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In less than 60 years we have witnessed the transition of nuclear electricity production from an experiment on the high desert of the western United States to more than 430 commercial nuclear power reactors deployed in 31 countries, supplying nearly 14% of all global electricity consumed. The speed at which this transition took place was stunning, as has been the evolution of the technology, business management and operations approach to civil nuclear electricity production. Even as the United States took a two-decade hiatus from the construction of new nuclear electricity plants, other nations embraced the technology and continue to do so. Today, there are 53 nuclear power reactors under construction, 142 planned and 327 proposed for development, including a number in the United States [1].

Clearly nuclear energy is and likely will continue to play a significant role in providing access to clean electricity on a global scale, although questions related to used fuel management, plant safety, and nonproliferation create some uncertainty as to scale and timing of this contribution.[2] However, as global population reaches an expected 8 billion people by 2030, primary energy consumption is expected to increase by almost 40% from approximately 520 exajoules consumed today to almost 740 exajoules. [2,3] Much of this increase is expected to come from non-Organization for Economic Cooperation and Development (OECD) nations, and Asia specifically. In these economies, energy used for transportation is expected to grow substantially, as is industrial, commercial and to a lesser degree residential energy use, creating considerable pressure on global and local energy markets. The magnitude and timing of growth in energy consumption likely will create a global imperative to deploy energy production technologies that balance the three pillars of energy security: [4]

- economic stability – related to the affordability of energy products, stability and predictability in their price, and the efficient and effective deployment of global capital resources in their development;
- environmental sustainability – related to minimizing the negative impacts of energy production to air, land, and water systems and advancing the long-term viability of using a particular resource in a way that does not limit future generations ability to prosper;
- resource security – related to the ability to access energy resources and products where and when necessary, in an affordable and predictable manner;

Some analyses [3] see this "scramble for energy" as being the source of significant tension, making advances in technology and infrastructure development based on the energy security paradigm described above a global imperative.

Clean energy resources such as nuclear, solar, and wind have the potential to satisfy part of the growing energy demands, even as global use of fossil energy, particularly coal, continues to rise.[2,3] However, fully leveraging these clean energy resources to advance energy security (as defined above) will require new technology and energy system deployment approaches that allow these resources to be more fully integrated into energy markets beyond electricity (primarily industrial processes and transportation). Additionally, approaches will be required that foster more efficient, effective electricity production and transmission systems. Such approaches should seek to mitigate the impact of intermittency created by integration of major renewable energy resources, and avoid mismatches between load and generation created by integration of large nuclear reactors in constrained electricity markets. These challenges cause either inefficiency in capital deployment and/or system instability. Simultaneously, development of energy production approaches that leverage clean energy resources with fossil energy resources, particularly abundant coal and methane, to provide energy products with lower lifecycle greenhouse gas emissions characteristics would be beneficial in promoting global energy security.

One approach to meeting these objectives is hybrid energy systems (HES). Broadly described, HES are energy product production plants that take two or more energy resource inputs (typically includes both carbon and non-carbon based sources) and produce two or more energy products (e.g. electricity, liquid transportation fuels, industrial chemicals) in an integrated plant. Nuclear energy integration into HES offers intriguing potential, particularly if smaller (<300 MWe) reactors are available. Although the concept of using nuclear energy in a variety of non-electrical process applications is certainly not new (e.g. Reference 5), renewed interest in more tightly coupled energy product plants (such as HES) that meet the objectives outline above have gained additional interest recently (e.g. Reference 6), an interest likely sparked by sharpening energy security concerns. Studies have shown that non-nuclear integrated (hybrid) energy systems can have appealing attributes in terms of overall process efficiency [7], enhanced electric grid stability, renewable energy integration, and economic performance [8,9,10], and lifecycle greenhouse gas emissions [11]. These attributes seem to be sufficiently compelling that several significant commercial investments in fossil-renewable HES are being made in the United States [12,13] while the U.S. Defense Advanced Research Projects Agency (DARPA) has openly solicited information regarding nuclear energy integration schemes [14]. In testimony before the U.S. Senate, a senior researcher at Rand Corporation summed up the potential value of hybrid systems well, stating "… the combined use of fossil and solar or nuclear technologies may make for cost-effective and environmentally superior approaches".[15]

To illustrate a few of the attributes of a nuclear HES, consider a system based on a 3 GWe high temperature reactor island, coupled with a coal gasification complex accepting 8,000 metric tons/day coal. Rudimentary process flow calculations show that such a process could produce approximately 50,000 barrels per day of synthetic liquids suitable for transportation fuel costing under $1.00 / liter (refinery gate price) and simultaneously provide 300 MWe to the electrical grid. The lifecycle CO_2 emissions of the transport fuel are very favorable at approximately 90% of the emissions expected from fuel derived from moderate quality petroleum. The lifecycle CO_2 emissions can further be reduced, in the extreme to 10% of the petroleum-based fuel case, by mixing or replacing the coal feedstocks with biomass. The ability of such a system to provide greater grid stability while accepting intermittent renewable electricity is also appealing. By producing more than one energy product, this HES adds an additional degree of freedom in the electrical production and distribution system, essentially acting like a large energy storage mechanism for the electrical grid in that baseload generation could be economically built in excess of peak electrical load, with the excess energy diverted to production of liquid transportation fuels and chemicals such as ammonia, fertilizer and other energy products. The liquid fuel / electricity / chemicals split could conceptually be managed to match varying energy product demand conditions on various time scales, from weeks to decades, providing appealing system flexibility. Such systems could therefore provide a "bridge approach" to greater electrification of the transportation sector. Additional detailed analyses performed [16] focused on high-temperature reactor applications and their attributes in a number of process schemes. It is important to note that although high-temperature reactor systems (those with outlet temperatures exceeding 700^0 C) may be more efficient drivers of HES than light water reactor technology (with outlet temperatures of approximately 320^0 C) for some applications (those requiring high process heat temperatures), the latter is likely still feasible in all applications with outlet temperature boosted by either fossil or renewable energy integration. Studies are now underway at Idaho National Laboratory to examine these light water reactor hybrid systems.

Nuclear hybrid energy systems such as the one described above may provide a new paradigm for advancing global energy security, allowing for more environmentally sensitive use of domestic carbon resources, electrical grid stability while integrating renewable energy, and lessening a states dependence on increasingly strained global energy trade. Through process integration, HES are able to extract the positive attributes of various energy resources while mitigating the negative attributes (e.g. CO2 emissions, variability). These systems are generally more efficient producers of energy products as compared to single-resource based systems, allow for a more fungible use of energy sources, and greater energy system flexibility and resiliency. These hybrid nuclear energy systems could extend the potential markets for nuclear energy substantially and offer an attractive route to more effectively manage the lifecycle of carbon resources across the entirety of the global energy market, not just electricity production. New advances in smaller, more affordable reactors may also expand the potential markets for nuclear HES by creating more flexible and affordable options for integrated system deployment.

Deployment of nuclear HES on a meaningful scale would be non-trivial. The nuclear and non-nuclear "islands" that comprise these systems each contain numerous technology challenges that must be addressed to assure economic feasibility, affordability, operability, and safety on a large scale. Most importantly, the systems would be tightly coupled, suggesting a significant influence on design attributes of between the nuclear and non-nuclear systems. This coupling would suggest that to advance the HES approach would require integrated dual-track research, development, and demonstration (RD&D) programs not now found in any significant instance in today's nuclear energy research and development programs. Such a coupled program would consist of a simultaneous focus on nuclear energy technology and nuclear energy integration technology. The former includes the focus familiar to many nuclear RD&D enterprises: reactor systems, fuels, fuel cycle systems, materials, licensing, etc. that are well summarized elsewhere (e.g. Reference 17). Additionally, a substantial role for nuclear energy beyond electricity production may significantly strain present global nuclear fuel cycle resources and would need to be carefully considered. The challenges of nuclear energy integration include myriad issues associated with the following RD&D areas, or "platforms":

- feedstock processing (e.g. bio-feedstock integration with coal, carbon feedstock extraction using nuclear energy);
- heat / energy management (e.g. advanced heat exchangers, process design);
- energy storage (e.g. H_2 production, liquid fuels synthesis);
- byproduct management (e.g. CO2 recycle approaches);
- systems dynamics, integration and control (e.g. process dynamics analyses and optimization, advanced prognostics, diagnostics, variable time scale control and flow sheet optimization).

These coupled-systems RD&D challenges, both nuclear energy technology and nuclear energy integration oriented, offer a rich area of research and a compelling need for pilot-scale process demonstration and testing. Addressing these challenges would provide the foundation for advanced deployment of nuclear energy. The U.S. Department of Energy Office of Nuclear Energy, Science and Technology is beginning to see the value in pursuing the nuclear energy integration approaches, as evidenced in their stated RD&D priorities [18] and the Idaho National Laboratory is building facility infrastructure associated with these HES RD&D platforms.

Global energy security imperatives will create a strong motivation, possibly the inevitability, of much stronger energy system integration. Nuclear energy will not be immune to this trend. Nuclear HES may offer compelling energy security attributes for both developing and more mature economies and could provide a paradigm shift in energy systems architecture that allows a faster transition from greenhouse-gas intensive systems to clean energy systems. A coupled nuclear energy technology, nuclear energy integration RD&D program focused on HES design and demonstration may be well suited for international collaboration, and become a hallmark for the next 60 years of nuclear energy development.

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