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Integrated Nuclear-Renewable Energy Systems: Foundational Workshop Report

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) recognizes the need to transform the energy infrastructure of the U.S. and elsewhere to systems that can drastically reduce environmental impacts in an efficient and economically viable manner while utilizing both hydrocarbon resources and clean energy generation sources. Thus, DOE is supporting research and development that could lead to more efficient utilization of clean energy generation sources, including renewable and nuclear options.

A concept being advanced by the DOE Offices of Nuclear Energy (NE) and Energy Efficiency and Renewable Energy (EERE) is tighter coupling of nuclear and renewable energy sources in a manner that produces new energy currency for the combined electricity grid, industrial manufacturing, and the transportation energy sectors. This integration concept has been referred to as a “hybrid system” that is capable of providing the right type of energy, at the right time, in the right place.

At the direction of DOE-NE and DOE-EERE leadership, project leads at Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL) and Massachusetts Institute of Technology (MIT) have identified and engaged stakeholders in discussing integrated energy systems that would optimize renewable and nuclear energy integration on a region-by-region basis. Subsequent work will entail conduct of technical, economic, environmental and socio-political evaluations of the leading integrated system options based on a set of criteria established with stakeholder input.

Accordingly, INL and NREL, in coordination with project partners at MIT, developed and led a foundational workshop July 8-10, 2014 at Idaho National Laboratory. Experts from industry (energy resource project developers, technology developers and suppliers), utilities and power management groups, State governments, DOE and DOE national laboratories, and U.S. academic and international institutions were invited to participate. This diverse mix of participants is necessary to develop system alternatives that will be viable and feasible for implementation by industry, the utilities, states and power management groups.

A primary workshop goal was to establish an inter-laboratory, university, and industry team for integrated energy systems development. The key workshop objective was to collect necessary information and to identify fundamental options – with stakeholder input – that will guide development of a multi-year technology development roadmap. Input collected at the workshop will be used to guide technical, environmental, and economic assessments of options for region-specific nuclear-renewable energy systems.

For this workshop, integrated energy systems were defined as individual facilities that take two or more energy resources as inputs and produce two or more products, with at least one being an energy commodity such as electricity or transportation fuel. The systems are comprised of two or more energy conversion subsystems that have traditionally been separate or isolated. In an integrated system, these subsystems are physically coupled to produce outputs by dynamically integrating energy and materials flows among energy production and delivery systems. This definition requires coupling ‘‘behind’’ the electrical transmission bus, where all subsystems within the hybrid energy system share the same interconnection so that the grid is exposed to a single, highly dynamic and responsive system.

Motivation

Increasing global concerns regarding climate change have resulted in requirements to significantly reduce greenhouse gas (GHG) emissions in the coming decades. One solution is non-emitting, intermittent renewable resources, which are being added to the grid in increasing quantities to meet established State and Federal policy goals. This increased role of intermittent renewables in many regions can lead to more frequent occurrences of low or negative electricity prices at times of high wind or solar output, reduced baseload generator market size and associated baseload generator power reductions (e.g. load-following operation). Most current markets do not reward clean baseload power for its positive environmental attributes; thus, the reduced profitability has contributed to premature closure of several nuclear plants. Continuing to operate generation systems in traditional baseload fashion as the penetration of renewable energy generation continues to increase is not a sustainable business practice for baseload energy suppliers due to low or negative electricity value at times. Likewise, variable renewable generation can suffer from low or negative electricity value at high penetration. That scenario will also increase the overall cost of renewable generation because the value can only be realized outside of those peak times.

Growth of renewable generation in some unregulated markets is contributing to the premature closure of nuclear plants, particularly in light of the current low cost of natural gas in the United States. In regulated markets utilities have the option to include costs for new, planned additions of nuclear capacity in their rate structures, essentially allowing cost recovery in advance of the new plant build. Unregulated markets require all generation sources to compete and sell electricity to survive. In scenarios where nuclear technologies are more expensive than gas and renewable generation (once all subsidies are included), they cannot compete and, in some cases, are being closed. Regulated markets are also challenged by the low cost of natural gas, but some utilities are proceeding to build new nuclear capacity as a hedge against volatile natural gas prices. New developments, including small modular reactors, are also providing a renewed interest in lower cost nuclear generation, which could spur the development of novel hybrid energy systems.

Additionally, the carbon footprint of non-electric energy sectors (industry, commercial, residential, and transportation) needs to be reduced for the U.S. to meet long-term emission goals. Some zero-carbon technology options are being developed, but most suffer from resource limitations. Integrated nuclear and renewable energy production technologies provide additional options for thermal, electrical, and/or chemical energy to meet industrial and transportation demands.

Integrated Nuclear-Renewable Hybrid Energy Systems are being proposed to address these challenges. This solution involves coupling energy sources behind the electrical transmission bus to meet electricity demand while storing and/or utilizing excess thermal and electrical energy for value-added processes. These systems could be tailored to regional resources and markets to dynamically optimize the use of thermal and electrical energy. Optimized operation of such hybrid systems would meet growing grid flexibility needs while allowing operation of both renewable and nuclear power sources at levels that maximize economic benefit. Renewable electricity supplied to the grid could thus be increased to near-maximum theoretical potential while avoiding the need for fossil or nuclear plants to operate solely as stand-by dispatchable power sources. The resulting excess generation could, for example, support the production of significant quantities of clean transportation fuels from domestic resources.

Postulated Benefits of Hybrid Energy Systems

Preliminary studies indicate that tightly coupled hybrid systems may provide a number of benefits, including:

- Reduced greenhouse gas emissions in the coming decades, thereby enabling progress toward the Administration's goals for reduced emissions,
- Increased energy conversion efficiency through deployment of advanced integration, control, and heat/process management technologies that allow generators, grid operators, and energy consumers to optimally utilize assets and maximize system reliability, electricity supply stability, and profitability,

- High reliability of electricity supply and consistent power quality by economically providing flexibility and other ancillary services to the grid,
- High penetration of renewable energy by transforming the grid infrastructure to provide grid-scale energy storage and dispatch,
- Reduced fossil fuel dependence for the transportation sector via expansion of clean energy sources that can be used by plug-in vehicles, hydrogen fuel cell vehicles, and for biofuel and synfuel production,
- Reduced fresh water withdrawals and consumption through higher efficiency thermodynamic power cycles, increased utilization of wind turbines and solar photovoltaics, desalination of seawater, and other productive utilizations of low-grade heat, and
- Conversion of U.S. natural resources to desirable, high value products that enhance the nation's economic gain in domestic and international markets.

Challenges to Hybrid Energy System Development

Design, development, and deployment of tightly coupled integrated energy systems face numerous challenges. These challenges can basically be grouped as follows:

1) **Integration Value:** Possibility for integration to increase the value of system components; added risk of integration relative to improvement in efficiency and energy availability; market structures that do not necessary monetize the value of grid services that might be provided by an integrated system.
2) **Technical:** Novel subsystem interfaces; ramping performance; advanced instrumentation and control for reliable system operation; safety risk assessments; commercial readiness of the technology and operational risks.
3) **Financial:** Business model; cost and arrangement of financing and risk/profit taking agreements; shifts in cultural values and associated market evolution trends for various products; assurance of high capital utilization efficiency.
4) **Regulatory:** Projected environmental regulations; deregulation or re-regulation of electrical and other energy markets; licensing of a co-located, integrated system; involvement of various regulatory bodies for each subsystem and possible "interface" issues.
5) **Timeframe:** Resolution of issues/challenges within the timeframe established based on external motivators for these systems (e.g. EPA carbon pollution standards); possibility of hybrid implementations at the rate market forces influence build-out of renewable resources; possibility for grid stability issues to drive alternative solutions that create alternative long-lasting capital investments/inertia.

Workshop Focus

The Foundational Workshop for Integrated Nuclear-Renewable Energy Systems was organized around the following objectives:

1. Identify and refine priority region-specific opportunities for integrated nuclear-renewable energy systems in the U.S.;
2. Select Figures of Merit (FOM) to rank and prioritize candidate systems;
3. Discuss development needs for enabling technologies;
4. Identify analysis requirements, capabilities and gaps to estimate FOM for integrated system options;
5. Identify experimental needs to develop and demonstrate nuclear-renewable energy systems.

The workshop opened with several presentations to initiate the process of bringing the audience to a common level of understanding on the proposed integrated energy systems to enable detailed discussions and brainstorming to take place throughout the remainder of the workshop. Additionally, two roundtable discussions were convened to ensure that stakeholder interests were captured and understood. Detailed discussions and brainstorming sessions held during the latter part of the workshop, along with tailored questions soliciting individual participant priorities and input, maximized the involvement and feedback from the meeting participants. Key outcomes from these sessions are summarized below.

Energy System Figures of Merit

A key purpose of the workshop was to develop and rank a set of "figures of merit" (FOM) that could be used to: 1) evaluate the technical, economic, environmental, and socio-political benefits of hybrid energy systems integration versus "business as usual" plant operations, and 2) reduce the number of leading regional hybrid options to two or three for initial detailed assessment. A general brainstorming activity by the entire group effectively narrowed the overarching goals of integrated NE-RE systems to the following:

1. Develop energy systems that can support economic health and quality of life as energy demand grows;
2. Control GHG emissions;
3. Demonstrate a business case that supports industry, economy, and service-providers;
4. Utilize domestically available resources (e.g. coal, natural gas, uranium, wind, sun, manufacturing materials, and capabilities).

A set of candidate FOM were presented by meeting organizers and refined via large-group discussion. With the above goals in mind, workshop participants independently selected the top ten FOM from the candidate list via an online form. The top-ranking FOM from this exercise represented each of the four defined FOM "categories" – Finance, Environment, Policy, and Design. Financial *pro forma* and GHG reduction were selected with the highest frequency, indicating a need for a good business case and environmentally responsible energy system designs. The next-highest-ranking selection was National Energy Security, signaling the participants' high value for independence from energy imports. In the Design category, high selection frequencies of Near Term Deployability and Grid Reliability reflect a common interest in completing the development and near-term demonstration of energy systems that will accelerate build-out of renewable energy on the grid while maintaining supply reliability.

Regional Opportunities and System Designs

A second purpose of the workshop was to identify key integrated system options for further analysis and consideration. A comprehensive view of the priority regional options will be used to identify research and development gaps and needs, with the intention of informing the roadmap to ensure that those gaps and needs are fully addressed. Note that some regions of the country may not be amenable to the economical use of renewables due to insufficient wind or solar intensity. Hence, a focus on regional evaluations is imperative in identifying attractive system options.

Eight system options were initially proposed for discussion. Each option focuses on a specific U.S. region based on resources, traditional industrial processes, energy delivery infrastructure, and markets. Nuclear-renewable energy systems can be organized into five subsystem categories: thermal energy generation (i.e. nuclear reactor); power conversion (electricity generation); renewable resources and related systems; industrial processes; and interface or storage technologies. By definition, each system in the current study must have a nuclear reactor; however, the other subsystems vary depending on the region's resources and market opportunities.

Workshop participants provided input on priority options for each region via small group discussions. The intent of those discussions was to develop a consistent understanding and possibly some consensus before requesting independent feedback. Additional large-group discussion provided multiple insights to system selection. In many of the regional options discussed, participants noted that the components are the same but the markets differ – which could significantly impact the business case. For the integrated systems roadmap, participants recommended a diverse technology portfolio instead of several selections for different regions having essentially the same technologies. In selecting options and regions, discussions highlighted the importance of the regional political landscape. Participants also suggested consideration of decentralized options, as the trend in many sectors seems to be moving away from large central facilities to smaller, decentralized facilities.

Independent online feedback was requested from participants to identify system options beyond the eight configurations initially proposed, taking into consideration the workshop discussions and outside knowledge. Each participant was asked to develop up to three specific configuration options for integrated nuclear-renewable energy systems, identifying a combination of renewable resources, industrial systems, and storage / interface technologies.

Participant responses were varied without a clear priority for initial analysis and development. Desalination was the most selected industrial process, appearing in over one-third of all submitted configurations. Land-based wind was the most selected renewable resource, followed closely by concentrating solar power (CSP) and solar photovoltaics (PV). Liquid thermal storage (e.g., molten salt) and hydrogen production via high-temperature electrolysis were the most selected storage / interface options. One should note that the subsystem combinations must be selected based on regional siting options; simple combination of the most-selected technologies in each category may not generate a feasible configuration. No single complete process (or small number of processes) emerged as a priority option for future efforts. Instead, the general input and key options identified will be used to aid selection of priority process options for consideration during roadmap development.

Path Forward

The Integrated Nuclear-Renewable Energy Systems Foundational Workshop accomplished the goal of initiating an inter-laboratory, university, and industry team for integrated energy systems development; additional input will be sought from stakeholders who were unable to attend. Significant progress was made toward identification of regional system configurations, prioritization of options for evaluation, and definition of key figures of merit necessary to evaluate the potential technical and financial performance of those systems. Additional work is necessary to refine the region-specific configurations before conducting detailed analyses and applying the key figures of merit that were identified. Analysis of two of the priority configurations is planned, and results of these analyses will inform the Integrated Systems Technology Development Roadmap. The draft roadmap will be distributed to the broad range of experts who are expected to contribute to the design, development, demonstration and use of integrated energy systems for comment before it is finalized to ensure that the planned activities are relevant and actionable.

Significant research is required to reduce development risk for advanced energy systems. Leadership by the DOE national laboratories in these early development phases is necessary to ensure the advancement of novel concepts that have the potential to significantly enhance the performance, reliability and sustainability of future energy systems in the U.S. and abroad. As technology gaps are reduced and a clear implementation path is defined, technology can and should be transitioned to industry leadership for prototype development and eventual commercialization.

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ACRONYMS

ANOVA	ANalysis Of VAriance
BLM	Bureau of Land Management
CAA	Clean Air Act
CSP	Concentrating Solar Power
DD&C	Design, Development, and Construction
DOE	Department of Energy
DOE-EERE	Department of Energy Office of Energy Efficiency and Renewable Energy
DOE-NE	Department of Energy Office of Nuclear Energy
EERE	Energy Efficiency & Renewable Energy
EIA	Energy Information Administration
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EPZ	Emergency Planning Zone
FOM	Figures of Merit
GHG	GreenHouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
INL	Idaho National Laboratory
IPP	Independent Power Producer
JISEA	Joint Institute for Strategic Energy Analysis
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
NE	Nuclear Energy
NEPA	National Environmental Policy Act
NERC	North American Electric Reliability Corporation
NGNP	Next Generation Nuclear Plant
NHES	Nuclear Hybrid Energy Systems
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
OE	Office of Electricity
PRA	Probability Risk Assessment
PV	PhotoVoltaic
ROI	Return On Investment

RTO	Regional Transmission Organization
SIP	State Implementation Plan
SMR	Small Modular Reactor
TRL	Technology Readiness Level
UAMPS	Utah Association of Municipal Power Systems
US DOE	U.S. Department of Energy
US-REGEN	U.S. Regional Economy, Greenhouse gas and Energy
V&V	Validation and Verification

1. INTRODUCTION

The U.S. Department of Energy (DOE) recognizes the need to transform the energy infrastructure of the U.S. and elsewhere to systems that, at a minimum, drastically reduce environmental impacts in an efficient and economically viable manner while utilizing both hydrocarbon resources and clean energy generation sources. Thus, DOE is supporting research and development that could lead to more efficient utilization of clean energy generation sources, including renewable and nuclear options. A concept being advanced by the DOE Offices of Nuclear Energy (NE) and Energy Efficiency and Renewable Energy (EERE) is tighter coupling of these two energy sources in a manner that better optimizes energy for the combined electricity grid, industrial manufacturing, and the transportation energy sectors. This integration concept has been referred to as a hybrid system that is capable of providing the right type of energy, at the right time, in the right place.

At the direction of DOE-NE and DOE-EERE leadership, a plan was made to engage stakeholders in discussing hybrid energy systems that would optimize renewable and nuclear energy integration on a region-by-region basis, and to conduct technical, economic, environmental, and socio-political evaluations of the leading options using a set of criteria established by relevant stakeholders. Accordingly, Idaho National Laboratory (INL) and National Renewable Energy Laboratory (NREL) jointly developed and led a workshop with a qualified set of participants from industry (energy resource project developers, technology developers and suppliers), utilities and power management groups, State governments, DOE and DOE national laboratories, and U.S. academic and international institutions.

Figure 1 illustrates a manner in which nuclear energy (one of the choices of Primary Heat Suppliers) could be integrated in a new operational paradigm. The thermal energy that is constantly produced can be dynamically apportioned between the conventional power generation train and any of the itemized industrial heat users. Actual system designs would vary between regions due to available resources, market conditions, and infrastructure for storage and delivery of resources and products. In addition to standard electricity transmission, one alternate delivery option could be production of hydrogen for fuels upgrading, fertilizer production, or combustion in fuel cell vehicles or plants that provide peak power generation needs and that help manage power quality conditions.

1.1 Motivation

The U.S. is currently undergoing a transformation of its energy systems in the way it produces, delivers, and consumes energy.[1] Improvements in information and energy technologies, and increased linkages between them, are enabling new paradigms that involve "system solutions" and have the potential to increase efficiency, reliability, flexibility, resiliency, and affordability of the overall energy system. One new paradigm involves tighter integration of clean thermal energy sources – nuclear reactors in particular – with intermittently-available renewable energy generators. Integrating renewable energy with nuclear generation in a single energy system could supply demand-following, low-carbon electricity to the grid while simultaneously increasing utilization of capital equipment by providing clean heat for hydrogen, biofuels or synfuels production, or other processes such as desalination. Coupled with electrification of much of the transportation sector and energy-intensive manufacturing industries, these systems could play a significant role in decarbonizing the U.S. economy.[2]

[1] Department of Energy. Energy Efficiency and Renewable Energy Office Grid Integration Multi-Year Program Plan, Draft, February 2014.

[2] Ruth, M., D. Arent, B. Hannegan, R. Boardman, S. Aumeier, and S. Bragg-Sitton. (2014). "Integrated Nuclear-Renewable Energy Systems – Assessment and Deployment Roadmap Plan", National Renewable Energy Laboratory and Idaho National Laboratory, draft (in review for final publication, 2014).

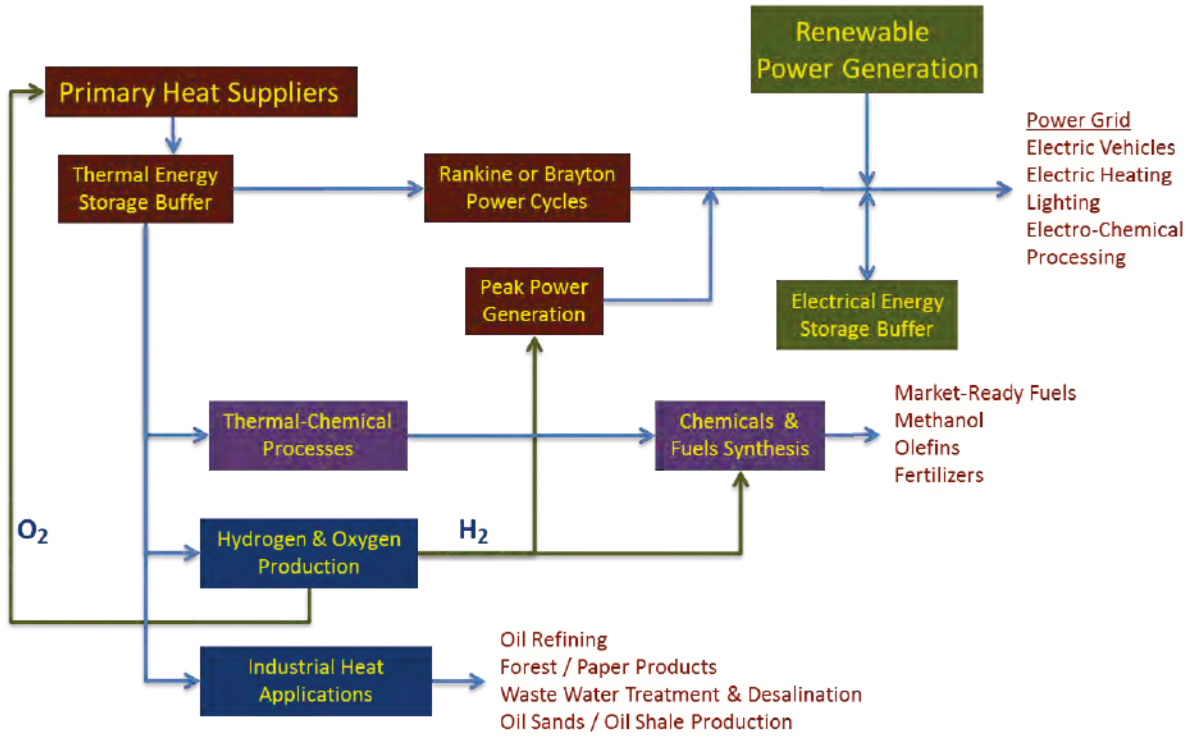

Figure 1. Conceptual Integrated Energy System.

The 2013 electricity generation mix in the United States consisted of ~13% renewables (hydropower, wind, solar, geothermal), 19% nuclear, 27% natural gas, and 39% coal.[3] In the 2011 State of the Union Address, President Obama set a clean energy goal for the nation: "By 2035, 80 percent of America's electricity will come from clean energy sources. Some folks want wind and solar. Others want nuclear, clean coal and natural gas. To meet this goal we will need them all." As Dr. Pete Lyons noted in his opening remarks at the workshop, the DOE Offices of Nuclear Energy (NE) and Energy Efficiency and Renewable Energy (EERE) recognize that "all of the above" means that we are called to best utilize all available clean energy sources.

1.1.1 U.S. Environmental Protection Agency Regulations

The U.S. Environmental Protection Agency (EPA) has proposed limits on carbon emissions from existing and new power plants under Section 111 of the Clean Air Act (CAA). In September 2013, Section 111(b) was proposed to establish a Federal program for new, modified and reconstructed plants, limiting the CO_2 emissions from new natural gas and coal plants to between 1,000 and 1,100 lbs CO_2/MWh, depending on the generation technology employed, fuel type, and plant size. In June 2014, Section 111(d) was proposed to establish a State-based program for existing generation sources, granting the States flexibility in complying with the rules. This program aims to produce a 30% reduction in greenhouse gas (GHG) emissions from existing power plants by 2030, relative to 2005 emissions. Overall, both regulations will serve as a significant impetus for investment in economic, reliable low-carbon generation technologies.

[3] U.S. Energy Information Administration, http://www.eia.gov/electricity/.

1.1.2 Increasing Penetrations of Renewable Energy

In recent years, the role of renewable energy has significantly increased in the U.S. electric generation sector. This growth is in response to a confluence of factors, including:

- Federal renewable energy production and investment tax credits
- Increasingly stringent state renewable portfolio standards
- High manufacturing learning rates and cost declines in a globalized technology market
- Increasingly favorable investment profiles at all project scales
- Emerging investment models (e.g. 3rd party solar leasing, publicly traded companies that own generation assets and securitize their cash flows – i.e., YieldCos)

In many regions of the U.S., as wind and solar penetrations have increased, market prices for electricity have decreased at times of high wind and solar output. This has resulted in reductions in baseload generator capacity factors, leading to decreased revenue for nuclear, coal, and natural gas combined cycle electricity generating systems. This scenario leads to an increasingly difficult business case for (1) many traditional baseload technologies including nuclear power plants, and (2) larger-scale use of renewables. Furthermore, increasing intermittent penetration is leading to an increased need for grid flexibility.

1.1.3 Clarifying the "Problem" and Potential Solutions for the Future Energy Grid

An **overall "problem statement"** driven by the current and anticipated future trends in energy generation was proposed at the beginning of the workshop. The following is a summary description of a refined problem statement that incorporates significant feedback from workshop participants. It can be summarized as follows:

1. **There is an overall desire to significantly reduce national GHG emissions in the coming decades.** President Obama has called for 80% of electric power generation to come from "clean" energy sources by 2035.[4]

2. **Non-emitting, intermittent renewable resources are being added to the grid in increasing numbers to meet the established state and federal policy goals – this is leading to an increased need for grid flexibility and maintained stability.** The increasing uncertainty in net load resulting from intermittent renewable generation necessitates an increased need for frequency regulation and higher dispatchable generator ramp rates and ranges. See Figure 2 for an illustrative example in which "net load" is the output the grid requires from non-wind generators to equalize supply and demand in the generator's balancing area (the metered segment of the electric power system in which electrical balance is maintained). Net load is high when demand for electricity is high and/or variable generation is low. Net load is low when demand is low and/or variable production is high.

   Frequency control is necessary to maintain grid stability. Traditionally, large mechanical power generation, such as the turbines in nuclear, coal, or natural gas, inherently support the grid frequency because they use rotating machinery to generate electricity. In scenarios where a large portion of the generation is provided by sources that cannot provide inertia, such as wind and solar, other solutions for grid stability are necessary.

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[4] http://www.whitehouse.gov/the-press-office/2011/01/25/remarks-president-state-union-address

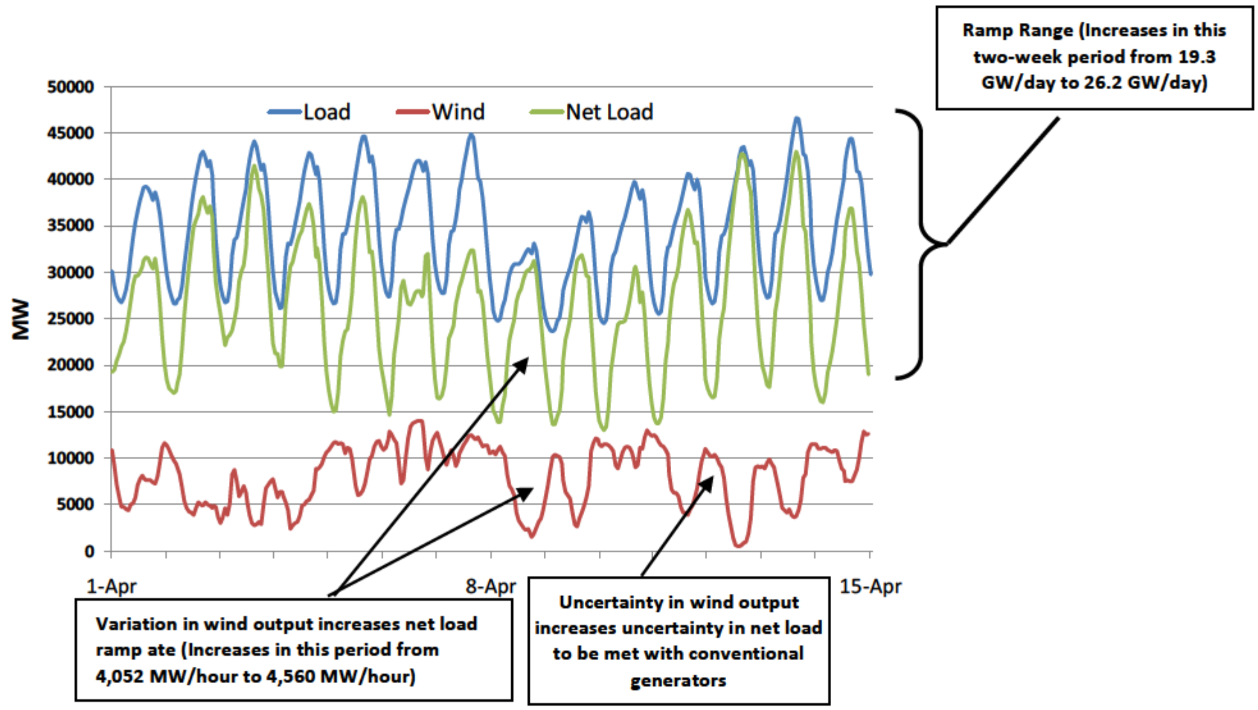
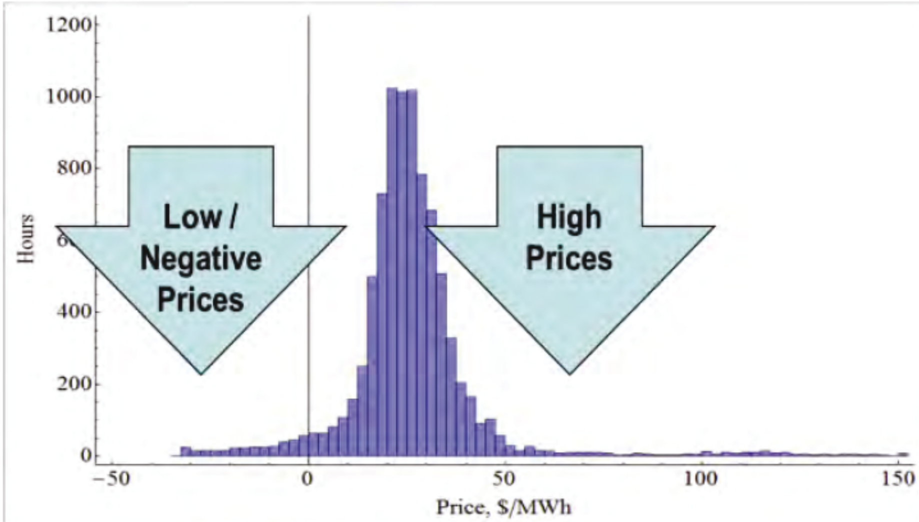


Figure 2. System load, wind generation, and net load for two weeks in April.[5]

3. **The increased role of intermittent renewables in many regions can lead to more frequent occurrences of low or negative prices, reduced baseload generator market size, and associated baseload generator output reductions.** This can lead to decreased capital deployment efficiencies and declining business cases for (1) baseload technologies such as nuclear and (2) renewables if they produce significant electricity. See Figure 3 for an illustrative example.

4. **The carbon footprint of all energy segments of the U.S. economy must be significantly reduced if long-term emission goals are to be met.** Utilization of low-carbon resources for heat and electricity presents a potential solution for decarbonization of all energy services, utilizing fossil fuel and biomass resources for the production of clean transportation fuels and higher value products in the chemical commodities manufacturing sector.

[5] Lew, D., G. Brinkman, E. Ibanez, et al. (2013). *Western Wind and Solar Integration Study Phase 2*. NREL Report No. TP-5500-55588.



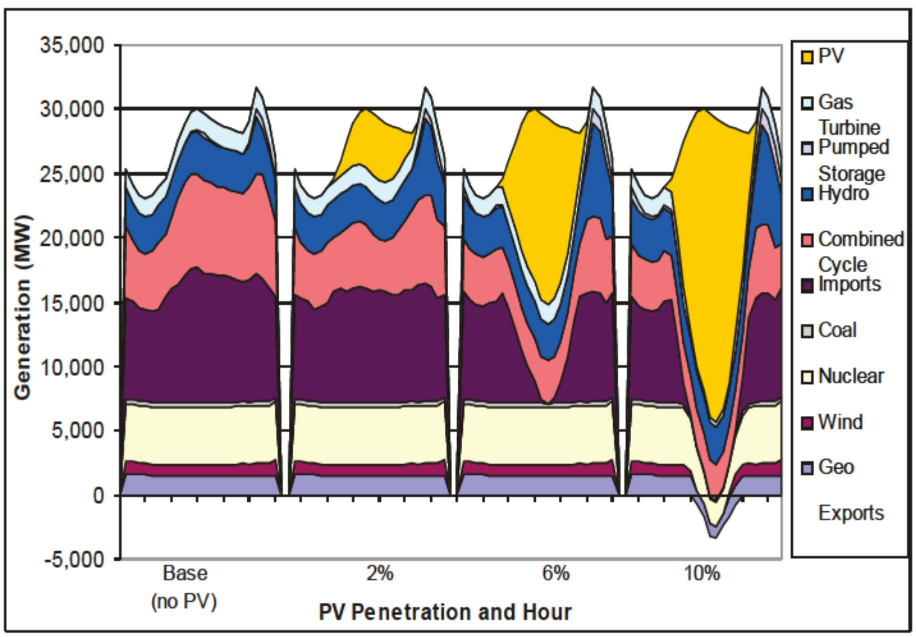


Figure 3. (Top) Distribution of California electricity prices in 2012[6] and (Bottom) simulated dispatch in California for four Spring days (24 hour period) showing how electricity generation changes with different fractions of electricity produced by PV. The PV fraction is defined as the fraction of all electricity produced by PV over the full year. PV production peaks in June and is at its lowest in December.[7]

[6] California ISO. (2012).“Binding Real Time Pre Dispatch Analysis Spreadsheet,” accessed August 2014, http://www.caiso.com/Documents/BindingRealTimePreDispatchAnalysisSpreadsheet-FERCOrderNo-764MarketChangesStrawProposal.xls.

[7] Denholm, P., R. M. Margolis and J. Milford. (2008) “Production Cost Modeling for High Levels of Photovoltaics Penetration” NREL/TP-581-42305.

Several potential solutions could be implemented in the future energy grid while providing grid flexibility. Each of these solutions has associated costs, limitations and region-specific implications that have been characterized to varying degrees. For a more detailed discussion on grid flexibility options, see relevant reports from NREL[8] and North American Electric Reliability Corporation (NERC).[9]

1. **Modifications to system operations.**
   Increased frequency of grid dispatch allows for decisions to be made closer to real time, yielding more economically efficient solutions. Improved wind and solar forecasting decreases the uncertainty in net load (the difference between the load and the variable generation; hence, generation requirement from dispatchable generators). That decrease results in less utilization of expensive peaking capacity. Expanding balancing area coordination efforts to larger geographic areas leads to increased access to dispatchable capacity, resulting in increased overall grid flexibility.

2. **Expansion of high-voltage transmission infrastructure.**
   Expansion of transmission infrastructure can increase interconnections with adjacent balancing areas, enable virtual grid-scale electricity storage, and decrease congestion (and associated congestion pricing) in electricity markets.

3. **Enrollment of demand-side resources**.
   Enabled by innovative information and communications technologies, coordinated utilization of demand response, distributed generation and storage resources across the residential, commercial and industrial sectors can help to provide flexibility to the bulk power sector. This is a novel approach to grid flexibility that must be enabled by appropriate regulation, market rules and associated business and investment models.

4. **Add grid-scale storage.**
   Grid-scale storage can be "charged" when generation is greater than load and "discharged" when the system has more load than generation. Today, pumped hydropower storage is commonly used; however, that resource does not match the projected need and has limited locations where it can be built. Other options under development include compressed air energy storage, hydrogen storage, conversion of excess electricity to methane, battery storage, and fly wheels.

5. **Enroll dispatchable generation to operate flexibly.**
   While all dispatchable technologies are, by definition, equipped to vary output to meet load, they may be limited by certain technical constraints (i.e. maximum turn-downs, ramp rates). Additionally, there are very limited zero-carbon options for flexible generation. Plants that are designed to provide flexible generation (i.e. gas combustion turbines) are expensive to operate and require high energy and ancillary service prices to remain financially viable. Flexible operation of baseload technologies is an option, although such plants may experience technical limitations on their ability to provide flexibility. Furthermore, this operational mode can result in reduced capital deployment efficiencies, increased operation and maintenance costs, and potentially shortened plant life times. The potential impact of load-following operation on the operational lifetime of a nuclear plant and reliability of the nuclear fuel requires additional study. Alternately, one could curtail renewable generators when load is insufficient. This action would

[8] Cochran, J., M. Miller, O. Zinaman, et al. (2014). Flexibility in 21st Century Power Systems. 21st Century Power Partnership. NREL Report No. TP-6A20-61721. http://www.nrel.gov/docs/fy14osti/61721.pdf.

[9] NERC. (2010). Flexibility Requirements and Metrics for Variable Generation: Implications for System Planning Studies. http://www.nerc.com/files/IVGTF_Task_1_4_Final.pdf.

be appropriate if the emissions benefits are equivalent between baseload (i.e. nuclear) and intermittent (i.e. wind, solar) generators.

6. **Develop a new operational paradigm: Industrial-scale, integrated energy systems with internally managed resources.**
   The proposed operational system would integrate generation sources behind the electrical bus. An internally managed, integrated system configuration offers the opportunity to operate baseload generation sources in a "load-dynamic" fashion rather than "load-following," enabling the plant to:
   i) Reliably and flexibly provide electricity to meet grid demand.
   ii) At times of low electricity demand, provide excess thermal energy input to alternate applications (maintaining the baseload plant at its nameplate operating capacity), thus minimizing cycling of baseload systems (e.g. the nuclear reactor) and maximizing capital deployment efficiency.

The energy generation sources considered in tightly coupled, integrated energy systems are not novel, but integration in this manner is a novel approach to achieving the goal of low-carbon, reliable energy supply. The integration of nuclear and renewable energy sources is currently coming to the forefront for a variety of reasons, as discussed below.

1.1.4 Why Nuclear-Renewable, and Why Now?

The increased demand for low CO_2 and other greenhouse gas emission energy generation – both thermal and electrical generation – is driving new perspectives on how to approach domestic energy resources. If the carbon-based resources in the U.S. can be converted to higher value commodities via heat generated from clean, non-emitting energy sources versus the current practice of burning fossil fuels to drive thermal processes, then GHG emissions could be reduced while still realizing the economic benefits of oil, natural gas, and coal resources.

Tightly coupled energy systems that include multiple input sources and multiple output products (e.g., heat and electricity), having significantly different temporal behaviors (e.g., subsystem response times), are complex. Operating such a system reliably will require advanced instrumentation and control systems that can predict pending changes to various energy service demands and appropriately modify system operation. Advances in information and control systems within power grids enable continuous online optimization of operations, and advanced instrumentation can be used to predict thermal and electrical energy demand changes. These enhancements, coupled with smart control systems, will enable an integrated system to smoothly transition operations to accommodate variable electrical and thermal needs. Efficient energy generation systems of the future should begin to shift from a traditional "power grid" approach, which focuses on providing electric power to meet demand, to a more generalized "energy grid" intended to efficiently meet both thermal and electrical energy demands across all sectors.

Integration of nuclear and renewable technologies potentially offers multiple advantages. Nuclear systems offer very high energy density, high temperature heat and low carbon footprint while maintaining a track record for high reliability, high capacity factors, and operational safety. In the U.S., the investment models and associated business cases for nuclear plants necessitate primarily baseload operation, although low-cost small modular reactors may allow for other operational paradigms. Renewable energy sources, such as wind and solar, capture available energy from our environment and produce zero-carbon emissions as they are used to generate electricity. These systems play an important role in the energy generation mix, but they are intermittent in their operation.

Coupling clean, reliable baseload generation with clean intermittent energy generation systems provides diversification of generation sources to reliably provide electricity on-demand. Close coupling of these resources in a manner in which the benefits from each system are maximized can accomplish the following:

- Avoids economic inefficiencies of underutilized capacity and cycling costs, which can result from forcing baseload power systems to load-follow to accommodate intermittent resources;
- Enables higher penetration of renewables through incorporation of dynamic generation and energy storage capacity, thus overcoming the challenges of intermittency;
- Opens markets for thermal energy beyond baseload power generation;
- Promotes better usage of carbon resources, such as coal, natural gas and biomass, while reducing GHG environmental impact (conversion to higher value products versus combusting them directly to produce industrial process heat).

Other options that could help meet national energy and carbon goals are possible, but were considered outside the scope of the workshop. Some options may offer near-term solutions to reduce carbon emissions and to maximize utilization of installed capital equipment, such as repurposing of currently installed nuclear plant capacity to thermal energy applications in regions that are currently being affected by high penetration of intermittent generation sources. Other, longer-term options may drastically impact the way we think about energy and how we use it. Achieving established goals for carbon reduction will require investment in both incremental, near-term options and potentially long-term game-changing options for the future energy grid.

1.2 Challenges to Integrated Energy System Development

Design, development, and deployment of tightly coupled integrated energy systems face numerous challenges. One goal of the workshop was to identify key challenges and possible paths to their resolution with input from potential system designers, industrial users, and electric customers. These challenges can basically be grouped as follows:

1) **Integration Value:** Possibility for integration to increase the value of system components; added risk of integration relative to improvement in efficiency and energy availability; market structures that do not necessarily monetize the value of grid services that might be provided by an integrated system.

2) **Technical:** Novel subsystem interfaces; ramping performance; advanced instrumentation and control for reliable system operation; safety risk assessments; commercial readiness of the technology and operational risks.

3) **Financial:** Business model; cost and arrangement of financing and risk/profit taking agreements; shifts in cultural values and associated market evolution trends for various products; assurance of high capital utilization efficiency.

4) **Regulatory:** Projected environmental regulations; deregulation or re-regulation of electrical and other energy markets; licensing of a co-located, integrated system; involvement of various regulatory bodies for each subsystem and possible "interface" issues.

5) **Timeframe:** Resolution of issues/challenges within the timeframe established based on external motivators for these systems (e.g. EPA carbon pollution standards); possibility of hybrid implementations at the rate market forces influence build-out of renewable resources; possibility

for grid stability issues to drive alternative solutions that create alternative long-lasting capital investments/inertia.

Many publications are available on cogeneration options for nuclear plants and on the possible integration of nuclear and renewable systems. A list of INL-authored reports on nuclear-assisted cogeneration is available in Appendix A. In addition, three previous workshops were convened by INL and NREL to discuss opportunities for tightly coupled nuclear-renewable energy systems:

- Nuclear and Renewable Energy Synergies, Workshop hosted by the Joint Institute for Strategic Energy Analysis (JISEA), September 2011 (held at NREL), *NREL/TP-6A30-52256*
- INL-JISEA Workshop on Nuclear Hybrid Energy Systems, April 2012 (held in Salt Lake City), *INL/EXT-12-26551 and NREL/TP-6A50-55650*
- Nuclear Hybrid Energy Systems Workshop, hosted by INL Institute for Nuclear Energy Science and Technology, July 2013 (held at INL; no published workshop report)

2. WORKSHOP SUMMARY

The foundational workshop was organized to establish an inter-laboratory, university, and industry team for integrated energy systems development, with the key workshop objective being to collect necessary information and to determine fundamental options – with stakeholder input – that will guide development of a multi-year technology development roadmap. Input collected at the workshop will be used to guide technical, environmental, and economic assessments of options for region-specific nuclear-renewable energy systems.

The workshop attendance was limited to experts for each aspect of the proposed integrated systems and the potential customer groups – energy users – to maximize the value of discussion sessions within the workshop. These diverse communities must first come to a common level of understanding to allow a rigorous but realistic program to be mapped out based on regional paths and solutions to low carbon emission energy systems. In this report, we attempt to synthesize the diverse opinions of workshop participants; however, any reference to the opinions of the group does not necessarily reflect that consensus was achieved.

Opening remarks at the workshop highlighted the fact that the current effort is focused on *industrial scale* applications of energy system integration. The residential community has significantly different needs and options to meet their energy needs than do industrial heat and electricity users. Although residential-scale decisions can certainly impact the larger grid, the initial focus will be on the larger energy users. The Technology Development Roadmap that results from this program will set the framework for technology development toward an industrial scale system.

The Foundational Workshop, held July 8-10, 2014 at the Energy Innovation Laboratory at Idaho National Laboratory, was organized around the following objectives:

1) Identify and refine priority region-specific opportunities for integrated nuclear-renewable energy systems in the U.S.;
2) Select Figures of Merit (FOM) to rank and prioritize candidate systems;
3) Discuss enabling technology development needs;
4) Identify analysis requirements, capabilities and gaps to estimate FOM for integrated system options;
5) Identify experimental needs to develop and demonstrate nuclear-renewable energy systems.

Accomplishing these goals required active participation in the workshop from experts in the research and development community, industry vendors, and potential users. Participants hailed from the following sectors (an attendance roster is presented in Appendix B):

i) Government Laboratories
ii) Academia
iii) Nuclear Industry
iv) Renewable Industry
v) Chemical Industry
vi) Power Systems and Grid
vii) Energy leaders and State Government

The workshop agenda is included in Appendix C. The primary deviations from the planned agenda were associated with the time allotment for participants to complete on-line forms to provide individual contributions to the definition and ranking of the figures of merit, described herein in Section 6, and to definition of key regional system configurations, as described in Section 7.

The opening afternoon of the workshop focused on presentations to begin the process of bringing the audience to a common level of understanding on the proposed integrated energy systems to enable detailed discussions and brainstorming to take place throughout the remainder of the workshop (see Appendix D for introductory presentations). Opening presentations were crafted to:

a. define an "integrated" energy system;
b. present the underlying motivation for the development of these systems;
c. outline system options based on regional interests, needs and resources;
d. present strawman figures of merit by which regional opportunities might be evaluated;
e. highlight some of the anticipated challenges for these systems; and
f. introduce some of the possible opportunities that could be capitalized by development of integrated nuclear - renewable energy systems in the near-term.

Two roundtable discussions were convened to ensure that stakeholder interests were captured and understood. The second day of the workshop began with an industry roundtable with representatives from NuScale, TerraPower, Southern Company, Westinghouse, First Energy Corp., Utah Association of Municipal Power Systems (UAMPS), Electric Power Research Institute (EPRI), Abengoa Solar, Morley Companies (wind project developer in several States) and representation of the chemical and fossil fuels resource community by the Next Generation Nuclear Plant (NGNP) Alliance. A second roundtable held later that day focused on state energy development and regulatory needs, with representation from Arizona, Utah and Wyoming, and international perspectives presented by the Chinese Academy of Sciences. The general set of questions and responses from the panel are summarized in Section 4.

Detailed discussions and brainstorming sessions were held on the second and third days of the workshop to maximize the involvement of and feedback from the meeting attendees. After presenting a preliminary set of candidate figures of merit, an online form was generated and distributed to participants to capture real-time feedback on the definition and prioritization of the figures of merit, with the results of that input being presented the following morning. Similarly, candidate regional system configurations were presented, briefly discussed, and then refined via small group discussions. Further participant input was captured via a second online form to allow individual input to definition and prioritization of regional cases for integrated energy systems.

The workshop discussions and online feedback will be used to guide researchers at INL and NREL in selecting cases for initial analysis and evaluation against the prioritized figures of merit.

3. STAKEHOLDER ROUNDTABLE DISCUSSIONS

A primary purpose of this workshop was to obtain input from key industrial stakeholders and state governments regarding the possible business case for nuclear and renewable energy deployment and integration into hybrid energy systems. Industrial participation was limited to a select cross-section of electrical power utilities, power brokers, nuclear and renewable technology developers, project developers, and chemical industries with knowledge of nuclear and renewable energy development and deployment opportunities and challenges.

3.1 Industry Roundtable

A roundtable discussion was conducted to clarify interests and concerns held by industry stakeholders. Each panel member was asked to introduce his or her organization and to provide general statements regarding the current and future market for renewable and nuclear energy. The panel members were invited to consider the following set of concerns and questions to help frame the dialog during the workshop.

Concerns:

1. What are the barriers to near term markets for nuclear and renewable energy- either in the U.S., South America, Asia, or elsewhere?
2. Who will finance new generation projects, and how are these investments authorized?
3. What are the barriers to cooperation among the power generation and industrial manufacturing industries?
4. What challenges impact the ability to site or construct renewable or nuclear projects in the U.S.?
5. How do regulated and non-regulated markets affect new generation choices?

Utility Company Prompts-

1. Are renewable portfolio standards or the proposed EPA Rule 111(d) impacting current power generation assets?
2. Is your utility planning to add new generation; if so, what considerations are being given to renewables and nuclear, or clean coal?
3. Is it plausible for utilities to consider co-location of an electrical generation plant and a hydrogen or chemical plant?
4. What regulatory or market challenges might impact decisions to build hybrid energy parks or complexes?

Renewable Project / Technology Developer Prompts-

1. What are the most significant barriers to building a vital solar or wind industry in the U.S. or abroad: technology cost; permitting; new power generation capacity; transmission; intermittent availability?
2. What technology development needs (or risks) may still need to be resolved? For example, do changes to the grid need to be made to input large amounts of renewable power on the grid? Is additional energy storage necessary to smooth renewable input or to firm its reliability?
3. What energy storage options are being considered for concentrated solar energy and how can these be adapted to management of thermal energy produced by nuclear reactors?

4. How can the reliability of renewable energy be mitigated by energy storage and dispatchable nuclear energy?
5. What energy storage options are being considered for concentrated solar energy and how can these be adapted to management of thermal energy produced by nuclear reactors?

Nuclear Technology Provider Prompts-

1. Is it plausible to conceive nuclear hybrid energy systems in your business case? If so, then what applications do you believe are the most relevant?
2. Is it plausible to believe an existing LWR can be repurposed for a hybrid energy application?
3. What is the timeline for siting and building a conventional or an advanced nuclear reactor?
4. How do new reactor designs improve safety or reduce market entry risks?
5. What considerations are necessary to operate nuclear reactors in dynamic load-managing scenarios?

Chemical Industry Prompts-

1. How could chemical industries be impacted in the future by low-carbon emissions policies or regulations?
2. Is it plausible to believe that nuclear-chemical hybrid energy applications can be built in the U.S.?
3. How can the chemical industries and nuclear technology providers work together to create hybrid industry solutions?
4. How does the chemical industry currently apply cogeneration to maximize profits?

The section below provides a summary of the industry participants' remarks during the roundtable discussion. Most relevant industries and user groups were present at the workshop, although some were unable to attend. Industry stakeholders who were not able to attend the workshop, such as representatives of the chemical industry, will be invited to weigh in on the dialogue as this workshop report is circulated. Circulating these positions and suggestions to a broader group will ensure that the range of perspectives from a diverse set of stakeholders is properly captured and used to frame the integrated systems roadmap.

Panel Members Opening Remarks:

Electrical Utility Representatives-

- The goal of some utilities is zero emission power for the next generation fleet.
- There are several extreme problems facing utilities companies; technology innovation such as hybrid energy systems is necessary to address these problems.
- It is important to find reasons to keep the existing nuclear plants operating.
- A continuous undulating revenue stream can back NE-RE integration.
- An integrated/consolidated energy plant may allow existing nuclear plants to stay on-line to generate revenue now that they are paid off.
- Many plants are now realizing a need to operate at less than 100% mode.
- Organizations outside of the U.S. are looking at using nuclear plants beyond electrical energy generation.
- EPRI projects there will be opportunities for advanced nuclear plants; integration within larger energy systems may be plausible.

- The job of power brokers is to provide reliable power 24 hours per day, 365 days of the year, with nearly zero power interruptions. Hybrid energy systems with nuclear energy may provide the best backup for renewables.
- UAMPS is working with NuScale and INL to put small modular nuclear reactor (SMR) technology into service; integrated energy systems are being considered in the first demonstration plant.

Nuclear Technology Developer/Providers-

- **Westinghouse** is the current U.S. leader for nuclear power plant construction. The company is following regulator and market trends that appear to be shifting toward an understanding of the importance of nuclear energy.
- The goal of **TerraPower** is to impact global environmental concerns and economics. TerraPower is developing high temperature reactors that will change concerns for proliferation, waste generation. TerraPower is considering reactor designs that may be useful for heat applications.
- **NuScale Power** is developing a safer nuclear reactor that could be placed in a variety of markets in the U.S. and abroad. This reactor will be a small modular reactor that can be scaled and applied in a distributed energy system. Licensing, manufacturing, delivery, and construction paradigms can change with small modular reactors. NuScale is also conducting hybrid integration case studies to better understand the options discussed in the workshop.

Renewable Technology Developer/Providers-

- **Abengoa Solar**, based in Seville, Spain, is the largest leader of transmission lines and concentrating Solar. The U.S. is now its largest market for solar energy. An Abengoa CSP plant in Arizona has a nameplate capacity of over 200 MW_e. Abengoa has demonstrated thermal energy storage is a feasible way of producing power during the peak demand spikes in the morning when people get ready for work and then in the afternoon when they come home.
- **Morley Companies, LLC** is based in Jackson, WY; it has built over 1000 MWe of installed wind capacity, and several new projects are now in the planning stages. Current wind farm siting challenges include:
    - Being able to acquire permit and power purchase agreement in similar time period;
    - NEPA – any complaints can cause problems going forward;
    - BLM – a frequent bottleneck is tied to the Endangered Species Act or unrelated regulations that vary according to area; a project often must deal with each BLM authority that has jurisdiction; and,
    - Renewable energy resources are seldom located close to where energy is needed, such that transmission is an issue.

  Morley Company is looking at combining gas, wind, etc. and will be participating in a study that will compare a gas turbine to a reciprocating engine for firming wind generation and power wheeling. It would be good to have a way to use wind energy when it is not needed for industry use; however, the challenge is selling a product that has not been sold before.

Chemical Plant Technology Developer/Providers-

- Several large U.S. and Canadian chemicals and fertilizer companies are paying attention to the business case for applying nuclear energy for direct and indirect industrial benefits.

- The NGNP Alliance includes large chemical companies such as DOW Chemical, Conoco, and others.
- An analysis was completed by the INL for Wyoming to look at the use of nuclear energy to help convert coal and natural gas to high value products. The case for integrating a nuclear plant with industrial processes has a positive economic *pro forma* given the vast fossil fuel resources in the state. Wyoming also has world-class wind, which can be complemented with hybrid systems.

Panel Response to Questions:

<u>How do State Renewable Portfolio Standards and/or the new EPA Clean Air Act rules provide incentive to develop combinations of nuclear-renewable energy?</u>

Utilities Comments-

- The proposed new EPA rule is an amalgamation of multiple rules and most utilities are not sure yet how this is going to shake out. In many ways, the new rules would create more certainty of where carbon is headed in the market.
- The case for carbon capture and sequestration and building nuclear power plants is similar– both are technically doable, but expensive, and storage for either case is an issue.
- A Bill was passed to allow nuclear technologies to qualify for the EPA mandates.
- With regard to the EPA rule – The U.S. has 60-plus year old coal plants that are relatively small but would require very large and expensive retrofits; thus, it is not worth it modifying these plants to meet the new standards.
- EPA CAA Section 111(d) focus may drive a couple of nuclear projects for some states. Time is awkward, however, because utilities and rate payers have to decide immediately whether they need to build a plant.
- Industry would be challenged with an investment for a large plant and demonstration plants; without a strong indication of what the plant would get for revenue beyond 2030, the decisions are very difficult.
- There is a hope for small modular reactors in the next 5 years. This may happen in states where flexible assets are coming out.
- The concern for utilities is the manner in which additional renewable energy projects and the inflexibility of fossil fuels plants are resulting in forced plant shutdowns.

<u>Question: If we have a national goal for high build-out of renewable energy, what do you see as having the most impact on utilities?</u>

Utilities and Power Broker Comments-

- There appear to be three significant opportunities or benefits: 1) flexibility on production side and flexibility on demand side, 2) increased or improved transmission, and 3) short and long distance applications of systems integration (or centralized and distributed).
- The biggest obstacles to nuclear and renewables are market uncertainties. There is uncertainty as to what revenue stream these markets will get. What capacity will be assigned? How will risks and profits be allocated?
- Going forward, as utilities see a need for steeper ramp rates and power quality, there are some emerging technologies that can replicate inertial response (e.g. wind generators).

- If the market structure exists to demonstrate a solid revenue stream to industry, then new technologies will come on board; however, there may be a need for incentives to enable these other technologies to come on board in light of social values.
- Some states already have actual or effective renewable portfolio standards – California is one example.
- EPA CAA 111(b) is essentially is a carbon tax. CAA 111(b) will probably change dramatically from the way we currently see it proposed; as currently proposed, these rules are expected to cause major coal plants in Utah and Arizona to shut down.
- Utilities will eventually have to deal with CO_2 emissions for natural gas plants.
- For coal plants to come into compliance, the price of electricity will go up quite a bit.
- In the West, there is not currently a regulated market in terms of "dispatch" but the West appears to be moving to this control.
- SMRs may increase reliability; the modular reactor concept is very simple for reliability purposes.
- Power quality in the U.S. is very important in preventing a blackout – There is a need to replace the "big muscle" (i.e. rotating turbine-generator sets) that maintains power quality; it is important determine how to do this when more renewables come into service.

Renewable Technology Providers and Project Developers Comments-

- It is important to look at how to market technologies; huge changes in power markets have occurred over the last 10 to 20 years.
- In the last 5 years, renewables have experienced large changes in manufacturing costs; for example, the cost of PV solar energy has dropped precipitously, and it is projected to get cheaper. We need to have a plan to deal with the impacts this will have on grid operations. Perhaps nuclear integration will be a profitable option.
- People are realizing that low cost power is not the only thing that is important; there seems to be change in the market – more maturity in how we cast power in a value sense.
- Environmental groups are driving the concept that wind and solar are good; demand then brings up manufacturing, which invites competition and reduces manufacturing and installation costs.
- There is a need for the nuclear power industry to be more flexible in generating electricity; however, it is important to think about integrating nuclear without introducing big risks.
- A conventional power plant owner would wonder – "Why would I add nuclear when everything is working just fine and on top of it, it adds more risk and cost?"
- CSP is a relatively expensive technology compared to solar PV; however, with thermal energy storage to address peak demand electricity needs, the value to the Power System Operator is higher.

Question: Is it plausible to integrate nuclear energy in a hybrid system? Is it part of your business case?

Utilities Comments-

- It is not part of the general business case yet for utilities. When the business model becomes clearer, then the probability for an integrated nuclear hybrid system will increase.
- Utility partners need to participate in developing the business model.

Nuclear Technology Developers/Providers Comments-

- TerraPower is looking at hybrid systems; for example, converting coal or biomass to products. It may be possible to produce synthetic fuels at refinery-scale. Nuclear energy as a thermal energy source is relatively clear, but it is important to understand who the owner and operator will be, as well as to establish a clear picture on what the combined technology would really look like. Analysis is definitely needed.
- NuScale is looking at the business case for hybrid SMR systems. Industry needs to understand the value of decarbonization of their operations and how hybrids can help in this cause. Clean Air Act Section 111 (b) starts pushing that way but only applies to power plants.

Utilities Comments-

- A new paradigm is needed to create the business case. Constructability is not a technical problem; it is a regulatory, social and economic problem. As a country, we need to know how we can build a system that can then be scalable. There will be constructability problems, and land mass and regulatory issues. With low cost natural gas, nuclear energy is down the road in the U.S. and an evolutionary path is probably necessary.
- Systems are already being coupled across the grid. As utilities look at coupling behind the grid, they need to find systems that have such improvement in efficiency.

Industrial Integration Perspective-

- Many industrial processes already practice cogeneration, including petroleum refining and fertilizer producers. Most burn their feedstock. The question here is whether the economics support consolidated energy systems.
- Opportunities appear possible under certain conditions: 1) Volatile energy pricing (especially natural gas) provides incentive for stable nuclear energy; 2) Energy resource supply / long-term assured supply, pointing to nuclear as a clear choice; 3) Increasing environmental requirements; Risk with nuclear is lower than any other.
- The following safety concerns need to be taken into consideration: 1) Safety case for small to medium reactors – co-location risks regarding an accident within the industrial facilities; 2) Complex and untried business model (economics erode as the ownership structure becomes more complicated); 3) Uncertain business case (possibility of sharing the financial risk across multiple owners); 4) Market rules for power and products.
- NE hybrids must address the risk of linking nuclear with other facilities; Abengoa saw similar risks with hybridizing CSP plants (i.e., it may make financing difficult).
- Hybrids must address market uncertainty; for example, the production tax credit waning.
- NE-RE integration must address bulk power market structures (capacity, ancillary services, etc.). The "baseload" concept will become less important.
- Systems should be designed to address flexibility of either the production side or demand side.
- Projects also need to consider transmission integration and elimination of transmission constraints.

3.2 State Government Commentary

Leadership from western states was invited to participate in the workshop to gain perspective on energy development strategy and education relative to the buildup of renewable energy and the potential to utilize nuclear energy to provide a clean energy source for power generation and manufacturing industries in a manner that can help manage renewable power intermittency and dynamic power demand. Over the past five years, INL and NREL have engaged with states in the Western Energy Corridor[10] where there is an abundance of all forms of fossil fuels, world-class wind and solar energy, and uranium. Representatives from Arizona, Utah, and Wyoming attending the workshop weighed in on the case for NE-RE integration opportunities and challenges.

Arizona

Representatives from the Arizona Governor's Office of Energy Policy, Arizona Corporation Commission (over public utilities regulatory control), and Arizona State Senator Robert Worsley (seated on key State energy and economic development committees and advisory boards and a National Governors Association energy board) commented on the opportunities and challenges of rapid build-up of solar energy in the southwest. Comments focused on the present opportunity to increase concentrated solar power (CSP) and photovoltaic solar (PV) given the cost-competitive breakthrough of PV solar. Arizona government supports efforts to better the environment by advancing cleaner energy sources; however, several market, regulatory, and technical issues must still be resolved. Some of the issues mentioned include: equitable revenue and infrastructure cost sharing associated with large PV solar additions to the grid; under-utilized electricity generating capacity that already exceeds approximately 2 GW_e; impact of renewable portfolio standards in the West (i.e. California), and Section 111(d) of the Clean Air Act on coal-fired power generation in the state; potable and agriculture water demand for a rapidly increasing population; opportunities to send power and other energy currency to Mexico, which only recently deregulated its power market.

During a lunch presentation, Senator Worsley recapped the challenges Arizona and other western states face in reducing greenhouse gas emissions with an infrastructure that is primarily based on large fossil fuel and nuclear power generation and transmission systems. He further commented on opportunities for CSP plants, citing the approximately 250 MW_e Abengoa demonstration facility in Arizona. This unit was designed to demonstrate thermal energy storage to help match power generation with consumer demand in the early morning and late afternoon. Opportunities to produce hydrogen and to desalinate seawater pumped to the State from the West Coast – both using excess generating capacity - were cited as valuable options to explore. Finally, the growth of corporate business in Arizona is increasing given the desire to utilize the clean PV and CSP solar energy that is being developed in the State. In order to maintain grid stability and cost competitiveness, implementation of clean and reliable energy sources, such as nuclear energy, and efficient use of this capital in integrated energy systems could be beneficial if proven economically feasible.

Utah

Representation from the Utah State Office of Energy Development spoke to the interest of Utah government to implement clean energy that helps meet regulatory requirements in an economic manner. Recent construction of wind and solar energy in Utah were cited as examples of projects that are changing the mix of power generation in the State. Additional renewable energy projects are anticipated. The

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[10] The Western Energy Corridor refers to a continuous region extending from the southwestern U.S to western Canadian provinces. The region includes the southern belt of solar energy in western Nevada, Arizona, New Mexico and Texas; the seam of high capacity wind energy running from Texas to Canada on the east side of the Rocky Mountains; a massive deposit of coal, gas, oil, bitumen, and kerogen concentrated in Utah, Wyoming, Montana, Saskatchewan and Alberta; and the extensive uranium deposits roughly co-located with the fossil fuels in the West.

concepts developed for nuclear plants may also be applicable to existing baseload coal fired power plants that are now being impacted by the emerging renewable power projects.

Utah has a general interest in supporting nuclear energy projects that compete in the market place. INL and the Utah Office of Energy Development recently completed a report on the status of nuclear energy technology and market opportunities in Utah.[11] NE and RE integration is cited as an example that may be beneficial to fossil fuels production and conversion in the State. A preliminary case study for oil shale production has been completed by MIT.[12]

Wyoming

Although key representatives from the State of Wyoming were unable to attend the workshop due to concurrent events sponsored by the State, Wyoming is a strong proponent of NE-RE hybrid development. The State Legislature recently supported a study on the opportunities and challenges for nuclear energy integration with coal and natural gas conversion to higher value products.[13] The Wyoming State Energy Development Strategy includes an outlook for opportunities to build cleaner energy systems that amplify the value of the State's resources through hybrid energy systems.

Figure 4 illustrates the economic benefit that can be realized by converting fossil fuel to higher value products in the transportation and chemical production sector. NE-RE integration with these carbon conversion plants can lower the life-cycle carbon footprint associated with synfuels and chemicals production. Hybrid systems can also help address renewable on-line capacity and transmission capacity issues that are an impediment to developing wind energy in Wyoming.

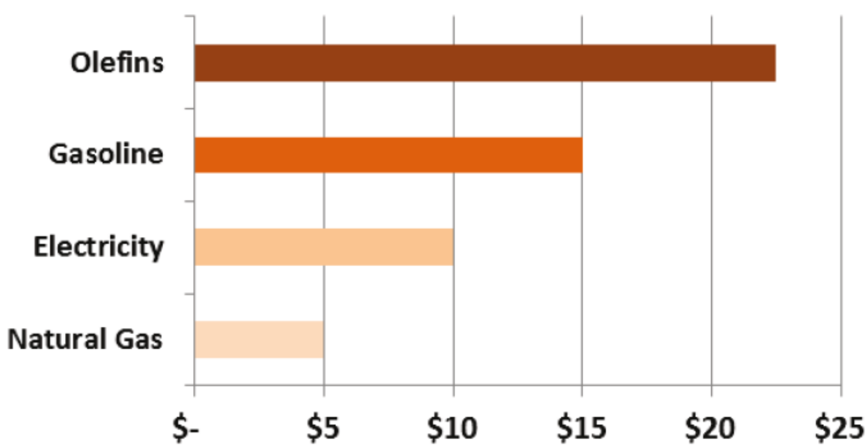

Figure 4. Relative market value of 1000 SFC natural gas when converted to other energy products.

[11] Idaho National Laboratory (2014). Nuclear Energy Overview: A Utah Perspective; Assessing Potential Applications for Nuclear Power. INL/EXT-14-31074.

[12] Forsberg, C. (2008). Sustainability by combining nuclear, fossil, and renewable sources. *Progress in Nuclear Energy*. 51(1), pp. 192–200.

[13] Idaho National Laboratory (2012). Preliminary feasibility of value-added products from cogeneration and hybrid energy systems in Wyoming, INL/EXT-12-27249, completed for the Wyoming Business Council.

3.3 Summary of Stakeholder Discussions

The overall comments from the industry and state government panels can be summarized as a series of concerns and opportunities regarding the potential investment profile of an integrated nuclear-renewable energy system. Several concerns about the investment case for such systems were raised:

- *An Undemonstrated Concept* – Integrated energy systems may have complex ownership structures, and hybridization technologies have largely not yet been demonstrated. Significant proof-of-concept work would have to be performed for industry and investor buy-in.

- *The Future of the Electric Utility* – The financial health and future direction of the electric industry was raised as a significant concern. Given the historically low levels of demand growth, rapid developments in distributed generation, and increasing penetrations of renewable energy, several industry panelists felt there was significant uncertainty as to the medium- to long-term energy needs of electric utilities, as well as uncertainty in what their role might be moving forward.

- *Uncertain Regulatory and Policy Environment* – Panel members expressed uncertainty as to whether or not the EPA 111(d) Clean Power Plan would go into effect. Additionally, uncertainty surrounding the availability of federal investment and production tax credits for renewables and nuclear was cited as a concern.

Many opportunities were also highlighted in the roundtable discussions:

- *Growing Market for Grid Flexibility* – Panelists expressed a relatively strong short- to medium-term certainty about an increasingly large, healthy market for grid flexibility services that an integrated energy system could provide.

- *Energy Price Volatility Hedging* – Long-term natural gas price uncertainty was cited as a key concern for electric utilities; integrated energy systems could serve as a significant fuel price hedge given the minimal, stable fuel costs of nuclear and renewable technologies.

- *Multi-purpose Capital Equipment to Hedge* – In contrast with discussion on the medium- to long-term uncertainty surrounding the future of the electric utility, several panelists expressed an opinion that if proposed systems could be dynamically repurposed for various industrial applications, their long-term investment risk profile may benefit despite the uncertain financial health of utility off-takers.

4. SITING AND LICENSING

The workshop featured several presentation and group discussion sections intended to stimulate dialogue on potential issues to consider surrounding integrated nuclear-renewable systems. The primary focus for these initial discussions was on siting and licensing.

4.1 Nuclear System Siting and Licensing Challenges

On the first day of the workshop, a reactor safety expert (G. Mays, Oak Ridge National Laboratory) presented an overview of potential issues around the siting and licensing of a nuclear system within an integrated energy system. Throughout the presentation, he proposed several starting points from which to address challenges.

4.1.1 Summary of Key Issues

The potential issues associated with siting and licensing of a nuclear plant in the vicinity of and connected to other industrial processes are summarized in the following sections. This list is not comprehensive and other issues may arise.

4.1.1.1 Physical proximity to other plants

Siting a nuclear reactor near industrial processes, particularly those including or producing combustible materials, may present a significant licensing challenge. Emergency planning requirements (e.g. emergency planning zones, exclusion area boundaries) and associated criteria may have to be adjusted, depending on the nature of the coupled industrial process. In addition to considering standard design-basis nuclear accidents, licensing criteria would have to consider the potential impact of postulated accidents at the industrial facility on the nuclear system and the potential impact of an external event on the industrial facility that could, in turn, impact the operating condition of the nuclear facility.

4.1.1.2 Regulation of integrated safety issues

NRC's licensing basis and regulations for commercial nuclear power plants essentially are focused on the design and operation of the plant for producing electricity. NRC's approach for reviewing and licensing a plant for an integrated energy application will need to accommodate a different deployment application (electricity and/or process heat) within the existing framework or augmented as appropriate to encompass integrated systems with a variety of potential uses for the process heat from the nuclear plant. Understanding "crossover" regulations and requirements from responsible regulatory authorities for the nuclear and industrial plants will be a novel challenge for system developers.

4.1.1.3 Novel deployment design application

The NRC Deployment Design Application for all licensed commercial nuclear reactors is based on electricity generation, and the highly extensive suite of NRC regulations has evolved around this premise. The NRC would have to systemically review and potentially alter their suite of regulations to cater to integrated systems with various potential uses for nuclear heat, thus creating a new paradigm for how nuclear power is regulated.

4.1.1.4 Screening criteria for nuclear reactor sites are stringent

Mays provided a high-level overview of nuclear power plant site screening criteria, emphasizing that greenfield site identification is not a trivial task, and that expansion of existing nuclear facilities to accommodate integrated energy systems may be a desirable approach. Nuclear siting criteria include proximity to geological fault lines, population density, cooling water availability, land slope, and proximity to protected lands (e.g. wetlands) or floodplains. These reactor siting criteria would have to be overlaid onto the additional siting criteria of the other components of an integrated energy system.

4.1.2 Potential Paths Forward

Despite the large number of unprecedented issues associated with the proposed licensing of an integrated nuclear-renewable facility incorporating an industrial process, there are many possible "starting points" to address these issues.

4.1.2.1 Explore design basis events for integrated energy systems

Development of a hypothetical set of potential design basis events for integrated energy systems could serve as an initial starting point for evaluating any impacts on licensing processes. The emergency planning impacts of new and existing design basis events would likely be pronounced, and could be a launching point for future work. Understanding potential integrated system transients, their potential impacts, and possible mitigation strategies would also provide insights into possible "crossover" regulations and requirements that may be under the jurisdiction of regulatory authorities besides the NRC.

4.1.2.2 Explore existing relevant NRC documentation

Several suggestions of relevant NRC documentation were offered to help inform the shape of future integrated energy system regulations. These suggestions include:

- Safety Evaluation Report Related to the Operation of Midland Plant, Units 1 & 2 (October 1982, Consumers Power Company) – twin pressurized water reactors designed for a power and process heat application (primarily for Dow Chemical Company)[14]
- NRC General Design Criteria[15]
    - 2 – Design Bases for Protection Against Natural Phenomena
    - 4 – Environmental and Dynamic Effects Design Bases
- INL work on the Next Generation Nuclear Plant (NGNP) – identified "typical" external hazards and siting challenges for NGNP-type process heat and energy supplies (see Appendix A — Reference List for Nuclear Cogeneration Studies Performed at Idaho National Laboratory)

4.1.2.3 Explore technology-neutral emergency planning requirements

NRC has identified in SECY-11-0152 their intent to develop a technology neutral emergency planning framework for SMRs. Requirements would be based on licensed reactor power level, accident source terms, potential fission product releases, and characteristics of the dose to nearby areas following a postulated accident. Using these factors, which are all a function of the reactor power level, NRC has suggested as a possible approach in SECY-11-0152 the development of a scalable emergency planning zone (EPZ) having several EPZ categories correlating the plume exposure EPZ at the site boundary and at 2, 5, and 10 miles, with corresponding dose limits at each of these distances.

4.2 Wind Farm Development and Siting Challenges

On the first day of the workshop, a renewable energy project developer (S. Morley, Morley Companies LLC) discussed issues associated with siting, permitting and assembling financing for wind farms, providing a sense to the group of the challenges an integrated energy system utilizing wind energy may face during the development process. While acknowledging that the regulatory burden associated with siting a wind farm is likely small when compared to a nuclear reactor, Morley emphasized that compliance is by no means trivial or inexpensive. Key challenges include:

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[14] http://www.ntis.gov/search/product.aspx?ABBR=NUREG0793SUPN2

[15] http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appa.html

- *Compliance with Federal environmental regulations* – e.g. National Environmental Policy Act, Endangered Species Act, Migratory Bird Treaty Act, Eagle Protection Act
- *Acquisition of financing* – environmental permits (local, state, federal) and power purchase agreements must be acquired on similar timeframes to demonstrate to investors that a project will actually be built
- *Wind resource is seldom close to demand* – sufficient transmission access can be an impediment to project development, and coordinated co-investment in transmission assets can be complex, time-sensitive and expensive

4.3 Other Considerations

On the second day of the workshop, a facilitated discussion was held to discuss siting, licensing and deployment considerations. That discussion expanded beyond those bounds and included a number of other considerations. A summary of the considerations discussed is provided below.

4.3.1 Potential Investment and Ownership Models

Participants raised the issue that many components of an integrated system will be shared by subsystems that do not provide value to electric ratepayers. Therefore, assembling financing for project construction with approval from a Public Utility Commission (PUC) may present difficulties. Regulatory community participants suggested the Independent Power Producer (IPP) model for an integrated energy system, whereby an electric utility signs a PUC-approved power purchase agreement with the integrated energy system, but the development risk is placed solely on the project developer.

Potential ownership structures were also discussed. While no consensus on an optimal ownership structure was achieved, participants acknowledged that optimal solutions would be highly system specific. Most discussion gravitated around consortium ownership. In this model, companies would design and invest in their individual components of expertise (e.g. a chemical company for an ethylene plant, an energy company for the nuclear system, an IPP for a wind farm, etc.). This consortium would likely need to include profit-sharing mechanisms to ensure optimal use of each technology.

4.3.2 Long-term Market Viability of Co-products

Participants expressed concerns that the coupled industrial processes for which the system was designed and licensed may not have a viable market for the full length of the energy generation system license (i.e. 40 years for an initial NRC license for the nuclear reactor subsystem). This mismatch might serve as a significant impediment for the investment case. The operating license for the nuclear subsystem, for instance, may only be approved for that particular industrial facility, resulting in a significant cost and regulatory burden to find another viable, coupled process should the initially selected industrial application no longer be viable.

4.3.3 Interface Issues

Improving and managing interfaces between sub-systems are essential to the success of integrated energy systems. The idea of a standardized thermal energy storage buffer that could be licensed to serve any industrial process was raised; the buffer would need to be sized to appropriately absorb large swings in power, governed both by design basis accident criteria and the needs of the various integrated subsystems.

Temporal interfaces also need to be considered. For example, if one sub-system requires a higher capacity factor than another either the first sub-system will need to be off-line more often than preferred or additional storage may be required. This issue is most likely to arise where the industrial process is a chemical process with a capacity factor higher than the nuclear generator.

4.3.4 Region-specific Siting Challenges

Participants cited a range of regional challenges, including:

- proximity to relevant infrastructure (e.g. feedstock delivery infrastructure, transmission availability, transportation infrastructure for non-electricity products),
- local siting and permitting processes,
- local political environment and receptiveness towards system construction,
- availability and quality of renewable resources, and
- local and regional market conditions for co-products.

4.3.5 Other Co-location Issues

Participants discussed several issues related to co-location of energy generation and industrial subsystems, including:

- potential for accidents in which one subsystem damages or disrupts another,
- premature shutdown (e.g. bankruptcy) of an integrated system sub-component which might affect the business case of the entire facility (in the event of consortium ownership),
- undesirable operational restrictions placed on coupled industrial process(es) by the NRC,
- concerns over the cost and requirements placed on an integrated energy system by nuclear insurance providers,
- physical security and safeguards concerns resulting from industrial process(es) in close proximity to a nuclear plant, and
- licensing issues surrounding the temporary on-site storage of nuclear waste.

The noted issues and challenges must be resolved if integrated energy systems incorporating nuclear and renewable generation and industrial processes are to become a reality. Separate, focused discussions with regulators will be required as the development of conceptual integrated system designs proceeds.

5. FIGURES OF MERIT DISCUSSION

A key purpose of the workshop was to invite the participants to help develop and rank a set of "figures of merit" (FOM) that could be used to: 1) evaluate the technical, economic, environmental, and social benefits of hybrid energy systems integration versus "business as usual" plant operations, and 2) reduce the number of leading regional hybrid options to two or three for initial detailed assessment. Capital project decisions in the U.S. have historically focused on "return on investment" (ROI). These ROI evaluations take technical, economic, regulatory, and safety risks into consideration. Project technical risk is generally mitigated by performing scaled demonstration of components and subsystems to confirm component operation and integration. Safety risks are mitigated by demonstrating that plant operations meet authorized risk probability thresholds upon completing a probability risk assessment (PRA). Economic risk can be evaluated based on sensitivity of cash flows tied to the projected future of natural resources and market preferences. Initial regulatory risk can be reduced by incorporating well-known, currently licensed subsystems and by siting the plant in a location that has previously been approved for the types of plants considered in the integrated system of interest (e.g. nuclear, chemical, etc.). Future regulatory risks can be mitigated by designing the plant with flexibility to adapt to evolving society values. Events of the past decade, including random disruption in foreign energy supply, the Fukushima nuclear reactor accident that resulted from the Great East Japan Earthquake and subsequent tsunami, and climate change concerns have driven a broader spectrum of social values for energy security as shown in Figure 5.

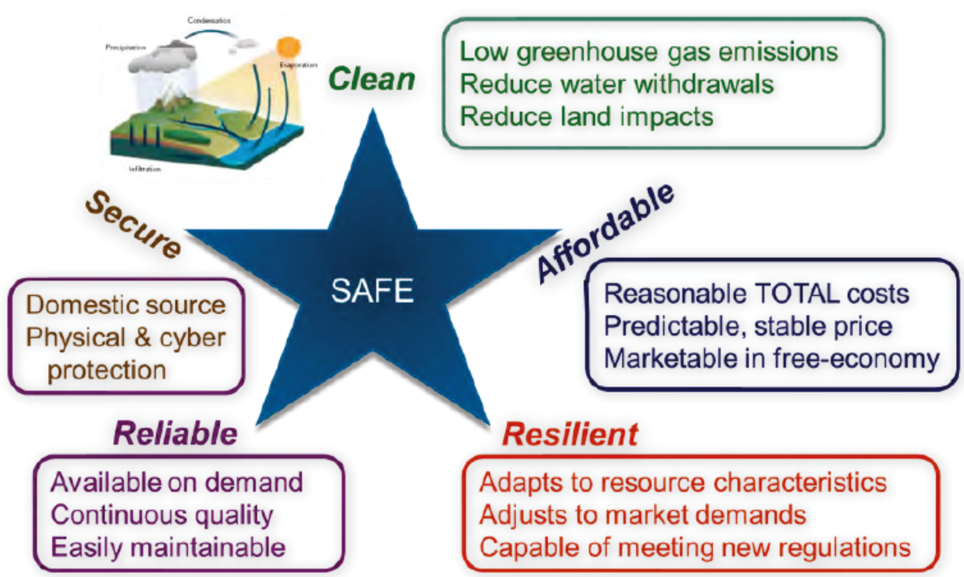


Figure 5. Attributes of Energy Systems.

Figures of merit may be binary (go/no-go); quantitative, tied directly to project goals and/or plant design criteria; or subjective, falling on a continuum from low to high social value. An effort was made to create and categorize a preliminary list of FOM for review, revision and prioritization by the workshop participants. The initial set of FOM is provided in Table 1 (black text). The FOM are divided into four categories that may be used to measure the value proposition for a proposed system based on 1) environmental, 2) economic, 3) technical, and 4) socio-political criteria.

The reference list of FOM was discussed and augmented in a large group discussion. Participants were then asked to complete an electronic form designed to rank the importance of the FOMs from lowest to highest value on a scale of 1 to 5 and to select the overall top ten FOM from the entire set. This exercise was also designed to allow participants the opportunity to provide individual comment on the figures of merit, and to suggest modifications or additions to the reference list. The resulting additions to the FOM are shown in red text in Table 1. The group average relative rankings are plotted in Figure 6 to identify the criteria that the participants viewed as the most important. A total of 38 participants completed the survey. Participants were asked to self-identify level of experience, employer type (government, national laboratory, academia, industry), and focus area (nuclear, renewables, grid, policy, etc.). Using this information, a statistical analysis of the individual input can be completed to correlate the results to each of these specifications.

Table 1. Reference Energy System Figures of Merit; Recommended Additions Derived from Group Discussion are Shown in Red Text.

Environmental	**Financial**	**Design Criteria**	**Policy**
GHG (CO_2-eq) emissions	Project Finance Indicators (Pro Forma)	System-Wide Efficiency	Domestic Resources, Markets
Other Air Pollutant Emissions regulated by the Clean Air Act and other regulations	Design, Development, and Construction (DD&C) Risk	Grid Reliability	National Energy Security
Water	Price Stability / Volatility (Manufacturing Costs and Product Revenue)	Grid Flexibility	Energy Contingency Planning
Land Use Needs	Capacity Factor	Controllability	National Economy
Land Use / Visual	Design Adaptability	Siting Feasibility	Supply Diversity
Stewardship of Resources	Business Model Viability	Licensing Feasibility	Political Climate
Waste Disposal	Business Case Sustainability	Near-Term Deployability	Clean Energy Hubs (a current theme of the DOE to focus R&D teams to help launch a target clean energy technology or process)
Other Ecological Impacts		Safety Risk	Existing Consortiums
Net Return on Energy (i.e., the ratio of energy input converted to energy services)		Component Technology Readiness Level (TRL)	Inclusion in EPA State Implementation Plans for Section 111(d) of the Clean Air Act
Impact on Human Life		Integrated System Readiness Level	Government Funding Potential
		Constructability (Staged Build-out)	
		Resiliency	
		Inherent Security	
		World-Wide Applicability	
		Design Adaptability	

A general brainstorming activity by the entire group effectively narrowed the overarching goals of NE-RE integrated systems to the following:

1. Develop energy systems that can support economic health and quality of life in a more populated world;
2. Control GHG emissions;
3. Demonstrate a business case that supports industry, economy, and service-providers; and
4. Utilize domestic resources.

With these goals in mind, the workshop participants selected the top ten FOM in the electronic form. These overall results are plotted in Figure 6 without respect to the responders' affiliation or experience. The top-ranking FOM represented each of the four FOM "categories" (Finance, Environment, Policy, Design). Financial *pro forma* and GHG reduction received the highest selection frequency among the 38 participants who completed the form. The high selection frequency for National Energy Security signals the participants' high value for independence from energy imports. The high selection frequencies of Near Term Deployability and Grid Reliability reflect a common interest in completing the development and demonstration of NE-RE integrated projects to accelerate build-out of renewable energy on the grid.

In general, the data show all of the criteria were considered to be important on an absolute scale (individually ranked for importance on a scale of 1 to 5, see Figure 7). When ranked independently on a scale or 1 to 5 for importance, economic *pro forma* indicators topped all criteria, followed by GHG reduction, national energy security, and design safety. A simple analysis of variance (ANOVA) reveals there is little statistical difference between many of the FOM. There are also several potential cross correlations among the FOM within each category and across the entire matrix. One example is under the financial category is "design, development, and construction" (DD&C) risk versus "business model viability." The ranking outcomes are statistically equal for these FOM.

Two similar FOM under the environmental and design criteria categories are "system-wide efficiency" and "net return on energy" (the latter FOM was added during the group discussions; this term refers to the ratio of energy input converted to energy services). Again, the ranking outcomes are statistically equivalent. These results demonstrate participant consistency in assigning FOM relevance.

The workshop participants provided several comments regarding the FOM, as recorded within the electronic form. A general comment referred to the need to establish absolute (quantifiable) figures of merit, and to organize these according to the major goals in a hierarchal structure. A refined list of FOM with qualitative metrics has been developed. The tables in Appendix E list the revised FOM with footnotes that capture the content of the participant feedback. The revised set of FOM can now be recast to conduct a statistically significant review for ranking and use during the evaluation of region-specific NE-RE integrated energy systems. However, the current high-ranking FOM are suitable for down-selection of regional cases for initial analysis and evaluation. A summary of detailed comments on the figures of merit is available in Appendix E.

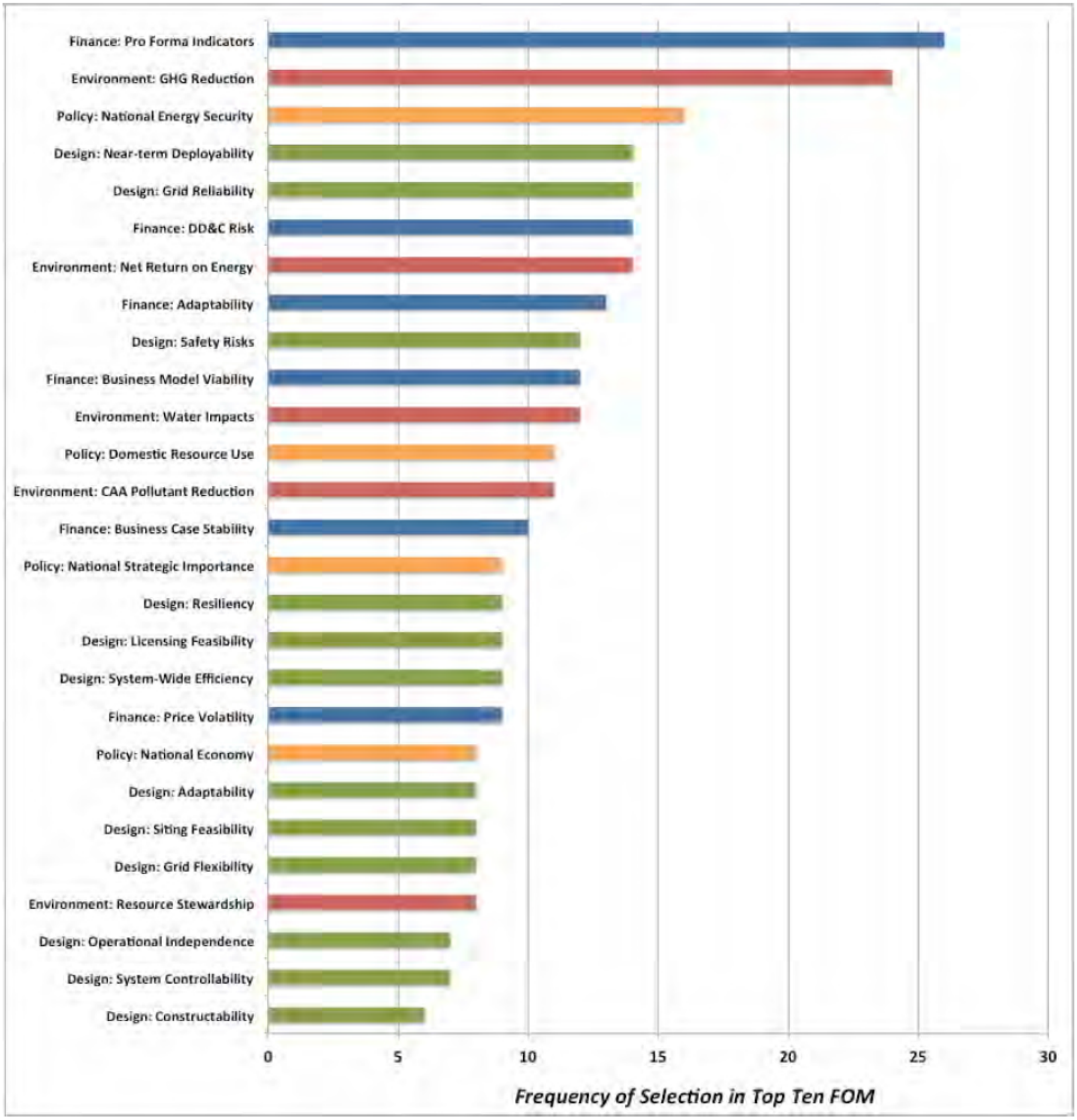
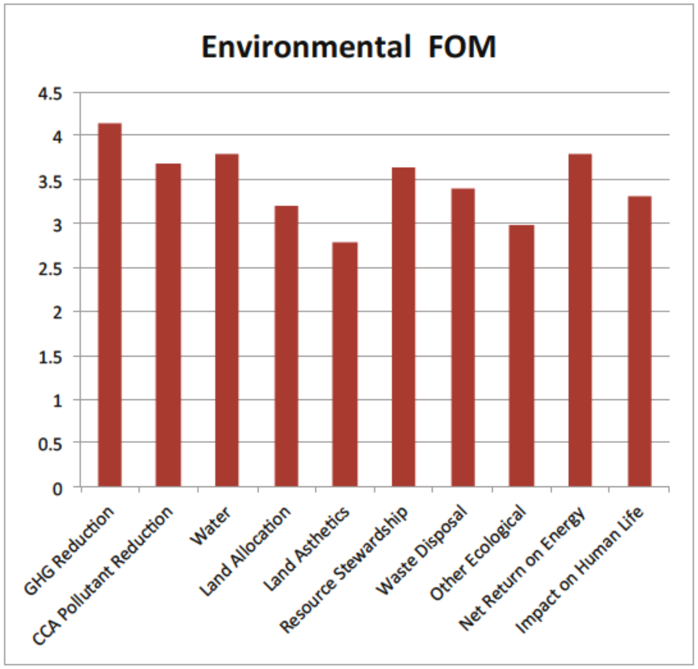
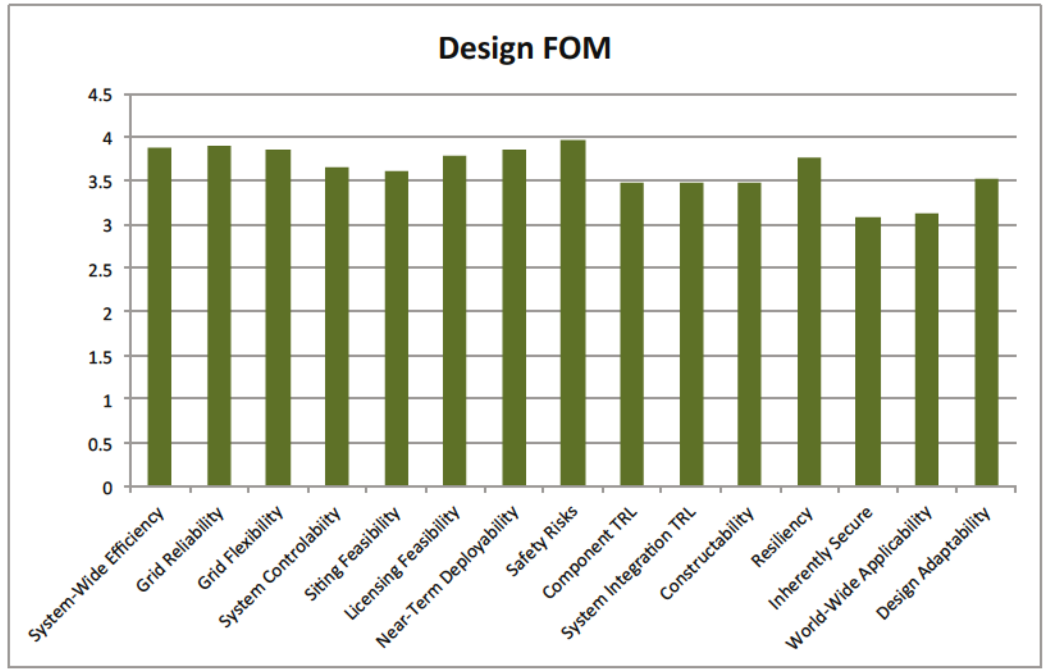
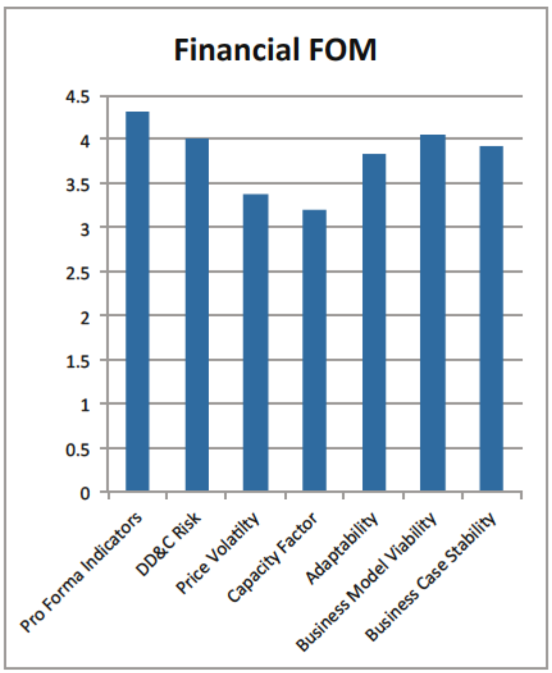
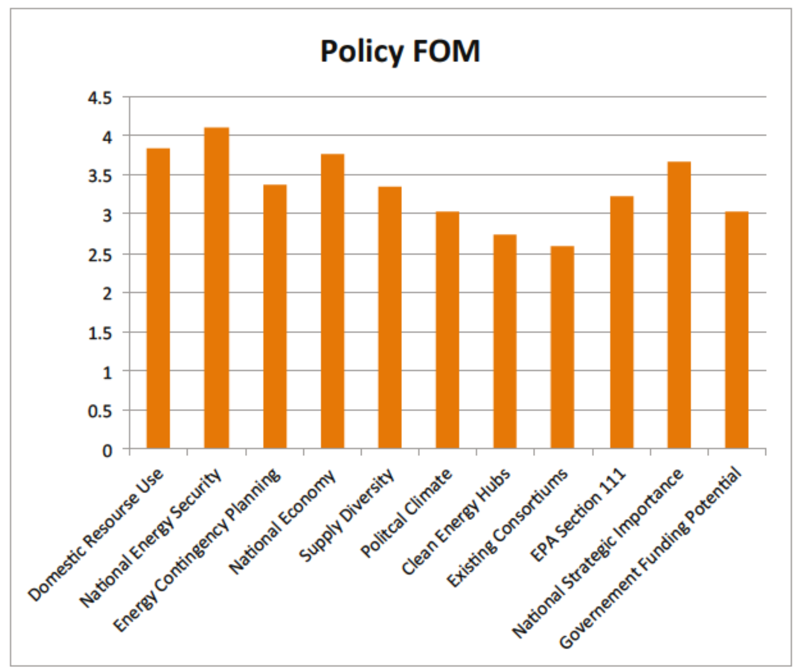


Figure 6. Frequency of selection of the top ten FOM by workshop participants.


Environmental FOM
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
GHG Reduction
CCA Pollutant Reduction
Water
Land Allocation
Land Asthetics
Resource Stewardship
Waste Disposal
Other Ecological
Net Return on Energy
Impact on Human Life


Design FOM
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
System-Wide Efficiency
Grid Reliability
Grid Flexibility
System Controlabiity
Siting Feasibility
Licensing Feasibility
Near-Term Deployability
Safety Risks
Component TRL
System Integration TRL
Constructability
Resiliency
Inherently Secure
World-Wide Applicability
Design Adaptability


Financial FOM
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Pro Forma Indicators
DD&C Risk
Price Volatility
Capacity Factor
Adaptability
Business Model Viability
Business Case Stability


Policy FOM
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Domestic Resourse Use
National Energy Security
Energy Contingency Planning
National Economy
Supply Diversity
Politcal Climate
Clean Energy Hubs
Existing Consortiums
EPA Section 111
National Strategic Importance
Governement Funding Potential

6. INTEGRATED NUCLEAR-RENEWABLE ENERGY SYSTEM OPTIONS

One desired workshop outcome was to identify key integrated nuclear-renewable energy system options for further analysis and consideration. In the development process that will be laid out in the technology development roadmap, priority figures of merit will be exercised on those key options to quantify their value and to provide insights for comparison and prioritization. In addition, a comprehensive view of the priority options will be used to identify research and development gaps and needs, with the intention of informing the roadmap to ensure that those gaps and needs are fully addressed.

For this workshop, integrated energy systems were defined as individual facilities that take two or more energy resources as inputs and produce two or more products, with at least one being an energy commodity such as electricity or transportation fuel. The systems are comprised of two or more energy-conversion subsystems that have traditionally been separate or isolated. In an integrated system, these subsystems are physically coupled to produce outputs by dynamically integrating energy and materials flows among energy production and delivery systems. This definition requires coupling ''behind'' the electrical transmission bus, where all subsystems within the hybrid energy system share the same interconnection so that the grid is exposed to a single, highly dynamic and responsive system.[16]

The required development timeframe for candidate energy systems was defined, for the purposes of the workshop and pending analyses, as technologies with the potential to have a number of commercial-scale facilities operating by 2035 to assist in meeting national GHG emissions goals. That timeframe requires either utilization of nuclear plants that are currently operating (or recently shuttered) or reactor technologies that can be licensed today. Advanced reactor technologies have the potential to improve future options; however, they are unlikely to be available soon enough to meet the development goals unless there is a national priority to develop such technologies.

To focus the discussion so valuable insights could be collected from workshop participants and key options identified, the workshop organizers developed a process that established a common understanding of the system boundaries, provided an opportunity to discuss options and offer feedback, and enabled identification of additional options and key deployment opportunities. The process involved three steps:

1. The workshop organizers presented an initial set of eight draft integrated system options to stimulate discussion and to serve as a basis for gathering feedback and generating new ideas.

2. A "gallery walk" was organized to allow every workshop participant the opportunity to discuss each of the eight regional options within a small group, improve his or her understanding of each option, identify concerns and benefits of each, and provide feedback.

3. An online form was created and distributed to allow participants the opportunity to identify additional system options and to prioritize the candidate options. Each participant was asked to develop three possible integrated systems that he or she believes would meet the key figures of merit. The options were collected and trends among them identified. A summary of the collected responses is provided in Appendix F.

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[16] Ruth, M.F., O.R. Zinaman, M. Antkowiak, R.D. Boardman, R.S. Cherry, and M.D. Bazilian, "Nuclear-renewable hybrid energy systems: Opportunities, interconnections, and needs," *Energy Conversion and Management*, Volume 78, February 2014, Pages 684-694, ISSN 0196-8904, http://dx.doi.org/10.1016/j.enconman.2013.11.030. (http://www.sciencedirect.com/science/article/pii/S0196890413007516)

6.1 Initial Integrated System Options and Summary of Participant Feedback

The workshop organizers presented a set of eight initial system options to the participants. Each of the eight options was developed for a specific U.S. region because the resources, traditional industrial processes, infrastructure for energy delivery, and markets are regionally diverse. The identified regions are shown in Figure 8. Each region is large; the suggested system option provided for each region may not fit all locations in that region and other options may fit into the region as well.

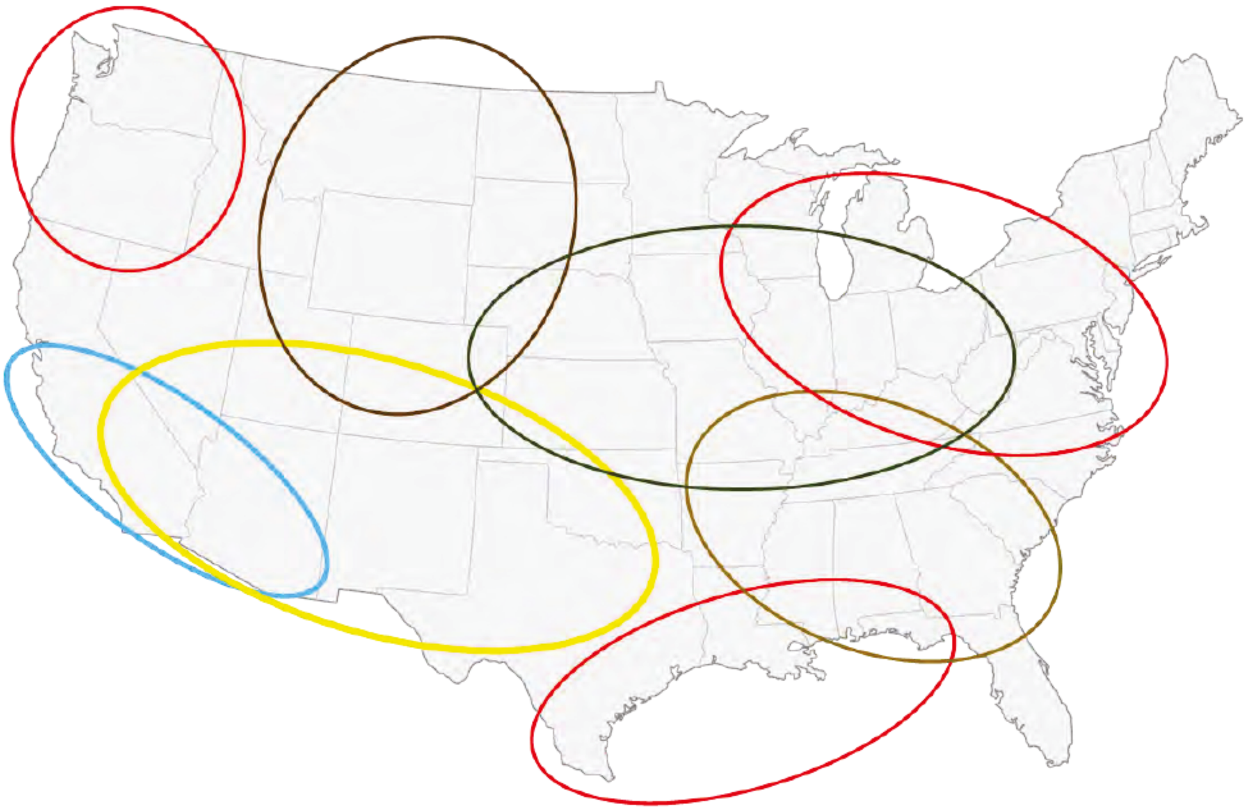

Figure 8. Regions selected for initial integrated system options.

Nuclear-renewable energy systems can be organized into five subsystem categories: thermal energy generation (i.e. nuclear reactor); power conversion (electricity generation); renewable resources and related systems; industrial processes; and interface or storage technologies. By definition, each system in this study must have a nuclear reactor; however, the other subsystems vary depending on the region's resources and market opportunities. Table 2 summarizes the options discussed for each subsystem. All integrated systems identified at the workshop include a combination of the subsystems listed. Note that the rows are not significant and do not imply a connection between options.

Biomass was not listed as a renewable resource; instead, it is captured under industrial processes. Biomass is both an energy source (like nuclear, solar, and wind) and a feedstock—it does not neatly fit into a single category. Biomass processing and its heat, electricity, and hydrogen requirements are similar to other industrial processes.

Table 2. Subsystem options discussed during the workshop.

Renewable Resources	Industrial Processes	Interface / Storage
Animal manure	Ammonia / fertilizer production	Battery storage
Concentrating solar heat	Bauxite to aluminum	Compressed air energy storage
Concentrating solar power	Biofuel production	Geothermal
Geothermal heat	Chlorine production	Hydrogen (via high temperature thermochemical production)
Geothermal power	Coal to non-fuel chemicals	Hydrogen (via high temperature electrolysis)
Solar photovoltaics	Coal to synfuels	Hydrogen (via nuclear-heated steam methane reforming)
Tidal power	Concrete production	Hydrogen storage - underground
Wind - land-based	Copper smelting	Pumped hydro
Wind - off-shore	Desalination	Steam accumulators
	District heating	Thermal storage - liquid (e.g., molten salt)
	H_2 + CO_2 to syngas and products	Thermal storage - direct electricity to heat
	H_2 for transportation	
	Iron reduction (direct)	
	Liquid nitrogen production	
	LNG liquefaction for export	
	Natural gas to ethylene	
	Natural gas to liquid fuels	
	Nitrogen liquefaction	
	Petrochemical processing	
	Petroleum recovery from oil sands	
	Petroleum refining	
	Remote mining processes	
	Shale oil recovery	
	Thermal refrigeration cycle	

Proposed initial integrated system options for each region – and the feedback received on them – are discussed in the following sections. Table 3 provides an overview of the renewable resource, industrial process, and interface/storage proposed for each region.

Table 3. Renewable resource, industrial process, and interface/storage proposed for each region.

Region	Renewable Resource	Industrial Processes	Interface / Storage
Mountain-West	Wind – Land-based	Natural gas to liquid fuels	Battery storage
Pacific Northwest	Wind – Land-based or off-shore	Bauxite to aluminum	Battery storage
Southern California	Tidal power	Desalination	Battery storage
Southwest	Concentrating solar power and geothermal power	Hydrogen for transportation	Hydrogen (via high temperature electrolysis) and compressed air energy storage
Gulf Coast	Offshore wind power	Petroleum refining	Hydrogen (via high temperature electrolysis)
Southeast	None*	Biofuel production	Hydrogen (via high temperature electrolysis)
Industrial Midwest / Northeast	Wind power	Natural gas to ethylene	Pumped hydroelectric storage
Agricultural Midwest	Wind power	Ammonia / fertilizer production	Hydrogen (via high temperature electrolysis)

* The Southeast Region does not have a renewable resource because the renewable resource used is biomass for the industrial process.

6.1.1 Mountain-West Region

The option initially proposed for the Mountain-West includes wind power as the renewable resource because the region has large areas with excellent wind resources. Natural gas to liquid fuels was proposed as the industrial process because advanced horizontal drilling and hydraulic fracturing techniques have enabled recovery of large quantities of natural gas. A storage option is necessary because many areas within the region are electric transmission constrained, thus requiring a system that can ration electricity to the system. Figure 9 shows how the nuclear reactor, electricity generation and other subsystems might be connected.

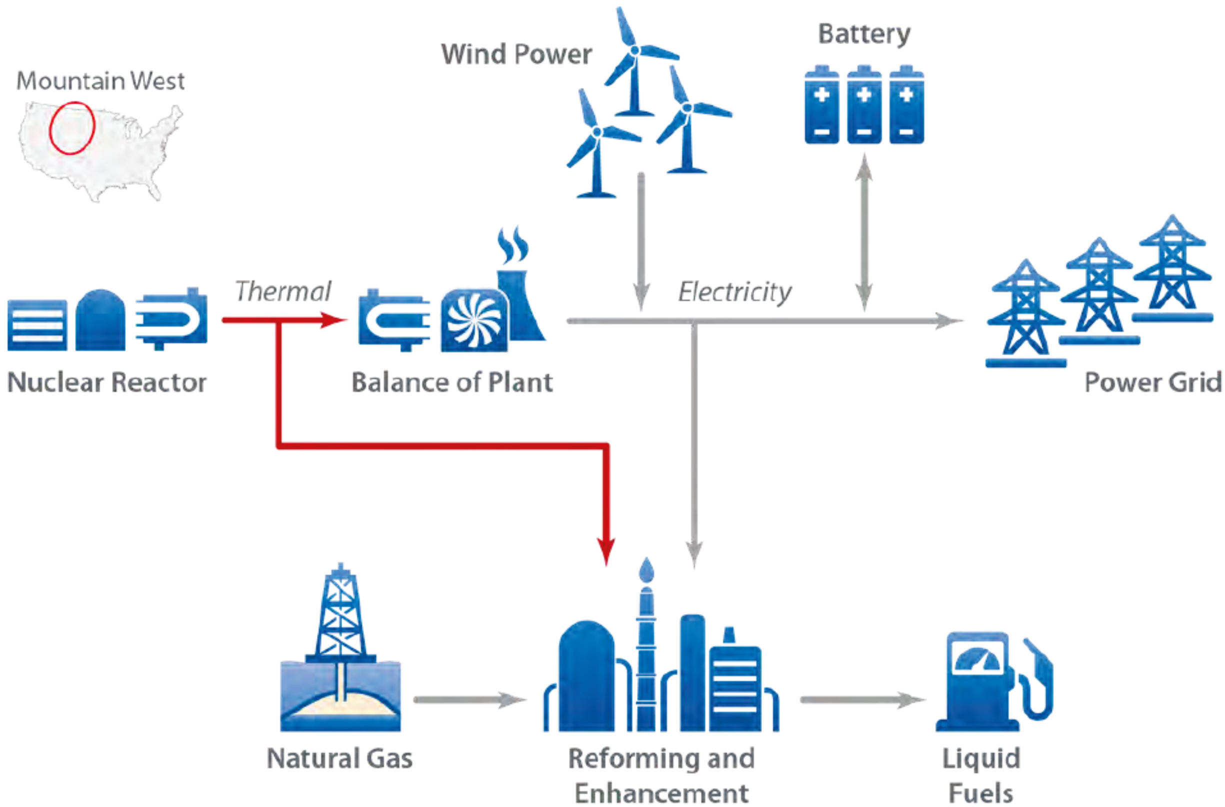

Figure 9. Initially proposed integrated system option for the Mountain-West Region; note that thermal energy is indicated using red connector lines.

Workshop participants agreed that wind is an ideal renewable resource in many parts of this region. They also identified geothermal power as an option that could replace wind or be coupled with it to improve the system depending on the specific location and electric system characteristics.

Natural gas to liquid fuels was considered a good option for the region; however, some participants expressed concerns about the size of the natural gas resource. Oil shale was identified as an option with a much larger potential, although the technology development, cost, and environmental issues that it has may preclude it from being a key option by the 2035 timeframe proposed. Participants also identified coal-to-synfuels (due to extensive coal fields in the region), petroleum recovery from oil sands in Alberta, and iron production from ore in Minnesota (with hydrogen from the Mountain west) as other options that should be considered for this region.

The selection of batteries for electricity storage was questioned due to the mismatch between wind and batteries and because the region has the potential for extensive pumped hydro; however, the environmental concerns around pumped hydroelectric storage were acknowledged.

Hydrogen (H_2) was another option discussed as an interface —particularly as a chemical feedstock to upgrade fossil fuels (e.g., coal, shale oil, etc.) to liquid fuels and to convert iron ore to iron by direct reduction. One concern with that option is that the pipelines necessary to transport the H_2 to markets would have to be developed for most of the regions. Another H_2 transport option for consideration is converting hydrogen to a chemical hydride such as methylcyclohexane (MCH).

6.1.2 Pacific Northwest Region

The option initially proposed for the Pacific Northwest includes wind power as the renewable resource because the region has some areas with excellent wind resources. Bauxite to aluminum was proposed as the industrial process because the region has a strong history of aluminum production. No thermal or electrical energy storage option appeared to be needed; however, a battery is proposed if necessary. Figure 10 shows how the subsystems might be connected.

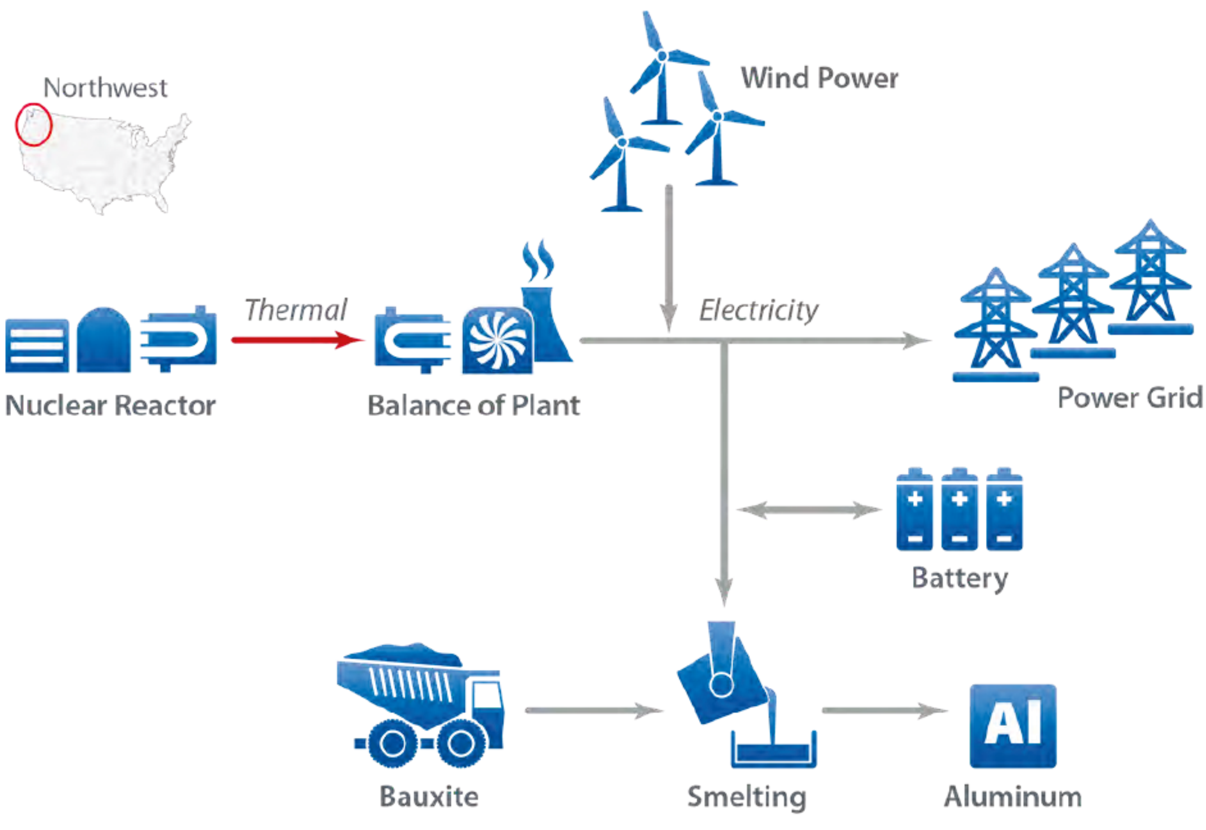

Figure 10. Initially proposed integrated system option for the Pacific Northwest region.

A primary question associated with aluminum smelting is whether it can be used to absorb variable amounts of electricity with variable aluminum outputs. Because it is such an electricity-intensive industry, it could act as an electricity sink. Workshop participants, however, commented on the relatively small size of the aluminum market; thus, bauxite to aluminum is not considered an ideal option.

Biomass processing is another option that should be considered for this region due to the extensive resource availability. Participants reported that parts of this region have excess transmission capacity and that availability may reduce the need for energy storage (like batteries in the proposed option). In addition, pumped hydroelectric storage (or hydroelectric generation with the ability to adjust the power output) could be used as a load-following option to provide grid flexibility. Hydrogen production, as discussed in the Mountain-West region, is another option worth considering.

6.1.3 Southern California Region

The option initially proposed for the Southern California Region includes tidal power as the renewable resource because the region is on the ocean. Desalination is proposed as the industrial process because the region suffers from water scarcity and drought issues. The region has issues with flexibility on the power grid, so batteries were proposed to provide storage. Figure 11 shows how the subsystems might be connected.

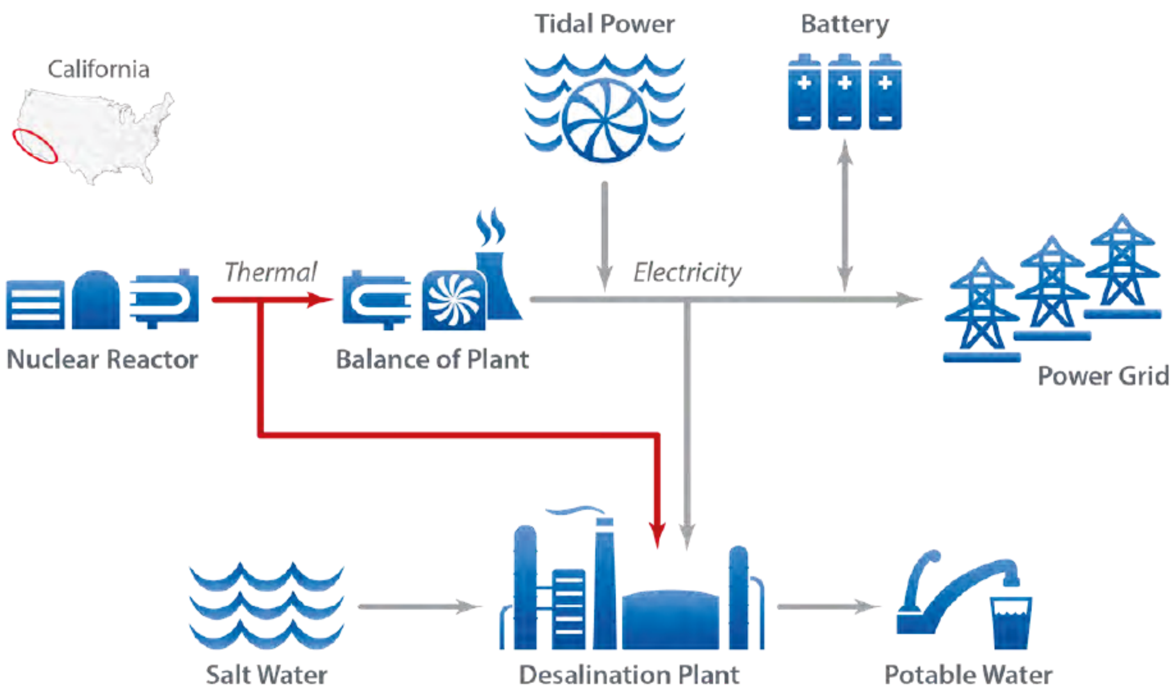

Figure 11. Initially proposed integrated system option for the Southern California region.

Workshop participants were concerned that the political climate in California may prevent an integrated nuclear-renewable energy system from being sited in this region. If one were to be developed in this region, cooling options should be a design focus. As an alternative to evaporative cooling, participants recommended using the ocean for cooling. Options could also be identified for using the low temperature heat, such as district heating or evaporative desalination.

Participants also noted that this region has a good political climate for alternative fuel vehicles; hence, plug-in electric vehicles can be used to provide flexibility needed by the grid and/or hydrogen can be produced from the integrated system and used in fuel cell vehicles.

6.1.4 Southwest Region

The option initially proposed for the Southwest Region included concentrating solar power and geothermal power as the renewable resources because the region is rich in both solar and geothermal resources. Hydrogen for transportation produced via high temperature electrolysis is proposed as the industrial process. Compressed air energy storage was proposed as the storage subsystem. Figure 12 shows how the subsystems might be connected.

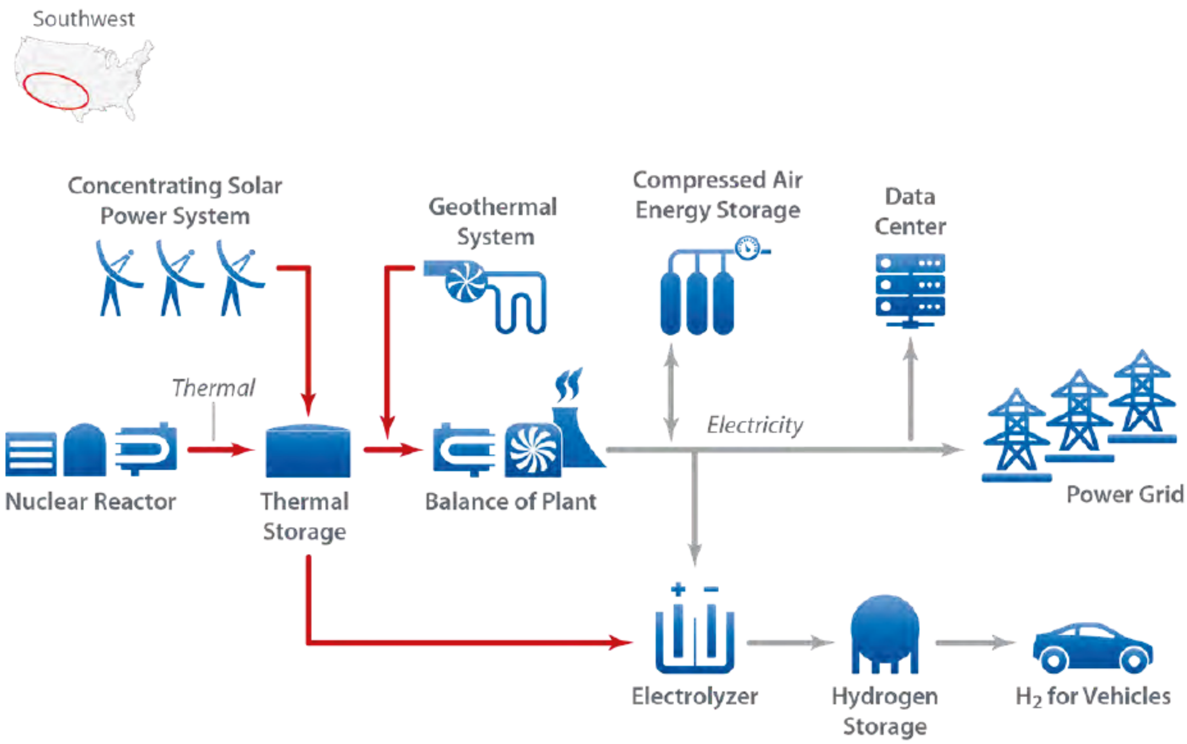

Figure 12. Initially proposed integrated system option for the Southwest Region.
Note that the concentrating solar power shown in the diagram, with connection on the thermal side of the system, could be replaced by solar PV, which would connect directly to the electricity side of the system, given current trends in the cost of PV technology.

Workshop participants identified the Southwest as a location with extensive resources and industrial capability and where the needs match the potential of an integrated nuclear-renewable system. In addition, the region contains transmission capacity that may not be fully utilized due to possible closures of coal generation units.

Workshop participants identified solar photovoltaics (PV) and land-based wind as additional key renewable resources. One participant noted that expected capacity additions of distributed photovoltaic systems in the region may increase the variability of the net load, thus increasing the need for generation flexibility. Arizona is currently adding significant solar PV capacity due to the ample solar energy input in the region and the rapidly decreasing cost of PV technology. PV may also be considered an option within an integrated nuclear-renewable energy system, as noted in the caption for Figure 12.

Workshop participants recommended that desalination be considered as the preferred industrial process for this region because of the need for potable water (see Figure 13). Further investigation into the desalination technology is warranted because it is unclear whether reverse osmosis, modified evaporative desalination, or another design fits best into the integrated system option. If hydrogen production is investigated, workshop participants recommended focusing on the merchant market and use of hydrogen as a means for energy storage. Additional comments on hydrogen match those reported in the section on the Mountain West region.

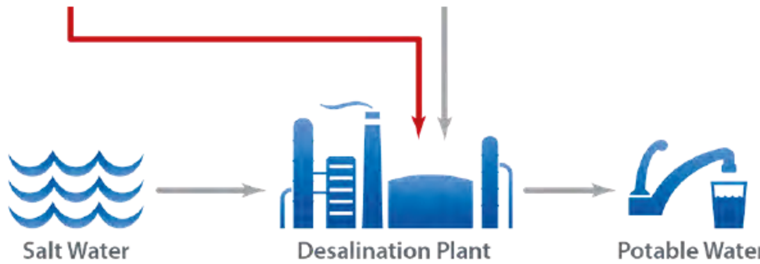

Figure 13. Desalination as an alternative industrial process for the Southwest Region; note that desalination requires both thermal and electrical input.

6.1.5 Gulf Coast Region

The option proposed for the Gulf Coast Region includes off-shore wind power as the renewable resource. The region has few renewable resources, but there is some wind potential in the Gulf of Mexico. There are also large wind resources in North Texas, near the edge of the Gulf Coast Region that could be included if transmission capacity is developed. Petroleum refining was proposed as the industrial process because of the large refineries and associated infrastructure already in the region. Hydrogen production is proposed as the interface because the refineries require a large and growing quantity of hydrogen. Figure 14 shows how the subsystems might be connected.

Workshop participants agreed that the proposed option fits the region. Key concerns with the option are related to safety and siting distance; both the nuclear and petroleum refining industries have strong safety requirements and siting regulations that may not be consistent, and possible interactions are a new concern.

Workshop participants also noted that the regulatory environment in Texas may be more likely to support nuclear-renewable systems than in most other states.

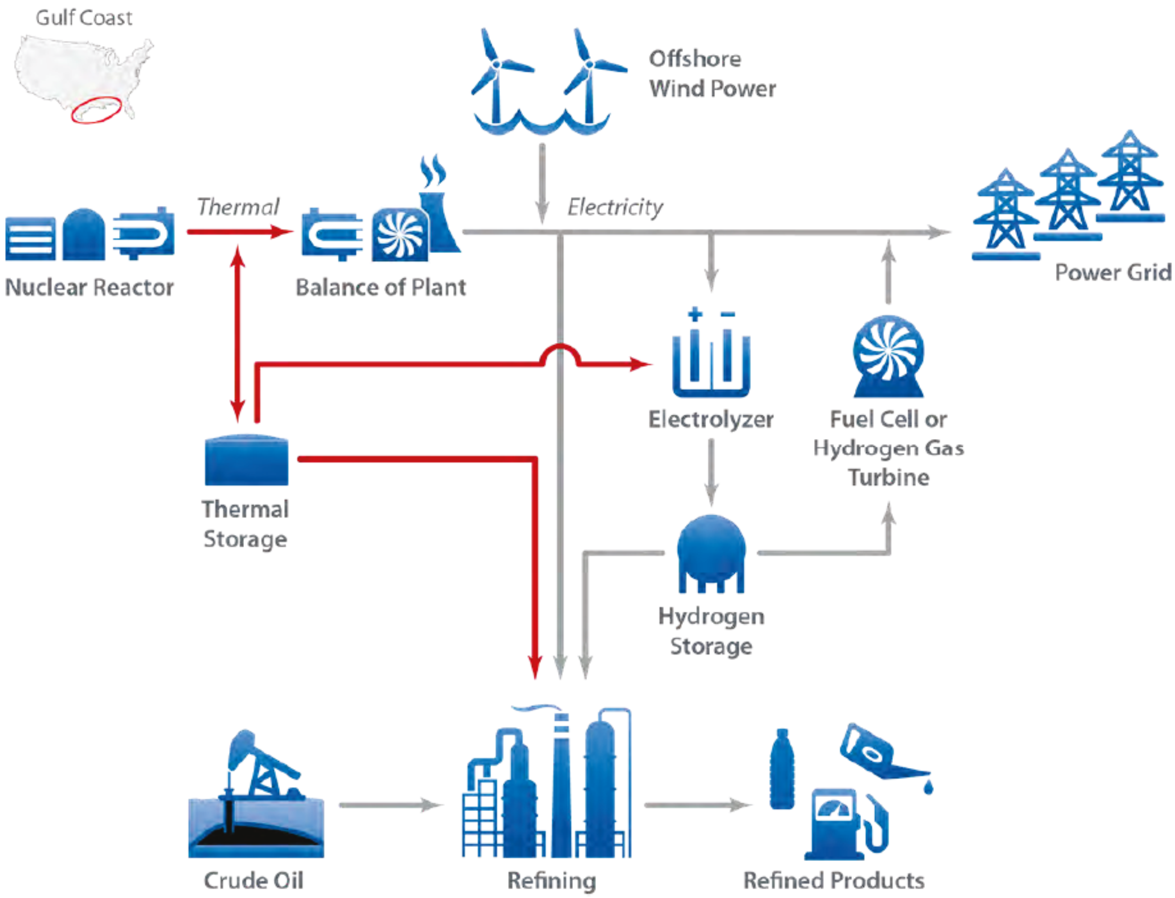

Figure 14. Initially proposed integrated system option for the Gulf Coast Region.

6.1.6 Southeast Region

The option proposed for the Southeast Region does not include a renewable resource like the other options presented. Instead, the renewable resource is the biomass used as a feedstock for the proposed biofuel production industrial process. Biofuel production was proposed for this region because it has excellent resources for biomass feedstock and is near petroleum refineries where some biofuels can be mixed with petroleum fuels and others can be used as refinery feedstocks. In addition, the infrastructure necessary to transport liquid fuels is available in the region. H_2 production is proposed as an interface because some of the biofuel processes require large amounts of H_2. Figure 15 shows how the subsystems might be connected.

Workshop participants noted that the only robust renewable resource in this region is biomass; hence, the proposed design fits the region. They also noted that new biomass collection and transport technologies are being developed as a result of Europe's demand for woodchips and China's demand for its pump mills. Those new technologies are enabling much larger scales for transport and, thus, for biomass utilization processes.

The only additional option suggested by workshop participants is desalination because of a growing regional concern about potable water. Workshop participants also noted the five nuclear reactors that are coming on line in this region; their assessment was that acceptance of nuclear power is high in this region, and regulators may be more likely to support siting.

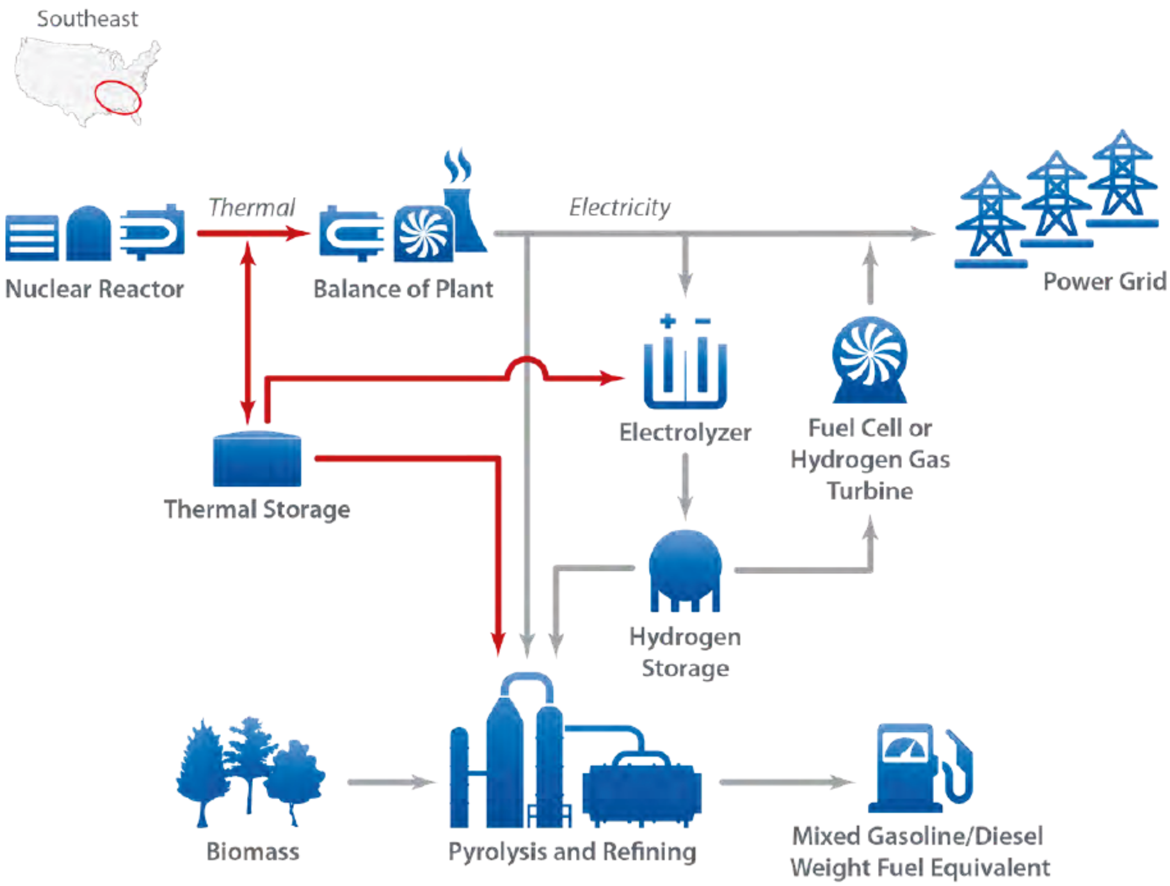

Figure 15. Initially proposed integrated system option for the Southeast Region.

6.1.7 Industrial Midwest / Northeast Region

The Industrial Midwest / Northeast Region is defined by its traditional industries: manufacturing, steel, and chemicals. The option proposed for this region focuses on the traditional chemical industry and the newly available natural gas resource. The selected industrial process is conversion of natural gas to a key chemical industry feedstock – ethylene. Wind power (likely off-shore or on ridgelines) is proposed as the renewable resource. Non-traditional pumped hydro storage (such as elevated weight options) is proposed for energy storage (if storage is determined to be necessary). Figure 16 shows how the subsystems might be connected.

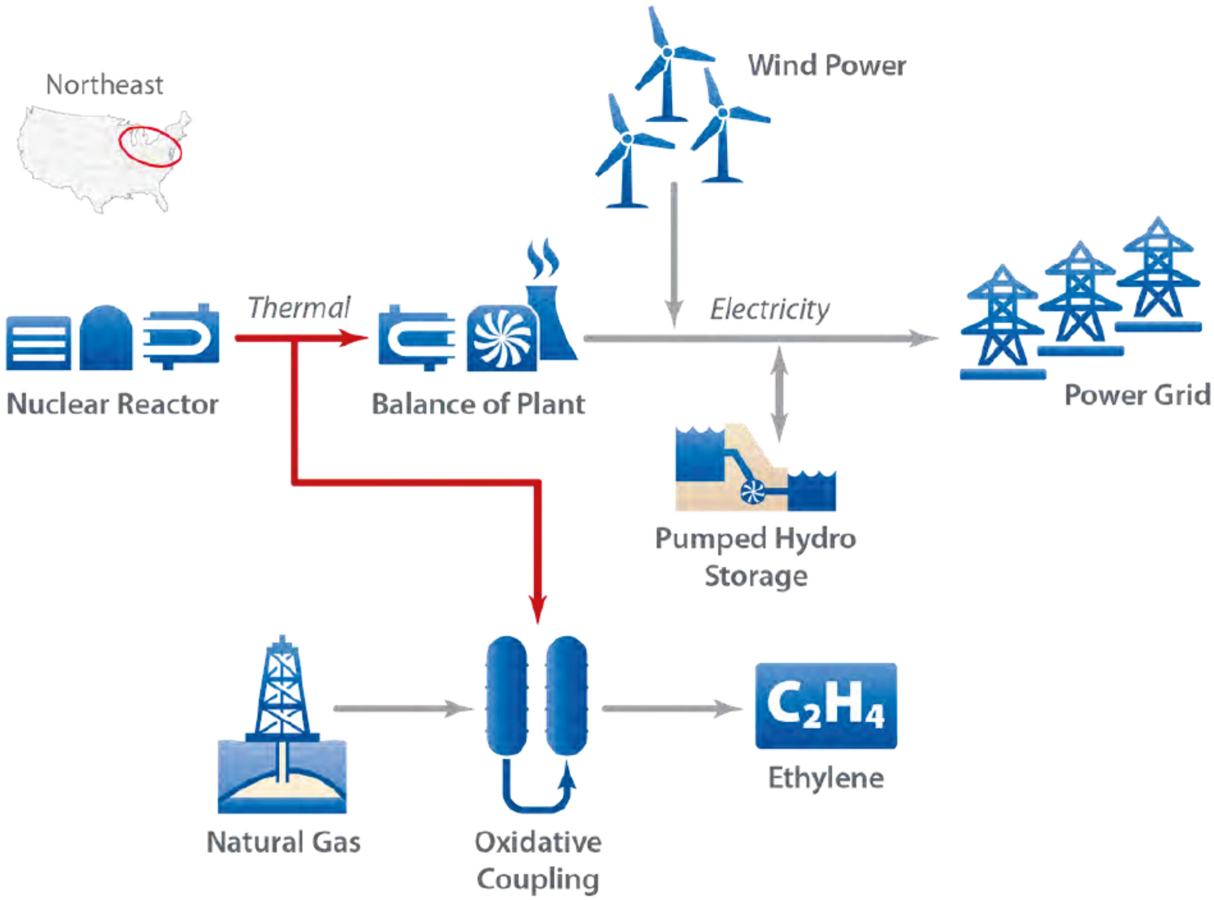

Figure 16. Initially proposed integrated system option for the Industrial Midwest / Northeast Regions.

Workshop participants identified some key challenges for this region: aging transmission and generation infrastructure; high population density, resulting in siting complications; lack of renewable resources; and political concerns regarding siting nuclear energy in the region. They were not optimistic that an integrated system could be built in this region. If one were considered, the workshop participants recommended also investigating two additional industrial processes: nitrogen liquefaction and district heating (due to the high population density).

6.1.8 Agricultural Midwest Region

The Agricultural Midwest Region has both an excellent wind resource and a large demand for ammonia as a precursor for fertilizers. Thus, land-based wind power is proposed as the renewable resource and ammonia / fertilizer production as the industrial process. Both require large amounts of electricity to separate nitrogen from air and large amounts of hydrogen to convert that nitrogen to ammonia. Hence, H_2 was the interface initially proposed. Figure 17 shows how the subsystems might be connected.

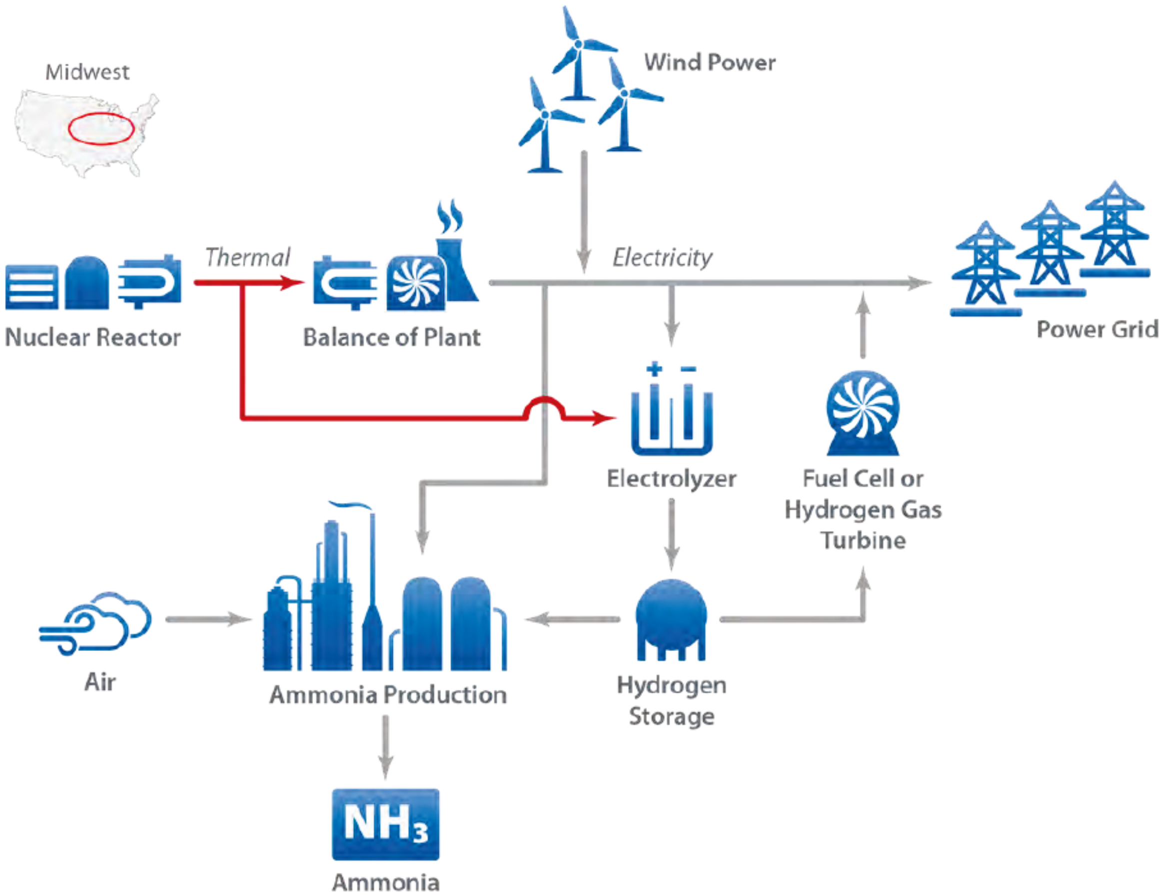

Figure 17. Initially proposed integrated system option for the Agricultural Midwest Region.

Workshop participants suggested that this region might provide the best opportunity for integrated nuclear-renewable energy systems, noting that if integrated systems will not work in this region, they probably will not work anywhere in the U.S. The region has abundant resources (wind, natural gas, coal, water); effective infrastructures (estuaries, rail, oil and gas pipelines, and electric transmission); a population who needs products and energy services; and both an agricultural and industrial history.

Participants liked the concept of making ammonia and fertilizers but recommended investigating other fuels/synfuels, chemicals, and transportation options as well. They also recommended looking for district heating opportunities. Finally, iron processing is an option that should be considered. Large iron deposits exist in Minnesota, Wisconsin, and Michigan and direct iron reduction, like ammonia production, has a large demand for H_2.

Some participants recommended an evolutionary development process in this region. Instead of starting with a nuclear-wind process, initial deployment could use natural gas as the thermal energy source and build up wind quickly. Then, when a nuclear reactor comes on-line, the natural gas contribution could be reduced and replaced with nuclear energy.

6.2 Selection and Prioritization of Integrated System Options

An online feedback method was used to identify additional options and to prioritize options. Each participant was asked to develop three system configurations that he or she believed would meet the key figures of merit. The options were collected and trends among them identified.

Before the online feedback was requested, workshop participants were asked to provide additional general considerations for system selection. Based on the input to the electronic form, key opportunities having the greatest potential for success will be identified for technical and economic analysis. These analyses will be used as the basis for a Technology Development Roadmap (Appendix G). This section summarizes general considerations, system identification and feedback process, and results.

6.2.1 General Considerations for Selection

Workshop participants provided input regarding selection of priority options prior to each making independent system selections. The intent of that discussion was to develop a consistent understanding and possibly some consensus before requesting independent feedback. The results of that discussion are also useful when priority systems are identified for the roadmap.

Participant input is summarized as follows:

(1) In many options discussed, the components are the same but the markets differ. For the integrated systems technology development roadmap (Appendix G), several technology combinations could be chosen to focus the work. If that is the adopted process, participants recommended a diverse technology portfolio instead of several selections with essentially the same technologies.

(2) In selecting options and regions, it is important to consider the political landscape. Candidates considered for initial system analysis should avoid regions that would not be amenable to nuclear energy, let alone to integrated nuclear-renewable systems.

(3) Potential decentralized electricity generation should be considered in analyzing the potential business case for proposed integrated systems, recognizing the apparent trend in many sectors to move away from large central facilities to smaller, decentralized facilities.

(4) Some participants recommended looking for specific sites for prototype systems with a focus on military bases for initial siting; however, military bases have their own objectives and most of those do not include nuclear energy technologies.

6.2.2 Solicitation of Alternative Options

The online feedback exercise described above was intended to identify system options beyond the eight configurations initially proposed, taking into consideration the workshop discussions and outside knowledge. The exercise was also intended to identify and prioritize key opportunities.

Online forms were distributed electronically to each participant. Each participant developed up to three specific configuration options for integrated nuclear-renewable energy systems, identifying a combination of renewable resources, industrial systems, and storage / interface technologies. In addition to selecting subsystems for integration, participants were asked to indicate the potential siting region and the scale at which the process could be implemented. Participants were directed to focus on options including high levels of renewable resources and where the selected industrial option might fit.

Participant responses were varied without a clear single choice. Thirty-seven different responses were collected with a total of 103 process options. No unique process options got more than three votes. Hence, there is a large variety of options and no clear favorites as selected by workshop participants.

Table 4 shows the number of times each technology was selected or written into the process options. Desalination was the most selected industrial process, appearing in 39 of the total options submitted. Other industrial processes with over 20 selections include production of syngas and other products by reacting hydrogen and carbon dioxide; coal to synfuels; and biofuel production. Land-based wind was the most selected renewable resource followed closely by concentrating solar power and solar PV. Liquid thermal storage (e.g., molten salt) and hydrogen production via high-temperature electrolysis were the most selected interfaces / storage options. Note that the combinations need to be selected based on regional siting options, such that combining the top "vote-getters" in each category to generate a possible configuration may not be feasible.

Appendix F displays the full set of options submitted, sorted by location provided. Participants provided a diversity of process options for consideration. Unfortunately, no single complete process (or small number of processes) was provided by enough participants to be the priority option for future efforts. Instead, the general input and key options identified in Table 4 should be used to help select priority process options for consideration during roadmap development.

Table 4. Summary of participant process option selections.

Industrial Processes		Renewable Resource		Interface / Storage	
Desalination	39	Wind - Land-based	45	Thermal storage - liquid (e.g., molten salt)	47
Hydrogen + CO2 to syngas and products	23	Concentrating solar power	39	H_2 (via high temperature electrolysis)	38
Coal to synfuels	22	Solar photovoltaics	31	Battery storage	23
Biofuel production	21	Wind - Off-shore	19	Steam accumulators	21
Natural gas to liquid fuels	13	Geothermal heat	10	H_2 (via high temp. thermochemical production)	18
Ammonia / fertilizer production	11	Tidal power	7	Pumped hydro	16
LNG liquefaction for export	11	Geothermal power	4	Geothermal	1
District heating	10	Animal Manure	1	Hydrogen (via nuclear-heated steam methane reforming)	1
Petroleum refining	9	Concentrating solar heat	0	Hydrogen storage - underground	1
Shale oil recovery	8			Thermal storage - direct electricity to heat	1
Copper smelting	5			Compressed air energy storage	0
Natural gas to ethylene	3				
Iron reduction (direct)	2				
Chlorine production	1				
Coal to non-fuel chemicals	1				
Liquid nitrogen production	1				
Remote mining processes	1				
Thermal refrigeration cycle	1				
Bauxite to Aluminum	0				
Chlorine production	0				
Concrete production	0				
H_2 for transportation	0				
Nitrogen liquefaction	0				
Petrochemical processing	0				
Petroleum recovery from oil sands	0				

7. STRATEGIES NECESSARY TO QUANTIFY FIGURES OF MERIT

Following discussion of the priority figures of merit and presentation of the regional options and participant input, a moderated discussion was held on how figures of merit could be quantified for each of the configurations considered. Although there was insufficient time to discuss quantification of all the FOM, the top-ranking FOM from Figure 6 were addressed.

7.1 Finance: Project Financial Indicators

The FOM receiving the largest number of selections within the top-ten FOM was in the Finance category, *Project Financial Indicators*. There are a variety of tools available to perform financial analyses for large projects. Participants suggested that financial analysis should begin with a market assessment; there is significant expertise to perform such analyses in many of the national laboratories. From the electric side, the market assessment should consider the market structures in different regions, as they vary around the country. Regional Transmission Offices (RTOs) should be capable of providing input and assistance in this area. Additionally, nonnuclear integrated systems that are currently in operation may provide significant guidance and input regarding costs, capacities, market structures and values, etc. Abengoa, for example, has demonstrated concentrated solar power systems with at-scale molten salt thermal energy storage to provide dispatchable electricity. This and other implementations can offer significant, real-world input on costs, operability, etc.

Workshop participants stated that expertise is more challenging to procure than tools. Multiple experts will need to be engaged to provide input to financial models and establish possible business cases for proposed systems. Experts from each technology area must be identified and engaged to provide realistic inputs to models, including capital cost estimates, to predict system economic performance. They can be supported by large *pro forma* financial and economic modeling tools that DOE has developed previously and can be leveraged for this effort. Participants also suggested investigating cross-cutting software that ties financial modeling to the technical solution in terms of analyses. Potential investors should be engaged to establish the possibility for government R&D funding, commercial funding, venture capitalist interest, etc.

7.2 Environment: Greenhouse Gas Emissions

Preliminary discussions on the quantification of greenhouse gas emissions from proposed integrated system configurations pointed to the potential use of the GREET model (https://greet.es.anl.gov). The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model, first released in 1996 and most recently updated in 2013, was developed by Argonne National Laboratory under DOE EERE sponsorship. The GREET model allows researchers and analysts to evaluate various vehicle and fuel combinations on full life-cycle / vehicle-cycle basis.

Emissions analyses should be driven by proposed guidance in EPA Section 111(d), such that potential developers, investors and users will be enabled to make sound decisions on the viability of a selected concept to meet the revised EPA State emissions targets. These analysis tools should allow for comparison of integrated system implementations to non-integrated systems as a baseline scenario, with complementary parametric economic studies performed based on assumed costs of CO_2 emissions. Where possible, validated tools and data should be used in these system models to predict performance and GHG emissions.

EPRI has also developed the U.S. Regional Economy, Greenhouse gas, and ENergy (US-REGEN) model that could be applicable to the current analysis efforts (eea.epri.com/models.html).

7.3 Policy: National Security Benefit

Maintaining national security is an important consideration as we look to develop advanced energy systems of the future. This general category is somewhat broad. For advanced energy systems, workshop participants suggested numerous aspects that should be considered.

One aspect is reducing oil imports. Advanced, hybrid energy systems have the potential to reduce them and to produce additional products or commodities within the U.S. These impacts can and should be quantified in evaluating potential impact on "national security." Other aspects involving the security and economic development of a nation are availability of clean water and food, which some have linked to the security of energy supply. New energy systems should maintain a "do no harm" principle in which they are focused on maintaining or improving upon the current U.S. security level.

Another aspect is reliability of electricity supply to critical assets such as hospital complexes and military bases. The ability to provide power to those assets during times of duress has a value. Coupling that value with a different value stream for times of normalcy would increase benefit of an integrated energy system.

Advanced energy systems also have significant potential to impact the security and economic development of other nations and global regions. People are often driven to migrate to new regions based on a desire to improve their quality of life. Increased accessibility of energy leads to clean water and food supplies, enhanced comfort (heating / cooling), and more. By providing these basic needs in developing regions, the drive to migrate to more economically advanced regions may be reduced. Hence, national energy assurance often leads to increased global stability – which, in turn, positively impacts U.S. security.

7.4 Design: Grid Reliability / Grid Support Design

Improved dynamic modeling and simulation tools are necessary to quantify and evaluate the impact of advanced energy systems on grid reliability and grid support. Workshop participants suggested reviewing early NGNP studies and developing a tool set to evaluate economic value of providing load-following energy to the grid. Analysis tools should utilize data and expertise available from existing implementations where available (e.g. impact of high wind energy penetration on grid stability, possibly in the West Texas region). Considerations of interest include the controllability of nuclear processes; system control across multiple units / subsystems (e.g. units displaced by a time lag); quantification of maximum system ramp rates, component response rates and subsystem response rates; maintaining the integrity of system structures over time; and dispatchability of the generated electricity.

7.5 Design: Near-term Deployability

Near-term deployability of a complex system is multifaceted, so multiple figures of merit should be used. The development timeline is impacted by maturity of component and subsystem design, interface technologies, instrumentation, and control systems; successful existing implementations of the same or similar technology; availability of validated models; and status of site permits. A site that is already approved for nuclear systems, and possibly permitted to support additional units, would have a significant advantage over a greenfield site with regard to rapid implementation of an integrated energy system incorporating a nuclear reactor. Hence, site approval is a key figure of merit.

Another figure of merit in this area is Technology Readiness Level (TRL) of both the components and the integrated system. Proven solutions for industrial processes of interest (TRL 7 or higher), such as a desalination plant, could dramatically shorten development timelines, focusing efforts on system integration and licensing issues.

The proposed reduction in EPA limits on carbon emissions for both existing [section 111(d)] and new [section 111(b)] power plants establish implementation timelines, and States have developed associated implementation plans. Guidance in 111(d) sets a target date of 2030 for reduction of emissions from existing plants, whereas 111(b) establishes standards for new, modified, and reconstructed emission sources. Development of advanced energy systems, such as those proposed within this workshop, should be conducted within the context of these State Implementation Plans (SIP) and EPA timelines. These target dates make near-term deployability a key attribute for low-carbon energy system solutions.

7.6 Path Forward on FOM Quantification

A variety of additional figures of merit will need to be quantified for complete evaluation of regional energy systems, as discussed in section 6. The high-ranking FOM identified within the workshop will be used for initial prioritization of regional concepts. Methods for quantifying these and other key FOM will be defined within the Technology Development Roadmap.

8. CONCLUSIONS AND PATH FORWARD

The Integrated Nuclear – Renewable Energy Systems Foundational Workshop accomplished the goal of initiating an inter-laboratory, university, and industry team for integrated energy systems development. Significant progress was made toward identification of regional system configurations, prioritization of options for evaluation, and definition of key figures of merit necessary to evaluate the potential technical and financial performance of those systems. Additional work is necessary to refine the region-specific configurations before conducting detailed analyses and applying the key figures of merit that were identified. Analysis of two of the priority configurations is planned, and results of these analyses will inform the Integrated Systems Technology Development Roadmap (see Appendix G for additional details on the roadmapping process). Selection of priority cases will be made by the INL, NREL and MIT leadership team based on past experience, knowledge of existing markets and infrastructure, consultation with stakeholders, steady-state scoping calculations, and preliminary estimates of system performance relative to the high level figures of merit. It is desirable to assess a broad range of technologies across the two to three configurations selected for priority dynamic analysis (e.g. each should incorporate a different renewable generation source and industrial process). The draft Roadmap that will be produced over the coming year will be distributed to the broad range of experts who are expected to contribute to the design, development, demonstration and use of integrated energy systems for comment before it is finalized to ensure that the planned activities are relevant and actionable.

The workshop closed with a discussion of development needs for integrated system design and development, including both modeling and testing infrastructure needs. Given the wide variety of physical components and subsystems that could be incorporated in the proposed energy systems, fruitful discussion on experimental testing platforms for model validation, system optimization and licensing must be deferred until preliminary system selections are made. Suggestions made by participants have been captured and will be referenced as system design and development proceeds. In the near term, a review of supporting experimental capabilities will be performed across the DOE complex and university system to develop a database of facilities that could potentially support the development of integrated systems, including facility purpose, constraints, size, accessibility, etc.

Appendix A — Reference List for Nuclear Cogeneration Studies Performed at Idaho National Laboratory

Report Number	Title	Publication Date
TEV-666	Nuclear-Assisted Ammonia Production Analysis	9/16/2010
TEV-667	Nuclear-Assisted Methanol-to-Gasoline Production Analysis	2/18/2010
TEV-671	Nuclear-Assisted Synthetic Natural Gas Production Analysis	2/18/2010
TEV-672	Nuclear-Assisted Coal and Gas to Liquids Production Analysis	11/8/2011
TEV-674	Power Cycles for the Generation of Electricity from a Next Generation Nuclear Plant	2/18/2010
TEV-693	Nuclear-Assisted Hydrogen Production Analysis	2/18/2010
TEV-704	Nuclear Assisted Oil Sands Recovery via Steam-Assisted Gravity Drainage	11/8/2011
TEV-953	HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Process Analysis	1/18/2011
TEV-954	HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Economic Analysis	8/17/2010
TEV-961	Sensitivity of Hydrogen Production via Steam Methane Reforming to High Temperature Gas-Cooled Reactor Outlet Temperature Process Analysis	1/18/2011
TEV-962	Sensitivity of Hydrogen Production via Steam Methane Reforming (SMR) to High Temperature Gas Reactor (HTGR) Reactor Outlet Temperature (ROT) Economic Analysis	8/30/2010
TEV-981	An analysis of the Effect of Reactor Outlet Temperature of a High Temperature Reactor on Electric Power Generation, Hydrogen Production, and Process Heat	8/18/2010
TEV-988	Sensitivity of High Temperature Gas Reactor (HTGR) Heat and Power Production to Reactor outlet Temperature (ROT), Economic Analysis	1/4/2012
TEV-994	Hydrogen Production via HTSE, Sensitivity to HTGR Reactor Outlet Temperature, Economic Analysis	8/25/2010
TEV-1029	Integration of Nuclear Power and Production From an in Situ Oil Shale Operation	1/4/2012
TEV-1091	Integration of HTGRs and an EX Situ Oil Shale Retort	1/4/2012
TEV-1147	HTGR-Integrated Bitumen Upgrading Analysis	6/20/2011
TEV-1174	Evaluation of HTGR Heat Integration for Iron Production and the Manufacture of Metallurgical Coke	6/20/2011
TEV-1196	Assessment of High Temperature Gas Reactor (HTGR) Capital and Operating Cost	1/5/2012
TEV-1276	Economic Analysis of Integrating HTGRs to an in Situ Oil Shale Operation	6/2/2011
TEV-1302	Integration of HTGRs and Seawater Desalination	1/3/2012
TEV-1321	Integration of HTGRs to an Ex Situ Oil Shale Retort Operation, Economic Analysis	1/3/2012
TEV-1351	Integration of HTGRs to an Ex Situ Oil Shale Retort Operation, Economic Analysis	11/8/2011
TEV-1390	HTGR-Integrated Biomass to Liquids Production Analysis	10/12/2011

Appendix B — Attendee List

Affiliation	Full Name
ABEINSA	Nazare Adum
Abengoa Solar	Hank Price
ANL	Richard Vilim
Argonne National Laboratory	Hussein Khalil
Argonne National Laboratory	Vladmir Koritarov
Arizona Governor's Office of Energy Policy	Olivia Doherty
Arizona State Senate	Robert Worsley
AZ Corp Commission	Bob Burns
AZ Corp Commission	Edward Stoneburg
CAES.University of Idaho	Akira Tokuhiro
Chinese Academy of Sciences	Yuhan Sun
DOE-EERE	Steve Chalk
DOE-ID	Raymond Furstenau
DOE-ID	Jihad Aljayoushi
DOE-ID	John Yankeelov
DOE-ID	Rick Provencher
DOE-ID	Alan Gunn
DOE-ID Intern	Monica Kokoszmj
DOE-NE	Andrew Richards
DOE-NE	Pete Lyons
EPRI	Tina Taylor
First Energy Corp.	Greg Halnon
Fraser Energy Consulting LLC	KP Lau
INL	Carl Stoots
INL	David Petti
INL	James O'Brien
INL	Todd R. Allen
INL	Cristian Rabiti
INL	Paul Roege
INL	Philip C. Hildebrandt
INL	Marsha Jo Bala
INL	Michael McKellar
INL	Richard Boardman
INL	Shannon Bragg Sitton
INL	Humberto Garcia
INL	Robert Cherry
INL	Steve Aumeier
INL	Wes Deason
INL	Phillip Finck
INL	Rob Hovsapian

Affiliation	Full Name
INL	John Collins
INL	Aaron Wilson
MIT	Charles Forsberg
MIT	Michael Golay
NCSU	J. Michael Doster
NREL	Mark Ruth
NREL	Bryan Hannegan
NREL	Clayton Barrows
NREL	John Nangle
NREL	Owen Zinaman
Nuclear Energy	Carl Sink
NuScale Power, LLC	Jose Reyes
NuScale Power, LLC	Christopher Colbert
Office of Energy Development	Eugenie Alair Emory
Ohio State University	Carol Smidts
Ohio State University	Jinsuo Zhang
ORNL	David Holcomb
ORNL	Gary T. Mays
ORNL	T. Jay Harrison
ORNL	A, Lou Qualls
S.R. Martin Group LLC	Darcie Martinson
SANDIA	Sal Rodriquez
Southern Company Services	J. Nick Irvin
Terrapower	Joshua Walter
U.S. DOE-Idaho	Keith Lockie
University of New Mexico	Joseph McDaniel
University of Wyoming	Maohong Fan
University of Wyoming	Don Roth
Utah Ass. Municipal Power Systems	Douglas O. Hunter
Westinghouse Electric Co.	Robin Rickman
Westinghouse Electric Co.	Layla Sandell

Appendix C — Workshop Agenda

Integrated Nuclear-Renewable Energy Systems Foundational Workshop
Idaho National Laboratory, Energy Innovation Laboratory
July 8-10, 2014

Workshop Objectives

1. Refine priority opportunities for integrated nuclear-renewable energy systems in the U.S.
2. Select Figures of Merit (FOM) to rank and prioritize candidate systems
3. Discuss development needs for enabling technologies
4. Identify analysis capabilities and gaps to estimate FOM for integrated system options
5. Identify experimental capabilities available to develop and demonstrate nuclear-renewable energy systems

Attire: Business Casual. Tour participants: Please wear sturdy, comfortable shoes (closed toe).

Day 1: Tuesday Morning, July 8th, Center for Advanced Energy Studies

Time	Agenda Item	Moderator / Speaker
7:45 a.m.	Van arrives at Shilo to pick up tour participants needing transportation	
8:00 a.m.	Van departs for Center for Advanced Energy Studies (CAES)	
8:15 a.m.	Badging at CAES for tour participants	**Kristie Berezay**, INL
8:30 a.m.	Welcome Tour overview and logistics	**Richard Boardman**, INL **Shannon Bragg-Sitton**, INL
8:45 a.m.	INL Facility Tours* *Must be pre-registered for tours to participate.*	**Richard Boardman**, INL
12:15 p.m.	Working Lunch at Energy Innovation Laboratory (EIL) Meeting Center (for tour participants) Significance of Hydrogen and Synfuels	**Carl Stoots**, INL (Hydrogen)

***INL Facility Tours Agenda - Group will be divided for 8:45 to 9:45 a.m. timeframe**

8:45 Group 1 – Computer Assisted Virtual Environment (CAVE) Demonstration
Group 2 – Presentations in CAES Auditorium (INL, NREL, Chinese Academy of Sciences)
9:15 Group 1 – Presentations in CAES Auditorium (INL, NREL, Chinese Academy of Sciences)
Group 2 – CAVE Demonstration
9:45 Presentation in CAES Auditorium/Q&A
10:00 Walk to Energy Systems Laboratory (All Tour Participants)
10:15 ESL Tours (Process Deployment Unit Lab, Systems Integration Lab, Energy Storage Lab)
11:30 Walk to Energy Integration Laboratory (All Tour Participants)
11:45 EIL Tour (Human Factors Lab)
12:15 Convene in EIL Meeting Center for Working Lunch (All Tour Participants)

Day 1: Tuesday Afternoon, July 8th – Official Start of Workshop - Setting the Stage

Time	Agenda Item	Moderator / Speaker
12:30 p.m.	Van arrives at Shilo for participants needing transportation	
12:45 p.m.	Van departs from Shilo to Energy Innovation Laboratory	
1:00 p.m.	Badging and registration for workshop General note: Wireless visitor access will be arranged for all participants, including foreign nationals.	**Kristie Berezay**, INL
1:30 p.m.	Welcome and opening remarks Welcome from INL Welcome from NREL	**Shannon Bragg-Sitton**, INL **Todd Allen**, INL, Deputy Laboratory Director **Mark Ruth for Bryan Hannegan**, NREL, Associate Lab Director
1:45 p.m.	NE-RE Systems Overview – DOE Perspective	**Peter Lyons**, DOE-NE, Assistant Secretary of Energy (Nuclear Energy) **Steven Chalk**, DOE-EERE, Deputy Assistant Secretary (Energy Efficiency and Renewable Energy)
2:00 p.m.	Integrated energy systems overview and workshop purpose	**Shannon Bragg-Sitton**, INL
2:30 p.m.	Roadmapping overview	**John Collins**, INL
3:00 p.m.	Regional resources and considerations • Planning and Operation of Electric Power Systems (15 min)	**Clayton Barrows**, NREL
3:15 p.m.	Break	

3:30 p.m.	Regional resources and considerations (continued)
	• Energy storage options and limitations (20 min)
	• Siting and licensing challenges (25 min)
	  o Nuclear Subsystems
	  o Renewable Subsystems
		Charles Forsberg, MIT
		Gary Mays, ORNL
		Scott Morley, Morley Companies, LLC

4:15 p.m.	Proposed Figures of Merit (FOM) for system alternatives	**Richard Boardman**, INL **Owen Zinaman**, NREL
4:45 p.m.	Integrated energy system alternatives for consideration	**Mark Ruth**, NREL
5:15 p.m.	Recap of day and overview of Wednesday discussions	**Shannon Bragg-Sitton**, INL
5:30 p.m.	Appetizer reception (Center for Advanced Energy Studies Gallery)	
6:30 p.m.	Adjourn / Van returns participants to Shilo	

Day 2: Wednesday, July 9th – Discussions and Decisions – Refining the Options

Time	Agenda Item	
7:40 a.m.	Van departs from Shilo to Energy Innovation Laboratory	
8:00 a.m.	Welcome and review of agenda	**Shannon Bragg-Sitton**, INL
8:10 a.m.	Industry Roundtable Discussion • System requirements and preferences from an industry perspective *Panelists consist of members of the industry attending the workshop, including all aspects of an integrated system – nuclear, renewable, chemical, grid, etc.*	Moderator, **Richard Boardman**, INL
9:45 a.m.	Break	
10:00 a.m.	Siting and licensing discussion • Identification of challenges: nuclear siting regulations (including co-location), resource availability, market availability, etc.	Moderator, **Owen Zinaman**, NREL
10:45 a.m.	Figures of Merit detailed discussion • Introduction to online FOM form • Review goals and grand challenges • Review, refine and quantify proposed FOM *Purpose: FOM resulting from workshop will be used to develop and weight specific criteria for ranking and prioritizing candidate systems.*	Moderator, **Darcie Martinson**, INL
12:00 p.m.	Working Lunch NREL Perspectives State interests in integrated systems International interests in integrated systems	 **Bryan Hannegan**, NREL Moderator, **Richard Boardman**, INL Arizona Utah Wyoming Chinese Academy of Sciences
1:15 p.m.	Prioritize Figures of Merit – Complete online form	
2:00 p.m.	Discussion of proposed regional system alternatives for further analysis ("Gallery Walk")	Moderator, **Darcie Martinson**, INL
3:45 p.m.	Break	
4:15 p.m.	Selection of priority regional concepts for initial evaluation	Moderator, **Shannon Bragg-Sitton**, INL
5:15 p.m.	Recap of day and overview of Thursday discussions	**Shannon Bragg-Sitton**, INL
5:30 p.m.	Adjourn / Van returns participants to Shilo	

Day 3: Thursday, July 10th – Capabilities Discussion and Path Forward

Time	Agenda Item	Responsibility
7:40 a.m.	Van departs from Shilo to Energy Innovation Laboratory	
8:00 a.m.	Welcome and review of agenda	**Richard Boardman**, INL
8:10 a.m.	Prioritization of regional opportunities – complete online form	
8:30 a.m.	Identification of tools necessary to quantify Figures of Merit *What simulations or experiments are necessary to estimate and begin to quantify each FOM for each system, component, etc.?*	Moderators, **Mark Ruth**, NREL, and **Shannon Bragg-Sitton**, INL
10:00 a.m.	Break	
10:15 a.m.	Detailed discussion of technology development roadmap and path forward	**John Collins**, INL

11:30 a.m.	System development for capabilities identification
	• Modeling/simulation capabilities and requirements
	  ○ Analysis Capabilities - static, dynamic, gaps, issues
	• Experimental capabilities and requirements
	  ○ What is available? What gaps exist?
	• Define the role of government, industry and academia
		Moderators, **Mark Ruth**, NREL, and **Shannon Bragg-Sitton**, INL

12:45 p.m.	Closing remarks and review of actions	**Shannon Bragg-Sitton**, INL
1:00 p.m.	Adjourn / Van returns participants to Shilo (or airport if necessary)	

Appendix D — Introductory Presentations

See separate file attachment.

Appendix E — Summary of Detailed Comments on Figures of Merit

Environmental FOM

FOM	Unit	Notes
Climate Emissions Abatement	[MT CO_2eq/yr]	Abatement may occur in various sectors • Single Plant • State or Regional
Other Air Emission Abatement • SOx, NOx, Hg • Particulate Matter, Criteria Pollutants, HAPS	[MT/yr]	Abatement may occur in various sectors • Single Plant • Ambient air pollution standards

Water Impacts
• Water Consumption
• Impact of Withdrawals
• Water Quality
  • Impact on Ecosystems
  • Impact on Geological Disposition
	[Gal/yr] consumption
	
	Qualitative Impacts
		Water impacts are highly regional;

Land Use Requirements	Acres	Total Area
Land Use Withdrawals or Visual Aesthetics	Qualitative Impacts	Reclamation or long-term stewardship
Stewardship of Resources • Limited fossil resources • Rare earths	Years to depletion	Recycle may be possible
Waste Disposal	Tons & ft^3	Depends upon disposal site availability
Net Return on Energy	%	
Impact on Human Life	Deaths / MMppl	Should also include mortality statistics and quality of life indicators
Other Ecological Impacts	Qualitative	

Notes based on workshop input:

- The measure for greenhouse gases is the sum of all GHG adjusted to the equivalent amount of CO_2 absorbing ultra-violet (UV) radiation in the atmosphere. Net (CO_2-eq)/yr should be quantified by a "Life-Cycle Analysis". The GHG reduction benefits should be computed for a single plant as well as the market potential for multiple integrated plants in a given region. The cost of GHG avoided for the hybrid operations versus BAU is another useful measure for evaluating cost/benefits of alternatives, and this should be included with the financial FOM.
- Clean Air Act regulations apply to both; a) substantive emissions rates and b) ambient concentration levels. Clean Air Act Section 111 (b) and (d) for new power generation and collective emissions in a State or region may drive NE-RE integration with industry users.
- Water withdrawal from the ecosystems is becoming increasingly important, especially in consideration of the impact of severe weather patterns and atmospheric temperature excursions that affect the available surface water at a given location. In arid regions where surface waters are practically nonexistent or where ground water withdrawals are rapidly aquifers, zero-water withdrawal may become a go/no-go requirement.
- Land Use Requirements should include the impact on local and regional populations. Considerations need to include essential, as well as publically acceptable "exclusion zones" around nuclear plants
- Waste disposal is a significant issue for public acceptance of nuclear energy. The lack of a permanent repository for nuclear waste has resulted in a moratorium on new nuclear power plants in California. Waste disposal of coal-ash and secondary products should also be considered. For example, some

processes currently burn carbonaceous by-products to produce heat. Hog fuel and petroleum coke are a couple of examples. Termination of combustion practices for cleaner air emissions may result in land impacts for the disposal of orphan wastes.

- Net Return on Energy quantifies the effective conservation and use of the total energy utilized in a given system.
- Impact on Human Life can be quantified by probability risk assessments, expectancy actuaries correlated to environmental and living conditions, and social standards for heating, lighting, and comfort.
- Other ecological Impacts may include impact on species diversity, species endangerment. These impacts are generally considered in a general Environmental Impact Statement (Study), which considers the cost-benefit of alternative, including no action or change.

Finance FOM

FOM	Unit	Notes
Project Finance Indicators		
• Net Present Value / IRR / ROI	%	Investment proforma
• Profitability Index	PI	Profitability normalized to non-integrated system
• Capital investment	$ CAPEX	Total capital investment
• Fixed operating costs	$ O&M	Predictable operating and maintenance costs
• Variability of cost certainty	$ OPEX range	Analysis of profit sensitivity on variable manufacturing costs uncertainty
• Revenue streams		
• Electricity	COE	Cost of Electricity
• Total system product revenue	$/yr	Cash flow profile
Design, Development, and Construction Risk		
• Period for permitting, construction, and start-up	Years	Affects ability to finance and cost thereof.
• First-of-kind plant versus nth-of-a-kind	P_C	Probability of investment and/or financial risk sharing
Performance at name-plate capacity	%	Capacity factor for system versus weighted average of individual plants
Viability of Business Model		
• Barriers to market entry	P_R	Probability of risk from competition
• Probability of continuing success	P_M	Probability of profitability based on analysis of market forecast
• Product elasticity	% / %	Relationship between price and demand
Sustainability of Business Case		
• Design adaptability	$	Cost of plant modification
• Longevity of plant operations	Years	Operation of plant beyond standard design life or capital payback

Notes based on workshop input:

- Profitability index is a measure of the ratio of any investment pro forma indicator for an integrated system versus a non-integrated system
- A tornado diagram can be constructed to visualize the financial risk of all project financial indicators
- Construction period to start-up is a subjective parameter which generally favors projects with the duration to achieve a positive cash flow
- First-of-a-kind plants that involve multiple technologies or cost-sharing require a "Wrap" on financing, meaning risk-sharing between all parties who stand to profit from plant design, construction, operations, ownership, and investment
- An important objective of integrated energy systems is maximizing utilization of capital assets
- Business viability requires an evaluation of macroeconomics relative to market competition. Probability indices are generated relative to options and market project forecasts. The probability of manufacturing cost certainty is captured in probability indices.
- Product elasticity is a measure of market share, and ability to perform in a competitive market
- Business sustainability captures the cost to adapt to changes in feedstock costs and products or service preferences.
- Plant longevity factors into investment decisions relative to profit certainty beyond the period of capital pay-down.

Design Criteria FOM

FOM	Unit	Notes
Technical Feasibility	go/no go	Meets functional and operational requirements
Technology Commercial Readiness Level	Index No. (years)	Uniform measure of unit operations commercial readiness Years to commercial operations
System Integration and Deployability Readiness	Index No. (years)	Uniform measure of interface connections operability and readiness
System-Wide Efficiency	%	Conversion of natural resources to energy products
Grid Reliability Impact	ΔR_F	Change in grid reliability factor
Licensing Certainty • NRC • Safety	 Years P_S	 Permit authority basis Probability risk assessment index
Grid Flexibility Services • Ramp rates • Turndown Range • Capacity	 %/min % of max MW	 Power dispatch potential and power quality control
Operability • Start-up and shutdown • Human-machine factors • Process control autonomy	 hours No. Operators Yes/No	 Capable of black-start recovery Isolated system control
Construction Flexibility • Scale of governing processes • Ease of field assembly • Staged or phased plant build-out capability	 MW $ Yes/No	 Incremental size Equipment and labor On-site versus field assembly
Manufacturing & Materials Supply • Equipment availability • Availability of materials of construction	 weeks Resource security Index	 Purchase delivery time Domestic or import of metals or materials
Design Resiliency • Upset incident recovery • Adaptability to market changes	 min. Capital recover factor	Vulnerability to extreme climate events and/or unexpected cyber manipulation Ability to address "black swans" (unforeseen events) Natural gas pricing

Notes based on workshop input:

- Design criteria FOM were sorted and modified to establish a definitive list consistent with typical "Front End Engineering Design" of commercial plants. Technical Feasibility is a "go/no-go" requirement based on Technology Readiness Levels. Functional and Operating Requirements (F&ORs) can be established to meet reliability requirements set by regulations and/or system stability requirements.
- Systems integration readiness requires modeling and simulation verification based on real world operations of appropriate scale interface equipment.
- Whereas a goal of integrated energy systems integration is to improve energy reliability, the load-dynamic benefits of systems hybridization need to be quantified. This must be accomplished by establishing realistic human and supervisory control capabilities for the system.

- Plant construction consideration must be based on equipment manufacturer data sheets.
- Mature equipment supply chains are needed to bring down costs for NOAK plants. Thus, comparative indicators for materials availability and domestic manufacturing and delivery systems must be quantified.

Government Policy Objectives FOM

FOM	Unit	Notes
National Economy	GDP	Captures jobs created, manufacturing industry support, and export potential
National Security Benefits		
• Energy independence	BOE /year	Import Barrels of Oil Equivalent reduced
• Energy diversity	R_F	Overall system reliability factor
• Resource supply diversity	Years	Resource supply projection based on domestic natural resources
National Strategic Importance		
• Replacing / maintaining aging electricity infrastructure	$ and Years	Transformation period and cost of new system
• Resiliency of energy system	CI	Capital conversion / repurposing index
Domestic Energy Contingency Planning	P_D	Supply disruption probability
Industrial Development Zones of Clean Energy Hubs		
• Renewable energy penetration	MW	Total deployment at regional capacity
• Clean energy supply for zero-emissions vehicles & industrial manufacturing	MW	Reduction of fossil fuel combustion emissions.
Federal-State-Industrial Consortium Potential	$	Total State or Federal cost sharing potential
International Impact		
• Environmental sustainability leadership	ppm CO_2	Stabilize and sustain atmospheric CO2 concentrations.
• Cost of energy in OEDC	$/MW	Cost of energy for developing countries

Notes based on workshop input:

- However important government policy objectives are to quantify, they may provide the most important FOM when addressing society values that are not necessarily captured in discounted cash flow model. Workshop participants provided useful input on policy metrics that address some of the respective overarching goals of energy systems integration.
- Key among government responsibilities is maintaining robust domestic production of goods and services leading to high employment rates.
- National security benefits can be tied to energy independence- measured as the reduction of energy imported from foreign countries. An overall energy diversity index can account for dependence on a mix of energy supply and conversion process.
- Replacement of the currently aging energy infrastructure will require a gradual transition to spread costs over a reasonable time frame. Energy systems integration options that help convert one system to another have considerable merit.
- Energy infrastructure that is resilient to market changes and extreme events required a new index for capital adaptability and security against extreme conditions in weather and cyber or physical attack.

- Development of clean energy technology requires national goals to reduce GHG emissions by all of the global commons. Therefore energy systems that can be exported to developing countries as well as other industrialized countries are important FOM.

Appendix F —List of System Options Provided by Participants

Renewable Resource	Industrial Processes	Storage and Interface Technologies	Location (regional or specific)	Scale envisioned	Additional details to describe the configuration you have designed
On-shore wind, Off-shore wind, Concentrating solar power , Solar PV	District heating, Desalination, this depends on temperature that is available for processes	Pumped hydro, Battery storage, Compressed air storage, Steam accumulators	1) again the location should foremost be where a demonstration can be realized in the near-term.	1) again, ideally from 1/32nd to 1/2-scale	1) again, I would go with what past, present and future (near-term) configurations that defines our knowledge base
On-shore wind, Off-shore wind, Concentrating solar power , energy storage	District heating, Desalination, this dependa on temperature required for processing	Pumped hydro, Battery storage, Compressed air storage, Liquid thermal storage (e.g. molten salt), Steam accumulators	1) in order to go forward the location should be where we can demonstrate a system 2) AZ, CA are perhaps front-running candidates	1) scaling has not been discussed much and each scale is a data point. 2) I think the guiding principle is to have it 1/32, 1/16th, 1/8th, 1/4 and possibly 1/2-scale. Scaling on what metric (thermal, electrical output or multiple parameters) needs to be studied.	1) a clearinghouse on what past, present and near-term demonstrations will define our experiential/knowledge base might be of paramount importance. 2) what configuration has been design may not be so important if it is only on paper
On-shore wind	Biofuel production, Copper smelting, Remote mining processes	Battery storage	Alaska's Seward peninsula and Yukon Kuskokwim delta possess vast reserves of gold and copper. Those considering remote mines in these areas will need power for refining purposes and sustainability of "man-camps". This area also contains good to superb wind resources according to NREL. In addition, mining requires heavy machinery, such as bulldozers and excavtors, that could benefit from using biomass to produce synthetic fuels.		
Concentrating solar power	Liquefaction of LNG for export	Liquid thermal storage (e.g. molten salt)	Anywhere where fracking produces an abundance of natural gas - PA Markets are worldwide.	Start smal with 50 MW	
On-shore wind, Solar PV	Copper smelting, Hydrogen + CO2 to syngas and products	Hydrogen via high temperature electrolysis, Liquid thermal storage (e.g.	Arizona	600MWe	

		molten salt)			
Concentrating solar power , PV	Desalination	Liquid thermal storage (e.g. molten salt)	Arizona	Replacement of coal and ng plants for a utility APS system - 3GW winter peak, 6 GW summer peak, 1-2 GW daily cycle	Assume 2 GW PV Assume 2 GW CSP (adjust to needs) Assume 4 GW nuclear (or adjust up to needs) Assume desal to meet all local water needs.
Concentrating solar power	Hydrogen + CO2 to syngas and products	Hydrogen via high temperature electrolysis	Arizona. Plenty of solar potential, requirement to change power production portfolio and markets, relatively close to big consumer (Phoenix, California).	SMR	SMR provides low T heat and electricity. Concentrated solar provides high T heat. Thermal storage should be considered as well. High T electrolysis produces H2 to be piped.
Concentrating solar power , Solar PV	Desalination	Battery storage, Hydrogen via high temperature electrolysis, Liquid thermal storage (e.g. molten salt)	Arizona. Population density that is increasing. CSP capacity to demonstrate thermal energy storage and dynamic use. Need for Potable water and irrigation water. State engagement and positive regard to improve the environment. New nuclear capacity [possibly] available. Have existing NGCC where the chemical integration of hydrogen or desalination can begin immediately while waiting for NRC authority to add to Palo Verde or new reactors. This is a good	1. In AZ. State with a 50 MWt demonstration. This is a good scale to demo hydrogen, heat exchanger designs, control valves, etc. This will help keep costs of the demo to a fundable level.	

			example for other nations like Africa where there are high energy needs now, and increasing in the future. Work with Arizona Public Services. This case could include a fuel cell to produce electricity. Maybe hydrogen storage. The fuel cell would be just a reverse SOEC. Therefore, this case will also study how the SOEC/fuel cell will provide restive load to test how this can inherently manage power quality/frequency dynamics in concert with PV additions in Phoenix.		
On-shore wind, Solar PV	Desalination	Compressed air storage, Hydrogen via high temperature electrolysis, Liquid thermal storage (e.g. molten salt)	California	500-1000 Mwt SMR	
Concentrating solar power	Desalination	Battery storage	California for water needs		
On-shore wind, Geothermal heat	Natural gas to liquid fuels, Coal to synfuels	Battery storage, Liquid thermal storage (e.g. molten salt)	Central (Midwest) US	Sufficient to offset some fraction of US oil imports used for transportation	The midwest has wind and geothermal, as well as natural gas. This area also has a large amount of transportation infrastructure to distribute the fuels generated.
Off-shore wind, Tidal power	Desalination	Pumped hydro	coastal areas	I think this could accommodate any scale	look for opportunity to integrate with water management needs (i.e., control flooding, provide water storage

					capabilities as well.
On-shore wind, Off-shore wind, Tidal power	District heating, Natural gas to ethylene, Biofuel production, Liquefaction of LNG for export, Hydrogen + CO2 to syngas and products	Battery storage, Compressed air storage, Hydrogen via high temperature electrolysis, Hydrogen via high temperature thermochemical production, Steam accumulators	Coastal Massachusetts - support of green initiatives, available wind and tidal	One or more "nuclear islands" with 4 or more HTGRs (300Mwe+ per reactor)	This one reflects least background knowledge.
On-shore wind	Shale oil recovery	Variable oil shale heating	Colorado, Utah, Wyoming. Only locations of major oil shale resources	Likely fleet of tens of reactors--could be SMR or larger. With SMRs economics of scale. Up to 100 GWt if want to replace other sources of oil.	Reactor steady state. At times of high electricity demand steam to turbine with electricity to the grid. At times of low electricity demand, steam heating of oil shale in closed loop steam lines. Must heat oil shale to 370C for oil production. LWR to 240C. Added heat provided by electricity from grid at times of low electricity prices. Capabilities: Remove all variable fossil electricity production from western grid by providing dispatchable nuclear electricity in system with baseload reactor operations.. Lowest greenhouse gas emissions per liter of gasoline or diesel of any fossil fuel option
Concentrating solar power, Solar PV	Desalination	Liquid thermal storage (e.g. molten salt)	Desert southwest	The desalination needs will set the size of the plant; however, I believe a 50-200 MWth nuclear	The problem with this case is that water does not really have a market; hence, the value of water is set arbitrarily and is low. That low value will lead to a process that is unlikely to meet

				facility is probably appropriate.	financial requirements.
On-shore wind, Off-shore wind, PV		Pumped hydro, Compressed air storage, Hydrogen via high temperature electrolysis, Liquid thermal storage (e.g. molten salt)	East Coast	Regional power supply	Can Nuclear, PV, wind, be used to replace fossil fuel on a region basis by adding storage.
On-shore wind, Off-shore wind, Tidal power, Solar PV, Chicken manure	Natural gas to liquid fuels, Biofuel production, Ammonia / fertilizer production, Liquefaction of LNG for export, Liquid nitrogen production, Hydrogen + CO2 to syngas and products	Battery storage, Compressed air storage, Hydrogen via high temperature electrolysis, Hydrogen via high temperature thermochemical production	East Coast (NJ, Del., MD) - available resources, markets	NuScale 12 pack.	Development of poultry waste processing is known to be problematic, from a corporate acceptance POV as well as technical maturity.
Off-shore wind	Liquefaction of LNG for export	Pumped hydro	eastern shores / pumped storage more inland		
On-shore wind	Desalination	Liquid thermal storage (e.g. molten salt)	Either coast as location Strong market for water in CA and AZ	Start with 50 MW	
On-shore wind	Ammonia / fertilizer production	Hydrogen via high temperature electrolysis	Farming areas of the midwest.	Scale will be set by hydrogen requirements for ammonia / fertilizer plant.	The best way to design this plant might be to be a fertilizer plant for 49 weeks out of the year and provide capacity value to the grid for the other 3 (instead of trying to run both and ramp)
Off-shore wind	Oil refining	Hydrogen via high temperature electrolysis	Gulf coast	Flexible - should use an existing refinery	We have considered a 250k bbl/ day refinery - but increments of 25 k fit with reactor size
On-shore wind	Natural gas to ethylene, Chlorine production	Battery storage, Hydrogen via high temperature electrolysis, Steam accumulators,	Gulf Coast -- industries requiring co-generated energy;	Typical large petrochemical process plants require on the order of 3 to 4 GW thermal total energy, split 60/40 power/steam. This includes n-1 or n-2 reliability to match the availability requirements of the process plant (approaching 100%) and the nuclear	

		hydrogen via nuclear heated steam methane reforming		heat source (e.g., 92%). The example is based on multiple units of 600 MWt reactor rating).	
Off-shore wind	Oil refining, Liquefaction of LNG for export	Hydrogen via high temperature electrolysis, Liquid thermal storage (e.g. molten salt)	Gulf Coast Area Besides chem companies and oil refineries - there are a number of DoD bases "clustered" together in a relatively small region with power and energy needs.	800 - 1000 MWe	Envision more dispersed system as opposed to directly collocated.
PV	Desalination	Pumped hydro, Battery storage	Gulf Coast because of the ease to site nuclear and proximity to chemical industry. Southern California for use of intermittent PV solar. Both locations could use more water long term.		
Concentrating solar power	Liquefaction of LNG for export	Battery storage	Gulf coast for future LNG export		
Off-shore wind, Geothermal heat	Oil refining, Biofuel production	Hydrogen via high temperature electrolysis, Hydrogen via high temperature thermochemical production, Liquid thermal storage (e.g. molten salt), Steam accumulators	Gulf coast US	Sufficient to supplement or offset some fraction of the existing domestic refining capacity	The gulf coast has geothermal and offshore wind and oil, as well as local refineries. This case would examine the augmentation of the US hydrocarbon fuel production industry.
Off-shore wind, Geothermal heat	Oil refining, Biofuel production	Hydrogen via high temperature thermochemical production, Liquid thermal storage (e.g. molten salt)	Gulf Coast US	Sufficient to offset some fraction of US imports used for transportation	The Gulf Coast has geothermal and offshore wind resources, as well as offshore oil resources. Final note: National Laboratory affiliation
On-shore wind	Oil refining, Biofuel production, Ammonia / fertilizer production, Direct iron reduction	Hydrogen via high temperature thermochemical production, Undergroun hydrogen storage	High Plains with best wind conditions.	20 GW (full capacity for large long distance hydrogen pipeline)	Wind plus nuclear for hydrogen and local electricity. Hydrogen to long distance industrial markets.
On-shore wind	Natural gas to ethylene	Steam accumulators	Midwest (Indiana or Ohio). Why?-	<200 MWt in Ohio, Michigan or Indiana as a demonstration scale. This	

			They have the greatest potential for growth, NG, electrical needs, and nuclear plants that are being shut down. This is a good opportunity to repurpose. Also there is a lot of wind here which would demonstrated the potential growth. Work with First Energy and others. This is the heartland. The product choices and flexibility are large; therefore, selecting the chemical product can be flexible- or even competitive. There is a also a source of coal and biomass in this single region. Therefore- a NE-RE test park could be a national test-bed. Also, this region could demonstrate this concept for a coal plant that is impacted by increasing wind. This case is a demonstration for a higher temperature reactor. The chemical demonstration can be done with a coal plant, thus giving design information for the H.T. Reactor. This scale can also include a grid connection - or RTDS with data feed from NREL.	is about the smallest synfuels plant that can be dimensionally scalable for a commercial plant. The risk is in the synthesis/catalysis reactors. Demonstration at this scale will greatly enable a commercial pathway.

			This scale will accommodate a small steam turbine that could be run dynamically to study ramp rates, etc.	

Appendix G —Roadmapping Process

The proposed integration of nuclear energy, renewable energy, and industrial processes poses multiple challenges and potentially complex, parallel development paths. Solving complex problems of this nature requires systematic management of technical risk, rigorous decision-making around the most promising technologies, and focusing of the collective knowledge and imagination of the brightest leaders in the field. A technology development roadmap is a tool to help accomplish these functions.

A roadmap is an action-oriented timeline that outlines a disciplined process for identifying the necessary activities and schedules associated with solving complex problems and managing technical risk. The roadmap is multi-year and multi-variable and will facilitate and inform sound decision-making. Highlights appearing in a roadmap include:

- selection of the most promising technologies;
- identification of key obstacles; and
- selection of the most efficient path through the issues and alternatives to achieve the desired end.

The roadmap serves to align technology maturation with design readiness to ensure that design does not proceed ahead of technology readiness (as depicted in Figure G.1), thereby introducing risk of project delay and cost overruns due to implementation of technologies that have not been sufficiently demonstrated.

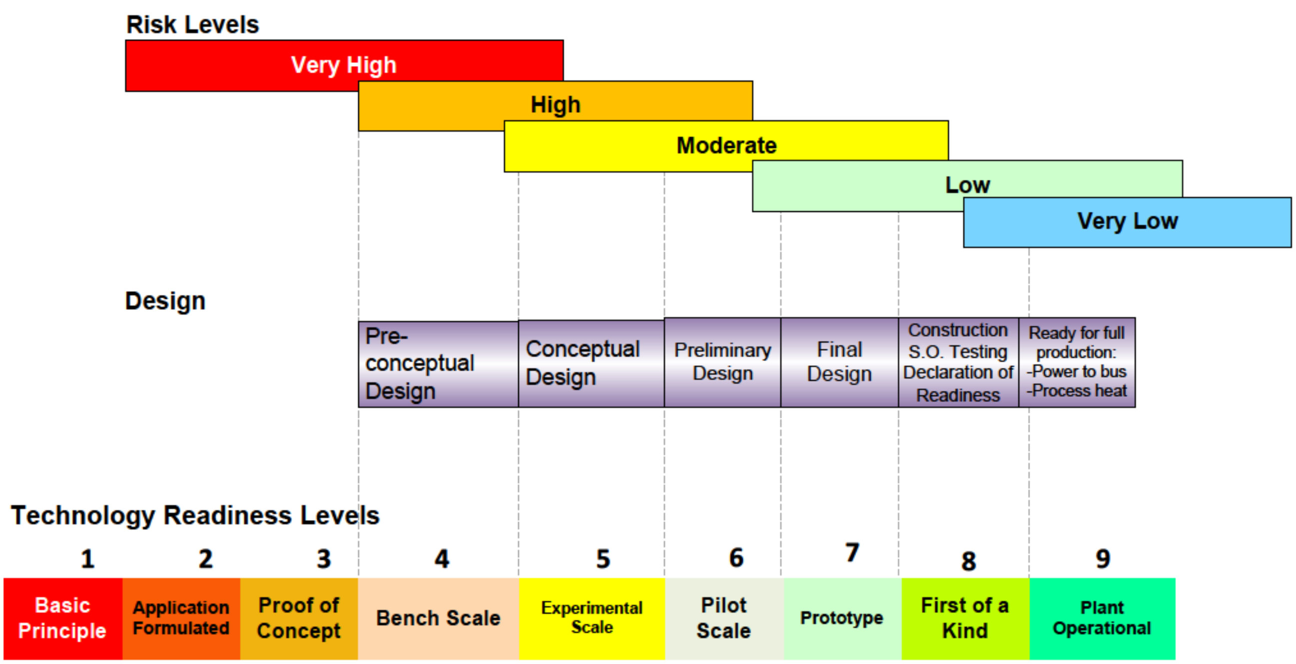

Figure G.1. Technology Alignment with Design Readiness Serves to Reduce Risk.

The integrated NE-RE roadmap will divide the project into four phases:

(I) Feasibility assessment and options study;

(II) Component and subsystem testing and system refinement;

(III) Detailed engineering design for prototype; and

(IV) Prototype construction and testing.

It is anticipated that the first two phases will be conducted via DOE leadership, in coordination and collaboration with industry partners, whereas the last two phases are expected to transition leadership to industry partners.

G.1 Phase I: Feasibility Assessment and Options Study

Phase I (depicted in block diagram format in Figure G.2) begins with identification of a number of regional opportunities for integrated energy systems, drawing on various energy supply and demand resources, which could provide economic and operational benefits. Concept definition and refinement will be performed by a team with representatives from national laboratories, universities, government, and industry. These regional energy resources and their interactions will be used to create a set of regional cases for feasibility analysis. Feasibility analyses will consider technical maturity of required technologies, an assessment against figures of merit, and steady state operability. The regional cases will be prioritized and those showing the most promise will be selected for detailed analysis and assessment. Detailed assessment will consist of:

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

Based on this detailed analysis, the concept viability will be assessed and industrial support verified. Some concepts may be eliminated, and others modified to obtain a prioritized set of regional cases for which a more detailed program of research and development (R&D) roadmap will be prepared.

G.2 Phase II: Component and Subsystem Testing and System Refinement

Activities in Phase II (depicted in Figure G.3) will further refine and optimize the selected regional cases through a series of component and subsystem tests to provide model validation data, address the technical gaps and mature the concept viability. To prepare the refined concept for detailed prototype design, further system analysis will be necessary, including design optimization for enhanced operational resilience; integrated control system design, optimization and dynamic simulation; and conceptual design development.

G.3 Phases III and IV: Prototype Engineering Design, Construction and Testing

It is anticipated that the final R&D phases will be performed under industry leadership to develop a detailed prototype design (Phase III) and to construct and test the prototype (Phase IV).

The integrated NE-RE roadmap will frame the problem to be addressed and enumerate the necessary tasks within each of the four development phases. This roadmap framework applies the current state of energy supply and delivery in the U.S. (and current trends) as a baseline condition and establishes the desired future state. The grand challenge in achieving the desired future state is articulated along with the unique approach that will be used to overcome the challenges. Once developed, the roadmap will feature the tasks (e.g. modeling, R&D, demonstrations) and decision points (e.g. down-selection of technology options, policy decisions, viability determinations) defined for energy systems development.

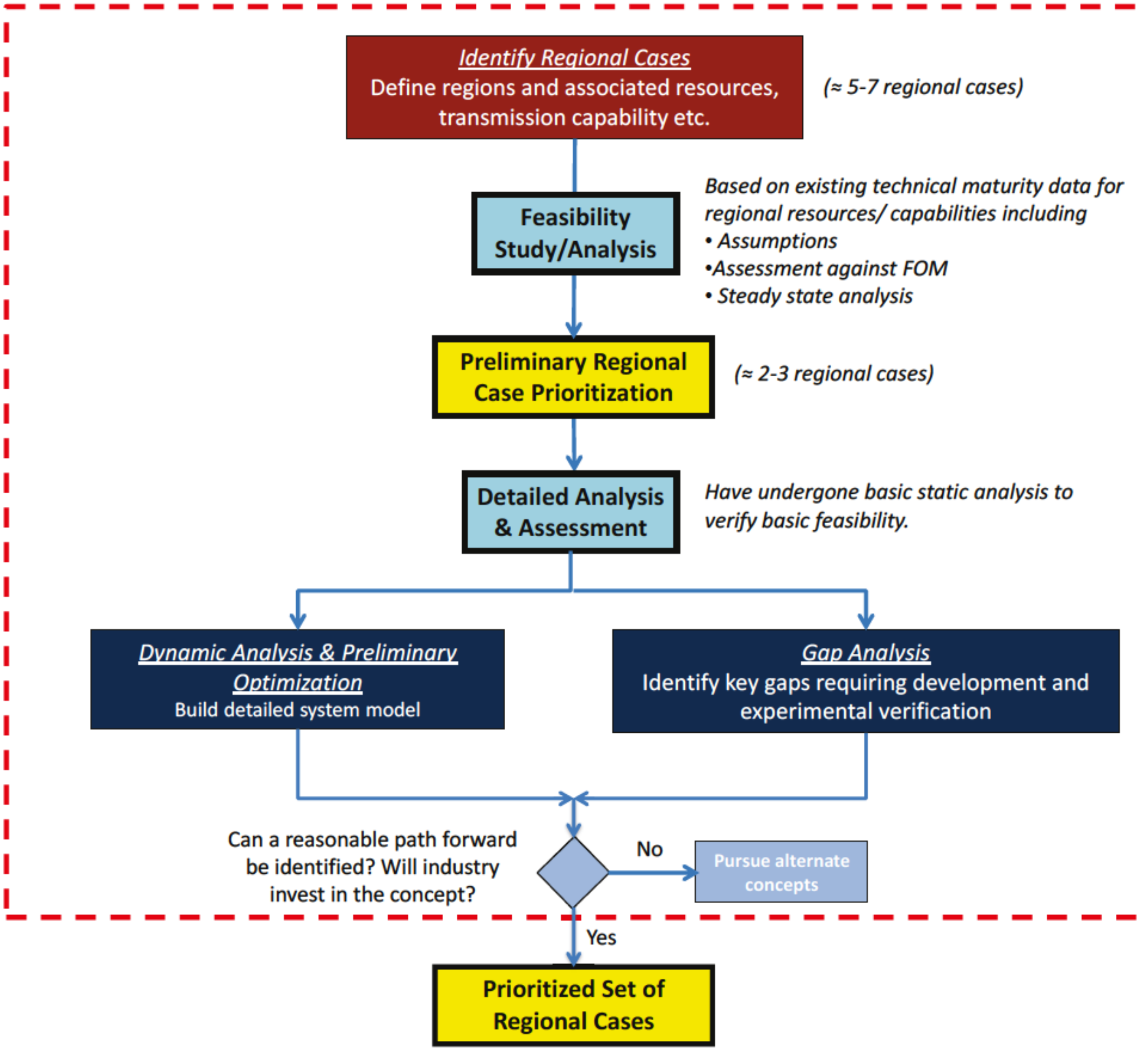

Figure G.2. Phase I: Feasibility Assessment and Options Study.

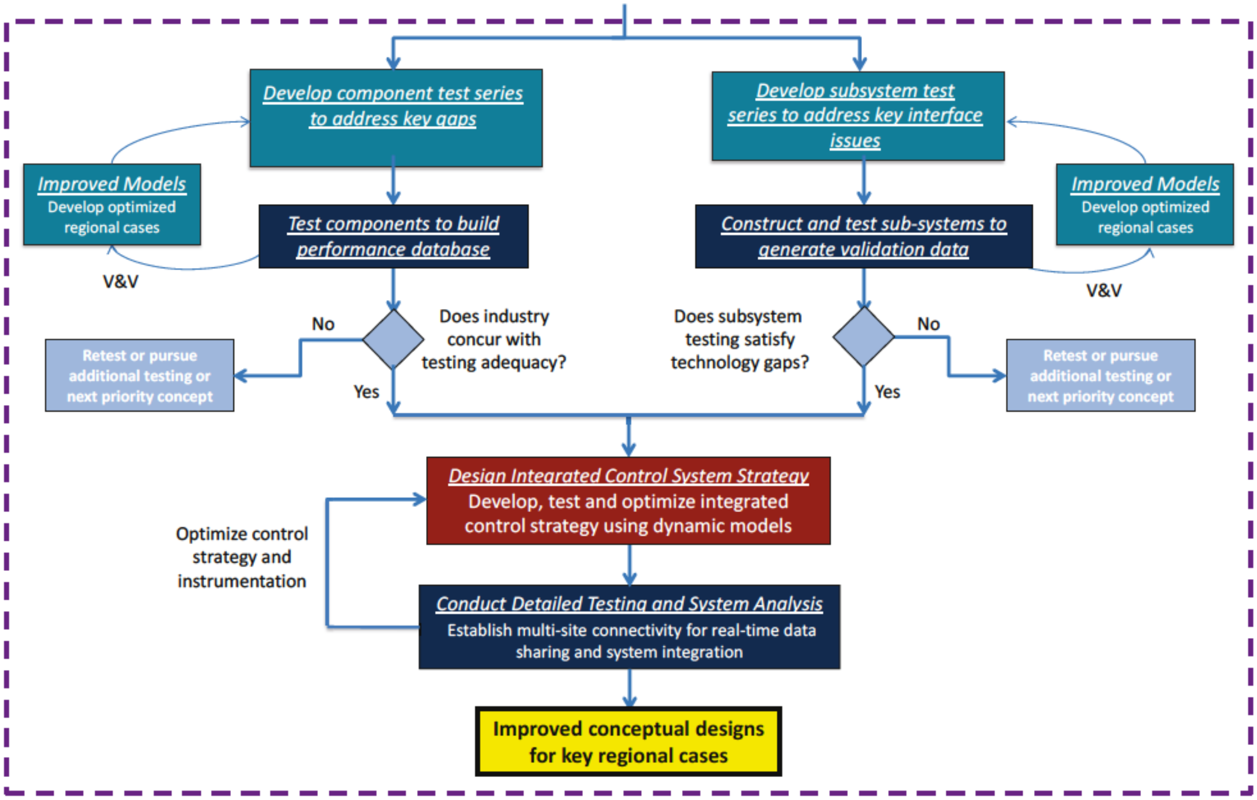

Figure G.3. Phase II: Component and Subsystem Testing, System Refinement. Note that V&V refers to validation and verification of models and simulations.