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International Workshop to Explore Synergies between Nuclear and Renewable Energy Sources as a Key Component in Developing Pathways to Decarbonization of the Energy Sector

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International Workshop to Explore Synergies between Nuclear and Renewable Energy Sources as a Key Component in Developing Pathways to Decarbonization of the Energy Sector

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Workshop Report

Background and Introduction

With more than 150 countries submitting plans to mitigate climate change in advance of the Conference of the Parties (COP) meeting held in Paris in December 2015, it is clear that there is increased interest in finding viable, financially sound approaches for providing low carbon, affordable, resilient energy solutions for power, chemicals, heat, and fuels for deep decarbonization. The principal options for low carbon energy include renewables, nuclear energy, and fossil energies with carbon capture, utilization, and sequestration. While many institutions have articulated interests in one or more of these options, few have explored the possible synergies among them.

An international workshop was organized in June 2016 to explore synergies between nuclear and renewable energy sources. Synergies crossing electricity, transportation, and industrial sectors were the focus of the workshop, recognizing that deep decarbonization will require efforts that go far beyond the electricity sector alone.

A key similarity between nuclear and renewable energy is that both require a relatively large capital cost and low (or zero) fuel costs. Costs for some renewables have dropped significantly in recent years, and are now competitive with other sources. Capital costs for nuclear plants are the key drivers regarding construction decisions.

A second similarity is that the operations of both nuclear and renewable technologies are limited – although in very different ways. Many renewable power sources depend on weather conditions to deliver their output, resulting in intermittent operation with capacity factors in the range of 25 to 55%. Without large scale, cost-effective, long duration energy storage, large dependence on renewables for the electrical grid presents significant challenges. Nuclear power runs optimally in a baseload, or constant power, mode, and ramping is limited as compared to combustion options. Nuclear plants provide very high levels of generation reliability (over 90% capacity factors in the U.S.) and have proven their ability to withstand weather extremes – operating effectively even in the frigid conditions of the polar vortex weather conditions that have occurred in recent years. However, nuclear plants are seldom operated in a load-following mode for regulatory and economic reasons, although many designs are technically capable of operating flexibly within a specified range and time scale (depending on the specific plant design). Hence, if the net load on the grid is insufficient to accept the full output from baseload plants, power output may need to be curtailed.

Synergies in energy generation options can be maximized via system design. One such example is a hybrid nuclear-renewable system that would be designed to deliver both electricity and desalinated water. Other examples include designs to produce electricity and hydrogen or other high energy chemicals. In each case, the products are produced through completely carbon-free processes and the products are useful beyond the electricity generation sector, and the electricity requirements of the grid would be fully met while producing these other products.

The workshop brought together international researchers from the many disciplines that would be involved in designing, demonstrating, and implementing the proposed nuclear-renewable hybrid energy systems to further explore these. The end goal of the workshop was to begin discussion on a potential framework for increased international cooperation to explore these synergies and to accelerate the quest for significant reductions in emission of greenhouse gases that would enable decarbonization of the energy sector.

Workshop participants represented multiple offices in the U.S. Department of Energy (DOE), national laboratories, industry, academia, and non-government organizations (NGOs). The workshop discussions expanded on ongoing DOE-sponsored work at Idaho National Laboratory (INL) and the National Renewable Energy Laboratory (NREL) and academic work to integrate nuclear, renewable, and industrial systems to economically provide low-carbon energy to the grid while simultaneously producing a valuable industrial product. In addition to DOE, INL, and NREL, the more than 60 attendees hailed from the Nuclear Energy Agency within the Organization for Economic Co-operation and Development (OECD/NEA); International Atomic Energy Agency (IAEA); International Energy Agency (IEA); Nuclear Energy Institute (NEI); MIT; nuclear energy agencies from Japan, China, Jordan, France, and Canada; NGOs; and many others. The complete workshop agenda and list of attendees are provided in Appendix A. This report summarizes the key points made within each presentation and highlights outcomes that were arrived at in the discussions. Presentations that have been provided for full public release are available at the meeting website.[1]

[1] Pathways to Decarbonization, https://snrworkshop.inl.gov/SitePages/Agenda.aspx, June 2016.

Session Summaries

1. A Welcome from NREL and INL Leadership

Workshop chair Dr. Pete Lyons (retired, DOE Office of Nuclear Energy) opened the meeting by introducing Dr. Robin Newmark (Associate Laboratory Director for Energy Analysis and Decision Support, NREL) and Dr. Mark Peters (Director, INL).

In her remarks, Dr. Newmark highlighted the renewed interest in developing new options for deep decarbonization on a global scale that derived from the 21st Conference of the Parties (COP-21) meeting held in December 2015. The outcomes from the COP-21 meeting are summarized on the website for the Center for Climate and Energy Solutions.[2] Dr. Newmark discussed potential opportunities for new technologies and enhancement of existing technologies that could be used to meet global decarbonization goals, noting that researchers need to provide politicians with substantive "ammunition" to make these technologies work in the policy arena. A system perspective will be critical in meeting the established goals, and the integration or coordination of nuclear and renewable technologies may hold significant promise – but work needs to be done to identify the opportunities and the barriers associated with this approach.

Dr. Peters echoed the potential opportunities for nuclear and renewable technologies to provide affordable energy in the future, noting that partnerships among laboratories, universities, industry, and international organizations are necessary to successfully reach the goals set out at the COP-21 meeting. The current collaboration between INL and NREL in energy systems analysis, accomplished via funding from the DOE Offices of Nuclear Energy (DOE-NE) and Energy Efficiency and Renewable Energy (DOE-EERE) will allow a better understanding of broad energy systems to be developed.

Workshop Objectives

The workshop was organized by NREL and INL, with support from Dr. Lyons, to share the status of ongoing studies in the U.S. and abroad, and to explore benefits of and options for greater international cooperation. Dr. Lyons summarized the overall workshop objectives before moving into the planned sessions. Dr. Lyons commented that renewables and nuclear are the only clean energy generation sources available today to meet the decarbonization needs. In the United States, hydroelectric power has essentially been built out to maximum capacity; hence, it cannot be expected to expand significantly to help meet the environmental goals. In addition, society must think beyond the electricity sector in order to solve the growing global climate issues. Dr. Lyons believes that integration of generation assets on a grid level will be essential to meeting the climate goals while providing supply diversity and reliability. Hybrid systems, proposed as an option for maximizing the penetration of clean energy assets (i.e. nuclear and renewables), will be designed to optimize the contribution of each of these generation sources to meet grid demand and industrial energy needs, including the possible production of transportation fuels.

2. COP-21 and Grand Challenges of Decarbonization

Dr. Doug Arent, Director of the Joint Institute for Strategic Energy Analysis (JISEA) at NREL, introduced and moderated the first panel session. Dr. Arent noted that this meeting was the fourth workshop of its type to be organized jointly by NREL and INL, as this format has been successful in enhancing dialogue across the wide array of experience and perspectives of energy experts.

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[2] Center for Climate and Energy Solutions, "Outcomes of the U.N. Comate Change Conference in Paris," November 30 – December 12, 2015, http://www.c2es.org/international/negotiations/cop21-paris/summary, accessed August 1, 2016.

Dr. Carla Frisch, Director for Climate Change for the U.S. DOE Energy Policy and Strategic Analysis (EPSA) office, provided a U.S. overview on the grand challenges for decarbonization, highlighting recent work on the Quadrennial Energy Review (QER) and Quadrennial Technology Review (QTR) in the U.S. The 2016 projections for emissions show a declining slope when considering current measures for limiting emissions and implementation of additional proposed measures. However, despite the anticipated decline in emissions, projections indicate a mere 8% probability that climate change staying below the 2^{o}C increase established as a goal at the COP-21 meeting. Hence, other strategies will be necessary to meet the established goals. Projections to 2050 by the International Energy Agency (IEA) indicate that increased penetration of nuclear and renewable energy can provide significant reductions in emissions. Parties to the COP-21 agreement agreed to communicate long-term strategies for GHG reduction to the rest of the group by 2020; the U.S. expects to issue a strategy by the end of 2016. Dr. Frisch also discussed the content of the 2015 QER and QTR documents. The QER identifies current energy infrastructure in the U.S. and provides a review of government-wide energy policy, noting both the current policies and policies that may need to be changed. The QTR, on the other hand, takes a technology focus, highlighting the R&D opportunities across the energy sector. These documents can be found at the DOE website.[3,4]

The conversation continued with a presentation given by Dr. Manuel Baritaud, Senior Energy Analyst for the International Energy Agency (IEA). Dr. Baritaud commented that the agreements reached at COP-21 in Paris have been a huge diplomatic success; it is now up to the parties to maintain the momentum from that meeting by focusing on implementation and tracking progress toward the established goals. Renewables have made significant progress in recent years, but nuclear energy appears to be at a crossroad. Achieving the 2^{o}C pathway will require innovation, investment, and policy ambition to bridge the gap.

Projections indicate that the power sector will require the largest investment – estimated at $19.7 trillion globally to 2040, with an estimated 60% of that investment going to renewable technologies. The IEA projections assume that nuclear generation technology must be maintained, with older plants being replaced as they reach end-of-life. In order to meet the goals for carbon reduction, the IEA projects that low-carbon power generation must be increased by a factor of four by 2040, with renewable energy (RE) providing half of the global power mix in 2040. In OECD countries this would be accomplished by maintaining the total generation from nuclear plants, but decreasing the percentage of power provided by nuclear. However, non-OECD countries anticipate expanded use of nuclear generation in the coming decades. When considering the economics of energy generation, innovation and scale-up have been driving down the costs of wind and solar PV, such that high levels of incentives are no longer necessary for solar PV and onshore wind generation. Despite these declining costs of renewables, the IEA NEA Projected Cost Study (2015) found that nuclear generation can remain in the competitive range given low financing costs and a price for CO_2. Under the current market conditions that result in a low wholesale price for electricity, and without a price for carbon, market-based nuclear investments are unlikely, and will remain limited for renewables. Several existing nuclear facilities in the U.S. and Europe are currently considering closure due to poor economic conditions in the market structures in which they operate. However, investments in energy technology should not be merely a matter of costs, but should also factor in the value of different technologies to the overall reliable performance of the electricity grid and the carbon footprint of the technology. Overgeneration at certain times of day due to higher penetration of renewable energy sources will need to be managed with additional flexibility options in the generation mix, including demand response and energy storage.

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[3] Quadrennial Energy Review: Second Installment, April 2015, http://energy.gov/epsa/quadrennial-energy-review-second-installment, accessed August 1, 2016.

[4] Quadrennial Technology Review, September 2015, http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015, accessed August 1, 2015.

In light of the agreements reached in Paris, IEA notes that the electricity market design must be aligned with decarbonization – this market design hinges on the portfolio of technologies available. Nuclear and renewables are both necessary to meet the decarbonization goals, can provide generation flexibility, and can both benefit from higher demand-side and energy storage flexibility.

Dr. Mianheng Jiang, President of Shanghai Technical University, Chinese Academy of Sciences, provided an Asian perspective to the discussion. Dr. Jiang commented that the U.S. and China are currently the world's two largest economies; hence, they are very important contributors to reaching the global decarbonization goals that have been set forth. Economic growth in China is expected to result in a 22% increase in CO_2 emissions by 2035, reaching a fraction of 28% of the global total. Energy security and reduction of CO_2 emissions are a significant short-term worry for China. The U.S. currently accounts for 14% of the global energy consumption and, by 2035, is expected to produce 15% of energy globally – becoming a net exporter. The Sino-U.S. Decarbonization Collaboration was established in 2014, a key predecessor to the 2015 agreements in Paris.[5] In this declaration, the U.S. aims to reduce carbon emissions by 26-28% of 2005 levels by 2025, and China aims to increase their use of non-fossil fuels to 20% by 2030 to begin to reduce emissions from their peak amount. To date, China has experienced unsatisfactory performance of wind farms in China due to issues with turbine quality, curtailment, and delayed grid connection. Similarly, nuclear is challenged by economic viability due to low natural gas prices, much like in the U.S. However, to achieve climate change goals, China is currently pursuing potential nuclear-renewable hybrid options in addition to traditional fuels, establishing collaborations with the U.S. on molten salt-cooled reactor concepts, nuclear fuel resources, and hybrid energy system design.

3. International Clean Energy Goals and Approaches

Dr. Daniel Iracane, Deputy Director General and Chief Nuclear Officer for the OECD/NEA opened the panel session on clean energy goals for the international community. Dr. Iracane pointed out that nuclear is already the largest low carbon energy source in OECD countries (18.1%) and is second in the world behind hydro (10.6% nuclear, 16.6% hydro). However, 73% of the world's reactors are greater than 25 years old (as of 2013). The current nuclear capacity needs to be maintained and needs to grow as demand grows, considering plant lifetimes and retirements in the anticipated plant construction rates. Key IEA reports, Energy Technology Perspectives, published in 2015 and 2016 note that nuclear, wind, and solar are key to achieving the desired reductions in CO_2 emissions by 2050. To meet the established goals, 12 GWe of new nuclear would need to be installed per year; however, since 2011, the global average has been only 5.3 GWe per year (although 9 GWe was installed in 2015). To meet the 2^oC goal, nuclear would need to increase to 16% of the global energy mix (900 GWe), up from a current 11% (390 GWe), and variable RE would need to increase to 30%. To make these changes a reality, long-term investment will be required and changes in the structure of the current electricity markets will likely be needed to fully value the merits of nuclear generation, such as price stability and grid support. The typical paradigm is that increasing the fraction of RE in the energy mix will meet the mitigation goals; however, experience is beginning to show that significant penetration of variable RE may actually collapse the electricity price for low carbon baseload technologies due to coincidence of generation (oversupply at certain periods during the day), leading to an increase in CO_2 emission due to the use of gas-fired backup power systems. Impacts of periodic overgeneration and low-cost natural gas are being observed for nuclear plants in the U.S., but they are also observed for other technologies, including some hydro generation in Europe and some solar PV parks in Chile.

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[5] U.S. White House, U.S.-China Joint Announcement on Climate Change and Clean Energy Cooperation, https://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c, November 11, 2014 (accessed August 2016).

Countermeasures to these trends could include establishing policy measures to sustain low CO_2 baseload generation sources and improvements in technologies that mitigate the variability of RE (e.g., energy storage, transmission enhancements, etc.). At high penetrations of variable RE technology, non-linear mechanisms begin to take place, such that the value of the generation begins to decrease and CO_2 actually begins to increase as carbon-emitting technologies are used to meet net load during times of low RE generation. The break-even point on the RE penetration that will provide the greatest reduction in CO_2 emission while maintaining the value of the generation is currently uncertain. Dr. Iracane noted that the present electricity market suffers from a significant structural issue in that it is driven by short-term optimization, putting long-term investment capacities at risk. This condition has motivated the NEA "system effects" studies to evaluate the broader electricity markets around the world. In a recent presentation, U.S. Energy Secretary Dr. Ernest Moniz identified market structures as critical, highlighting the need to realistically recognize the full value of all generation options.[6] Overall, Dr. Iracane concluded that policymakers need to be made aware of the various market mechanisms related to large-scale variable RE penetration, among other considerations and constraints, to ensure that the best decisions are made regarding energy technologies.

Dr. Francoise Touboul, Scientific Advisor to the Chairman at CEA (France), followed Dr. Iracane's presentation. European Energy Policy established the European Climate and Energy Package in 2014, setting climate and energy targets for 2030. The current European energy supply relies on ~80% fossil fuels. This package sets 2030 goals for reduction of the overall primary energy consumption by 27%, reduction of GHG emissions by 40%, and increase in the renewable energy share to 27%. France currently generates almost 80% of its electricity via nuclear plants. The recent French Energy Transition Law targets 2030 goals of reducing fossil fuel use by 30%, increasing renewable energy generation in the energy mix to 32%, and achieving 40% GHG emission reduction. Goals for 2050 would then reduce GHG emission by 75% (relative to today's levels) and reduce primary energy consumption by 50%. The two pillars of the French energy mix will thus be variable renewables and nuclear energy. While total nuclear generation is expected to be maintained at its current level of 63.2 GWe, demand growth will be met through the addition of renewable technologies, such that the fraction of electricity provided by nuclear is expected to drop to 50% by 2025. Three pillars are fundamental to achieving the French objectives:

- Energy savings,
- Development of renewable energy resources,
- Simplification, regulation, and strategies.

Future energy production schemes must have a system approach to ensure power system reliability. Nuclear and renewables offer significant complementarity through the provision of reliable carbon free electricity to support production of "green" hydrogen, synthetic fuels (e.g. biomass to liquid), industrial fabrication processes, etc. Association of nuclear with non-grid applications will help compensate for the intermittency of renewables.

Touboul concluded that in spite of the recent Fukushima accident, the use of nuclear energy still remains necessary for many countries. Nuclear has the potential to contribute even more using Generation IV technologies that are being developed. Renewable energy R&D should focus on removing technical and economical barriers that hinder the expanded use of renewable energies. In the future, nuclear energy and renewables are both expected to contribute to the global energy mix. Continued R&D and international collaboration is key to achieving an optimal energy mix that will be both sustainable and economically competitive.

[6] Moniz, E., remarks made at the "DOE Summit on Improving the Economics of America's Nuclear Power Plants," May 19, 2016, as reported by World Nuclear News, May 24, 2016.

Kamal Araj, Vice Chair of the Atomic Energy Commission of Jordan, provided a perspective from a developing country that is striving to become more energy independent. Jordan currently imports fossil fuels to provide more than 97% of the country's electricity needs. The Jordanian government would like to bring both nuclear and renewable generation into the country, while remaining dependent on fossil fuels to support the growing energy consumption in the country. Solar and wind projects are expected to come online in 2016, and the Jordanian nuclear project is moving "full speed ahead." The nuclear power plant project will build two 1000 MWe, Generation III+, VVER 1000-AES 92 pressurized water reactors (PWRs), with an estimated operational date of 2024-2025. While smaller scale, small modular reactors (SMRs) that can be strategically located might be preferred, Jordan is currently pursuing large nuclear reactors since SMRs have not yet been commercially deployed.

Jordan hopes to take advantage of the synergies between nuclear and renewables that can be expected for small grids, particularly through the development of hybrid energy solutions that can support needs beyond electricity alone, such as desalination to increase potable water availability. The Jordanian grid is currently being upgraded, factoring in the structural changes that will occur with introduction of the planned new generation sources. A desalination project is also in progress, which aims to produce up to 80×10^6 m^3 of drinking water per year.

4. DOE-NE and DOE-EERE Clean Energy Program Outlook

Both the U.S. DOE Offices of Nuclear Energy (DOE-NE) and Energy Efficiency and Renewable Energy (DOE-EERE) currently have programs that focus on the future of U.S. energy systems, with a goal of deploying larger amounts of clean energy technologies across all aspects of the energy sector.

Mr. Steve Capanna, Director of Strategic Priorities and Impact Analysis for DOE-EERE, stressed the importance of the Climate Action Plan that was put in place in January 2014. The EERE strategy for a clean energy future includes cost reduction and performance improvement, technology demonstration and risk reduction, and market barrier reduction. Five key EERE technologies have made significant cost reductions of 40-90% since 2008: land-based wind power, distributed and utility scale PV, batteries, and LEDs. Key EERE programs in both wind and solar technologies have aided achievement of these cost reductions. The Renewable Electricity Futures Project predicts a path that would lead to 80% electricity generation from renewable sources by 2050, although significant economic and operational challenges must still be overcome. Ongoing projects that are expected to make significant advances in decarbonization include the Grid Modernization Initiative and the Hydrogen at Scale program that are just beginning.

Ms. Suibel Schuppner, Senior Program Manager in the Science and Technology Innovation office in DOE-NE, provided the nuclear energy perspective on the U.S. clean energy outlook. There are several policy drivers that support the expansion of clean energy: Executive Order 13693 (March 2015), which targets 40% reduction of GHG emissions in federal facilities by 2025; the Clean Power Plan (August 2015) that sets CO_2 emission performance goals for every state in the U.S.; and the COP-21 (December 2015) that were discussed previously. As stated by Secretary Moniz at the COP-21 meeting in Paris, "…nuclear can provide 24-hour baseload power…to achieve the pace and scale of worldwide carbon reductions needed to avoid climate change, nuclear must play a role." Despite its significant benefits, nuclear still faces challenges to innovation, including a lengthy development and deployment timeline, high capital costs, and government bureaucracy. DOE-NE is currently investing in several programs to spur nuclear innovation: SMR licensing technical support; advanced reactor design and development; and nuclear-renewable hybrid energy systems (N-R HES). The recently established Gateway for Accelerated Innovation in Nuclear (GAIN) aims to accelerate commercial readiness of innovative technologies by facilitating the accessibility of national asset test and demonstration facilities at the national laboratories to industry. [7] The N-R HES program seeks to maximize the utilization of clean energy technologies – both nuclear and renewable – for electricity generation and industrial applications through a collaboration between DOE-NE and DOE-EERE.

5. *Pathways to Deep Decarbonization in the United States*

Dr. Jim Williams, Director of the Deep Decarbonization Pathways Project (DDPP),[8] provided a compelling lunchtime talk on how the U.S. might achieve deep decarbonization goals. DDPP manages independent research teams across 16 countries. The analysis of U.S. pathways to decarbonization focused on the following questions in assessing how the U.S. might achieve 80% GHG reduction below 1990 levels by 2050:

- Is it technically feasible?
- What would it cost?
- What physical changes are required?

Additionally, the study then asks what the policy implications may be in the US with regard to the solution strategies. DDPP reports are available on the project website.[8] At a high-level, the study identified four technology pathways that could achieve an 80% reduction in CO_2 emissions by 2050. The four 2050 scenarios evaluated are referred to as mixed, high renewables, high nuclear, and high carbon capture and sequestration. The mixed case includes high levels of electrification and large increases in nuclear and renewable generation capacity. It also includes a transition of pipeline gas from primarily natural gas to conversion of biomass. That pipeline gas is used within industry and provides some transportation energy. The analysis estimated that the net energy system cost in 2050 is approximately 0.8% of the gross domestic product (GDP) without including the economic benefits of avoided pollution or climate damage.

Three pillars are required in all scenarios that achieve 80% reductions in CO_2 emissions by 2050: energy efficiency, decarbonization of electricity, and end use fuel switching to electric sources (e.g. electrification of the transportation sector). Those three pillars have been found to be consistent in other nations including China, India, and the U.K.; however, the fraction of decarbonization driven by each pillar differs between nations.

The study used the PATHWAYS model that performs cost assessments of various future demands. PATHWAYS is an energy system model that tracks energy generation and utilization stocks and considers retirement times and impacts of long equipment lifetimes on supply and demand. Several design constraints were included in the model: infrastructure inertia, electric reliability, meeting projected energy service requirements, technology development (i.e., all technologies considered are either commercially available or near commercially available), and environmental limitations on resources (e.g., hydro power and biomass).

Dr. Williams highlighted the challenges and opportunities that might be shared by renewables and nuclear under the deep decarbonization goals. These include:

- Rapid, large-scale expansion of generation
- Coordination with large-scale electrification
- Regionalization of grid planning and operations
- Siting of generation, transmission, and flexible demand
- Large-scale power to gas (e.g. H_2) and liquid fuels
- Sustainable utility business model
- Wholesale market structure

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7 https://gain.inl.gov

8 http://deepdecarbonization.org/

- Public perceptions of readiness, acceptability
- Policy community conventional wisdom.

As was highlighted later by speakers in the grid modernization session, deep decarbonization is a system problem that will require coordination across sectors and between the supply and demand sides. Hence, future scenarios must be evaluated from a system cost perspective. When looking at these solutions from a high-level system perspective, it is possible to see additional solutions, such as those that have significant linkage between the supply and demand sides of the equation. For example, inflexible or nondispatchable generation sources may be accommodated by large-scale flexible demand. The DDPP analyses have shown this approach to be beneficial for both the high nuclear and high renewable scenarios. The challenges associated with both the high nuclear and high renewable electricity system cases are the near zero variable costs, which challenge allocation of fixed costs on a time-dependent basis; the necessity to meet net load versus the traditional load; establishing appropriate linkages between the supply and demand side; and managing a new paradigm for asset utilization (i.e. net load factor versus traditional load factor).

6. Grid Modernization

The grid modernization discussion covered insights from the both the U.S. and Europe. Jennie Jorgenson, Energy Systems Engineer at NREL, opened the session by clarifying the need for grid flexibility that is evident with increasing penetration of renewables due to coincident generation for regional renewable sources. System reliability is a chief goal of the electricity grid, which must achieve this goal despite supply and demand that can change seasonally, weekly, hourly, and even instantaneously. This matching of supply and demand is the job of regional balancing authorities. Variations in demand have traditionally been balanced using conventional thermal and hydro generation, but variable renewables that increase the uncertainty in net load complicate this traditional paradigm. Ms. Jorgenson introduced several options for flexibility that are currently being developed, offering different levels of intervention in the grid operation at different economic price points.

Dr. William D'Haeseleer, Professor at the KU Leuven Energy Institute, University of Leuven, Belgium, introduced the European experience with generation intermittency. The European Union is currently facing a significant challenge as it tries to simultaneously satisfy the internal market (economics), supply security, and environmental goals. The EU Energy Policy sets targets for 2020, 2030, and 2050 – targeting a CO_2 reduction of >85% by 2050. Achieving this goal will require an energy revolution and paradigm shift. In establishing individual country goals for renewables, the EU broke down renewable generation goals by each country's gross domestic product rather than by actual capacity potential, neglecting major system effects that, if not addressed, could jeopardize future progress. A recent IEA/NEA report on system costs attempts to reconcile previous studies to provide a nonbiased view on electricity generation costs.[9] In order to be successful in energy planning to meet overall goals, one must first clearly define the problem to be solved. In this case, the 'problem' is global reduction in CO_2 emissions (versus simply regional reduction). The established emissions trading system (ETS) in the European Union is well intentioned, but this system has actually prevented high RE penetration from reducing CO_2 emission.[10] Because of caps for ETS, less CO_2 in one region actually allows more CO_2 to be emitted elsewhere. Five major "flexibility-enabling elements" that could be a part of the future energy system solutions may include backup reserves from dispatchable thermal plants, large-scale electrical storage, transmission grid expansion, active demand response, and curtailment of RE production. System integration via interaction between the electricity and thermal sectors can also aid in the management of excess electrical energy. Dr. D'Haeseleer concluded that, overall, significant transitions in the energy

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[9] IEA and NEA, *Projected Costs of Generating Electricity*, 2015 Edition.

[10] For more information in ETS, see http://ec.europa.eu/clima/policies/ets/index_en.htm, accessed August 2016.

sector will take time. System effects must be taken into account, the regulatory environment must be stable and relatively simple, and integration of the various sectors (electricity, heating, transportation) within the broader energy sector will be necessary to achieve established goals.

Mr. Nadav Enbar, Principle Project Manager for EPRI Power Delivery and Utilization, further discussed the approaches that may be available to increase grid flexibility. The current electric power system is based on central generation and predictable consumption, with power only flowing from generators to consumers. EPRI anticipates that the future power system will evolve to a more dynamic end-to-end power system in which generation is more flexible, loads are interactive and dynamic, power flows both directions between generators and consumers, and transmission and distribution are more controllable and resilient. A dynamic power system will require an integrated approach that includes grid modernization, communications and standards, integrated planning and operations, and informed policy and regulation. New technology necessary to accomplish the established goals may be best developed through the use of technology pilots that allow for experience-based knowledge development. EPRI reported that 19 technology pilots for the integrated grid are currently ongoing in the U.S. One pilot seeks to maximize existing flexibility using dynamic line rating technologies; this technology is currently being adopted by the Electric Reliability Corporation of Texas (ERCOT). A second pilot is leveraging smart invertors, which convert direct current (DC) energy from solar modules to alternating current (AC) energy, in order to interface solar photovoltaic (PV) systems with the grid. These smart invertors provide voltage management, allowing greater penetration of solar PV technology. These and other pilot technology programs can be extremely valuable in developing and implementing technologies that will support grid flexibility needs while introducing technologies to reduce emssions, such as additional variable generation (e.g. solar and wind).

Dr. Marco Commetto, Nuclear Energy Analyst at the OECD/Nuclear Energy Agency (NEA), further addressed the question of system effects in low carbon electricity systems that were previously introduced by Dr. D'Haeseleer. With a focus on Europe, Dr. Cometto provided information on the technical and economic impacts of the rapid buildout of variable renewable energy on electricity systems in many OECD countries. Traditional metrics, such as the levelized cost of electricity (LCOE), are no longer sufficient to characterize different generation sources; rather than consider components in isolation, one must begin to evaluation the electricity system as a whole. In the short-term, the European experience indicates that the buildout of RE with zero marginal costs replaces technologies having higher marginal costs, including nuclear, gas, and coal. As a result, a smaller fraction of the load is met by dispatchable power plants, resulting in lower load factors. When this is compounded with reduced average electricity prices in wholesale power markets, dispatchable generators begin to see declining profitability. Study of the potential long-term impacts of these trends suggests that increased RE penetration will change the generation structure for remainder of the system. As renewable penetration increases, the need for generator flexibility will also increase, resulting in more high cost ($/MWh) technologies being introduced to meet the net load. Current data trends indicate that these effects will increase substantially with increased RE penetration. NEA analyses indicate that coincident generation from RE sources (auto-correlation) reduces its effective contribution to the system, thus reducing market value at increasing penetration. Countries such as France, Germany, and Belgium already implement significant flexible operation on nuclear power plants, implementing daily and weekly load following via primary and secondary frequency control. Studies by EdF on the economic impact of flexible operation primarily point to the reduced load factor as the primary consequence of load following (no evidence of increase fuel or major component failures has been identified, although some correlation is seen between load following an increased maintenance). Overall, data indicates that the value of RE generation decreases drastically with increasing penetration, impacting the overall market and system value. The system costs are country specific and are strongly interrelated across the generation mix, but they are large and must be appropriately accounted for and internalized in making system decisions.

Audience discussion focused on the question "What flexibility option would you choose?" While EPRI offered that energy storage technologies must be a major contributor to grid flexibility, Dr. D'Haeseleer succinctly suggested that we should allow the market to choose the best option. Regulatory stability is key to that market choice. In this scenario, however, each component or subsystem must be subjected to its real costs, without subsidy, and carbon pricing must be introduced if we are truly serious about decarbonization.

7. Expanding the Use of Nuclear and Renewable Energy

A discussion on specific technology developments followed the grid flexibility session. Dr. Shannon Bragg-Sitton (INL), Lead for the DOE-NE program on Nuclear-Renewable Hybrid Energy Systems (N-R HES), introduced the concept of hybrid energy systems as an option of using energy resources in a more effective manner through both electric and thermal energy applications. Both light water cooled reactors (LWRs) and high temperature reactors (HTRs) can be leveraged for use in industrial applications, diverting excess energy when net load is reduced during times of high renewable generation. INL, with support from collaborators at NREL, ORNL, and ANL, has studied the dynamic operation of selected hybrid energy system options that would manage energy input from nuclear and either wind or solar generation to meet electricity needs and to provide energy input to other industrial applications (e.g. desalination, hydrogen generation, synfuels production, etc.). While dynamic analyses have been limited thus far, static analyses and initial dynamic analysis results suggest that such hybrid systems could support flexibility needs, reduce GHG emissions from the industrial section, and generate a profit to the HES owners (or consortium of owners). Hence, DOE is embarking further in the investigation of such systems for both LWR and HTR technologies.

Mark Ruth (NREL), Technical and Project Lead for the DOE-EERE HES program, followed with a discussion on the possible market opportunities for N-R HES. Postulated benefits of N-R HES include:

- Dispatchable, flexible, very low-carbon electricity generation that can support adequate resources on the grid
- Reduced GHG emissions in the industrial sector
- Synchronous electro-mechanical (real) inertia that supports the grid
- Alleviation of the impacts of electricity price suppression at high penetration of low-marginal cost generation (e.g., nuclear and renewables).

NREL is currently conducting analyses for N-R HES for the production of synthetic gasoline, desalination, provision of thermal energy (as a product/commodity), and hydrogen production.

Dr. Yuhan Sun, Director of the Chinese Academy of Sciences (CAS) Shanghai Advanced Research Institute (SARI) discussed options for carbon conversion in China. China has expressed significant interest in developing hybrid systems that can convert coal to liquid fuels (CTL systems) versus burning coal directly for energy. The geography of China will impact what types of hybrid systems would be developed and operated, but these systems are expected to have an impact on the overall GHG emissions from the country, resulting in a positive impact on the potential growth of China.

Mr. Mark Haynes, President of Concordia Power and Senior Advisor to the Next Generation Nuclear Plant (NGNP) Industrial Alliance, brought the discussion to advanced reactor technologies for international development of integrated energy systems. Such an advanced reactor deployment, developed via international partnership, would be designed to provide process heat, electric power, and hydrogen production. The NGNP Alliance is focused on deploying a High Temperature Gas-cooled Reactor (HTGR) demonstration plant, reflecting the significant potential for both the electrical and process heat markets in North America. Establishing such a project as an international collaboration is expected to aid the deployment process via cost sharing, increased potential for funding stability, decreased technical risk via increased technical expertise and test facility availability, and increased market opportunities. The international need for emissions reductions suggest that the time may be right to move forward with such an HTGR project. Mr. Haynes reported that the four parties interested in such an approach include the NGNP Industry Alliance (U.S.), Japan Atomic Energy Agency, Korean Atomic Energy Research Institute, and Poland and the EU's Nuclear Cogeneration Industrial Initiative. A successful initial plenary meeting on the proposed International HTGR Project/Enterprise was held in March 2016, and several potential sites are currently being evaluated for siting a demonstration plant. A second meeting planned for Fall 2016.

Sam Suppiah, Nuclear Hydrogen Program Lead at the Canadian Nuclear Laboratories), provided a Canadian perspective on the development of hydrogen production technologies as a means to achieve decarbonization goals. Canada has been a leader in hydrogen technologies for several decades, with research and development activities on multiple hydrogen production options. Hydrogen is currently used for ammonia production, methanol production, oil refining, and upgrading of synthetic crude oil, with a current global demand of 50-60 Mtonne/year. Hydrogen could also be used for a clean-burning transportation fuel in the future. Several key questions must be addressed regarding the production of hydrogen using nuclear technologies for thermal and electrical energy input:

- Is it cost competitive to generate hydrogen intermittently when electricity prices are off-peak?
- Will the hydrogen price be stable?
- Is this production method environmentally friendly?
- Can production achieve continuity of supply (e.g. via H2 storage technologies)?

Nuclear hydrogen production technologies could include low temperature electrolysis, high temperature steam electrolysis, or thermochemical cycles. The copper-chlorine cycle has been identified as particularly attractive to Canadian researchers due to the expectation for high efficiency (41% estimated), low temperature requirement (<530^{o}C), standard materials of construction, and inexpensive raw materials.

8. *Emerging Nuclear Technology and Market Applications*

The final technical presentations at the workshop focused on emerging nuclear technologies and market applications.

Dr. Jun Sun, Associate Professor at Tsinghua University, gave a presentation on behalf on Dr. Zuoyi Zhang, Director and Chief Scientist for the Tsinghua University Institute for Nuclear and Energy Technology. Dr. Zhang's research focuses on the development of a pebble-bed high temperature reactor, which will extend the application of nuclear energy to process heat in China. The HTR Pebble-bed Module (HTR-PM) will provide for the cogeneration of supply steam up to 600^{o}C for petroleum refining, oil sand and oil shale processing, sea water desalination, district heating, etc. The first concrete was poured at a site near Beijing for the 200 MWe HTR-PM in December 2012, and the pressure vessel was installed in March 2016. The final plant will include two 250 MWt units with a single 210 MWe steam turbine. Additional component and fuel testing is currently being conducted, with grid connection planned for the end of 2017.

Dr. Zhiyuan Zhu, President of the Shanghai Branch of the Chinese Academy of Sciences, discussed an alternative reactor technology that is of interest for development in China. The Thorium Molten Salt Reactor Energy System (TMSR) is a CAS initiative that was started in 2011, with a mission to develop both solid and liquid fuel TMSRs in the next 20-30 years. Test facilities are currently being established, and research and development is ongoing for the production and purification of molten salts. A goal has been established to build a 10 MW Solid-Fuel (TMSR-SF) and a 2 MW Liquid-Fuel (TMSR-LF) experimental reactors and a demonstration of the Th-U fuel cycle around the year 2020.

Dr. Joshua Walter, Lead for Hybrid Energy Applications at TerraPower, highlighted the forward-looking nature of TerraPower. TerraPower's Innovation Group continuously evaluates new ideas and approaches across of variety of technology areas. TerraPower is currently focused on developing two new reactor technologies: the Traveling Wave Reactor (TWR) and the Molten Chloride Fast Reactor (MCFR). They believe that development of these technologies will support the company's focus on next generation nuclear energy systems that excel in economics, safety, resource utilization, waste, and proliferation resistance. TerraPower supports the pursuit of thermal applications of nuclear energy are, noting that renewable energy technologies may provide a stepping-stone through complementary technology development, such as salt-based thermal energy storage. Coupling cost-effective advanced reactor technologies to multiple industrial energy users in a clean energy park could provide a business plan that would reduce the overall cost of energy while also decreasing environmental impacts.

Mr. Chris Colbert, Chief Strategy Officer for NuScale Power, discussed the light water cooled small modular reactor technology that is currently under development. Each NuScale power module would provide 50 MWe, with twelve modules making up a full 600 MWe plant. NuScale has evaluated several options for integration of variable renewable energy generation with a NuScale plant. The Western Initiative for Nuclear (WIN) Program establishes a partnership among Utah Associated Municipal Power Systems (UAMPS), Energy Northwest, NuScale, and Idaho National Laboratory that is currently planning to build a prototype plant on the INL Site. The plan, which has strong support from state, local and federal officials, is currently targeting 2024-25 for commercial operation.

Dr. Kazuhiko Kunitomi, Director General of the High Temperature Gas Reactor (HTGR) Hydrogen and Heat Application Research Center at the Japan Atomic Energy Agency (JAEA), again turned the discussion back to the use of HTGR technology for GHG reduction. Japan has a long-term goal to reduce GHG emissions by 80% from the 2013 level by 2050. The country currently envisions a need to use both nuclear and renewable energy technologies to achieve this goal, noting that the use of nuclear energy for non-electric applications is "unavoidable" to meet these aggressive targets. Hence, HTGRs for cogeneration are of interest. The Strategic Energy Plan approved by the Japanese Cabinet in April 2014 provides R&D funding for nuclear technologies that "…serve the safety improvement of nuclear use…in various industries including hydrogen production…" The Japan Revitalization Strategy, revised and approved in 2015, further points to the need for international engagement and cooperation in this R&D. METI also issued a Strategic Roadmap for Hydrogen and Fuel Cells in June 2014, which would be linked to the R&D for HTGRs. Several tests have been conducted on hydrogen production to date, notably achieving 8 hours of continuous hydrogen production in February 2016.

The final technical presentation on emerging nuclear technologies was given by Simon Irish, President and CEO of Terrestrial Energy, USA. Terrestrial Energy is pursuing the development of a molten salt reactor concept in which the fuel would be dissolved in the salt coolant. Terrestrial Energy researchers believe that the integral molten salt reactor (IMSR) technology is at a high technology readiness for market deployment in the 2020s, with an expectation that it will be able to compete with fossil fuels. Given increasing deployment of variable RE technologies, the electricity market places a high value on the ability of generators to ramp. The "rampability" of a nuclear system is defined by the core neutronics, balance of plant, and economics associated with the plant operation. Based on analyses to date, Terrestrial Energy expects the IMSR to meet the needs for power ramping very well, while also providing clean energy that is not subject to volatility in feedstock prices. Use of a nonnuclear solar salt for energy transport to the balance of plant significantly reduces cost and allows for remote use of the thermal energy output from the IMSR. Significant technical development and demonstration remains, but Terrestrial Energy has high confidence that the technology will be successful.

9. *Putting Synergies into Action: Integration of Nuclear and Renewables in Competitive Electric Markets*

Two breakout sessions were held on the second day of the workshop to further discuss the technical R&D needs and opportunities for collaboration to achieve deep decarbonization using clean nuclear and renewable energy technologies. The basis for these breakout sessions was established in a brief discussion moderated by Dr. Steven Aumeier, INL Associate Laboratory Director, Energy and Environment Directorate. The breakout sessions were focused around technical synergies and energy markets:

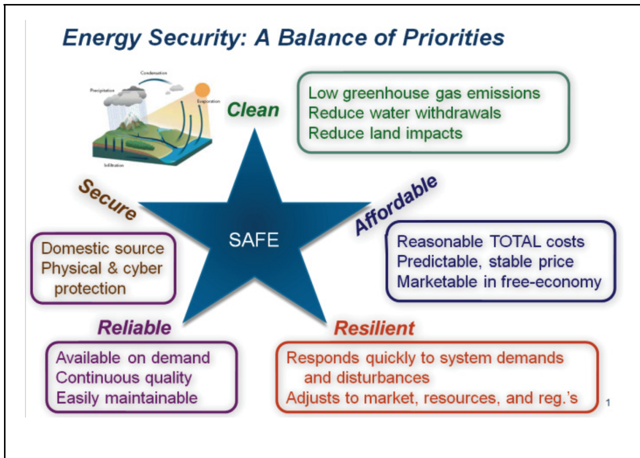
Breakout 1: Nuclear and Renewables – Research, Development and Deployment (RD&D) Synergies
Facilitators: Richard Boardman (INL) and Francoise Touboul (CEA)

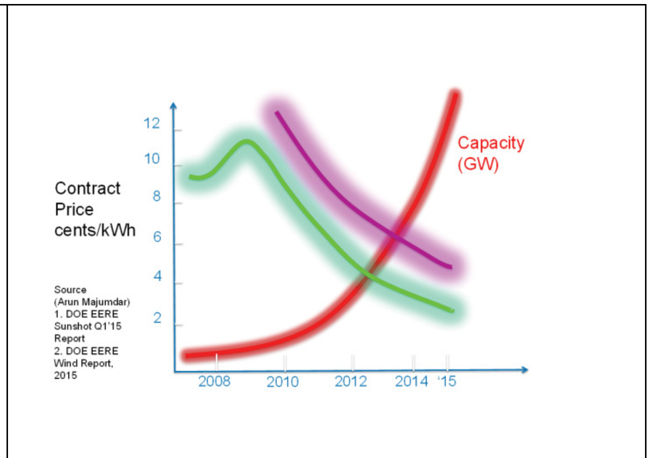
Breakout 2: Opportunities to Coordinate Analysis and Simulation
Facilitators: Mark Ruth (NREL) and William D'Haeseleer (Univ. of Leuven)

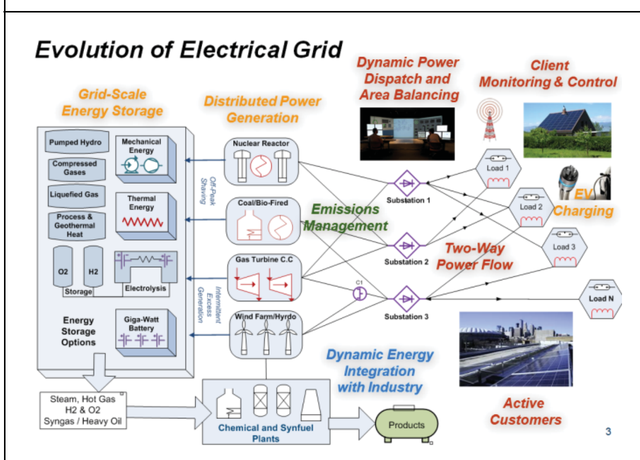
Participants rotated between the breakout topics in two groups. The overall conclusions/outcomes from each of the breakouts are summarized below.

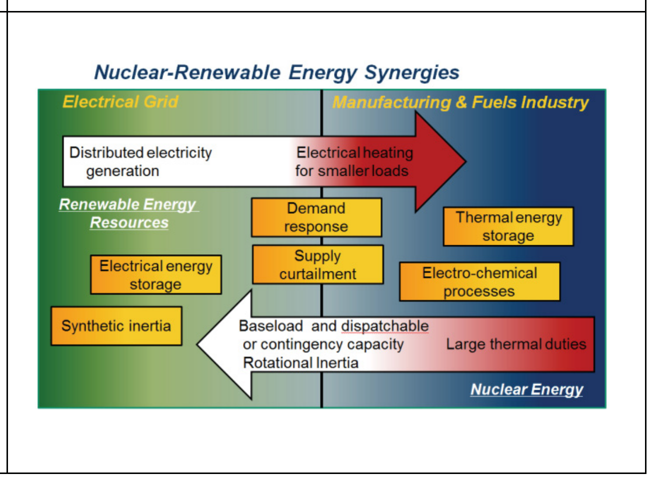
Breakout 1: RD&D Synergies
Facilitators: Richard Boardman and Francoise Touboul

The following charts were displayed to motivate the discussion of this interactive session:









- Frame 1 (upper left) was displayed to motivate discussion about the evolving social goals of energy production. In the future, it is anticipated that energy security will be valued versus just cost, reliability, and public safety – which are the main requirements for energy production today.
  - Workshop participants agreed that deep decarbonization must be the driver for future energy systems.
  - Participants noted that some energy sources, such as natural gas, are cleaner than coal, such that a transition to a low carbon society would likely pass through a series of changes in response to the price of energy and policy or regulatory requirements.
  - Clean coal was noted as one option for clean energy sources – potentially comparable to nuclear, but still facing the challenge of solving carbon capture and utilization or sequestration. The overall recommendation was to move beyond fossil fuel, although there appears to be a trend to use more fossil than nuclear energy to support the coordination with wind energy. It was noted that this practice is contributing to increased CO_2 emissions in some areas rather than reducing CO_2 to the extent desired or expected with renewables. A strong suggestion was made to look for new ways to operate nuclear plants in a flexible manner, and to increase the overall understanding of the safety of nuclear energy such that it will be more acceptable to the public. Education was mentioned as the key to building new nuclear reactors that could provide net load demand.
  - Regarding impacts on land, one contributor remarked that renewable energy sources and new power lines will occupy a large area, while nuclear energy is a concentrated source of energy. A suggestion was made to consider the synergy in the value for renewable energy as a distributed source on roof tops, and for wind where wide open spaces and marginal land value would not impact future land needs. On the other hand, nuclear energy might best serve locations where industry is concentrated to provide heat and electricity to industrial users as a priority.
  - A question was raised regarding nuclear's high water use for cooling towers given that LWRs demonstrate approximately 30-33% thermal-to-electrical conversion efficiency. Developers of advanced nuclear technologies asserted that high temperature gas reactors will use a Brayton power cycle, which does not involve steam systems. Other advanced reactors will also achieve higher efficiencies and, therefore, will likely use significantly less cooling water for equivalent power output. One individual remarked that at least one nuclear plant, the Diablo Canyon Power Plan, operates a desalination plant to purify water for plant cooling systems needs.
  - The discussion about water prompted a short discussion on use of concentrating solar energy and nuclear plants to produce fresh water. The regional case study conducted by INL and NREL for the state of Arizona was called out. In this case study excess electricity is used to dynamically operate a brackish water desalination plant.
  - The topic of resiliency was defined as two components – capability of the electric grid and industrial energy services to respond to price volatility of fossil fuels (and nuclear fuels to a much lesser extent) and the ability of the future grid to withstand disturbances in extreme climate conditions, including weather patterns that could affect with renewables or nuclear. The recent accident at Fukishima was noted as a one type of risk to nuclear. This comment motivated a brief discussion about the possible importance of microgrids with distributed

generation, such that the energy systems do not become entirely co-dependent. In addition, the role of small modular reactors was noted as a form of distributed energy.

  - The roles of hydrogen generation and energy storage were called out as a means of establishing greater resiliency and reliability. France, Canada, India, Japan, China, Germany, Denmark, and the United States were each mentioned as countries interested in the value of hydrogen generation. Ongoing research in hydrogen generation and utilization for power generation using large fuel cells, transportation using fuel cell vehicles, and industrial needs for hydrogen were recognized by several participants. The topic of producing hydrogen at scale (introduced as a DOE Big Idea referred to as H2@Scale) was discussed.
  - The low marginal cost of renewable energy, and over-generation capacity is motivating interests in using low-cost electricity to produce alternative products when the cost of electricity is low. These products could simply be thermal energy, clean water, or hydrogen. Business case analysis of the availability, cost of electricity, and market demand for the alternative products was discussed relative to participating countries.
  - The value of flexible operation of nuclear reactors – providing either electricity or steam/heat – was noted as a possible synergy with renewables. In the case of nuclear energy, the heat produced by the reactor can be used for power generation, or to provide an industrial user with heat, thus offsetting fossil fuel combustion. Participants noted that concentrating solar energy could also provide clean heat.
- Frame 2 (upper right). The future of renewable energy was noted by observing that mass manufacturing and economies of scale have reduced the cost of power production for solar PV and wind energy, but not for concentrating solar energy at this time. Comments from the participants included:
  - The cost of electricity was questioned; e.g., how much does the low cost of electricity production for renewables depend on investment tax credits (ITC) and production tax credits (PTC)?
  - The impact of renewable energy build-out on nuclear power plant operations was noted. Urgency was expressed in finding practical off-grid solutions to use nuclear energy.
  - The issue of replacing nuclear with low-cost gas-fired turbines was mentioned. Natural gas costs in the United States are currently low. Natural gas turbines can rapidly ramp up or down in response to net demand with increasing renewables. The concern mentioned was replacing nuclear plants with fossil-fuel based power plants, resulting in increased emissions. If nuclear reactors can be valued for their low-carbon electricity, then there would be incentive to keep these [nuclear] plants in operation while alternative [flexible] operations are developed.
  - A question was raised regarding mass production of SMRs and permitting costs: how can these costs be reduced with the 2^{nd}, versus the 10^{th}, reactor?
- Frame 3 (lower left). The evolving grid suggests several coordinated roles for renewables and nuclear energy. Here, the discussion was framed around the gird, energy storage, and energy delivery to industry and the transportation sector [not featured in the figure]. Comments addressed:
  - Energy storage via batteries is best for short time scales, but long time scales will require conversion to chemicals that have relatively high specific energy content. Geological storage would be necessary to use the excess generation capacity available during Spring and Fall to create stored energy.

- Battery technology will probably work best for hourly or daily electricity energy storage. However, storage of thermal energy from nuclear sources should also be considers, as should solar salt thermal reservoirs.
- Electrical energy can be stored by a concept referred to as resistive heating of firebricks. This would be done when the cost of electricity is suppressed. This proposed storage solution would be agnostic to renewables or nuclear energy. It was suggested that this could supply high quality “clean” thermal energy to industry. It was suggested that this might also provide “additive” efficiency to gas turbine or air Brayton power cycles.
- Longer energy storage at grid scale levels may support chemical production. This may take advantage of large seasonal variation between demand and generation capacity. A number of chemicals have been proposed. Hydrogen is a chemical that could be used for fuel cell vehicles and industrial applications. Hydrogen is needed in refineries, it is used for ammonia production, and it can be used for steel manufacturing. These markets all produce large CO_2 emissions. Hydrogen substitution for natural gas [Power2Gas] is considered a viable conversion route for excess generation capacity. This, in turn, will cut residential, commercial, and industrial CO_2 emissions that derive from burning natural gas to produce steam, or simply for space heating.

- Frame 4 (lower right). This figure was used to motivate discussion on synergies between renewable and nuclear energy where nuclear reactors may provide cost-competitive heat to industry and provide ancillary services to the grid, such as reserve capacity and mechanical/rotational energy to maintain grid stability. Renewable energy may extend beyond electricity markets. Manufacturing industries may be able to utilize electricity for heating and new electrochemical processes.
  - The importance of power quality control was mentioned. Frequency, voltage, and reflected power are currently maintained with power generators that provide discipline to the grid with large rotational turbine/generator sets that help maintain the frequency requirements. The ability to use power electronics to maintain power quality (referred to as synthetic inertia) was noted. Studies are needed to determine the cost-benefit of real versus synthetic inertia with increasing additions of renewable energy.
  - A study by NREL and INL to identify heat market opportunities was mentioned. The potential for electrification of industry was called out as a research opportunity.
  - SMRs can provide distributed power, and distributed heat generation for micorgrids or smaller industries. However, business models for energy parks could be considered.
  - Most chemical plants operate at steady state for technical and economic reasons.
  - EPRI recently completed a study on multi-energy/energy parks. This concept is applicable to nuclear-renewable energy systems.
  - Hybrid energy systems that utilize both nuclear and renewable energy sources to provide both heat and electricity are the subject of an NE-EERE partnership.

Discussion pertaining to collaboration among the various academic and government-sponsored institutions was mentioned throughout this session. A perspective on flexible [or hybrid] technology choices for near-term commercialization was mentioned as a priority for utilities that have operating nuclear plants.

Breakout 2: Opportunities to Coordinate Analysis and Simulation
Facilitators: Mark Ruth (NREL) and William D'Haeseleer (Univ. of Leuven)

The second breakout session focused on opportunities to coordinate analysis and simulation for energy systems. These discussions were facilitated by Mark Ruth (NREL) and William D'Haeseleer (KU-Leuven). The participants focused on the differences in analysis and simulation performed by the nuclear and renewable communities and identified areas in which the nuclear and renewable communities should work together to either ensure that communications are consistent or to leverage tools that have been developed by the other community. The breakout groups organized the opportunities into six categories:

- Benefits of nuclear, renewable, and nuclear-renewable systems;
- Environment / economics / policy;
- Power system interactions;
- Integrated energy systems;
- Communications and policy; and
- Fundamentals to analysis and simulation.

In the benefits category, participants focused on metrics, synergies, and trade-offs for nuclear, renewable, and nuclear-renewable systems. Regarding metrics, participants identified the need to quantify and communicate as many metrics as possible within analyses. Specific metrics that were recommended include the value of energy, capacity, ancillary services, resilience, sustainability, affordability, and security. Participants also recommended that analysts and policy-makers focus on the value of dispatchable power because that capability seems to be undervalued in today's markets and analysis. Two key metrics are profitability and risks to that profitability. Participants noted that low marginal costs and the uncertainty of future energy prices have the potential to reduce profitability and are definitely impacting investment decisions at this time. Participants noted that the levelized cost of energy (LCOE) metric is no longer a useful metric to identify potentially profitable options. Participants also requested a better quantification of synergies in tightly coupled nuclear-renewable hybrid energy systems that identify where the complexity provides value and communicates how compelling the hybrid energy system concept is and to whom.

In the environment / economic / policy category, participants focused on metrics that are often outside the investors' ledgers or are brought into ledgers through policy means. Participants recognized that identifying services provided to society is the key starting point in this category. Those services include energy necessary for heat, light, cooling, and transportation. Since the ability of different energy sources to provide those services differs (through the ability to store, through cleanliness of the method converting the energy carrier to the service, etc.) those should be included in the options. These metrics often include greenhouse gas (GHG) emissions, but other metrics often requiring analysis include water use, security, land use, and waste management. In addition, the impacts of those metrics are often dependent upon the region. Thus, participants noted that there is a synergistic need of both communities to improve the ability to perform life cycle assessments and communicate their findings. Participants also noted the importance of the energy system transition/evolution; hence, there is a synergistic opportunity to improve the tools and methods to evaluate energy system evolution and the impacts of new technologies within it and on the environment and society as a whole.

Another key category relates to interactions between nuclear, renewable, and nuclear-renewable systems and the power system (grid). Participants noted that electricity market design is of great interest to both the renewable and nuclear communities and that electricity may be undervalued as compared to other products; thus, the two communities would be well served to work together to inform decisions in market design. One key aspect of power system interactions is the potential for new transmission lines. These transmission lines may be difficult to build, so analyzing transition scenarios with and without new transmission lines would help identify potential issues and determine where society may prefer to select diverse technologies to prevent being locked into an uncertain future. Participants also noted that distributed energy resources are growing and likely to impact the overall value of generation options; a better understanding of that impact will help identify potential issues that both communities should address. In addition, participants are concerned about potential impacts on grid reliability and resilience especially with regard to external shocks including those caused by terrorism, weather, and solar weather.

The fourth category of opportunities is interactions within the integrated energy system (e.g., the grid as a whole). For participants, a key aspect of this category is the methodology and metrics used to assess the system as a whole. They identified the impacts of flexibility, capacity factors, and potential price suppression as key system-wide metrics for nuclear, renewable, and nuclear-renewable systems within the integrated energy system. Participants focused particularly on time signatures within these necessary analyses, especially regarding control designs and capabilities. Participants also recommended that incorporation of specific needs and constraints are often warranted within the system. One example is remote and islanded systems. Participants also discussed hydrogen production as another specific societal need that can be addressed jointly by the nuclear and renewable communities. For multiproduct systems such as N-R HESs, market issues such as uncertainty, development of effective business models, and opportunities to provide storage to the broader energy system likely need to be addressed via analyses by both communities. Safety issues were also discussed within this category. Safety issues include impacts on reliability, emergency response, and the basis for licensing nuclear reactors.

The fifth category that participants identified for potential coordination was communication and policy development. In that area, participants focused on implications of market surveys and competition to determine how the technologies might be synergistic. Participants also identified the need to look for cross-technology opportunities for initial demonstrations that can show benefits and help improve the story of joint benefits. Finally, participants discussed how to communicate the value of nuclear energy, particularly in two types of locations: (1) where renewable energy is well supported and (2) where there is a bias against nuclear reactors but not against reactors used for defense purposes.

The final category for synergies involves analysis fundamentals. Participants developed a short list of guiding principles for use in any analysis of the two types of technologies. That list includes:

- Guidance that all analyses should be compared to the competition;
- Evaluation of the implications of climate change on the technologies;
- Consideration of whether the analysis is most valuable for new (greenfield) facilities or for retrofitting (brownfield) facilities;
- Simple analyses should be performed initially and more complex analyses only as necessary (i.e., don't overthink the problem).

Participants also identified some foundational components that are likely to be valuable to both communities. These components include dynamic modeling capabilities; development, availability, and use of common data sources; and workforce education.

In conclusion, participants identified a number of opportunities for the two communities to interact and work together to improve the overall energy system, clearly conveying that further cooperation is warranted and desired.

Next Steps

From the perspective of the Workshop Chairman, this first "International Workshop to Explore Synergies Between Nuclear and Renewable Energy Sources as a Key Component in Developing Pathways to Decarbonization of the Energy Sector" succeeded in bringing together significant representation from most of the countries exploring the approaches by which the available clean energy sources (renewables, nuclear and, in the future, clean fossil) can work together to address the global challenge of major reductions in carbon emission. The assembled group generally agreed that synergies among clean sources will be essential to success and that diversity of clean sources will be vital, with recognition that reliance on a limited suite of clean sources may not provide the optimum global solution. The group also recognized that the current focus in several countries on reducing the carbon emission from electricity production can be only an early, partial start towards a solution, but this approach alone cannot enable a satisfactory resolution of the global carbon reduction dilemma. While there was limited discussion on technology options, the bulk of the Workshop discussion focused on system-level perspectives that require further exploration to develop detailed technological solutions appropriate to the constraints and interests of each nation and region.

There was strong consensus that future workshops of this type will be highly beneficial as alternative solutions are evaluated around the globe, initially with careful analysis and then with actual demonstration projects. Future workshops can serve both as a policy forum, to discuss evolving policy considerations, as well as an opportunity to consider specific technologies and solutions in greater detail. On behalf of the Chinese delegation, Dr. Mianheng Jiang offered China as the host country for the next Workshop – this offer was welcomed by the assembled group. The next Workshop will hopefully include countries that were unable to participate in the U.S.-based meeting, such as Korea, India, and the United Kingdom, as well as additional participants from some of the countries pursuing related work.

Appendix A

Workshop Agenda and Participants

Agenda

National Renewable Energy Laboratory, Golden, Colorado
June 9-10, 2016

Thursday, June 9

7:30 - 8:00 a.m. Continental breakfast

8:15 a.m. Welcome

- Mark Peters, Laboratory Director, Idaho National Laboratory
- Robin Newmark, Associate Laboratory Director-Energy Analysis & Decision Support, National Renewable Energy Laboratory

8:30 – 8:45 a.m. Workshop Objectives and Flow (Pete Lyons, Workshop Chair)

8:45 – 10:15 a.m. COP-21 and Grand Challenge of Decarbonization (Doug Arent, Moderator)

- Carla Frisch, Director for Climate Change, U.S. Energy Policy and Systems Analysis (EPSA)
- Manuel Baritaud, Senior Energy Analyst, International Energy Agency
- Mianheng Jiang, President, Shanghai Tech University, Chinese Academy of Sciences (CAS)

10:15 - 10:30 a.m. Break

10:30 -11:15 a.m. International Clean Energy Goals and Approaches (Pete Lyons, Moderator)

- Dr. Daniel Iracane, Deputy Director-General and Chief Nuclear Officer, Nuclear Energy Agency (NEA)
- Francoise Touboul, Scientific Advisory of the Chairman, French Alternative Energies and Atomic Energy Commission (CEA)
- Dr. Kamal Araj, Vice Chair, AEC, Jordan

11:15 -11:45 a.m. DOE NE and EERE Clean Energy Program Outlook (Mike Hagood, Moderator)

- Steve Capanna, Director, Policy and Analysis, U.S. Department of Energy - Energy Efficiency & Renewable Energy
- Suibel Schuppner for Shane Johnson, Deputy Assistant Secretary for Science and Technology Innovation, U.S. Department of Energy - Nuclear Energy

11:45 a.m. – 12:00 p.m. Buffet Lunch Pickup

12:00 – 12:45 p.m. Pathways to Deep Decarbonization in the United States, Jim Williams, Deep Decarbonization Pathways Project

12:45 – 2:00 p.m. Grid Modernization (Mark Ruth, Moderator)

- Jennie Jorgenson, Power System Analyst, NREL, Grid Operations and Flexibility
- William D'Haeseleer, Professor, University of Leuven, Belgium, Grid Modernization in Europe
- Nadav Enbar, Electric Power Research Institute (EPRI) Power Delivery and Utilization, Grid Modernization in the U.S.
- Marco Cometto, Nuclear Energy Analyst, OECD/Nuclear Energy Agency (NEA), System Effects in Low Carbon Electricity Systems

2:00 – 3:15 p.m. Expanding the Use of Nuclear and Renewable Energy (Daniel Iracane Moderator)

- Shannon Bragg-Sitton, NE-HES Technical & Project Lead, Idaho National Laboratory, LWR and HTR market opportunities
- Mark Ruth, RE-HES Technical & Project Lead, National Renewable Energy Laboratory, Nuclear Renewable Hybrid Energy System Market Opportunities
- Yuhan Sun, Director, Chinese Academy of Sciences, Shanghai Advanced Research Institute, CAS Hybrid Energy Systems Development in China
- Mark Haynes, President of Concordia Power, Next Generation Nuclear Plant (NGNP) Industrial Alliance, A Growing International Project for an Advanced Reactor Based Integrated Energy System
- Sam Suppiah, Nuclear Hydrogen Program Lead, Canada Nuclear Laboratories (CNL), Hydrogen production and utilization

3:15– 3:30 p.m. - Break

3:30 – 5:30 p.m. Emerging Nuclear Technology and Market Applications (Shannon Bragg-Sitton, Moderator)

- Zuoyi Zhang, Director and Chief Scientist, Institute of Nuclear and New Energy Technology (INET)
- Zhiyuan Zhu, President, Chinese Academy of Sciences (CAS) - Shanghai Branch
- Joshua Walter, Lead for Hybrid Energy Applications, TerraPower

6:00 p.m. - No host dinner

The Keg Steakhouse & Bar
14065 W. Colfax Drive, Lakewood, Colorado; (303) 238-7500

Friday, June 10

7:30 - 8:00 a.m. Coffee, Continental breakfast

8:00 – 9:00 a.m. Emerging Nuclear Technology and Market Applications (Shannon Bragg-Sitton, Moderator)

- Chris Colbert, Chief Strategy Officer, NuScale Power
- Kazuhiko Kunitomi, Director General of the High Temperature Gas Reactor (HTGR) Hydrogen and Heat Application Research Center of JAEA, Japan Atomic Energy Agency (JAEA)
- Simon Irish, President, CEO, Director, Terrestrial Energy USA

9:00 – 9:15 a.m. Setting the Stage with Objectives and Vision (Pete Lyons, Workshop Chair)

9:15 – 10:30 a.m. Breakout Group Brainstorming and Discussion

- RD&D Synergies (Richard Boardman & Francoise Touboul) in San Juan room
- Opportunties to Coordinate Analysis and Simulation (Mark Ruth & William D'Haeseleer) in Gunnison room

10:30 – 10:45 a.m. - Break

10:45 – 11:15 a.m. - Readouts

11:15 a.m. - 12:00 p.m. Frame next steps

- What are the collaborative R&D interests?
- How might we best collaborate?
- Is an international steering committee appropriate?
- Develop a charter to work together for deep decarbonization (or an agreement to form a consortium to form a charter), with a possible Secretariat

12:00 - 12:15 p.m. - Buffet lunch pickup

12:15 – 12:45 p.m. - Putting synergies into action - integration of nuclear and renewables in competitive electricity markets - Charles Forsberg, MIT

12:45 – 1:15 p.m. – Pete Lyons, Workshop Chair – Wrap Up

1:30 - 2:15 - Research Support Facility (RSF) Tour

2:15 - 2:30 - Walk to ESIF

2:30 - 3:30 - Energy Systems Integration Facility (ESIF) Tour

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June 9 – 10, 2016

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