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# Integrated Energy Systems: 2020 Roadmap

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IES
Integrated Energy Systems

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# Integrated Energy Systems: 2020 Roadmap

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**Rev. 1**

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# EXECUTIVE SUMMARY

Many cities, states, utilities, and public commissions are setting energy standards that aim to reduce carbon emissions. In order to realize a clean and resilient energy future, new methods of energy production, distribution, and use will be required. Renewable energy technologies are currently being deployed in significant numbers around the world in response to the desire to reduce emissions, coupled with decreasing costs for these technologies. However, despite this growth, data reported in the International Energy Agency (IEA) *Future of Nuclear* report that was released in May 2019 indicate that the fraction of clean energy contributions to electricity generation has not changed over the last 20 years. This unexpected trend results from the increasing penetration of variable sources driving nuclear energy out of the market in some regions, resulting in the shutdown of some large-scale, non-emitting plants when non-emitting renewable resources are added to the grid. The advent of historically low-cost renewable generation sources, alongside low cost and high availability of natural gas, has driven down the price of electricity, decreasing the minimum baseload generation required to meet load at certain times of the day or year. These factors serve to diminish the role of traditionally baseload nuclear generation. Many nuclear plants have responded to increasing volatility in net demand by operating flexibly, reducing power output to reduce the financial impact to the plant from very low or negative market prices. This practice preserves the contribution of nuclear energy to grid stability and reduces economic losses associated with negatively-priced electricity sales, but it does not reduce the plant operating costs. Nuclear energy is a proven low-emission option that can provide consistent, dispatchable power to meet electricity demands while also providing high quality heat that can meet energy demands beyond the electricity sector—energy system design should seek to maximize these assets.

This roadmap defines proposed integrated nuclear-renewable energy systems and identifies key technology gaps to realizing deployment of commercial scale systems for the production of a variety of electric and non-electric products. Integrated energy systems (IES) under consideration could incorporate multiple energy generation resources and energy use paths, with a focus on low-emission technologies such as nuclear and renewable generators. Together these technologies provide affordable, reliable, and resilient energy while simultaneously reducing environmental emission of $CO_2$ and greenhouse gases (GHGs).

IES are cooperatively-controlled systems that dynamically apportion thermal and/or electrical energy to provide responsive generation to the power grid. They are composed of multiple subsystems, which may or may not be geographically co-located, including a thermal energy generation source (e.g., nuclear), a turbine that converts thermal energy to electricity, additional electricity generation source(s) (e.g., renewable generation, either directly integrated with the nuclear plant or present in the grid balancing area), and one or more industrial processes that utilize heat and/or power from the energy sources to produce a commodity-scale product. IES design and optimization considers both technical performance and economic viability within various deployment markets. Various subsystem designs, integration options, and deployment scenarios are considered in evaluating gaps to commercial-scale deployment of IES.

This document presents a high-level overview of technology development needs for commercial deployment of IES for current fleet light water reactors (LWRs), LWR-based small modular reactors (SMRs), and advanced reactors. This roadmap was compiled by the DOE Office of Nuclear Energy (DOE-NE) Crosscutting Technologies Development (CTD) IES program, but it highlights a broad set of research needs that are being addressed by multiple Department of Energy (DOE) research and development (R&D) programs and by industry. Specific areas of research that will be addressed by the DOE-NE CTD IES program, along with associated timelines and budget needs, will be addressed in a follow-on CTD IES program plan. Other program-specific activities will be addressed in individual program plans as appropriate.

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# ACRONYMS

| | |
|---|---|
| AE | alkaline electrolysis |
| AM | additive manufacturing |
| AR | advanced reactor |
| ART | Advanced Reactor Technologies |
| APS | Arizona Public Service |
| CFPP | Carbon Free Power Project |
| CFR | Code of Federal Regulations |
| CHP | combined heat and power |
| CTD | Crosscutting Technologies Development |
| DED | direct energy deposition |
| DETAIL | dynamic energy transport and integration laboratory |
| DOE | Department of Energy |
| EBR-I | Experimental Breeder Reactor I |
| EERE | Energy Efficiency and Renewable Energy |
| FSR | fast spectrum reactor |
| GHG | greenhouse gas |
| HERON | holistic energy resource optimization network |
| HRSG | heat recovery/steam generation |
| HSSL | human systems simulation laboratory |
| HTGR | high temperature gas-cooled reactor |
| HTSE | high temperature steam electrolysis |
| IEA | International Energy Agency |
| IES | integrated energy system |
| INL | Idaho National Laboratory |
| IRR | internal rate of return |
| JUMP | Joint Use Modular Plant |
| LCOE | levelized cost of electricity |
| LTE | low temperature electrolysis |
| LWR | light water reactor |
| LWRS | Light Water Reactor Sustainability |
| LW-SMR | light water small modular reactor |
| MAGNET | microreactor agile non-nuclear experimental test bed |
| MSR | molten salt reactor |

| | |
|---|---|
| NE | Nuclear Energy |
| NPM | NuScale Power Module |
| NPV | net present value |
| NRC | Nuclear Regulatory Commission |
| NREL | National Renewable Energy Laboratory |
| NRIC | National Reactor Innovation Center |
| PBF | powder bed fusion |
| PEC | photoelectrochemical |
| PEM | proton exchange membranes |
| PG&E | Pacific Gas & Electric |
| PI | profitability index |
| PV | photovoltaic |
| R&D | research and development |
| RAVEN | reactor analysis and virtual control environment |
| RO | reverse osmosis |
| SMR | small modular reactor |
| STCH | solar thermal $H_2$ production |
| TEDS | thermal energy distribution system |
| TES | thermal energy storage |
| TRL | technology readiness level |
| UAMPS | Utah Associated Municipal Power Systems |
| V&V | validation and verification |
| VHTR | very high temperature reactor |
| VRE | variable renewable energy |

# Integrated Energy Systems: 2020 Roadmap

## 1. INTRODUCTION

Many cities, states, utilities, and public commissions are setting energy standards that aim to reduce carbon emissions. In order to realize a clean and resilient energy future, new methods of energy production, distribution, and use will be required. Renewable energy technologies are currently being deployed in significant numbers around the world in response to the desire to reduce emissions, coupled with decreasing costs for these technologies. However, despite this growth, data reported in the International Energy Agency (IEA) *Future of Nuclear* report that was released in May 2019 indicate that the fraction of clean energy contributions to electricity generation has not changed over the last 20 years (IEA 2019). This unexpected trend results from the increasing penetration of variable sources driving nuclear energy out of the market in some regions, resulting in the shutdown of some large-scale, non-emitting plants as more non-emitting renewable resources are added to the grid. The advent of historically low cost renewable generation sources, alongside low cost and high availability of natural gas, has driven down the price of electricity (achieving negative values in some regions during times of high renewable production and low demand, sometimes leading to significant overproduction) and has decreased the minimum baseload required to meet load at certain times of the day or year. These factors serve to diminish the role of traditionally baseload nuclear generation. Many nuclear plants have responded to increasing volatility in net demand by operating flexibly, reducing power output to reduce the financial impact to the plant from very low or negative market prices. This practice preserves the contribution of nuclear energy to grid stability and reduces economic losses associated with negatively-priced electricity sales, but it does not reduce the plant operating costs. Nuclear energy is, however, a proven low-emission option, currently providing 55% of the non-emitting electricity generated in the U.S. (Nuclear Energy Institute 2020). Nuclear energy can provide consistent, dispatchable power to meet electricity demands while also providing high quality heat that can meet energy demands beyond the electricity sector. To fully realize these benefits, it is necessary to better characterize the potential role or roles for nuclear energy amid the growing field of variable renewable generation technologies. This document defines proposed integrated nuclear-renewable energy systems and identifies key technology gaps to realizing commercial scale systems for the production of a variety of electric and non-electric products.

### 1.1 Scope

This roadmap defines potential industrial-scale integrated energy systems (IES) and identifies key technology gaps to achieving commercial deployment of such systems. IES under consideration could include multiple energy generation resources, with a focus on low-emission technologies such as nuclear and renewable generators, and energy use pathways. Together these technologies provide affordable, reliable, and resilient energy while simultaneously reducing environmental emission of $CO_2$ and greenhouse gases (GHGs). System design and optimization consider both technical performance and economic viability within various deployment markets.

IES are cooperatively-controlled systems that dynamically apportion thermal and/or electrical energy to provide responsive generation to the power grid while also supporting the production of other energy products. IES are composed of multiple subsystems, which may or may not be geographically co-located. Envisioned configuration options are described in section 1.2. In the proposed integrated system architecture options presented herein, electricity is considered the primary output, ensuring that grid demand is reliably met within the analysis region (i.e., the grid balancing area, which may include other grid-connected resources). A second operating premise is that the nuclear plant should be maintained at its nominal operating power level at all times. Once electricity demand is met, the integrated system architecture would be designed to dynamically apportion any remaining primary energy to energy storage or to the production of a secondary product. 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 to buffer the dynamics between subsystems and to provide energy on different time scales. For some regions and energy markets, the business case for the IES may suggest that the non-electricity co-product is the preferred primary system output. If this is the case, then producing electricity to meet grid demand, and providing other ancillary services to support the grid, would be the secondary system output. The optimization process for system design and energy dispatch must consider the hierarchy of importance of these output streams, and the IES supervisory control system must also adopt the appropriate hierarchy.

This document describes potentially viable options to shift the paradigm for how nuclear energy is utilized, considering both existing plants and new build plants, describes key energy use technologies to support industry, defines technologies necessary to realize the proposed energy systems, and identifies technology gaps or research and development (R&D) needs to make these systems a reality. While the focus of this document is on nuclear and renewable (e.g., wind, solar photovoltaic [PV], and hydro) energy as primary generation sources, 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 concentrating solar energy systems. Some of the identified technology development needs will be addressed via the Department of Energy (DOE) Office of Nuclear Energy (NE) IES program within Crosscutting Technologies Development (CTD), while other gaps are filled by other relevant programs within DOE-NE (e.g., Advanced Reactor Technologies [ART], Light Water Reactor Sustainability [LWRS], Microreactor program), DOE Office of Energy Efficiency and Renewable Energy (EERE) (e.g., H2@Scale), or other offices. A detailed technical program plan will later be developed as a supporting document to clarify the specific research goals, timelines, and budgetary needs for the CTD IES program. Other program specific activities will be addressed in individual program plans as appropriate.

## 1.2 IES Definition and Proposed Configurations

Proposed IES are categorized based on how subsystems are connected to one another, and how they interact with one another and with the grid. All of the system architecture options described in this document would support grid electricity demand to some extent. Additional energy production can be dynamically apportioned to the production of another commodity or multiple commodities based on the defined goals of the system design, operational dispatch requirements and constraints, and economic factors. Recognizing that these integrated systems would likely be managed by a single financial entity, this flexibility can be used to maximize overall system profitability or return on investment (versus profitability of a single subsystem), ensuring that the system will be competitive within the broader energy market while simultaneously providing non-emitting electricity to the grid. Additional subsystems that provide small scale thermal, electrical, and/or chemical storage may be included within the system architecture to better manage energy within the system boundary and with the grid.

This roadmap focuses on the technical development needs for three proposed IES configurations, as 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 may include chemical energy storage components, or they could entail conversion of stored electrical energy to heat to drive an industrial process. Optimization of configuration architectures would include component and subsystem sizing as it relates to the renewable energy potential, electricity demand, product market, and time-dependent costs and revenues in light of technical constraints associated with the system operation. Three general categories considered for IES architectures are summarized below.

1. *Tightly Coupled IES*. Multiple generation sources (e.g., nuclear, renewable, fossil), energy storage, and industrial process(es) are directly integrated behind the grid (thermally and electrically) and co-controlled, such that there is a single connection point to the grid and a

single financial entity managing the IES (i.e., economic performance of the IES is optimized for the integrated system rather than for each system independently). See Figure 1.

2. *Thermally Coupled IES.* Subsystems may have more than one connection to the same grid balancing area and may not be co-located; however, the generation subsystems are co-controlled to provide electricity and ancillary services to the grid. This category includes thermally and electrically 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 IES.* This configuration is controlled in a similar fashion to the thermally coupled system, but generators would only be electrically coupled to industrial energy users (no direct thermal coupling of subsystems). This scenario allows 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 or repurposing of existing generation facilities with fewer regulatory challenges. These systems may 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 generators, specifically nuclear and renewable power systems in this report, 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.

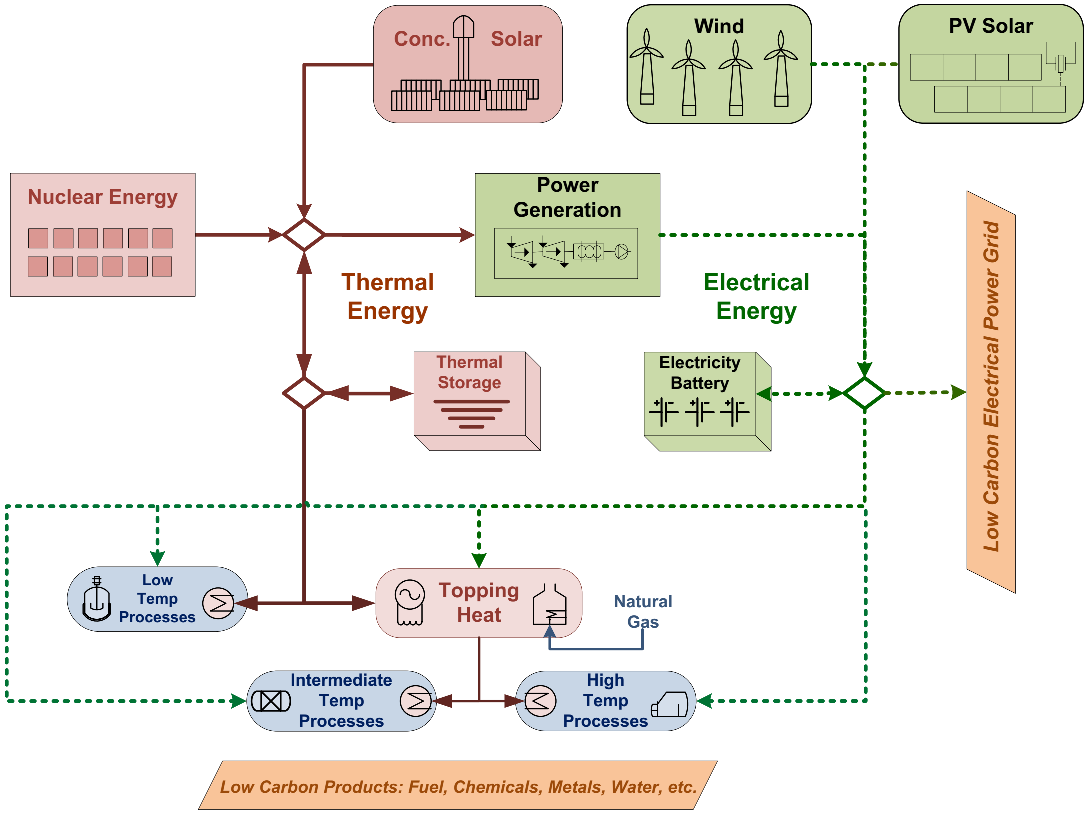



Figure 1. General architecture for a tightly coupled IES, where the generation sources are integrated behind a single connection point to the grid and are managed by a single financial entity. Topping heat may or may not be necessary for intermediate and high temperature processes as a function of the outlet temperature of the selected nuclear reactor technology. Note that, depending on the supported industrial processes and secondary products, chemical energy storage may also be added to this system configuration to further increase its operational flexibility.

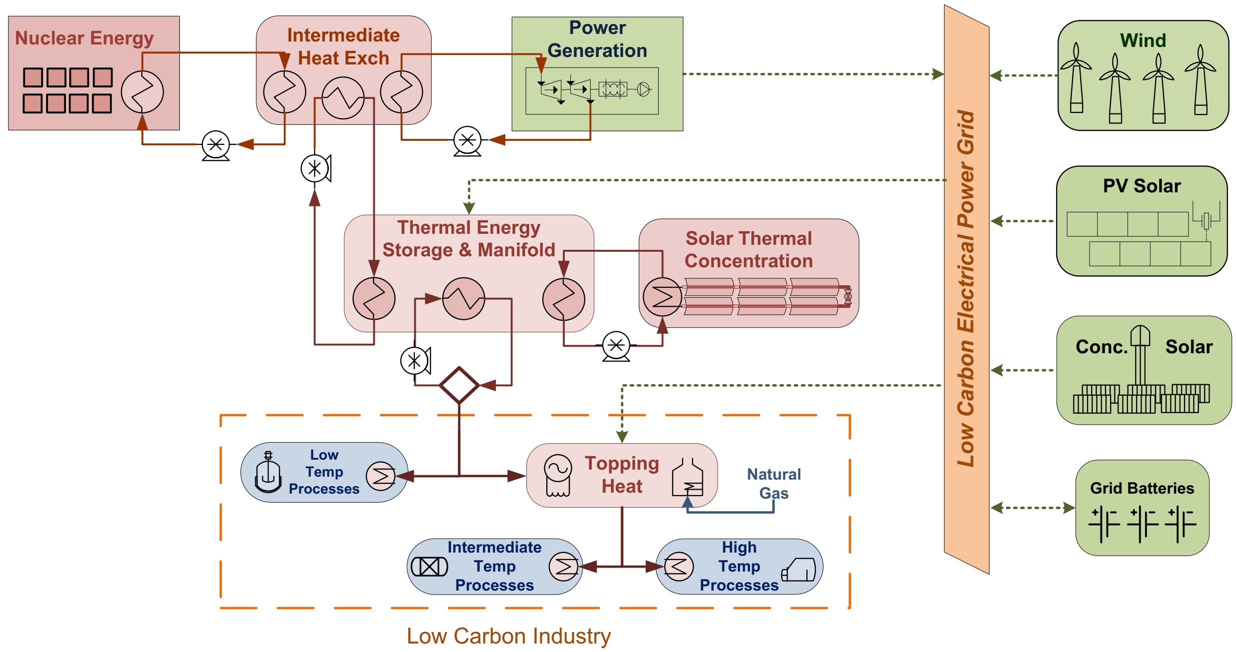



Figure 2. General architecture for a thermally coupled IES, where the nuclear and renewable generation sources are co-controlled and managed by a single financial entity but may not be co-located. Topping heat may or may not be necessary for intermediate and high temperature processes as a function of the outlet temperature of the selected nuclear reactor technology. Note that, depending on the supported industrial processes and secondary products, chemical energy storage may also be added to this system configuration to further increase its operational flexibility.

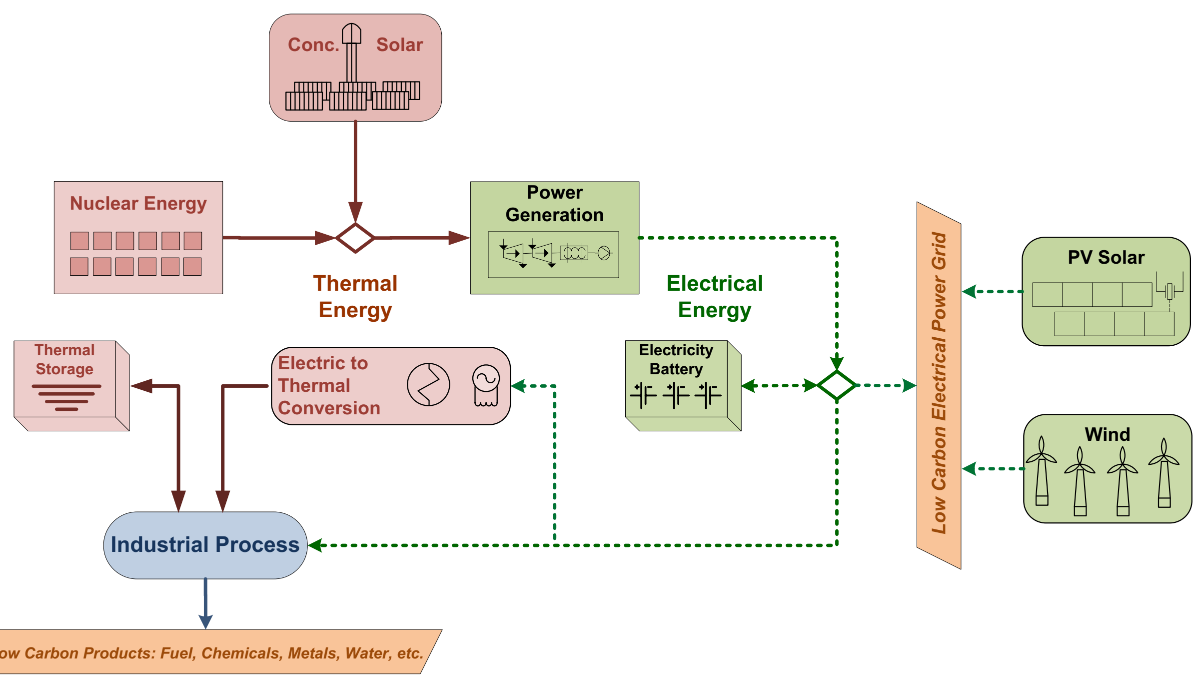



Figure 3. General architecture for a loosely coupled (electricity only) IES, where the generation sources are only electrically connected to the industrial process. Note that electrical-to-thermal energy conversion systems may be included to drive some processes, and, depending on the supported industrial processes, chemical energy storage may also be incorporated.

As shown in Figures 1 to 3, the IES considered herein may include 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[1] to cover operating and capital costs and have a profitable internal rate of return; note that operating at a constant thermal energy output to support secondary products in addition to electricity production will have similar impact on the 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. Note that advanced reactor systems may utilize alternative, non-steam power generation subsystems having similar functionality.
- *Renewable energy generator(s).* Depending on location, renewable source(s) can provide comparatively low-cost electricity and heat. The cost competitiveness of renewables can be strongly influenced by favorable state renewable energy policies that lead to subsidies. More recently, utility companies are aligning with the state goals by setting aggressive net zero emissions power production targets. Solar, wind, hydropower, and purpose-grown crops are considered low-carbon/low GHG energy sources. However, electricity generation by variable renewable technologies (i.e., PV solar and wind) is not dispatchable, meaning that it cannot provide power to follow grid load. Stand-alone renewable energy supply requires sizing the capacity and energy storage systems to meet diurnal, weekly, and seasonal energy demand throughout the year. It would also require a significant build-up of transmission lines to balance area demands and vast new power electronics to deal with power quality conditions. New electrical heating, solar-concentrating, and/or geothermal extraction and enhancement systems would be required to support the basic energy needs of industry.
- *Industrial process.* When coupled within an IES, 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 IES. When heat from the nuclear reactor is diverted to electricity production, the heat delivered to the industrial process can be reduced, or the heat necessary to operate the process must be derived from another source (e.g., natural gas, or stored hydrogen if the aim is to reduce carbon emissions).

  A second option resembles a traditional combined heat/power system in which the nuclear reactor would be owned by a given industry or complex of industries with the nuclear reactor(s) providing a dedicated source of heat and power to the industrial processes but occasionally directing electricity to the grid under a contract to provide reserve capacity when needed. This option is similar to the manner many combined heat and power (CHP) units operate today. However, the evolution of the public electricity grid to include more variable generation sources may require more frequent support of grid peak demand to the extent that the industrial CHP units may be contracted to provide spinning or non-spinning reserve capacity or even power modulation to help regulate the grid.

  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

[1] The capacity factor for an electricity producing installation is defined as the ratio of the actual electrical output over a period of time to the maximum possible electrical output from the installation over that same time period.

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 or to defer energy delivery to a later time. Electrical storage options primarily focus on batteries. 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. Chemical energy storage may include production of hydrogen, which can later be combusted or used for the production of electricity. Note that the specific need for and potential benefits of energy storage may differ for each IES architecture.

The defined tightly coupled and thermally coupled IES concepts require a dual heat delivery system and the controls necessary to apportion heat between electrical power production and a given industrial process. Similarly, the electrical output is apportioned between the grid and the industrial process as required to meet various constraints established for the system. If necessary, power may be drawn from the grid and combined with the heat and/or electricity delivered from within the IES 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 CHP mode to provide both thermal energy and electrical energy. In this example the thermal energy generators (e.g., nuclear reactor and solar concentrator) supply 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, traditional energy generation systems in the base case connect independently to the grid. Interaction between these generators is managed via an independent system operator; all plants in this scenario are owned and operated by independent entities. In the base case, 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. Current State of the Art

Most generators that currently supply electricity to the grid operate independently, producing only one product (i.e., electricity) and working with other grid-connected generators via a grid balancing authority. This is certainly true for nuclear power plants in the U.S. which do not currently support thermal energy needs in industry. This section describes the state of technologies currently in commercial use and technologies that are in the development stage as they relate to the proposed IES applications.

## 2.1 Nuclear Technologies

Nuclear energy has been powering the grid in the U.S. since the Experimental Breeder Reactor I (EBR-I) first sent power to the grid in 1951. Current fleet plants in the U.S. are all light water reactors (LWRs), most of which produce on the order of one gigawatt of electricity (GWe). The field of reactor options is, however, poised to change with the development of microreactors (~1-10 MWe) and small modular reactor (SMR) technologies (<300 MWe) and non-water cooled advanced reactor (AR) technologies. Each of these systems may offer different opportunities to IES applications and may require different interface options. The state of these technologies, specifically as they relate to IES, is briefly described in each of the sections below.

### 2.1.1 Current Fleet (LWRs)

The current U.S. nuclear reactor fleet faces economic challenges in regions of the country where subsidized renewable energy buildup has reduced the wholesale price of electricity to levels that are difficult for nuclear power plants to clear the market throughout the entire year. As natural gas prices continue to decline, large-scale nuclear plants will not be able to compete with natural gas turbines in most regions of the country. Several large-scale nuclear plants, particularly those that operate in deregulated markets, are facing economic challenges that will result in early-plant closures (prior to plant license expiration) (Szilard et al. 2017). Since 2013, six U.S. nuclear power plants have closed, and utilities have announced plans to close nine more reactors within the next ten years. Currently, only Georgia Power Company, which is operating in a regulated market, is moving ahead with the construction of two new nuclear reactors at Plant Vogtle. Unfortunately, this project continues to experience schedule delays, resulting in cost overruns that are likely to dampen the enthusiasm for future nuclear power projects. At the same time, there are positive signs for nuclear energy. Several states, municipalities, and utilities have taken action to be technology-inclusive in achieving carbon reduction goals, allowing nuclear energy to be a key part of the solution for future energy systems.[2] In another action, the Energy Harbor (previously FirstEnergy Solutions) Davis-Besse Nuclear Power Station is receiving State assistance that has allowed the plant to rescind its notice of an intent to close. The state assistance allows the Davis-Besse plant time to prove that it can become economically competitive within an evolving electricity market, as will be discussed further below.

Recent modeling and simulation efforts have effectively demonstrated the value of flexible operation of LWR plants (Boardman et al. 2019; Epiney et al. 2019b; Frick et al. 2019). Earlier analysis results and significant stakeholder engagement led to a new Flexible Plant Operation and Generation R&D Pathway under the LWRS program in FY2019 to complement the CTD IES program. This Pathway is adapting the modeling and simulation tools developed under CTD IES to evaluate location-specific applications of LWRs as operating within an IES. The focus of such analyses is the role of flexible nuclear plant operations (i.e. flexible electrical output to the grid while maintaining constant reactor thermal power) in supporting U.S. industries and the transportation sector by providing low-cost, low-emissions energy. Potential nuclear plant connections to large U.S. industries are shown in Figure 4, where the nuclear power plant is the primary source of energy for producing fuels, ammonia, steel, polymers, and hydrogen.

[2] For more information on these clean energy targets and associated policy actions, see "Clean Energy Targets are Trending" at https://www.thirdway.org/graphic/clean-energy-targets-are-trending, published by Third Way on December 11, 2019.

In the illustrated system configuration, hydrogen is a key energy currency and can effectively incorporate nuclear energy into existing or new U.S. industries. These opportunities are further described in section 2.2.3.

These modeling and simulation efforts helped promote two LWR hydrogen demonstration projects that will be carried out at nuclear power plant sites, one at a plant owned by Exelon Corporation in the U.S. Midwest and a second similar project at the Davis-Besse Nuclear Power Station currently owned and operated by Energy Harbor. Additional projects have been proposed for other current fleet LWRs, and multiple DOE offices are making funds available to support projects via Funding Opportunity Announcements that will support private-public partnerships. See section 4.4.1 for additional discussion on these projects.

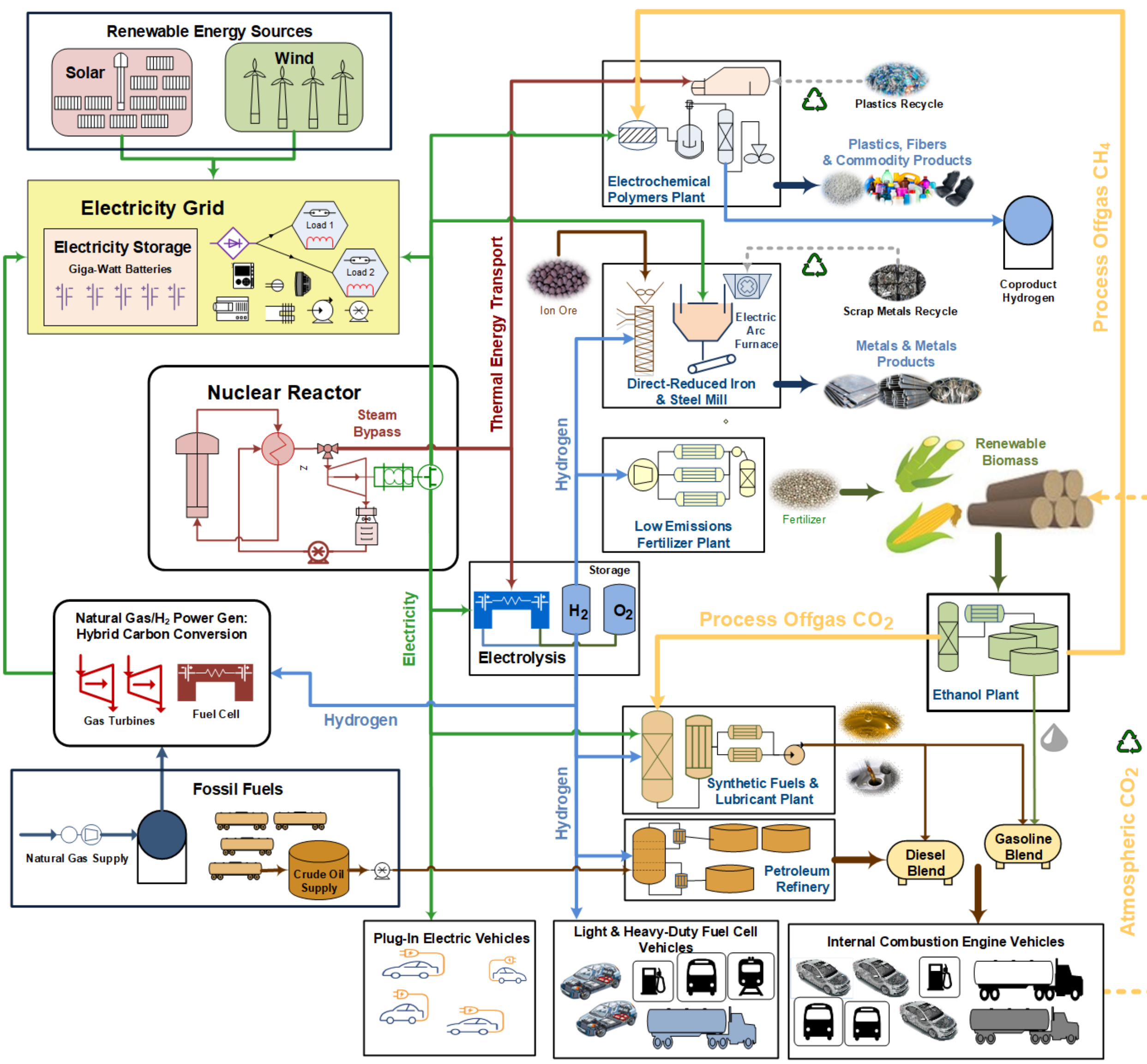



Figure 4. Illustrative examples of near-term integration of existing LWRs with various industry applications.

### 2.1.2 Light Water Small Modular Reactors

By definition, SMRs produce less than 300 MWe per reactor unit, although many SMR concepts would be deployed in multi-module plants that could produce significantly higher amounts of electricity in total. Microreactors are a subset of SMRs that could produce hundreds of kilowatts (kW) to tens of megawatts (MW) of electricity. This section focuses on opportunities for light water cooled SMRs (LW-SMRs), as these systems are anticipated to be the first SMRs deployed commercially in the U.S., with NuScale Power leading in this area via significant federal support. Section 2.1.3 addresses technology development for advanced, non-water cooled reactor technologies, and section 2.1.4 provides additional description of microreactor technologies. The NuScale SMR is an integral pressurized water reactor that would be deployed in a multi-module plant. The NuScale plant concept of small, highly hardened and independent power trains in a shared pool environment offers the potential for diverse utilization of individual modules; a full NuScale nuclear power plant would include up to 12 NuScale Power Modules™ (NPMs), nominally 60-MW electric (MWe) each. In such configuration each NPM would have a dedicated balance of plant, such that some modules could be dedicated solely to electricity production whereas other modules could be dedicated to the production of non-electric products. For the purposes of this roadmap, it will be assumed that a single SMR module would be deployed to support both electricity generation and production of alternative products. Key considerations for such a plant include:

- Interface of the SMR module to thermal energy users via appropriately designed heat exchangers, including the possible need for a tertiary loop to ensure system isolation;
- Control system design for dynamic apportionment of energy generated by the SMR module;
- Sensors necessary to enact the desired control functions;
- Multi-module operation, wherein modules operated from a single control room may simultaneously be producing electricity and directing their energy to the production of alternative products.

At present, no SMR designs have received design certification by the U.S. Nuclear Regulatory Commission (NRC), although NuScale is well along the way in this process and anticipates completion of the final safety evaluation report in September 2020 (Business Wire 2019; U.S. NRC 2020). IES demonstration within a NuScale SMR will require industry partnership, as will be described in section 4.4.2.

### 2.1.3 Advanced Reactors

Numerous advanced reactor (AR) concepts are currently under development by private industry and, in many cases, with the support of federal research laboratories. These concepts focus on inherent safety, waste minimization (optimal use of resources), generation of cost-competitive electrical power, and nonproliferation, but the characteristic most relevant to IES is the potential to extract heat at higher temperature to drive industrial processes. The six advanced reactor systems studied under Generation IV International Forum efforts include: sodium cooled fast reactor, lead cooled fast reactor, supercritical water cooled reactor, very high temperature gas cooled reactor, gas cooled fast reactor, and molten salt reactor. All of these concepts have been researched or deployed to varying degrees both nationally and globally. The three technologies being pursued within the U.S. via the DOE-NE ART program include Liquid Metal (sodium-cooled) Fast Spectrum Reactors (FSR), High Temperature Gas Cooled Reactors (HTGRs), and Molten Salt Reactors (MSRs). Draft roadmaps have been developed for each of these reactor types by the relevant ART program. As technology gaps are resolved for the commercial deployment of these reactor concepts, additional application of such concepts for non-electric applications within an IES may be considered. The sodium-cooled FSR, HTGR, and MSR concepts are currently targeted for commercial demonstration by the early 2030s, whereas other advanced reactor concepts are seeking engineering demonstration by that timeframe. For further information on AR technology development needs see the identified references (Advanced Reactor Technologies 2018; Kim et al. 2017; GIF 2018).

The operation of different AR concepts can leverage a variety of research and operational experience to support deployment within the proposed timelines (Flanagan et al. 2012):

- Modern coal-fired power plants have provided design experience with advanced supercritical-water power cycles.
- LWRs have shown the potential of transparent, high-heat capacity coolants with low chemical reactivity.
- FSR R&D has provided design experience on using low-pressure liquid coolants, passive decay heat removal, and hot refueling.
- HTGR R&D has provided experience with coated particle fuel and graphite components.
- MSR R&D in the proper design configurations has provided data about appropriate materials, procedures, and components necessary to use high-heat capacity liquid fluoride salts as primary or secondary coolants.

The potential of achieving much higher temperatures (500 to 750 $^{o}$C) with ARs opens up possibilities with various industrial users to meet their thermal need and electricity need while maintaining environmental stewardship (Sabharwall et al. 2012). Although most of the global R&D for advanced reactors focuses on temperatures below 750 $^{o}$C, note that some R&D associated with development of very high temperature reactors (VHTRs) still continues. VHTR research seeks to achieve operating temperatures as high as ~900 $^{o}$C, but these systems will require additional development due to significant materials challenges.

### 2.1.4 Microreactors

As noted previously, microreactors are a special class of SMRs designed for unique applications in which MW-scale energy generation is otherwise unavailable or prohibitively expensive. These reactor concepts are designed to produce on the order of 100s of kWe up to 20 MWe and are designed to be factory manufacturable, easily transportable (truck, train, plane, or ship), and neutronically simple so as to allow for semi- or fully-autonomous operation. Microreactors could support distributed generation in a traditional electric grid, or they may be dedicated to an isolated microgrid to provide electricity and to support coupled applications via thermal and/or electrical energy when needed. Microreactors are expected to operate for several years without refueling.

Envisioned microreactor applications include small-scale power generation in remote locations, at deployed military installations, and in locations recovering from natural disasters. The U.S. Department of Defense is pursuing the concept as its military operations become more energy intensive and require portable, dense power sources. Remote, rural communities in the U.S., many of which fly or truck in diesel to run generators, are considering microreactors to support long-term on-site power generation. Their potential use as sources of industrial process heat opens up potential new markets for zero-carbon energy for desalination, hydrogen production, and other industries.

Various microreactor concepts have special R&D needs that must be addressed before they can be deployed by the U.S. nuclear industry. Their small power output necessitates a reduced staffing contingent if the economics are to be competitive. Their operation will need to be semi-autonomous with the human operator acting in a high-level supervisory role with monitoring and control functions highly automated. This will include automatically meeting the time varying demands of the electricity and process heat energy markets. Such semi-autonomous operation is novel in nuclear energy applications and must be demonstrated prior to broad commercial adoption.

Microreactors will require special testing facilities to verify and validate novel interface technologies associated with their design requirements. Concepts proposed to date exhibit very tight coupling of the reactor core to the heat engine, placing stringent operating requirements on the system to avoid material issues related to temporal temperature variations. Turbomachinery will be in close proximity to the core and will require careful shielding considerations.

Microreactor concepts are on a rapid development timeline, via separate investments by the U.S. DOE, Department of Defense, and private industry. In March of 2020, Oklo Power LLC submitted a combined license application to the U.S. NRC, becoming the first advanced fission company in the U.S. to have a combined license application accepted for NRC review in June 2020. Microreactors are expected to be demonstrated in the U.S. as early as the mid-2020s.

## 2.2 High-priority energy use technologies

A key assumption of IES 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 potential heat transfer media (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 ExaJoules of delivered energy, of which approximately 20% is 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). Over 90% of the primary energy required is currently derived from combustion of fossil fuels. Hydroelectrical 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.

Table 1. Development needs for chemical manufacturing process heating and electrification with nuclear energy.

<table>
<tr><th>Type of Heat Duty</th><th>Process Examples</th><th>Process Temp.[3] (ºC)</th><th>Nuclear Reactor Options</th><th>Heat Transfer Media</th><th>Process-related R&D Needs</th></tr>
<tr><td>Feedstock Drying & Minerals Concentration</td><td>• Biomass<br>• Lumber<br>• Phosphate production<br>• Food dehydration and cooking<br>• Wood pulp production and paper/cardboard plants</td><td>50 – 175</td><td>All</td><td rowspan="3">Steam or hot gases; phase-change heat storage media</td><td rowspan="3">Heat transport networks and other thermal energy storage and delivery approaches</td></tr>
<tr><td>Sub-combustibility</td><td>• Biomass torrefaction<br>• Thermal plastics forming and modeling</td><td>50 – 300</td><td>All</td></tr>
<tr><td>Evaporation</td><td>• Ethanol distillation</td><td>120-150</td><td>All</td></tr>
<tr><td>Petroleum Distillation</td><td>• Reboiler heating</td><td>550-600</td><td>MSR, VHTR</td><td>Superheated steam, hot gases, molten salts</td><td>Reboiler design; heat circulation systems</td></tr>
</table>

[3] Note that low process temperatures can be supported by electric heating versus direct thermal integration.

Table 1, cont.

| Type of Heat Duty | Process Examples | Process Temp. (ºC) | Nuclear Reactor Options | Heat Transfer Media | R&D Needs |
|---|---|---|---|---|---|
| Biomass and Coal Pyrolysis | • Indirect heating | 500-650 | MSR, VHTR | Hot gases, molten salts | Reactor heating concepts to support pyrolysis; heat circulation systems; heat augmentation |
| Combined Heat and Power | • Brayton or Rankine power cycles | 450-950 | SFR, MSR, HTGR, VHTR | Steam or hot gases | Power cycles turbo-machinery |
| Hydrotreating or Hydrogenation | • Fluid catalytic cracker | 700-750 | MSR, HTGR, VHTR | Hot gases | Reactor heat transfer design and testing |
| Steam cracking | • Natural gas reforming<br>• Olefin reforming | 800-850 | VHTR | Helium | Bottoming heat use (e.g., power generation); reforming process modifications |
| Oxidative Coupling | • Benzene for styrene, etc. | 800-850 | VHTR | Helium | Bottoming heat use; e.g. Power generation |
| Calcination | • Lime and quick lime | 800-850 | VHTR | Helium | Bottoming heat use; e.g. Power generation |
| Low Temperature Electrochemical Process Heating | • Formic acid production<br>• Low temperature electrolysis | 25-80 | All | Hot oil, pressurized water | Low cost heat transport manifold and heat recuperation |
| Intermediate Temperature Electrochemical process heating | • Alkane deprotonation<br>• Aqueous $CO_2$ reduction<br>• Proton-conduction solid-oxide electrolysis | 500-600 | MSR | Hot inert gases | Low cost heat transport manifold and heat recuperation |
| High Temperature Electrochemical Process Heating | • High Temperature Electrolysis | 800-850 | All | Ultra-supercritical steam; hot inert gases | |

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). SMRs and ARs 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 LWRs through temperature augmentation 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 may require a significantly longer development time and currently have high cost uncertainties (note, however, that industry-predicted costs for ARs are lower than costs to build a large-scale LWR). Heat augmentation technologies represent a key technology gap for IES that could enable utilization of lower temperature reactor technologies (e.g., LWRs) for high temperature process applications. Options include high-temperature heat pumps, resistive heating, or chemical heat pumps, in conjunction with LWRs and renewables to provide heat to industrial processes.

Detailed assessment is required for integration of current and future industrial processes that may benefit from nuclear and renewable energy sources. In summary, integrated 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 IES that can impact U.S. manufacturing industries: unlike fossil fuel plants that are heavily impacted by the price of natural gas and coal, nuclear and renewable energy are not susceptible to supply and price volatility, 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.

### 2.2.1 Water Purification

Increasing penetration of variable renewable energy (VRE) is altering the profile of the net demand.[4] One possible solution to manage net demand volatility is adding stabilizing (responsive) loads to the grid. Depending on the location, another current challenge is that population growth, concurrent with drought conditions, challenges the limited natural surface and groundwater reserves, resulting in rising value (and cost) of water resources. Consequently, plant cooling water may become a non-negligible fractional cost of power generation.

Water purification has the potential to address both of these challenges. Water purification has many applications, such as production of process or potable water as well as demineralization of feedwater and cooling water. Multiple water purification and desalination technologies are used commercially. The most common commercially-operated water desalination technology is Reverse Osmosis (RO). RO relies solely on electricity input to drive a pump that pushes saline water through a membrane. The semi-permeable membrane allows water but not salts to pass through, thus separating the fresh water from the saline feed water. A system is typically composed of six to eight membrane modules connected in series. The concentrate water rejected by the first membrane module plays the role of the feed water for the second membrane module, and so on. These pressure vessels are arranged in rows in each membrane stage, with two-stage membrane separation being typical in brackish water desalination. Each stage has a recovery rate of 50–60%, achieving overall system recovery of 70–85%. A wide selection of commercially available membranes exists for removal of different constituents as well as different salinity levels of the source water. The overall system recovery rate decreases with salinity, and membranes specifically designed for seawater have a recovery rate around 60-70%. As mentioned, other less common water purification methods exist that either rely solely on thermal input or on a combination of thermal and electricity input. The two most common of these technologies are Multiple Effect Distillation and Multi-Stage Flash.

[4] Net demand is the remaining demand that must be met by conventional dispatchable generation sources after variable generation is subtracted from the total electricity demand. VRE generally is not curtailed as a means of managing over-production.

Water purification via RO can be accomplished by coupling an existing nuclear power or other baseload plant in a loosely coupled, electricity only configuration for near-term IES implementation. In the U.S., the Diablo Canyon nuclear plant, operated by Pacific Gas & Electric (PG&E), processes 2200 $m^3$ of seawater per day using RO technology to support all onsite water use needs, including plant cooling and potable water use. The brine that results from the desalination process is rejected and returned to the ocean after being mixed with other rejected water so as to not measurably increase local salinity. The plant is also permitted to provide water for fire suppression to the surrounding area should they be called upon to do so. PG&E considered increasing the size of the desalination facility to provide potable water to the surrounding communities, but decision to shut down the plant at the end of the current licenses for both reactor units halted the proposed expansion plan. General areas that need further investigation for IES incorporating water purification processes include:

- *Water purification technology selection*: Benefits (economic and operational) should be investigated with respect to the different water purification technologies available. In particular the choice between electricity only (loose coupling) or thermal coupling (tight coupling) need to be addressed. The feasibility of steam extraction (especially for existing nuclear plants) plays a major role in the technology selection and needs particular attention. However, careful selection of the most appropriate solution depends on the source of the feedwater and the treated water quality required.
- *Potential for grid stabilization and volatility absorption*: Even large water desalination plants do not require significant energy input compared to the scale of existing large baseload plants. In order to have adequate potential for volatility absorption through load following of a coupled water desalination plant, proper sizing of the nuclear plant (existing large plant, or future SMR or microreactor) and water purification plant is essential. Furthermore, operational limitations and dynamics of the different water purification technologies need to be addressed to assess their suitability for flexible operation. These include start-up and shut-down times, ramp rates, and minimum production levels.
- *Economics*: Economic impacts and viability of coupling a water purification plant with a nuclear plant need to be addressed. In particular, the assessment should include evaluation of the Levelized Cost of Useful Water produced relative to other water resources, the impact and possible cost reduction of nuclear plant cooling water acquisition/production, and the benefit of adding a responsive load of the size of the proposed desalination plant to the grid.

For further information on the applicability of water desalination technology to IES, see (Epiney et al. 2019a, 2019b).

### 2.2.2 Hydrogen Production

The H2@Scale program managed by the DOE Office of Energy Efficiency and Renewable Energy (EERE) is focused on investigating the technical and economic merit of industrial-scale hydrogen generation, including definition of the market potential. Analysis of systems that would utilize nuclear energy for hydrogen production is a focus of collaboration between the DOE-EERE H2@Scale and the DOE-NE IES programs.

Two general types of hydrogen generation technologies are currently used: 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. Reforming technologies produce hydrogen at the lowest cost due to currently inexpensive fossil fuels, such as natural gas; hence, reforming provides a target price point for alternative carbon-free hydrogen production technologies. A third emerging option is to abstract hydrogen from alkanes during alkane deprotonation for the production of alkenes such as ethylene, propylene, and butene. In this case, hydrogen is considered a by-product of the deprotonation process, as the alkenes are feedstock for polymers (see also section 2.2.3 on carbon conversion processes).

Water splitting technologies can be divided into three categories: thermo-chemical cycles, electrolysis, and direct photoelectrochemical (PEC). The EERE HydroGEN consortium under the Fuel Cell Technologies Office is supporting early stage R&D on these three approaches (HydroGEN 2019). Thermo-chemical cycles use high-temperature heat and chemical or metal oxide redox reactions to produce hydrogen and oxygen. Heat for these cycles can be derived from a nuclear power plant or from concentrated solar plants, as in the case of solar thermal hydrogen production (STCH). However, these processes generally involve corrosive acids (Sulfur Iodine process) or extremely high temperatures (STCH). A longer-term opportunity is the PEC pathway which directly uses solar radiation to split water using semiconductor-based devices. However, PEC currently has a low technology readiness level.

Nearer-term electrolysis processes can be further divided into two categories: low temperature and high temperature electrolysis. Low temperature electrolysis (LTE) 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 commercially available technology that could be adopted in near-term integrated systems. High temperature steam electrolysis (HTSE) utilizes high-temperature heat and electricity to split water into hydrogen and oxygen, where the additional heat reduces the amount of electrical work needed. Solid oxide electrolysis cells are used to electrochemically separate the hydrogen and oxygen from steam at temperatures around 800°C. Although the temperature of the steam is high, LWRs can be used by employing heat augmentation techniques, such as resistive heating or chemical heat pumps (see section 2.3.1.3). Chemical heat pumps, which utilize reversible chemical reactions, have shown the potential for temperature lifts of several hundred degrees Kelvin through entirely thermal pathways (i.e., no mechanical work required), resulting in high exergetic efficiency (Sabharwall, Wendt, Utgikar, 2013; Satmon et al. 2017). Alternately, HTSE can be directly coupled to high-temperature nuclear reactors in future deployment scenarios. Since both heat and electricity are required for HTSE, the overall efficiency of the process is strongly coupled to the thermal efficiency of the power cycle used to produce power. Details and status of HTSE development can be found in (Laurencin and Mougin, 2015; O'Brien, Stoots, and Herring, 2010).

The choice of nuclear reactor design to support hydrogen production ultimately depends on the cost of producing electricity and heat relative to the capital cost of the hydrogen plant and operation and maintenance costs. In terms of process efficiency, HTSE can be 30-50% more efficient than LTE by either alkaline electrolysis (AE) or proton exchange membrane (PEM) (see Figure 5). In addition, high reactor outlet temperatures yield high thermal-to-electricity efficiencies (McKellar, Boardman and Bragg-Sitton, 2018). These efficiencies are compounded when a high temperature reactor can be matched with HTSE, as shown in Table 2. The significance of the efficiency gains with advanced reactors is three-fold: 1) a reduction in energy required, and, hence, reactor size due to higher temperature; 2) a reduction in fuel used and, hence, spent fuel generated; and 3) for Rankine power cycles, a reduction in cooling water required.

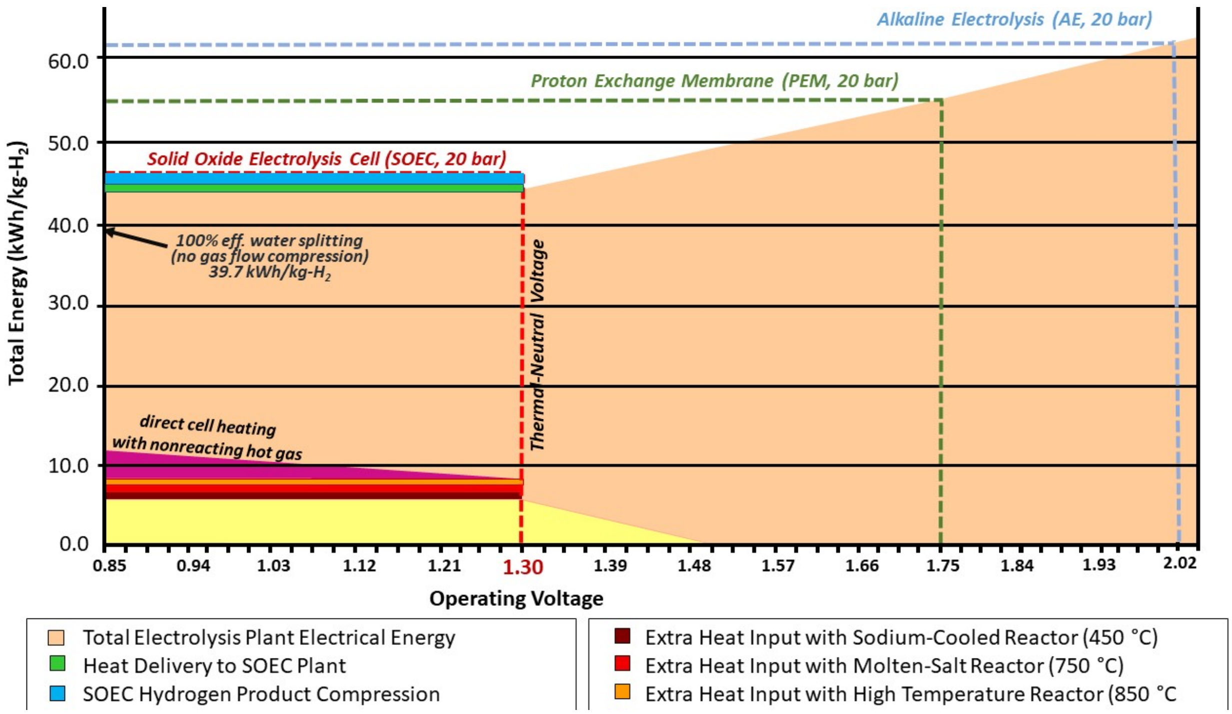



Figure 5. Comparison of total energy use for hydrogen production via electrolysis.

R&D needs for hydrogen production within an IES that incorporates an AR include power cycle efficiency demonstrations and measurements. The supercritical $CO_2$ power cycle will be tested in a pilot plant currently being constructed in San Antonio, Texas. Operational data from the pilot plant can be used for verification and validation (V&V) of modeled power conversion efficiencies. Testing also needs to be completed for other gas-Brayton cycles to verify the calculated efficiencies for various operating conditions. The dynamic operating characteristics and ramp-up and ramp-down limits need to be established for these new cycles that could be incorporated in many IES configurations that utilize high temperature reactor concepts.

It is important to conduct thermal systems integration testing to establish the flexibility of hydrogen production in IES configuration. Such flexibility of the coupled process can allow the IES to provide basic grid services, such as spinning or non-spinning reserves and voltage and frequency regulation on the transmission grid. In addition, thermal integration with HTSE will increase electrolysis efficiency. Analyses to date indicate that incorporation of LWR heat reduces the power required by electrolysis. A higher temperature AR can contribute more heat to the process, further reducing the electrical energy required. The anticipated benefit of high temperature ARs is summarized in Table 2. Higher thermal-to-power generation efficiencies combined with higher heat contributions to HTSE result in significantly higher thermal-to-hydrogen efficiencies.

Optimizing thermal and electrical energy in thermo-electrocatalytic processes will maximize the benefit of nuclear energy. R&D is needed to demonstrate coordinated delivery of the two energy streams in IES, given that electrical power and thermal energy are delivered through systems with differing time scales and inertia. In addition, research is needed to further develop methods to transfer the heat from the delivery system to the principal electrolysis stack or hot boxes containing the electrolysis units. For HTSE, the ratio of thermal-to-electrical energy increases with nuclear reactor peak outlet temperature. For example, the optimum ratio for a VHTR is approximately 20% thermal, 80% electrical. Other thermo-electrical processes, such as alkane deprotonation, requires a ratio of 50% thermal, 50% electrical. Dynamic modeling and experimental test systems are needed to develop and demonstrate thermal energy delivery systems that allow these processes to respond by ramping up or down to optimize system variations in energy availability.

Table 2. Comparison of thermal energy utilization efficiencies for hydrogen production via electrolysis.

| Reactor Type | T-Out (Celsius) | Power Cycle | Power Cycle Thermal Energy Efficiency* | Carnot Thermal Efficiency | Total Electrolysis Energy (kWh/kg-$H_2$) | Overall Thermal Energy Utilization Efficiency |
|---|---|---|---|---|---|---|
| LWR | 300 | Rankine | 32% | 50% | 55 (PEM) | 23% |
| | | | | | 32 (HTSE) | 38% |
| Sodium Fast Reactor | 500 | Supercritical Rankine | 44% | 63% | 125 (PEM) | 32% |
| | | | | | 30 (HTSE) | 54% |
| Molten Salt Reactor | 700 | Supercritical $CO_2$ Brayton | 50% | 70% | 110 (PEM) | 38% |
| | | | | | 29.5 (HTSE) | 62% |
| Very High Temperature Gas Cooled Reactor | 900 | Air Brayton | 56% | 75% | 98 (PEM) | 40% |
| | | | | | 29 (HTSE) | 70% |

*Modeled thermal energy to hydrogen conversion efficiency based on assumptions stated in (McKellar, Boardman, and Bragg-Sitton, 2018). HTSE efficiencies are based on (O'Brien 2008). Hydrogen product is 20 bar.

### 2.2.3 Chemical Manufacturing

The chemical manufacturing industry creates products by transforming organic and inorganic raw materials into fungible fuels, paper and cardboard, wood products, polymers and resins, metals, calcium/alumina/silica cementitious and refractory materials, glass, semiconductors, fertilizers, detergents and cleaning agents, and pharmaceuticals. Nuclear fuel production, fuel reprocessing, and waste immobilization also require an appreciable amount of energy. Food processing is also included in the industrial sector and may be considered as a candidate for nuclear energy integration. While there are over 100,000 chemicals produced today, it is important to concentrate on the most energy intensive industries and to focus on the energy duties and forms that can be supplied by nuclear reactors. With the advent of microreactors, the possibility of deploying and using nuclear energy for oil and gas production and minerals mining and pre-processing at the mine mouth become possible. For the purposes of this roadmap, it is sufficient to categorize the levels and quality of energy that is required for chemical manufacturing.

Rather than attempt a correlation of the energy duties and requirements of each specific industry, this roadmap addresses the form of energy that is used by industries in general and how this can be supplied by nuclear reactors. Table 1 listed many of the large resource production and chemical plant heat requirements. It is important to understand the principals of process heat transfer that is needed to replace current heat transport and exchangers. This is addressed in section 2.3. See also (McMillan et al. 2016) for further discussion of possible approaches to heat integration. It is also important to understand temperature profiles and pinch points in heat exchangers and the general method for heat exchanger area calculations. Development of intermittent heat transfer and direct heat deposition in concentrators, evaporators, and new microchannel chemical reactors is needed to respond to the temporal requirement of the IES, to maximize heat utilization, and to avoid exergy destruction. It is rational to expect that the nuclear heat transport media will be isolated from radiological contamination by at least one heat exchanger barrier. In cases where steam or any other heated gas will be consumed by the process or come in direct contact with the chemical product or material, then double isolation will likely be required. Figure 6 illustrates heat transport from a nuclear reactor to a chemical reactor heated by a hot-gas jacket.

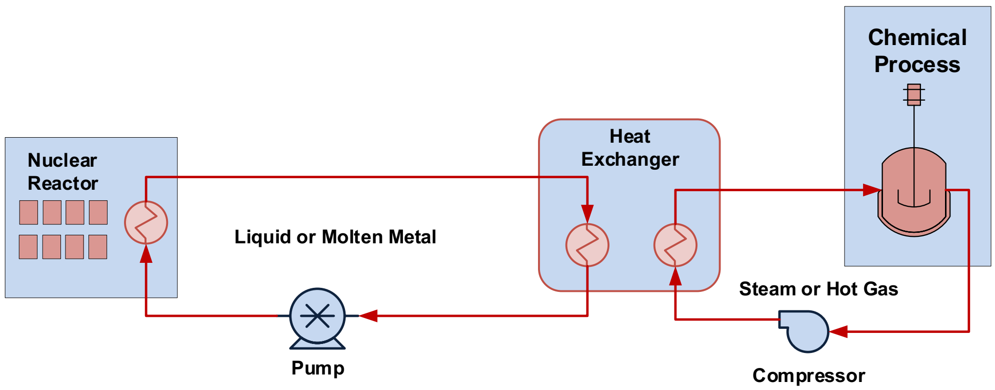



Figure 6. Illustration of heat transport and heat transfer to a stirred chemical reactor.

Several of the processes featured in Table 1 are reaching a high technology commercialization readiness level and are benefitting from the interests of technology developers, industrial gas supply companies, and industry associations. For example, manufacturers of heavy-duty trucks, passenger vehicles, and forklifts have started building hydrogen fuel cell-powered drive systems. Over the past decade, dozens of ethanol plants and bio-digesters have been established throughout the U.S. Midwest. Nuclear plants in this region can increase the revenues for biofuels produced by ethanol and bio-digesters by diverting the $CO_2$ by-product from the bio-digesters to a process that makes synthetic motor fuels using heat generated by the nuclear system. These synthetic fuels are compatible with existing gasoline and diesel fuel supply systems. As domestic and global demand for steel continues to rise, nuclear power plants can provide hydrogen and electricity to produce direct-reduced iron briquettes and to operate electric arc furnaces. With the incorporation of nuclear energy, steel-making emissions can be reduced by as much as 90% as compared to traditional integrated blast-furnace and open-hearth steel plants (Millner et al. 2017).

#### 2.2.3.1 Electricity and steam duties

Electricity and steam are simple to produce with any nuclear reactor; only the efficiency of electricity generation and the level of steam superheating and delivery needs to be considered. There are no technology development needs in this area, and the methods of power generation and steam delivery are well known. Current CHP and heat recovery/steam generation (HRSG) systems can be duplicated or replaced by more efficient SMRs and microreactors where the typical duties may range from less than a few MWe to 1-2 GWe, as in the case of a large oil refinery, a complex of refineries, steel plants, or minerals reduction plants. These details are obtained by completing process-specific plant design studies.

#### 2.2.3.2 Heat duties

Nuclear heat is well-matched to heating, and in some cases vaporizing, chemical feedstock entering a reactor process. Nuclear heat can be directly substituted for steam that is used indirectly to dry, concentrate, or distill most aqueous solutions and to fractionate petroleum distillates. In some cases, nuclear heat can be used to break low-order chemical bonds such as biomass ligands or coal moieties. In summary, approximately 75% of all industrial heat duties require less than 700°C, with about 50% of the duties being less than 300°C.

The main challenge for nuclear reactors is replacing fired-heaters that provide on-demand heating of chemical processes. Fossil fuels and combustible wastes provide about one-third of the energy required by industries. In many cases, hydrocarbon-flames transfer heat by radiation to heat exchanger surfaces and reactor vessels. Cement kilns and metals decarbonization are examples of processes that require very high temperatures that cannot be indirectly transferred to the solid process feeds. Hydrogen that is produced via nuclear-generated heat and electricity can be burned to provide very high temperature gases; however, hydrogen flames are virtually invisible and produce very little radiant heat to support indirect heating of a material.

The basic concepts for nuclear assisted process heating, evaporation, and reaction heating are illustrated in Figure 7. The choice of heat transport media should be selected on the basis of the heat duties, reaction or phase-change process temperatures, and heat transfer components. Table 1 provides a general breakdown of the corresponding thermal duties by category. By understanding and prioritizing the top chemical market opportunities, IES designers can evaluate and match nuclear reactor types and heat transport systems that will provide the least cost solutions for near-term application, versus long-term market opportunities to the chemical and manufacturing industries. This approach will identify additional R&D needs for the chemical industry that may be accomplished via other DOE programs or private industry. When evaluating the use of nuclear heat sources for the chemical industry, it is important to understand the chemical processes and the equipment used for feed heat-up, phase-changes, and reaction enthalpy requirements. Heat recuperation needs to be optimized in a manner that optimizes the use of the nuclear heat source. Finally, heat augmentation may be needed, but only when the net effect uses the energy contributed by the nuclear heat source (for example, see Figure 7(f)); see section 2.3.1.3 for further information.

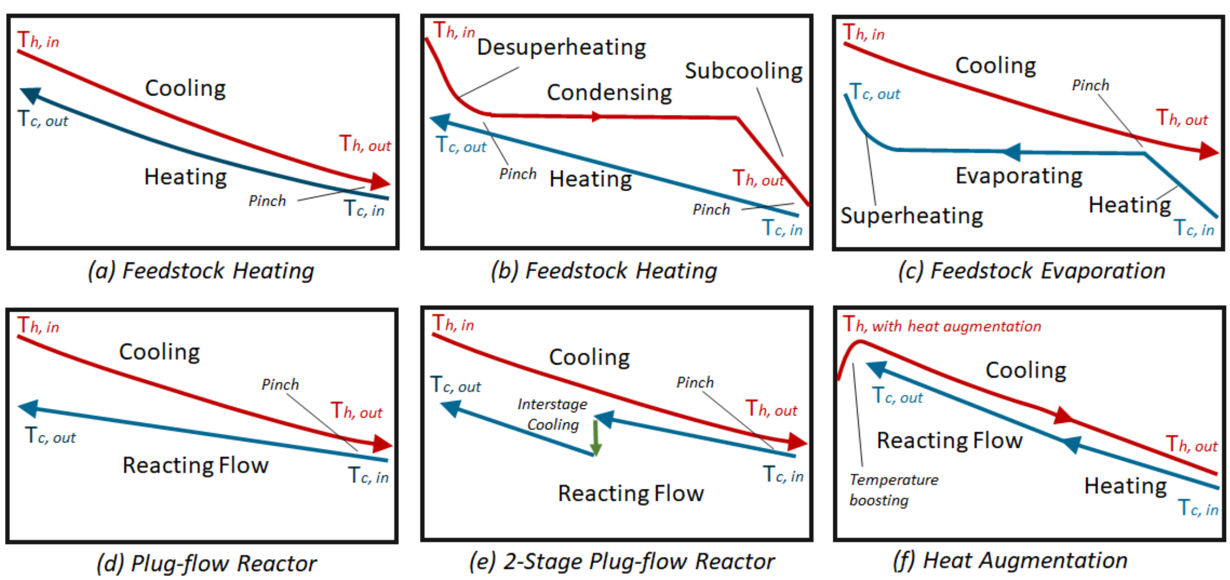



Figure 7. Nuclear heat transport to chemical process heaters and chemical reactors (figure adapted from Hewitt, Shires, and Bott, 1994).

#### *2.2.3.3 Electrochemical processes*

Until recently, electrically heated and electrochemical synthesis processes were limited due to the high cost of electricity compared to thermally driving reactions with fired heaters. However, with clean and affordable energy that can be provided with the SMRs or microreactors, it is timely to revisit industrial electrochemical processes and to develop new thermo-electrochemical manufacturing processes. Electrochemical processes rely on energetic electrons to initiate chemical processes at much lower temperatures than is possible with purely thermal energy and molecular collisions in either homogeneous or heterogeneous catalysis processes. The combination of electricity and heat from nuclear reactors is a good match for many cool-plasma or electrochemical cell processes that are now emerging. For example, this includes non-oxidative deprotonation of alkanes and ammonia synthesis within solid-state ion-conducting ceramic cathode/electrolyte/anode cells (Ding, Wu, and Ding, 2019; Ding et al. 2018), liquid-phase electrode reduction of $CO_2$ to alcohols (Dufek and Lister, 2012) and formic acid (Brix 2020).

Electrical heating, whether resistive or inductive Joule-heating, may also be effective methods of heat transfer to a chemical process unit operation. Design and testing are needed for HRSG units and thermal energy storage units that best utilize topping heat or bottoming heat relative to specific process heat requirements and the nuclear reactor inlet and outlet temperature.

#### *2.2.3.4 System coupling*

IES that support the chemical manufacturing industry will likely involve energy supply to an integrated complex of industrial processes in order to capitalize on feedstock and energy exchanges that optimize productivity and revenue. Figure 4 illustrates a plausible industrial complex that takes advantage of thermal and electrical energy, as well as intermediates such as hydrogen that can be produced and stored in a buffer to meet user demands. Scheduling energy delivery from the nuclear plant requires the development of data management and control systems that dispatch energy according to the coupled application and customer needs.

### 2.2.4 Thermal Energy Storage

Many of the applications described above require both thermal and electrical integration. However, many of these will not operate on the same characteristic time scales. In addition, many of the applications described do not work well with cyclic operation and instead require nominal full power operation. To accommodate these challenges energy storage will play a key role in IES; specifically, thermal energy storage (TES). Introducing thermal storage into a system allows the system a holdup of energy that can be utilized in several ways. It can be utilized as a peaking unit in deregulated markets for system wide profit maximization (store power when electricity production exceeds demand, causing the electricity selling price to be low or negative, and sell power when the price is high). It can smooth out the transition between process applications that operate on different characteristic time scales. Further, TES has a pronounced economic advantage compared to electrical storage when integrated with thermal generators that operate on a Rankine cycle (coal, nuclear) due to the low thermal to electric conversion rate (~40-45% maximum).

TES are generally categorized as sensible heat, latent heat, and thermochemical. Although promising in terms of storage performance, thermochemical and latent heat are still primarily in the “research phase” of development having largely been relegated to laboratory experiments. To be employed in IES, significant research to design, demonstrate, and scale up these technologies is still required. Sensible heat storage, on the other hand, is currently a commercially viable technology that has been utilized in the concentrated solar power industry since the 1980s. The most common sensible heat technology is a two-tank system that utilizes either molten salt or thermal oil. Such a configuration has been shown to be applicable to nuclear power plants (Frick, Doster and Bragg-Sitton, 2018) in a configuration similar to that shown in Figure 8.

Another viable TES option is a single tank thermocline heat storage system. Compared to a two-tank TES system, this technology may provide substantial economic benefit of up to 35% by replacing the expensive heat transfer fluid with low-cost heat storage medium (Brosseau et al. 2005; Libby 2010). However, single tank thermocline heat storage is at an earlier stage of development than the two-tank storage system because the operational experience at large scale is relatively limited (Esence et al. 2017; McDonnell Douglas 1986). In addition to these two TES designs there exist a multitude of other options ranging from concrete storage to thermochemical batteries.

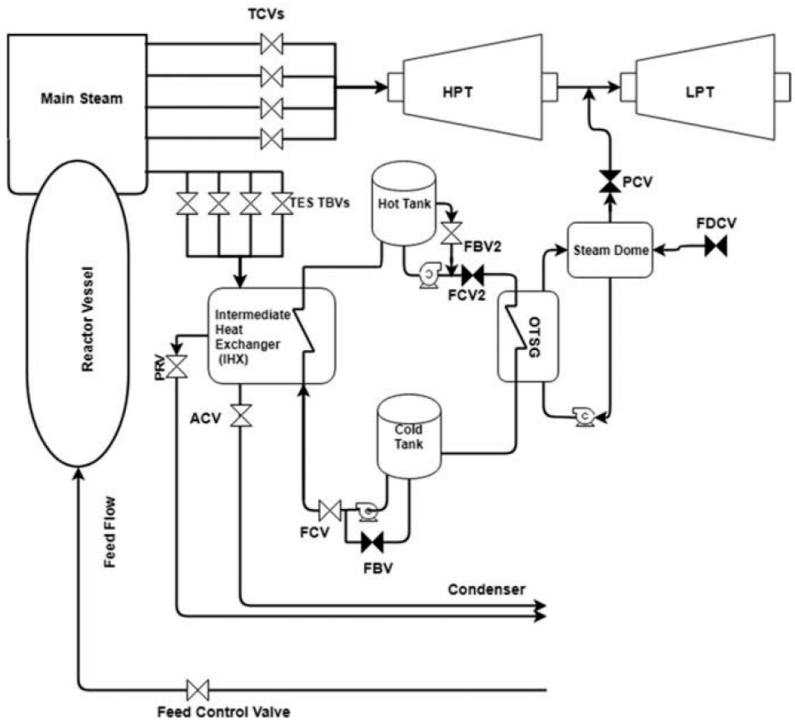



Figure 8. Schematic of a possible design for a nuclear reactor connected to a two-tank sensible heat TES system.

A recent study evaluated thermal storage integration readiness levels for integration with nuclear facilities (Mikkelson et al. 2019). This work developed a phenomena identification ranking table analysis to rate each thermal storage technology in terms of both technology readiness level (TRL, explained further in section 3.1.1) and interoperability with nuclear generators. This study revealed three stages of thermal storage development: commercially available systems (TRL 7–9), systems on the brink of commercialization (TRL 5–6), and systems still in the developmental phase (TRL<5). These systems are summarized in Table 3.

Table 3. Thermal energy storage systems and estimated TRL (Mikkelson et al. 2019); see section 3.1.1 for further description of TRL categories.

| Technology | TRL | Technology | TRL |
|---|---|---|---|
| Underground thermal energy storage | 9 | Thermochemical | 4 |
| Hot/Cold water storage | 9 | Phase change materials | 4 |
| Concrete | 5 | Thermocline storage | 5 |
| Firebrick | 3 | Two-tank storage | 9 |
| Geothermal | 2 | Steam Accumulators | 9 |
| Liquid Air Energy Storage | 6 | | |

Operability of a selected TES in an IES can be classified by development stage. Each stage of development has unique concerns and challenges. While not every technology would be subject to the same challenges, these generalized questions and challenges are applicable to many of the technologies under consideration. Key challenges for TES at each stage of development are summarized below.

*Commercialization challenges (technologies at TRL 7-9):*

1. Thermal integration components (e.g. heat exchanger selection, tertiary loop design)
2. Interface point between the nuclear plant and TES (e.g., secondary side of the nuclear power plant)
3. Control authority and hierarchy definition (e.g., is there energy balancing authority for these energy parks that determines the offtake rates from the plant to the TES?)
4. Classification of TES as independent generation units, or as an integral part of a larger generator station; in the latter case, can these generators now operate in a manner that provides rapid response to market signals?

*Scale-up and demonstration challenges (~TRL 5-6 technologies, plus challenges identified for TRL 7-9):*

1. Cyclability for long term operation (15+ years)
2. Scalability for commercial-scale deployment.

*Developmental phase challenges (~TRL 1-4, plus challenges identified above):*

1. Fundamental physics concerns (material degradation, dynamic thermal behavior)
2. Options for integration into a traditional thermodynamic cycle.

Thermal storage will be a key component in IES as both a buffer between processes and as a contributor to the electricity market. However, it is vital to resolve the challenges identified for commercial-scale deployment. Beginning to answer these questions will provide a clear path forward not only for these higher TRL technologies but also for developing technologies as they move toward commercialization. Lower TRL technologies still in the process of development and deployment can utilize the information and lessons learned from this first wave of TES deployment to better adapt their technology for the marketplace.

### 2.2.5 Electrical Energy Storage

Conventional approaches to electrical energy storage include batteries, supercapacitors, and dielectric capacitors. The key factors associated with these storage devices are energy density, which measures how much energy can be stored in the device, and power density, which governs how quickly the energy can be transferred. Batteries possess high energy density but modest power density due to the relatively slow kinetics of the redox processes involved. Dielectric capacitors offer limited energy density but high power density as only electrons are transported during charge/discharge. Supercapacitors offer an attractive balance between energy and power density and have a range of useful applications (Friedrich and Breuer, 2015; Budde-Meiwes et al. 2013). Supercapacitors avoid any solid-state redox reactions, since charge is only collected at high surface area electrodes, and they are suitable for short-term storage and as high-power density sources. However, when used in conjunction with a battery, supercapacitors are useful for load-leveling applications, providing peak power demands and reducing the damaging loads on batteries which can deteriorate their performance. Supercapacitor electrodes have the attractive feature that they do not change dimensions when they are being electrically charged or discharged, and the material can last for an extremely long time (surviving for up to a million charging cycles). Battery systems, in contrast, offer higher energy densities, but their electrodes typically change shape as current passes through them, leading to stresses and degradation (surviving typically only 1000 - 5000 cycles). Table 4 provides a quantitative summary of the different attributes of these electrical energy storage devices.

Table 4. Comparison between different critical parameters for conventional electrical energy storage devices (Budde-Meiwes et al. 2013).

| Parameters | Capacitors | Supercapacitors | Batteries |
|---|---|---|---|
| Energy density (Wh/kg) | 0.1 | 3-10 | 100 |
| Power density (W/kg) | $10^7$ | 3000 | 100 |
| Charging time (s) | $10^{-3}$-$10^{-6}$ | 0.3-30 | >1000 |
| Discharging time (s) | $10^{-3}$-$10^{-6}$ | 0.3-30 | 1000-10,000 |
| Cyclability | $10^{10}$ | $10^6$ | 1000 |
| Operational lifetime (years) | 30 | 30 | 5 |
| Efficiency (%) | >95 | 85-98 | 70-85 |

Feasibility of electrical storage in IES configurations as a function of such factors including the nature of the energy market, which would include niche, regional, and reserve markets, and other factors such as projected price decreases and characteristics of the storage technology are necessary. Initial expectations are that electrical storage can play at least a diurnal role in energy storage. For longer durations, such as those supporting seasonal storage needs, electrical storage is not expected to be competitive. Technoeconomic modeling can be used to investigate the role of these factors to identify deployment scenarios for electrical storage that not only have economic value but may also be of value to the IES owner in providing grid stability and resilience.

### 2.2.6 Low Quality Heat Utilization

Heat rejection associated with advanced power systems can be utilized in a variety of bottoming cycles and loops; however, the low-grade heat generated by chemical plants and power systems that involve low-temperature Rankine power cycles continues to be a challenge and an opportunity for IES. Recent advances in geothermal power systems, such as organic Rankine power cycles and geothermal systems enhancement, are applicable to IES and need to be taken into consideration. District heating, although an opportunity near dense populations, is well proven and does not need further development. Additional R&D activities that can support IES include:

- Desorption of sorbents used for chemically looping/heat augmentation systems
- Desorption of mass separating agents used for forward osmosis systems
- Thermal fluidics pumps based on low-temperature boiling fluids using heat pipe concepts.

## 2.3 Interface Technologies

Integration of technologies in IES may be accomplished via direct thermal integration or electrical integration, each of which pose different technical and regulatory challenges. This section addresses anticipated approaches to each of these integration options and their current status of development.

### 2.3.1 Thermal Connection

Thermal interconnection among energy generation sources and energy users (e.g., industrial processes) within tightly coupled systems can dramatically increase the energy use efficiency within the IES. However, thermal connection can introduce greater interdependence among subsystems that require additional analysis to ensure safe operation under all postulated operational modes. Heat exchangers, heat transfer loops, and instrumentation and control systems must take a number of parameters into consideration in their design, including materials compatibility, working fluids, operational temperature and temperature limitations, and potential ramp rates under normal operation, transients, and possible failure modes. These systems present some of the most significant technology gaps in the development and deployment of IES for various applications.

#### 2.3.1.1 Heat exchangers

Heat exchangers provide a means to transfer heat to or from fluids of differing pressures, temperatures, and compositions. This is one of the key components needed to thermally connect IES subsystems. Key functional requirements of heat exchangers for IES have been described in the 2016 *Nuclear-Renewable Hybrid Energy Systems Technology Development Program Plan* (Bragg-Sitton et al. 2016) as follows:

1. *High efficiency/performance*. The heat exchanger should be able to transfer heat efficiently with minimal heat and pressure losses within reasonable physical dimensions.
2. *Provide pressure boundary*. The heat exchanger must act as a pressure boundary between interconnected subsystems and corresponding working fluids.
3. *Provide chemical boundary*. The heat exchanger must provide a chemical boundary and prevent cross-contamination between the subsystems.
4. *Material compatibility*. The heat exchanger structural material must be compatible with the working fluids' composition, temperatures, and pressures.
5. *Phase change*. For heat exchangers that involve condensation or evaporation, the heat exchanger orientation and dimensions must avoid severe flow restrictions, or slugging, that may result in a heat transfer pinch.
6. *Reliability under dynamic conditions*. The heat exchanger must maintain its structural integrity under highly fluctuating pressures, temperatures, and flows for both short and long-term operations.
7. *Economics*. Manufacturing and operating costs must be economical; economies of scale need to be achievable.

To satisfy the above requirements, advanced heat exchanger design and manufacturing capabilities such as diffusion bonding or additive manufacturing may be needed. Advanced heat exchanger design can be complex, resulting in geometries that are potentially unobtainable by conventional manufacturing processes, but are needed to overcome technical challenges such as high thermal gradients associated with a variety of thermal operating conditions and interactions with subsystems that can result in the mechanical/structural failure of the heat exchanger in long-term operation.

Advanced multi-physics computational modeling and simulation will be a very useful and powerful tool for design, analysis, and optimization of heat exchanger thermal and structural performance. Computational fluid dynamics coupled with finite element method-based mechanics will provide detailed thermal and structural information. Evaluation of the sensitivities of various design parameters for optimization can be accelerated using deep learning-based artificial intelligence (Sasaki and Igarashi, 2019). Atomistic thermodynamic modeling can also be used to predict corrosion and oxidation of heat exchanger materials, to analyze weld and bond interfaces within the heat exchanger, and to predict transport phenomena such as fouling, leaching, and material splitting.

Additive manufacturing (AM) provides a highly flexible and cost-effective fabrication method for complicated geometries. Powder bed fusion (PBF)-based methods and direct energy deposition methods can be used for 3D printing of metals or alloy powders. Many metallic materials such as stainless steels, aluminum alloys, titanium alloys, nickel-based alloys can be manufactured using PBF-based AM processes (Herzog et al. 2016). However, there are technical challenges (Ngo et al. 2018) to be addressed and resolved, e.g., limited resolution and dimensions of AM products, void formation, anisotropic behavior. Additive manufacturing could be a promising solution for fabrication of complex heat exchanger geometries where a customized design and configuration is needed.

Candidate IES advanced heat exchanger designs should be developed using multi-physics computational modeling methods. It is expected that heat exchanger designs will vary depending on imposed requirements of the coupled subsystems. The applicability and scalability of AM technologies can be investigated via computational approaches, followed by fabrication and testing of selected heat exchanger prototypes. The thermal-hydraulic, structural, and dynamic performance of heat exchangers can then be evaluated via nonnuclear, thermal hydraulic test facility infrastructure prior to implementation in nuclear systems. Some of this testing infrastructure is introduced in section 4.3; facility requirements and status for testing of integration components will be further discussed in the subsequent detailed technical program plan that will be developed for the CTD IES program.

##### *2.3.1.2 Tertiary loops and multiple working fluids*

Tightly coupled IES requiring thermal integration are expected to require a tertiary loop to deliver heat and/or power for industrial processes. Such design is not standard to nuclear systems, but this integration approach can provide isolation of the nonnuclear systems from the nuclear system, ensuring that the coupled process is isolated from potential radiation contamination under all normal and off-normal operating scenarios. It is important that these tertiary loops be well understood and characterized for all potential applications. While, in principle, thermal energy is simply being redirected for alternatives purposes, issues can still arise that lead to system failures. Incidents such as the failure of the thermocline storage tank at the Solar One project (Boer 2012) illustrate the significance of this design approach, particularly when considering integrated energy parks that involve different working fluids in different loops. The Solar One incident was caused by a water leak between the systems that resulted in over-pressurization of the tank. This condition resulted in subsequent flashing to steam and ultimately ruptured the tank. Had the design teams considered this connection point and working fluid differences more in depth there may have been design options identified that could have avoided this event.

Within integrated energy parks, tertiary loops will need to be viable for all systems directly attached to it from both a hazards and an operational perspective. These requirements will likely mean there will be different working fluids selected depending on the systems being integrated, potentially requiring a range of step-down fluids in the tertiary loops. For example, a gas turbine that operates at 600°C will require a different tertiary loop fluid than a nuclear power plant that operates at 300°C. The selected industrial application and its corresponding temperature requirement will also affect the working fluid selection for tertiary loops. Understanding fluid interactions between loops will be a vital part of the selection process.

Introducing tertiary loops will require further research on the potential safety issues that may occur via thermal interfaces. Research has been conducted on high temperature tertiary loops that are typically involved with concentrated solar power plants. One example is the experimental study performed by Sandia National Laboratories on the reactivity between thermal oil and molten nitrate salt in case of a leak in the oil-to-salt heat exchanger (Laruent 2000). Given that such reactions may cause a serious consequence such as a fire and explosion in an IES, the potential safety concerns must be clearly identified and addressed in the design process.

Limited research is publicly available on the mass transport of thermal energy via these loops for medium temperature applications applicable to many IES configurations. Research is being conducted for various medium temperature intermediate loops through several research projects (Stoots et al. 2018). However, increased R&D investment is needed on the possible fluid interactions between loops, loop control systems, amount of holdup required, and siting relative to different thermal generators. Without this research, design of the connection between different energy applications will be completed on a case-by-case basis, potentially without the proper expertise needed to identify possible hazards such as that which caused the Solar One incident in 1986.

#### 2.3.1.3 Heat Augmentation

In some applications it may be effective to boost the temperature of the heat transfer media through heat augmentation. Heat can be added by electric heating, a fired heater (including hydrogen-fired), compression, or heat pumping. Chemical heat pumps can achieve very high temperature amplification if the cost/benefit is justified. The main principal that must be satisfied is whether heat augmentation results in more effective use of the available exergy of the heat source. Exergy quantifies the ability to complete work. Figure 7(f) illustrates one case in which the temperature of the heat transfer media is boosted to raise the temperature in a plug-flow heat exchanger reactor that extracts the added heat plus some high percentage of the primary heat source. In another example, heat augmentation may be useful to raise the temperature of the reactant to an optimal reaction temperature. In HTSE, for example, the steam and air sweep gas that have been heated with a nuclear heat source can be boosted to the electrolysis cell stack operating temperature (~800°C). In this case, the majority of the feed stream heating is accomplished with thermal energy provided by the nuclear heat source.

Chemical heat pumps generally involve a reversible reaction where the forward reaction is exothermic while the reverse is endothermic. In this manner, the low temperature reaction is promoted and sustained by the nuclear heat source. The exothermic reaction is carried out at a temperature that is considerably higher than the nuclear heat source. Intermediate chemicals may also be stored and reacted when the high temperature heat source is needed. Cost-benefit justification requires analysis of round-trip efficiencies and capital costs.

Common examples of heat augmentation approaches include:

- *Methane reforming and re-methanation.* Reforming can be carried out at 800-850°C with the heat supplied by a VHTR. Methanation is a fast reaction that can produce temperature up to the thermodynamic limit of the forward chemistry (around 1500°C). At that temperature the heat flux would be comparable to a fired heater.
- *Metals oxidation/reduction.* Chemical looping combustion exploits the principle of oxygen delivery by reduction of a metal oxide in a flame. Metals re-oxidation can be completed with steam, air, or pure oxygen (for example, the oxygen obtained when splitting water with an electrolyzer). A metals reduction/oxidation loop that operates in the reverse direction can deliver heat rather than oxygen for process heating. Reduction may be accomplished electrolytically.
- *Reversible calcium carbonate/calcium oxide system.* Calcium and magnesium carbonates decompose at 600-650°C. The resulting calcium/magnesium oxide can be re-carbonated in the presence of $CO_2$ at a lower temperature. With this system it is not possible to boost the temperature of the thermal energy input; rather, this chemical loop is only effective in storing thermal energy in a massive system for future recovery.
- *Reversible adsorption/desorption.* Adsorption is typically an exothermic process that leads to runaway temperature climbs. Moisture adsorption on carbon is one example. The reverse of this process may require a pressure-swing system. The round-trip efficiencies and systems benefits have to be considered.

### 2.3.2 Behind-the-grid Electric Interconnection

Some IES configurations benefit from power transactions behind the grid. Industrial users often include batch operations. These operations can be coordinated to smooth the overall power use profile to optimize the operating efficiency of the nuclear plant. Industrial parks can be designed to share the capital costs of the plant. In addition, the industrial complex can engage in power transactions with the grid when the value of selling power to the grid will increase the revenue of the industrial processes. These arrangements currently are very difficult to negotiate in a regulated electricity market, while they are more common in deregulated markets.

In addition to industrial park operations, other forms of power consumption are emerging and take the form of largely uncontrollable exogenous inputs to the IES. Electric vehicles, which include personal vehicles as well as heavy-duty applications in the transportation sector, are expected to grow and significantly transform the electricity and hydrogen markets. The connections of these vehicles to the power grid will create a significant change in expected demand profiles. Also expected is an increase in small-scale, distributed solar PV (i.e., rooftop PV systems). The IES will need to plan for these new producers and consumers through capacity-expansion modeling and will need to account for their integration. Unlike many of the assets on the electric grid today, outright curtailment is not a preferred management policy so grid stability may become more important. Modeling the IES will need to expand to include policy incentives designed to reduce the uncontrolled variability of these behind the grid assets.

Increasing levels of variable power generation and retirement of baseload synchronous power generators results in power conditions and instabilities that can be corrected by providing power to the grid on various time scales. Opportunities include:

- Spinning/non-spinning reserves: Provide power to the grid within 10 minutes of request
- Reactive power management: Provide or withdraw power from the grid within seconds of request
- Frequency and voltage regulation: Provide or withdraw power from the grid in under one second, preferably within 15 microseconds.

In order to provide these transactions within the integrated systems of power users or with the grid, it will be necessary to develop technical guidance for data collection, analysis, and decision systems with the associated monitoring and control systems that are needed to flexibly use both electricity and heat from a nuclear source in an industrial complex.

The electrical power system within a nuclear plant is typically considered the most-important engineered safety feature in the system because it supplies power to all systems in the plant on both the primary and secondary side, including safety systems. The design of the electric power system in a nuclear plant must be engineered with every possible contingency in mind. Direct integration with the industrial users will require modifications to a typical switchyard to account for power delivery to the coupled plant, such as a hydrogen plant, and other unit operations that divert more than about 10% of the total capacity of a nuclear reactor in a hybrid system. It is recommended that the electric system of an IES also be modeled in power-system software, such as Power Systems Computer Aided Design, to verify that the modified power distribution and transmission systems retain realistic behavior and to reduce the risk of tripping the nuclear reactor. In addition, a new order of communications with the grid operator needs to be developed that enable the operators to command the nuclear-industry systems functioning behind the grid to effectively use the system for grid services.

# 3. Gaps and Barriers to Implementation

Commercial implementation of IES must take into account what technologies are currently available, scale of those technologies, and implications of integrating the proposed technologies. The benefits of IES must consider technical and economic performance of such systems relative to independently operated systems that produce the same products for the market. In many cases the desired systems may be readily available commercially but may be available at different scales than desired or driven by different energy sources, such that operation within an IES has a relatively low "integration readiness" level for deployment. This section explores classification schemes used to describe technology availability, regulatory aspects associated with IES, considerations for insuring agencies to back IES operations, and engagement of stakeholders to ensure acceptance of such technologies.

## 3.1 Technology Availability

Various technologies described in section 2 are available or are in development that could benefit from the proposed IES configurations. In many cases the technologies being considered, such as LWRs and RO desalination, are commercially available as independent systems. However, integration of those technologies is either limited or nonexistent for nuclear energy systems. Hence, the primary gaps associated with IES commercial deployment are associated with integration needs: heat exchangers, intermediate loops, thermal energy storage systems, and approaches to effectively couple technologies, such as heat augmentation to thermodynamically match the energy generation resource to the energy use technology. Appropriate control systems to efficiently operate multi-application energy systems must also be demonstrated. This section provides an overview of the technology readiness level classifications applied to various technologies, available technology scales and what might be needed to move from lab scale to commercial scale systems, and market considerations to support the proposed technologies.

### 3.1.1 Technology Readiness Levels

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 can be applied to IES as a tool to assess the maturation of these systems. A simplified overview of the TRLs and the associated experimental testing scale is provided in Figure 9. TRLs can be roughly grouped as follows:

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

TRL 4–6: Develop and Test (Experiment-scale to Pilot-scale)

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

TRL 9: Operational (Commercial Plant)

In general, the role of federally funded R&D laboratories is to support early stage R&D to reduce risk of commercial adoption. In this fashion, DOE programs, particularly those associated with development of nuclear systems, conduct analyses and hardware demonstrations to mature concepts through TRL 6. Industry partnership is necessary 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 IES to TRL 7, which would include system prototype demonstrations in a relevant operational environment (i.e. a nuclear-fueled system), will require industry leadership.

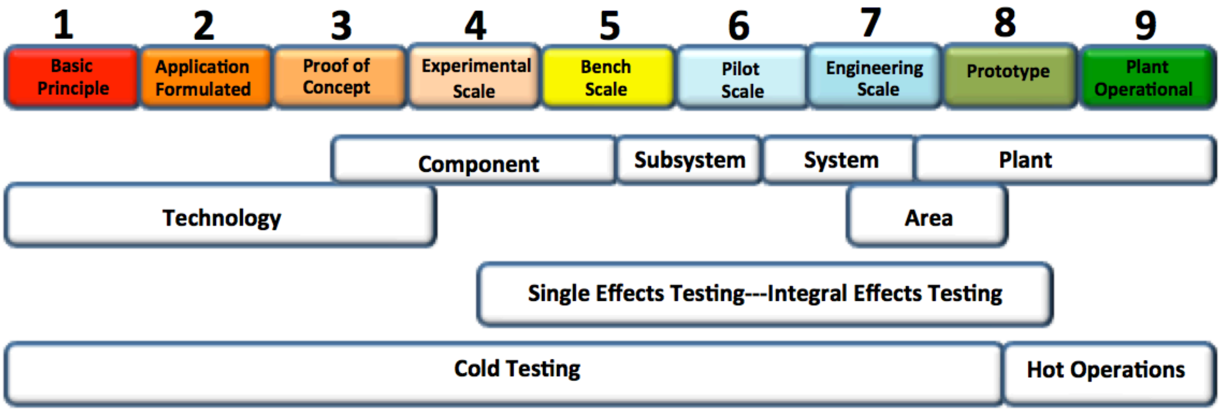



Figure 9. Simplified overview of TRLs (modified from Collins 2009).

### 3.1.2 Technology Maturation

Technology maturation is accomplished through multiple science-based R&D pathways. As discussed, IES usually involve diverse energy sources applied to multiple energy sectors. Experience repeatedly demonstrates the consequences of proceeding with projects using technologies that are not sufficiently mature or that have been designed and operated based on empirical observations or non-validated process models. The proposed science-based development of IES involve three key R&D pathways summarized in Figure 10:

1) Energy System and Process Modeling, Simulation, and Analysis (blue);
2) Component Development, Testing, and Demonstration (lavender); and
3) Process and System Monitoring, Control, and Maintenance (red).

The R&D pathways are highly correlated. Advancement of IES through basic concept definition and analysis, preliminary experimental demonstration, and scale-up to prototypes and commercial operation will engage cross-cutting research using test facilities at national laboratories, academic research facilities, and industrial facilities.

The analysis tools being developed to simulate system and component behavior will support the design and operation of bench-scale and pilot-scale facilities and scale-up to commercial-scale prototype systems. In order to build confidence and assurance in the proposed commercial system design, it is necessary to show that the simulation results reflect the real response of the system via experimental validation. This V&V effort will require data input from representative single-effect and integral-effect tests performed in relevant environments of physical systems. Proposed V&V tests should include:

- Analytical tests—measurement of model parameters and verification of model accuracy
- Separate effects tests—tests intended to isolate a particular phenomenon of interest from other associated phenomena that may complicate the interpretation of the results
- Integrated effects tests—tests that combine particular phenomena of interest to determine their cumulative or synergistic effects on a component or subsystem
- Plant tests—tests conducted in a relevant environment such as an actual plant or a plant prototype.

These empirical test data and the derived relevant information will advance understanding of the physical systems in relevant environments, inform licensing efforts, and help identify needed enhancements to analytical tools.

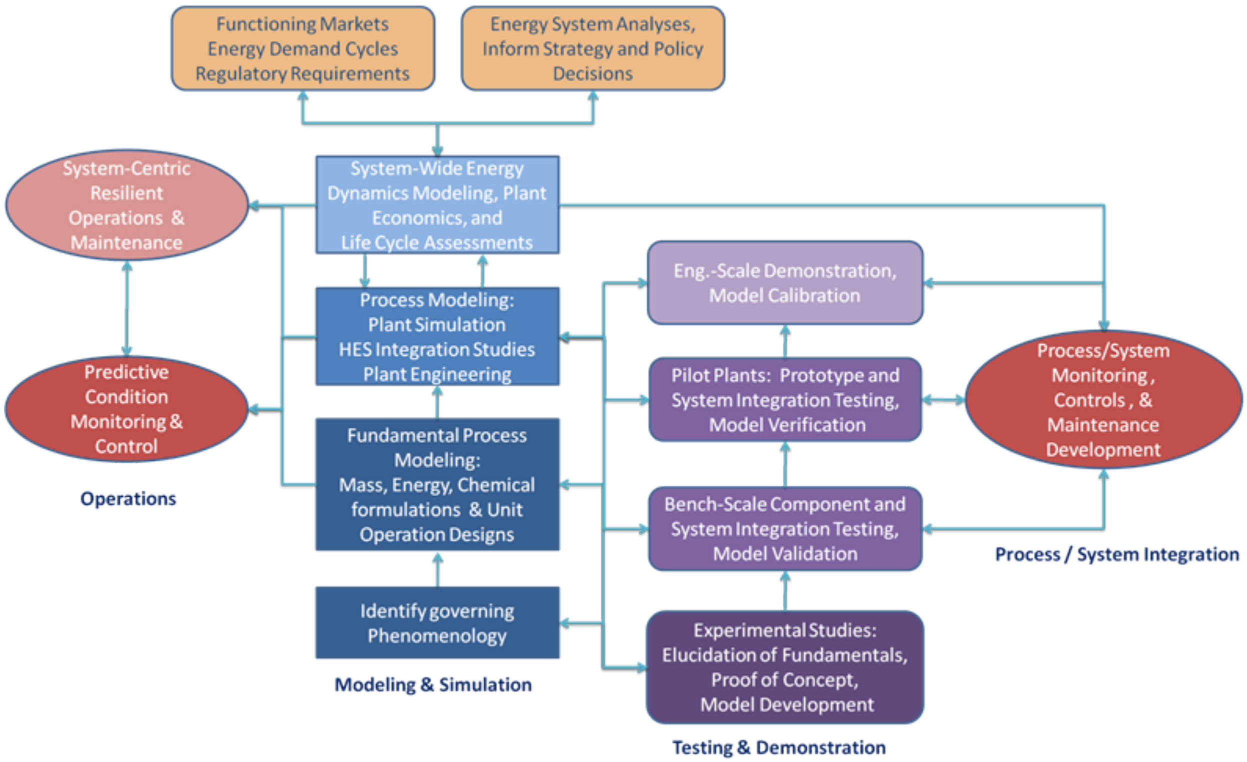



Figure 10. Summary of the technology maturation approach involving modeling and simulation, testing and demonstration, process integration, and operational activities.

### 3.1.3 Technology Scale

Scaled testing and demonstration of components, subsystems, and integrated systems provide the required information to systematically perform decision analysis, reduce risk, and mature technologies in a cost effective and timely manner. TRL assessment is a common approach to measure the level of technical maturity of a technology, that is, the ability to design, fabricate, and deploy a component or system at the desired commercial scale. Depending on the IES design, the overall TRL of the system will vary. Currently, most subsystems under consideration for IES have been shown to be feasible at low to medium TRL. Once these individual systems are coupled, however, their TRL further drops, as the integrated system lies outside the validation envelope applied previously for the individual system. In order to enhance the TRL many development efforts are being undertaken at various Universities and national laboratories. R&D testing should be closely coordinated with modeling, as noted in Figure 10, which serves to improve the design and fabrication of scaled demonstrations. The TRL system assumes that higher TRL corresponds to greater reliability, that technologies function more closely to the desired end-state of the technology, and that the cost of performing a validation test increases at larger-scale demonstrations. Because of the high cost of larger scale demonstrations, the largest risk and uncertainty must be reduced with small scale demonstrations, testing, and modeling.

## 3.2 Market Competitiveness

Commercialization of a new technology is a daunting challenge. How to cross the “valley of death” illustrated in Figure 11 is always a subject of debate within the DOE complex and among technology developers. Federal investment to de-risk commercial investment helps to mitigate this problem. DOE research laboratories can proactively address this challenge by providing, to the greatest accuracy possible, an estimation of costs and revenues that would be associated with a commercial deployment of a system or technology.

Certainty of costs and revenues allows private investors to move a technology across the valley of death and therefore absorb the first-of-a-kind costs to reach the nth of a kind, sustained by a promise of future returns. Low uncertainty in finance also corresponds to low required rate of return that is highly beneficial in capital intensive investment, as is required for nuclear energy.

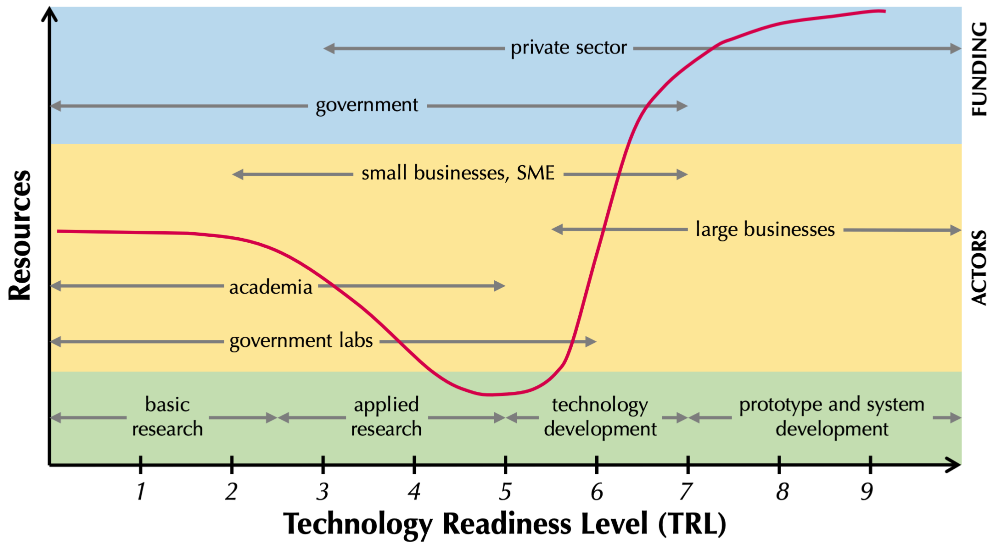



Figure 11. Resource availability as a function of technology maturation. The central depression between TRL 3 and 6, where few resources are available, is known as the technology valley of death (figure adapted from Hensen et al. 2015).

### 3.2.1 Cost and Revenue Assessment

The quality of a cost assessment is tightly connected to technology TRL, but there are actions that can be undertaken to minimize uncertainty at any TRL. Close coordination with technology suppliers is key in acquiring high quality data, particularly given that much of the information needed is highly business sensitive. Experimental testing and demonstration of technologies can also be used to support characterization of performance efficiencies, which are a key aspect of cost assessment. As technologies and systems are advanced toward commercialization, readiness of the supply chain should be assessed, allowing operational data to be collected and qualified and accuracy of cost estimates to be improved.

The revenue side of cost estimations is more complicated. There are several aspects that should be considered. First, as highlighted previously, an IES has several revenue streams. One of the benefits of an IES is its ability to be opportunistic by dispatching services in the most lucrative way. Unfortunately, it is rather challenging to accurately assess the size of the heat and electricity markets in which the IES could participate.

#### *3.2.1.1 The heat market*

The heat market does not formally exist, as individual needs are supplied locally without establishing a broad market because it is not efficient to move heat over large distances. The only approach to assess the value of these heat markets is to cost the alternatives, which typically are natural gas and coal. While costing heat from those sources is possible, it is not a given that they will be available in the future. In fact, corporate choices to move toward a greener economy are influenced by legislators and customers. Under a zero $CO_2$ emission scenario, costing the alternative of supplying heat from nuclear energy could instead revert to costing a transition toward electrification of the industrial processes, with electricity being provided by VRE and storage. This would be much more expensive than the current fossil-fueled options but would support a non-financial goal or externality. It is possible that nuclear-generated heat may be competitive with the electrification option in the future, at either small scale in regional microgrids or at a focused industrial site, or in large industrial centers that share heating resources around large nuclear power plants to create local heat markets.

#### *3.2.1.2 The electricity market*

The electricity market is also characterized by a high level of uncertainty. While many projections indicate low cost of electricity in the future, it is not clear how this will be possible without heavily relying on low-cost natural gas. Scenarios having low electricity prices and zero carbon emission (without nuclear) may not be realistic unless a drop in the price of energy storage of more than 80% is realized (Ziegler et al. 2019). It is expected that nuclear will need to play a significant role if future electricity markets are to realize zero emission scenarios. However, nuclear cost structure is such that the cost of nuclear-generated heat and electricity becomes increasingly expensive as the utilization factor of the plant decreases. This is a primary motivation for considering IES in which the cost of absorbing demand volatility in grids with high level of VRE penetration is mitigated by the ability of industrial process to better tolerate (financially and technically) fluctuation of heat or feedstock supply. Hence, it can be inferred that the presence of IES would be beneficial in a deregulated market to mitigate price spikes and in a regulated market to decrease the overall cost of reliably covering demand.

While these are evident conclusions, the capability, in deregulated markets, to predict the value and depth (market elasticity) of price spikes in the long run is highly dependent on future policy regarding $CO_2$ emissions and future cost of competing technologies, such as batteries. Simulation capabilities to predict these future market characteristics are currently the object of many discussions and are highly uncertain. Uncertainties in potential electricity market revenues could be mitigated, in a deregulated market, by the recent introduction of markets aimed at removing some of the long-term uncertainties. One example is the capacity market, which is fairly new and still evolving.

In the case of regulated markets an additional challenge needs to be addressed. In a regulated market asset utilization is approved by the state energy commission that represents the interest of the ratepayers. The utilization of heat or electricity produced by a nuclear power plant for uses other than electricity to be provided to the ratepayers needs to be approved by the state representative. This approval can be obtained only if there is a stringent case that such operation of the plant leads to a lower financial burden for the ratepayers. This requirement reestablishes the need to predict the benefit of the IES to reduce the cost to reliably cover the electricity demand.

### 3.2.2 Closing the Competitiveness Gap

The key take-away from section 3.1 is that the ability to predict future revenue streams for a proposed technology is fundamental to bridging the valley of death. The current ability to conduct long-range predictions for the electricity market at the necessary level of fidelity is limited at best. This is a key gap that can be addressed by DOE-funded R&D that focuses on developing needed new analysis and simulation methodologies, integrating analysis tools and approaches that are available across DOE offices (e.g., the NE, EERE, and Fossil Energy) and those developed across multiple DOE-NE programs. In particular, close collaboration across the CTD-IES and LWRS programs allows sharing the burden to develop and test methodologies that will support commercialization of nuclear-based IES. Moreover, the close collaboration that LWRS has with the current fleet LWR plants provides a learning experience for understanding market behavior and how to better define financial performance in regulated and deregulated markets. LWRS also provides significant insight to costing of nuclear technologies that may be incorporated in IES. Collaboration across AR development programs and AR developers will provide preliminary costing and technical profiling of the new nuclear technologies to support IES design and analysis.

## 3.3 Regulations and Licensing

In the U.S., civilian nuclear reactors are licensed and regulated by the U.S. NRC. 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 of the Code of Federal Regulations (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 IES 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 IES 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; such consideration is currently under review by the NRC. 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 a chemical or industrial 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 energy 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 an IES and thermal efficiencies for thermally coupled systems.

While the NRC regulatory authority conventionally only deals with the nuclear island, deployment of nuclear reactors within an IES 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 thermally coupled configuration in Figure 2, where the hot stream from the reactor is apportioned between the balance of plant and process heat users through a thermal manifold and storage system. 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 IES configuration will likely be more extensive than that of a reactor that only generates electrical power. Therefore, it will not be possible to deploy a standard reactor design into a tightly or thermally coupled IES without license amendments during the combined operating license and site suitability approval process.

Because the nuclear facility thermal hydraulically interacts with the nonnuclear facilities through an interface, such as a thermal energy storage unit, 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.

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 IES to ensure that regulatory hurdles do not arise in the licensing process.

At a high level, there appears to be no regulatory challenge that would prohibit deployment of nuclear power plants within an IES configuration. However, there are potential impediments related to nonconventional deployment of nuclear reactors that must be addressed in a timely fashion. For a successful deployment scenario, key issues should be identified, and R&D efforts should be planned for timely resolution. 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. Evaluation of potential accidents is common practice for nuclear systems, and is a standard component in the licensing process. However, understanding the potential risk posed by coupled industrial facilities may require additional detailed mechanistic analyses (similar to mechanistic source term calculations) beyond what is traditionally conducted for standard nuclear power plants. Finally, R&D on resilient instrumentation and control architectures may be necessary to ensure safe performance of the integrated system.

Potential regulatory aspects of IES should be addressed in collaboration with industry partners. 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.

## 3.4 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 IES configuration is outside of the standard scope of nuclear power plant operation, the structure of the insurance coverage and the associated insurance premiums are anticipated to be somewhat different than for a currently operating plant. Obtaining insurance to build and operate an IES will be the responsibility of the operating utility. Although the DOE-led R&D intended to advance the IES 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 should be conducted with industry collaboration during the laboratory testing, scale-up, and system refinement development to ensure that there will be no significant roadblocks to commercialization of the proposed IES. Nuclear insurance in the U.S. is provided through American Nuclear Insurers.

# 4. Implementation

The optimal IES design will vary significantly as a function of the intended deployment location and products to be produced. This section identifies possible technical and economic metrics for evaluation of IES, although these metrics may be weighted differently as a function of the intended application. Possible operational constraints and optimization goals are proposed, as well as analysis approaches for design and operational optimization and facilities required for experimental demonstration of proposed systems to raise the TRL of individual components or subsystems, or to demonstrate integration hardware and control approaches in advance of commercial system deployment.

## 4.1 Metrics

Candidate system configurations should first be assessed relative to a series of technical performance criteria to ensure viability of a proposed configuration, followed by economic analysis and system design optimization relative to an established goal function. This section proposes a number of design and operational constraints, performance goals, and economic metrics to be included in the system design and analysis described in section 4.2.

Table 5. Reference figures of merit for IES design and deployment.

| Design Criteria | Environmental |
|---|---|
| System-wide efficiency | GHG ($CO_2$-eq) emissions |
| Grid reliability | Other air pollutant emissions regulated by the Clean Air Act and other regulations |
| Grid flexibility, system flexibility | Water use |
| Controllability | Land use |
| Siting feasibility | Land use / visual impact |
| Licensing feasibility | Stewardship of resources |
| Near-term deployability | Waste disposal |
| Safety risk | Other ecological impacts |
| Component and subsystem TRL | Net return on energy (i.e., the ratio of energy input converted to energy services) |
| Integrated system readiness level | Impact on human life |
| Constructability (staged build-out) | |
| Resiliency | |
| Inherent security | |
| Broad (e.g. global) applicability | |
| Design adaptability | |
| **Financial** | **Policy** |
| Project finance indicators | Domestic resources, markets |
| Design, development, and construction risk | National energy security |
| Price stability / volatility (e.g., manufacturing costs and product revenue) | Energy contingency planning |
| Capacity factor | National economy |
| Design adaptability | Supply diversity |
| Business model viability | Political climate |
| Business case sustainability | Clean energy hubs or targets |
| | Existing consortiums |
| | Inclusion in Environmental Protection Agency State Implementation Plans for Section 111(d) of the Clean Air Act |
| | Government funding potential |

Various figures of merit for IES design were proposed in the 2014 *Integrated Nuclear-Renewable Energy Systems: Foundational Workshop Report* (Bragg-Sitton et al. 2014). Table 5 summarizes figures of merit that continue to be relevant to the potential commercial deployment of IES. These considerations are roughly binned into design, environmental, financial, and policy categories. Analysis tools further refine these categories to establish specific performance criteria or optimization goals for system design and operation.

### 4.1.1 Technical Performance Constraints and Optimization Goals

Technical performance constraints employed in system design and evaluation will depend on the specific subsystems of interest, component and subsystem designs, materials of construction, etc. Hence, these design and operational constraints must be assessed independently for each proposed IES. The selected evaluation framework should be designed to accommodate such constraints to ensure that the system optimization properly addresses them. Potential operational constraints that can be applied independently to each component or subsystem include:

- Minimum/maximum operating temperature
- Minimum/maximum operating pressure
- Minimum/maximum flow rates
- Maximum ramp rate (up or down)
- Minimum turndown (i.e., minimum operation level) as a function of full (nominal) capacity.

While working within these constraints, the optimization process may take into account a number of performance goals, with a goal function properly designed to reflect the hierarchy of importance of each of the performance parameters. Performance goals of interest may include:

- System efficiency (utilization of energy generated)
- Capacity factors for each subsystem
- Environmental impact (e.g., $CO_2$ and other pollutant emissions, land use [permanent and/or recoverable], water use)
- System reliability (e.g., must achieve an established level of reliability under all planned operational scenarios and anticipated off-normal scenarios)
- System resilience to man-made and weather-related events

Other figures of merit included in Table 5 may lend themselves to qualitative evaluation (e.g. design adaptability) rather than quantitative evaluation and hence cannot be included in an optimization routine. These qualitative measures should be considered in design selection by relevant stakeholders as go/no-go characteristics or on a sliding qualitative scale for prioritization of design options.

In evaluating the technical performance of an IES significant data is required to ensure that the analysis is relevant to the intended deployment location. Such data include:

- Renewable resource availability (e.g. wind and solar profiles, hydro potential)
    - Raw resource data (wind speed, solar irradiation)
    - Currently installed capacities and projection of future capacities
- Electricity market data
    - Type of market (regulated/deregulated)
    - Policy altering the market structure (e.g. tax benefit)
    - Type of markets (day ahead, capacity market, etc.)
    - Time dependent depth of markets (electricity demand, reserve demand, etc.)

    - Marginal cost of suppliers outside IES (supply curve) or clearing prices of the different markets
- Co-products (industrial commodities):
    - Time-dependent energy demand for coupled processes
    - Demand curve of co-products
    - Supply curve for feedstock

Once technical operation is proven feasible, and operating constraints applied, an appropriate goal function can be defined in an analysis and optimization toolset to achieve the desired technical performance goals and economic goals, as described in sections 4.1.2 and 4.1.3.

### 4.1.2 Economic Optimization

Proving the economic viability of a technically feasible IES configuration is key to ensuring commercial deployment. The selected economic figures of merit may differ for each potential investor. For utilities operating in a regulated market the final goal is to prove that the investment will lead to a decrease in the electricity cost to the ratepayer in excess of its costs. In this situation the necessary approach is to determine that the decrease in system cost, which may derive from lower reserve requirements, reduced fossil fuel use, etc., exceeds the capital investment for the project. From a computational point of view the problem for the regulated market is formulated as the minimization of the effective levelized cost of electricity (LCOE) to cover demand, which is the cost to reliably cover the electricity demand. In a deregulated market the desired figure of merit is a profit metric, such as net present value (NPV), internal rate of return (IRR), or profitability index (PI), which should be maximized.

Key economic factors necessary to support analysis include capital costs (including interest incurred during construction), resource costs (e.g. fuel, feedstock, etc.), and operations and maintenance costs (fixed and variable). For a more detailed list of cost input parameters necessary for the analysis and optimization, see section 5 of reference (Epiney 2017). For nuclear plants it should also be noted that end-of-life costs for used nuclear fuel storage or disposal and the cost of nuclear plant decommissioning are built into the cost structure while the plant operates; hence, funds are available to manage the waste stream from nuclear plants at the end of life. Similar cost structure may not be applied in an equivalent manner to nonnuclear generators; hence, additional life-cycle costs should be included for coupled subsystems in future analyses.

## 4.2 Analysis Approach and Tools

The IES program has established a computational framework that leverages advanced modeling and simulation tools developed through the support of multiple DOE-NE programs while incorporating specialized tools necessary for the economic optimization of integrated systems. This framework is applied to conduct analysis of the technical and economic viability of a range of possible IES configurations and, at the end, to optimize those configurations within a specific U.S. region. The analysis tools and approach are briefly summarized in Figure 12.

The first step in evaluating a candidate IES is to determine the technical feasibility of the system. High fidelity tools, where “high” fidelity is relative to the level of complexity of the systems modeled, are used to determine the steady state performance of the IES configuration in order to derive efficiency of the thermochemical processes and necessary scaling factors to assess plant costs. This step is performed primarily using commercial tools, such as ASPEN HYSYS.

Following this step, the dynamic aspects of the systems are assessed by creating a dynamic model of the plant in the Modelica language. These models are used to determine controllability of the system, characteristic ramp rates, and overall operability in transient situations. A common control system is designed and tested to ensure that coordination among the different components/subsystems is achieved and no component exceeds its technical limits.

Modelica models are usually relatively slow to run for the number of years necessary to perform financial evaluation of the investment (usually 30+ years); therefore, surrogate models are usually adopted in the next step of the process. The original Modelica models are run when the time horizon is short and the analysis is more focused on capturing the ability of the IES to respond to the dynamic nature of the market. When this type of simulation is performed the accelerated aging of components needs to be captured to provide negative financial feedback that derives from the corresponding increase in maintenance costs, shorter asset lifetimes, and asset replacement. Accelerated aging models to capture this aspect of performance represent a gap in IES development and deployment; however, such models are currently under development by the CTD-IES program.

At the next step the INL-developed Reactor Analysis and Virtual Control ENvironment (RAVEN) is used to process raw market data to create synthetic data that represent the market while embedding its stochastic nature (Talbot et al. 2019). In this step the boundary conditions for the system are created. A set of RAVEN plugins (i.e. Holistic Energy Resource Optimization Network [HERON] and CashFlow) are used to perform the multi-year financial optimization of the IES in agreement with the financial figures of merit appropriate to the type of market under consideration (Talbot et al. 2020; Epiney 2017). HERON is used to optimize the dispatch of different IES resources to the grid or the co-product markets (inner loop in right side of Figure 12) and to optimize the individual component sizes within the IES (outer loop in right side of Figure 12). HERON implements a stochastic optimization approach to manage the stochastic nature of the market itself. During the dispatch optimization in which the response of the IES as whole is optimized, advanced control strategies are necessary. Control systems appropriate to IES represent a current technology gap that is being studied by CTD-IES.

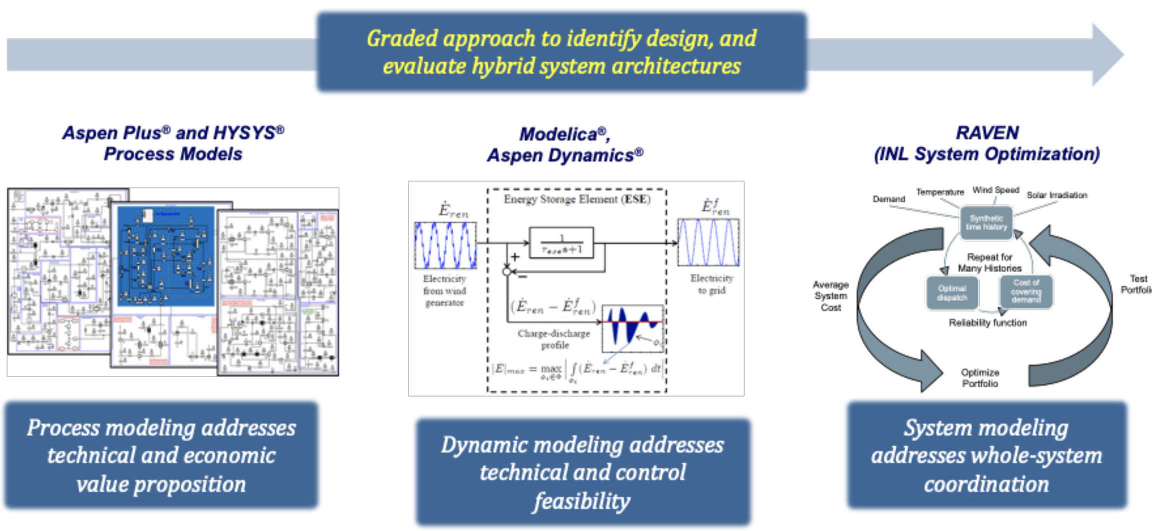



Figure 12. Summary of analysis approach being applied for IES configurations.

At present there are still gaps in regard to the various analysis tools necessary to support refinement of IES design that must precede commercial deployment. First, long-term portfolios are not yet defined in the analysis framework; hence, there are no capacity expansion features in HERON. For IES analyses completed thus far, long-term portfolio projections have been conducted using the ReEDS tool developed by the National Renewable Energy Laboratory and, if needed, market clearing has been assessed using PLEXOS. A developing collaboration with the National Energy Technology Laboratory and Sandia National Laboratories proposes to couple tools developed at the collaborating laboratories to provide similar capabilities that will further enhance HERON capabilities.

Another less significant analysis gap is the fact that HERON, due to the generality of its approach, cannot be used to optimize dispatch for very large regions (several plants). As a result, for some specific applications it is necessary to provide the market clearing price as input using the PLEXOS code. In the future this is a problem that may need to be addressed if the simulation accuracy with low fidelity simulations can be accepted.

Among optimization dispatch analysis tools, RAVEN/HERON is the first to adopt a fully stochastic approach; such approach is now being followed by other commercial tools. Therefore, some challenges are expected. Most of the work in this respect is focused on reduction of the necessary number of samples to ensure a reliable convergence of the stochastic optimization under probabilistic constraints. For further details on the simulation framework see references (Rabiti et al. 2017; Epiney et al. 2018; Epiney et al. 2019; Talbot et al. 2018).

## 4.3 Lab-scale Testing

Lab-scale testing and demonstration of individual or coupled technologies should be employed to demonstrate performance characteristics, integration approaches, and system control options. This type of scaled testing may also provide data for validation of computational models employed in broader system design and optimization prior to demonstration on a nuclear system. Scaling of technologies from the lab to commercial scale can entail unique challenges that can impede commercial-scale deployment. Considerations in the scaling of components and systems, and the status of anticipated nuclear demonstrations, are provided in this section.

### 4.3.1 Scaled Experiments

Experiments are scaled to understand and replicate certain phenomena of interest without having to incur the prohibitive cost and labor required to develop a fully functional prototype system. The scaled facility should replicate all of the important phenomena of interest. Scaling analysis is used to relate the results obtained in the scaled system to the expected behavior of the full-scale plant. In addition, a scaled experiment can be an economical method of analyzing the interconnections between IES components and associated system time constants.

Scaling of single components involves matching the relevant nondimensional parameters between the model and the prototype for the component of interest. For single-phase steady-state forced-convection thermal-hydraulic components, these parameters include the Reynolds number and Prandtl number. For single-phase components with natural convection, the Rayleigh number must be added to the list. For components with two-phase flow and boiling or condensation heat transfer, additional parameters must be added including the Jakob number, the Bond number, the Weber number, and others. In addition, geometrical parameters such as orientation (vertical or horizontal) become explicitly significant for two-phase thermal hydraulics. If the transient behavior of thermal-hydraulic components is of interest, the scaling analysis of even a single component is significantly more complicated, and parameters related to heat conduction in the solid material must be considered.

In some cases, integrated system experiments may be performed to characterize the coupled behavior of two or more components or subsystems. Ideally, a perfectly scaled miniature version (perhaps at reduced pressure and temperature) of a much larger multi-component system of interest could be built that would faithfully reproduce all of the important phenomena associated with integrated operation of the full-scale system, including two-phase and transient behavior. Unfortunately, this idealized approach is not achievable due to the multiple disparate scales of the phenomena of interest. For complex multi-component multi-phase systems, such as nuclear steam supply systems, it is generally not possible to match all of the relevant nondimensional parameters in subscale models. Scaling analysis of these integrated systems typically requires the introduction of many additional nondimensional groups. Therefore, compromises must be made and an assessment of the importance of scaling distortions must be performed. System scaling will be taken into consideration as IES technologies are developed and tested to support characterization and V&V activities prior to full scale deployment of nuclear systems.

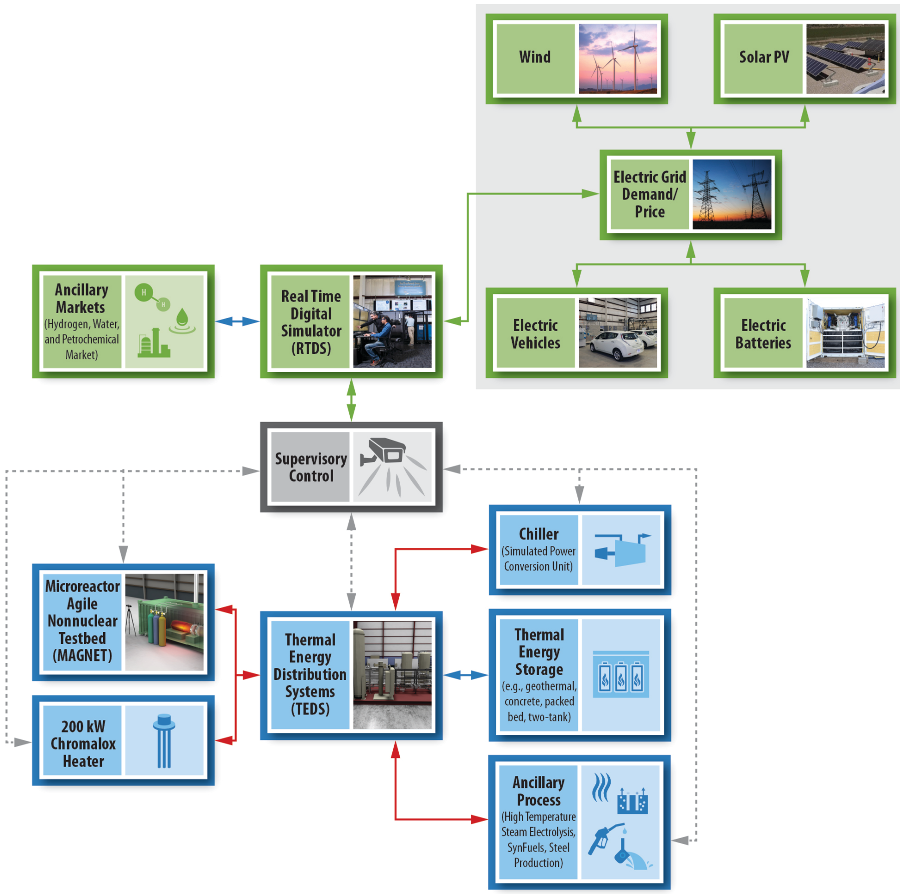
### 4.3.2 Bench Scale Testing of Individual Technologies

Bench-scale testing is conducted to demonstrate technologies at various readiness levels in order to decrease risk of future commercial adoption and deployment. Such testing can provide needed performance data, V&V support for detailed models, and operational experience. Current laboratory work focuses on the demonstration of selected technologies to support IES development and deployment to reduce the risk of commercial deployment of these plants. For example, bench-scale testing is underway on a heat-pipe-cooled microreactor emulator. Electric cartridge heaters provide heat input, which is transferred to a heat sink via a heat pipe. This test will demonstrate gas-gap calorimetry for the heat removal from the heat pipe to a chilled water stream, heat transfer via radiation, convection, and a small amount of conduction between cartridge heaters, the "core" block, the heat pipes, and the gas-gap calorimeter. It will also validate the experimental set up for the larger scale testing of the microreactor agile non-nuclear test bed (MAGNET) that will be constructed at the INL Energy Systems Laboratory, which will again provide valuable performance data prior to design and deployment of a nuclear fueled system.

### 4.3.3 Integrated Systems Testing

Maturation of IES technologies through TRL 6 will likely require a series of independent and integrated component and subsystem tests to demonstrate key performance characteristics. Nonnuclear, electrically heated test facilities can be employed to better characterize system integration approaches and controllability of the system operation under normal and off-normal operating conditions. A nonnuclear configuration may utilize resistance heaters to emulate the thermal energy that would be generated by a nuclear reactor. Controllable heater elements can be used to simulate heat production from nuclear fuel using sophisticated control algorithms to provide accurate simulation of subsystem dynamics within the integrated system. INL and other national laboratories and industry partners have developed or are developing electrically heated, nonnuclear test facilities that can be employed in various stages of IES development and testing.

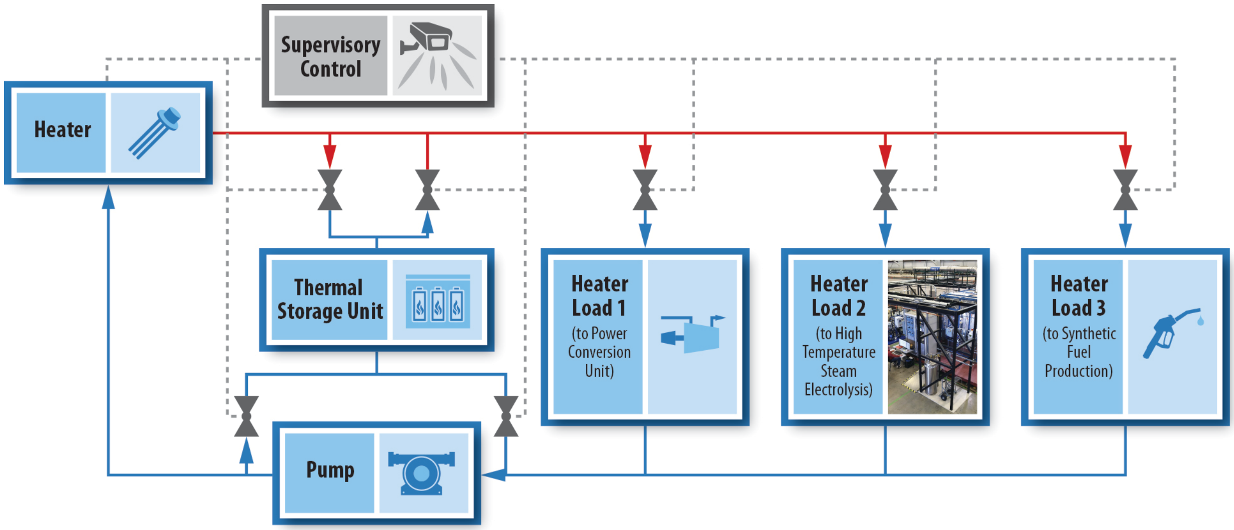
The dynamic energy transport and integration laboratory (DETAIL) at INL is an example of such a facility that contains multiple experimental systems to be integrated both thermal-hydraulically and electrically. The HTSE system, the thermal energy distribution system (TEDS), and MAGNET are thermal-hydraulic systems currently in operation or under construction in the laboratory (see laboratory rendering in Figure 13). Each of these systems has connections available and are designed for interconnection via heat exchanger. TEDS is designed to be a "plug and play" network of valves, pipes, and heat exchangers that allows the mass movement of thermal energy between connected subsystems, such that it serves as the backbone of DETAIL (see Figure 14). A real time digital simulator provides the ability to electronically integrate these systems with systems at other laboratories and/or customer sites to further extend integrated system demonstration capabilities. A battery storage and charging laboratory and a microgrid test facility allow for opportunities to demonstrate how each of these systems can respond to changes in demand or supply on the grid. Finally, a supervisory control approach and associated hardware is being developed for DETAIL and will be integrated with the Human Systems Simulation Laboratory (HSSL) that emulates a nuclear power plant control room. Integration of DETAIL and HSSL will allow demonstration of control approaches for industrial utilization of nuclear-generated thermal energy and/or steam, in addition to electricity production and utilization, and will provide valuable information on the associated human factors aspects of operating integrated systems. Tests conducted in the interconnected facilities will include real-time operation of the thermal energy management components or unit operations of the integrated energy user, initially the HTSE system, functioning dynamically to match non-spinning grid capacity reserves.




(a)


(b)

Figure 13. System configuration of the INL Dynamic Energy Transport and Integration Laboratory, (a) overall planned configuration of all components, and (b) rendering of key laboratory facilities.




(a)


(b)

Figure 14. Simplified system configuration for the INL Thermal Energy Distribution System, showing (a) flow paths and (b) rendering of hardware components.

## 4.4 Nuclear System Demonstration

IES involving nuclear energy systems will ultimately require demonstration at a nuclear facility. Demonstration of IES for current fleet LWRs may incorporate high TRL subsystems, such that the primary benefit of system demonstration is to raise the TRL of the integration hardware and operational schema. Once demonstrated for current fleet plants, the relative scale of the technology gap for next generation SMRs and other advanced reactors may be significantly reduced. However, each configuration may entail different integration hardware, instrumentation, and control approaches as a function of the selected subsystem technologies. Hence, additional technology gaps may be present for each IES instance that will require some level of testing, safety analysis, and regulatory approval.

### 4.4.1 Current fleet demonstrations

In 2019, two private/public hydrogen production demonstration projects at nuclear plant sites were awarded through DOE Financial Assistance Funding Opportunities Announcements: 1) U.S. Industrial Opportunities for Advanced Nuclear Technology Development; DE-FOA-001817, and 2) FY 19 H2@Scale, DE-FOA-0002022. A project led by Energy Harbor (formerly FirstEnergy Services), Xcel Energy, and Arizona Public Service (APS) was awarded to demonstrate low-temperature proton-exchange membrane hydrogen production technology at the Davis-Besse Nuclear Power Station. INL and the National Renewable Energy Laboratory (NREL) are partners on this award which will also complete detailed technical and economic assessments for Xcel Energy and APS. A second hydrogen production demonstration project at an Exelon plant was awarded to Exelon and partners INL and NREL.

#### *4.4.1.1 Energy Harbor/Xcel/APS*

The principle objective of the project awarded to the tri-utility consortium of Energy Harbor, Xcel Energy, and APS is to carry out planning, design, installation, testing, demonstration, and evaluation of non-electric, integrated energy technologies connected to a LWR power plant, with a focus on scalable hydrogen generation pilot plant. The project will install a LTE hydrogen generation pilot plant unit at Davis-Besse Nuclear Power Station. Major interfaces required for integrated LWR operations (e.g. dynamic controls to apportion power output between the electrical grid and LTE unit) will be developed, tested, and refined in this project. The expected result is to have a fully functional operating hydrogen generation skid that has been integrated into the normal operating routine of a nuclear power plant. In addition, accumulated operating data will highlight the technical feasibility and economic viability of this integrated system. Results from the system demonstration will ultimately be available to other nuclear power utilities to support large-scale commercialization of the IES technology at the 100s MWe scale.

The project will also include technical and economic assessments for APS and Xcel Energy, which operate nuclear power facilities in different electricity markets in the U.S. These assessments will support the technical and financial feasibility of integrated system operations for hydrogen generation. This information, along with pre-front-end engineering design input from the collaborating utilities, will support development of an investor-grade report summarizing the business case for undertaking similar projects to implement hydrogen generation at other LWR power plants.

#### *4.4.1.2 Exelon*

A similar project led by Exelon Corporation will demonstrate an end-to-end integrated grid-scale carbon-free $H_2$ production, storage, and utilization pilot plant at an Exelon-owned nuclear generating facility, providing necessary data to further reduce technical and financial risk associated with commercial IES deployment. This project will evaluate market opportunities and regulatory requirements related to the participation of integrated hydrogen production and nuclear plant facilities in organized power markets by demonstrating dynamic control and operation of the electrolyzer and assessing the economics of dynamic participation combined with the revenue streams from hydrogen production. The main objective of this project is to demonstrate that hydrogen can be economically produced at large scale using nuclear energy. This demonstration will also verify the proposed operating scheme by testing the response characteristics of a commercially scalable hydrogen electrolysis unit and the ability to support grid regulation while producing hydrogen for local users.

### 4.4.2 LW-SMR Demonstration

The Carbon Free Power Project (CFPP) aims to deploy the first SMR plant in the U.S. Led by the Utah Associated Municipal Power Systems (UAMPS), the CFPP plans to construct and operate a 12-module SMR plant based on the NuScale SMR design on the INL site. The premise of the Joint Use Modular Plant (JUMP) Program is to enable both commercial use and R&D activities within a single multi-module nuclear plant, wherein a specific module would be allocated to R&D use via a prearranged agreement between the operating utility and the national laboratory conducting the research activities. Based at INL, the JUMP program would seek to establish a unique platform to demonstrate IES in this fully commercial SMR power plant environment. The JUMP platform would be used to demonstrate coordinated use of nuclear generation with nearby renewable installations (e.g., wind and hydro generation near the INL site) and non-electric use of thermal energy produced by the JUMP module. Energy users would include thermal energy storage systems that are currently being reviewed for applicability to the NuScale system design (Mikkelson et al. 2019) and one or more industrial processes designed to produce various commodities. While no specific technology has been selected for initial demonstration within JUMP, thermally integrated HTSE for hydrogen production is under consideration. Demonstration of IES operation within a multi-module nuclear plant would support demonstration of plant flexibility in response to various external signals (e.g. renewable generation, electricity demand) and provide operational data associated with the selected integration design and control system for dynamic apportionment of thermal energy. The facility would also offer a unique opportunity to study human factors aspects of multi-modular plant operation, particularly when some modules may be dedicated either in part or whole to non-electric applications. Additional details on the proposed JUMP RD&D scope can be found in (Bragg-Sitton et al. 2019); an updated report on the requirements and constraints associated with the proposed RD&D scope will be issued in September 2020. In mid-2020 DOE placed the JUMP program on a deferred status, pending an updated CFPP schedule and funding allocation to support JUMP. Although it is not yet apparent if the JUMP program will be authorized by DOE to continue in coordination with the UAMPS and NuScale CFPP, the foundation established by initial JUMP program activities for demonstration of IES within a multi-module SMR plant will provide insight to planning related demonstrations for other advanced reactor plant designs.

### 4.4.3 Microreactor Microgrid Applications

Microreactors, and in some cases somewhat larger SMRs, can provide the needed reliability and operational flexibility to power a microgrid. Microgrids are power distribution systems with distributed energy sources, storage devices and controllable loads. Integrating several resources (i.e., wind and concentrated or photovoltaic solar) with the right storage option can result in a system of variable and controllable resources that is both flexible and manageable. Microgrids are envisioned to serve in energy intensive industrial settings that require both electricity and process heat. They are expected to serve remote communities where diesel currently provides electricity and residential heating. The U.S. military is also investigating the use of a microreactor and microgrid for the diverse energy needs of both domestic and forward operating bases. These bases are increasingly becoming energy intensive with the need for electricity to charge batteries, hydrogen for vehicles, electricity to run the base, and for water purification.

Microgrids powered by microreactors bring a host of novel technical requirements that will require special testing facilities. There is a need for testing the integrated operation of energy storage devices, load banks, smart inverters, a power distribution system, and switchgear. Load control capabilities and grid interaction algorithms will be assessed for demand response, peak shaving and ancillary services, component interactions, and performance. Demonstration of microreactor technologies anticipated by the mid-2020s may provide opportunities for demonstration of microgrid configurations that would incorporate IES concepts.

### 4.4.4 Advanced Reactors

The National Reactor Innovation Center (NRIC), officially established at INL in FY2020, will support the demonstration of multiple advanced reactor technologies in collaboration with multiple reactor technology developers, with these demonstration systems potentially ranging in size from MW-scale microreactors to 100s MW-scale systems. Evolution of the electricity markets and opportunities enabled by high-temperature reactor technologies have resulted in many of these developers to look beyond electricity-only operation of these advanced reactor systems. NRIC will work with innovators to develop and demonstrate IES configurations, using both thermophysical and simulated interfaces. These demonstrations are anticipated within the next 10 years.

## 4.5 Estimated Timeline to Close R&D Gaps

Timelines associated with the deployment of IES will be highly dependent on the coupled technologies. Current fleet demonstrations, particularly those adopting electrical integration approaches such as those described in 4.4.1, can be conducted within the relative near term, while thermally integrated IES will require a longer design and development timeline, as well as associated safety reviews and licensing. The notional timelines for LWRs is provided in Figure 15, noting options for both electrical and thermal integration. Novel IES incorporating SMRs and other ARs will have more protracted development timelines reflective of their current development stage, as estimated in Figure 16 and Figure 17.

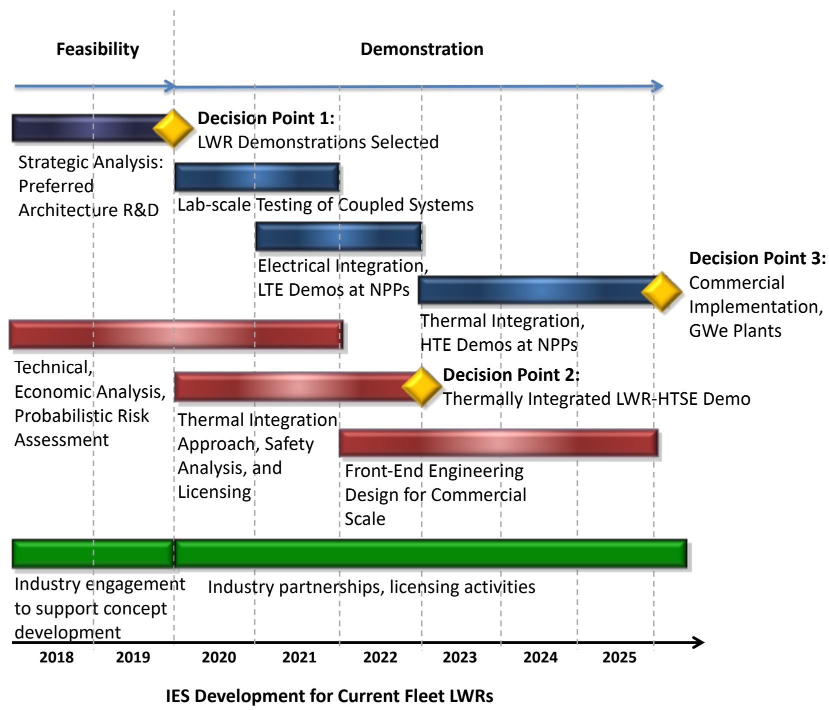



Figure 15. Notional IES deployment timeline for current fleet LWRs.

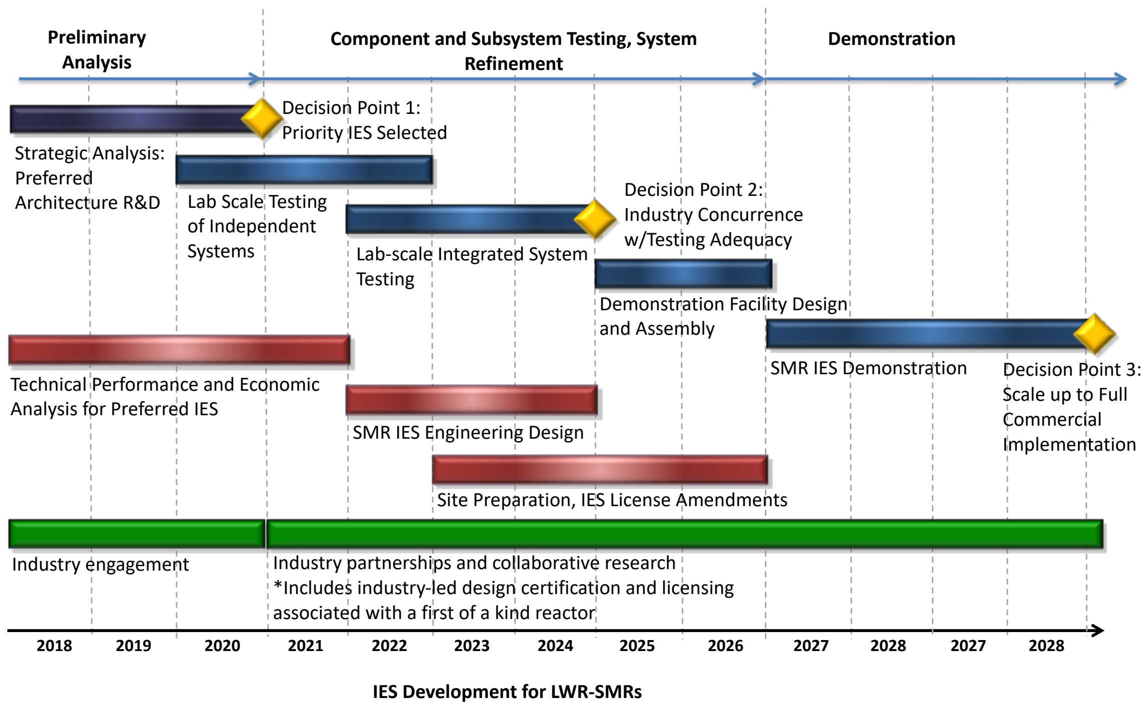



Figure 16. Notional IES deployment timeline for LWR SMRs based on the currently published schedules for the CFPP and JUMP programs.

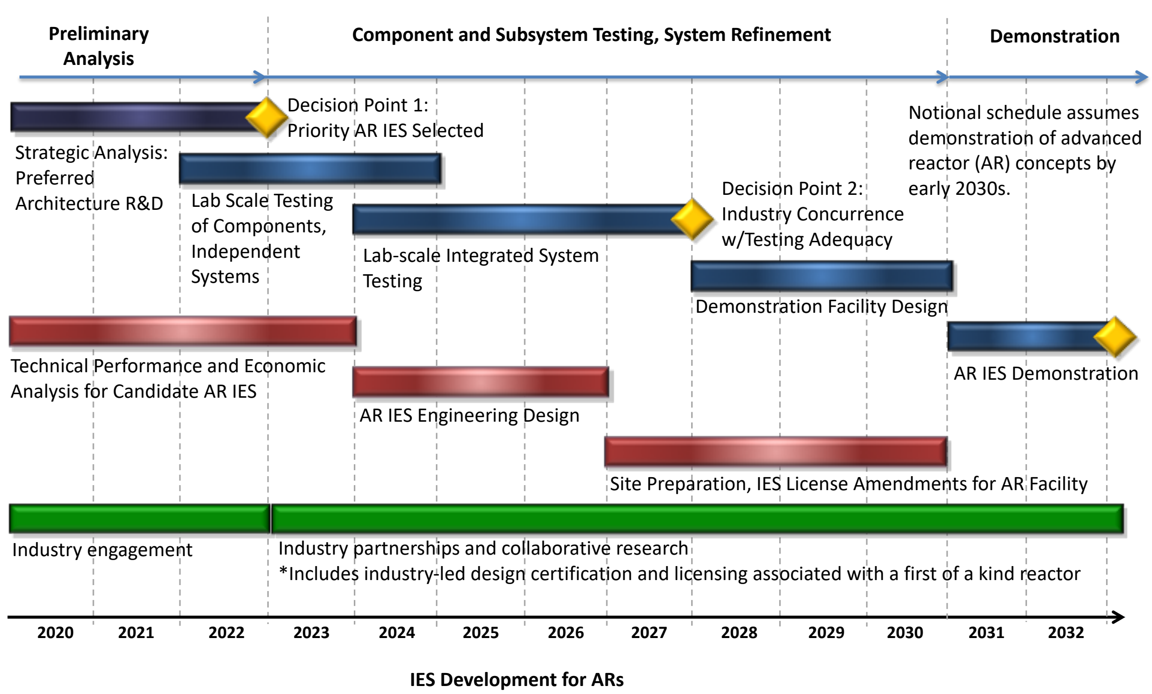



Figure 17. Notional IES deployment timeline for advanced reactors. Start date of 2020 reflects large-scale advanced reactors. Microreactors may be demonstrated on a shorter timeline and could include IES applications.

# 5. Key Participants

The development of technologies and conduct of research associated with the ultimate commercial deployment of IES is conducted by numerous DOE-funded programs and private industry. Programs anticipated to play a role in the development and deployment of IES are summarized here, but this is not intended to be an exhaustive list. Relevant programs include:

DOE Office of Nuclear Energy

- Crosscutting Technologies Development Integrated Energy Systems
- Light Water Reactor Sustainability Program
- Advanced Reactor Technologies (FSR, MSR, and HTGR programs)
- Nuclear Cybersecurity
- Advanced Sensors and Instrumentation
- Nuclear Energy Advanced Modeling and Simulation
- National Reactor Innovation Center

DOE Office of Energy Efficiency and Renewable Energy

- Fuel Cell Technologies Office, H2@Scale Program
- Advanced Manufacturing Office programs

DOE Office of Fossil Energy

- Hybrid Carbon Conversion

DOE, Multi-office

- Grid Modernization Initiative
- Applied Energy Tri-Laboratory Consortium

Work to be conducted under each program to address technical gaps relative to the respective program scope is captured under program-specific roadmaps and technology development plans. Advances in each of these programs will be leveraged in the CTD IES program to aid in the development and ultimate deployment of IES alongside strategic industry partnerships. As noted in the proposed schedule in section 4.5, industry partnerships are critical to demonstration of technologies in the higher TRL stages prior to full-scale commercialization. Partnerships with industry stakeholders thus should be established early in IES development to ensure program relevance to industry.

# 6. Summary

Nuclear energy can provide consistent, dispatchable power to meet electricity demands while also providing high quality heat that can meet energy demands beyond the electricity sector—all without emission of $CO_2$ or other GHGs. To fully realize these benefits, it is necessary to better characterize the potential role or roles for nuclear energy amid the growing field of variable renewable generation technologies. This document defines proposed integrated nuclear-renewable energy systems and identifies key technology gaps to realizing commercial scale systems for the production of a variety of electric and non-electric products. As described, IES that leverage nuclear energy generation systems can effectively touch all major manufacturing industries, including fuels, chemicals, metals, and the paper product industries, as well as smaller industries associated with food production, biofuels plants, minerals concentration, and water purification.

Integration of energy generation, storage, and use technologies present different technical, economic, and regulatory challenges for electrical and thermal integration approaches. R&D is needed to demonstrate coordinated delivery of the two energy streams in IES, particularly given that electrical power and thermal energy are delivered through systems with significantly different time scales and inertia. As described, much of the necessary R&D for maturation of integrated systems focuses on integration technologies, development and validation of the models used to design and optimize IES for specific regional applications, and establishing regulatory approaches that are suited to the unique design and implementation options for IES.

Coupled energy generation systems (e.g., novel reactor technologies) and advanced industrial applications may not be commercially deployed at present, but necessary steps toward technology maturation are being addressed through various federal R&D investments and private industry investment. These advances in the technical readiness of independent components and subsystems will provide much-needed performance data to validate and improve modeling, simulation, and optimization of integrated systems that may employ these technologies. Key technology gaps specifically associated with IES applications include advancement of the readiness level of components for heat transport and heat exchange across diverse systems, thermal energy storage, heat augmentation, electricity management, and control systems developed specifically for IES that can safely and securely manage the multi-application nature of IES.

Technology maturation will be accomplished via multiple R&D pathways for system and process modeling and simulation; component development, testing, and demonstration at increasing scale; development and demonstration of system monitoring and control approaches and tools; and integrated system demonstration. Notional timelines for development of IES for LWRs, LW-SMRs, and ARs have been proposed, noting that the necessary research may be completed by various federal and private industry research programs. Specific areas of research that will be addressed by the DOE-NE CTD IES program, in coordination and partnership with industry when appropriate, along with associated timelines and budgetary needs, will be covered in a follow-on CTD IES program plan.

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