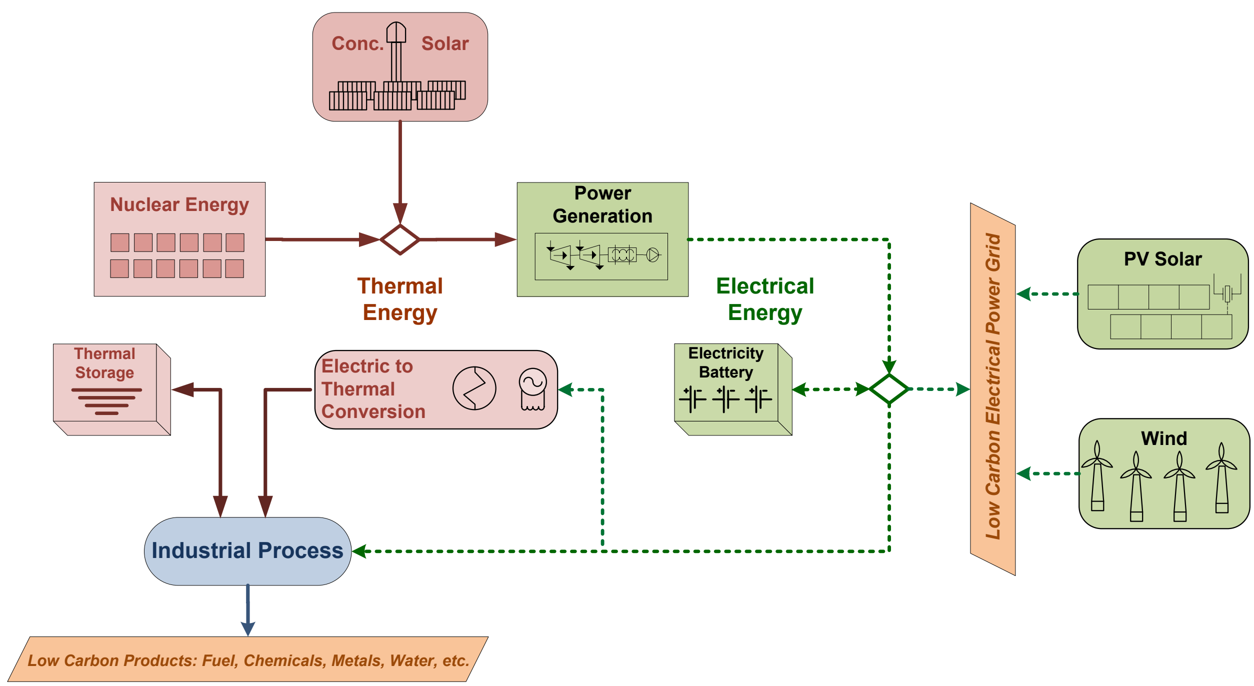

Figure 3. General architecture for a loosely coupled (electricity-only) nuclear-renewable hybrid energy system, where the generation sources are only electrically connected to the industrial process. Note that electrical-to-thermal conversion systems may be included to drive some processes.

As shown in Figures 1 to 3, N-R HES can have the following subsystems:

- *Nuclear reactor(s).* The nuclear reactor provides baseload heat and power (via the power conversion subsystem) without emission of GHGs. The nuclear subsystem should operate at a high capacity factor to cover operating and capital costs and have a profitable internal rate of return. The reactor(s) will also perform more efficiently and maintenance costs will be minimized if operated at or near steady-state design conditions. Nuclear-generated heat will be apportioned to the industrial process and storage based on net load.
- *Power generation.* The steam turbine in the power generation subsystem converts thermal energy generated by the nuclear reactor into electrical power. The amount of power generated can be ramped up or down depending on the amount of steam dispatched to it; hence, it is a flexible generator of electricity. In the U.S., steam turbines run synchronously with the grid at 60 Hz. Because they are large, rotating equipment, the inherent inertia within turbines supports frequency management of alternating current (AC) power on the grid.
- *Renewable energy generator(s).* The renewable source(s) provides low-cost energy (heat and/or power) without emission of GHGs. Generation by variable renewable technologies (i.e., photovoltaic [PV] solar and wind), however, is not dispatchable, meaning that it cannot provide power to follow grid load. Electricity and heat from renewable energy sources may also be used by the industrial process or stored.
- *Industrial process.* When coupled within an N-R HES, the industrial process receives heat and/or power from the nuclear reactor(s), the turbine, and the renewable energy source as needed, or as heat/power is available. The process uses that energy and additional feedstocks to produce highly valued commodity products that provide another income stream to the N-R HES. When heat from the nuclear reactor is diverted to power production, the industrial process output can be reduced, or the heat necessary to operate the process must be derived from another source (e.g., natural gas). Most industrial processes require constant operation for economic profitability and optimal performance, although some processes could be designed to operate flexibly if sufficient economic incentives are offered. The ability to ramp many industrial processes is limited due to performance reduction, impacts on economic profitability, and wear or damage on the process equipment. These implications must be considered in process development.
- *Storage (electrical, thermal, and/or chemical).* Energy storage buffers may be used to attenuate the dynamics of subsystems. Electrical storage options include batteries and flywheels. Thermal storage options include both liquid (e.g., molten salt) and solid (e.g., firebrick) forms. Heat removed from storage can be used either directly in the industrial process or to generate steam that will be fed to the steam turbine. Electrical energy may also be stored in the form of heat for conversion back to electricity when needed for use in thermally driven processes. Note that the specific need for and potential benefits of energy storage integrated within a hybrid system will be evaluated as this project is executed.

The defined tightly coupled and thermally coupled N-R HES concepts require a dual heat delivery system and the controls necessary to apportion heat between power production and a given industrial process. Similarly, the electrical output is apportioned between the grid and the industrial process as necessary. If necessary, power may be drawn from the grid and combined with the heat and/or electricity delivered from within the hybrid system to operate the industrial process. In the described thermally coupled case the renewable subsystem may be loosely coupled and operated in close coordination with the nuclear subsystem via the grid balancing area, with the nuclear subsystem (and possibly a concentrated solar plant) operating in a combined heat and power mode to provide both thermal energy and electrical energy. In this system design the thermal energy generators (e.g., nuclear reactor and concentrated solar power) supplies heat, steam, and power to the manufacturing industry, primarily interacting with the grid when providing peak power or when power regulation is more valuable than the goods manufactured by the integrated industrial plant. These systems can operate as dynamic cogeneration plants, adjusting output to meet grid needs and to maintain economic operation of the overall plant.

By comparison, non-hybridized traditional energy generation systems in the base case connect independently to the grid. Interaction between these generators is managed via an independent system operator (ISO); all plants in this scenario are owned and operated by independent entities. In this scenario, flexible operation can be accomplished by modifying the power output from one or more generation source, via control maneuvers or release of excess thermal energy (i.e., steam) to the environment. This describes the standard operating mode for current electric generators, but this may not offer the best use of the available exergy as the grid net load becomes more dynamic.

2.2 Desired N-R HES System Attributes

This project plan targets the development of highly responsive N-R HES designed to have the following attributes:

- The system will dynamically vary and apportion its heat and power on an industrial scale. Heat and power from the nuclear energy source can be diverted to the grid, storage, and industrial processes as needed.
- The system will be highly flexible and will have the ability to adjust electricity generation to meet the needs of the grid on an hourly, daily, weekly, and seasonal basis. This flexibility may enable higher grid penetration and utilization of renewable generation systems, while mitigating technical and economic impacts of periodic over-generation on the grid.

  For example, Figure 4 plots the projected net load[2] required of dispatchable power generation sources as a function of annually increasing solar PV electricity generation available to the California Independent System Operator (ISO) (CAISO 2013). As PV generation increases, the risk of periodic over-generation (during times of abundant solar energy input) also increases; over-generation can lead to periodic price suppression as the market becomes saturated. According to this projection, dispatchable resources may need to be curtailed for significant amounts of time in the 2020 scenario. Then, when the sun is setting, generation capacity must be rapidly ramped up by as much as 70 MW/min over approximately 3 hours, per this example. This type of plot is commonly referred to as the "Duck Curve." In this case, the operational goal of an N-R HES would be to respond to the net load by diverting thermal and electrical energy to an alternative user in accordance with the grid dynamics, hence, avoiding over-supply and the associated price suppression. In this manner, N-R HES will support levelizing of energy costs daily, weekly, and seasonally. This result supports the financial viability of the ISO and power generation operators, while simultaneously ensuring the financial viability of thermal/electrical power generation assets. N-R HES are one of several options being considered to manage higher penetration of variable renewable generators. Other options under study for grid management are discussed in relevant reports from the National Renewable Energy Laboratory (NREL) and North American Electric Reliability Corporation (NERC) (e.g., Cochran et al. 2014, NERC 2010). N-R HES offer the additional benefit of aiding the decarbonization of the industrial sector while meeting grid flexibility needs.
- N-R HES will maximize the overall system performance as a function of technical, economic, and reliability figures of merit (FOMs) by producing multiple products. When the grid net load is low, the nuclear baseload generator can divert its heat and power to industrial processes to produce products such as water, liquid fuels, industrial chemicals, processed minerals, and hydrogen. Note that one or

[2] Net load is the remaining load that must be met by conventional dispatchable generation sources after variable generation is subtracted from the total load (electricity demand).

more products could be included in a single HES configuration. Operating the nuclear plant at high capacity will lead to higher efficiencies and better project economics.

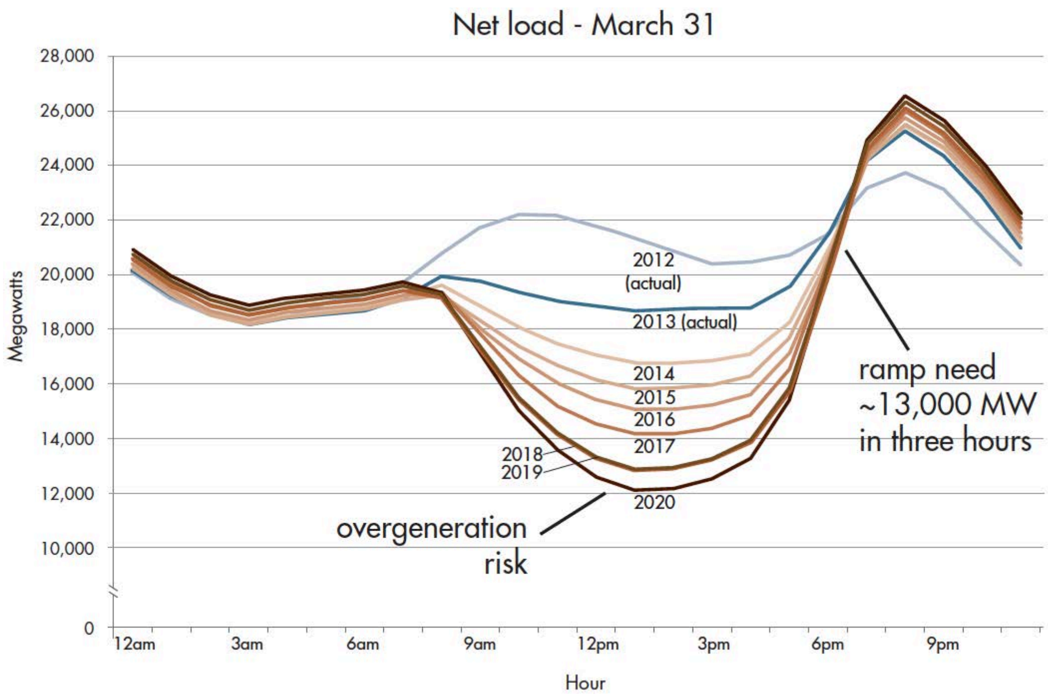

Figure 4. Daily net load as a function of hour and renewable penetration goals; the "duck curve" shows steep ramping needs and over-generation risk (CAISO 2013).

- N-R HES have the ability to maintain synchronous electrical power generation inertia to maintain grid power quality conditions (i.e., frequency, voltage, and power phase) that are impacted by dynamic grid load and variable renewable power generation. The degree to which this is possible depends on the form of coupling within the hybrid system. The benefits of "real" inertia on the grid are currently being evaluated under the DOE Grid Modernization program relevant to demand response and energy storage agents, new power electronics, and power management among balancing areas. N-R HES augment grid modernization choices and will be evaluated in parallel with all possible options.

  Other factors such as environmental benefits, energy prices, energy quality, and reliability of electricity supply will be included to optimize resource utilization, deliver quality and economical products, and reduce environmental impact.

2.3 Key Assumptions: Concept of Operations

This program plan targets the evaluation and development of tightly coupled, thermally coupled and loosely coupled nuclear-renewable hybrids. As described previously, these systems will be capable of operating as highly responsive systems to support grid operations. The future grid will require more coordination of generation sources and multiple/complex control functions as more variable generation sources are connected to the grid. The R&D described in this program plan is needed to determine the potential impact of N-R HES generators on the stability and reliability of the future grid within the affected balancing area and to demonstrate the proposed integrated system technology. As presented in Section 3, it is presumed that the N-R HES will provide resources for grid management to support high penetrations of variable renewables and will support further reduction of carbon emissions across the energy sectors. These attributes are important to the current grid and will become much more important in future scenarios (e.g., tightly regulated energy systems or monetized via carbon tax).

This program plan focuses on N-R HES configurations that can be deployed in the relative "near-term" (from the perspective of the nuclear subsystem). This requirement entails integration of high TRL subsystems and components, such that the majority of the research effort is on the integration technologies, communications, and control algorithms rather than development of novel subsystem technologies. Hence, the plan addresses N-R HES that incorporate new installations of LWR concepts with an initial focus on small modular reactors (defined by a unit size of <300 MWe). Note, however, that the described loosely coupled N-R HES architecture could be applicable to retrofit of some plants in the existing LWR fleet that are beginning to see requirements for increased flexibility as variable renewable penetration increases in their respective grid balancing areas.

The program plan primarily assumes greenfield installations for all subsystems. Retrofit of existing LWRs is considered possible, pending further evaluation conducted in coordination with industry partners, but issues such as direct heat delivery to industrial processes would present significant regulatory hurdles. New industrial facilities could be constructed near existing nuclear plants and designed to receive power, and possibly to utilize heat via electric-to-thermal energy conversion. Such a configuration would fall into the "loosely-coupled (electricity-only)" category described previously.

Initial R&D efforts conducted within Phase I will prioritize the development of technologies and equipment that are common to a wide variety of system configurations. No single N-R HES configuration will be successful in all regional implementations; hence, efforts will be taken to support parallel research paths for high-priority configurations and to develop technologies applicable to multiple regions. R&D efforts in Phase I will include a strong focus on modeling and simulation with limited hardware development and experimental demonstration. This approach will ensure that the down-selection of the configuration and technology options is not conducted too early in the technology maturation process, thereby offering a greater chance for programmatic success. Technology needs for multiple configurations may include the following (note that technologies needed in the HES that will not be specifically developed within the NE program are not listed here [e.g., the nuclear and renewable generators], although representation of these systems may be necessary in the integrated system testing):

System-wide technologies

- *Instrumentation and controls (I&C) for multi-agent distributed and resilient control.* Advanced instrumentation and controls for highly dynamic systems, Strategic Management Analysis Requirements and Technology (SMART) flow-control valves, rheology meters, real-time species measurement in reacting flows, power frequency and power factor monitors (Rieger, Moore and Baldwin 2013).
- *Interoperability systems and protocols.* Neural networks, communication networks, and data transfer and storage, supervisory control advisory and/or automatic control primacy.

Subsystem technologies

- *Power conversion equipment.* Fast response/fast ramping turbines—gas, steam, and condensing steam, interstage heat extraction.
- *Interconnections.* Heat exchangers, fluids and piping to transfer heat over long distances, and electrical and optical interconnects.
- *Energy storage.* Solid state batteries, flow batteries, flywheels, compressed air, thermal, and pumped hydro-power (Department of Energy 2013); other options to be considered as they are developed.

Common modeling efforts that will support multiple N-R HES options include:

- *Steady state process modeling.* Steady-state modeling of hybrid systems supports determination of heat and mass balances, equipment sizing, and integration of industrial processes with nuclear and renewable sources and with storage.

- *Dynamic systems modeling.* Dynamic modeling to develop an understanding of the transient relationships between the diverse components to develop and implement effective control and monitoring strategies.
- *Component modeling.* Modeling of the behavior of specific equipment using software such as computational fluid dynamics, computer aided design, and stress analysis.

2.4 Industrial Application Opportunities

A key assumption of N-R HES is the apportioning of energy between power production and heat generation for an industrial application. The U.S. manufacturing industry can be broken down into a number of energy-intensive sectors, categorized in Table 1 based on heat requirement and characterized by total energy input needs in Figure 5 (Pellegrino et al. 2004). Specialized markets, such as pharmaceuticals, that require tight quality control and do not demand a large electrical or thermal input are not listed here.

The manufacturing industry currently uses about 25 Exa-Joules of delivered energy, comprised of approximately 20% from electricity (with about one-third produced onsite for captive use), 40% from steam (all generated onsite), and 40% from fossil-fired combustion as a source of either direct heating, such as in a cement kiln, or indirect heating, such as in fired-heaters (Ruth et al. 2014). A breakdown of the principal manufacturing industries, showing the conventional source of energy and the approximate thermal range of heat transfer is shown in Table 1. Over 90% of the energy currently used in industry is derived from combustion of fossil fuels. Hydro-electrical dams that support the aluminum metal production industry and biomass refuse combustion in CHP plants are still the main source of non-fossil energy sources used by the industrial sector.

A key advantage of nuclear energy as a baseload energy source is its reduced pollutant emissions relative to other baseload supply (i.e., fossil resources). Small modular reactors (SMRs) have the potential to provide heat (primarily via steam heating and indirect heating) and electricity to meet the needs of many industrial processes. A majority of the industrial steam and heat duty requirements could be directly derived from light-water reactors (LWRs) through temperature amplification techniques. Steam super-heating with a fossil fuel, chemical heat pumps, or other technologies could be used to amplify LWR steam temperatures to the necessary service temperatures of processes requiring heat in excess of 300°C (the approximate temperature at the outlet of an LWR) with minimal GHG emission. Use of high-temperature reactors, especially gas and molten salt-cooled designs, would reduce the need to augment steam heating, but these designs will require a significantly longer development time and currently have high cost uncertainties. As will be discussed in Section 5.3, temperature-boosting technologies will be investigated in the N-R HES program. This research will provide the necessary information to assess the cost and efficiency of using high-temperature heat pumps, resistive heating, etc., in conjunction with LWRs and renewables to provide heat to industrial processes.

As a part of program execution, a detailed assessment of current and future industrial processes that may benefit from nuclear and renewable energy sources will be completed. In summary, hybrid systems can effectively touch all major/heavy manufacturing industries, including fuels, chemicals, metals, and the paper-product industries, as well as smaller industries associated with food production, biofuels plants, and minerals concentration, to name a few. It is important to note two factors associated with N-R HES that can impact U.S. manufacturing industries: nuclear and renewable energy are not susceptible to supply and price volatility (vs. fossil fuel plants that are heavily impacted by the price of natural gas and coal) and the clean energy they provide is essential to meeting all current and future environmental regulations. Both of these factors are critical considerations for capital investment decisions.

Table 1. Breakdown of the principle manufacturing industries, including the conventional energy source and the approximate thermal range of heat transfer. LP – low pressure steam (< 1 MPa), IP – intermediate pressure steam (1 – 10 MPa), and HP – high pressure steam (> 10 MPa).

	Industry Application	Conventional Energy Source or Conversion Process	Heat Source Temperature (°C)	Potential Nuclear Reactor Energy Delivery
Steam Heating	District heating Drying processes Evaporation processes	Combined heating and power with fossil fuels or biomass combustion	30 – 200	Hot water LP steam
Steam Heating	Miscellaneous steam applications Pulp and paper products Food processing	Fossil-fired boilers Black liquor combustion	100 – 300	IP steam
Steam Heating	Petrochemical refineries	Oil, natural gas, tail gas, and petcoke boilers	Distillation: 200 – 500 Thermal Cracking: 400 – 650	HP steam Hydrogen
Steam Heating	Hydrogen production by water splitting	Electrolysis Thermochemical looping reactions	Water Electrolysis: < 100 High T. Electrolysis: 750 – 850 Thermal Loops: 450 – 900	IP – HP steam Hot gas Molten salt
Indirect Heating	Inorganic minerals production (phosphates, soda ash/sodium hydroxide, chlorine, fertilizers, etc.)	Fossil-fired heaters	Minerals retorting: 350 – 500 Minerals concentration: 150 – 250	HP steam Hot gas Molten salt
Indirect Heating	Biofuel refineries	Biomass-processing and thermal conversion Distillation Steam methane reforming	Distillation: 150 – 200 Torrefaction: 250 Pyrolysis: 500 Gasification: 850 – 1000	LP – HP steam Hot gas or Molten salt H_2 enriched flames Hydrogen for fuels upgrading
Indirect Heating	Chemicals manufacturing (methanol, 1,4 butanediol ethylene/ propylene, acetic acid, formaldehyde, resins, hexamethylene diamine etc.)	Distillation / Concentration Heat transfer reactors Fossil-fired heaters Heat recuperation	Distillation: 150 – 200 Softening/Melting: 150 – 300 Reactions: 300 – 600	LP – HP steam Hot gas or Molten salt H_2 enriched flames Hydrogen for chemical synthesis Electro-chemical processes
Indirect Heating	Hydrogen production from hydrocarbons	Two-stage auto-thermal partial oxidation of NG	750 – 900	Hot gas Molten salt
Combustion & Electric Arc	Coal gasification for synfuels and chemicals synthesis	Partial oxidation Shift reactor Fischer-Tropsch fuels (F-T) Methanol to gasoline (MTG)	> 1,000 – 1,300	O_2 for oxy-fired gasifier H_2 for fuels synthesis
Combustion & Electric Arc	Glass and fused silica manufacturing; Iron and steel making; Aluminum production; etc.	Fossil-fired heaters Metallurgical coke H_2 for reduction Electricity from inexpensive supplier	> 1,000 – 1,500	Induction heating, Electric arc / Plasma Electro-chemical processes H_2 enriched flames H_2 as a reductant
Combustion & Electric Arc	Portland cement ($xCaO$- yAl_2O_3- $zSiO_2$) Lime (CaO / CaOH)	Combustion-fired kiln	> 1,300 – 1,800	H_2 enriched flames H_2 as a reductant

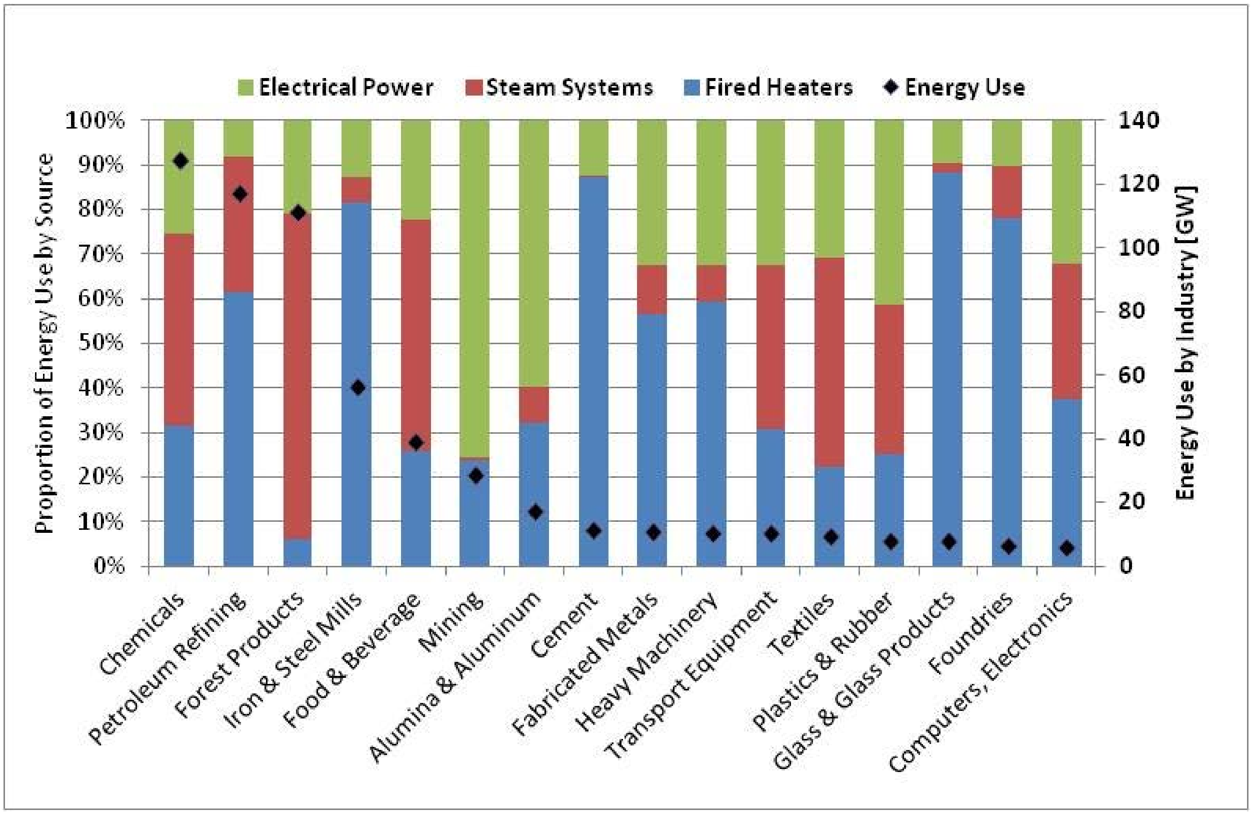

Figure 5. Energy use by U.S. manufacturing and mining industries for 2004 (data adapted from Pellegrino et al. 2004).

2.5 Definition of Terms

Common terms used within this program plan are defined below for clarity.

System. Nuclear-Renewable Hybrid Energy System, as shown in Figures 1 through 3. Note that all components shown may not be incorporated in the selected N-R HES configuration.

Subsystems. Individual units within the larger system that are integrated to create the N-R HES.

- Nuclear subsystem: Comprised of one or more nuclear reactor, provides thermal energy in the form of steam
- Renewable energy generator: Generates electrical, or thermal and electrical, energy depending on the type of generator (wind, solar PV, concentrated solar, biopower, hydrokinetic, geothermal, etc.)
- Industrial process subsystem: Requires thermal and/or electrical energy input; outputs a marketable commodity
- Power generation: Power conversion subsystem that converts thermal energy to electricity
- Energy storage: Any system that has capacity to retain a form of energy until it is recovered from storage, principally including thermal reservoirs, electrical capacitors or batteries, and chemical media or holding tanks.

Component. Constituent units of a subsystem.

Interconnections. One of many connections within the coupled system, involving a transfer of material, energy, or information. Six distinct types of interconnections were defined in Ruth et al. (2014): thermal, electrical, chemical, hydrogen, mechanical, and data transfer. Specific interconnections include:

- Electrical interconnections
- Heat exchangers
- Energy storage elements: Note that storage elements may be classified as interface "components" or "subsystems" depending on their specific design
- Dynamic energy distribution elements
- Electronic signals, digital data transmitters or communications links.

Resilience. A resilient system is one that maintains an acceptable level of operational normalcy in response to process disturbances, such as electronic signal noise, including threats of an unexpected and malicious nature (Rieger 2010). Criteria often include the speed at which the system recovers normal output following a disturbance.

Net load. The remaining load that must be met by conventional dispatchable generation sources after variable (nondispatchable) generation is subtracted from the total load (demand) (Denholm and Hand 2011).

Ancillary services. Services necessary to support transmission of electricity from seller to customer to maintain reliable operation of the interconnected transmission systems. Functions performed by generation include "…load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch service, and energy imbalance services" (FERC 2016).

Flexibility. The ability of an electric system's conventional generation fleet to vary output and respond to the variability and uncertainty of the net load (Denholm and Hand 2011).

3. EXPECTED BENEFITS OF N-R HES

The U.S. electricity grid is evolving due to changes in society's concerns for global climate change. A major cause of global climate change is generally accepted to be the growing emissions of GHGs as a result of increased use of fossil fuels (Wuebbles and Jain 2001). The global electricity supply sector generates the largest share of GHG emissions (38% of total CO_2 emissions), while the transportation sector contributes 34%, the industrial manufacturing sector 18%, and residential and commercial heating sector 10% (LLNL 2015). The electric power industry is adding significant capacities of non-emitting, variable renewable energy sources, especially wind and PV solar. Those additions are helping stakeholders meet state Renewable Portfolio Standards (Ruth et al. 2014) and will aid in meeting U.S. federal goals for reduced emissions. Build-out of nuclear generation will also reduce GHG emissions. SMR technologies are being developed to complement the current and future fleet of large LWRs with the ability to provide clean, reliable power. Advanced coal-fired and natural gas-fired power generation will ultimately require advanced capture and management of CO_2 emissions to adhere to GHG emissions goals.

Increased penetration of variable renewable generation on the grid is leading to new grid operation challenges. Variability in renewable generation has increased the need for dispatchable electricity production that can flexibly respond to changes in the net load. Additionally, as large power plants are curtailed in favor of renewable energy, power line voltage, line frequency, and power phase is becoming more challenging to manage (Fu et al. 2012). Increasing renewable generation can also result in electricity price suppression during times of high supply of variable renewable energy, which, in the absence of other investment incentives, can impact economic viability of generators in both regulated and deregulated markets.

N-R HES are innovative energy system options that can provide technical, economic, and environmental benefits versus electricity-only plant operations. The following subsections address these anticipated benefits in more detail.

3.1 Provide Dispatchable, Flexible and Carbon-Free Electricity Generation for the Grid

Daily and seasonal load variations are currently managed on the grid through the use of dispatchable generation (i.e., generation technologies that can be turned up, down, on, and off to match the load). Increasing penetration of variable renewable generation raises technical and economic challenges in terms of electric grid integration and stability due to the increasing variability and uncertainty in net load (Hamsic et al. 2007 and Hittinger et al. 2010). In general, up to approximately 20% penetrations of variable renewable generation can be accommodated through the use of operating reserves and other ancillary services (Cherry et al. 2012 and Panwar et al. 2015). Beyond a 20% penetration level, additional flexible generation or other methods are required to manage the variability (see options described in Cochran et al. 2014 and NERC 2010). N-R HES are able to provide dispatchable energy resources to meet the needs of electric grid balancing regions by rapidly increasing or decreasing electricity outputs. Other potential solutions include making residential/commercial and industrial loads more responsive, and adding compensatory energy storage to the system.

Dispatchable generation is typically provided by low capital cost facilities, such as simple-cycle gas turbines. These resources only operate at intermediate and/or high levels of net demand; as a result, they do not generate revenue many hours during the year. They can be expensive to operate and require high energy and ancillary service prices to remain financially viable (Bragg-Sitton et al. 2014). These systems may also be limited by certain technical constraints, such as maximum turndown and ramp rates. There are limited zero-carbon or low-carbon options available for this type of flexible generation.

Flexible operation of electricity-only baseload generators (e.g., nuclear power and fossil fuel-fired combined cycle power plants) is technically achievable and is currently conducted in certain regions.

However, this operational mode can result in reduced capital deployment efficiencies, increased operation and maintenance costs, and potentially shortened plant life. The potential impact of load-following (flexible) operation on the operational lifetime of a nuclear plant and reliability of the nuclear fuel requires additional study, particularly for transients on the minute to hourly scale that result from significant penetration of variable generators. Limited flexible operation experience exists for nuclear plants. Flexible operation in France, Spain, and some regions in Canada, for example, requires preplanned power reductions on a seasonal and weekly basis, resulting from a large fraction of the generating capacity being met by traditional baseload generators (i.e., large nuclear capacity in the balancing region). The increased ramping needs and reserve response due to uncertainty in predictions of variable generation may not be achievable with load-following baseload generators.

N-R HES can provide flexibility through integration with industrial applications that provide energy management options via responsive load. In many cases these responsive loads can respond to changing net load more rapidly than generators. Grid-scale energy storage can also provide added flexibility to grid balancing areas, although the available options are currently limited. N-R HES can incorporate smaller-scale energy storage within the system boundary to provide an additional energy management option, and chemicals produced via the coupled industrial process (e.g., hydrogen) offer versatile storage options that can supplement electricity generation or can be sold as a commodity. Additional details on grid flexibility options are included in Appendix A.

3.2 Provide Synchronous Electromechanical Grid Inertia

Traditionally, power system operation is based on the assumption that electricity generation involves rotating synchronous generators. These generators add rotational inertia via their stored kinetic energy, which is an important property of frequency dynamics and stability (Ulbig et al. 2013). Due to electromechanical coupling, a generator's rotating mass provides kinetic energy to the grid (or absorbs it from the grid) during frequency deviations. The grid frequency is directly coupled to the rotational speed of a synchronous generator and thus to the active power balance (i.e., the total power feed-in minus the total load consumption). This has implications for frequency dynamics and power system stability and operation. Frequency dynamics are faster in power systems with low rotational inertia, making frequency control and power system operation more challenging; in the worst case, these dynamics can end in fault cascades and blackouts.

Inverter-connected generation sources, such as wind turbines and solar PV, do not provide rotational inertia. The traditional assumption that grid inertia is sufficiently high with only small variations over time is not valid for power systems with high penetration of renewables. These challenges could arguably be mitigated by the inclusion of sources that provide virtual inertia (Denholm and Hand 2011); this solution is being investigated external to the N-R HES program. See, for example, Winter et al. (2015).

N-R HES integrate a nuclear power plant that provides the large rotational inertia with renewable energy sources that do not provide any rotational inertia. As energy conversion subsystems are internally coupled and share the same interconnection within the given N-R HES configurations, they are integrated "behind" the electrical transmission bus. Thus, such systems are able to provide high levels of rotational inertia in a power system.

3.3 Reduce the Carbon Footprint of the Industrial Sector

To significantly impact GHG emissions, the carbon footprint of non-electric energy sectors (industry, commercial, residential, and transportation) must also be reduced for the U.S. to meet long-term emission goals (Bragg-Sitton and Boardman 2015). N-R HES can reduce industrial GHG emissions by providing carbon-free thermal and chemical energy that is transferred to the transportation, industry, and residential/commercial energy sectors. In particular, the industrial sector is the third-highest emitting sector after electricity and transportation. It accounts for 18% of the total GHG emissions in the U.S. (Egilmez et al. 2013). N-R HES could significantly reduce GHG emissions and other harmful air emissions from the industrial sectors (both heat and electricity users), while meeting industrial energy demands. This is achieved by transferring steam or high-temperature heat generated from a nuclear plant at times of low electricity prices to the industrial subsystem, reducing or eliminating its need to combust fossil resources and thereby reducing emissions. Table 1 in Section 2.3 provides an overview of industrial energy users in the U.S. – many of which can be serviced with nuclear energy. Candidate industrial applications vary by region and will depend on several factors such as the form of energy required, the scale (or quantity) of energy used, and the required timing for energy supply. The geographical location of the industrial process depends on required heat quality, heat losses to the environment along the heat delivery system, and the required exclusion zone around the nuclear plant. Industrial uses will also depend on the availability of resources by region and concentration of industrial manufacturing centers.

In addition, nuclear-fossil liquid-fuels production can promote better usage of carbon resources, such as coal and natural gas, while reducing GHG environmental impact through conversion of these resources to higher value products, rather than combusting them directly to produce industrial process heat. One example begins with the use of nuclear power to produce hydrogen (and oxygen) by the steam electrolysis of water (McKellar et al. 2009). The hydrogen can be used in the conversion of coal to a synthetic vehicle fuel. By using external nuclear power rather than the feed coal to generate hydrogen, the percentage of the feed coal carbon that ends up in the synfuel increases from approximately 30 to 96% (Cherry et al. 2012).

A recent Idaho National Laboratory (INL) study considered an N-R HES configuration that integrates a small modular nuclear reactor and a wind farm as energy generation sources in West Texas (Garcia et al. 2015). In this case, thermochemical cycles refine natural gas into synfuels (gasoline and diesel) through a series of chemical reactions (including steam methane reforming, a primary means of producing hydrogen) by utilizing nuclear-generated heat. For the N-R HES configuration studied, which includes 600 MWt (180 MWe) nuclear generation and 45 MWe wind generation, an annual reduction of 1.4 million metric tons of CO_2 emission is achieved by using a nuclear reactor as the baseload unit relative to using a natural gas-fired baseload unit.

3.4 Levelize and Reduce Energy Costs

Many renewable generation technologies (wind, solar, and geothermal) and nuclear generation are low-marginal cost generators. In other words, these units cost much less to operate than the competition. However, their primary costs are the capital investment required to build each type. Due to their low-marginal costs, they will operate and sell power as often as possible even when the market price is low or near zero. Dispatchable, low-marginal cost baseload generators will recover their capital costs only when peak demand requires the intervention of dispatchable sources. When dispatchable units are used, the whole supplier stack is paid at their marginal production cost, providing an opportunity to recover capital cost to the baseload suppliers. Moreover, nuclear power plants, which have long ramp up/down time, are forced to sell even at negative prices to be ready to supply electricity during peak demand periods in the near future during which electricity will sell at a high price. The times during which generators are forced to sell at a loss become more frequent with the increasing presence of nondispatchable, variable renewable generators (e.g., wind and solar PV) because their generation is coincidental (i.e., most of each type of generator in a region will generate during the same time periods, thus producing a large fraction of the power during those periods). Reductions in selling price due to increased penetration of the low-marginal cost technologies, resulting in over-supply at some times, will lead to reduced income over the life of the equipment, thus reducing the profit on the capital investment for each installation. Ultimately, the income projected for new units will be too low to justify further investment so the generation capacity will not be built (Mills and Wiser 2012).

N-R HES, when coupled with a dedicated industrial customer, can mitigate the impact of these market conditions. When the electricity market bears a price favorable (i.e., profitable) to the power generators, some fraction (potentially 100%) of the power is sold to the grid. When the electricity market bears an unfavorable price, some fraction (potentially 100%) of the power is redirected to the industrial process. The actual fractions and forms of the power (thermal or electrical) are a function of the N-R HES itself. Thus, the industrial process sets the price floor for the thermal or electrical power, thereby limiting the impacts of price suppression.

3.5 Reduce Impact on Water Resources

In the U.S., the power sector is heavily dependent on water resources, withdrawing more water than any other sector (Macknick et al. 2011). The U.S. Geological Survey estimated (on a national level) that 41% of all freshwater (surface and groundwater) withdrawals in the U.S. in 2005 were for thermoelectric power operations, primarily for cooling needs (Kenny et al. 2009). N-R HES may reduce energy sector impacts on water resources by reducing overall water consumption, as a result of decreased heat rejection needs, and by producing potable water. Excess thermal and electrical energy can be used to treat industry and agricultural waste water, to desalinate or remove excess nutrients from rivers and geologically produced brackish waters, and to enhance geothermal energy systems, among others. Hybrid energy systems also may provide alternative heat transfer systems that reduce industry steam duties with either high-temperature nuclear reactors, or when renewable electricity is converted to thermal energy.

Nuclear power plants employ cooling system technologies, typically wet cooling technologies (once-through and evaporative cooling towers), to reject waste heat to the atmosphere through the cooling of a water stream to a lower temperature. Non-thermal renewable energy technologies, such as wind and solar PV, do not require such cooling systems. Thus, integration of nuclear and non-thermal renewable technologies supports the reduced operational water[3] consumption and withdrawals per unit of electric generation. Operational water requirements per unit of thermal generation in N-R HES could also be reduced, when applicable, through other productive utilizations of low-temperature heat, such as district heating or evaporative (multi-stage flash and multi-effect) desalination. Freshwater use impacts can be diminished by utilizing dry cooling[4] (air-cooled condensing) or by using non-freshwater sources[5] as a cooling medium for use in N-R HES that integrate the concentrating solar thermal technologies. One may note that these benefits are not unique to N-R HES versus other future energy system scenarios that would also provide decreased GHG emissions (e.g., large-scale build-out of variable renewable generation). However, N-R HES present a benefit with regard to water use relative to the current state of technology while also allowing the benefits presented in Sections 3.1 to 3.4 to be realized.

Freshwater resources can be increased, during times of excess power production, through electrically driven desalination (e.g., RO of seawater or brackish water). For example, the results of the study by Kim and Garcia (2015) showed that the nuclear-solar PV HES option in that was studied for northeast Arizona, which includes 600 MWt (180 MWe) nuclear generation and 30 MWe solar PV generation, could supply 60.6 billion gallons of fresh water per year, meeting about 88% of the current total water consumption in Phoenix and Tucson, Arizona (68.7 billion gallons per year). A present day example of the application of nuclear-powered RO desalination is the Diablo Canyon nuclear power plant (a two-unit 1,150 MW_e plant) in San Luis Obispo County, California (Sneed 2015). This plant has an onsite RO desalination facility that it uses to generate fresh water from seawater, both to cool the plant and for employees' drinking water needs. However, the RO desalination plant currently only uses about 40% of the facility's full capacity; operation at full capacity could make up to 0.825 million gallons of fresh water available to South County residents each day. It is expected that, with some expansion, the facility could supply 1.65 million gallons of fresh water. These upgrades could be accomplished as soon as late 2016 under a plan that was recently granted preliminary approval by the county supervisors.

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3 Operational water use in the power sector includes cleaning, cooling, and other process-related needs that occur during electricity generation.

4 Dry cooling may have cost and performance penalties.

5 These alternatives could be limited by locally available resources.

3.6 Benefits Estimation for Policy Development

A number of expected outcomes and benefits of N-R HES are detailed in Sections 3.1 to 3.5. This section describes the program element that will quantify those benefits. DOE and other entities need benefits estimates to justify program funding, to compare programs for prioritization purposes, and to support claims regarding the benefits of the program.

Benefit Evaluation Requirements

The key goal of the benefits estimation activity is to provide concrete estimates to DOE, other federal agencies, states, and regional entities. The required quantitative benefits of implementing a specific technology solution, such as N-R HES, are dependent upon the policy questions and needs; thus, these desired values cannot be fully defined at this time. Key policy questions are expected to include:

- Ability of an N-R HES to provide dispatchable energy at a specific location on the grid, and its potential impact on economic carrying capacity for variable generation
- Expected impacts on a region's GHG and other emissions due to installation of N-R HES
- Expected impacts on requirements for spinning electricity-only generators to provide inertia
- Expected impacts on price suppression within a region
- Expected impacts on a region's water resource due to installation of N-R HES.

Other policy questions will be identified as the program evolves.

Current State of Development and Development Needs

Many tools exist to perform the analysis necessary for this effort. Production cost models such as PLEXOS (California ISO 2010), GridView (Feng et al. 2002), and GE MAPS (GE Energy 2010) will be used to chronologically simulate security-constrained unit commitment and economic dispatch of generators to the grid, where security-constrained refers to the ability of the energy systems connected to the grid to meet grid reliability requirements. Electricity sector capacity expansion models include ReEDS (Short et al. 2011) and SWITCH (Wei et al. 2012). Various life-cycle assessment tools are available for this application, such as GREET (Argonne National Laboratory 2012). It is expected that the estimation of benefits as described here will be accomplished using the currently available tools.

Development Effort

Operational impacts on electricity generators can be analyzed using a tool such as PLEXOS. Results from PLEXOS simulations capture all the costs of operating a fleet of generators and will be used to estimate impacts on price volatility and minimum prices. Dynamic power flow simulation tools will be used to estimate the need for and benefits of real inertia provided by turbines.

Electricity sector capacity expansion and energy sector evolution models, such as ReEDs, will be used to estimate potential build-out rates of N-R HES and the associated impacts on national emissions, energy use, and the economy. Various scenarios will be developed, and results from those studies can be used for policy development. Parameters that can be adjusted in the studies include those that impact prices of natural resources such as oil, coal, and natural gas; carbon policies; and renewable portfolio standards.

Model results will be used in life-cycle assessments to estimate overall impacts on national GHG emissions and other emissions for the N-R HES configurations identified using the processes described in Sections 5.1 and 5.2. The assessment tool has not been selected, but a likely candidate is GREET. Other environmental aspects will be considered on a case-by-case basis. For example, impacts of water use and generation will be analyzed for N-R HES configurations under consideration in areas with high amounts of water stress.

4. PHASED TECHNOLOGY DEVELOPMENT PROCESS

Technology Readiness Level (TRL) scales are used to quantitatively assess the maturity of a given technology. TRL assessments help inform programmatic decisions concerning technology advancement, technology down-selection, task planning, risk analyses, task prioritization, and allocation of resources. The TRL concept will be applied to N-R HES as a tool to assess the maturation of these systems. TRL assessments referred to for the N-R HES correspond to the integrated system versus individual components or subsystem technologies. A simplified overview of the TRLs and the associated experimental testing scale is provided in Figure 6. See Appendix B for further details on TRL advancement. TRLs can be roughly grouped as follows:

TRL 1–3: Discover and Analyze (Basic Principles to Proof-of-Concept)

TRL 4–6: Build (Experiment-scale to Pilot-scale)

TRL 7–8: Demonstrate (Engineering-scale to Prototype)

TRL 9: Operational (Commercial Plant)

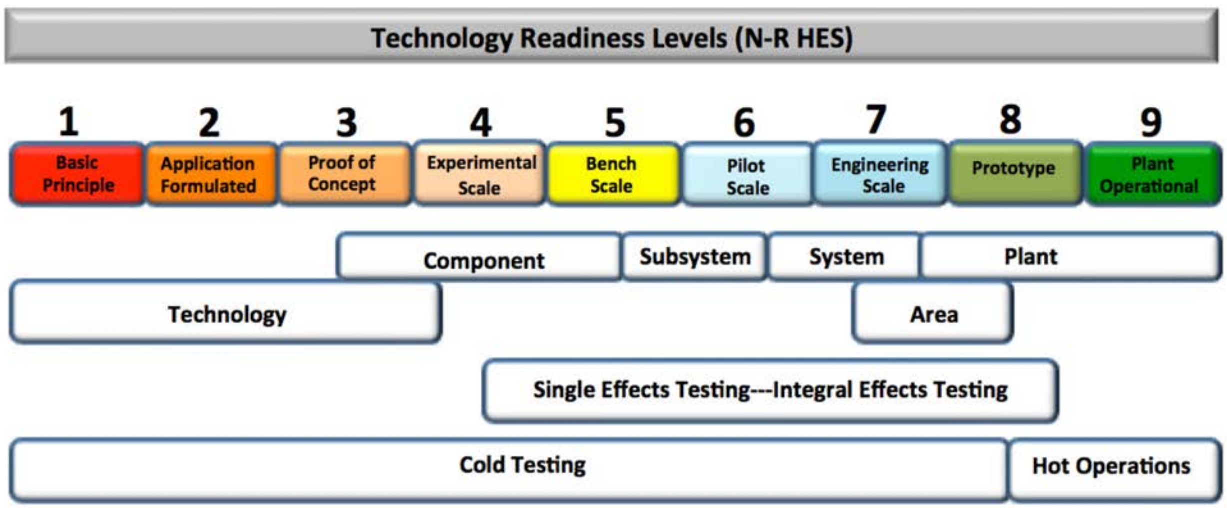


Figure 6. Simplified overview of TRLs (modified from Collins 2009).

This preliminary program plan outlines a technology development process that involves program planning and execution guidance relative to organizing the research team and execution of the necessary fundamental science, systems engineering, market analysis, and project execution to raise the TRL of N-R HES components and interface technologies. This program plan assumes that the DOE-led program will conduct analyses and hardware demonstrations to mature the N-R HES concept and one or more specific N-R HES configurations through TRL 6. Industry partnership will be established during the early development phases to ensure research relevance and to more easily transition to an industry-led project for development beyond TRL 6. Maturation of the N-R HES to TRL 7, which would include a system prototype demonstration in an operational environment (a nuclear-fueled system), will require industry leadership and funding (possibly jointly funded by DOE and industry). Figure 7 and Figure 8 illustrate the planned development and evaluation approach, which will be used throughout program execution. Figure 9 provides an initial overview of the dynamic analysis approach that will be discussed further in Sections 5.1 and 5.2. The overall development approach divides the technology maturation into four phases, which can be assigned to specific TRLs using Table B-1 in Appendix B.

DOE Leadership:

Phase I: Preferred Architecture Research and Development

Phase II: Component and Subsystem Testing, Architecture Refinement and Integrated System Demonstration

Industrial Leadership or Joint Investment:

Phase III: Detailed Prototype Engineering Design

Phase IV: Prototype Construction and Testing

It is anticipated that the first two development phases will be conducted via DOE leadership, in coordination and collaboration with university and industry partners (see Section 6.1), whereas the last two phases are expected to transition leadership to industry partners. The preliminary timeline associated with this phased development is provided in Figure 10. This timeline will be updated following identification of prioritized options and identification of all key technology gaps associated with those configurations at the end of Phase I.

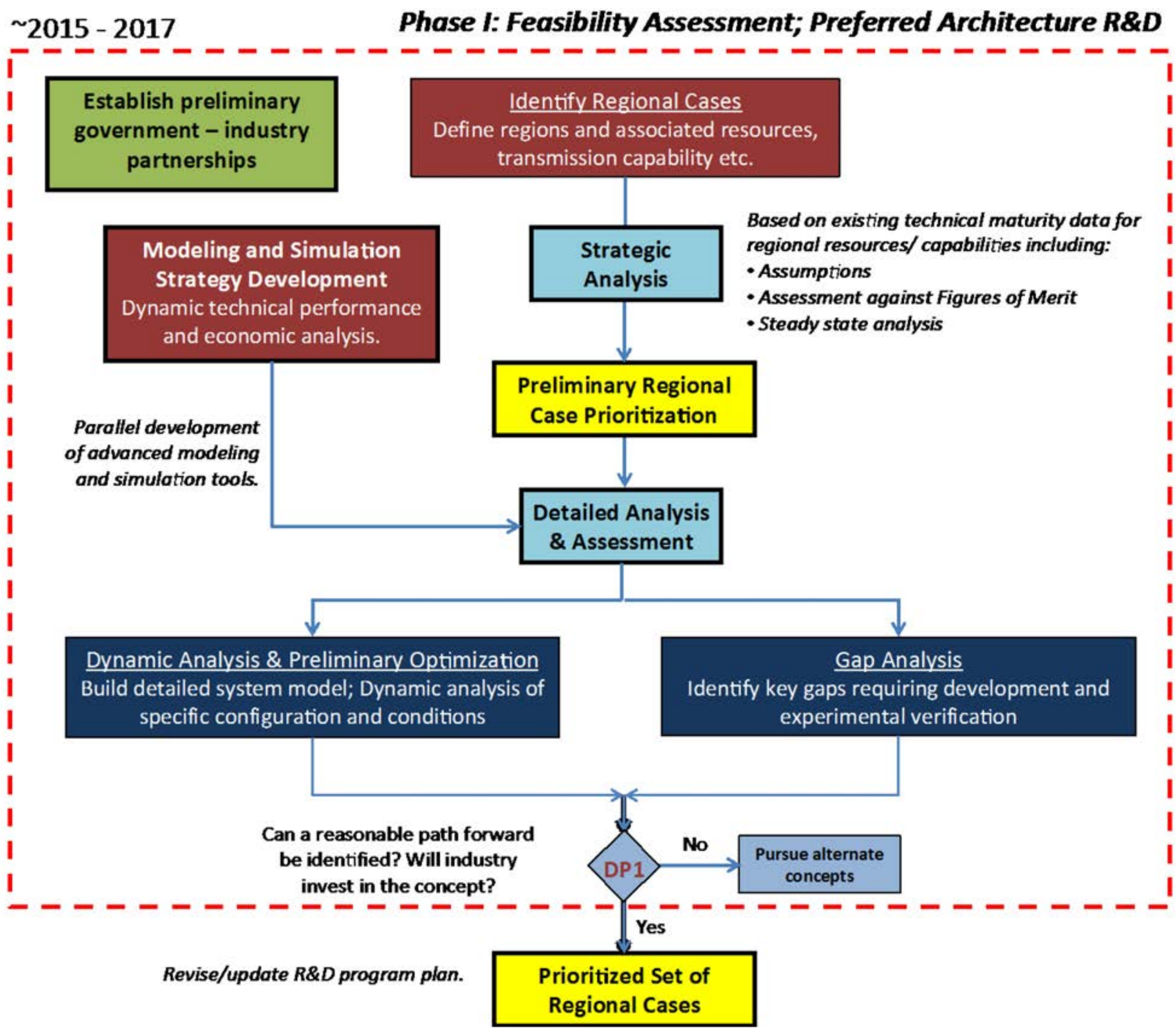
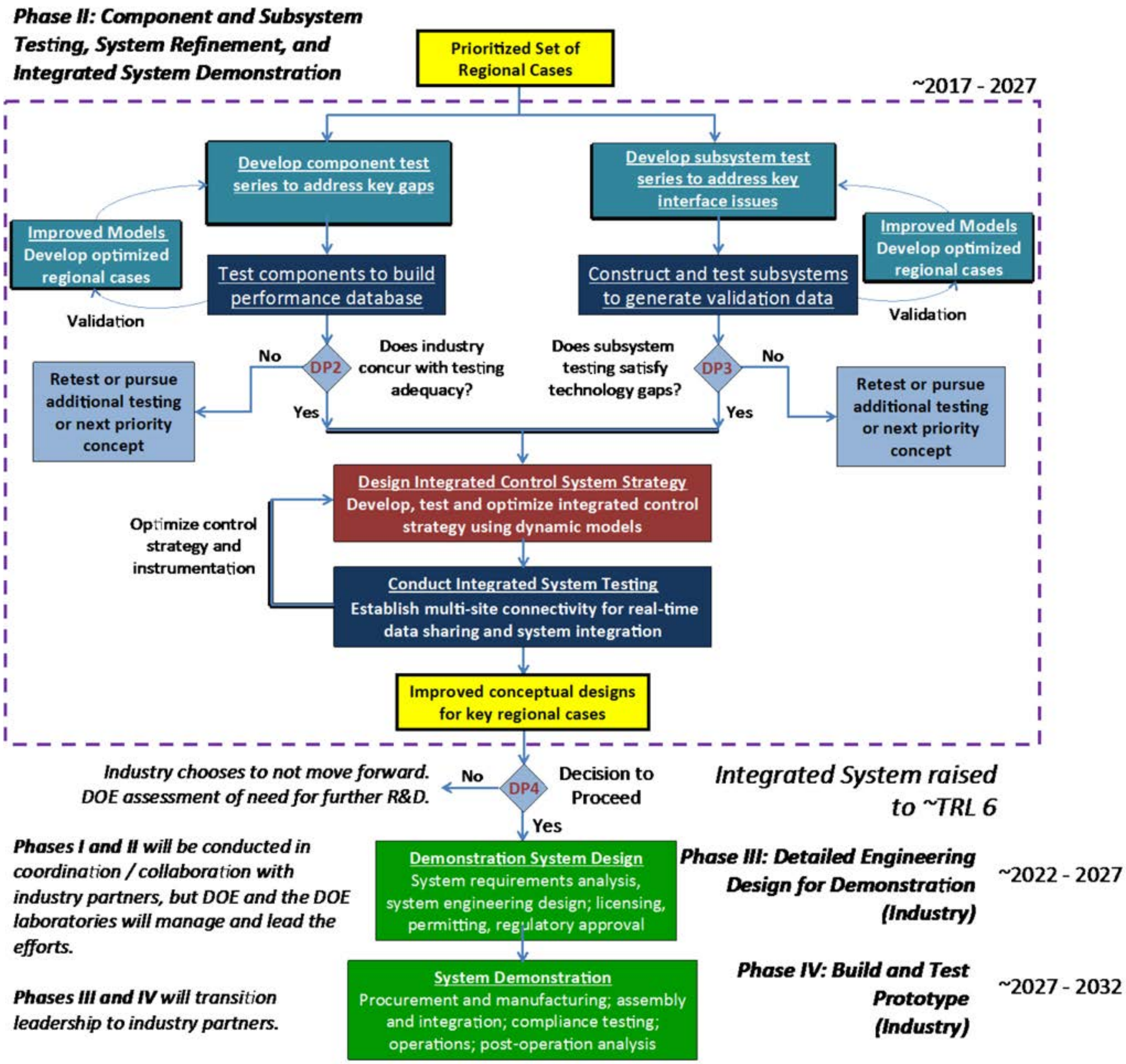


Figure 7. Illustration of the Phase I development and evaluation approach for integrated N-R HES.



Note: The estimated timeline suggests a possible 2022 start of demonstration system design, with system refinement and nonnuclear, scaled system testing continuing throughout the design process. This Phase II research will assist in defining system requirements, etc. for the demonstration system design. The estimated timeline is consistent with the target dates for SMR prototype deployment external to this program. An integrated HES platform could be a follow-on to an initial SMR prototype. The process to license a demonstration facility could take on the order of 5 years. Parallel completion of Phase II and initiation of Phase III are intentional in this work flow.

Figure 8. Illustration of the Phase I development and evaluation approach for integrated N-R HES.

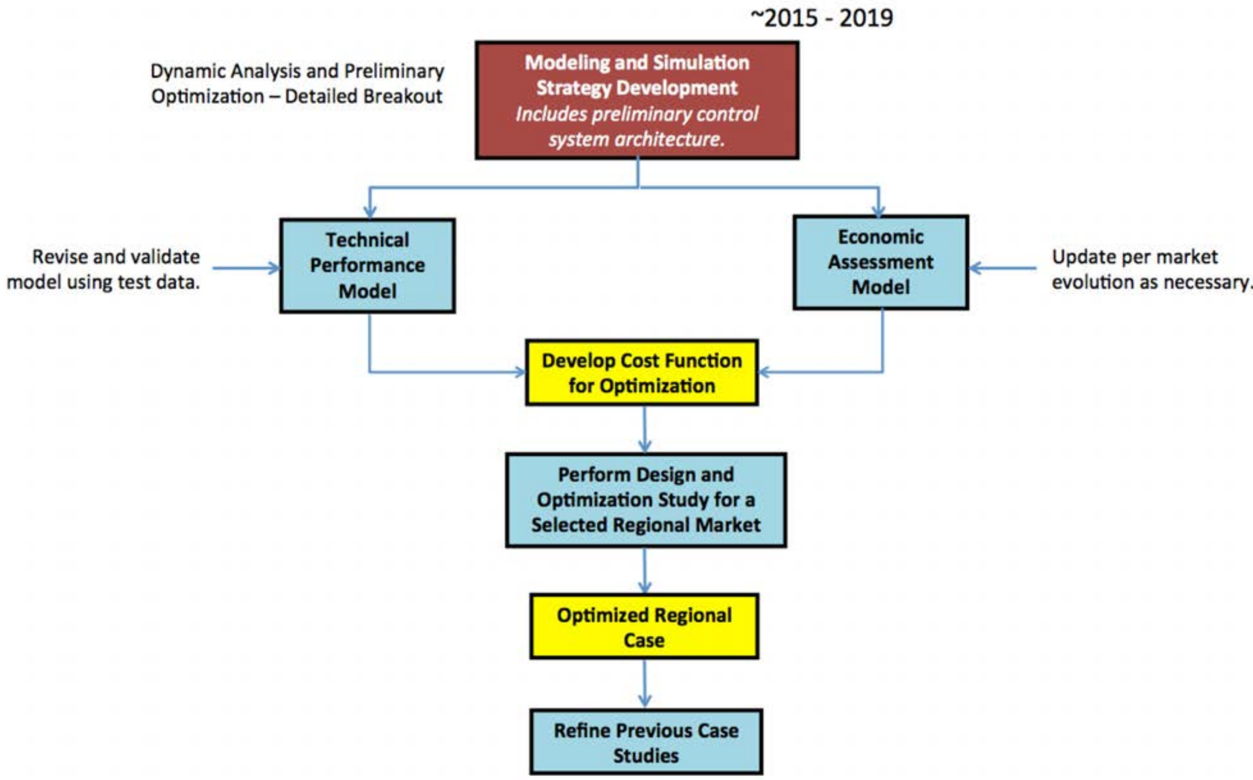


Figure 9. Dynamic analysis and preliminary optimization efforts that span Phase I and II development.

4.1 Phase I: Preferred Architecture R&D

Phase I (depicted in block diagram format in Figure 7) begins with identification of a number of regional opportunities for integrated energy systems, drawing on various data regarding energy supply resources and load, which could provide economic and operational benefits. The strategic analysis approach associated with Phase I is discussed further in Section 5.1. Metrics definition, system architecture selection and system refinement is performed by national laboratory researchers with additional support and guidance provided by DOE, university partners, and industry. Regional energy resources and their interactions will provide the basis for defining a set of regional cases for feasibility analysis. Feasibility analyses consider the current technical maturity of required technologies (components, subsystems), an assessment of the integrated system concept against FOMs defined early in Phase I (see metrics definition in Section 5.1.1), and steady-state operability of the coupled system. The N-R HES designs will be prioritized based on these evaluations, and those showing the most promise will be selected for detailed analysis and assessment (see Section 5.1). Detailed assessment will consist of:

- A dynamic analysis and optimization that includes a detailed system model to determine technical, operational, and economic viability
- A gap analysis that identifies technical, policy, and programmatic issues requiring development and experimental verification.

Note that the details of the advanced modeling and simulation dynamic analysis and preliminary optimization efforts that span Phase I and II development are shown in Figure 9.

Go/No-Go Decision Point 1

Based on the strategic analysis and preliminary dynamic analysis, the viability of the specific N-R HES architecture configuration will be assessed and potential industrial support verified at what is shown as Decision Point 1 (DP1). DP1 is a Go/No-Go decision point on the technology under consideration. Assessment of this decision point is based on the following questions, using the FOMs that will be defined (see Section 5.1) to determine how well the technology may be able to meet the defined criteria with further investment:

- Decision Point 1 (DP1). *Can a reasonable path forward be identified for the selected N-R HES configuration?*
- Decision Point 1 (DP1). *Is there good potential for industry investment in the concept based on the performance characterization to date?*

Some N-R HES concepts may be eliminated at this point, while others may be modified or refined to obtain a prioritized set of regional cases that will be investigated in Phase II. Should findings of the dynamic analyses indicate that N-R HES are, in general, not viable for either technical or economic reasons, and no modifications of the analyzed configurations are evident that could modify this result, the overall N-R HES concept could be abandoned at this time. Other solutions capable of providing the benefits identified in Section 3 should be further investigated.

4.2 Phase II: Component and Subsystem Testing, Architecture Refinement and Integrated System Demonstration

Activities in Phase II (depicted in Figure 8) will further refine and optimize the selected regional cases through high-fidelity modeling and simulation (see Section 5.2) and a series of component and subsystem tests to provide model validation data, address the technical gaps, and mature the concept for commercial viability (see Section 5.3). To prepare the refined concept for integrated system testing and detailed prototype design, further high-fidelity simulation and analysis is necessary, including design optimization for enhanced operational resilience; integrated control system design, optimization and dynamic simulation; and conceptual design development. Early work in Phase II includes design and assembly of the general test facility infrastructure that will support testing of any of the selected hybrid architecture configurations.

Go/No-Go Decision Points 2, 3

Test design for components and subsystems will involve industry representatives to verify concurrence with testing adequacy and ensure that test data will satisfy the identified technology gaps to mature N-R HES through the defined TRLs. Development and execution of experimental work for components and subsystems, and the use of the data collected for model validation, will include two decision points, as shown in Figure 10:

- Decision Point 2 (DP2). *Do the high-fidelity simulation results support further development of the selected N-R HES architecture?*
- Decision Point 2 (DP2). *Does industry concur with component testing adequacy?*
- Decision Point 3 (DP3). *Does subsystem testing satisfy technology gaps?*

If at either point testing is determined to be inadequate or demonstrates that the technology tested cannot be successfully used in the planned N-R HES configuration, or if the detailed analyses do not support further development, then the component or subsystem should be modified or redesigned, or the integrated system configuration should be abandoned to investigate the performance of the next priority configuration identified.

Advancement through component and subsystem testing, as will be discussed in Section 5.3, and the corresponding model improvement and validation steps, will allow for design of the pilot-scale integrated system test and design of the detailed control logic using the refined integrated system analysis tool. The integrated system test will be performed at pilot-scale and will utilize nonnuclear, electrically heated components to simulate the heat that would be provided by the nuclear reactor(s). Initial testing of the integrated system will exercise the defined control strategy and installed instrumentation in a nonnuclear test environment to maximize safety as the integrated system is tested to determine response characteristics and possible failure points. Pilot-scale testing could involve real-time data integration of geographically dispersed laboratories located across the DOE complex, or at partner university or industry facilities.

Go/No-Go Decision Point 4

Completion of the pilot-scale integrated system testing will lead to a decision point to proceed to engineering design of the prototype system. At this point, the program would transition to industry leadership with reduced DOE involvement, or to joint investment by industry and DOE.

- Decision Point 4 (DP4). *Has the selected N-R HES configuration been demonstrated sufficiently to proceed to engineering design of a nuclear prototype under industry leadership?*

DP4 indicates a transition from DOE leadership to industry leadership, although it is anticipated that DOE would continue as a partner, with continued investment possible, in the further development of N-R HES. This decision point could lead to a prototype, or industry could choose to abandon the N-R HES concept. If the latter occurs, DOE must decide if any further R&D is warranted.

4.3 Phases III and IV: Prototype Engineering Design, Construction and Testing

It is anticipated that the final R&D phases will be performed under industry leadership to develop a detailed prototype design (Phase III) and to construct and test the prototype (Phase IV). Hence, these phases of development are not addressed further as they are outside of the scope of this program plan. Phase III activities will include development of an engineering design for a prototype facility, site selection, permitting, licensing, etc. Site selection and approval can take a number of years to accomplish, but these steps can be initiated prior to final design selection through collaboration with industry partners. Hence, this phase could begin in parallel with later Phase II testing of the integrated nonnuclear system under the leadership of the industry partner(s). This parallel approach is illustrated in Figure 8, which shows Phase III beginning in approximately 2022, while Phase II continues through 2027.

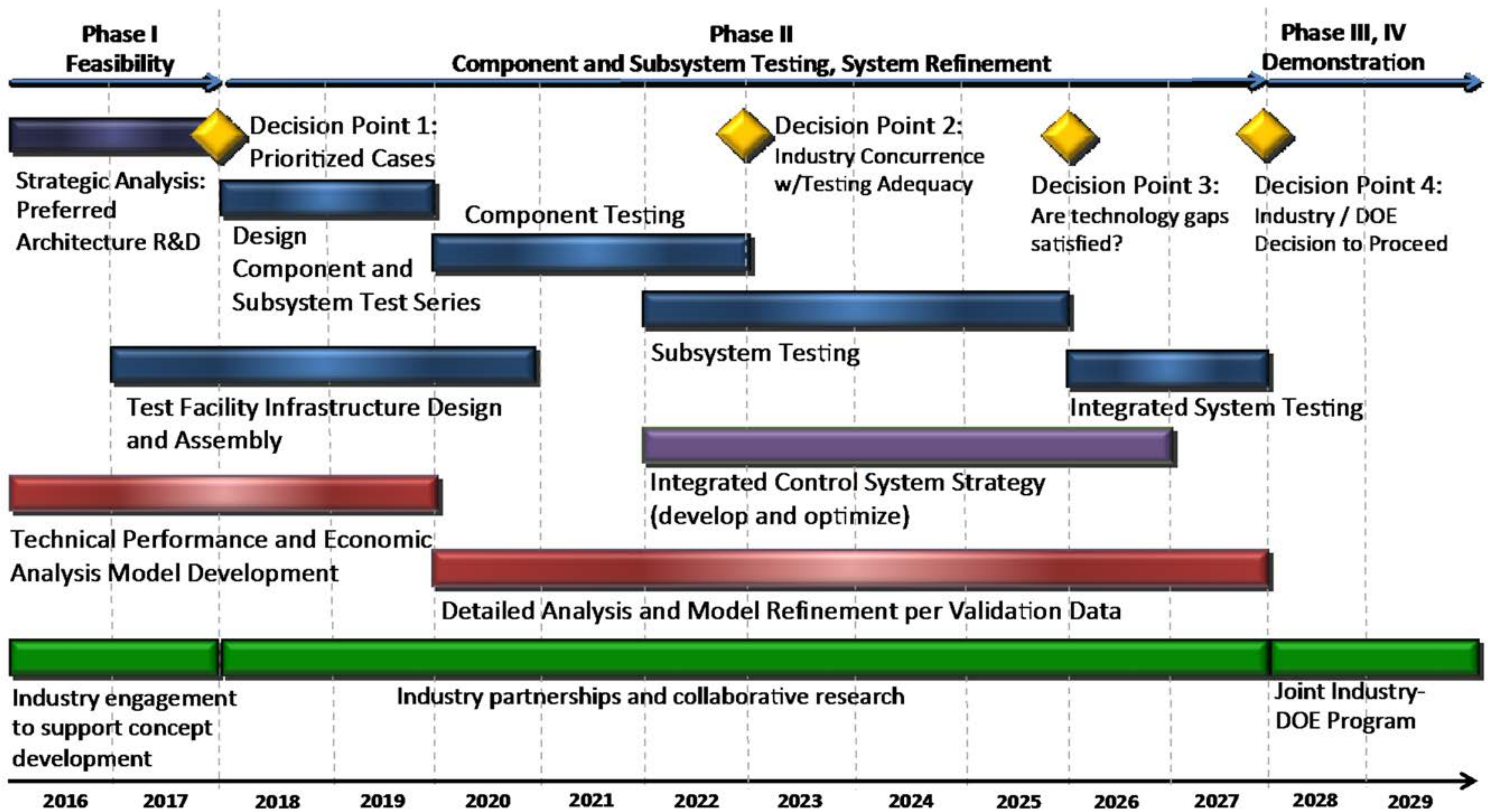


Figure 10. High-level timeline for N-R HES R&D activities.

5. PROGRAM EXECUTION

The driving factors motivating development of a novel energy system were discussed in Section 2, and the anticipated benefits of coordinated operation of nuclear and renewable technologies in concert with industrial processes were discussed in Section 3. Strategic analysis of N-R HES architectures must begin with clear definition of a set of metrics, or FOMs, by which the performance of candidate architectures can be rated and prioritized. Following definition of these metrics, feasible system architecture options must be identified and evaluated relative to those metrics.

As described in Sections 5.1 and 5.2, analysis activities will employ many existing tools, but will also necessitate the development of new tools, to evaluate dynamic behaviors of integrated energy systems and their interaction with the evolving grid. The new tools may involve integration of various existing models to provide a framework that simulates transport and transmission systems for tightly coupled energy generation sources, and energy conversion into products and services. More sophisticated, high-fidelity models will be needed especially to evaluate operation of the nuclear and ancillary thermal energy transfer systems, develop methods for real-time embedded diagnostics/prognostics control schema, support front-end engineering and design, and demonstrate that integration of nuclear reactors in a hybrid configuration will not compromise core damage frequency or other safety basis in the plant operating license.

Hardware and system process control development and testing needs will be identified throughout the analysis process, with the primary purposes of experimental work being to develop an improved understanding of specific technologies, provide validation data for the various models used in the integrated system analysis, and demonstrate safe operation of a tightly coupled, integrated system. Anticipated testing needs for components, subsystems, and interconnections are identified in Section 5.3; these testing needs will be updated as analyses progress and N-R HES configurations are refined. The program will also monitor evolving and emerging technologies that could support HES operation; these emerging technologies will be incorporated in the models and in the testing program where appropriate. This program plan will be updated upon completion of Phase I and periodically thereafter.

5.1 Strategic Analysis: Metrics Definition, Options Identification, and Prioritization

A key aspect to any R&D project is a strategic analysis effort that formalizes the process of identifying and prioritizing options. The strategic analysis for N-R HES is described here as a continuous screening process, where the fidelity of the simulation is increased at each step while the number of possible configurations that are capable of meeting the established metrics is decreased. It is important to note that this process is performed at the onset of the program and will be repeated periodically as system models are refined via R&D activities and higher fidelity simulations become possible. Figure 11 illustrates a single screening step. At each subsequent screening step the number of possible configurations to be evaluated decreases, but the increased fidelity of the simulation in the subsequent step causes it to be more expensive in terms of computational cost and human resources. At each step (beginning with the left box in Figure 11):

1. A model of the N-R HES is built with a specific level of fidelity (higher than the one used in the previous screening step) for each possible configuration variant (e.g., different industrial heat users, different subsystem sizes, etc.)
2. The model is used to perform optimization for each possible configuration
3. The optimized set of possible configurations are ranked with respect to the absolute value of the evaluated FOMs and the possible performance improvements as a function of additional R&D investment necessary (e.g., sensitivity analysis is performed to determine parameters that will have the most significant impact on system performance)

4. R&D activities are performed to improve the performance of the selected configurations guided by the sensitivity analysis
5. Process repeats at Step 1.

The model applied in a screening test should be selected such that at each step the ratio of rejected configurations to the cost of the test is maximized. In this manner the overall cost of the selection is minimized since increasingly fewer configurations are examined at each iteration with increasingly more expensive tests being conducted. The cost of the test is usually proportional to the level of fidelity at which the real system is represented in the test (ranging from simple global mathematical models, to a dynamic system model, to validated safety codes, and, finally, to hardware-in-the-loop).

The implementation of such a process requires metrics definition, definition of the configuration space, and identification of different testing levels characterized by resource cost and an estimation of the screening capability of each test. At each screening step R&D needs will be identified. These needs could include a collection of more detailed system component costs, data for detailed model validation, experimental testing of components, etc. These refined R&D pathways will be documented and provided as updates to this program plan.

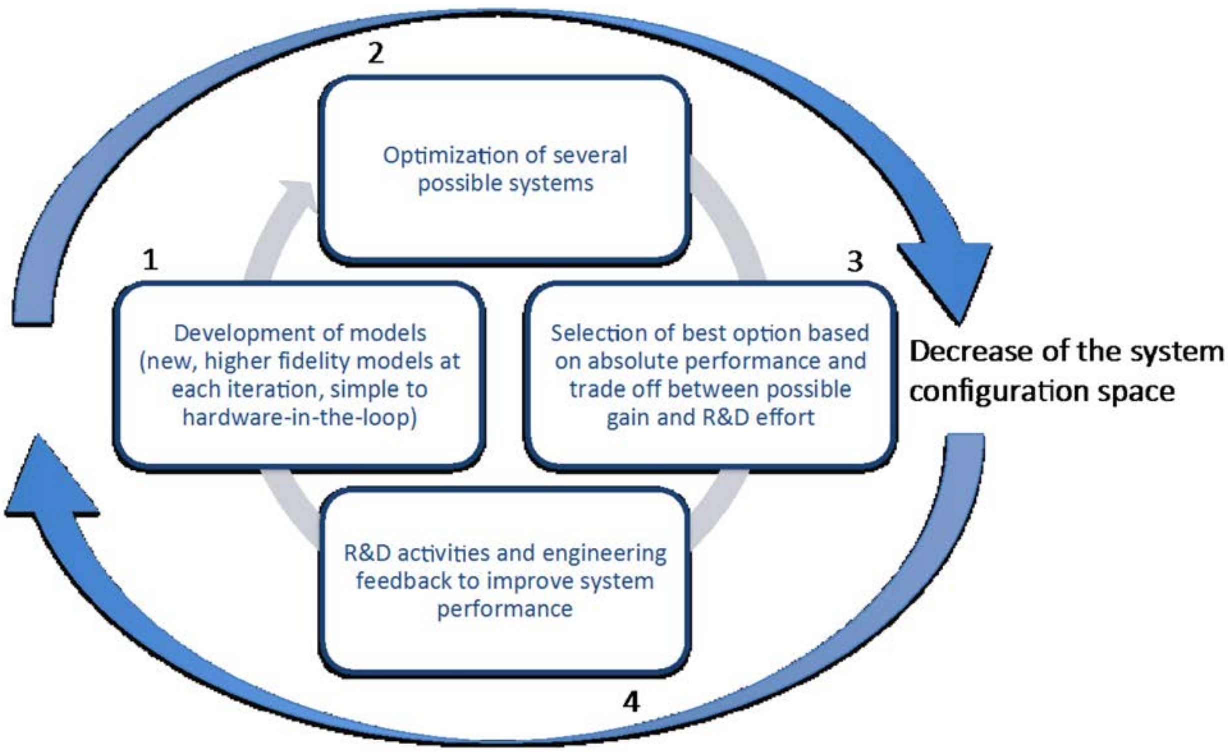


Figure 11. Screening process selection/prioritization schema.

5.1.1 Strategic Analysis Task 1: Metrics Definition

Metrics definition is the first step in defining a selection process (this will be referred to as Strategic Analysis Task 1, or SA1). It is important to note that some metrics are "hard," having associated numerical values with a relatively low range of uncertainty, while others are "soft," making them more challenging to quantify. As a result, the selection process cannot be completely automated. Screening will require human input to assess the performance of candidate system architectures with respect to the "soft" metrics. Other metrics may be highly impacted by the level of accuracy of the simulation used to assess the metric. A classic example is ease of licensing for a selected system; while licensing may have a large impact on cost, the licensing process and associated challenges can be difficult to assess with low fidelity modeling. Minimization of electricity production cost will be used in the early stages of the architecture selection process performed with lower fidelity simulations. The process of metrics definition and evaluation can be considered an "aided engineering selection" due to the combination of the described types of metrics.

Four general types of metrics will be evaluated using existing tools and tools that will be developed within this project: technoeconomic, environmental, design, and resilience.

Technoeconomic Metrics

Defining technoeconomic metrics involves the technical performance of the system, the project's financial aspects, and economic impacts on the region. The fundamental system metric will be the cost of electricity production for a prototypical electricity and heat demand (constrained by the grid requirement to cover the load). This type of analysis could be used to assess the impact of the overall cost of electricity from large-scale deployment of N-R HES.

As the N-R HES configurations are further developed to optimize technical performance (e.g., exergetic efficiency), metrics measuring the profitability of the N-R HES within different energy markets (specialized demand profile, electricity market, and heat market) will be considered. The comparison of the two sets of metrics (cost of electricity production versus profitability) will expose how the local markets affect the achievability of the optimal electricity cost.

Environmental Metrics

Environmental metrics include estimates of air emissions including both GHGs and criteria pollutants (e.g., NOx, SOx, particulates). They also include water consumption, withdrawal, and impacts on fresh water availability that may be increased if the N-R HES includes a desalination subsystem. Results will be compared to alternative N-R HES configurations and to other technology options that can provide the same services.

Design Metrics

The ratio between expected performance improvement and R&D costs will be estimated before R&D activities are performed. Design metrics will be used to estimate the probability of successful development and operation of the N-R HES options. Impacts of alternative configurations and topologies will be considered in the analysis. Several types of criteria will be included:

1. Complexity and reliability of the system
2. TRL of the subsystems and the integrated system

   The TRL metric is based on the development stage, demonstrated scale, and integration. It will be tracked throughout the R&D process; the probability of achieving the next level will be assessed periodically. TRL definitions tailored to N-R HES are defined in Appendix B.

3. Safety

   This metric is focused on defining design basis accidents (the postulated accidents that the N-R HES or at least the nuclear subsystem must be built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety). Safety analysis will involve evaluation of the integrated system's response in the event of design basis accidents.

4. Licensing challenge

   The licensing challenge will be impacted by the type of N-R HES configuration selected (tightly coupled, thermally coupled, or loosely coupled). The boundary between the nuclear subsystem and the industrial process for the tightly and thermally coupled systems must be clearly defined, as this interconnection represents the most significant departure from traditional energy systems.

Note that some of the design metrics could be converted to economic metrics (e.g., reliability, safety), but this conversion is often subjective. Hence, it is important to analyze both the raw metrics and the monetized version of those metrics to identify priority options.

Resilience Metrics

The final metric associated with system architecture design focuses on resilience to changes in the external system, such as changes in resource availability, changes in the grid, and changes in the industrial product infrastructure.

Task 1 Outcome: Clearly defined set of metrics against which N-R HES architecture options will be evaluated; metrics evaluation will be performed at each step of the screening process.

5.1.2 Strategic Analysis Task 2: Definition of the Configuration Space

While the strategic analysis process is designed to prioritize and downselect configuration options, the smaller the initial option space is, the faster those options can be prioritized and reduced to the architectures having the highest probability of success. This task, which will be referred to as Strategic Analysis Task 2 (SA2), focuses on identifying the best locations for an N-R HES; analyzing the resources, market opportunities, and constraints in those locations; and identifying the systems' boundary conditions (i.e., the interactions with other systems in the balancing area).

Task 2(a): Identify Regional Opportunities

As suggested in (Rabiti et. al. 2015) the N-R HES will, most likely act as a "price taker" with respect to selling the industrial products produced by the N-R HES. Under such assumption, it is possible to perform a pre-screening of regional cases of interest. Practically, given local prices for industrial commodities and cost of the necessary feedstocks, it is possible to perform a prescreening of configuration options that would be valuable in different U.S. regions using the corresponding prototypical electricity net demand as input data. Since the deployment of an energy system is not a purely economic question, the screening potential of this step can be improved by a process that engages industry and regional stakeholders. Such a process will be developed to identify possible locations and opportunities for N-R HES. Key criteria for regional implementation of N-R HES include renewable resource availability; anticipated electricity load growth; projected grid needs, including resource adequacy and flexibility; industrial product markets and infrastructure; political support for nuclear generation; and many others.

Task 2(b): Resources and Markets

Market analysis will include a review of regional resource availability based on historical data and forecasts, a review of potential thermal and electrical energy customers and the types of contracts to which those customers are accustomed, and the regional power markets and transmission availability. In addition, other market opportunities will be considered, such as the possibility of co-management with other nearby resources that are not connected to the N-R HES. When optimal configurations have been identified via iterative analysis for a selected region, it will be useful to analyze the local possibility of commercialization. At this stage the local market will be taken into account in the analysis of the potential profitability of the N-R HES within the given region and market.

Task 2(c): Ownership Models

The final step of the profitability analysis will be to consider ownership models to establish profitability of the integrated system versus profitability of independent systems. These models include the business structures, such as ownership of the N-R HES by a single entity or ownership of each subsystem by a different entity with transactions between them (e.g., a consortium of owners acting as a single financial entity with respect to the grid). The latter option would require determination of profit sharing for each subsystem, but may not realize the maximum profit for the N-R HES in its totality.

Another consideration is how the products might be sold. For example, if one product is thermal energy and it is sold to a mix of customers outside of the N-R HES boundary, the sales methods are likely to involve both volumetric (the amount of thermal energy or exergy) and dynamic (timing and ramp rates) aspects. Allowable rates of change in energy flows may also need to be considered in managing exergy within and external to the system.

Task 2 Outcome: List of the most promising N-R HES options within specific U.S. regions, with a detailed set of information concerning prototypical demand, market structure, possible ownership structure, etc.

5.1.3 Strategic Analysis Task 3: Definition of Test Sequence

Strategic Analysis Task 3, or SA3, describes the process by which the continuous screening process is accomplished. As discussed, the process by which the final optimal design of an N-R HES for a selected region is determined is a multi-step process where the option space is reduced at each step. It is not possible to define *a priori* the level of modeling and simulation fidelity that will correspond to each screening step or how many steps will be necessary to define the final configuration(s), particularly recognizing that multiple configurations will be possible given the different geographical markets in which the N-R HES will be contextualized. However, engineering judgment can be used to identify broad characterizations of the level of simulation fidelity (ordered in increasing cost):

1. Steady state process models
2. Simple dynamic models (low frequency)
3. Complex dynamic models with real-time control system models (low frequency)
4. Safety impact evaluation with validated models
5. Complex dynamic models with real-time control system models (high frequency), possibly embedding hardware-in-the-loop

To maximize the effectiveness of this process, additional factors should be actively considered:

- Increase the complexity of the modeling and simulation should be always done to maximize the resulting reduction in the number of possible N-R HES configurations
- Coordinate the screening process with the R&D activities that provide the new boundaries and constraints for the next screening test
- Ensure the screening process provides information to guide the R&D process via sensitivity analysis on multiple parameters.

Task 3 Outcome: Definition of an optimal hierarchical screening process that minimizes resource consumption.

5.2 Systems Design, Analysis and Controls

Optimization of the N-R HES design and operation is focused on economic performance of an integrated system after first meeting the technical performance metrics identified via SA1 (Section 5.1.1). This integrated system must coordinate the production and distribution of heat and electricity among multiple subsystems. The system needs to be designed initially for such purpose, as an inherently attack-resilient, multi-agent control system will be needed to achieve a degree of coordination among subsystems to enable the desired benefits.

The modeling and simulation effort will focus on development of models and control systems for the N-R HES considering co-control for tightly coupled, thermally coupled, and loosely coupled systems. To encompass each of the described scenarios, the physical boundary for the simulation is defined by the grid control area/balancing area (currently in the U.S. and Canada, these control areas range from 38 MWe to 136 GWe). This boundary condition allows for definition of the net load, which is impacted by the generation mix outside of the N-R HES. This boundary also offers the opportunity to redesign the supplier mix within the balancing area to verify that coverage of the net load can be achieved at a lower cost using an optimized N-R HES than for the base case (independent systems). Models incorporated in the simulation that are outside of the N-R HES island will be lower fidelity, built to establish the proper context for the HES but not to model specific dynamic control logic outside of the N-R HES. Figure 12 illustrates the integration of the three strategic analysis tasks defined in Section 5.1 with the detailed dynamic simulation activities, where these steps begin with metrics definition (SA1) and market evaluation (one aspect of SA2). These steps may be iterated several times until the level of fidelity and optimization is believed sufficient for further development of the technology in experimental testing programs.

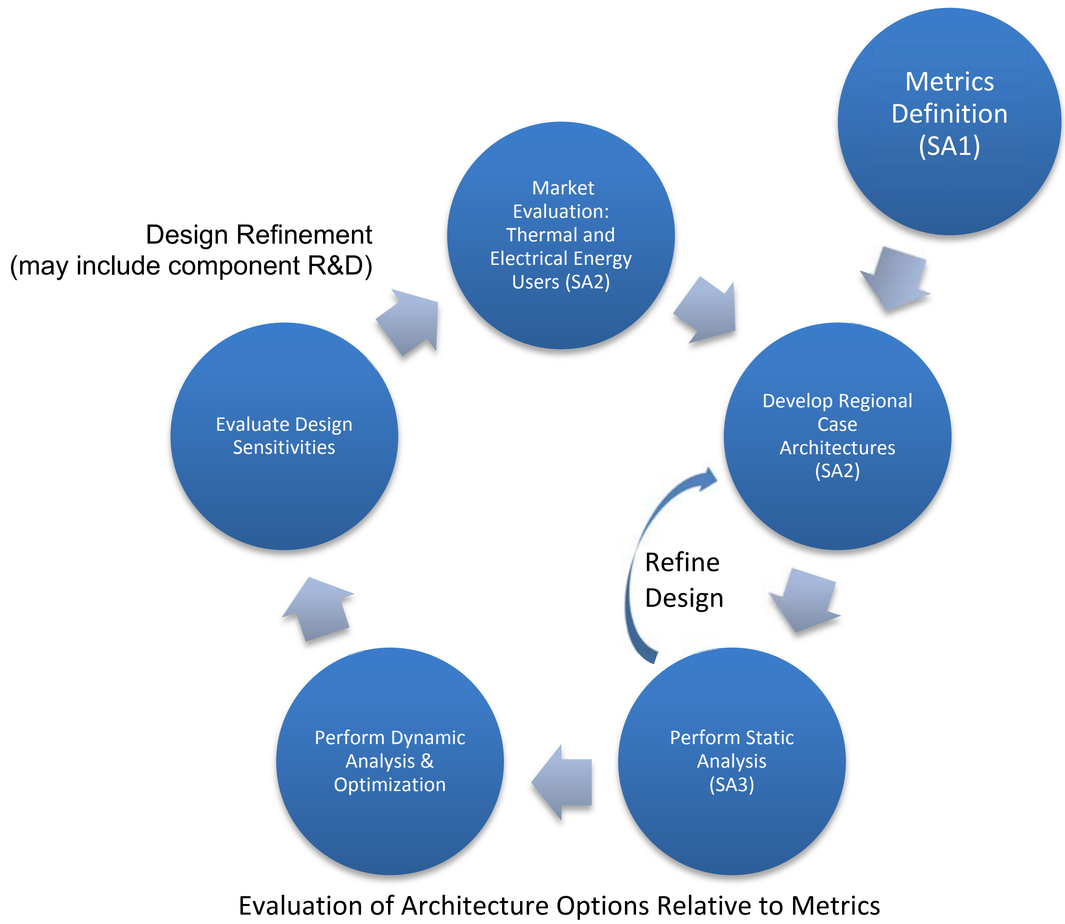


Figure 12. Illustration of the iterative simulation process, from strategic analysis through detailed dynamic analysis and architecture optimization.

5.2.1 Develop Advanced Dynamic Modeling and Simulation Framework and Tools

Following the options identification in SA2, detailed analysis will be required to further assess the system performance. This step will require the creation of a complex software tool that simulates the dynamic performance of the hybrid system (Rabiti et al. 2015). The goals of this advanced tool development are to:

- Design an optimized hybrid system and associated subsystems based on defined technical and economic performance metrics

- Develop an optimal control strategy that maximizes the performance of the optimized hybrid system
- Verify performance of the system configuration in off-normal conditions (i.e., design basis accidents)
- Design and verify the N-R HES control system to ensure system resilience.

The construction of the software framework for dynamic analysis of N-R HES will be based on the following guidelines:

- Each physical component of the hybrid system must have a software representation (subsystem model).
- The subsystem models must communicate dynamically to simulate the complete, integrated hybrid system (i.e., a communication "Hub" must be established).
- The N-R HES performance must be evaluated using data (weather parameters, renewable generation, electricity demand (load), electricity price, and industrial product price) that are statistically realistic.
- The N-R HES operation needs to be coordinated as a whole to respond to time-varying load and renewable availability.
- A model of grid operation can initially be embedded as part of the input signal used for electricity load; this will later be enhanced in a more comprehensive dynamic model that will integrate an existing grid model.
- The simulation of the HES performance should generate cash flow that includes proper modeling of capital cost recovery.
- The optimization process should be:
  - Economically driven
  - Constrained by subsystem operational limits and grid reliability requirements.

5.2.1.1 Subsystem Models. For reasons that will be clarified in subsequent discussion, each subsystem model will possess several representations having different levels of fidelity and accuracy. While high-fidelity representation of each subsystem is generally preferred, high-fidelity models are likely too computationally expensive to use directly in the optimization search process because optimization search algorithms require a very large number of executions of each individual model.

High-fidelity models are physically based and must be validated. The validation constraint can be relaxed for the lower fidelity models, or a softer validation could be selected relative to the high-fidelity model. Relaxed validation requirements are acceptable for the lower fidelity models because the feasibility of the optimal system configuration will be confirmed later using the highest fidelity models.

Provision for lower fidelity models in the optimization process, with later validation of the optimal configuration using high-fidelity models, allows the program to leverage models that have been developed and validated elsewhere. Modeling tools that may be employed include RELAP5-3D (RELAP5-3D 2005) or RELAP-7 (Berry et al. 2015), depending on the development timeline, and component model libraries in Aspen (Aspen Plus 2000) and Modelica (Elmqvist and Mattsson 1997).

While this approach has the advantage of using well-accepted modeling tools for each subsystem, such as RELAP5-3D for nuclear systems, it also has some drawbacks. Using models that are not specifically developed for N-R HES implementation leads to challenges in the integration of such models, particularly when the analysis of the mutual interaction of those models is key in the work to be performed. This challenge is less prominent when dealing with lower fidelity models. In fact, the development time for new low-fidelity models could be comparable to the development of interfaces to ensure communication among the different models. As systems analyses proceed, the program will take advantage of models already available in the community, where possible, and will evaluate the trade-off between the cost of developing new models (with validation) versus the cost of developing interfaces between existing models that may already be validated.

Models currently under consideration for direct use are the nuclear power plant models developed in RELAP5-3D or RELAP-7. It is not within the program scope to develop new high-fidelity nuclear plant models. If component or subsystem models are not available, then new models will be developed within a development platform that already includes large component libraries to support subsystem and integrated system model development.

Renewable energy subsystem models have been developed by NREL for solar thermal, solar PV, and wind power technologies. The public versions of these models are available in the System Advisor Model (SAM). These models have differing pedigrees, but are generally implemented via C++ coding. The SAM Simulation Core software development kit is a collection of developer tools for creating renewable energy system models using the SAM Simulation Core library. SAM itself is merely a desktop application that provides a user-friendly front end for the library. The Software Development Kit (SDK) allows one to create unique applications using the SAM Simulation Core library; for example, an application can be built for integration with models in other programming environments.

The modeling environments currently being considered for use in N-R HES evaluation are Modelica, MATLAB, and Aspen. The benefits and detriments of each modeling environment will be carefully evaluated for each subsystem. At present, it appears that the interface between models developed in Modelica, Aspen, or comparable environments can be leveraged for all the models built using the same environment.

Models that are not physically derived belong to a special class of models referred to as meta-models, reduced order models, or surrogate models. These models are mathematical constructs that are useful in system optimization; they will be discussed in more detail in Section 5.2.4.1. Table 2 summarizes the subsystem modeling approach.

Table 2. Subsystem modeling approach summary.

Fidelity	Model Development Choice	Validation	Example	Interface
High	Leverage codes available in the community as much as possible	Needed, may have already been performed	RELAP5-3D	To be built
Medium	Use development environments where large component libraries are available	Soft validation relative to high-fidelity codes	Modelica, MATLAB, Aspen	Built in a generic fashion for all system developed within a certain environment

5.2.1.2 Subsystem Model Integration. Integration of subsystem models is critical to the evaluation of proposed N-R HES constructs. To minimize the cost of developing interfaces for the integration system model, a hub-and-spoke strategy will be adopted versus a model-to-model coupling. In a hub-and-spoke approach each subsystem model communicates with a coordination platform that receives and dispatches information and synchronizes the evaluation of the models, as illustrated in Figure 13. The hub-and-spoke strategy requires all the models to be capable of communicating with the hub and not to any other model. In other words, for N different models (assuming each model is developed independently from the others), N information exchange protocols are needed instead of N*(N-1)/2.

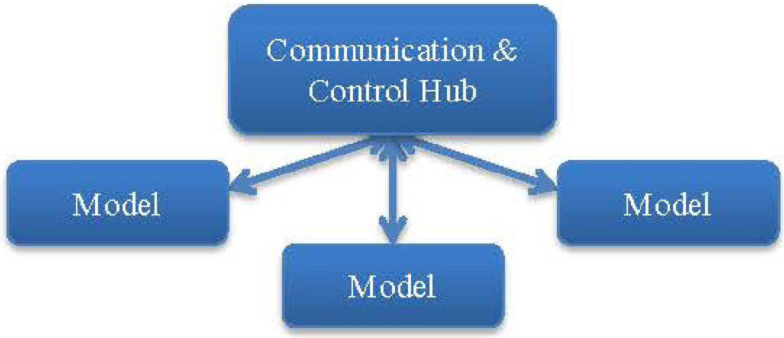


Figure 13. Hub-and-spoke communication pattern.

Three software frameworks are currently under consideration to act as the hub: Ptolemy II (Ptolemaeus 2014), MOOSE, and RAVEN. Each option has pros and cons, which are briefly summarized below:

- Ptolemy II is Java-based and is probably the most advanced of the three proposed frameworks. It already possesses interfaces based on Functional Mockup Interfaces (FMIs) to use Functional Mockup Units (FMUs) (Blochwitz et al. 2011) and many more standard communication protocols. FMI/FMU are standard protocols for the exchange of information among independent software. This interface is, for example, automatically available for compiled Modelica code. The development language, Java, simplifies the portability across different platforms. However, Ptolemy II lacks management capability for distributed computing on a large cluster and lacks an embedded solver (each model is required to bring its own solver). Ptolemy II has the capability to coordinate the system components using a discrete events, discrete time, or continuous time based control system.
- MOOSE (Multiphysics Object-Oriented Simulation Environment) (Gaston et al 2009) is a C++-based framework. The framework was originally built to solve models based on partial differential equations on large clusters. Application Programming Interfaces (APIs) were later made available for interfacing external applications. Synchronization options are still limited, and the parallel implementation lacks some of the needed flexibility; however, a control logic system is being developed to allow discrete event, discrete time, and continuous time synchronization. The MOOSE framework is still under development by the DOE-NE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program.
- The RAVEN (Risk Analysis Virtual Environment) (Rabiti et al. 2015) framework is Python-based. While the hub infrastructure is a completely new development for the code, RAVEN has existing coupling with optimization algorithms and meta-models and has reasonable capabilities for management of parallel computing. RAVEN is currently under development by the DOE-NE Light Water Reactor Sustainability (LWRS) and NEAMS programs. For N-R HES simulation and analysis the control system will be part of the new hub infrastructure development. Other programs have expressed interest in developing this capability inside RAVEN; tool selection will be driven by optimization of personnel resources and availability of the required capability when it is needed for the N-R HES project.

5.2.2 Data Requirements

The N-R HES architecture design and operation must be optimized and tested with consideration given to the natural profile of wind and solar availability in the intended region, electricity load, and/or heat demand. These quantities will be referred to as source terms. Existing, publically available databases will be accessed for relevant renewable source terms and load curves. A list of possible candidates for the availability of variable renewable resources and electricity load is provided in Table 3.

Table 3. Database for variable renewable availability.

Dataset	Type	Link	Resolution	Note
Eastern and western wind integration dataset	Wind	http://www.nrel.gov/electricity/transmission/about_datasets.html	10 min	Used for regional case study (TX) (Garcia et al. 2015)
Wind integration national dataset toolkit	Wind	http://www.nrel.gov/electricity/transmission/wind_toolkit.html	5 min	
National solar radiation data base	Solar	http://rredc.nrel.gov/solar/old_data/nsrdb/ https://nsrdb.nrel.gov/nsrdb-viewer	1 hour and 30 min	Both historical data and TMY (typical meteorological year) data available from 1991 to 2014
Measurement and Instrumentation Data Center (MIDC)	Solar	http://www.nrel.gov/midc/ssrp/	1 min	Used for regional case study (AZ) (Garcia et al. 2015) Discontinuous coverage
Electric Reliability Council of Texas (ERCOT) Hourly Load Data	Electricity load	http://www.ercot.com/gridinfo/load/load_hist/	1 hour	Used for regional case study (Garcia et al. 2015)
Federal Energy Regulatory Commission (FERC)	Electricity load	http://www.ferc.gov/docs-filing/forms/form-714/data.asp	1 hour	Used for regional case study (Garcia et al. 2015)

While these databases are extremely useful resources, the time spans covered are not sufficient for direct use in stochastic optimization. Synthetic time histories can be developed to overcome this difficulty. The N-R HES program will develop an algorithm to generate these time histories as a necessary step in the development of the advanced modeling and simulation tools. Development of synthetic time histories is accomplished by using the original databases to train statistical models that can be used to produce time histories similar to those in the databases, where "similar" indicates that a database constructed using synthetic time histories has the same statistical properties as the original database. Synthetic time histories can also be used to evaluate future scenarios, as renewable profiles will not change significantly (nominal capacity of the generators can be scaled). For a first approximation the future load can also be scaled. If it is necessary to account for profile changes that could result from implementation of new practices, such as demand-side management, it will be necessary to determine the changes in the structure of the synthetic time histories that could result from such practices.

5.2.3 Control System

An integrated control system will be designed such that, based on the current system state and forecasted net load (where the net load will be a prototypical demand generated by synthetic time histories), decisions can be made regarding system operation to improve overall economic performance while meeting the electricity, and possibly heat, demands. This imposes the creation of the control system at the level of the communication and control hub, where the information concerning the performance of all subsystems is available.

The laws of control logic must be designed to optimize the performance of the overall N-R HES, not just a single subsystem, avoiding local optimization traps and accounting for the stochastic nature of the overall system. The control laws must be physically constrained by the known response time of each subsystem while trying to follow the net grid electricity load and the internal heat demand for the N-R HES. The development of such a control system is challenging, as it will need to operate over different time scales, from day ahead planned output changes to millisecond response to variation in the net load. It is unlikely that standard, already available, approaches will work for N-R HES control system optimization, as it would push the simulation into a degree of fidelity in which linear behavior will not be sufficient to model the dynamic response of the system. Consequently, optimization based on linear integer programming, which is the common approach used to deal with this class of problems, may not be sufficient. Specific approaches for optimization of the N-R HES control system, which must also be designed to ensure system resilience (Rieger 2014), will be further evaluated as the simulation tools are developed.

In spite of these challenges, the described software infrastructure will have to be highly flexible to allow testing of several control strategies. For example, the models used to generate synthetic time histories could be used as predictive models within the control system. Reliable predictive models allow the control system to optimize the system configuration for the present time and for likely system conditions in the near future.

The predictive capability of the control system will be supported by the introduction of meta-models capable of being evaluated faster than real time (see Section 5.2.4.1). What is relevant for the construction of the control system is that the software framework will support the automated creation of simple mathematical models that provide, within a defined uncertainty, the capability to predict the future response of each subsystem. If this evaluation is completed faster than real time, it is possible to use this capability in a predictive fashion to enhance the effectiveness of the control system.

5.2.4 System Optimization and Software Requirements

Optimizing the N-R HES design for a selected regional application is the first step in building the simulation framework. After meeting the technical and functional requirements (T&FRs) for the energy system, the primary FOM driving the optimization process is the electricity production cost under the constraint of reliability of supply availability (i.e., ensuring the steady supply of electricity to meet grid net load for the impacted grid balancing area; meeting the reliability constraint allows N-R HES to also bid into the capacity market). Subsystem models will need to be augmented to provide the cash flow information proportional to their fuel usage and invested capital (this could change depending on the nominal capacity needed by each subsystem). The system cash flow must also account for the revenue generated by selling products from the coupled industrial process, cost of the disposal of any type of waste, and possibly for the internalization of externalities such as CO_2 production, water usage, land withdrawals, etc.

Ensuring that the N-R HES can match the net demand via the reliability constraint (at least in some probabilistic sense) captures the value of the N-R HES's ability to absorb volatility (Rabiti et al. 2015). A comparative analysis to the base case (independent systems) should reveal that independent nuclear and renewable systems would have a higher cost to achieve the same level of reliability in covering the net demand versus the coupled systems. For example, a renewable generator cannot bid into the capacity market as an independent system because it is not dispatchable and cannot guarantee supply at a certain time. Nuclear generators can bid into this market due to their high capacity factors and dispatchability, although an electricity-only nuclear plant may not have the same ramping capability and response time as a coupled hybrid system.

The optimization process will begin with the selection of a set of parameters that define the N-R HES configuration (e.g., nominal capacity of each subsystem, control parameters, etc.), followed by testing of such configuration for a statistically meaningful set of time histories representing the source term of the system. The outcome of this step will be the mean value of the electricity production cost. The optimization process will continue until the set of parameters that minimize the cost to produce electricity, for a given probability of system availability to meet load, is achieved. This approach aims to optimize both the system control logic and the fraction of the nominal power covered by each supplier (i.e., the relative penetration of the different energy suppliers within the N-R HES).

RAVEN is the initial tool selected to "wrap" the simulation framework and perform the optimization. RAVEN is currently being developed under the LWRS and NEAMS programs for probabilistic analysis of complex systems. Hence, it already possesses several of the capabilities necessary for the optimization task and has established synergies with existing DOE programs.

For a given N-R HES configuration, the cost of supplying electricity will vary depending on the time histories representing the source terms. Wind and solar generation and electricity load are stochastic in nature; therefore, an optimal solution for the configuration design and the system operation can only exist in a statistical sense. For this reason, stochastic optimization algorithms (better known as robust optimization theory) that are currently implemented in RAVEN will be used.

The optimization algorithms considered require a very large number of runs for each N-R HES configuration using different realizations of the source term in addition to the already sizable number of configurations that need to be tested by a standard optimization algorithm. Even if each simulation run is computationally "cheap" (~hours to run), the stochastic optimization process might easily become computationally untreatable. For this reason acceleration schemes are usually required. The acceleration schemes proposed here are based on an ensemble approach that is currently under study for a similar problem identified within the LWRS Risk Informed Safety Margin Characterization Pathway.

5.2.4.1 Meta-models. Meta-models have been named differently and with slightly different meaning in several fields. The most commonly used additional terms are surrogate models, reduced order models, and supervised learning. A meta-model is a mathematical model that can be "trained" to represent the response of a system for a restricted range of the system input space. This is obtained by properly choosing a set of parameters for the equation used to build the meta-model. The most common are linear regressors that replace the response of a system by a linear model that best fits (by least square minimization of the error) a set of realizations of the system response. Examples of meta-models used to replace a desalination plant are, for example, reported in Rabiti et al. 2015.

The training of a meta-model is the optimization process during which the parameters of the equation in the meta-model are chosen such that they best fit a set of data (i.e., training set). The meta-model possesses the capability of approximating the system response even for points that do not belong to the training set. The risk of misusing the meta-model outside its predictive range should be carefully accounted. While there are general theories on this subject, some specific development will be needed for usage in the context of the present work. The predictive characteristic of meta-model training can be used to replace the representation of the original model by a meta-model that is usually several orders of magnitude faster to execute than the original model.

5.2.4.2 Using Meta-models in the Optimization Strategy. Stochastic optimization requires a very large number of runs with very similar system conditions. This offers an ideal opportunity to deploy meta-models to decrease the computational time. The software infrastructure needed is illustrated in Figure 14. The original subsystem models and the meta-models are embedded in a common infrastructure that communicates with the rest of the system. When a new inquiry is made to the embedding infrastructure, the algorithm inside will decide if the meta-model is already trained sufficiently for use as a replacement of the original model. If the training is sufficient, the meta-model is used; if not, the original model is used and its response is added to the training set. In this way, the more similar runs that are performed, the more the meta-models are used to replace the original model and the simulation progresses more rapidly.

While this approach could be generalized to any level of fidelity and any time scale, it is unlikely and outside of the scope of this program to extend it to very high-frequency and to off-normal condition analysis. This optimization scheme will be used for low-frequency system optimization under normal conditions and for time scales ranging from minutes to days. Once an optimal system is designed for these conditions, the configuration can be tested for high-frequency stability and for performance under off-normal events.

High-frequency testing will likely be performed by replicating the system configuration within a Real Time Digital Simulator (RTDS) (Manitoba 2010), followed by testing the configuration over very short time spans for specific events. The off-normal events will need to be modeled using safety class codes, such as RELAP5-3D or RELAP-7, but this will not be included in the global optimization strategy. Even with the above limit introduced and the acceleration schemes described, the optimization process will remain computationally challenging. The current development approach will use Modelica-based subsystem models, with optimization driven by RAVEN using high performance computing clusters. Initial testing indicates the feasibility of this approach.

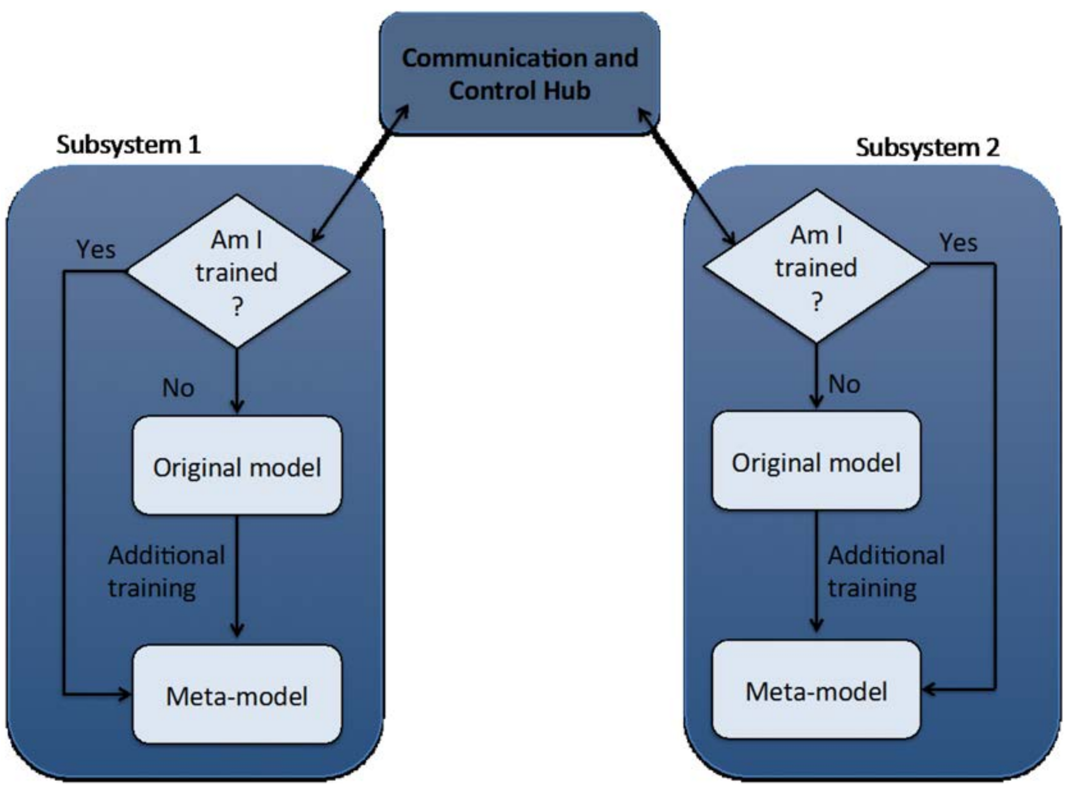


Figure 14. Simulation acceleration scheme using meta-models.

5.2.5 Grid Modeling

Explicit grid modeling is not addressed early in the optimization of the system design, but existing models will later be integrated with the system model. The grid is essentially a boundary condition for the N-R HES operation. The described optimization process will produce the most economically viable N-R HES configuration and the associated control laws for optimal operation, given the synthetic time histories that describe the renewable supply and electricity load. Selection of the databases used to generate these histories creates some specificity in terms of geographical location of the N-R HES, but it does not really define a specific spatial location and grid balancing area. This allows the optimization problem to be cost-driven and to remain as generic as possible, without accounting for the pricing strategy of any given market. At the same time, it should be recognized that this evaluation approach does not constitute the totality of the grid and electricity market, which may be regulated (which can be considered cost-driven) or deregulated (marginal cost-driven). The profitability of N-R HES needs to be tested under real market conditions, particularly for the deregulated case, to determine if the current pricing structures will allow the deployment of the optimized N-R HES with positive profitability.

Although the specific methodology is still being developed, the system design optimization will likely be performed first for a generic situation, as described above, followed by embedding the optimized configuration in a grid/market simulator such as PLEXOS (PLEXOS User Manual). To accomplish this approach, it will be necessary to develop a simplified representation of the optimized N-R HES for integration in such software. A possible option is the development of a piecewise linear regression approach for the N-R HES, which can then be integrated within PLEXOS.

While PLEXOS is a grid model at the time scale of minutes to hours, the final N-R HES will also need to be tested for stability and reliability at much higher frequencies. The higher frequency stability evaluation will be completed only after the optimized N-R HES configuration has been determined and has been demonstrated to be economically viable via simulation results. At this point, if there is an indication that additional value will be provided by adoption of the evaluated N-R HES, as described by increased reliability, resilience and/or stability of the system, RTDS models that incorporate the power system behavior can be developed to verify such hypothesis. Coupled RTDS models can also be used to demonstrate N-R HES value in terms of providing synchronous electromechanical inertia to the grid ("real" inertia) versus the reduced grid inertia that would result from high penetration of variable renewable generators.

5.2.6 Modeling and Simulation with Hardware-in-the-Loop

As will be discussed in Section 5.3, testing of components, subsystems, and the optimized integrated system design is a necessary part of N-R HES development to verify model results. This development and testing process will likely require incorporation of some physical component testing in conjunction with simulated components that are either well-understood (e.g., commercially available components for which validated models are available) or difficult and costly to test at an early development stage (e.g., nuclear-fueled reactor component). Testing that simultaneously involves both physical and virtual components is generally referred to as "hardware-in-the-loop" (HiL) testing. When real and simulated components are coupled, it is necessary that the simulated component models are capable of being evaluated in real time or faster. This condition is difficult to achieve with standard code; hence, component models will be implemented on RTDS for this purpose.

The RTDS is a real-time ElectroMagnetic Transient (EMT) simulation platform capable of performing electric power system simulations with a typical time step of 50 µs. RTDS uses custom-designed Field-Programmable Gate Array cards to run the mathematical calculations for the simulations. In addition to the real-time simulation capabilities, RTDS also supports HiL simulations. Thus, an actual hardware device, such as power electronic inverters, relays, or controller hardware, can be interfaced with the RTDS and a controller, or power hardware can be tested as controller HiL (CHiL) or power HiL. This provides the ability to test an actual hardware prototype and provides fidelity against modeling errors where a highly detailed model is required for system representation. RTDS supports most communication protocols, such as IEC61850 and DNP3, which can be used for interface communication of HiL in the testing and simulation. RSCAD® is the graphical user interface for modeling, which contains a built-in library of power system and control system components. RTDS can also be used to simulate highly detailed, fast switching power electronic devices with a smaller time steps of up to 2 μs.

5.2.7 Off-normal and Accident Scenario Simulation

Although the nuclear plants considered within this program plan are derived from well-known LWRs, the environments in which they are operated will be different. In particular, the transients seen by the secondary side of the plant may differ due to the direct coupling with heat users for tightly or thermally coupled N-R HES. Moreover, the initiating external events could lead to scenarios presenting multiple subsystem failures driven by common cause failure phenomena.

While there are new conditions to be considered in the risk analysis for off-normal operation and accident scenarios, standard, validated LWR evaluation tools are available for the analysis of accident scenarios (e.g., RELAP5-3D). Consequently, the simulation framework used to perform the can also be used to identify possible new accident scenarios and their related probability of occurrence. This information can be used in conjunction with the above mentioned accident simulation tools to verify N-R HES safety.

The possibility of feeding the results of the safety analysis back into the N-R HES optimization will also be taken into account. The new class of transients that could occur in coupled systems may increase the wear and tear on the plant components. It will be necessary to consider the trade-off between the economics of operation and the accelerated deterioration of the N-R HES and possible increased safety concerns.

5.2.8 Consideration of Grid Resilience and Cyber Security

Coupling of traditionally independent energy systems is expected to provide improved economic performance overall due to both the implementation of new technologies and increased coordination of energy resources. This increased coordination has two side effects: increased communication requirements and increased interdependence among the subsystems. Increased communication among subsystems increases the exposure of the coupled system to cyber attacks, while an increased degree of coordination both within the N-R HES and with the grid increases the risk of a common cause failure. Hence, unless it is carefully designed, the final N-R HES configuration could be more fragile and vulnerable to cyber attacks than independent energy systems.

Assessing cyber resilience requires a fairly high degree of fidelity in the simulation of the system, especially when the intended outcome of the cyber attack is the initiation of an accident scenario in the nuclear plant. In such a case, the N-R HES control system developed in the last stage of the optimization process plus the high-fidelity models developed for safety related simulations are expected to be the modeling infrastructure necessary to analyze system resilience. Resilience tests could be performed through the introduction of random failures and anomalous behavior that could result from cyber attacks. The possibility to couple the high-fidelity simulation models with commercial codes commonly used for this type of analysis at the grid level will be explored.

A comparative approach is suggested to evaluate the resilience performance of the N-R HES relative to an economic performance. Note that while the interdependence of subsystems within the N-R HES island have the potential to be more fragile with respect to cyber attacks than independent systems, the expected benefits associated with increased N-R HES flexibility to respond to changes in the electricity net load should increase the overall resilience of the grid, particularly as the penetration of variable renewable generators increases. Design of the system architecture will aim to first design a control system that minimizes the fragility of the N-R HES. The overall benefit to the resilience of the grid balancing area due to the introduction of one or more hybrid energy systems can then be assessed.

5.2.9 Software Quality Assurance

Each national laboratory is mandated to follow a certain Quality Assurance (QA) procedure for any work performed for DOE; however, the QA specifications can differ from laboratory to laboratory. For this reason, several programs that work across multiple laboratories have adopted dedicated QA protocols that supersede the laboratory-DOE agreements. In this manner a program can employ a standard QA protocol across laboratories, subcontractors, etc.

The initial N-R HES effort has adopted the QA protocol from the DOE Advanced Reactor Technologies (ART) program. However, as the N-R HES program grows and becomes independent of the ART program, it will be useful to define an N-R HES-specific QA standard. At present, the most conservative approach is adopted.

Software applications typically adopt a graded approach to QA. The most stringent approach is necessary for software having the quality level designation of "commercial safety related," followed by "commercial," and finally by the "R&D classification," which requires the least stringent approach. While R&D software requires the least stringency, it still provides a sufficient degree of reliability while leaving the researchers reasonable latitude for testing and exploring innovative solutions.

The RAVEN development flow is currently being updated for a level three assessment (R&D classification); hence, QA processes employed for RAVEN software development can be used as an example as to the process for software development for R&D purposes.

First, a copy of the code is kept on a server that tracks the history of the code. Any modification of the code is recorded and the status of the code at any point in time can be rebuilt from the repository. The process to modify the software involves the following steps:

- During a development cycle, a developer checks out the most up-to-date version of the code for further development.
- Once finished, the developer submits a "merge request" to an independent reviewer containing:
    - Code modifications
    - The modification to the user and theory manual, if needed
    - A set of input decks used to test the added features.
- The reviewer verifies that:
    - The code conforms to the code standards
    - None of the previously existing code features have been inadvertently changed (this is done by running a pre-existing series of tests that constitute the regression test suite)
    - The new input decks provided by the developer ensure the testing of at least 80% of the newly submitted code.
- Once the reviewer agrees, the merge request is "merged upstream" where an automatic system check verifies the compatibility of the modification again with the most up-to-date version of the code in the repository. Only at this point do the modifications become part of the code.

Each step is traceable in terms of time, developer, reviewer, and results of the tests performed. While this process ensures traceability of all modifications, it still lacks two components: the generation of a software manual and the decision-making process for the addition of features and/or modifications. The software manual is generated automatically using "Doxigen." Doxigen is a software tool that is capable of reconstructing the internal structure of the software, thereby offering a new developer the opportunity to understating the code more quickly. To work properly, Doxigen requires a specific commenting style within the code. This style is defined within the code development guidelines and is part of the independent reviewer checklist.

Each modification in the code is initiated after a ticket is generated. The "Tracks" software is used to keep track of the tickets and their labels. Labels are used to distinguish between the addition of new features and bug identification. Each ticket is assigned to a developer who communicates the end of a development cycle by closing the corresponding tickets. Ticket history is also kept in the repository.

The above development process is currently adopted for the RAVEN code; thus far, this process appears to be compliant with the most stringent requirement for the R&D software classification. It is foreseeable that any other software development under HES would follow a similar path. As the software matures, a higher QA standard compliant with the commercial grade classification can be applied.

5.3 Hardware Technology Development Needs

The continuous screening process described in Section 5.1, in conjunction with the more detailed dynamic analyses described in Section 5.2, will result in identification of N-R HES configuration options, prioritization of those options, and optimization of the specific configuration designs to meet both technical and economic performance requirements. However, the ability to combine and direct energy within these optimized designs is dependent on the technology available to do so. By identifying the capabilities necessary to accomplish favorable power system configurations and comparing those capabilities to available technology options, gaps can be identified and targeted for development.

Technology needs that can support multiple HES configurations will be prioritized in the component and subsystem testing conducted in Phase II of the N-R HES program, which overlaps the detailed, high-fidelity simulation and analysis work described in Section 5.2. These common technology areas include thermal energy generation to represent a small modular reactor, interconnections (including heat exchangers, valves, piping), thermal and electrical energy storage, power conversion equipment, instrumentation and controls, and interoperability systems and protocols. Early Phase II work will include design and assembly of the general test facility infrastructure that will be required for testing of any of the N-R HES configuration options. The analysis activities conducted in Phase I and Phase II of the N-R HES program and described in Sections 5.1 and 5.2 will further define the specific technologies that will be tested/demonstrated within the N-R HES program.

Figure 15 shows a block arrangement of the individual components that could be included in an N-R HES. Note that components can be configured to emulate any of the coupling options described in Section 2.1 and illustrated in Figure 1 to Figure 3. This program does not focus on the development of each of these component technologies, but instead focuses on the integration of relatively high TRL components and/or subsystems into a functional integrated system. Although the selected components and subsystems within the N-R HES may be commercially available or have been developed to high TRL under other R&D efforts, the TRL of the integrated system has not been established. Hence, the N-R HES program will take the steps necessary to demonstrate performance of the integrated system to achieve industry acceptance and commitment to demonstrate a first-of-a-kind (FOAK) N-R HES. Demonstration of such an integrated system will require interconnection of multiple technologies. Technologies expected to be necessary for a pilot-scale demonstration are identified here, highlighting specific technologies to be *developed* within the N-R HES program. Additional components may be necessary in the planned demonstration system to accomplish the integrated system operation.

The component, subsystem, and control technologies necessary for integrated energy system demonstration are:

1. System-wide technologies
    a. Instrumentation and controls: Technology and equipment for resilient, multi-agent distributed control
    b. Interoperability systems and protocols: Analytics for component, subsystem, and system state awareness; communications networks; data transfer; etc.

2. Subsystem technologies

    a. Nuclear reactor:
    Reactor design is not included within the program scope; however, thermal energy generation and distribution of that energy will be required to demonstrate integrated system operation. Accurate representation of the thermal energy that would be generated by the reactor(s) will require electrically heated components and specific control algorithms.

    b. Power conversion/electricity generation:
    Power conversion dynamics are an essential feature of hybrid energy systems. Turbomachinery and electrical generator sets will experience higher cycling duties than is currently typical, and faster response times may be required for N-R HES to meet transient net load.

    c. Renewable generator(s):
    No specific development is included within the program scope, although connection of these components may be necessary to demonstrate integrated system operation. However, the program may leverage parallel technology development efforts supported by other programs.

    d. Industrial processes:
    No specific development is included within the program scope. However, the program may leverage parallel technology development efforts supported by other programs. Development and demonstration of technologies to interface with these components may be required to characterize the impacts of coupled system operation. Table 1 lists key manufacturing industries and the potential applications of nuclear energy. Development efforts may include temperature-boosting technologies to allow use of LWR-generated thermal energy (reactor outlet temperature ~300°C) with industrial applications requiring high-temperature thermal energy input.

    e. Hardware interconnections
        i. High-temperature flow control equipment
            (1) Highly instrumented valves, sensors, and SMART control systems
            (2) High-pressure chamber and manifold design for stable flow redirection
            (3) Variable-speed pumps rated for high-frequency thermal cycling
        ii. Heat exchangers (designed for high duty cycles)
        iii. Heat transfer fluids other than steam, such as high-temperature organic fluids or low melting point salts.

    f. Energy storage
        i. Thermal: options may include a solid or liquid material providing sensible heat capacity, a latent-heat phase-change (solid/liquid) media, or an chemical adsorption/desorption system; also referred to as thermal capacitors in this report
        ii. Electrical: options considered in this report include batteries or capacitors; a derivative option could include storage of electrical energy that would then extracted as thermal energy (e.g., firebrick storage as discussed in Forsberg 2015)
        iii. Chemical: options may include new energy currencies, such as hydrogen
        iv. Mechanical: options include flywheels, compressed air, and pumped hydro.

    g. Grid interface
    No specific development of grid technologies is included within the program scope. However, the program may leverage parallel technology development efforts supported by other programs (e.g., advanced high-voltage/high-power semiconducting and cabling technologies). Power converters, power transformers, and power management units may reside as actual physical components or may be created using real-time digital simulators of the power systems components.

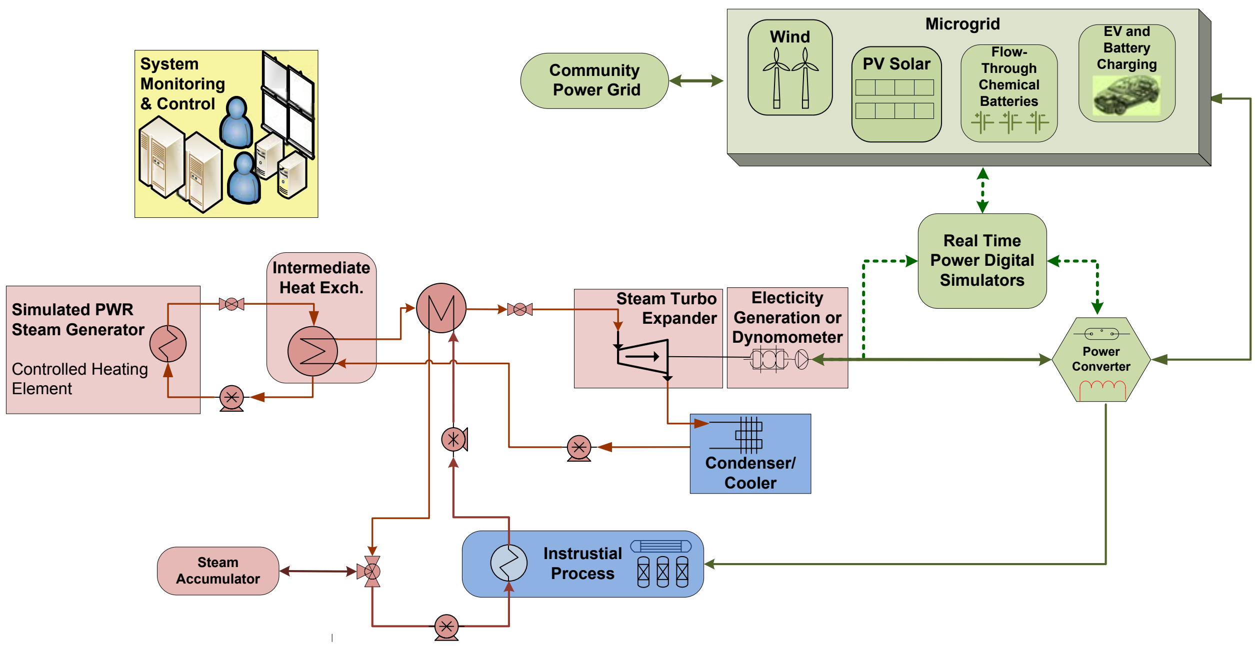


Figure 15. Simplified block arrangement of individual components that could be included in an N-R HES test facility. Component coupling may vary depending on the type of N-R HES being demonstrated.

Subsystem and component technologies necessary in integrated system testing for N-R HES configurations could be represented physically in the N-R HES test bed, or could incorporate some level of virtual representation based on the current level of development and understanding of those technologies and the availability of validated simulation models. An example of a possible integrated test bed is illustrated in Figure 15. The primary purpose of this arrangement is to test the response of a typical steam turbine to variable grid load as a function of some set of renewable power generation being co-fed to the grid. Simultaneously, the thermal energy must be synchronously maneuvered between power generation and the heat user in a manner that least impacts the operation of the nuclear reactor. The placement of heat exchangers and the quality of heat delivered to a thermally coupled industrial process depends on many design factors, including the industrial heat user process and distance to the industrial plant. The objective for the hybrid system is to efficiently provide clean energy input to the grid and industrial processes, address grid variability concerns by providing flexibility and responsiveness, and provide grid stability.

5.3.1 Overview of the Planned Test Facility

Maturation of N-R HES and associated technologies through TRL 6 will likely include development of a reconfigurable N-R HES test facility that can be used to demonstrate components, component integration into subsystems, and dynamic integrated system performance with the associated control methodology. New component technology development is first conducted on either the experimental or bench-scale to study equipment performance relative to design and functional requirements and relative to single-effect conditions. Demonstration of unit operation in an integrated pilot-scale plant, necessary to achieve TRL 6, is subsequently required to characterize component performance on a scale where physical and temporal phenomena are representative of real-world conditions.

This program plan is predicated on the following system design assumptions:

1. Near-term N-R HES will likely involve LWR technology, with a specific focus on SMR designs undergoing or nearing Design Certification with the NRC. Future work could include evaluation of advanced reactor technologies in N-R HES architectures.

2. Experimental-scale testing will likely occur on a scale of 10–100 kW-thermal; integrated bench-scale system testing of $1/100^{th}$ scale will likely require a system rated for 1–2 MWt and will depend on analysis of dimensional parameters such as Reynolds number (Re), Prandtl number (Pr), Grashof number (Gr), etc.
3. The thermal generation ramp rate for the primary heat generation source is expected to be at least 1.0% per minute, or 100% in 100 minutes. Appropriate ramp rates and system limitations will be verified with relevant technology vendors.
4. Thermal energy will be produced using an electrically heated, pressurized-water heat exchanger. Electric heating can be designed to deliver a heat flux similar to a small modular light water reactor with buoyancy-driven water circulation. Start-up, shut-down, and transient heating of the simulated reactor core can be programmed to match customer-specific design parameters (see Bragg-Sitton et al. 2010 for an example of this testing approach).
5. Steam is generated in a primary heat exchanger. The primary steam loop interfaces with an intermediate heat exchanger for steam delivery to the power cycle.
6. Power is generated by a condensing steam turbine having multiple steam extraction stages and equipped with a total condenser. The turbo-expander is connected to either an actual electricity generator or to a dynamometer that simulates an electric power generator while measuring the torque applied on the turbine shaft. If actual power is generated by the test system, then it will feed to a power converter that is connected to an electrical service line or a load. If a dynamometer is used, it can be electronically connected to a data recorder.
7. The heat user block, labeled "industrial process," can be configured with any process that uses low-to-intermediate heat. A heat rejection system may be designed to simulate a variety of heat transfer options that would be used in a given industry.
8. A steam accumulator, or possibly a steam relief, may be used to buffer transients between power generation and heat delivery to the user.
9. System instrumentation is implemented to monitor and control core heating, flow valves, pumps/circulators, turbine, and dynamometer conditions. Control functions are set by project needs. In general, instruments and controls are capable of passing information in a timely manner to monitor the state of the system and to resiliently respond and re-optimize set points.
10. Depending on the test objectives, instruments and data collection systems used in the pilot-scale test may or may not need to meet required QA specification for NRC Design Certification. See Section 5.3.7 for additional information on QA in hardware testing.

Additional discussion on system scaling, demonstration and validation principles are provided in Appendix C.

5.3.2 System-wide Technologies: Instrumentation, Control, and Interoperability

Instrumentation and Controls (I&C) are critical to system operation. The integrated N-R HES will require advanced control systems that provide feedback control on and among the coupled thermomechanical and electromechanical subsystems. There are limitations in each domain that must be measured and maintained. Control systems have responsibility to ensure stability and provide set points. There will be cooperation between low-level control loops that must rapidly respond to any disturbance, mid-level control loops responsible for maintaining and responding to adjustments for set points to provide optimal use of resources, and a top-level control loop responsible for strategic planning. Human operators will be able to supervise all levels, with the most interaction occurring at the mid- and high-level. The control system is expected to utilize state estimators installed within the various subsystems and signals from the grid operators to determine real-time, semi-autonomous control of the integrated systems to augment sensors, thus providing for full state variable feedback. There has been significant research in online monitoring under different DOE programs, including LWRS in DOE-NE, and other programs within EERE and Office of Electricity Delivery and Energy Reliability (OE), that can be leveraged for the N-R HES program. Depending on the coupled system, issues or challenges in the performance and reliability of the protection systems, including the common-cause failures, diversity, and defense in depth will have to be studied on a case-by-case basis and understood with modeling and experimental testing before higher confidence in the overall system can be attained.

Instruments are necessary to identify and characterize the state of the system, establish the health of the system by identifying potential component or system failures, and provide both input and response to control strategies. Controls are used to operate the system within the constraints of the operating space. Controls are also used to startup or shutdown the system, subsystems, and components. Controls can be used to mitigate failures.

Technical and Functional Requirements

Significant instrumentation is necessary to monitor system state in order to design and implement a robust, reliable and resilient N-R HES control system. Instrumentation and control systems should adhere to the following requirements:

- Instrumentation needs to be sufficient to establish the state of the system. For thermal-fluid systems, pressures, temperatures, and flows are needed to characterize pressure and heat losses and to establish thermodynamic states to calculate mass, heat, and energy flows.
- Instrumentation is needed to diagnose the health of the system. Failures of components, subsystems, or systems can be predicted by appropriate instrumentation. By predicting failures, the system, subsystem, or component can be shut down or bypassed before failure when possible. Diagnostics, alarms, and safety procedures will be in place for the system and operators to respond when unpredicted failures occur, such that safety is never compromised.
- Instrumentation needs to be sufficient to allow for the operation of the system using hierarchical controls. Instrumentation will provide input data to the control systems and provide feedback to the controls.
- Instrumentation is required to monitor the electrical production system. Specifically, sensors that measure voltage, current, phase, and frequency at various points within the generators, within the transformers, and at the boundary of the transmission to the external grid for state and situational awareness of the health of the connected external grid.
- A visualization and control console will be required to support the monitoring and control provided by human operators of the system.

Current State of Development

It is currently anticipated that most instrumentation necessary for monitoring the system conditions as described above are commercially available for use in the N-R HES. Control methodologies for N-R HES have, thus far, been limited to implementation in simulations. Related control systems in energy production and distribution systems may be leveraged. The hardware implementation requires control decisions to be sent to the necessary actuators and sensors. Proposed control room and instrumentation designs have been developed in general. Specific needs must be addressed based on the selected N-R HES configuration. Feedback control technology and algorithms are available to regulate temperatures, maintain mechanical state variables, etc.

Key Barriers/Gaps

Unique coupling of the diverse systems in an N-R HES is a challenge in complexity that goes beyond the current energy industry control systems; thus, it is anticipated that instrumentation needs will also exceed that of standard energy systems. The optimization goals of an N-R HES require all systems to be harmonized, and full sensor and data information to be present within specified ranges. System degradation or faults are destined to occur and the control system must respond by de-tuning from the optimal production to one predominantly directed at stability and safety until resolved.

Development Approach

The development and optimization of N-R HES control systems was discussed in Section 5.2.3. Specific tasks that will be conducted, with the support of process and dynamic system modeling, include:

- Key instrumentation will be identified for controlling the integrated system, subsystems, and components.
- The optimal control methodology determined via high-fidelity simulation will be demonstrated in the integrated nonnuclear test facility to verify performance for nominal operating conditions and anticipated operational occurrences.
- Deliberate and controlled failure of key components and subsystems within a nonnuclear N-R HES test facility will be used to characterize the failure modes and identify and demonstrate key instruments to predict failure.
- Instrumentation to monitor component ageing and degradation will be selected. This instrumentation will be installed and tested in the nonnuclear test facility to demonstrate performance ability and to test algorithms developed to monitor aging and alert operators to potential issues. For example, thermocouples and pressure transducers will be positioned at the inlets and outlets of heat exchangers to characterize internal fouling.
- The program will apply expertise within the DOE complex to ensure human operators and supervisors are provided with the tools needed to perform their jobs (e.g., visualization, procedures, controls), utilizing the expertise in human performance that is available.
- System security and resilience will be developed using best practices from those communities.

5.3.3 Subsystem Technologies: Nonnuclear Heat Generation

A dynamically controlled, electrically heated thermal energy production unit will be employed for integrated system testing through TRL 6 to emulate thermal energy that would be generated by a nuclear reactor(s). It is possible to use a bank of electric heaters to simulate heat production from nuclear fuel using sophisticated control algorithms to provide accurate simulation of the subsystem dynamics within the integrated system.

Technical and Functional Requirements

The integration of thermal hydraulic hardware tests with simulated neutronic response, referred to as “simulated reactivity feedback testing,” provides a bridge between electrically heated testing and full nuclear system tests. Incorporation of a reactor model that accurately simulates reactor performance offers insight into system integration issues, provides a basis for characterization of integrated system response times and response characteristics as it offers a low-risk platform for demonstrating control system architecture under nominal and off-nominal conditions, and provides an opportunity to assess potential design improvements at a small fiscal investment relative to a nuclear-fueled system (Bragg-Sitton et al. 2010). The combined system will provide a demonstration of real-time integration with the electrical grid, renewable energy inputs, and energy storage. As such, the entire energy network can be simulated to understand how to optimize energy flows while maintaining stability and efficient operation of all assets in the system.

Figure 16 shows the flow of heat and power to the heat users within the N-R HES and to the grid. Heat from the reactor core generates steam, and the steam generator is within the reactor subsystem boundary. The steam may be expanded to generate power within the power conversion unit or may be used to provide heat to the heat user. For safety reasons, the steam from the steam generator is isolated from the other subsystems of the N-R HES. Power generated from renewable resources may be used locally within the N-R HES or sent to the grid.

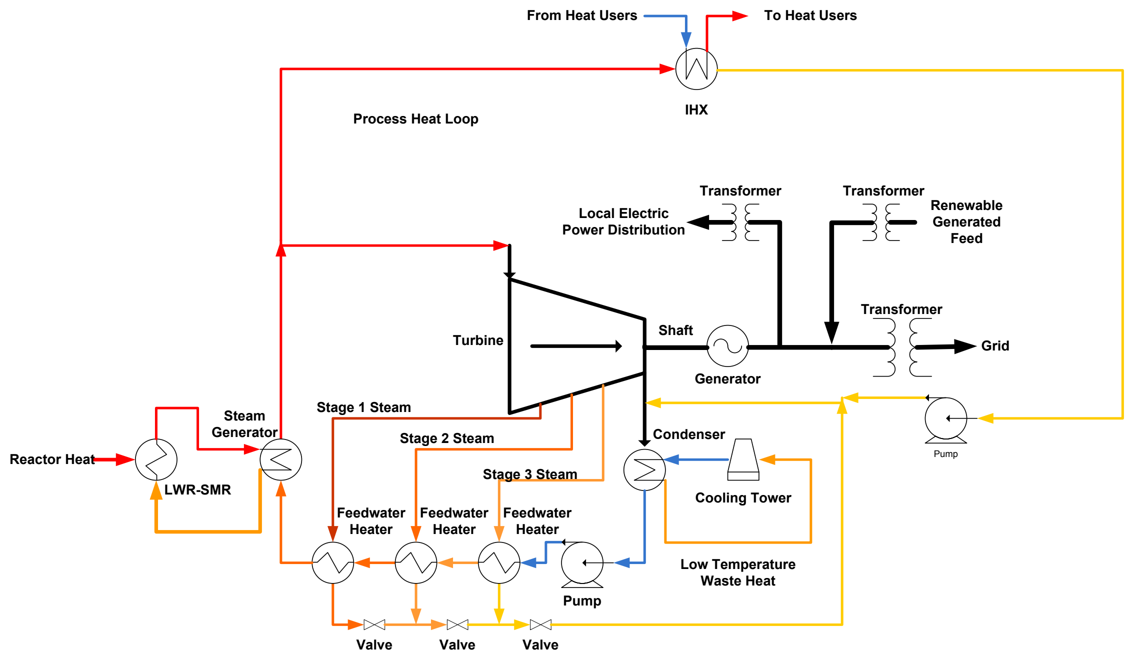


Figure 16. Power and heat generation for heat users and the grid.

Key Gaps

- *Reactor Safety.* To ensure the safety of the reactor, research should focus on keeping the reactor functional should all heat sinks be cut off or shut down. Most new reactor designs have inherent safety features that keep the reactor cool in the event of accidents. These same features should keep the reactor safe and functional should the connections between the reactor and the users of its heat and power be compromised. Establishing proper design constraints for the integration of the thermal energy derived from the nuclear subsystem with the industrial user will be necessary to ensure operational safety.
- *Time Varying Loads.* Another area of research is to determine the capability of the coupled nuclear subsystem to handle time-varying loads that would include magnitude, duration, and ramp rates.
- *Buffer Nuclear Reactor from Grid Dynamics*. The N-R HES should inherently buffer the effects of grid dynamics on the nuclear reactor. Research will be needed to protect the HES from natural disasters and deliberate attacks on the grid.
- *Aid in Prevention of Cascading Failures in the Balancing Area.* Other areas of research include demonstrating that, by addressing grid dynamics issues internally, the hybrid energy system can support prevention of cascading grid failures. In the rare event of a grid failure, the reactor could completely couple with the industrial process to supply minimum heat and power for both systems to maintain operation and to prepare for rapid deployment when the grid becomes responsive. Thermal storage can also be used, to an extent, to act as a heat sink for the nuclear reactor.

Current State of Development

Electrically heated test platforms and methodologies applied to nuclear systems testing reduce the overall cost, risk, and complexity of testing nuclear systems while allowing researchers opportunity to evaluate the operation of an integrated nuclear system within a reasonable timeframe, providing valuable input to the overall system design. This approach has been used in the development and testing of nuclear technologies for space applications to test integrated system operation in a laboratory environment (Bragg-Sitton et al. 2010).

Development Approach

The Advanced Reactor Technology Integral System Test (ARTIST) facility illustrated in Figure 17 is designed to be a multi-fluid, multi-loop thermal hydraulic facility. The planned facility has three thermally interacting flow loops: helium, molten salt, and steam/water. Once built, the facility can be used to simulate the thermal performance of the primary loop of a nuclear reactor, test intermediate heat exchangers, and supply thermal heat to integrated processes (O'Brien et al. 2014). The ARTIST facility design is being developed in parallel to the N-R HES program. It is anticipated that the design of the water-cooled loop within ARTIST will be finalized in collaboration with the N-R HES program in parallel with Phase I analysis and design optimization. Thermal energy generation representing a nuclear reactor subsystem will be required for any N-R HES configuration under consideration. Hence, a thermal subsystem will be a part of the basic test facility infrastructure. Design of the thermal generation system, which will include assessment of the existing ARTIST design and evaluation of its applicability to N-R HES demonstration, will be conducted late in Phase I R&D, and assembly of the thermal subsystem will be initiated late in Phase I and early in Phase II. Activities will include: 1) detailed system design relative to T&FRs for the thermal generation system that will be defined in Phase I, 2) final system design, 3) initial hardware procurement, and fabrication of any custom components, 4) flow loop assembly, and 5) shakedown testing. Conduct of this work late in Phase I through early Phase II will ensure that the facility will be available to support Phase II component and subsystem testing.

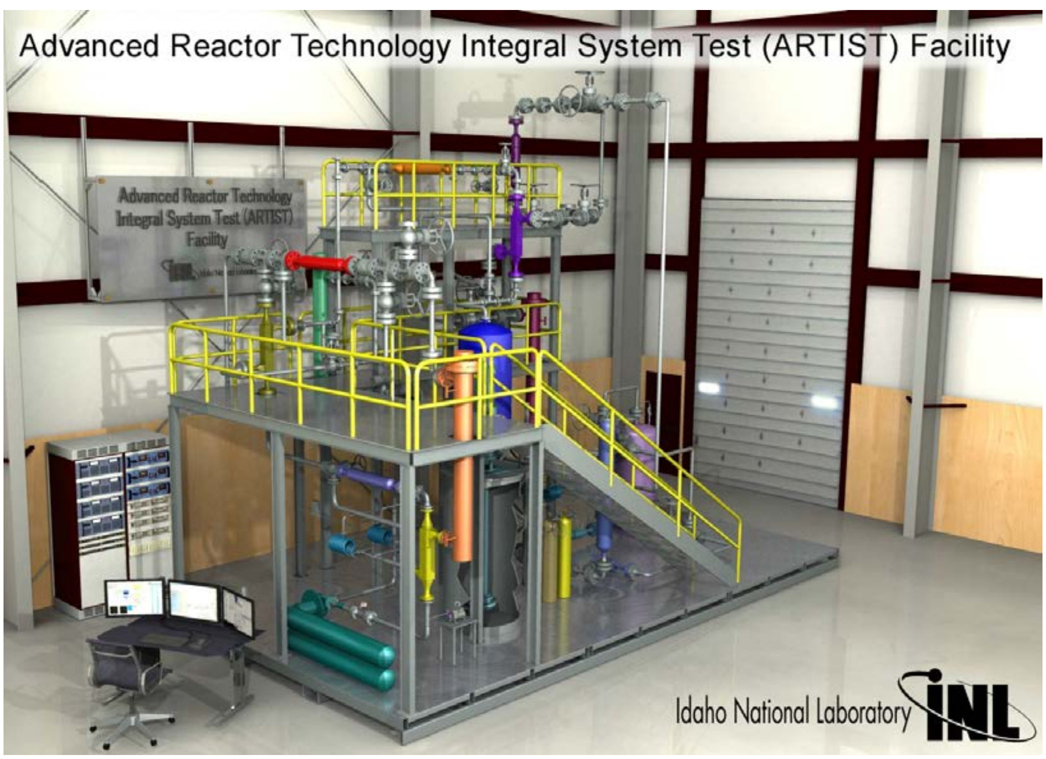


Figure 17. Conceptual ARTIST thermal hydraulic facility.

5.3.4 Subsystem Technologies: Power Generation and Management

Power generation and management incorporate the power conversion unit, which converts thermal energy to electrical energy, and the connection to the grid to deliver that electrical energy.

5.3.4.1 Power Conversion Unit. For a pressurized water SMR the power conversion unit (PCU) will most likely deploy a steam Rankine power cycle. A gas turbine with Rankine combined cycle could be used for peak power production using natural gas or compressed hydrogen that is produced by the hybrid system. The Rankine cycle consists of a steam generator, multi-stage steam turbine, condenser, ambient cooling (water, air, cooling tower), pumps, and recuperating heat exchangers (feed water heaters), as illustrated in Figure 16. The turbine will likely be a condensing turbine to maintain the condenser vacuum and to maximize power production. The other type of turbine is a non-condensing or back-pressure turbine that exhausts steam for process heat in industrial facilities. These components are affected by or can have an affect on the other subsystems within the N-R HES. The primary responsibilities of the power conversion unit are to provide variable power to the grid as a function of the load and to supply power to other components and subsystems within the N-R HES boundary. The PCU can also provide heat through steam at various stages of expansion and as waste heat from the condenser.

Technical and Functional Requirements

The PCU has the following requirements:

- The PCU must be able to respond to the dynamic grid load. The grid is affected by daily and seasonal loads as well as the variability introduced by the addition of renewable generation. The PCU must redirect, reduce, or increase power production to accommodate the grid demand.
- The PCU cooling system (condenser, cooling tower, air cooling, etc.) must be resilient to changes in the environment, whether those changes are due to daily and seasonal changes or due to overall climate change. High humidity (>80%) and high air temperatures (>90°C) affect the efficiency of the cooling tower, which, in turn, can decrease power production.
- The steam generator within the SMR must run close to design conditions to ensure proper operation of the core cooling system. Modern water-cooled SMR designs are trending to natural circulation as the means for core cooling and emergency cooling. The cooling system acts as a thermosiphon in which flow rates can be disrupted if the steam generator conditions change. Changing inlet and outlet conditions on the steam side will affect the cooling flow rate for the reactor core.
- The PCU has the potential to supply heat to industrial processes. Heat rejected by the PCU could be used in very low-temperature industrial processes, such as district heating. Steam from the various stages of the turbine may also be used to provide heat to coupled processes, such as thermal desalination processes (e.g., multi-effect distillation).
- Wear on the turbine will require periodic maintenance. Alstrom energy, a major steam turbine manufacturer, has recommended maintenance inspections at interval of 100,000 hours of operation (Alstrom Energy 2014).

Current State of Development

For near-term deployment, the PCU cycles under consideration are commercially available. The Rankine cycle has a long legacy of development and has been used in the nuclear industry. Gas turbines are also commercially available, and the transient use of these cycles for peak production is well known (U.S. Energy Information Administration 2013).

Key Barriers or Gaps

Key barriers to PCU integration within N-R HES include:

- *Constant conditions at the steam generator.* The inlet and outlet conditions of the steam generator (e.g., temperatures, pressures, flows) must be maintained to ensure the proper cooling of the reactor core. It is important to keep the nuclear power plant operating at design capacity, hence the need to develop technologies that either use the extra electricity generated or the excess heat.
- *Environmental impact on the PCU*. A key factor to power production is the exchange of heat from the PCU to the environment. A pressurized water reactor rejects two-thirds of its core heat as low-temperature heat to the environment. This heat rejection occurs within the PCU at the condenser of the cooling towers and can be impacted by the environmental conditions. The temperature at which this heat is rejected strongly affects the efficiency of power production. Lower environmental temperatures allow the condensing temperature and pressure to decrease, which allows for more expansion through the turbine and, therefore, higher power production. Water cooling of the condenser allows for more effective heat transfer and lower condensing temperatures. Air cooling tends to raise the condensing temperature because the heat transfer is not as effective. However, water usage is becoming a critical environmental concern and steps are being taken to reduce water usage in power production. Global warming also affects power production by increasing the ambient temperature, which in turn will decrease power production.
- *Process heat integration from the PCU to industrial processes*. Technology development in the areas of controls, instrumentation, piping, valves, heat exchangers, and vessels is needed to transfer the heat from two primary areas of the PCU: the steam turbine and the condenser. Alternative usage of the steam from the various stages of expansion could allow a more rapid turbine response, reduce the production of power in response to the grid, and provide process heat to lower temperature industrial heat applications. Utilization of the rejected heat will improve the overall thermal efficiency of the PCU.

Development Approach

A pilot-scale N-R HES is necessary to raise the overall TRL of the integrated system to a value of 6. By including a Rankine cycle with at least one feed water heater, the program can model and test PCU control strategies, test process heat interconnections between PCU and process heat applications, and explore ambient cooling technologies. Areas of research are outlined as follows:

- *Constant conditions at the steam generator*. Control strategies and pilot-scale testing of the strategies will be needed to maintain inlet and outlet conditions of the steam generator. As shown in Figure 16, the heat flows to and from industrial users, dynamic demands from the grid, and power usage by the grid can affect the inlet and outlet conditions. Dynamic modeling of the N-R HES is critical to the development of the control strategies. Testing these strategies within a pilot scale system will verify or aid in improving the strategies.
- *Environmental impact on the PCU*. Research is needed to develop condensers and ambient cooling technologies to increase thermal efficiency, reduce water usage, and provide more resilience against impacts of climate change. Process and computational fluid dynamic modeling of key components will aid in finding designs that accomplish these goals. Dynamic system modeling of the N-R HES, the grid, and the ambient conditions will aid in determining the impact of the environment on the system. Pilot-scale testing will be used to test ambient cooling systems to validate models and to develop full-scale cooling systems.
- *Process heat integration from the PCU to industrial processes.* The impact of transferring heat from the PCU to the heat user needs to be understood. Removing heat by using the feedwater steam streams will impact the turbines. Steady process and dynamic modeling of the PCU system will be

used to determine the impact of heat removal from the PCU. Component modeling will also aid in predicting the impact on the turbine and the feedwater heaters. Thermal stresses on all the PCU components due to heat cycling also needs to be characterized and understood.

5.3.4.2 Grid Interconnect Power Management. The N-R HES electrical side is comprised of the linkage from the rotating mechanical energy input provided by the turbine(s) in the thermal system to the external electric grid. The external electrical grid is a boundary condition primarily determined by the voltage, frequency, and phase angle at the transmission interconnect(s) to the grid. The electrical energy system has the role of supporting the electricity needs of the N-R HES. The system exports electricity when energy markets provide an economic driver and imports electricity during outages of the nuclear reactor.

The local substation, which connects the generator to the external grid transmission line, is comprised of step-up transformers and interconnection hardware including protection systems, relays, and fuses. The substation connects a transmission line(s) between the N-R HES and the external grid. The subsystem may also provide any transformers needed to support distribution to local N-R HES electricity needs or to accept power from renewable and/or fast responding fossil fuel generation to support demand peaks.

The control of the various adjustments is supported through sensors called phasor measurement units (PMU) that may be part of the protection system. PMUs provide direct state measurement rather than depending on transmission state estimation to determine the power flow to the larger grid.

Reactive power compensation is a necessary element to maintain voltage stability at the N-R HES with regard to maintaining the power factor of the N-R HES at unity from the perspective of the connected external utility when local loads operating at various power factors are switched on and off. The reactive power can be regulated by various static and dynamic reactive power sources.

As briefly discussed in Section 5.2.5, it is possible for the generator and power grid to be simulated by RTDS so that the internal distribution and external electric grid can be structured to an arbitrary complexity. However, this requires additional braking hardware to provide the torque created by the generation of electric power. The external grid could be emulated in the testing of the integrated pilot-scale N-R HES using RTDS. This simulated grid can impact the physical hardware through power inverters, variable loads, and power amplifiers structured outside the boundary of the HES.

Technical and Functional Requirements

Interconnection of the generated energy to the external grid in a manner that allows for the monitoring of key state variables concerned in maintaining voltage and frequency stability and control of the phase angle with respect to the boundary grid to control dispatched power require the following:

- Standard substation for step-up transformers as well as necessary distribution circuits to support electrified components of the N-R HES. This includes protection circuits for monitoring disconnection of transmission circuits under fault conditions. Modern standard protection hardware, such as that available from Sweitzer Engineering Laboratories, contains voltage, frequency, and PMU capabilities.
- Dynamic VAR sources to provide reactive power compensation for voltage stabilization support.
- Demand response capability of any non-critical loads in the N-R HES to allow response to short-lived variations in internal or external power needs.
- Power converters will require fast response to power transients from storage sources within the N-R HES.
- Integration with the control system is required to provide feedback control for voltage and frequency stability as well as external power flow control.

- RTDS should be provided either in concert with a dynamometer or variable load components to emulate the desired complexity to the loads of the internal electric grid.

Current State of Development

Many of the described needs are available in current state-of-the-art commercial electric grid equipment. There are similarities within the N-R HES to the additional stresses put on power generation that is expected to be agile (e.g., gas turbine generation) with the added complexity of considering the internal needs as well as the external commitments for energy delivery. Full implementation of currently available grid protection and control electronics along with flexible alternating current transmission system (FACTS) devices with sophisticated global control architecture may be sufficient for maintaining stability and control of external power flow.

Key Barriers/Gaps

Implementation of an HES takes advantage of many advances in smart grid and microgrid technology. Providing realistic transmission components in the demonstration system to emulate the connection to the external grid in a manner so that power flow can be realistically varied, monitored, and controlled may be challenging. Unknowns include:

- The frequency of hard switching of electrical components inducing undesirable power quality with harmonics.
- The physical stresses and loss of efficiency in the turbine and power train of the generation system.
- The stresses resulting from harmonics on transformers (Geduldt 2005).

Development Approach

Control system design must consider the big picture of stresses on the N-R HES when tuning the response times to stabilize and adapt to the electrical power needs of the internal and external customers to the generators. Key program tasks include:

- The program will study in detail the transients of the proposed components and specifications for the rate of ramping up or down the external power with a total cost of ownership including maintenance and repairs for the HES stakeholders.
- Utilization of building load and microgrid assets at the host laboratory for system testing, as well as the relationship with the local utility, are anticipated to allow the electrical grid components of the system to be fully realized without undue burden.
- Demonstration of the R&D platform will utilize significant RTDS systems and expert users for efficient implementation of system complexities and to ensure accurate representation of the power systems in the broader balancing area in which the HES would be deployed.

5.3.5 Subsystem Technologies: Hardware Interconnections to Industrial Processes

N-R HES will be a dual-purpose system, meeting both power needs and providing heat for industrial applications. Efficient design of a heat delivery system is necessary to ensure high-quality heat is delivered to the industrial plant. This system is divided into heat exchangers, smart controls (such as valves, pumps, circulators), and temperature-boosting technologies.

Several possible configurations for transferring heat between a nuclear reactor(s) and the industrial user facility were previously studied under the Next Generation Nuclear Plant (NGNP) program. A brief overview is provided here; further details can be obtained from Davis et al. 2005. One aspect of the heat delivery system is choosing the correct medium for transporting thermal energy. Previous work concluded that steam/water and molten salts perform better than gases, primarily because low-pressure gases such as helium require extremely high pumping power. The high pumping power makes the process very inefficient and economically nonviable for both low and high-temperature applications (Yoon et al. 2014 and McKellar et al. 2011). The key fluid decision discriminators include heat transfer capacity, melting point, infiltration to the primary loop in an accident scenario and ease of recovery; availability of the fluid; purification capability (removal of tritium); material compatibility; and cost. The selected industrial application and its corresponding temperature requirement will dictate which coolant is utilized for transferring thermal energy.

Another option that may be considered is simply transferring electricity to the industrial process plant where it can be converted back into thermal energy via Joule or induction heating. This could be accomplished via heat storage media, such as firebrick or a consolidated alumina body (Forsberg 2015 and Stack and Forsberg 2015), a molten salt typical of those being developed for concentrated solar energy (Abengoa Solar 2014), or an adsorption/desorption system (such as ammonia-water). The increasing electrification of industry via heat pumps and electro-chemical processes as shown in Table 1, combined with the increased capacity of existing corridors through the use of a high voltage direct current, implies that N-R HES would be used primarily for power generation.

5.3.5.1 Heat Users. Process heat and power users provide a means to buffer the dynamic net load. Power and heat from the reactor subsystem can be diverted from the grid to produce a variety of products that may be stored and used within the N-R HES or sold outside of the N-R HES.

Technical and Functional Requirements

The heat delivery system should be designed with the following considerations relative to the selected N-R HES configuration:

- *Process Responsive to Economic Signals.* Heat delivery to the industrial processes is scheduled and synchronized with power generation in accordance with some demand function, such as overall revenue generation, or in accordance with power purchase agreements that may include providing ancillary services to the grid.
- *Process Operation Capacity Factor and Technical Considerations.* For most processes to function economically and efficiently, reliable sources of heat, power, and feedstock are needed. Therefore, an alternative intermittent heat source may be required during high net load, or when the nuclear plant is experiencing a scheduled or forced shutdown. A thermal or electrical energy storage buffer may reduce the duty of the auxiliary heat source.
- *Heat Reliability Factors.* Some processes, such as electrolysis and reverse osmosis desalination, require only power, while other processes such as biomass to liquid fuels require heat, power, and feedstock.
- *Heat Amplification.* Heat sources may need to be augmented to supply heat at higher temperatures needed for the selected process.
- *Heat Integration.* Industrial processes will need unconventional integration to access the heat from the reactor. Low-temperature and high-temperature recuperation techniques will need to be considered.
- *Siting and Ownership.* The industrial process may be sited with the reactor, relatively nearby, or a long distance from the reactor. Siting distance will depend on the selected configuration and will impact design of the heat delivery system.

Current State of Development

Numerous industrial processes are commercially operating. Fossil fuels, such as natural gas, are currently used to provide heat for many of these processes. The processes are well understood and locations of heat and power input are known. Some of these processes only electrical power input (e.g., low-temperature electrolysis and reverse osmosis), some require primarily power and high-temperature heat (e.g., high-temperature electrolysis), and some require primarily heat (e.g., fuel production; district heating and thermal desalination require only low-temperature heat).

Hydrogen production and desalination processes integrated with nuclear reactors are under consideration and development throughout the world. More advanced heat-dependent processes have been modeled under programs such as NGNP and ART.

Key Technology Gaps

Key technology gaps for heat users that are of interest to the N-R HES program include:

- *Thermal stress and thermal expansion.* The dynamic response of the heat to and from the industrial process will cause thermal stresses within heat exchangers. Process heat applications sited far from the reactor will have potential problems with the interconnecting piping due to thermal expansion.
- *Thermal capacitance of heat transfer and process equipment.* Heat exchangers, piping, and tanks are heat and fluid capacitors that can reduce the response time of the industrial process to grid dynamics. Industrial processes located far from the reactor will have additional thermal and fluid capacitance due to the interconnecting piping.
- *Heat integration.* Unconventional heat integration is required between the source of heat and the industrial process. Heat amplification, if required, must be optimized through pinch analysis and heat integration with the specific heat user.
- *Dynamic operation of the industrial process.* Many industrial processes can operate with little or no dynamic response (i.e., they need to maintain steady-state operation). Other processes that can operate flexibly given sufficient economic incentive may be desirable for N-R HES integration.
- *Heat and pressure losses.* Heat losses within equipment and process piping will reduce the temperature of the available heat. Pressure losses require auxiliary compression or pumping power, which reduces process efficiency.

Development Approach

To address the concerns and challenges identified, the following approach will be taken:

- *Thermal stress and thermal expansion.* Thermal stress and expansion of components will be modeled using Computational Fluid Dynamics (CFD) and stress analysis packages. Industry experience with piping over long distances may be used to overcome this barrier. Research into materials may also be needed to help resolve these issues.
- *Thermal capacitance of heat transfer and process equipment.* Dynamic models of the system should characterize the thermal and fluid capacitance of the N-R HES. Transfer functions for the piping and equipment should simulate the response time of the system. Pilot-scale testing can characterize some of the response times of tanks, piping, and heat exchangers.
- *Heat integration.* Optimal heat integration of the industrial application to the available heat can be modeled. Detailed component design of the coupling heat exchangers will be modeled with CFD. Low-temperature and high-temperature heat recuperation techniques can be applied to reduce the amount of high-temperature process heat needed.
- *Dynamic operation of industrial process.* The dynamic response of the industrial process can be simulated using process modeling coupled with dynamic system modeling. The operational constraints must be defined so that the operating space can be determined. With constraints in place, control strategies using key instrumentation and controls can be used to keep the process within the operating space. Supplemental heat from natural gas or electric power can be used. Testing of these

processes using a pilot-scale testing facility can validate control logic and identify issues and gaps not predicted by modeling.

5.3.5.2 Heat Exchangers. Heat exchangers provide a means to transfer heat from fluids of differing pressures, temperatures, and compositions. Examples of heat exchangers within the N-R HES are steam generators, which produce heat for power and industrial processes; condensers, which reject heat to the ambient environment; and feedwater heaters, which recuperate heat within processes to increase thermal efficiency.

The heat exchanger must effectively transfer heat between fluids for heat supply, heat rejection, and heat recuperation. The heat exchanger needs to provide reliable and durable pressure and chemical boundaries between heat flow loops, processes, and heat sources.

Technical and Functional Requirements

The heat exchanger should be designed to fulfill the following requirements:

- *Enable efficient thermal energy transport.* The heat exchanger needs to transfer heat efficiently with minimal heat and pressure losses.
- *Provide a pressure boundary.* The heat exchanger must act as a pressure boundary between the working fluids. For example, the steam generator in a pressurized water reactor uses high-pressure water as the primary coolant with lower pressure steam generation on the other side of the boundary.
- *Provide a chemical boundary.* The heat exchanger must provide a chemical boundary and prevent cross-contamination between the working fluids. Highly reactive fluids, such as liquid sodium and water, can exchange heat as long as the heat exchanger boundary is maintained.
- *Material compatibility.* The materials of the heat exchanger must be compatible with the working fluids' composition, temperatures, and pressures.
- *Perform reliably under dynamic conditions.* The heat exchanger must maintain its structural integrity under highly fluctuating pressures, temperatures, and flows.
- *Must be economical.* Large surface areas allow for more effective heat exchange but are more costly. Material and fabrication costs increase with increasing surface area (size and surface enhancement), temperature, and pressure.

Current State of Development

Potential options for heat exchanger to the process application are shell and tube, plate, plate and fin, printed circuit, helical coil, and ceramic. Each of these heat exchanger concepts is described in more detail in Sabharwall et al. 2011. The key to high efficiency in a process is a highly effective heat exchanger, so an efficiently designed heat exchanger is critical for effective use of the transported thermal energy. The heat exchanger design options will vary depending on imposed requirements of the coupled process. Selection of a specific heat exchanger design to be used in hardware demonstration will be made following selection and optimization of the high-priority N-R HES configuration(s).

Key Barriers/Gaps

Key technology gaps for heat exchangers that are of interest to the N-R HES program include:

- *Dynamic pressure variations.* Hybrid systems will impose large pressures changes within each working fluid. These swings will induce stresses that can lead to fatigue and failure of the heat exchanger's pressure boundary.
- *Dynamic temperature variations.* Large temperature variations due to the dynamic response of heat transport can induce thermal stresses in the heat exchanger material. The nature of the hybrid system

will test the interface between the hot and cold medium; thus, thermal cycling behavior of the exchanger needs to be well understood.

- *Pressure and temperature differences.* Temperature and pressure differences of the working fluids across the pressure boundary and between, in the inlets and outlets of the heat exchanger, can cause separation of bonds and welds within the heat exchanger.
- *Materials.* The heat exchanger materials must be compatible with the working fluids. However, even small amounts of contaminants introduced from the environment, heat exchanger fabrication, installation, or maintenance can promote corrosion or fouling (accumulation of unwanted material on the surface area), which can lead to reduced performance or failure of the heat exchanger. Material compatibility information with potential heat transport coolants is limited and needs to be expanded.
- *Limited experience with dynamic operation.* Not much data is available for heat exchangers at anticipated operating conditions for candidate N-R HES configurations.

Development Approach

To address the concerns and challenges identified, the following approach will be taken:

- Evaluate the possible heat exchanger candidates for the selected N-R HES configuration and rank them based on effectiveness and overall cost.
- Employ small-scale facilities, such as the small pressure cycle test rig (SPECTR) shown in Figure 18, to conduct single effect tests (Landman 2011). The SPECTR facility cycles pressures and temperatures to age and test components at relevant conditions in support of the development of fabrication methods for components like heat exchangers.
- Use steady state process modeling tools to identify design conditions for the heat exchangers within the optimized N-R HES.
- Use the planned ARTIST facility to test heat exchangers at reactor cooling loop temperatures and pressures and with appropriate fluids within the heat transfer loop (O'Brien et al. 2014).
- Apply atomistic thermodynamic modeling to predict corrosion and oxidation of the heat exchanger as it interacts with working fluids and contaminants within the fluids. These models can also be used to analyze weld and bond interfaces within the heat exchanger and predict transport phenomena such as leaching and material splitting.
- Use computational fluid dynamics and stress analysis to predict thermal and pressure induced stresses.
- Employ pilot-scale demonstration to test the selected heat exchangers to mature the technology to TRL 6. For example, thermocouples and pressure transducers at the inlets and outlets of heat exchangers can be used to characterize the fouling within the heat exchangers.

Figure 18. SPECTR test facility used for high-pressure and high-temperature testing of components as well as cyclic testing.

5.3.5.3 Pump/Circulator/Compressor. Pumps, compressors, and circulators provide pressure potential to move working fluids, and to obtain desired pressures. They provide the thrust to overcome pressure drops within piping and components as well as provide necessary process pressures. These components ensure that the required flow rates are maintained within flow loops. They must be reliable and sufficiently robust to handle change in flow rates, be able to ramp up and down as required by changes in the load, and provide necessary process and component pressures.

Technical and Functional Requirements

Specific requirements for pumps, circulators, and compressors include the following:

- *Circulates working fluid through flow loops*. These components control and maintain desired flow rates through the system at the working fluid's design pressure.
- *Provides desired process or component pressure*. These components provide pressures needed for process operations and power production. For example, high-pressure steam required in a Rankine cycle is provided by a pump for power production.
- *Dynamic response*. These components must respond dynamically to processes operating within the N-R HES with high reliability.

Current State of Development

Pumps, circulators, and compressors have been extensively used in industry. Thus, for most of coolants being considered for N-R HES, these components can be obtained from commercial manufacturers.

Key Barriers or Gaps

Key gaps associated with these components as they relate to N-R HES include:

- *Dynamic operation of pumps, circulators, and compressors.* The dynamic nature of hybrid energy systems pushes the operating limits of these devices, which may cause them to stall, promote cavitation, or reach maximum rotational speeds. Rapid ramping can age and fatigue the components.
- *Induced thermal stresses.* Thermal stresses and cracking may occur as pumps, circulators, and compressor experience rapid changes in the temperatures and flows of the working fluids.

Development Approach

To address the concerns and challenges identified, the following approach will be taken:

- *Dynamic modeling of the N-R HES*. Dynamic modeling will aid the development of optimal control strategies that keep pumps, circulators, and compressors within their operational design space.
- *Process modeling*. Process modeling will provide design criteria for these components for pilot-scale testing and will predict off-design behavior based on efficiency design curves for the component. Process modeling can be used to identify alternate operating points where expected temperatures and temperature differences are lower. Use of modeling to identify preferred operating conditions will aid in reducing thermal stresses and also provide better compression efficiencies.
- *Pilot-scale testing*. Pilot-scale testing will provide a test bed for the control strategies developed. Temperatures measured at the inlets and outlets of the pumps, circulators, and compressors will provide information about potential thermal stressing.
- *Computational fluid dynamics*. If necessary, computational fluid dynamics can be used to determine potential thermal stresses within these components.

5.3.5.4 SMART Valves. The main function of the SMART valves is to perform system flow control (throttling) and flow direction functions. They also perform flow isolation and flow initiation functions to take the plant through various modes of operation (startup, operation, shutdown) and also perform response to system and plant off-normal events.

SMART valves will operate to ensure that the required downstream flow rate is maintained and will prevent reverse flow while maintaining pressure in the secondary process heat transport loop. These valves integrate embedded sensors and intelligent algorithms for sensing and self-assessment of valve and system conditions. This design allows for reporting and trending of system parameters (e.g., flow, pressure) without requiring external instrumentation or hardware and provides the required system resilience.

Technical and Functional Requirements

Specific requirements for system valves include the following:

- Initiate, isolate, and direct flow and control flow rates for all modes of system and plant operation
- Support resilient strategies for the detection, isolation, mitigation, and recovery from disturbances
- Allow self-control and coordination with other networked valve systems, as programmed or directed
- Allow automatic response or remote control from an operator
- Communicate and conduct predictive condition monitoring without external instrumentation.

Current State of Development

SMART valves are currently being developed in other programs. Proof of concept work has been performed with a single small-diameter butterfly valve. Application to other valve types such as gate, globe, and ball valves requires additional development. These valves are still a new technology and are currently at approximately TRL 2.

Key Barriers or Gaps

Key gaps associated with these components as they relate to N-R HES include:

- Not easy to scale (i.e., direct extrapolation is not possible)
- Models currently available are mostly unique to a specific valve.

Development Approach

To address the concerns and challenges identified, the following approach will be taken:

- Work with SMART valve developers to expand proof of concept to other valve designs, such as gate, globe, and ball valves
- Obtain and build experimental database
- Perform sensitivity study with flow and pressure changes using embedded instrumentation (e.g., strain gauge).

5.3.5.5 Temperature-Boosting Technologies. First generation N-R HES technology will be based on LWRs. These LWRs provide thermal energy at temperatures of approximately 300°C, while the desired temperatures for many chemical processes are much higher (see Table 1). To realize the benefits of N-R HES with LWRs, selection and development of a complimentary temperature upgrading technology is necessary for integration with industrial processes that require higher temperature input. The specific need to develop and/or demonstrate temperature-boosting technologies in an integrated system test will be determined following Decision Point 1, which marks the selection of high-priority system architectures for further development.

Technical and Functional Requirements

Temperature-boosting technologies are needed to provide higher quality heat (higher temperature) for heat users under highly variable operating conditions. Key requirements include:

- Rapid response to dynamic thermal loads.
- Efficient and economic provision of heat

Current State of Development

One option for temperature boosting may be chemical heat pumps. Chemical heat pumps are systems utilizing reversible chemical reactions to change the temperature level of the thermal energy, which is stored by chemicals. Chemical heat pumps based on the hydration-dehydration reactions of $CaO/Ca(OH)_2$ are a potential candidate for energy storage and temperature amplification/boosting, as this system offers several advantages: high-energy density, fast kinetics, ease of reversibility, low toxicity, material availability, and wide range of output temperature (Matsuda et al. 1994 and Hasatani et al. 1992). The maximum temperature amplification reported in literature is up to 1200 K (Hasatani et al. 1992) using hydration-dehydration reaction of $CaO/Ca(OH)_2$. The efficiency of such a process will be further investigated before making design selections.

Heat recuperation techniques can facilitate use of lower reactor outlet temperature with industrial applications requiring high-temperature thermal energy input via waste heat recovery. Heat recuperation is accomplished with a counter-flow energy recovery heat exchanger, which keeps the flow systems isolated but exchanges the thermal energy, thus reducing the heat load.

An example application that would require temperature boosting for integration with LWRs is high temperature steam electrolysis (HTSE), which currently utilizes steam injected into the solid oxide electrolysis cell at temperatures around 800°C. Figure 19 shows the temperature-entropy (T-S) diagram of water applicable for a HTSE plant, where heat and electrical power are produced by a pressurized water SMR. A low-temperature heat recuperation scheme (Interval 1 in Figure 19) is used to cool the hot hydrogen (and oxygen) product streams to preheat the HTSE feed water. The nuclear heat (Interval 2) from a light water SMR delivers the heat necessary to boil and flash the preheated HTSE feed water, and then to partially superheat the high-pressure steam. A high-temperature heat recuperation scheme (Interval 3) is used to superheat the inlet steam (and gas recycle flows) with waste heat from the hot product streams. Finally, electrical power from the SMR (Interval 4) is used to boost the inlet temperature of the HTSE feed steam and recycle gases to around 800°C.

Figure 19. T-S diagram for water.

Key Barriers to Development

Key gaps associated with temperature boosting technology as it relates to N-R HES include:

- Reactor inlet and outlet temperatures must be maintained at or near design value. Some light water SMR designs need to maintain these temperatures to utilize natural convection pumping.
- While heat pumps are efficient, they are not very fast when compared to electric heating; hence, they will not be as responsive to the dynamic needs of the N-R HES.
- Electric heating responds rapidly to dynamic loads; however, thermal efficiency of the overall production of heat from electricity is low.
- Sophisticated instrumentation and control strategies will be needed to prevent the recuperating heat exchangers from pinching (high-temperature – low-temperature crossover), which would greatly reduce the heat transfer capabilities of the heat exchangers.

Development Approach

To address the concerns and challenges identified, the following approach will be taken:

- Technology will be experimentally demonstrated to verify simulation model results with particular attention paid to heat recuperation methods.
- Process modeling will be used to identify opportunities for heat recuperation.
- Dynamic system modeling will be used to identify time constants for recuperators and heat pumps. It can also aid in the development of control strategies for temperature boosting technologies.

- Potential hybrids of different temperature boosting techniques will be investigated, as they may provide more efficient and economical processes.

5.3.5.6 Linkage to Coupled Industrial Processes, Example: Hydrogen Production. As previously discussed, a variety of industrial processes are considered for HES integration depending on the specific markets and market needs within the intended HES site location. Hydrogen generation is used in the ensuing discussion as an example to illustrate possible T&FRs and development needs. Hydrogen was selected for this example as it has a two-fold purpose: to provide a chemical means to store energy, and to provide a highly valued product that can be used for other applications. During times of excess power generation, or when hydrogen production is economical, hydrogen is produced and may be used in the following ways:

- The hydrogen may be stored onsite in a pressure vessel or in large underground facilities with the same technology used to store naturally occurring hydrogen. This option would provide chemical energy storage for the N-R HES.
- During times of high-grid demand, the hydrogen may be used to provide power by using the hydrogen within fuel cells or combusting the hydrogen with air and oxygen and then extracting power from the combustion products within a gas turbine.
- Hydrogen can also be exported and used by chemical processes external to the N-R HES. Hydrogen can be used as a transportation fuel, to process chemicals such as fertilizers, to refine heavy crude oils into refined fuels, for welding and metal fabrication, and food processing.

Technical and Functional Requirements

Specific requirements for hydrogen generation include the following:

- Rapid ramping of the technology is desired to ensure that the system can respond to the dynamic net load in the grid balancing area. Ideally, the technology could be switched on and off as needed.
- For near-term N-R HES configurations, hydrogen production must be compatible with LWR technology. The reactor outlet temperature determines the quality of heat available, but that heat may be augmented by temperature-boosting technologies, as discussed in Section 5.3.5.5.
- High-pressure storage may be a requirement to reduce the footprint of the necessary equipment.
- Materials of construction for process equipment must be resistant to hydrogen embrittlement.

Current State of Technology

Two general types of hydrogen generation technologies exist today: reforming technologies and water splitting technologies. The reforming technologies use fossil fuels or biomass and steam to produce hydrogen, but they also produce carbon dioxide. The reforming technologies produce hydrogen at the lowest cost due to inexpensive fossil fuels, such as natural gas. Typical plant sizes range from 1000 m^3/hr to 120,000 m^3/hr (The Linde Group 2015). The reforming technologies require constant operation and process heat temperatures near 850°C. Water splitting technologies can be divided into two categories: thermo-chemical cycles and electrolysis. Thermo-chemical cycles use heat and chemical reactions to produce hydrogen and oxygen. Heat for these cycles can be derived from a nuclear power plant or from concentrated solar plants. However, these processes generally involve corrosive acids or volatile chemicals.

Electrolysis processes can also be divided into two categories: low-temperature and high-temperature electrolysis. Low-temperature electrolysis is accomplished by either placing electrodes in an electrolytic solution or using membranes to separate the hydrogen from the oxygen. Low-temperature electrolysis is a technology that is available now and could be used in near-term hybrid systems. Industrial low-temperature electrolytic plants can be as large as 50 MW_e (NEL Hydrogen 2015). Proton exchange membranes (PEM) use a semipermeable membrane that conducts protons, but not gases such as hydrogen or oxygen. Commercial units exist for PEM but are smaller in size (Proton Onsite 2015).

HTSE utilizes heat and electricity to split water. The additional heat reduces the amount of work needed to split the water into hydrogen and oxygen. Solid oxide electrolysis cells are used to separate the oxygen from the hydrogen. The process uses steam at temperatures around 800°C. Although the temperature of the steam is high, pressurized water reactors can be used for this application. The efficiency of the process is strongly coupled to the thermal efficiency of the power cycle used to produce power. Details and status of this technology can be found in O'Brien et al. (2010). A 15 kW_e integrated laboratory scale facility has been operated for over approximately 1,000 hours continuously. Additionally, a pressurized system with up to 25 cells has been built and tested up to 1.5 MPa. This work has set this technology to a TRL of 5.

Key Barriers to Development

Key gaps or barriers associated with hydrogen production as it relates to N-R HES include:

- *Variable operating conditions, including ability to turn on/off with minimal impact.* Typical electrolyzer operation entails constant operation at a given power set-point and minimization of the number of starts that the equipment experiences. If continuous operation is desired, determine a means to continue production at times when heat or power is not available from the SMR.
- *Process heat quality*. Determine if the temperature of the available nuclear process heat is sufficient for hydrogen production; if not, other means must be developed to achieve the necessary heat quality.
- *Process equipment material*. Determine if the material is capable of operating at the temperatures, pressures, and chemistry conditions expected from the process. Determine potential hydrogen embrittlement issues. Determine potential for materials to handle the thermal stresses induced by rapid heating and cooling.
- *Cell degradation, particularly with respect to HTSE*. Progress has been made in this area; however, continue further research to make the process commercial.
- *Siting onsite production.* Hydrogen has its own set of safety codes, standards, best practices, and regulations (Ruth et al. 2014). Ensure more rigorous scrutiny and application of 10 Code of Federal Regulations (CFR) 50 and 52 nuclear power regulations are applied in the presence of a volatile flammable substance (Young 1994).

Development Approach

To address the concerns and challenges identified, the following approach will be taken:

- *Variable operating conditions.* A pilot-scale testing facility can be used to explore the operational flexibility of a hydrogen production unit. Testing can demonstrate whether a hydrogen production unit within an N-R HES is able to respond sufficiently fast and for a sufficiently long duration to participate in dynamic energy management on the utility scale and at end user facilities. The key operating properties to be quantified are initial response time, ramp rate, settling time, duration, minimum turndown, startup time, and shutdown time. The program will: (1) develop control and instrumentation strategies to dynamically optimize the use of excess energy, and (2) in support of operations and maintenance, develop an online condition health monitoring capability for the subsystems within an N-R HES.
- *Process heat quality.* The heat recuperation and/or electrical heating can be applied to achieve the desired process heat quality for hydrogen generation.

5.3.6 Subsystem Technologies: Energy Storage

Energy storage can help build peaking capacity for high-pressure steam and can help in meeting dynamic needs of the grid. Small-scale storage systems (thermal, chemical, electrical) could be integrated within N-R HES configurations to provide power smoothing and increase renewable penetration in the grid. Energy storage has the ability to smooth out the net load curves and could enhance system reliability. Energy storage integration will enable N-R HES to operate in a dynamic manner that could successfully respond to changing energy demands and also maximize the revenue generation by charging and discharging as frequently as possible (i.e., charging when electricity prices are low, and discharging when prices are high).

Technical and Functional Requirements

Specific requirements for energy storage components include the following:

- The main function of energy storage is to provide and build peaking capacity for high-pressure steam and power smoothing.
- Energy storage capacity will be defined for the specific N-R HES configuration, system size, and storage duration needs.
- Energy deposition and recovery times must meet dynamic system needs.

Current State of Development

Different types of energy storage include mechanical, electrical, chemical, and thermal. The different options within each of these categories are summarized in Table 4.

Table 4. Categorized energy storage options.

Mechanical	Chemical	Thermal	Electric
Pumped Hydro	Batteries	Phase-Change Materials	Capacitor (Firebrick)
Compressed Air	Flow Batteries	Molten Salt	Superconducting Magnet
Flywheels	Hydrogen Fuel Cells	Solid Media	
		Steam Accumulators	

As of 2013, pumped hydro storage supplied 23.4 GW of the U.S. grid storage with the remainder provided by 431 MW of thermal storage, 304 MW of battery storage, and 423 MW of compressed air storage (Department of Energy 2013). One potential candidate for electric energy storage is firebrick. Firebrick Resistance-Heated Energy Storage (FIRES), currently under development by researchers at the Massachusetts Institute of Technology (MIT), consists of an electrically heated firebrick recuperator. This recuperator can primarily be used for thermal energy transport to industries requiring much higher temperatures, such as glass, steel, production plant, and refineries. FIRES hot air temperature can be adjusted to the required furnace temperatures by either mixing with cold air or heating with auxiliary natural gas (Forsberg 2015).

Another energy storage candidate is steam accumulators, shown schematically in Figure 20. The basic principle behind this type of energy storage is to inject steam into insulated, pressurized accumulator tanks when the demand is low. When the demand increases again, the steam is flashed out into a secondary steam turbine that generates electricity. An advantage of the separate peaking set is the capacity reserve it offers (Gilli and Beckman 1973). Steam accumulators have been successfully deployed in other energy sectors, such as those currently being used in a solar thermal plant in Spain with 30 to 60 minutes of peaking storage (Forsberg 2011). The storage capacity and efficiency of steam accumulators for HES configurations is currently being studied (Schneider et al. 2016 and Misenheimer and Terry 2015).

Key Barriers to Development

Key gaps associated with energy storage as it relates to N-R HES include:

- Adding energy storage to an integrated system increases the upfront capital cost. Thus, if determined to be necessary in the dynamic analyses conducted, ways need to be identified to make it economically attractive.
- Integrating energy storage components with energy sources other than fossil fuels has yet to be demonstrated. Current electricity production is dominated by fossil fuels, which requires short-duration storage services, if any. Other energy sources may have significantly different storage requirements.

Development Approach

To address the concerns and challenges identified, the following approach will be taken:

- The need for energy storage will be determined via dynamic analysis, and the T&FRs will be defined for the selected configuration.
- Possible energy storage options will be evaluated and ranked based on effectiveness relative to the T&FRs and overall cost.
- Experimental facilities will be used to develop and test scaled storage systems to achieve a higher technology maturity, thereby improving understanding of the individual component performance and performance in an integrated system.

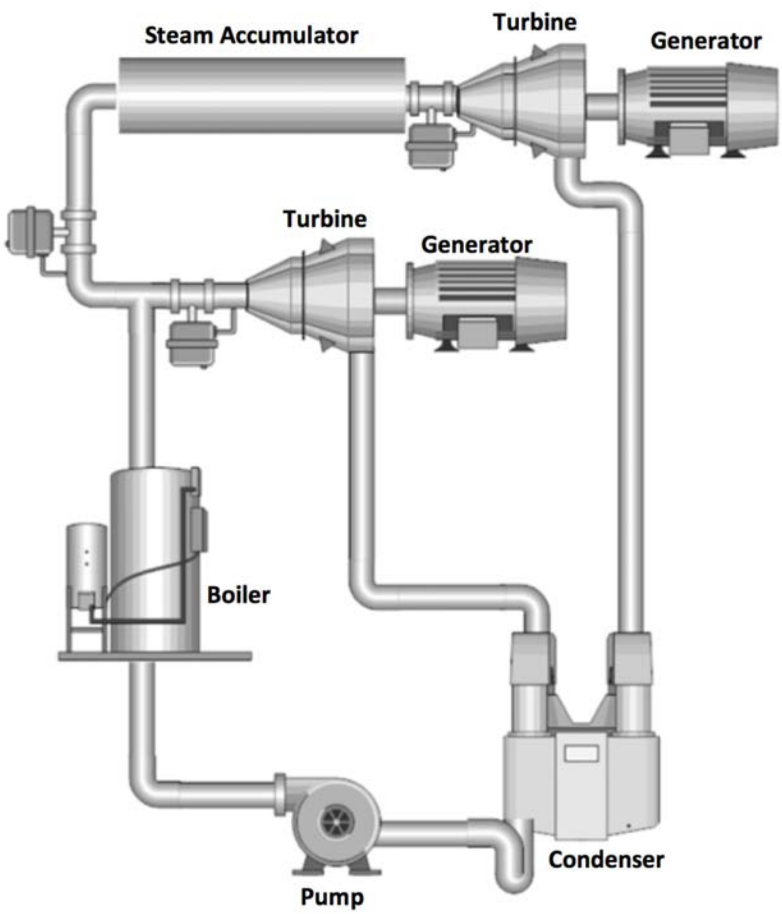


Figure 20. Steam accumulator design.

5.3.7 Quality Assurance in Hardware Testing and Development

A Graded Approach to Work Management will be invoked for all test activities described in the program plan. It is generally expected that the research activities will involve a level of risk that is "Greater than Low Risk." Consequently, these activities will require a laboratory instruction, with support of subject matter experts and approval by a laboratory instruction committee. Equipment setup and testing activities will fall under the jurisdiction of the laboratory manager for the test spaces designated to conduct the experimental activities.

A relevant quality assurance program will be adopted for all testing activities, per the requirements of the laboratory hosting the facility. A graded approach to quality is applicable when a single or uniform method of applying a requirement across a facility or activity does not add value or reduce risk. Therefore, the graded approach to determining the Quality Level Designation is applicable to the activities outlined in the N-R HES program plan and will be performed by an authorized Quality Level Analyst at various stages of the testing activities.

A graded approach is defined by 10 CFR 830, "Nuclear Safety Management," and DOE Order 414.1D Admin Change 1, "Quality Assurance" (QA Order) as the process of ensuring the level of analysis, documentation, and actions used to comply with requirements are commensurate with:

- The relative importance to safety, safeguards, and security
- The magnitude of any hazard involved
- The life-cycle stage of a facility or item
- The programmatic mission of a facility
- The particular characteristics of a facility or item
- The relative importance to radiological and non-radiological hazards
- Any other relevant factors.

A Quality Engineer will be involved during equipment design, fabrication, and construction to ensure components and systems meet applicable QA requirements. A Quality Assurance/Quality Control Plan (QA/QC) will be developed prior to conducting experimental activities that reach a Quality Level 2 designation (if the unmitigated risk is medium).

5.4 Regulations and Licensing

In the U.S., civilian nuclear reactors are licensed and regulated by the Nuclear Regulatory Commission (NRC)—an independent agency of the United States government established by the Energy Reorganization Act of 1974. The NRC's role is to protect public health and safety related to nuclear energy generation as well as other radiological sources. The NRC licensing process is codified into law in Title 10, "U.S. Nuclear Regulatory Commission Regulations," of the CFR. Licensing of nuclear power plants is carried out in accordance with either Part 50, "Domestic licensing of production and utilization facilities," or Part 52, "Licenses, certifications, and approvals for nuclear power plants," of Title 10. All of the existing nuclear power plants in the U.S. have been licensed through the Part 50 process.

The licensing of nuclear power plants is a highly structured process. Detailed guidance, review plan and applicable acceptance criteria are provided in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (U.S. Nuclear Regulatory Commission 2014). Licensing of the nuclear island should be treated independently within the N-R HES framework. The system design constraints should be defined such that the nonnuclear systems cannot impact the operation and safety of the nuclear subsystem. Potential regulatory issues specific to a particular N-R HES configuration can be addressed by the integrated system owner or operator.

One of the NRC regulations, 10 CFR 50.34, requires an exclusion boundary to be imposed around the plants, the size of which is based on impact to the public in the event of a severe accident. Most LWRs have adopted a standard radiation source term that the NRC has approved for use in calculating the exclusion boundary. Using those guidelines, the boundary is generally about 0.5 mile in radius. It is possible to reduce this boundary if the designer provides a reduced site-specific source term for calculation of site boundary dose and the NRC accepts its use. Therefore, for a smaller core inventory, such as that for an SMR, it may be possible to reduce this exclusion boundary. The coupled industrial process and renewable generators should be located outside the required exclusion zone around the reactor, such that these processes will not be under the NRC license. Similar conclusions were reached in a 1986 study by the Tennessee Valley Authority while examining the use of the Yellow Creek Nuclear Power Plant to produce industrial steam (Tennessee Valley Authority 1986).

Having the chemical facility just outside the exclusion boundary will place it in an area called the low-population zone, as defined in 10 CFR 50.34. Persons living and working in the low-population zone are expected to be able to take cover or evacuate the area in the case of an accident at the nuclear plant. This implies that the integrated industrial user, such as a chemical facility, would be involved in the emergency planning aspects of the nuclear plant. Safe shutdown activities within the chemical facility would need to be rapid enough that the operators and workers can evacuate in a timely manner in the event of an accident at the nuclear facility. An emergency planning zone extends out to a 5 to 10-mile radius from the nuclear plant.

In a recent Policy Issue (U.S. NRC 2016) the NRC acknowledges the fact that the use of a mechanistic source term calculation for design-basis accidents for SMRs will potentially result in smaller source terms (when compared to large LWRs), primarily due to reduced fuel content and passive designs. This may have significant implications in terms of required separation between nuclear and nonnuclear subsystems, which directly affects the minimum land area for a hybrid energy system and thermal efficiencies for thermally coupled systems. The NRC has not yet voted on the use of mechanistic source terms in design basis accident dose analysis and siting.

While the NRC regulatory authority conventionally only deals with the nuclear island, deployment of nuclear reactors within an N-R HES configuration may bring additional regulatory impediments due to non-conventional interaction paths between the nuclear systems and nonnuclear systems. In a conventional deployment, the nuclear reactor interacts with the external world through two nominal interfaces: (1) cooling water intakes from the ultimate heat sink (typically a stream or a large body of water), which accounts for about two-thirds of energy rejection into the environment, and (2) electrical connection to the grid. Any deviations from the nominal deployment model must be scrutinized, particularly at the interfaces where the nominal heat rejection path is varied.

An example case is shown in the tightly coupled configuration in Figure 21, where the hot stream from the reactor is apportioned between the balance of plant and process heat users through a thermal storage system shown with label No. 2. This configuration indicates that the heat rejection path from the nuclear reactor to the ultimate heat sink includes a manifold that may need to be qualified for nuclear service. Furthermore, the coupled design must provide assurances that the steam generator feedwater supply will not starve under normal conditions or during anticipated operational occurrences. It should be noted that the list of anticipated operational occurrences for a nuclear power plant deployed within an N-R HES configuration will likely be more extensive than that of an LWR that only generates electrical power. Therefore, it will not be possible to deploy a standard reactor design into a tightly or thermally coupled hybrid energy system scenario without significant licensing amendments during the combined operating license (COL)/site suitability approval process.

Because the nuclear facility thermal hydraulically interacts with the nonnuclear facilities through an interface, such as the thermal storage unit in Figure 21 (label No. 2), this boundary will most likely require regulatory analysis. An example analysis is the steam generator tube-rupture event, which would cause a radiological event in the thermal storage unit. While this is a routine analysis for balance-of-plant systems in nuclear power plants, the analysis may be more challenging if the system of interest is outside the nuclear island. One potential solution might be to incorporate the interfacing subsystem into the nuclear island.

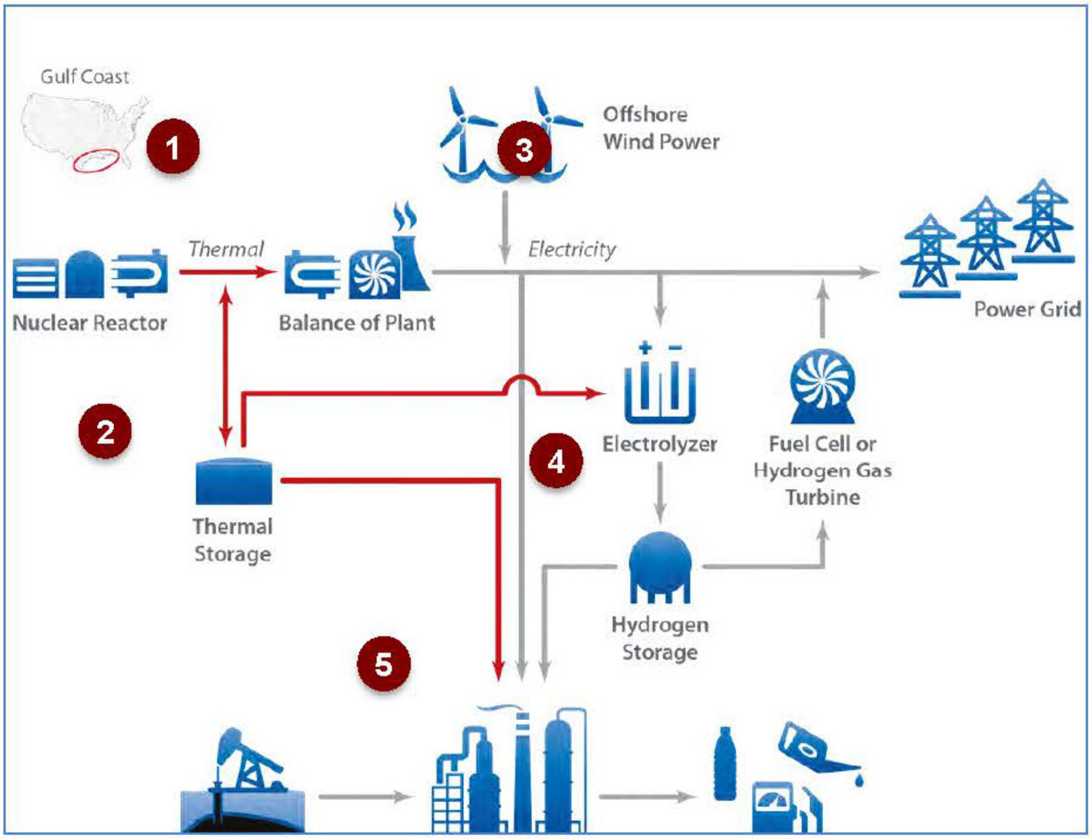


Figure 21. A potential integrated system scenario for the Gulf Coast Region.

Appendix A to 10 CFR 50 contains the general design criteria that establish the minimum requirements for the principal design criteria for LWRs. While these criteria are specifically written for nuclear systems, some provide requirements for protection against external events and potential issues due to sharing of structures, systems and components (SSCs). These design criteria should be reviewed in the development of design requirements for N-R HES to ensure that regulatory hurdles do not arise in the licensing process.

Recommendations

At a high level, there appears to be no regulatory setback that would prohibit deployment of nuclear power plants within an N-R HES configuration. However, there are potential impediments related to nonconventional deployment of nuclear reactors that must be addressed in a timely fashion.

Recommendation 1. It is highly likely that the nonconventional deployment of nuclear power plants will face some regulatory challenges. Therefore, for a successful deployment scenario, key issues should be identified, and R&D efforts should be planned for timely resolution. Regulatory uncertainty may obscure potential economic and environmental benefits that N-R HES can offer.

Recommendation 2. A risk-informed, performance-based approach should be adopted early on for SSCs that either directly interface with the nuclear subsystem, or have indirect risk-significant function in its safe operation and shutdown. Detailed failure modes and effects analyses (FMEAs) may help developing a strong regulatory case.

Recommendation 3. The N-R HES ownership model, which could include a consortium of owners, must define the control boundaries in emergency response, and allocation of authority.

Recommendation 4. Evaluation of potential accidents is common practice for nuclear systems; in particular, the Level 3 probabilistic risk assessments (PRAs) from a radiological release standpoint should be completed. However, understanding the potential risk posed by coupled industrial facilities may require detailed mechanistic analyses (similar to mechanistic source term calculations).

Recommendation 5. R&D on resilient I&C architectures may be necessary to ensure safe performance of the integrated system.

Potential regulatory aspects of N-R HES will be addressed in the Phase I and II R&D activities. It is important to note that site permitting and ultimate acquisition of a construction and operating license will be the responsibility of the industry partner who will build the prototype system. Detailed engineering design and the process for site permitting (Phase III) is slated to begin while Phase II activities are still ongoing, as these efforts can take multiple years to complete (see Section 4).

5.5 Nuclear Insurers

Development and operation of a nuclear site in the United States requires that the operating company obtain insurance for the site during construction and for the operating facility. As the N-R HES 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. Obtaining insurance to build and operate an N-R HES will be the responsibility of the operating utility. Although the DOE-led R&D intended to advance the N-R HES concept to TRL 6 will not require siting and construction of a nuclear-fueled facility, preliminary investigation of the anticipated insurance requirements for an operational facility will be conducted with industry collaboration during Phase II of the N-R HES development to ensure that there will be no significant roadblocks to commercialization of N-R HES.

Nuclear insurance[6] in the United States is provided through American Nuclear Insurers (ANI). ANI was established following the 1957 Price-Anderson Act, which amended the Atomic Energy Act of 1954. Its purpose is to encourage commercial development of nuclear energy and to establish a framework for handling potential liability claims. This was accomplished through the pooling of stock insurance companies to create ANI. This pooling leads to a large insurance capacity spread over a large number of insurance companies.

ANI insures all areas of the nuclear fuel cycle, including:

- Power plants
- Test and research reactors used by industry, medicine, and academia
- Enrichment facilities

[6] Information in this section has been summarized from various websites, including:
http://pbadupws.nrc.gov/docs/ML0327/ML032730606.pdf
http://www3.sce.com/sscc/law/dis/SongsOIIDocLibrary.nsf/0/D16F36EF2D02A81E88257AF0006D05D4/$file/NEIL%20Primary%202011-12.pdf
http://www.amnucins.com/?wpdmpro=need-for-nuclear-liability-insurance
http://www.ans.org/pi/ps/docs/ps54-bi.pdf
http://www.amnucins.com/?wpdmpro=ani-brochure

- Fuel fabricators
- Low-level waste management and disposal facilities
- Shippers and transporters
- Suppliers of nuclear-related products and services.

With respect to new construction, ANI and Nuclear Electric Insurance Limited (NEIL) currently insure Georgia Power Company's Vogtle site, Units 3 and 4, and SCANA's V.C. Summer site, Units 2 and 3, NRC regulations require licensees to carry onsite property insurance, which is only provided through NEIL. For the balance of the site, the insurance regulations, requirements, and markets have a wider selection of providers and options. Additionally, the insurance regulations, requirements, and markets depend on the nature of the coupled industry.

6. KEY PARTICIPANTS

The multi-disciplinary nature of nuclear-renewable hybrid energy systems requires the engagement of experts across the DOE national laboratories, universities and industry for the design, development, analysis, and testing of components, subsystems, integrated systems and the associated interconnections and control infrastructure. The current program plan describes the DOE Office of Nuclear Energy plan for development of N-R HES, with INL designated as the lead laboratory. Work is conducted in parallel with related activities funded by the DOE Office of Energy Efficiency and Renewable Energy, with NREL designated as the lead laboratory. It is anticipated that, as the N-R HES concept is further developed, the DOE-NE and EERE activities will merge in a single roadmap. The current NE program organization, management, and execution are described below. Additionally, potential synergies with other programs across DOE are identified.

6.1 Program Organization

The organization of the N-R HES program assumes central management of the program via the lead national laboratory. During Phases I and II of the N-R HES development, a majority of the research will be led by national laboratories. It is anticipated that universities will also provide significant research contributions through competitive awards, such as the Nuclear Energy University Program (NEUP) through DOE-NE and through R&D directed to the INL National Universities Consortium (NUC). As the program matures, industry partnerships will be established to ensure technology relevance and to support transition of the program into Phases III and IV. The current program plan covers technology maturation through TRL 6, marking the end of Phase II. At that time, industry is expected to lead the final stages of development to reach commercialization of nuclear-renewable hybrid energy systems. Figure 22 illustrates the current program organization, showing program leadership, focus areas, and specific technical areas into which the work is divided.

6.1.1 National Technical Director

The N-R HES program will be centrally managed by a National Technical Director (NTD) and Deputy National Technical Director. The NTD and Deputy NTD will be selected to cover the broad experience area necessary to manage research across the broad technical areas inherent to N-R HES.

6.1.2 Focus Areas and Technical Areas

Focus area leads will be selected for modeling and simulation, hardware development and testing, and industry relations, each having a subset of technical areas defined within them.

Modeling & Simulation Focus Area

Technical Areas: Simulation framework design

Component and subsystem performance models

Model integration, optimization, and control

Hardware Development & Testing Focus Area

Technical Areas: Infrastructure Design and Installation:

- Laboratory Design (Principal Researcher): Mechanical, electrical, process, instrumentation design
- Laboratory Construction and Installation (Laboratory Manager)
- Work Authorization Committee: Quality engineer, fire engineer, industrial safety and health specialist, subject matter experts

Thermal Systems: Thermal energy generation system, heat transfer subsystems and thermal energy storage (includes concentrated solar thermal energy tie-in)

Power Cycles: Design of power cycles, electricity generation and distribution, electrical energy storage, and demand response agents

Renewable energy power generation and microgrid connections

Industrial energy users

Instrumentation, monitoring, and controls: Data systems and visualization

Industry Relations Focus Area

Technical Areas: Interaction with and coordination of current and potential partners

Industrial Advisory Committee interface

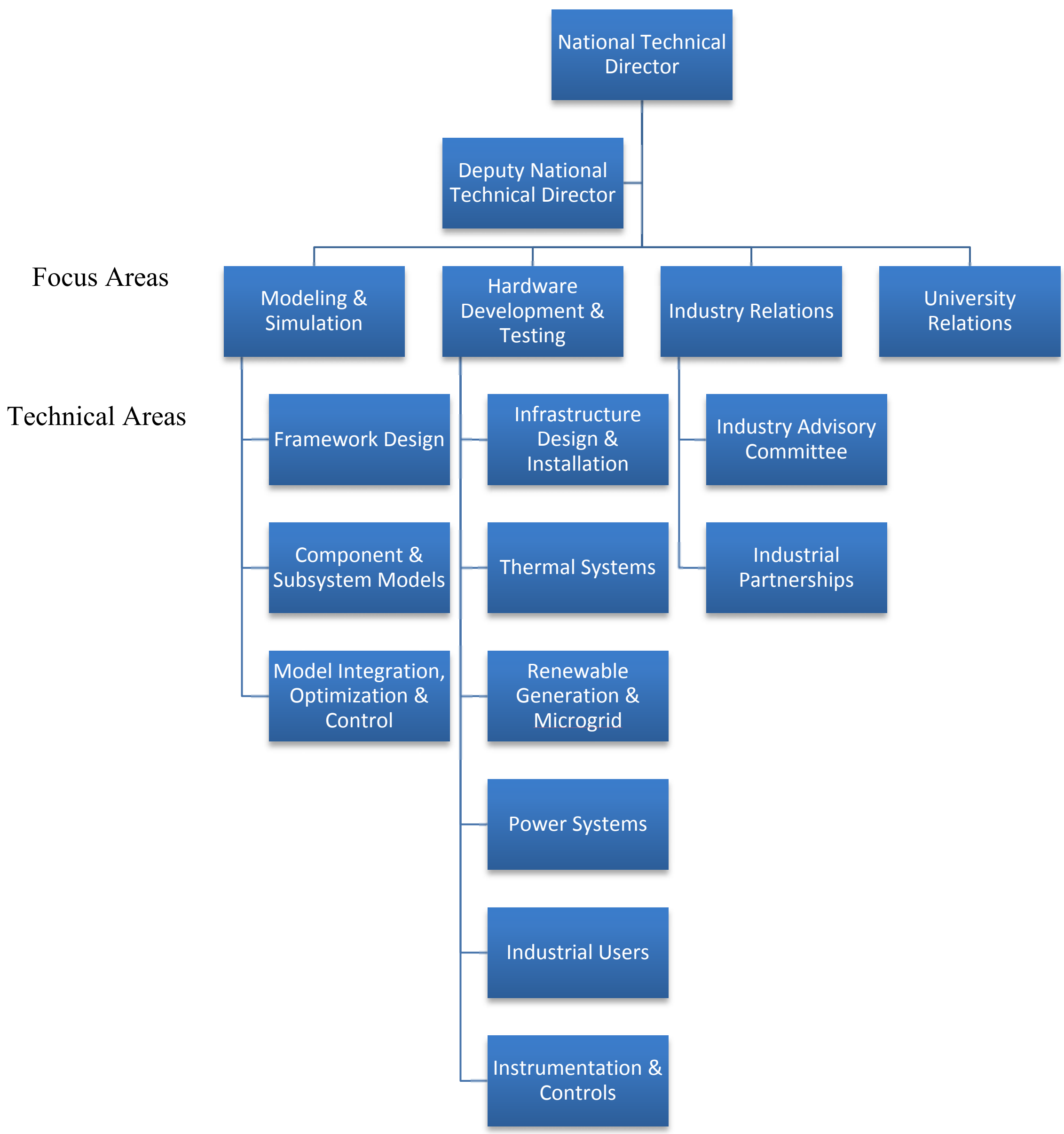


Figure 22. Program organization showing leadership, focus areas and technical areas.

6.1.3 Key Laboratory Roles

The primary roles of each DOE-NE participant laboratory currently involved at the onset of the N-R HES program are defined below. Each of the laboratories has modeling and simulation experience and experimental capabilities that may be used to support component testing, leading up to integrated systems testing and verification. These test facilities may be used to validate computational models, which may in turn be used to create virtual component interaction in the integrated test bed. It is anticipated that, as the program matures, additional team members will be added and roles will be expanded where appropriate.

Idaho National Laboratory

- Program management and strategic direction
- Dynamic integrated system modeling and associated simulation framework development
- Nuclear systems modeling
- Industrial process development
- Next generation distributed and resilient control systems
- Market analysis
- Metrics definition and evaluation, benefits estimation, and options selection
- Economic analysis
- Hardware design, development, and testing.

Oak Ridge National Laboratory

- Component modeling
- Dynamic system modeling
- Metrics definition and evaluation, benefits estimation, and options selection
- Economic analysis.

Argonne National Laboratory

- Component modeling
- Next generation distributed and resilient control systems
- Grid modeling/system interface with the grid
- Metrics definition and evaluation, benefits estimation, and options selection.

Note that parallel activities at NREL will be coordinated with the DOE-NE-led program. Key areas for NREL contribution include metrics definition and evaluation, benefits estimation, architecture options selection, market analysis, grid modeling, renewable system modeling, industrial process development, and electricity interface development.

6.1.4 Internal Program Communications and Information Exchange

The NTD will host regular (e.g., weekly) meetings among the program participants to ensure strong cross-laboratory communications. A private-access SharePoint site has been established to facilitate data and file sharing among all participants. A secure repository will also be established for exchange of model components to support development of integrated system simulations.

6.1.5 Industry Partnerships

Potential technology developers and adopters, including reactor vendors, renewable developers, etc., will be engaged early in the N-R HES program. This process will include the following steps:

- Identify key stakeholders
- Engage stakeholders in research definition via laboratory/industry/university workshops
- Develop early R&D partnerships.

Early definition of potential industry partnerships will allow definition of a strategy for transition from DOE leadership to industry leadership following achievement of TRL 6 testing of a pilot-scale integrated system in a nonnuclear test facility. It is anticipated that industry will be engaged in research definition and structure in Phase I, and will be active partners in Phase II with funding provided via a DOE Funding Opportunity Announcement or other similar mechanism.

6.1.6 University Partnerships

DOE-NE engages university researchers through competitive research grants that are managed through NEUP. Specific research needs for the N-R HES program will be included in the annual NEUP call for proposals to ensure that university research is targeted in areas that are not currently being developed within the laboratory structure. As additional funding becomes available, it is anticipated that a larger university-led research project will be established through a NEUP Integrated Research Project (IRP), which allows financially larger projects to be awarded to university researchers in specific topic areas. These topical areas are also defined in the annual NEUP call for proposals. NEUP proposals are reviewed for programmatic relevance by laboratory and DOE-NE program management and are then distributed to independent reviewers for detailed technical review.

INL is operated by Battelle Energy Alliance, LLC. Governing members include an NUC comprised of MIT, North Carolina State University, Oregon State University, The Ohio State University, and University of New Mexico. These universities have strong research programs in nuclear reactor systems modeling, instrumentation and controls, materials development, novel heat integration and energy storage concepts, and power cycles analysis and development. These universities will be specifically engaged to become active contributors in the R&D team early in the program, while also encouraging other external universities to apply for research grants.

Massachusetts Institute of Technology is uniquely positioned to support N-R HES studies as a member of the INL NUC. Faculty, students and staff conducting research in the MIT Nuclear Engineering Department and under the MIT Energy Initiative have significant research experience in advanced energy systems, such as N-R HES (Forsberg 2015). Hence, MIT will serve as the lead university partner in N-R HES R&D activities. Key MIT roles include market analysis and component modeling.

6.1.7 Industry Advisory Committee

An Industry Advisory Committee (IAC) will be established during Phase I R&D activities. The N-R HES IAC will provide advice to the co-NTDs on relevant research areas of interest to the intended industrial user community. The IAC will advise the co-NTDs on an appropriate path forward for the maturation of integrated N-R HES, including tightly coupled, thermally coupled and loosely coupled systems. The IAC will be comprised of approximately ten representatives from multiple industrial communities: reactor vendors, renewable (wind and solar) developers, chemical industry, independent system operators, etc.

6.2 Potential Synergies with Other DOE Programs

This program plan emphasizes the development path for N-R HES, which directly couple clean energy generators to the electric grid and industrial manufacturing industries, including connection of the transportation industry via alternative fuel options. The Quadrennial Energy Review (U.S. DOE 2015a) and its companion Quadrennial Technology Review (U.S. DOE 2015b) acknowledge the growing need for flexible power generation assets that either adapt to, or enable build-up of, renewable energy on the grid. Hybrid energy systems can provide this flexibility, while simultaneously providing additional benefits as described in Section 3.

It is envisioned that the U.S. energy sector will evolve to become significantly more connected than it is today, including use of thermal and chemical energy currencies (primarily hydrogen) to move energy between the electricity, transportation and manufacturing services. This evolution suggests a potential DOE cross-cutting effort across NE, EERE, Fossil Energy (FE), and OE. Participation of the Advanced Research Projects Agency-Energy, and regulatory division participation of NRC and FERC is also expected. Some examples of potential program synergies are listed Table 5. Inclusion in this table does not imply current or future commitment of any office, except as specifically noted.

This program plan assumes that a new generation of small modular nuclear reactors will begin to enter the power generation market beginning in the mid-2020s. N-R HES may then follow with a prototype facility around 2030, starting a path to inclusion of integrated systems in future energy markets. These nuclear-renewable hybrid energy systems are likely to include configurations that support hydrogen production to support grid ancillary services, fuels refining, biofuels production, and environmentally friendly manufacturing. Focused R&D in N-R HES design, optimization, and testing for high-priority hybrid configurations, coupled with the identified complimentary research programs, will enable a more efficient, environmentally sustainable energy sector in the future.

Table 5. DOE Cross-cutting development of N-R HES.

DOE Office	Program Office	R&D Synergy Potential
NE	Nuclear Reactor Technologies	• LWR sustainability program • SMR license certification • Thermal energy transport • Human factors in plant operations • NEUP projects
NE	Advanced Reactor Technology	• High-temperature SMR reactor design • Supercritical CO_2 power cycles • Reactor instruments and controls
OE	Grid Modernization	• Power systems management • Demand response by residential, commercial, and industrial users • Energy Storage: pumped hydro, compressed gas, flow batteries, plug-in hybrid vehicles
EERE	Energy Efficiency: Advanced Manufacturing Office	• Clean Energy Manufacturing Innovation Institute; Advanced sensors, controls, platforms, and modeling for manufacturing • Combined heat and power (CHP); Higher efficiency integrated set of technologies for simultaneous, on-site production of heat and power • Electronics National Manufacturing Innovation Institute (Power America) • Next Generation Electric Machines; Power electronics and motors with high-speed integrated MV drive systems for a wide variety of critical energy applications • Clean Energy Manufacturing Initiative • Advanced Manufacturing Technology Consortia (AMTech) Program
EERE	Renewable Power Office: Wind, Solar, Geothermal, Water	• Strategies for incorporating increasing amounts of wind energy into the power system • Thermal energy storage relevant to concentrated solar energy management • PV solar integration with the grid • Enhanced geothermal; supplemental heating of rock or fluids • Brackish and seawater water desalination
EERE	Advanced Transportation: Vehicles, Hydrogen and Fuel Cell Technologies, Bioenergy	• Vehicle batteries for electrical energy storage • Hydrogen production, storage, and delivery on an industrial scale • Biomass feedstock supply and biofuels
FE	Clean Coal Research: Advanced Energy Systems	• Clean coal power with oxygen from electrolysis and water splitting • Hydrogen combustion in gas turbines and solid oxide fuel cell • Unconventional fossil fuels conversion to synfuels and value-added carbon products

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Appendix A

N-R HES BENEFITS: FLEXIBLE GENERATION

Appendix A

N-R HES Benefits: Flexible Generation

N-R HES can provide flexibility through integration with industrial applications that provide energy management options via responsive load. In many cases these responsive loads can respond to changing net load more rapidly than generators. Grid-scale energy storage can also provide added flexibility to grid balancing areas, although the available options are currently limited. N-R HES can incorporate smaller-scale energy storage within the system boundary to provide an additional energy management option, and chemicals produced via the coupled industrial process (e.g., hydrogen) offer versatile storage options that can supplement electricity generation or can be sold as a commodity.

A.1 Flexibility via Responsive Load

Responsive load, which can be integrated at the level of the grid or within an N-R HES, is one option to increase grid flexibility. In many cases, responsive loads are significantly faster to respond and are more accurate than generators. For example, incorporating fast load response into microgrids further extends the reliability response capabilities that can be offered to the interconnected power system (Kirby et al. 2007). A potential candidate for a responsive load is an electrolyzer, which uses electricity to separate water into hydrogen and oxygen. This concept has been tested previously by NREL; the findings show that electrolyzers, acting as demand response devices, can respond sufficiently fast and for a sufficienty long duration to participate in energy management on the utility scale and at end user facilities (Eichman et al. 2014 and Harrison et al. 2009). Another attractive option for a responsive load is reverse osmosis (RO) desalination, which uses electrical power to separate the fresh water from the saline feedwater. Case studies performed by Idaho National Laboratory (INL) show that an RO plant can respond quickly, settle sufficiently fast, and maintain the required change for a long enough duration, in support of various types of ancillary services, such as operating reserves (i.e., regulating, ramping, and load following) (Garcia et al. 2015).

A.2 Flexibility via Energy Storage

Another alternative for grid flexibility is grid-scale energy storage. Potentially beneficial energy storage technologies include pumped hydro (mechanical), compressed air (mechanical), hydrogen-based approach (chemical), and flow batteries (electro-chemical).

Pumped hydro plants have excellent energy storage characteristics and currently account for 99% of a worldwide storage capacity of 127,000 MW_e of discharge power (Dunn et al. 2011). However, hydroelectric plant designs depend upon large differences in elevation that exist only in limited locations. Furthermore, their output power and stored energy density are very low compared to those resulting from other energy storage technologies (e.g., flow battery). Thus, pumped hydro storage requires a large reserve area to achieve the same generation output, resulting in high construction costs.

Compressed air energy storage uses air as the storage media. When excess low-cost power is available, air is compressed and stored in underground caverns. At times of peak demand, the compressed air is drawn from the cavern and flows to a combustion gas turbine to produce electricity. This type of storage has a large-scale capacity comparable to pumped hydro storage, but with (relatively) lower cost and fewer geographic restrictions (Bullough et al. 2004). Several systems are in operation, and the coupling of such systems to solar electricity has been proposed (Zweibel et al. 2008). However, as in pumped hydro storage, the energy content of compressed air is low, making it expensive to use for seasonal storage of electricity. Additionally, the use of compressed air is limited by the amount of air that is used by the fleet of combustion turbines serviced. This practical limit may be only a few percent of the desired energy storage capacity for some periods of the year when renewable energy capacity is consistently high.

Hydrogen is another clean, versatile energy carrier that can supplement electricity generation. It can be produced by an electrolyzer, as discussed above, when net electricity demand is low, stored onsite, and used later in a fuel cell system or combusted to provide electricity and heat (Ruth et al. 2014). Unlike electricity, hydrogen can be stored inexpensively for days, weeks, or months in large underground facilities with the same technology used to store natural gas (Egilmez et al. 2013). Its high-energy density would drastically reduce the gas storage volume and corresponding storage costs. However, the round trip efficiency from electricity to hydrogen and back to electricity is less than for thermal heat storage (Forsberg and Aumeier 2014). Therefore, hydrogen may serve as an energy currency for non-electrical needs (e.g., a reductant for iron and steel making, fertilizer production, hydrotreatment and hydrocracking in the fuels refining industry, or biofuels production). It can also be used to enrich hydrocarbon combustion. The oxygen co-product can also be used throughout industry and for oxy-fired combustion. The latter may support clean power from coal-fired power plants equipped with carbon capture technology.

A flow battery (often called a redox flow battery) is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and separated by an ion-selective membrane (Badwal et al. 2014). The electrolytes are stored externally in tanks and pumped through electrochemical cells that convert chemical energy directly to electricity and vice versa, on demand. Flow batteries have the advantages of: a high number of full charge/discharge cycles (over 10,000 cycles) before replacement is needed, flexible operation during charge/discharge cycles, modularity, easy transportability, high power efficiency and fast response, and can be deployed at a large scale (on the order of 100 kW_e to 10 MW_e) (Ponce de León et al. 2006). The modularity and scalability of these devices means they can easily span the kW_e to MW_e range. As a result, their main development is presently focused on standalone remote area power systems or grid-energy storage/support in combination with renewable energy generation (Badwal et al. 2014). A major drawback of the flow battery systems is the increased capital and operating costs associated with a chemical plant due to the involvement of pump systems and flow control with external storage (Divya and Østergaard 2009). Their low operational energy efficiencies and resultant high operating costs are attributed to the energy needed to circulate the electrolyte and to the losses resulting from chemical reactions.

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Appendix B

TECHNOLOGY READINESS LEVEL DEFINITIONS

Appendix B

Technology Readiness Level Definitions

The Technology Readiness Level (TRL) process is used to quantitatively assess the maturity of a given technology. The National Aeronautics and Space Administration (NASA) pioneered the process in the 1980s to develop and deploy new systems for space applications. It was subsequently adopted by the Department of Defense (DOD) to develop and deploy new technology and systems for defense applications and the Department of Energy (DOE) to evaluate the maturity of new technologies in their major construction projects. As the project goes forward, performance criteria will be established for each TRL decision gate. The components must successfully meet these criteria to be granted the next TRL, which represents significantly increased technical maturity. As described, TRL indicates the maturity level of a given technology, where 1 corresponds to a basic principle observed and 9 indicates that the system has reached commercial operations.

System maturation follows an iterative process of modeling and analysis involving the development of analytical tools, identification of testing needs, and measurement of data in representative tests that increase in fidelity and similitude with the intended commercial application as the technology is matured. This project follows DOE Guide 413.3-4A, “Technology Readiness Assessment Guide” (DOE 2011), using TRLs with a tailored scale of 1–9 that is comparable to the standard 1–9 scale used by NASA and DOD. TRLs are an input to inform project management of the readiness of a particular technology, component, or system. An assessment for TRLs 1–5 typically occurs on an individual technology or component with a calculated roll-up TRL for the associated subsystem or system made up of individual components. Small-scale and relatively inexpensive testing through TRL 5 facilitates the discovery of technology enhancements that can be incorporated into the final design with high confidence of success because they have been demonstrated prior to full-scale deployment.

As a technology or component progresses to higher levels of maturity, integrated testing occurs. Integrated testing allows TRL assessments to be made directly for subsystems and fully integrated systems. TRL is not an indication of the quality of technology implementation in the design. The integrated testing or modeling occurs at increasingly larger scales and in increasingly relevant environments as the TRL advances.

Key definitions that must be understood in assessing TRL are summarized as follows:

- *Scale*. The size of the test increases from experimental-scale to full-scale.
  - *Experiment-scale:* Experiments performed inside laboratory hoods, walk-in hoods, or with mechanical components up to full-scale equipment pieces.
  - *Bench-scale:* Test scale large enough to simulate transport, mixing, and reaction processes that are representative of real-world conditions, including recycle streams and heat recuperation. Generally at least $1/100^{th}$ of full-scale.
  - *Pilot-scale:* Test scale large enough to ideally simulate integrated component operation accounting for mass transfer and heat recovery integration, including central process control. Generally 1/25th to 1/10th of full-scale.
  - *Full-scale:* All subsystems, components, etc., are tested at the full scale of the commercial system.
- *Integrated Systems*. The technologies tested are progressively integrated to include multiple components and subsystems, culminating in coupled testing of the integrated plant.

- *Relevant Environment*. The testing environment (temperature, pressure, fluid, flow rate) becomes increasingly identical to the prototypic environment. For nuclear systems, "relevant environment" may entail electrical heating to simulate energy input from nuclear processes.
- *Operational Environment.* The testing environment is the same as that for the intended application, including nuclear processes.

The technology readiness assessment assesses how far technology development has proceeded based on documented evidence. It is not a pass/fail exercise, nor is it intended to provide a value judgment of the technology developers or the technology development program. Rather, it is a review process to ensure that critical technologies reflected in a project design have been demonstrated to work as intended before committing to construction expenses (DOE G 413.3-4A). Because of the high cost of larger scale demonstrations, the largest risk and uncertainty must be reduced at lower TRLs and with small-scale demonstrations, testing, and modeling.

The major technical risks identified for each component/subsystem represent the overall uncertainties that must be addressed and reduced to enhance the probability of a successful coupled energy system. These risks are generally reduced as technology is developed. The coupling of components represents a risk that must be reduced through integrated and large-scale systems testing rather than mere component testing or single effects testing. This risk is not reduced entirely until the component demonstrates full system operability and successfully achieves TRL 8. As the project goes forward, performance criteria will be established for each TRL decision gate. The components must successfully meet these criteria to be granted the next TRL, which represents significantly increased technical maturity. The program-specific TRL descriptions are provided in Table A-1, respectively.

Table B-1. TRLs Defined for N-R HES.

TRL	Definition	Environment/Purpose	Scale/Assumptions
1	Pertinent N-R HES concept defined (Basic Principle)	Hypothesis formulated and proven with physics/ science-based first principles approach to quantify value proposition. Literature review completed to identify governing phenomenology and to establish specific technical challenges.	Concept relative to a given N-R HES technical function or operational objective. Idea or concept vetted by technical peers and industry stakeholders.
2	Enabling technology conceptual design and/or application formulated	Physical or computational model of technology or critical subcomponents designed. Technical feasibility supported via low-fidelity modeling and simulation. Technology technical and functional requirements established. Dynamic systems process models used for process development, optimization and process control schema. Technology performance and system efficiency impacts and benefits simulated. Preliminary economic feasibility	Qualified software packages and codes used for component or systems conceptual design, modeling, and simulation. Technology technical risks identified and linked to essential testing activities.

Table B-1. (continued).

TRL	Definition	Environment/Purpose	Scale/Assumptions
		addressed based on applicable figures of merit.	
3	Experimental and analytical proof-of-technology concept, device, or critical function (Proof of Concept)	Governing phenomena and mechanistic behavior characterized through parametric experimental observations. Measurements of critical performance characteristics, relative to N-R HES application, using bench-scale component testing. Rigorous analytical confirmation of technology capability and performance using system modeling and simulations.	Small-scale testing of components to prove physical concept based on governing phenomena and engineering principles. Scale determined based on what is necessary to simulate real-world flow regimes, heat transfer, and reacting systems. Scale is typically on the order of 0.01 to 0.5 L/hr for gas-liquid reaction processes.
4	Extended experimental scale testing to demonstrate technology feasibility	Component technical and functional performance testing and validation at experimental scale. Component performance characterized under relevant pressure, flow rate and/or temperature test conditions. Components integrated to the degree necessary to characterize functionality in the intended integrated subsystem. Model validation based on component response characteristics (e.g., testing of control logic on the affected component).	Component-level experimental-scale testing of components based on technical and functional requirements. Scale is based on geometry necessary to simulate real-world flow regimes, heat transfer, and reacting systems (generally on the order of 0.1 – 1.0 L/hr for gas-liquid reacting processes).
5	Verification of components and interface technologies using bench-scale testing	Component or interface function characterized at bench scale. Components have been defined, acceptable technologies identified, and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection is performed. System is operated with either centralized control or coordinated control of subsystems.	Scale is typically 0.2 to 2.0 L/hr for gas-liquid reacting processes. Test duration is typically continuous for 1 day to 1 week. Nuclear reactor thermal input is simulated with electrically heated components. Real-time digital simulation of some components is applied for renewable components through a power converter.

Table B-1. (continued).

TRL	Definition	Environment/Purpose	Scale/Assumptions
		Assessment of component design scalability.	
6	Technology and system/ subsystem demonstration at pilot scale	Components/subsystems integrated into a system and tested in a relevant, nonnuclear environment. Technical and functional performance viability of critical and/or pre-commercial technologies confirmed on a scale having dimensional similitude of hydraulic flow regimes and heat and mass transfer transient response matching. Test configuration includes control systems and subsystems, instrumentation, monitors, supervisory control, and auto-control conditions.	Pilot plant is generally 1/100th to 1/10th full-scale for each subsystem depending on scalability of the prototype. Scaling of the integrated system may not be the same across all subsystems. Test duration is generally on the order of days to weeks of operation. Nuclear reactor component is simulated with nonnuclear, electrically heated components. Pilot plant design is generally based on a conceptual design basis of the systems. Duration of test operations is from days to weeks depending on test objectives.
7	Prototype technology and subsystem demonstration in nuclear operational environment (Engineering Scale)	Technical and functional performance and viability of heat transfer and apportionment demonstrated on a scale appropriate to address commercial design risks. Provides design basis for Engineering and Plant Construction Front-End Engineering Design of commercial system. Thermal system connected to a nuclear reactor in accordance with the complexity allowed by the NRC licensing certification process.	Demonstration is typically 1/10th – 1/4th full-scale depending on scalability of prototype. An Operational Readiness Review is possible based on preceding non-nuclear TRL 6 testing activities.

Table B-1. (continued).

TRL	Definition	Environment/Purpose	Scale/Assumptions
8	First-of-a-Kind (FOAK) Commercial technology demonstration (Prototype Scale)	Operation of a full N-R HES prototype in the intended operational environment. Multi-stakeholder partnership demonstration of N-R HES commercial application. Provides design basis for Engineering and Plant Construction Final Commercial Design. Thermal system is connected to a nuclear reactor in accordance with the complexity allowed by the NRC license certification process.	1/4th to full-scale commercial technology demonstration depending on scalability of components. Combined License (COL), Design Certification, and Early Site Permit Applications for New Reactors is possible based on preceding TRL 7 nuclear operational environment testing.
9	Actual technology deployed by commercial technology providers and project owners	Commercial design and operation of many kinds of N-R HES systems in accordance with license authority.	Full-scale; commercial operation

Note 1. Scaling factors are consistent with the Chemical Process Industry and Heat Transfer Unit Operations geometric scale-up factors for flow in conduit and planar geometrics; for example, see Zolotarskii et al. (2014).

Note 2. Methodology for scaling up thermal/chemical/mechanical processes generally invokes three basic approaches: (1) *physical approach,* with dimensional and dynamic similarity of governing phenomena for relevant (a) geometric, (b) mechanical (static and kinematic), (c) thermal energy generation and transfer, and (d) chemical reaction mechanisms; (2) *experimental*, also called the empirical approach which involves trial and error and the use of rules of thumb; and (3) *fundamental approach,* in which the development of phenomenological-based models for the description of process behavior in applied. The fundamental approach requires simulation with parametric variation (e.g., usage of a Hankel matrix).

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Appendix C

SYSTEM SCALING, DEMONSTRATION AND MODEL VALIDATION

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System Scaling, Demonstration and Model Validation

System demonstration and model validation reduces both technical and economic risks associated with the novel energy systems studied in this program. Nuclear energy systems have complex and coupled thermal hydraulics, neutronics, and structural mechanics. Safety is initially judged through transient simulations using computational analysis, as full-scale test facilities are expensive and in some cases not feasible. Validation of numerical models and codes is required to demonstrate that all key phenomena, including the various interactions between phenomena, can be correctly determined for the scenarios of interest. Code application requires Phenomena Identification and Ranking Table (PIRT) applicability, validation, and uncertainty analyses (Rohatgi 2015). Numerical models are qualified using validation data from a scaled facility or individual experiment, where the scaled facility is designed to ensure acceptable representation of the most important and relevant phenomena. Experimental data gathered under prototypical conditions also enables the component or system to achieve higher TRL, as described previously in Section 4.

Scaled experiments to demonstrate a concept or phenomena provide performance data, identify scalability issues, and quantify technology gaps. This appendix provides an overview of the relevant attributes of scaled tests to advance the TRL of components, subsystems, and integrated systems (for further details refer to Sabharwall et al. [2015]).

The primary objectives of the scaling analysis are:

1. Obtain the physically scaled dimension for the model based on the prototype of interest.
2. Predict and simulate relevant thermal hydraulic flow and heat transfer behavior at the component and system levels.
3. Obtain key thermal hydraulic data for validation of thermal hydraulic safety analysis codes.

General test matrix objectives for N-R HES are:

1. Validate models using thermal hydraulic and performance data of scaled tests.
2. Demonstrate the mechanical performance and coupling interfaces of the system under normal and transient operating conditions.
3. Demonstrate the performance and viability of advanced instrumentation for coupled systems.
4. Demonstrate operation and control of coupled N-R HES subsystems (e.g., power production, hydrogen production, reverse osmosis for desalination, etc.).
5. Verification and validation (V&V) of methods, codes and models to support N-R HES technology.
6. Assess dynamic response of scaled integrated components and systems prior to full-scale demonstration.
7. Develop and demonstrate startup and in-service inspections test procedures that will be vital for full scale or commercial level.
8. Identity and address the design and development needs within the selected N-R HES configuration at a smaller scale.

In short, the purpose of scaled test facilities is to provide an experimental database that can be used to confirm the phenomena of interest, verify the performance of the system, and support transient computer code V&V. Operation of the scaled facility will also provide valuable insight into transient system behavior and will support the development of abnormal and emergency operating procedures.

Component experiments are generally designed to be as large as practical. Experience demonstrates that components may be scaled successfully at approximately 1/3 scale (Schultz 2015; Levy 1999). Validation matrix experiments are designed as a set to create a "validation pyramid" comprised of supporting levels (Schultz 2015):

- Fundamental experiments provide data that describe the behavior of key phenomena in an environment free of extraneous influences (e.g., influences from other phenomena)
- Separate effects experiments provide data that describe the behavior of key phenomena in typical system components
- Integral effects experiments give data that demonstrate the interactions between key phenomena for the scenarios of interest
- Different scales used in the experiments of the validation pyramid provide a check of the measured experimental phenomena scaling.

In some cases, it will be necessary to perform integrated system experiments to characterize the coupled behavior of two or more components or subsystems. Scaling analysis of these integrated systems typically requires the introduction of many additional non-dimensional groups. Therefore, compromises must be made and an assessment of the effects of scaling distortions must be analyzed. Experimental infrastructure development for testing and feasibility studies of coupled systems can support other projects having similar developmental needs and can generate data required for validation of various models. Experiments will acquire performance data, identify scalability issues, and quantify technology gaps and needs for hybrid or other energy systems going forward.

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