Rethinking the Future Grid: Integrated Nuclear Renewable Energy Systems

Preprint

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Presented at the 9th Nuclear Plants Current Issues Symposium: Moving Forward
Charlotte, North Carolina
December 7–10, 2014

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Conference Paper
NREL/CP-6A20-63207
January 2015

Contract No. DE-AC36-08GO28308

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RETHINKING THE FUTURE GRID: INTEGRATED NUCLEAR-RENEWABLE ENERGY SYSTEMS

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ABSTRACT

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 [1]. 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." The U.S. Department of Energy (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. To meet the stated environmental goals for electricity generation and for the broader energy sector, there is a need to transform the energy infrastructure of the U.S. and elsewhere. New energy systems must be capable of significantly reducing environmental impacts in an efficient and economically viable manner while utilizing both hydrocarbon resources and clean energy generation sources.

The U.S. DOE is supporting research and development that could lead to more efficient utilization of clean energy generation sources, including renewable and nuclear options, to meet both grid demand and thermal energy needs in the industrial sector. One concept under consideration by the DOE-NE and DOE-EERE is tighter coupling of nuclear and renewable energy sources in a manner that better optimizes energy use for the combined electricity, industrial manufacturing, and transportation sectors. This integration concept has been referred to as a "hybrid system" that is capable of apportioning thermal and electrical energy to first meet the grid demand (with appropriate power conversion systems), then utilizing excess thermal and, in some cases, electrical energy to drive a process that results in an additional product.

For the purposes of the present work, the hybrid system would integrate two or more energy resources to generate two or more products, one of which must be an energy commodity, such as electricity or transportation fuel [2]. Subsystems would be integrated ''behind'' the electrical transmission bus. Energy flows within the system would be dynamically apportioned as necessary to meet grid demand via a single, highly responsive connection to the grid that provides dispatchable electricity while capital-intensive generation assets operate at full capacity. Candidate region-specific hybrid energy systems selected for further study, and figures of merit that will be used to assess system performance, will be presented.

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1. 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 renewable output and/or low demand, reduced baseload generation market size and associated baseload generator power reductions (e.g. load-following operation). Additionally, most current markets do not reward clean baseload power for its positive environmental attributes. 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 many baseload energy suppliers. Likewise, intermittent renewable generation suffers from the same low or negative electricity prices at high penetrations as conventional generators.

Growth of renewable and natural gas generation in some deregulated markets is contributing to the premature closure of nuclear plants, particularly in concert with the current low cost of natural gas in the United States (e.g. the Kewaunee nuclear power plant in Wisconsin was shut down in mid-2013 due to unfavorable economics in light of low natural gas prices [3]). Deregulated markets require all generation sources to compete to sell electric energy and services to meet grid demand. In some scenarios, nuclear technologies are more expensive than natural gas and renewable generation (once all subsidies are included); thus, they often cannot compete directly. 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 and throughout the construction of a new nuclear plant. However, clean baseload generators are also challenged in regulated markets where, in some cases, natural gas is being selected over new nuclear units due to the current low cost of natural gas. Despite this challenge, some utilities are proceeding to build new nuclear capacity as a hedge against volatile natural gas prices. New developments in nuclear technology, including small modular reactors, are also providing renewed attention toward nuclear generation, which could spur the development of novel hybrid energy systems.

To significantly impact GHG emissions, one must look at changes beyond the electricity sector – the carbon footprint of non-electric energy sectors (industry, commercial, residential, and transportation) must also be reduced for the U.S. to meet long-term emission goals. Many zero-carbon technology options are resource limited (e.g. wind, solar); thus, a portfolio with a variety of options is needed. Integrated nuclear – renewable energy production technologies would provide additional options for thermal, electrical, and/or chemical energy to meet industrial and transportation sector demands. These systems would 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 maximum capacity factors – hence maximizing economic benefit. Renewable electricity supplied to the grid could thus be significantly increased 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.

1.1 Possibilities for the Future Energy Grid

The current and anticipated future trends in the mix of energy generation sources on the grid point to a need for increased flexibility. The "problem statement" being addressed by the current work 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.** The increasing uncertainty in net load[6] resulting from intermittent renewable generation necessitates an increased need for frequency regulation and higher dispatchable generator ramp rates and ranges. See Figure 1 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 employed 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 do not provide mechanical inertia, such as wind and solar, other solutions for grid stability are necessary. This challenge could be mitigated by a number of technologies, such as inclusion of sources that provide real or virtual inertia [5], but additional research is necessary to fully understand these challenges.

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 scenario can lead to decreased capital deployment efficiencies and declining business cases for baseload technologies and renewables alike. See Figure 2 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.

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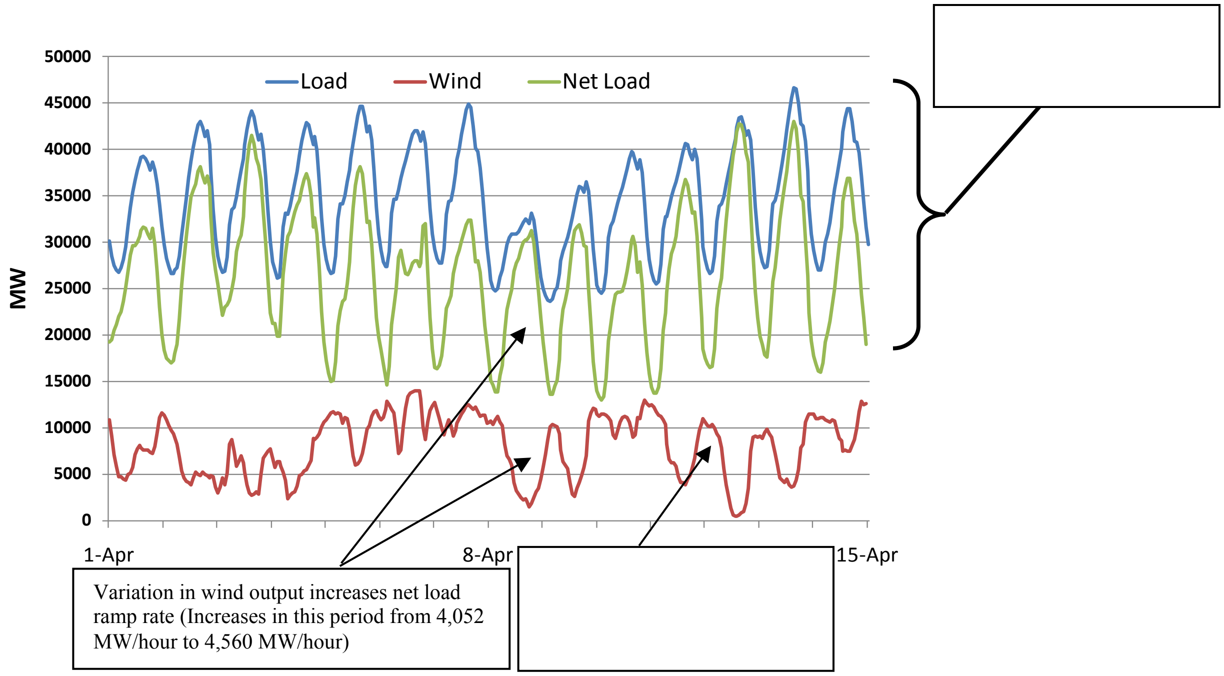
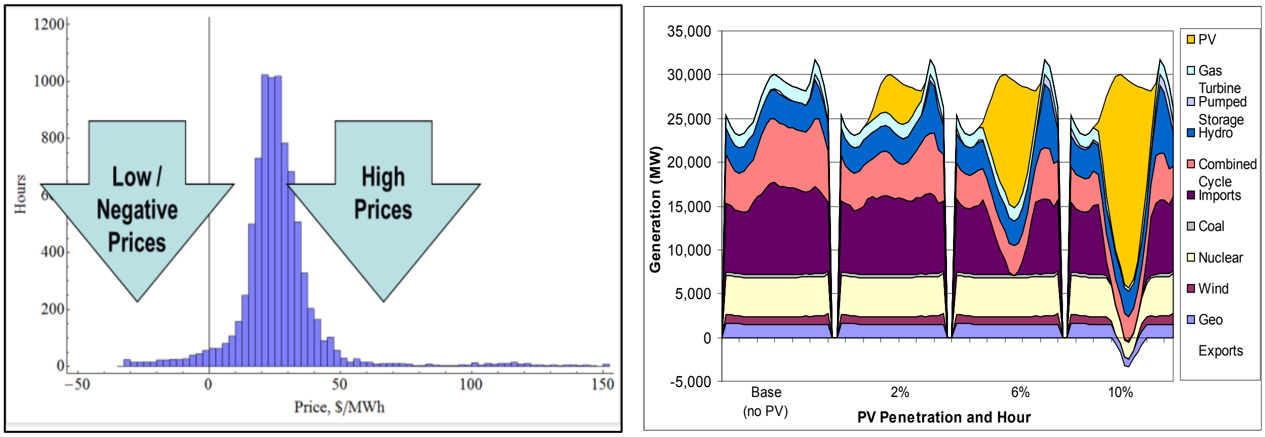
[6] Net load is the remaining demand that must be met by conventional generation sources after variable generation is subtracted from the total load (demand).



Variation in wind output increases net load ramp rate (Increases in this period from 4,052 MW/hour to 4,560 MW/hour)

Figure 1. System load, wind generation, and net load for a two-week period in April. This plot uses Electric Reliability Council of Texas (ERCOT) grid data from 2005 along with 15-GW of spatially diverse simulated wind data from the same year [5].



(a) (b)

Figure 2. (a) Distribution of California electricity prices in 2012 [6] and (b) simulated dispatch in California for four Spring days (24-hr 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].

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) resulting in reduced 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 meet the projected need and has limited locations where it can be built [10]. 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 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.

1.2 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.

1.3 Challenges to Hybrid Energy Systems Development

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. Design, development, and deployment of tightly coupled integrated energy systems face numerous challenges. These challenges can generally 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.

1.4 Engaging Stakeholders: Foundational Workshop

In July 2014 a Foundational Workshop was held at Idaho National Laboratory (INL) under the leadership of principal investigators at INL, the National Renewable Energy Laboratory (NREL) and the Massachusetts Institute of Technology (MIT) [11]. The workshop focused on five primary 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 accomplished the goal of initiating an inter-laboratory, university, and industry team for integrated energy systems development; additional stakeholder engagement will ensure proposed energy systems are relevant and marketable to a potential customer. Significant progress was made at the three-day workshop 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.

2. ENERGY SYSTEMS DESIGN AND ANALYSIS

Figure 3 illustrates a manner in which traditionally baseload power systems (Primary Heat Suppliers) could be directly integrated with renewable generation sources. Nuclear generation is the selected thermal energy resource for the current study, recognizing the benefits of nuclear technology as a high energy density, non-CO_2 emitting, reliable energy supply that has demonstrated an excellent safety record. The thermal energy that is constantly produced can be dynamically apportioned between the conventional power generation train and a selected industrial heat user (list provided in Figure 3 is not comprehensive; other applications may be appropriate). Operation in this manner allows the system to reliably meet grid demand, manage the intermittency of the renewable resource, and maximize use of the thermal energy produced by the capital-intensive nuclear subsystem. Optimal system designs will vary across 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 in plants that provide peak power generation needs and that help manage power quality conditions.

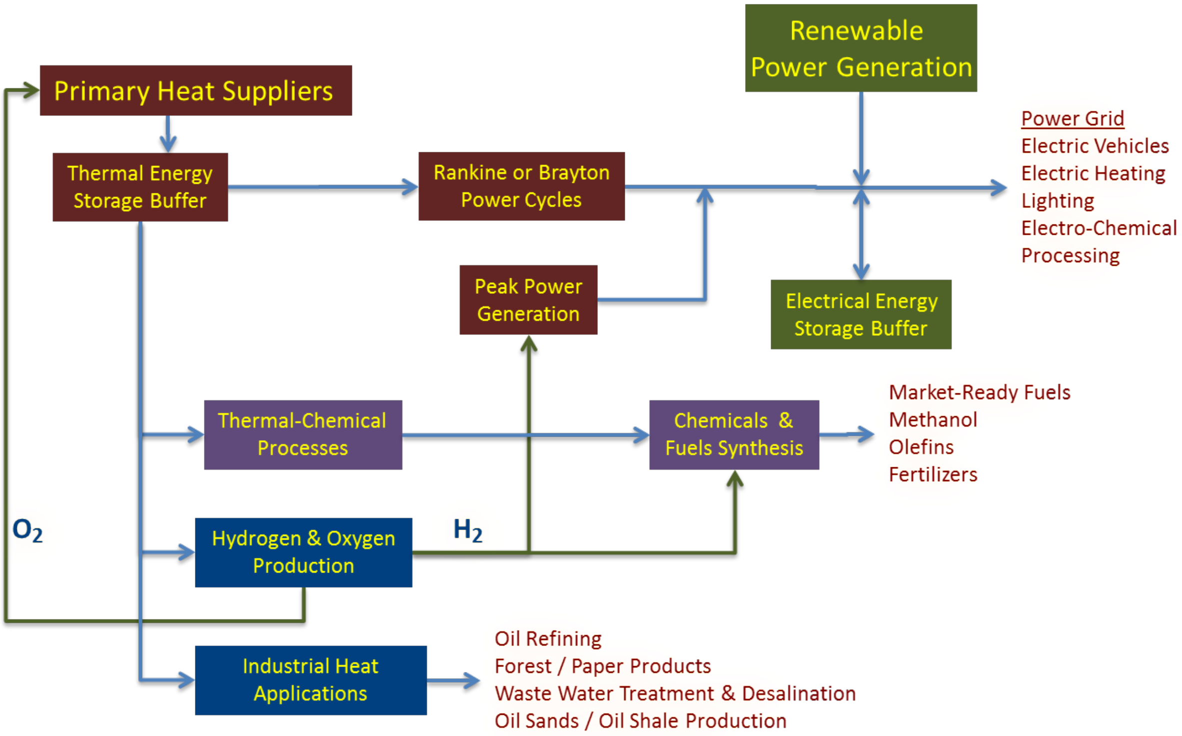


Figure 3. Conceptual Integrated Energy System.

2.1 *Priority Regional Energy Systems*

Integrated Nuclear-Renewable Hybrid Energy Systems must be tailored to regional resources and markets to dynamically optimize the use of thermal and electrical energy. Definition, prioritization and analysis of key options based on selected figures of merit is necessary to identify energy systems that have the greatest likelihood for success in a specified region. Results of these studies will feed a technology development roadmap; a roadmap is targeted for completion in late 2015.

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. For the purposes of the current study, technologies of interest should be capable of deployment at a commercial scale by 2035 to assist the nation in meeting the GHG emissions goals. This 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 preferred timeline unless there is a national priority to develop such technologies. Hence, all of the currently proposed regional cases would incorporate a nuclear subsystem utilizing light water reactor technology. A large number of industrial processes are available for possible integration, as are interface and storage technologies. These options are detailed in the Integrated Nuclear-Renewable Energy Systems Workshop Report [11].

Table 1 provides an overview of the energy system configurations proposed to stakeholders for eight regions around the continental U.S., specifying the renewable resource, industrial process, and interface/storage components. Stakeholders have been engaged to aid in the refinement of these proposed cases, such that some of the listed cases could be modified prior to detailed analysis. Dynamic analyses planned for early in fiscal year 2015 will focus on two distinct cases selected based on stakeholder feedback. One case would be sited in the West Texas region, utilizing land-based wind and nuclear generation sources to produce electricity and to support a natural gas to liquid fuels plant (see Figure 4; note that this could also be applicable to the Mountain West region, although the market and supporting transmission infrastructure would differ in each region). The second case would be sited in the Southwest (Arizona), utilizing solar photovoltaic and nuclear generation sources to produce electricity and potable water, in light of significant interest and feedback from energy leaders in that region.

Table 1. 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 and geothermal power OR Solar photovoltaic	Hydrogen for transportation	Hydrogen (via high temperature electrolysis) and compressed air energy storage OR Water desalination
Gulf Coast	Offshore wind power	Petroleum refining	Hydrogen (via high temperature electrolysis) and thermal storage
Southeast	None*	Biofuel production	Hydrogen (via high temperature electrolysis) and thermal storage
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.

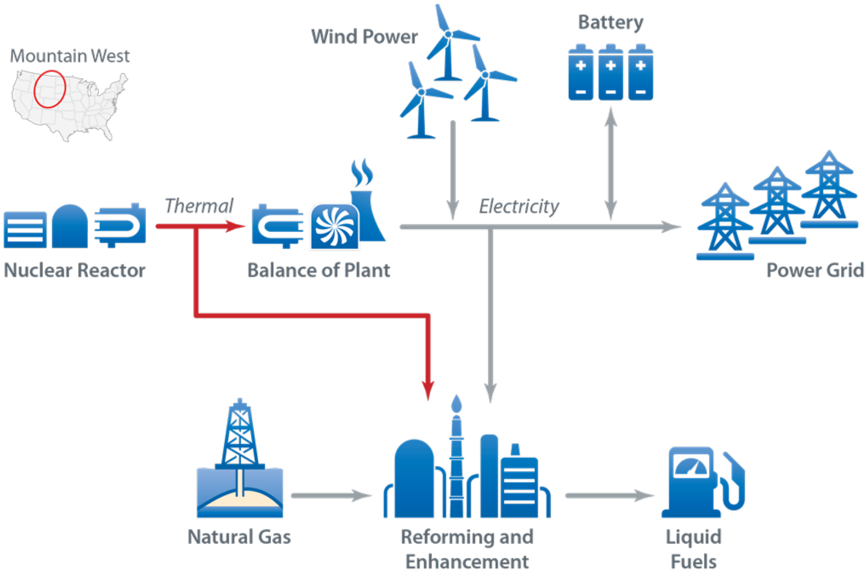


Figure 4. Example regional case that could be applicable to West Texas or the Mountain West.

2.2 Key Figures of Merit for System Evaluation

Many figures of merit (FOM) can be defined to evaluate the technical, economic, environmental, and social benefits of hybrid energy systems integration versus "business as usual" plant operations. 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 probabilistic 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.

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. The proposed FOM can roughly be 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/design, and 4) socio-political criteria. A preliminary set of FOM were presented to stakeholders for review and input. Stakeholder input via an informal survey resulted in top-ranking FOM from each of the four FOM categories. Although there was an insufficient number of stakeholder participants to provide statistically significant results, the following FOM were clearly important in reviewing the performance of regional cases:

1. Financial *pro forma* analyses – need a good business case that supports industry, economy, and service-providers

2. Environmental greenhouse gas emissions – needs to be environmentally responsible
3. Provides / establishes national energy security – energy independence, diversity
4. Near-term deployability
5. Grid reliability

The FOM will be further refined and quantified where possible as the dynamic analysis of each case is refined. The current high-ranking FOM will be suitable for down-selection of regional cases and optimization of the system configurations. More details on the proposed FOM can be found in the Integrated Nuclear-Renewable Energy Systems Workshop Report [11].

3. PATH FORWARD

Significant research is required to reduce development risk for advanced energy systems. Design, development, and deployment of tightly coupled integrated energy systems face numerous challenges that must be addressed. Technical challenges to tight system integration can be addressed via system modeling and simulation and hardware testing. Additional challenges can be categorized as financial (demonstration of a feasible business model), regulatory, and time available to meet the demands for non-emitting energy solutions. 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. A Technology Development Roadmap for Integrated Energy Systems will be issued in 2015.

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