Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments

U.S. DEPARTMENT OF ENERGY

Hybrid Nuclear-Renewable Energy Systems

Chapter 4: Technology Assessments

Introduction and Background

This Technology Assessment summarizes the current state of knowledge of nuclear-renewable hybrid energy system (N-R HES) concepts and associated technology development needs. Some of the principles addressed in this technology review may also apply to other hybrid energy systems (see Chapters 2 and 7 of the main report of the Quadrennial Technology Review). The main purpose of an N-R HES is to use nuclear energy, variable renewable energy sources such as wind and solar, biomass energy, or others as clean energy sources to support electrical and thermal duties of electricity generation, fuels production, chemical synthesis, and other industrial processes at competitive prices and to thus decrease greenhouse gas emissions (GHG) by the electricity, transportation, and industry sectors. Such hybrids would differ substantially from traditional systems that typically use just one or perhaps two energy sources (e.g., biomass co-firing with coal) to produce electricity and sometimes useful heat (cogeneration systems).

Wind and solar power generation accounted for about two-thirds of all U.S. electricity generating capacity additions in 2015. Increased penetration of variable renewable energy systems such as wind and solar PV increases the need for flexible generation—as can be provided by dispatchable intermediate and peaking units, as well as through more flexible loads—as can be provided by demand-side management, in order to maintain system voltage and frequency within limits. (Intermediate units serve the large fraction of demand between baseload units, which provide nearly constant demand 24 hours per day, and peak units, which serve the very highest demands that occur a few percent of the year or that serve demand when events such as a generator or transmission failure require the rapid response capabilities of peaking units.) Such flexible generation generally also has greater value in electricity markets than baseload or variable supplies. N-R HES may serve an important role in providing this flexibility.

Flexible N-R HES architectures of interest include the following:[1]

1. **Tightly Coupled N-R HES:** In this architecture, nuclear and renewable generation sources and industrial processes would all be linked and co-controlled behind the electricity bus, such that there would only be a single connection to the grid, as shown in Figure 4.K.1. The closely coupled system would likely be managed by a single financial entity to optimize profitability for the integrated system.
2. **Thermally Coupled N-R HES:** This architecture would thermally integrate subsystems and tightly couple them to the industrial processes, but the nuclear and renewable electrical subsystems could have more than one connection to the same grid balancing area and would not need to be co-located, but would be co-controlled to provide energy and ancillary services to the grid. The thermally integrated subsystems would need to meet industrial process requirements considering the required heat quality, the heat losses to the environment along the heat delivery system, and the required exclusion zone around the nuclear plant. These systems would likely be managed by a single financial entity (see Figure 4.K.2).

3. **Loosely Coupled, Electricity Only N-R HES:** This configuration would be electrically coupled to industrial energy users but there would be no direct thermal coupling of subsystems. This design would allow management of the electricity produced within the system (e.g., from the nuclear plant or from renewable electricity generation) prior to the grid connection. Although there would not be a direct coupling of thermal energy to the industrial processes, the system could include electrical to thermal energy conversion equipment to provide thermal energy input to the industrial process(es). Such an option may allow for potential retrofit of existing generation facilities with fewer regulatory challenges. These systems could have more than one connection point to the grid but would likely be managed by one financial entity (see Figure 4.K.3). Molten salt reservoirs such as those currently being used to store concentrated solar energy, or a mass of firebrick similar to heat recuperators used by the steel manufacturing industry[2] may provide thermal energy storage for the heat that can be generated from electricity. In principle, electrical-to-thermal energy conversion would be economical when the cost of producing heat by these systems drops below the cost of producing heat from traditional combustion-fired process heaters. The type and quality of heat must match the industrial heat user technical specifications.

Figure 4.K.1 General architecture for a tightly coupled nuclear renewable hybrid energy system, where the generation sources are integrated behind a single connection point to the grid and are managed by a single financial entity.

Credit: Idaho National Laboratory

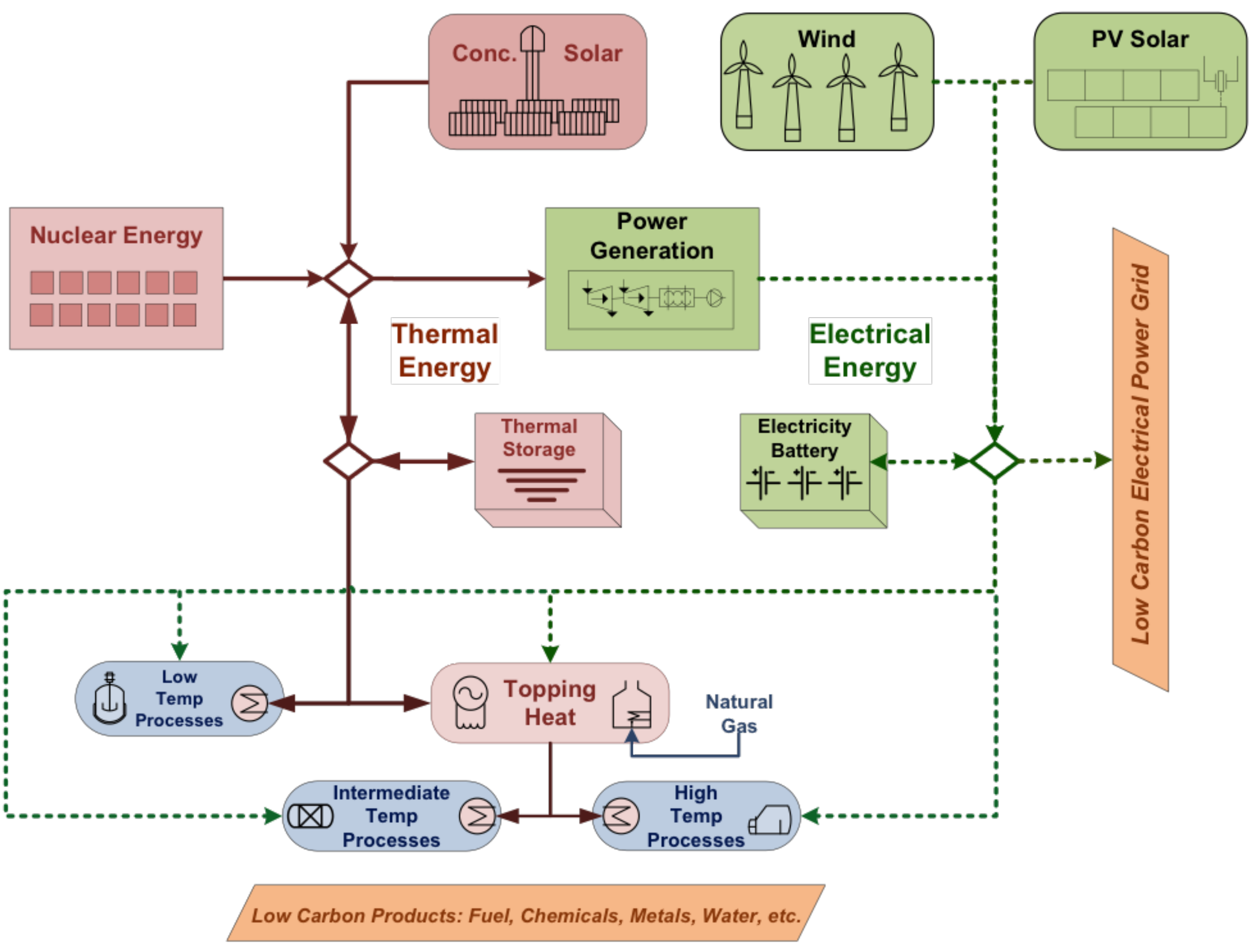


Figure 4.K.2 General architecture for a thermally coupled nuclear renewable hybrid energy system, where the nuclear and renewable generation sources are co-controlled and managed by a single financial entity but may not be co-located.

Credit: Idaho National Laboratory

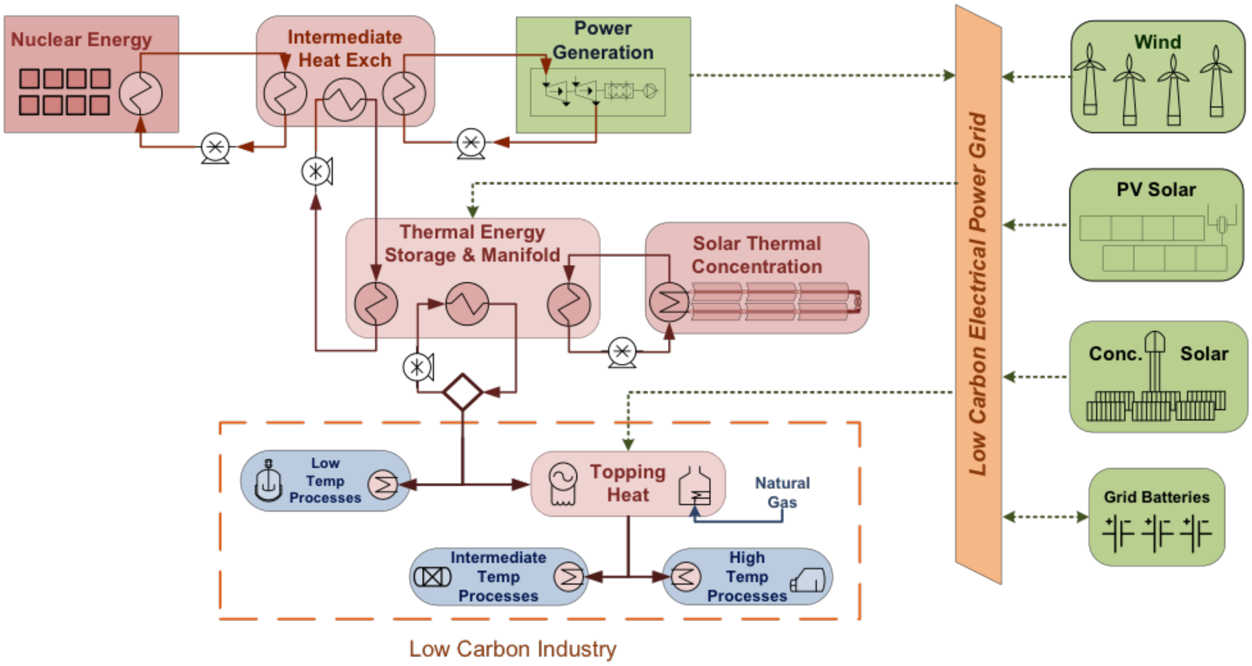
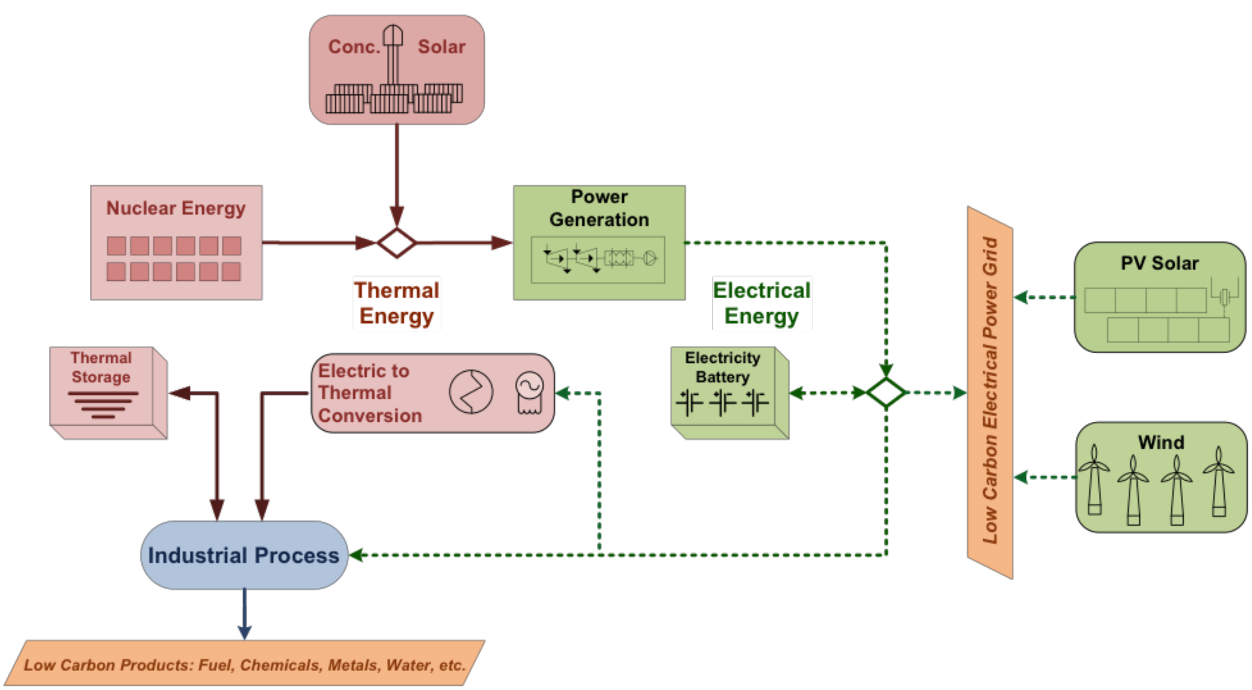


Figure 4.K.3 General architecture for a loosely coupled (electricity only) nuclear renewable hybrid energy system, where the generation sources are only electrically connected to the industrial process. Note that electrical to thermal energy conversion systems may be included to provide thermal energy to some processes.

Credit: Idaho National Laboratory



The following major components would be present in each of the illustrative N-R HES:

- *Nuclear reactor(s).* The nuclear reactor would provide baseload heat and power without direct[3] emission of GHGs. The nuclear system should operate at a high capacity factor to cover capital and operating costs. The reactor(s) would also perform more efficiently and maintenance costs would be minimized if operated near steady state design conditions. Nuclear generated heat would be apportioned to the industrial process and storage, to the power generation system, and to fuels production (such as hydrogen) based on net loads and optimum earnings.
- *Power generation.* The steam turbine in the power generation subsystem would convert thermal energy generated by the nuclear reactor into electrical power. The amount of power generated could be ramped up or down depending on the amount of steam dispatched to it; hence, it would be a flexible generator of electricity. The other thermal energy produced by the nuclear reactor could be used for industrial processes, fuels production, or stored. Steam turbines' large mass provides significant rotational inertia, and together with the synchronous generators they drive, they could help support grid frequency stability.
- *Renewable energy generator(s).* The renewable source(s) would provide near-zero marginal cost energy (heat and/or power) without direct emission of GHGs. Generation by variable renewable technologies (i.e., solar photovoltaic [PV] and wind), however, is not substantially dispatchable, meaning that it cannot provide large amounts of power as needed to follow grid load. Electricity and heat from renewable energy sources could also be used by the industrial process, fuels production, or stored.
- *Industrial process.* When coupled within an N-R HES, the industrial process would receive heat and/or power from the nuclear reactor(s) and the renewable energy source(s) as needed or as available. The system would use that energy to produce high value products or fuels that would provide another income stream for the N-R HES. When heat from the nuclear reactor is diverted to power production, the heat needed by the industrial process could be provided by stored thermal energy or derived from another clean energy source such as a biomass boiler when constant operation of the industrial process is necessary or desired.

  N-R HES differ from combined heat and power systems to the extent that the goal is not solely co-generation of heat and power for local industrial plant uses; rather, the goals also include the transfer of as much low-carbon energy to the industrial process as possible. N-R HES are essentially a co-optimization approach to support grid reliability and stability and to support industrial production, providing power generation and thermal energy to industry while maximizing profitability and minimizing GHG emissions. Details on DOE's CHP research activities can be found on the DOE-EERE home pages.[4]

  With the advent of Small Modular Reactors and Concentrating Solar Thermal Power (CSP) systems, the potential exists to apply these to CHP applications in the traditional manner where heat generation is located in proximity to the industrial process. DOE is currently completing a technical assessment of heat markets in the U.S. Opportunities for nuclear and renewable energy sources for heat applications are currently being evaluated.[5]
- *Storage (electrical, thermal, and/or chemical).*[6] Electrical storage options include batteries and flywheels. Thermal storage options include both liquid (e.g., molten salt) and solid (e.g., firebrick) forms.[7] Chemical storage could include hydrogen production, such as through thermally-assisted electrolysis. Heat removed from storage could be used either directly in the industrial process or to generate power.

Tightly coupled and thermally coupled N-R HES concepts would require a dual heat delivery system and the controls necessary to apportion heat between power production, a given industrial process, or fuels production. Similarly, the electrical output would be apportioned between the grid, the coupled industrial process, or fuels production. If necessary, power would be drawn from the grid and combined with the heat and/or electricity delivered from within the hybrid system to operate the industrial process. In the thermally coupled case, the renewable subsystem could be loosely coupled and operated in close coordination with the nuclear subsystem via the grid balancing area. Thermal energy generators (e.g., nuclear reactor and CSP) could supply heat, steam, and power to the manufacturing industry or power to the grid, apportioned to maximize earnings. These systems could operate as dynamic cogeneration plants, adjusting output to meet grid needs and to maintain economic operation of the overall plant.

By comparison, traditional nuclear power plants typically connect to the grid alone.[8] Interaction between generators is variously managed by independent system operators (ISO), Regional Transmission Organizations (RTO), utilities, cooperatives, Federal systems, etc., depending on the location and level.

Successfully developed, N-R HES could potentially provide significant benefits, including:

- Reducing the cost and volatility of energy production, particularly by helping balance electricity supplies from variable renewable sources;
- Providing dispatchable, carbon-free electricity generation for the grid, with little to no impact on the nuclear reactor operations profile which can have technical impacts on the core, fuels, and heat transfer loops;
- Providing more efficient utilization of capital equipment by providing a second customer for the heat that can be generated by the nuclear reactor, which at some point may be lower cost than producing heat from combustion sources;
- Providing greater grid support than variable renewable sources alone;
- Reducing the carbon footprint of the industrial sector; and
- Reducing energy system impact on fresh water resources when using excess thermal or electrical energy to produce potable water, and by coupling low temperature heat rejection to an industrial heat user rather than relying on a cooling tower to condense the power cycle water.

Matching Energy Capacity and Energy Markets

In 2014, the U.S. electrical power generation capacity exceeded 1,068 GW.[9] In this same year, U.S. electricity consumption totaled 3,900 billion kWh in sales to end users,[10] or about 450 GW on a continuous output basis. This indicates a significant amount of the overall power generation capacity (about 60%) is idle for substantial periods during the year. Depending on the season of the year and diurnal use patterns, the location and type of power generation facilities, and the disposition of hydro and variable electricity generation sources, a significant percentage of the power generation capacity could, in principle, be directed part-time to industrial processes. Initial estimates indicate that about one-third of the current power generation resources could be re-directed to manufacturing and fuels production.[11] Hybrid energy systems look to expand thermal and power generation to industrial manufacturing and fuels production with better overall capacity utilization. With the build-out of renewable power, hybrid systems could offer an alternative off-take for baseload nuclear plants that are optimally operated at their name plate capacity. Additionally, hybrid systems may offer another option for managing the electricity that will be produced by renewable energy sources.

Market opportunities to apply a large amount of energy on a variable basis have been presented in recent publications by researchers at the Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL), and the National Renewable Energy Laboratory (NREL).[12, 13, 14, 15] A breakdown of the energy use of the top six industrial energy users is summarized in Table 4.K.1. Other industries with large energy use include inorganic minerals production (cement, phosphates, sodium carbonates, silica, etc.), textiles, glass, and computers and electronics. Prime opportunities for using N-R HES include industrial plants that have high steam duties and processes that require low to intermediate temperature heat. Small modular reactors (SMR) are an appropriate size to service some of these plants and could be located near these end users to service them.

Table 4.K.1 Annual Energy Use of the Six Largest U.S. Industrial Users of Energy in Exajoules (EJ)[16]

	EJ Electrical	EJ Steam Systems	EJ Fired Heaters	EJ Total by Industry
Chemicals	1.1	1.7	1.3	4.1
Petroleum Refining	0.3	1.1	2.2	3.6
Forest Products	0.8	2.6	0.2	3.6
Iron & Steel Mills	0.2	0.1	1.5	1.8
Food & Beverage	0.3	0.6	0.3	1.2
Mining	0.7	0.03	0.2	0.9
Total (EJ)	**3.4**	**6.1**	**5.7**	**15.2**

The benefits of SMRs potentially include reduced manufacturing costs, safety advantages, incremental scalability, reduced land use, and, in the case of high temperature reactors, reduced water usage.[17] Some designs provide passively-safe, gravity-driven, natural circulation through the primary core. Some designs are submerged in the coolant pool to provide long term to permanent emergency cooling and some are below ground to be more tolerant of physical damage by earthquakes or tornados. Multiple barriers are designed-in to prevent the release of radiation should an accident occur and could potentially allow an SMR to be located adjacent to an industrial user, and in closer proximity to population centers.[18]

Flexible operations could also enable production of clean water from saline or compromised water sources for use in power plant, industrial, or even community services. Water desalination is one option for flexible operation of an existing plant or for future SMRs.[19] The IAEA has an on-going program to address the issues related to the use of nuclear energy for desalination of alternative sources of water, including wastewater from municipalities, agricultural runoff, brackish groundwater, or seawater.[20] A recent study of a N-R HES indicates fresh water may be efficiently and cost-effectively produced from brackish water in the Southwest U.S. when future demands exceed fresh water availability.[21] Clean-up of water displaced from deep saline aquifers by future CO_2 injection into these reservoirs to sequester the carbon is another potential application. Low-rank coal drying could release significant by-product water that could be cleaned and used for other purposes.

New energy systems might also be integrated with process heat applications.[22] This could, for example, reduce the water cooling requirements of SMRs that are located in proximity of the heat application. Such cases could operate like a traditional CHP system where the SMR is located near the industrial heat user, such as for inorganic minerals concentration and drying, or for distiller grain drying and for distillation in corn-ethanol plants. Other less apparent industrial uses might include paper pulp operations (~10-20 MWt is typical), food processing plants (~5-20 MWt is typical), and chemical plants (e.g. methanol distillation), with a typical plant using 100 MWe and 90 MWt).[23]

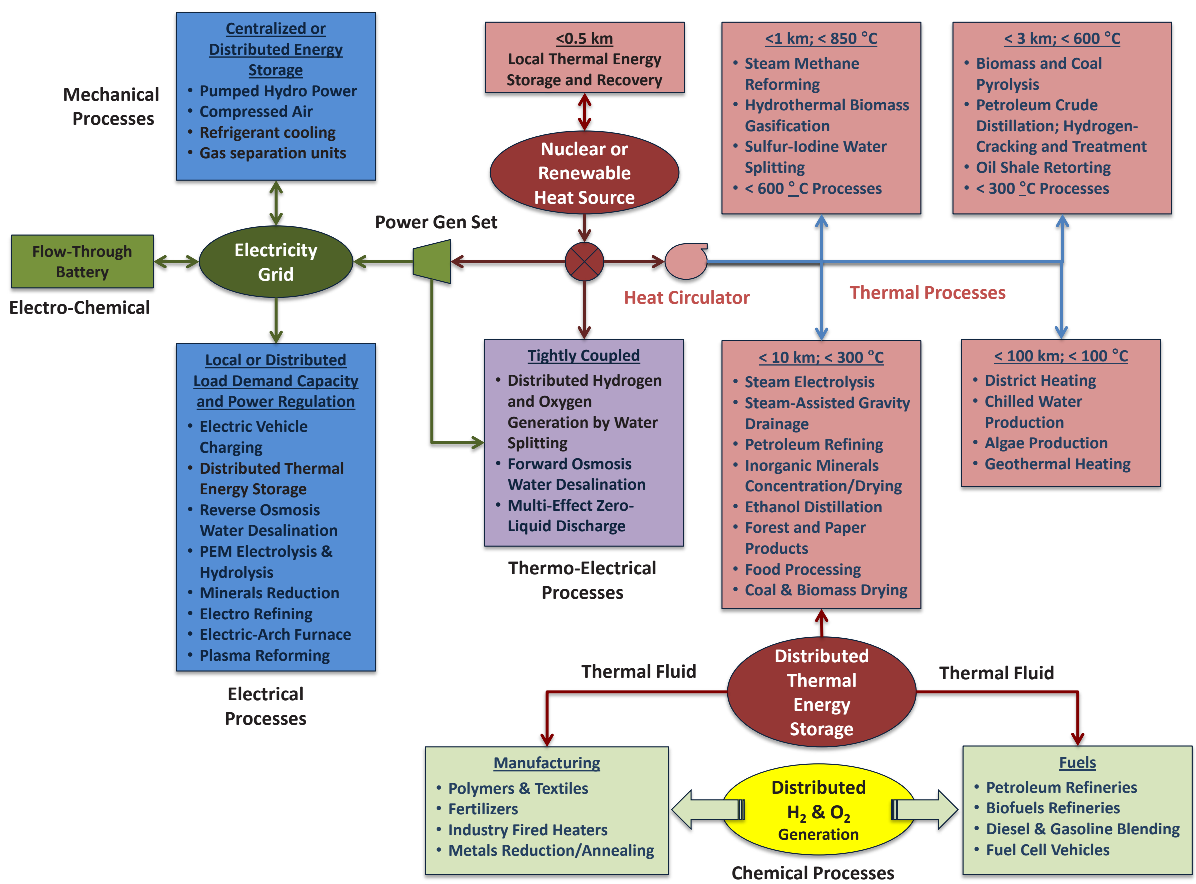
The reactor design could be optimized for a particular industrial service, considering the process heating requirements relative to scale, peak temperature, steam quality, time-of-use, overall conversion efficiency, and other factors. In some cases thermal energy storage in a steam accumulator or a molten salt or liquid metal tank could be used to buffer the thermal/electrical energy available from the N-R HES or from the grid. Technical assessment of the scale, duty cycles, and associated costs of thermal energy storage buffers is needed for future DOE or industrial consideration of possible hybrid configurations. Hybridization options will vary in accordance with regional resources, industry, electricity, and financial markets.

Nuclear Hybrid Energy System Configurations

Figure 4.K.4 illustrates possible industrial opportunities for N-R HES. The design basis for these depends on case-specific industrial user technical requirements and economic drivers associated with these or other options. Systems should be tailored to regional resources and markets to dynamically optimize the use of thermal and electrical energy. Definition, prioritization, and analysis of key options based on pertinent figures of merit are necessary to identify energy systems that have the greatest likelihood for success.

Figure 4.K.4 Summary of potential N-R HES applications indicating energy conversion varieties possible and their appurtenant processes.[24, 25] Heat transfer distances are only an approximation based on preliminary calculation under the Next Generation Nuclear Plant (NGNP) Program.[26] Arrows indicate energy flows. Color is only intended for graphical rendering.

Credit: Idaho National Laboratory



Heat delivery to meet end user requirements depends on the physical properties and temperature of the heat transfer fluid and the design of the thermal hydraulics system. Temperature and distance comparisons are indicative of the challenges of distributing heat at a specific temperature (and for a particular working fluid and heat exchanger) from a nuclear reactor to an industrial user. The distances shown are an initial approximation of the distances that various heat levels can be economically circulated for heat deposition at the industrial user site. Actual distances will vary depending on design and economics of the system. Direct (or tight) coupling with the industrial user can include purely thermal energy, purely electrical energy, or a combination of the two. Thermal, electrical (e.g., Compressed Air Energy Storage, Battery Storage), and chemical derived energy can be stored and then delivered to industry when needed.

Previous DOE efforts have included technical and economic evaluation of the use of nuclear heat for cogeneration applications under the Next Generation Nuclear Plant (NGNP) program.[27, 28] The NGNP Alliance with industry continues to develop heat application markets for the high temperature gas reactor (HTGR) with an outlet of approximately 750°C helium based on current code-qualified materials. The results of these studies indicated one or more of the nominal 600 MWt plants could supply the quality and quantity of heat needed for steam methane reforming to produce hydrogen, ammonia and ammonia-based derivatives (ammonia-based fertilizers, nitric acid, urea), synthetic chemicals, and non-conventional fuels (from oil sands, oil shale, coal, and natural gas). Although the capital investment for a nuclear plant is comparatively higher than traditional fossil-fired heat sources and steam boilers, the analysis indicates that heat produced from nuclear reactors could favorably compete if fossil fuels combustion took into account estimated externality costs of GHG emissions.

Currently, N-R HES applications for all classes of reactors are being investigated by the DOE Office of Nuclear Energy (DOE-NE). Program milestone reports compare the differences between potential N-R HES applications in the electrical power market with coordinated synthesis of methanol from natural gas and hydrogen production through high temperature steam electrolysis, as two examples representing large chemical industries in the United States.[29, 30]

In a project that is coordinated between DOE-NE and DOE-Energy Efficiency and Renewable Energy (DOE-EERE), the value proposition and technical integration challenges of nuclear and renewable energy in hybrid systems are being evaluated.[31] Two regional cases were selected for detailed evaluation in West Texas, where wind and natural gas are plentiful, and in northeast Arizona, where solar energy is abundant and brackish water can be purified for potable use. These studies are intended to help identify the hybrid systems R&D needs, and some of the findings are provided below.

Nuclear Hybrid Energy System Example

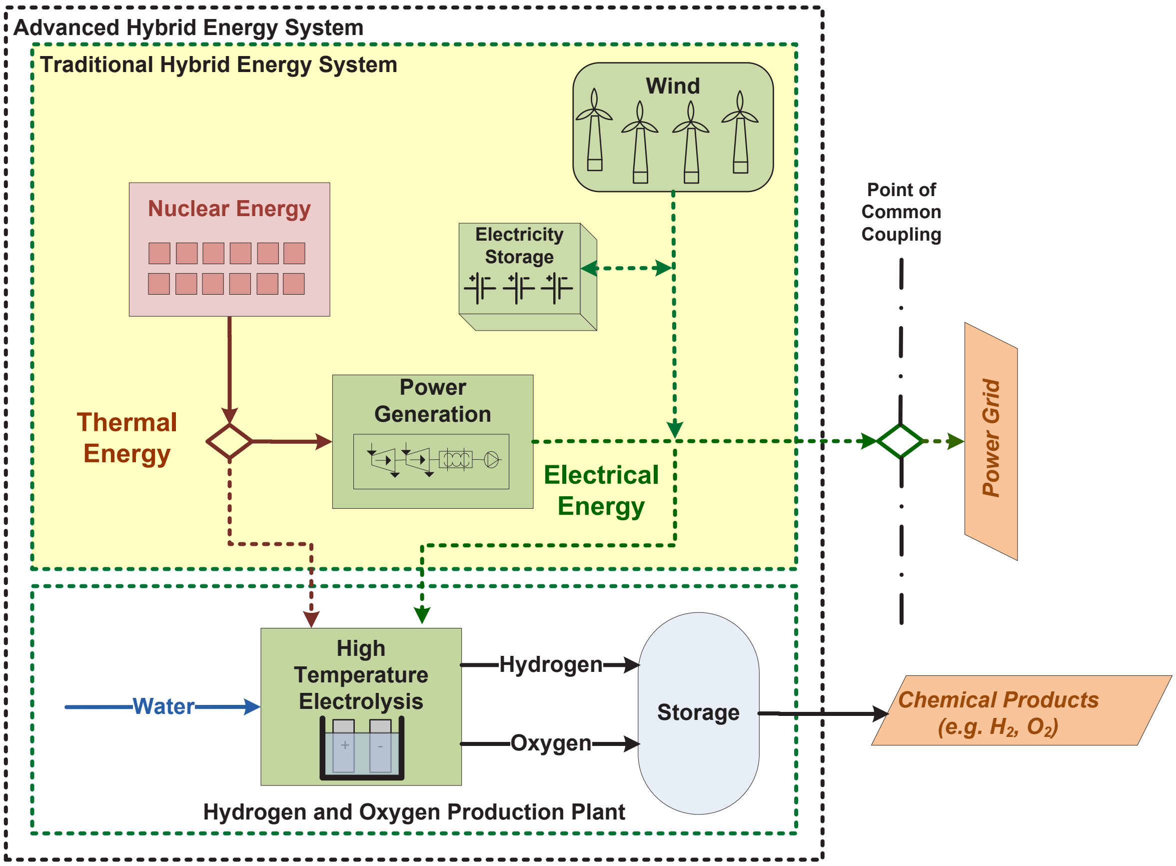
In evaluating N-R HES, the first question that arises is, "Can electricity and heat be manipulated in a dynamic manner that corresponds to the ramp-up or ramp-down demands of grid load-following power generation dynamics?" The second question becomes, "How efficient is the utilization of capital investments?" The latter question should be cast relative to alternative capital investments that are required to accommodate the variability of renewable energy sources, whether the capital investments are new transmission and distribution lines for wider area balancing control, storage, demand response agents (i.e., meters and controls), or hybrid energy systems components.

Figure 4.K.5 illustrates the coupling of nuclear and wind to produce power in response to grid demand up to the maximum generation capacity of the combined resources, and to produce hydrogen by steam electrolysis when demand for electricity falls below the capacity of the system.[32] In this illustrative example, power generation was assumed to be the highest priority, even when the market may actually drive the systems to produce hydrogen any time the value of hydrogen is higher than electricity.

In general, a loosely coupled, electricity-only HES involves only power production with multiple generators supplying a single output of electricity to the electrical grid-as described in a recent DOE report.[33] The "advanced hybrid energy system" defined within this study falls into the category of a thermally coupled HES through the addition of time-varying hydrogen production when heat and electricity are transferred to the steam electrolysis plant, creating a second product output.

Figure 4.K.5 Possible configuration for a traditional hybrid energy system (yellow box) versus an advanced hybrid energy system (large box).[34]

Credit: Idaho National Laboratory



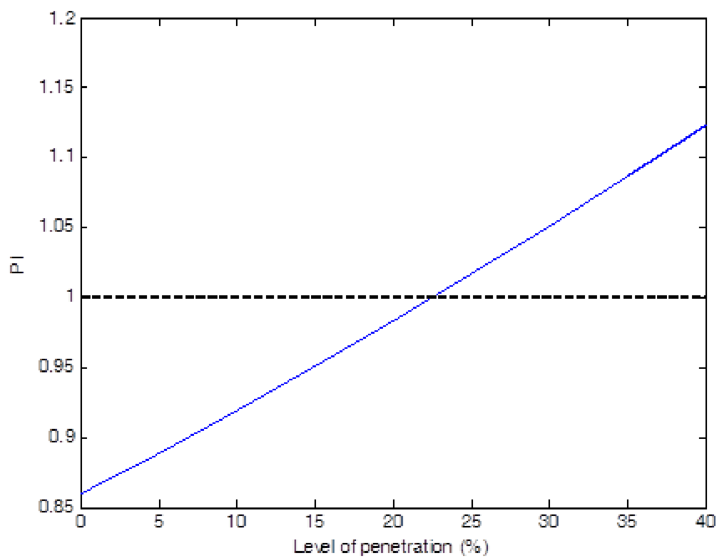
A transient physics-based model was developed to address the technical feasibility of shifting electricity and heat to the electrolysis unit based on a representative wind farm operating in Wyoming, and a load profile representative of the Midwest.[35, 36] The dynamic simulation for this case demonstrated that the advanced nuclear hybrid solution is physically capable of resolving the power generation variability introduced by wind turbines down to a minute-by-minute time scale. The electrical battery storage unit helped smooth the transients associated with power generation spin-up and spin-down. The electrolysis unit, with gas flow and heat recuperation, is also capable of being operated intermittently as functionally required. Physical testing of this modeled outcome is needed to confirm these conclusions.

In order to address the question regarding economic viability, the ratio of cash flows (computed as the profitability of the system as a percentage of the total wind power generation in the system) was calculated for both the traditional and the advanced HES. The ratio of profitability (referred to as the Profitability Index, or PI) is plotted in Figure 4.K.6. When PI is less than 1.0, then the additional profit gained by operating the electrolysis unit does not justify the additional capital investment for this unit. In other words, the rate of return on investment for the advanced system would be less than construction and operation of only the traditional HES when $PI < 1$.

For the example considered, when the wind capacity exceeded 23 percent, the additional revenue for hydrogen production from excess generation that would otherwise be curtailed (assuming commodity prices of \$2.50/kg-H_2 at the plant gate and \$0.12/kWh electricity) was sufficient to cover the cost of capital and operating costs for the electrolysis unit and the profitability index of the overall system is greater than 1.0. Further increases in the penetration of wind raised the percentage of time that electricity was dedicated to hydrogen production, resulting in higher PI. These results may not be specifically relevant in all power markets, and additional technical-economic analysis of this case is being performed by DOE in 2016.

Figure 4.K.6 Profitability Index (PI) of advanced (thermally coupled) N-R HES as a function of the fraction of the grid demand met by variable renewable sources.

Credit: Idaho National Laboratory

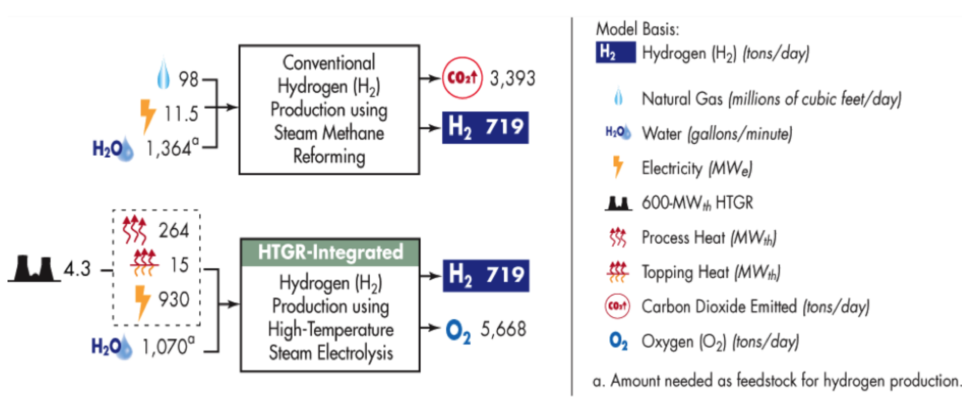


In this example, providing ancillary services to the grid—such as regulation-up or regulation-down load, power stability control, or contingency reserve—was not factored into the economic analysis.

Analysis of the material balance for steady-state steam electrolysis with electrical and thermal input versus hydrogen production by a conventional steam methane reforming process is summarized in Figure 4.K.7.[37] Almost 5 tons of CO_2 is produced by steam methane reforming for each ton of hydrogen produced. Assuming a cost of $50/ton for CO_2 capture, compression, delivery, and permanent storage, this would add about $0.25 per kilogram of hydrogen produced from natural gas. With the hybrid system, the cost of hydrogen production by electrolysis depends on the cost of electricity. Hence, in cases where the price of electricity is low, for example when renewable sources are at their low marginal cost of production, then the N-R HES hydrogen co-product hybrid system may compete with steam methane reforming. Additional analysis, as outlined below, is needed to understand the overall cost/trade-off benefits of the hybrid systems for realistic markets.

Figure 4.K.7 Mass and energy balance calculation results for the HTGR-integrated process for hydrogen production via the high temperature steam electrolysis process.[38]

Credit: Idaho National Laboratory



Technology Development Needs Summary (R&D Pathways)

Nuclear hybrid energy systems are currently in the early stages of development. Several of the identified development needs correspond to technology needs for flexible and resilient energy structures. DOE-NE and DOE-EERE are jointly supporting analysis of nuclear-renewable hybrid energy systems based on specific regional opportunities. Government, university, and industry are engaged through workshops and colloquia.[39, 40] Workshops with subject matter experts were held in May, 2015, and in June, 2016, with DOE support to discuss pathways to a low-carbon energy economy, including the role of nuclear energy and relevant technology development program needs.[41] An initial gap analysis of technology development needs was completed to identify the necessary tools, experimental facilities, and component testing that is needed to develop hybrid systems that could be marketable in the relatively near term. The following is a summary of the most important development subjects relevant to N-R HES.[42]

Dynamic Modeling Tools for Impact Assessment and Design Optimization Studies

Hybrid energy systems require the development and application of new dynamic modeling and simulation tools to account for the time variability, dynamic interaction of unit operations, and transient phenomena that may impact hardware performance and control of hybrid energy systems. These tools are now being developed by the DOE national laboratories under DOE sponsorship, with additional support being provided by U.S. universities.[43, 44, 45, 46] These tools are needed to understand the case-specific interactions with the electrical grid, behavior of the nuclear reactor and associated heat transfer systems, behavior of power cycle ramp rates, energy storage and recovery rates, and chemical plant reaction response to changes in heat transfer and material feeds. Multi-physics transient behavior modeling of the hybrid systems can help evaluate nuclear reactor choices and help establish reactor design and operating requirements that are driven by technical needs as well as probabilistic risk assessment during reactor licensing. The dynamic models can help optimize the design solutions for real options, while addressing monitoring and control methods for the tightly-coupled system.

A modeling and simulation framework to assess the economic viability of N-R HES is also needed to find the optimal configuration that will minimize the cost of electricity production, while accounting for defined constraints on the capability of the N-R HES to meet demand. These constraints play a fundamental role in enabling the economic evaluation framework by monetizing the ability of the N-R HES to help cope with electricity demand volatility. DOE has begun an effort to develop a framework to assess and optimize the value of energy utilization by considering the value of ancillary services and other figures of merit that are important for grid operations, reliability, and resiliency, as well as other societal priorities such as environmental impacts on air, water, and land.[47]

Nuclear Reactor Design

Potentially new operating characteristics are necessary for nuclear reactors to accommodate flexible operation, including the system flexibility inherent with nuclear hybrid operations. Design requirements include reactor size (i.e. size of SMR and number of modules), heat delivery systems, and safety considerations that derive from direct coupling of subsystems. Modeling and simulation activities will assist in the evaluation of nuclear reactor choices based on the thermal energy output and operating characteristics of the reactors for specific N-R HES applications. The current N-R HES cases studies by DOE emphasize operation of nuclear reactors at steady state near their nameplate capacities, although some advanced nuclear reactor designs may be able to respond to the dynamic dispatch requirements of the modern grid. Consequently, future nuclear reactor designs, including SMRs, may need to verify rapid transient operation capabilities that meet Nuclear Regulatory Commission (NRC) design certification requirements. Alternatively, thermal energy buffers may be required when maneuvering heat from power generation to an industrial process.[48]

Thermal Hydraulics Interconnections

Thermal energy interconnections for hybrid energy systems will require new heat exchanger and heat circulation designs. The analysis of heat transfer fluids, heat delivery systems, and heat deposition systems is being undertaken by the DOE-Nuclear Energy Advanced Reactor Technologies Program. Relative to N-R HES, dynamic heat delivery ramp-up and ramp-down rates need to be characterized for industrial systems and storage options.

New heat exchanger designs are likely necessary to dynamically and safely apportion heat between the power generation and heat application users. In particular, an intermediate heat exchanger that can rapidly maneuver heat for power production and industrial users without significant impact on reactor operations needs to be developed for each of the possible N-R HES reactor types. This work should include high temperature thermal fluid circulators and new control valves. Materials and heat exchanger designs for increased thermal and mechanical cycling need to be developed and tested.

Reactor outlet temperature (ROT) and reactor inlet temperature (RIT) must be reliably maintained within operating specifications. This requirement may necessitate a thermal buffer such as a steam accumulator or heat sink to ensure stable reactor operations. Engineering design, heat exchanger fabrication, and prototype testing are major elements in the N-R HES R&D that will lead to a demonstration system.[49]

Electrical heating can be used to heat a thermal storage reservoir when the cost drops below that of natural gas heating.[50] Excess electricity can similarly be used to chill water or other fluids that can be cooled and stored and used by an industrial plant or building for cooling loads during the day. Commercial ice storage systems exist which cool commercial buildings, reducing the use of air conditioning during peak hours and charge the ice banks during off-peak hours.[51, 52] This concept for energy storage is being considered by some universities around the U.S.; for example, the University of Texas-Austin.[53] Electrical-to-thermal conversion systems can deliver heat up to very high temperatures.[54]

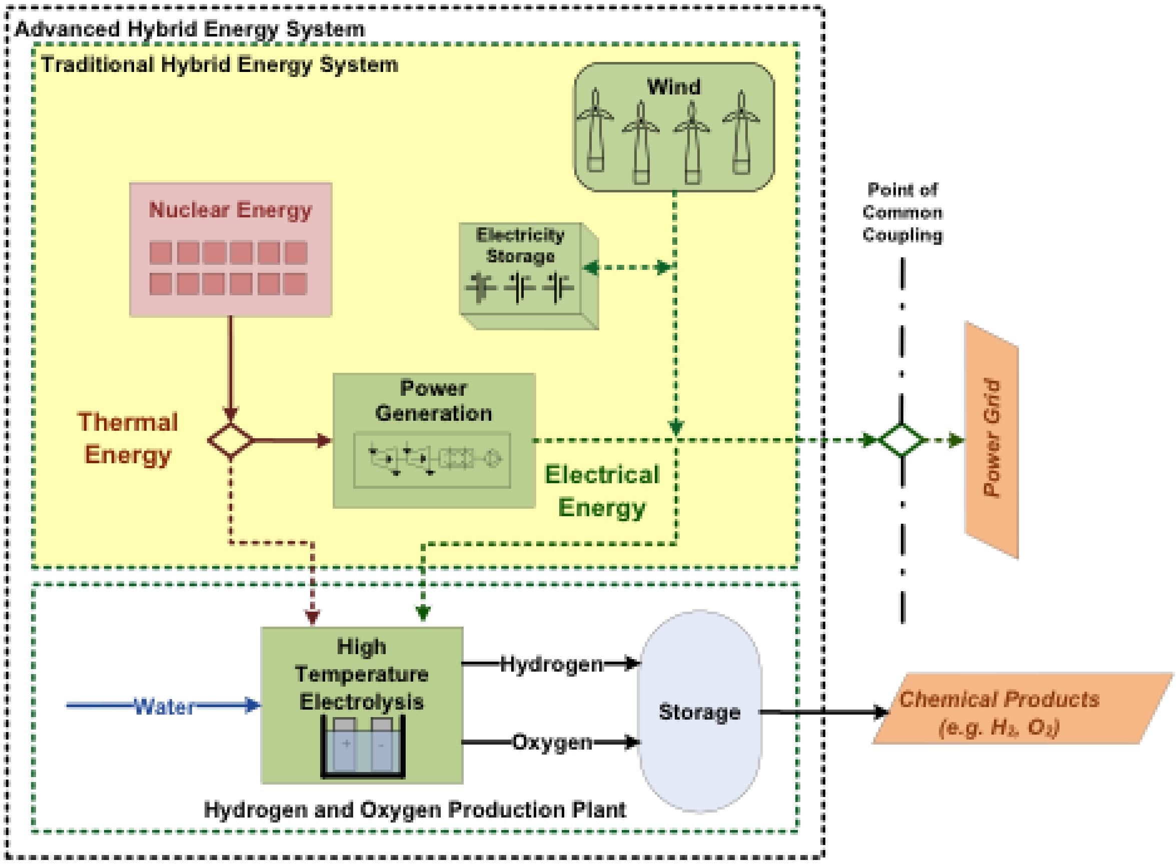
Power Generation Systems

The heat-to-power conversion system for a N-R HES must incorporate turbine technology and power generation blocks that are designed to respond to rapid shifts in power demand. Technical issues pertaining to transient response needs of the turbine and generator set are outlined in early efforts to model the transient behavior of these unit operations.[55]

Nuclear power has the capability to load follow based on the French and German experiences.[56] The load following capabilities of nuclear plants are on the order of coal-fired plants but below that of open cycle gas turbines. For example, the maximum ramp-up rate of a typical European nuclear reactor ranges from 1-5%/minute, while an open-cycle gas turbine can ramp up at a rate up to 20%/minute and a combined-cycle gas turbine power plant can ramp up at a rate of approximately 5-10%/minute. The current fleet of U.S. nuclear reactors was designed to operate close to their name plate capacity, however, and because of a different control rod configuration than used in typical European plants their ramp rates are lower. They are usually ramped up or down at a percent or two per hour. These limitations are due more to the heat source than to the turbine.[57]

Figure 4.K.8 Potential nuclear hybrid energy system heat delivery options. For an HTGR, high temperature gases exiting the reactor can be used as high temperature process heat. Gas or steam can be extracted during expansion stages or exits of turbines to provide process heat at medium temperatures. Heat rejected by power conversion units can be used as low temperature process heat.

Credit: Idaho National Laboratory



Research activities in this area will need to consider new Brayton power cycles (e.g., super-critical CO_2 power cycles currently under development; see QTR Technology Assesment 4.R Supercritical Carbon Dioxide Brayton Cycle), or a combination of Brayton and Rankine cycles that allow heat to be extracted from various stages in the power cycle, as illustrated in Figure 4.K.8. These combined cycles are similar to natural gas/combined cycle power systems.

Alternatively, smaller parallel turbines and generation sets that can be independently ramped may best accommodate load-following power generation. This concept embraces the design philosophy of some SMRs for which individual reactors modules could be matched with small power turbine units.

Energy Storage

Thermal energy storage reservoirs will likely be needed to soften the imposition of rapid transitions on the thermal hydraulic systems of nuclear systems. Energy storage technologies that are being developed for CSP systems may also be applicable to nuclear hybrid energy systems. The scale of the thermal reservoir must be scaled to the needs of the hybrid energy system. Technical and economic assessments are needed to arrive at an understanding of the costs and benefits of capital investments that support different temporal scales—from minutes, to hours, to days, to seasonal—of storage operation for both electricity and thermal supply and demand. Results to date indicate production of the non-electric product is often economically more compelling;[58] but further analysis is needed to understand the value of providing grid stability, and the real value of clean electricity in potential carbon-constrained markets. Projections for the cost of future nuclear SMRs also need to be developed for comparison to NGCC with CCS.

Electricity Interconnection

When designing and operating a hybrid energy system, both internal uses for electricity and its dynamic market value must be considered. With sufficient operational flexibility, a hybrid system can respond to market signals and choose the most profitable use of its electric power and thermal energy. Application of real-time digital simulators can help evaluate the electric grid and provide automatic or supervisory control updates.

As the grid incorporates more distributed power generation, N-R HES potentially offer a new paradigm for "micro-industrial grids." SMRs, including both light water and high temperature reactors, may find increased opportunities for applications with industrial complexes. This may lead to independence from the grid with potential benefits of more reliable power and heat delivery. The modularity of SMRs can allow for staggered refueling which could create a nearly constant heat source for process heat applications. As a backup, natural gas could be used to supplement process heat supply should the entire nuclear plant shut down.[59]

Instrumentation, Information, and Controls

Hybrid systems will require control systems that co-process input signals from the electric grid, the processing plants, and the nuclear plant. System diagnostics and prognostics for intelligent control of large complex systems are becoming possible with faster computer processors and artificial intelligence. In addition, methods to detect and manage cyber security issues will need to be further developed and implemented (see Chapters 2 and 3 of the main QTR report).

Operator control room environments need to be developed to account for human factors. Hybrid plant complexity will require careful development of the panels, alarms, and supervisory decisions that may need to be made to maintain stable operations for the dynamic operating conditions that will be characteristic of N-R HES.

Reactor Licensing and Permitting

DOE-supported licensing activities are underway for advanced reactor designs and commercial small modular nuclear reactors. These efforts would need to be expanded for hybrid operations when market applications have been determined. Industry input from both nuclear reactor developers and industrial users, as well as input from the Nuclear Regulatory Commission, is needed for this technology area.

Endnotes

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Acronyms and Glossary

AC	Alternating current
CO_2	Carbon dioxide
CSP	Concentrated solar thermal power
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy (A division of the U.S. Department of Energy)
EJ	Exajoule

GHG	Greenhouse gas
GW	Gigawatt
HTGR	High temperature gas reactor
IAEA	Molten salt breeder reactor
INL	Idaho National Laboratory
ISO	Independent system operator
MIT	Massachusetts Institute of Technology
MIMO	Multiple input, multiple output
MISO	Multiple input, single output
MW	Megawatt
MWe	Megawatt electric
NE	Nuclear Energy (A division of the U.S. Department of Energy)
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
N-R HES	Nuclear-renewable hybrid energy system
PI	Profitability index
PV	Photovoltaic
QTR	Quadrennial Technology Review
R&D	Research and development
RIT	Reactor inlet temperature
ROT	Reactor outlet temperature
RTO	Regional transmission operator
SMR	Small modular reactor
TRL	Technology readiness level
$TW_e hr$	Terawatt hour (electric)