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Nuclear-renewable hybrid energy systems: Opportunities, interconnections, and needs

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ABSTRACT

As the U.S. energy system evolves, the amount of electricity from variable-generation sources is likely to increase, which could result in additional times when electricity demand is lower than available production. Thus, purveyors of technologies that traditionally have provided base-load electricity—such as nuclear power plants—can explore new operating procedures to deal with the associated market signals. Concurrently, innovations in nuclear reactor design coupled with sophisticated control systems now allow for more complex apportionment of heat within an integrated system such as one linked to energy-intensive chemical processes.

This paper explores one opportunity – nuclear-renewable hybrid energy systems. These are defined as integrated facilities comprised of nuclear reactors, renewable energy generation, and industrial processes that can simultaneously address the need for grid flexibility, greenhouse gas emission reductions, and optimal use of investment capital. Six aspects of interaction (interconnections) between elements of nuclear-renewable hybrid energy systems are identified: Thermal, electrical, chemical, hydrogen, mechanical, and information. Additionally, system-level aspects affect selection, design, and operation of this hybrid system type. Throughout the paper, gaps and research needs are identified to promote further exploration of the topic.

1. Introduction

The U.S. energy system, like many others, is evolving to better meet environmental constraints and at the same time continuing to provide secure, reliable, and affordable energy services to the economy. In practice, this has led to an increased interest in producing low-carbon electricity in the power sector and utilizing domestically sourced alternatives to imported petroleum in the transportation sector.

To this end, in the electric power industry, significant capacity additions of variable renewable energy systems such as wind and photovoltaic power are likely to continue. These changes, although beneficial in terms of greenhouse gas (GHG) emission reductions and improved fuel diversity, in some cases have led to a need for additional operating reserves and other ancillary services [1]. Continued integration of these variable renewable resources drives the need for flexible generation to accommodate fluctuations in supply and demand. Such load-following flexible facilities typically are used as intermediate or peaking plants (utilized for a relatively small number of hours during times of high net demand[1]). Thus, under the current paradigm, a large amount of capital equipment (and, ultimately, investment capital) is not being utilized near its capacity when demand is lacking. In many cases, the equipment could be out of use during the majority of the year.

At the same time, energy use by industrial processes (e.g., major chemical manufacturing and minerals conversion industries) is large in scale and diverse in the proportions and types of energy services required. Fig. 1 shows a breakdown of energy use by industry for 2004. The breakdown is based on energy used directly by the industry; it does not show primary energy use that would include the efficiency losses in generation of electricity and steam.

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[1] Net demand, as defined herein, is the output the grid requires from an individual generator to make supply and demand equal in the generator's balancing area (the metered segment of the electric power system in which electrical balance is maintained). High net demand can occur when demand for electricity is high and/or variable production is low. Low net demand can occur when demand is low and/or variable production is high.

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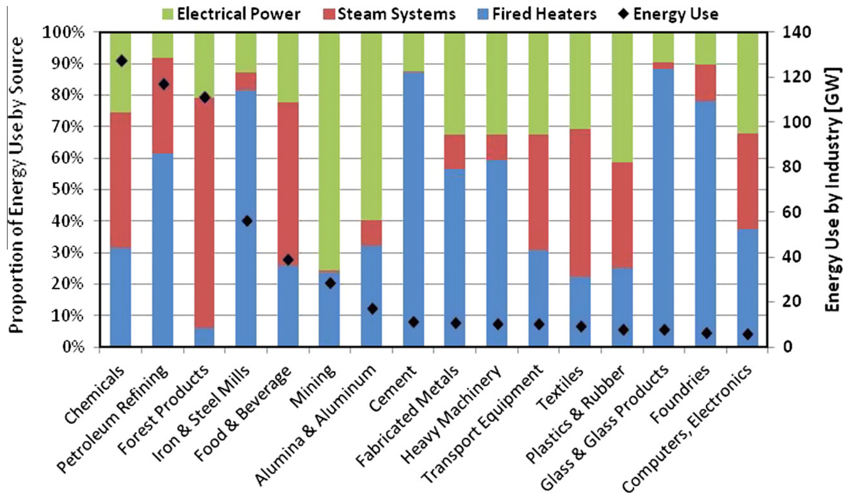

Fig. 1. Energy use by U.S. manufacturing and mining industries for 2004 (Pellegrino et al. [2]).

If primary energy use was shown, energy use by industry values would increase and the percentages for electrical power and steam systems would be higher. Overall, approximately 40% of the energy used in these industries was provided by fossil-fired heaters, 43% by steam systems, and 17% from electrical inputs, though each industry differs [2].

Additionally, changes—including advanced informatics, energy management systems and forecasting—are enabling new innovation in integrated plant design [3,4] and power system operations [5]. These innovations can be utilized to design new types of hybrid energy systems which (a) allow the use of traditionally base-load systems to generate economical load-following power, (b) improve grid flexibility[2] and allow for multiple types of ancillary services, and (c) produce additional commodities such as fuels for the transportation sector.

This paper explores a potential concept for accomplishing these goals—hybrid operation of nuclear reactors coupled with renewable energy technologies and industrial processes in a single facility which has the potential to provide secure, reliable, and affordable, low-carbon energy services. The intent is to define the concept for potential future development and implementation. Interface and system-level issues are explored (including ownership, regulatory, design, construction, and operational issues) to identify gaps and research needs as a way to promote further exploration of the topic. Detailed assessments of specific systems and their potential business cases are beyond the scope of this paper; however, examples from a growing body of literature on this subject are discussed briefly.

2. Hybrid energy systems

The term "hybrid energy system" is used to describe various concepts. As an example, a long history of work exists on small, decentralized hybrid energy systems which utilize multiple generation sources, often with storage, to provide electricity to remote populations. This includes concept proposals (see, e.g., Borges Neto et al. [6]), analyses of technical challenges and opportunities [7], feasibility studies (see, e.g., Nixon et al. [8], Rehman and Al-Hadhrami [9], Zoubeidi et al. [10]), and cost-benefit analyses (see, e.g., Kaldellis et al. [11]). Single energy source centralized generation facilities that provide multiple services (e.g., electricity, heating, cooling, water) also have been referred to as hybrid energy systems, and research has been exploring those concepts from various standpoints [12]. Co-generation (or combined heat and power (CHP)) optimizing both design and output in accordance with technical constraints and market signals [13] also can be termed a hybrid system.

A less extensive body of work exists for larger, hybridized electric generation facilities which use fossil fuels in combination with renewables. Kang et al. [14] developed a generalized computational framework to determine optimal operation procedures of an integrated system consisting of a coal-fired power station, a temperature-swing absorption carbon-capture facility powered by a natural gas combustion turbine, and a wind farm. Kieffer, et al. [15] proposed using the term flex-fuel poly-generation systems for multi-feed, multi-product energy systems. Researchers developed techniques to measure and optimize cost, sustainability, and resilience of such systems. Phadke et al. [16] performed an economic and technical feasibility assessment on a system consisting of a coal gasification combined-cycle power plant equipped with carbon capture, a wind plant, and the option for a fuel production or hydrogen/carbon monoxide gas mixture (referred to as syngas) storage facility. Inclusion of a syngas storage facility or fuel production plant in the integrated system increased utilization of capital and reduced the levelized cost of electricity. Cherry et al. [18] corroborated the results of Phadke in an evaluation of the technical and economic benefits of hybrid systems that integrate chemical and fuels synthesis plants with wind power to help ameliorate wind power intermittency. Work has also been done to assess the feasibility and added utility of a hybrid energy system in which solar-generated steam is injected into fossil power cycles, such as that described by Turchi and Ma [19]. Analysis indicated that a hybridized design of a gas turbine with a concentrated solar power (CSP) system could produce electricity more efficiently and dispatchably than either system could produce alone [20].

Some researchers have extended the definition of hybrid energy systems to include systems with components coupled across the electrical grid. Forsberg [21] explores several integrated system solutions for the larger U.S. energy system, which include combining nuclear, fossil, and renewable energy sources to sustainably create electricity and transportation fuels. Cherry et al. [18] concluded that the amount of excess capacity in the power-generation systems could be cost-competitively converted into chemicals and fuels, thus replacing one-third or more of all foreign oil imports into the United States. Accounting for electrical and thermal energy management, Garcia et al. [22] modeled and predicted the

[2] Grid flexibility is the ability of an electric system's conventional generators to vary output and respond to the variability and uncertainty of the net load [17].

ability to load-follow increasing amounts of variable energy integration on the grid in association with battery storage and chemical production (methanol) [22,23].

This paper defines a hybrid energy system as a single facility which takes two or more energy resources as inputs and produces two or more products, with at least one being an energy commodity such as electricity or transportation fuel. These systems are comprised of two or more energy-conversion subsystems that are traditionally separate or isolated. In hybrid systems, they are physically coupled to produce outputs by dynamically integrating energy and materials flows among energy production and delivery systems. Our definition of hybrid energy system requires coupling "behind" the electrical transmission bus, where all subsystems within the hybrid energy system share the same interconnection so that the grid is exposed to a single, highly dynamic and responsive system. Several coupling opportunities exist to link the energy conversion subsystems. They include thermal, electricity, chemical, hydrogen, and mechanical interconnections. Additionally, data transfer between subsystems is essential to a functioning hybrid energy system.

An important feature of this type of hybrid energy system is that it produces several products. These products can include electricity either for merchant or captive use, hydrogen for merchant or captive use, substitute natural gas and hot process gases or steam for merchant or captive use, and transportation fuels. Additionally, this type of hybrid energy system might be designed to produce many non-energy outputs whose production is energy-intensive, such as chemical feedstocks for fertilizer, polymers, plastics, and textiles; potable water from desalination of seawater and brines; minerals from geothermal brines; and CO_2 for enhanced oil recovery or as a heat-transport medium. The inclusion of such products allows a broader range of operations to maximize overall system performance and profitability.

Because the proposed hybrid energy systems operate dynamically, large nominally base-load power plants could be used flexibly within hybrid systems to produce the electricity necessary to mitigate times of either high demand or low production from variable sources. Increased efficiency is achieved by matching electrical output to demand while utilizing excess generation capacity for other purposes when it is available. Hybrid energy systems provide an alternative approach to systems optimization, leveraging previously untapped attributes of energy production, increasing efficiency, and offering a greater return on investment.

3. Nuclear-renewable hybrid energy systems

Because of their large capital costs and low fuel costs, nuclear power plants require a high load or capacity factor to be economically viable (i.e., they need to be run as many hours annually as possible) [24]. Transient reactor operation can also increase costs of nuclear facility operation by accelerating wear on various nuclear system components [25–27]. Integrating nuclear energy and renewable energy into a single hybrid energy system, coupled through informatics linkages, would enable a nuclear plant to run at high capacity while simultaneously addressing the need for flexibility of generation rates and producing energy services, ancillary services, and low-carbon co-products.

A future hybrid nuclear-renewable energy facility, incorporating an appropriate industrial process, presents opportunities to produce revenue from a variety of product streams and avoid capital inefficiencies of underutilized capacity. Such coupling allows the system to respond to market signals, diverting electricity to spot or ancillary service markets or internal industrial processes. It relies upon advanced informatics and market data to choose which activity is most profitable. This type of operation has become feasible as a result of several factors: Increased demand for low-CO_2 energy generation; the advent of a new generation of small modular nuclear reactors (SMRs) having energy output similar to the needs of a large chemical process complex; and increased data generation, collection, and utilization capabilities to make continuous online operational optimization possible. Furthermore, such a system might reduce the integration costs[3] of variable renewable electricity sources by providing firming power to such sources within the hybrid system and additional grid flexibility to sources outside the system. Although fully integrated hybrid systems such as these have not yet been demonstrated, the component technologies are mature. It is expected that proposed nuclear-renewable hybrid systems will continue to operate component technologies similarly to how they have been operated independently. Thus, key technical issues will involve interconnections and additional system issues due to the added complexity of integration.

Numerous renewable energy sources can be used as inputs to a nuclear-renewable hybrid energy system: wind, solar, hydroelectric, biomass (such as forest and agricultural residues as well as purpose-grown energy crops and algae), geothermal, and marine technologies (wave or tidal). These are just as varied and numerous as the inputs currently used for existing single input, single output plants, and each resource has different geographic, economic, and environmental considerations, making some far more practical than others. The different energy resources, possible products, and coupling modes allow for many combinations. A few examples of potential nuclear-renewable hybrid energy systems are summarized in Table 1. The table reports resources used by those hybrid systems, products sold by the systems, aspects of interaction between subsystems, and a potential mode for energy storage.

There are more design and scale options available for hybrid systems than ever before because recent developments in the nuclear industry have resulted in options for smaller reactors. The advent of SMRs allows for nuclear reactors capacities as low as 10 MW while maintaining favorable economics. Renewable facilities are scalable and range from very small to large capacities. Currently, many wind farms have a capacity over 100 MW and at least one is over 1 GW. Likewise, many solar power stations over 100 MW capacity exist and there is at least one with a nominal capacity of over 250 MW [87].

Renewable resources—such as electricity produced by wind turbines and photovoltaics—are characterized by variability of generation. High penetration of those sources requires a flexible grid and, consequently, other generators such as nuclear-renewable hybrid energy systems that can provide outputs at the rates necessary to meet demand.

There is a growing body of literature on the economics and business cases for nuclear-renewable hybrid energy systems. Cherry et al. [63] analyzed the technical and economic performance of a nuclear-renewable hybrid energy system that produces methanol from natural gas. Methanol can be used as a fuel or precursor for other fuels using heat from a nuclear facility during non-peak hours for electricity. The resultant cost of methanol from a hybrid facility was 10% higher than a conventional, non-hybrid facility; however, cost externalities such as reducing GHG emissions, utilizing resources more efficiently to extend their lifetimes, and producing vehicle fuels domestically were not included in his estimate.

Garcia et al. [22,23] explored the feasibility of a nuclear-renewable hybrid energy system that uses the nuclear facility and storage to balance variability of wind-generated electricity. Excess heat from the nuclear facility is used in a chemical plant

[3] Integration costs are the costs associated with providing reliability necessary to accommodate variable renewable electricity sources onto the grid.

Table 1
Examples of nuclear and renewables in a hybrid energy system.

Resources	Coupling mode	Storage mode	Products
Nuclear and wind energy	Electrical	Hydrogen	Electricity, hydrogen
Nuclear and biomass	Thermal	Chemical	Electricity, biofuels
Nuclear and CSP	Thermal	Thermal	Electricity, heat
Nuclear, wind energy, and natural gas	Electrical and thermal	Chemical	Electricity, chemical products (e.g., ethylene), diesel fuel

complex. The focus was specifically on dynamic response and its value instead of time-averaged output as used for other economic analyses. The proposed hybrid energy systems become more profitable than conventional configurations at 20% wind-electricity penetrations on the grid with greater profitability at higher penetrations. At 40% wind-electricity penetration the additional return is 4% higher than the conventional configuration.

In further analysis, Cherry et al. [18] assessed the potential for the state of Wyoming to upgrade coal and wind resources to obtain higher values using nuclear-renewable hybrid energy systems. One particular system design uses electricity from a nuclear facility to balance variability of wind-generated electricity. Excess heat from the nuclear facility is used as an energy input for production of gasoline from coal resources (via methanol). That study found the coal–gasoline process is competitive with conventional methanol-to-gasoline processes, earning a 12% IRR with a gasoline wholesale price of $2.13/gallon.

Bragg-Sitton et al. [86] presents the technical and economic value associated with the hybridization of SMR architectures that are dispatched in concert with wind energy produced by the system. Conventional systems are compared to integrated hybrid energy systems producing hydrogen (via high temperature electrolysis) and methanol in addition to electricity. This study found that, when wind energy penetration exceeds about 30% of the total electrical power generation, the internal rate of return of the integrated hybrid energy systems is higher than that of the conventional systems.

4. Aspects of interaction

The following sections discuss how nuclear and renewable energy sources can be coupled within a hybrid system to produce desired energy products. Although the conversion from energy resource to energy product can be done using many different processes, the forms of energy are limited and therefore provide a convenient way to structure the discussion. Each section identifies coupling interconnections, discusses opportunities for their use, and proposes work necessary before the interconnection can be used for nuclear-renewable hybrid systems.

5. Thermal interconnections

A key motive for nuclear-renewable hybrid energy systems is the efficient alternative use of the heat generated when it is not needed for electric power production due to low net demand conditions. Heat from nuclear reactors is a key focus point; however, renewable sources such as solar energy in concentrated solar power systems, biomass, and geothermal have the similar issues and opportunities [28]. These concepts also would apply to coal-fired power plants and natural gas combined-cycle plants [29]. Technologies that enable heat utilization in an industrial process—instead of reducing reactor output or releasing the energy through cooling—can create new revenue streams.

Shared use of nuclear reactor thermal energy is not a new concept. Nuclear heat is currently used for combined power generation and district heating in Europe [30,31]. The proposed load-following behavior in a system that incorporates a greater percentage of variable power generation, however, requires systems that are more complex than district heating. This is due to timing (when the heat is available), time scales (required response rate), and the large amount of excess heat. Industrial processes potentially can be designed to absorb the heat at time scales more closely aligned with heat availability.

The range of dynamic apportionment between power production and process-oriented heat use must be considered for selection and design of the nuclear subsystem. This includes analyses of heat versus electrical tariff structures, the range of electrical versus heat demands of the industrial process, and the ramping limits of the nuclear system. It is likely that small and medium-sized reactors will have several technical or economic advantages in different markets/installations, and modular designs also could allow phased expansion of the hybrid system, or hedge against times of contraction. Operational optimization techniques for industrial CHP [32,33] can be transferrable to nuclear-renewable hybrid systems, but techniques to optimize designs need to be developed.

Many industrial processes requiring large thermal inputs could be well-suited for coupling in a nuclear-renewable hybrid system. For example, steam in a power cycle could be diverted to energy storage or an industrial user prior to the final condensing turbine. Table 2 classifies temperature ranges corresponding to industrial process reaction mechanisms and identifies potential heat sources.

Many other industrial processes could utilize heat from a nuclear reactor. In the realm of petroleum production, lower/intermediate temperature heat is widely used in hot water extraction [38,39] and steam-assisted gravity drainage [40] processes for heavy crude and oil sand bitumen extraction (300–350 °C steam). Also, petroleum refineries use 300–500 °C steam to refine crude oil into asphalt, fuels, and distillate products. This steam often is generated by combustion of residual coke and vacuum bottom residuals, which typically contain high levels of sulfur (up to 10% by weight) and metals, and can result in toxic air emissions [41]. In the future, the organic kerogen in oil shale can be depolymerized and converted to crude oil and combustible gases by thermally retorting the shale over the temperature range of 350–500 °C [42,43].

Biofuel production can use process heat for a variety of purposes. Low-temperature heat can be used for purposes including feedstock drying and thermal torrefaction [44]. Temperatures in the range of 350–500 °C [45,46] are considered ideal for biomass decomposition and pyrolysis, which converts biomass into a bio-crude that, after hydro-treating, is fungible with petroleum crude [47]. Integration opportunities could exist to store excess energy in the form of biofuels, and to combust these fuels in times of high demand.

Higher-temperature chemical production processes which typically utilize fossil-fired process heat, such as natural gas reforming [48] (850 °C), biomass gasification [49] (800–1000 °C), and coal gasification [50] (1000–1200 °C), also could be coupled with nuclear-renewable hybrid systems. Heat recuperation, topping combustion, and alternative heat generation by electrically powered plasma generators or induction heating effectively can achieve higher temperatures for these processes. This will necessitate process reactor designs or plant layouts different from those currently used with conventional fossil-fired process heating.

About thirty different designs for small (10–300 MWe) and medium (<700 MWe) nuclear reactors are in development around

Table 2
Heat sources and applications organized by operating temperature range.

Temp. range	Mechanism	Examples	Potential heat sources
High (1000–1500 °C)	Metal refining; heterogeneous gas–solid reactions; high temperature gas phase reactions	Coal gasification; steel; cement and glass manufacturing; steam superheating	Combustion of natural gas or coal; electric arc; high temperature plasma generation; concentrating solar power
Higher/intermediate (700–950 °C)	Multi-bond scissioning; hydrogen abstraction reactions	Steam methane reforming, cracking of natural gas liquids to ethylene and propylene; biomass gasification; high temperature steam electrolysis	High temperature gas-cooled nuclear reactor
Lower/intermediate (350–600 °C)	Devolatilization endothermic reactions, organic compound pyrolysis	Distillation, cracking, and reforming of petroleum heavy end products; biomass pyrolysis; in situ oil shale retorting	Molten salt reactor; liquid metal cooled nuclear reactor; biomass combustion
Low (50–320 °C)	Saturated steam production; sensible heating	Many chemical processes; biomass torrefaction; water desalination; district heating	Light water nuclear reactors; geothermal sources

Information drawn from Hamel and Brown [34], Bartok and Sarofim [35], Meyers [36], Babcock and Wilcox Co. [37], and Taibi et al. [28].

Table 3
Thermal characteristics of U.S. small modular reactors under development [51].

Reactor class/name	Manufacturer	Max heat delivery temperature (°C)	Thermal capacity (MW)
Light water reactors			
NuScale	NuScale Power Inc.	300	165
Westinghouse SMR	Westinghouse	310	800
mPower	Babcock and Wilcox	320	500
Liquid metal-cooled reactors			
PRISM	GE-Hitachi	485	471
Hyperion Power Module	Gen4 Energy, Inc.	500	70
Gas-cooled reactors			
GT-MHR	General atomics	750	350
Energy multiplier module	General atomics	850	500

the world; many are still at the conceptual stage. These reactors are more versatile than traditional large reactors of 1000–1700 MWe (roughly 3000–5000 MW thermal) that were designed to capture economies of scale operating as base-load plants. The thermal demand of a large chemical plant is in the range of a few hundred megawatts, so one or even a few small or medium-size reactors can be matched to industrial-scale process plants to make a single operating complex. The seven U.S. designs under development in 2011 are representative and are summarized in Table 3.

All nuclear systems deliver their heat to a primary coolant (e.g., water, a molten metal mixture, helium) flowing in a closed loop. The primary coolant transfers heat to a secondary coolant through an intermediate heat exchanger isolating the power block and chemical process from each other and mitigating the potential of radioactive contamination entering the chemical process [52]. In a hybrid energy system, the secondary coolant then can then be dynamically apportioned between the power generation block, a thermal energy storage buffer, and an industrial process. One example of this is shown in Fig. 2.

The selection of the secondary heat transfer medium depends on various factors, including the outlet temperature of the primary coolant, the power generation cycle of choice, and the nature of the thermal coupling with the industrial process. If high-temperature heat is available, combinations of Brayton and Rankine cycles can be considered to attain electrical generation efficiencies approaching 50% [53,54]. The possibility of dual external thermal hydraulic loops that independently serve the power generation block and the industrial process could be considered as well.

Thermal interconnections with the dynamics and scale necessary for nuclear-renewable hybrid systems require research and development before they can be implemented. That research could start with optimization of the hybrid configuration using both static process models and dynamic system predictive models to understand system response to variable and uncertain grid demand and on-site variable energy production. Multi-physics transient behavior modeling can 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. Technical and economic evaluations should consider the costs and benefits of design alternatives for the nuclear reactor, external thermal heat transfer loops, the power block, and the energy storage buffer.

The heat-to-power conversion system for a nuclear-renewable hybrid energy system should incorporate turbine technology and power generation blocks that are designed to respond to rapid shifts in power demand. Power turbines and electrical power generators that vary power output in accordance with dynamic demand cycles have already been developed for nuclear power plants [55,56]. Alternatively, smaller, parallel turbines and generation sets that can be independently ramped could be developed and operated such that they perform load-following. This concept embraces the philosophy of some small-modular reactors that match individual reactors modules with small power turbine units.

Thermal energy storage reservoirs might be needed to soften the imposition of rapid transitions on the thermal hydraulics systems. Energy storage technologies being developed for CSP are likely applicable to nuclear hybrid energy systems. However, storage required for a nuclear reactor could be hundreds of megawatt-hours, which is far greater than the thermal storage reservoirs currently under development for CSP [57,58]; hence, new systems would have to be developed to that scale.

Research and development (R&D) can help make effective use of relatively low-temperature heat from light water nuclear reactors in the petrochemical and industrial manufacturing processes. The R&D could focus on efficient methods to boost the temperature of steam or hot gases from 200–300 °C to 500–900 °C. Vapor compression or electrical heating systems could be effective for this purpose. Topping heat also can be provided by the process user

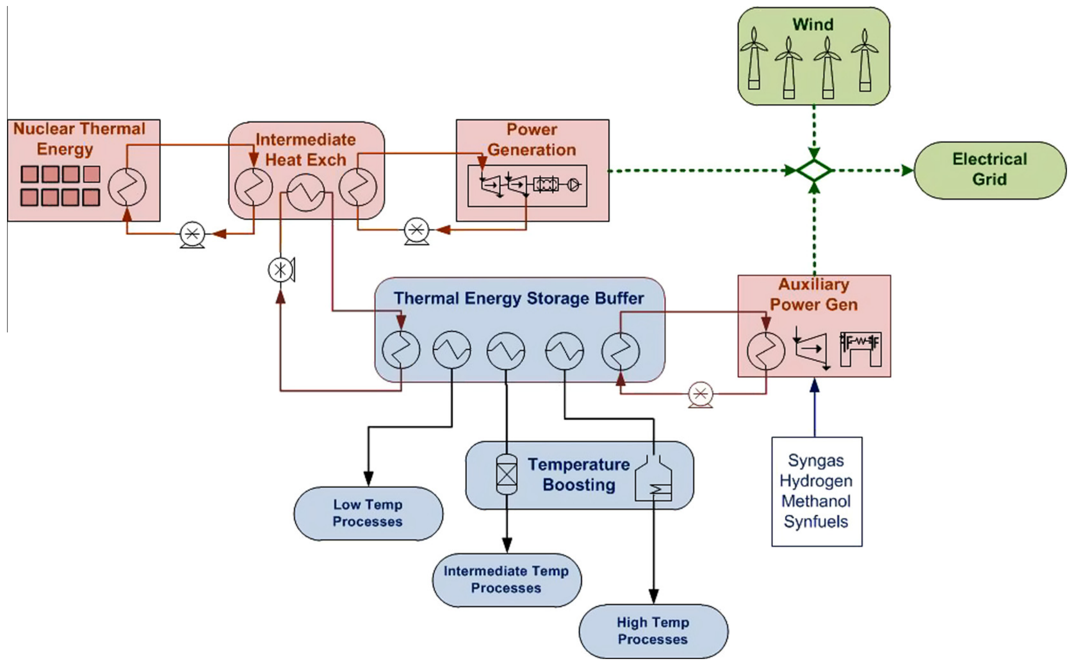

Fig. 2. Schematic of a light water nuclear-renewable hybrid system utilizing wind energy, coupled with generalized industrial processes classified by operational temperature.

through heat recuperation, electrical heating, or fossil-fuel combustion. Another option is chemical heat pumps. In most designs, temperature boosting should be done close to the point of use to avoid high-temperature heat transfer materials costs and significant heat loss. Additionally, new remote flow monitoring and control valves and pumps for high-temperature thermal hydraulic fluids, gases, molten salts, liquid metals, and ultra-supercritical steam will be needed. High-temperature heat circulation for aggressive environments associated with high-temperature steam, molten salts, and gases requires validation of metallurgy and possibly new heat-exchanger fabrication techniques.

6. Electricity interconnections

Electricity is a key interconnection because it is both valuable on an existing market and useful internally. Thus, while designing and operating a hybrid energy system, one must consider both internal uses for electricity and its dynamic market value. With sufficient operational flexibility, facility operators can respond to market signals and choose whether to utilize electricity internally or divert energy to the market.

In times of high net demand, ancillary services or spot-market electricity prices can become elevated, incentivizing a diversion of energy from an on-site industrial process toward maximizing electrical output. In times of low net demand, electricity prices are reduced and a hybrid energy system can be producing excess electricity. To increase revenue, it might become more profitable for the operator to divert energy from nuclear and variable renewable energy production to industrial processes.

Use of electricity internally will not only be dependent upon momentary market demands but also ramp rate requirements of equipment using the electricity; thus, adjusting the electricity use within the hybrid system will require both short and long term planning. In addition, excess electricity in hybrid systems also could be stored using batteries, pumped hydropower, or compressed air energy technologies and dispensed when it is economically attractive to do so. System costs and round-trip efficiency affect the economics of storage options.

Research and development is necessary to allow hybrid systems to respond rapidly, efficiently, and safely to electricity market signals. This includes development of advanced, interconnected sensing and informatics systems that identify all needs and provide information to the control system, thus enabling control systems to optimize profitability. In addition, advanced power electronics are necessary. They need to be low cost, highly responsive, durable, and able to switch between multiple uses without disruption to operations [59].

There are unique concerns for financing a hybrid nuclear-renewable system using electrical interconnections. Nuclear power plants are a significant capital investment, and historically have required the long-term certainty of a return on investment to attract capital [60,61]. This certainty can be granted by a public utility commission representing a large group of ratepayers, which determines an appropriate retail electricity rate and provides a guaranteed market for the plant operator. Current legal and regulatory frameworks do not have established methodologies to valuate—on behalf of ratepayers—a system that (a) in addition to electricity, produces an industrial product not sold to ratepayers, (b) transfers production dynamically to maximize profits, (c) cannot accurately predict its long-term operation schedule, and (d) requires purchase and construction of components/systems shared by multiple processes—not all of which provide a service to ratepayers. Instead of the long-term certainty resulting from a ratemaking process, plant operators might have to agree to power purchase agreements which could have shorter contract lengths or less profitable terms. This could make the cost of capital more expensive to operators or discourage investment. Analysis of market redesign solutions could help mitigate project financing issues. Cochran et al. [5] argue that electric markets in their current form do not always assign appropriate value to plants which provide grid flexibility. Establishing market mechanisms which properly reward the flexibility that a power plant provides to the grid might reduce barriers to entry of a nuclear-renewable hybrid energy system.

7. Chemical interconnections

Recognition of the central role for chemical intermediates can expand the role of hybrid energy systems in the chemical industry. Nuclear plants can be designed to generate heat to produce chemical products such as syngas, high purity hydrogen, and other key chemicals that can then be transported to industrial processes. Syngas is produced by reforming natural gas with steam [48], or by gasifying coal or biomass and separating gas diluents and impurities to produce a clean mixture of hydrogen and carbon monoxide [50]. Both processes require thermal energy that is produced by burning up to 65% of the carbonaceous feedstock, resulting in carbon dioxide emissions. Nuclear reactors can supply both the process heat and steam necessary to carry out these reactions. High-temperature, gas-cooled nuclear reactors can provide superheated helium that could replace the burners in the steam reforming process [62]. The steam produced by a light water reactor can also significantly reduce combustion requirements with changes to the reforming process [18,63].

Syngas and hydrogen can be used as fuel for a gas turbine to produce power in the manner of an integrated-gasification/combined-cycle facility. Alternatively, syngas and hydrogen can be converted into commodity chemicals and products, fertilizer, and synthetic fuels as shown in Fig. 3. Methanol is a noteworthy chemical intermediate that is used to produce key chemicals such as formaldehyde, acetic acid, ethylene glycol, vinyl acetate, and olefins [64]. Methanol also can be converted into a fungible motor gasoline substitute by the methanol-to-gasoline process [65] or to produce biofuels via trans-esterification of fatty oils [66].

Diesel production by the Fischer–Tropsch catalysis and refining process is a second route to producing synthetic fuels in hybrid energy systems. This technology has been advanced by several energy companies and catalyst companies [67,68]. Various unit operations in the product upgrading and refining section of the plant can utilize the steam or heat provided by a nuclear reactor [69]. Some case studies for the high-temperature, gas-cooled reactor have been recently completed for steady-state, co-generation operations in which favorable return on investment cases for synthetic fuels and chemical production were demonstrated [43,70].

Multiple design and technology improvements are necessary before implementing hybrid energy systems with chemical interconnections. Because chemical manufacturing plants are generally designed to run at nearly constant operation, new design schemes that are resilient to time-varying electrical and thermal inputs are needed. Designs might require dual steam sources (e.g., a nuclear facility and a supporting natural gas-fired boiler).

Additionally, heat integration issues might require new reactor designs that improve heat transfer into the chemical reactor vessels. Heat recuperation schemes could require modification, resulting in new designs of heat exchangers and gas production equipment. Induction heating for electrically induced plasma arc heating of gaseous inputs and reacting flows could to be considered. Materials qualification will likely be necessary for these new chemical reactors.

In-plant power generation also could be considered in hybrid process plants. New micro-turbines or reciprocating internal combustion engines can burn syngas. Fuel cells that burn hydrogen, methane, or vaporized methanol also are becoming commercially viable [69]. Auxiliary power production using stored chemical energy could help smooth transitions in nuclear and wind-power conversions.

8. Hydrogen interconnections

Hydrogen is a special case of chemical coupling of energy systems. Much work has been done to develop hydrogen production technologies, and hydrogen is a common feedstock in chemical and industrial processes. Hydrogen also offers an important possibility for storing energy. Although it is currently produced primarily from natural gas via steam methane reforming [71], hydrogen created using nuclear reactor heat (and electricity) has been researched intently in recent years (see, e.g., National Academies Press [72]; Herring et al. [73]; Forsberg [74]). Hydrogen can be produced in a nuclear-renewable hybrid energy system by two primary means: thermo-chemical (T-C) cycles and electrolytic processes.

Thermo-chemical cycles produce hydrogen through a series of chemical reactions that extract hydrogen and oxygen from water, requiring heat at temperatures of between 750 °C and 1000 °C

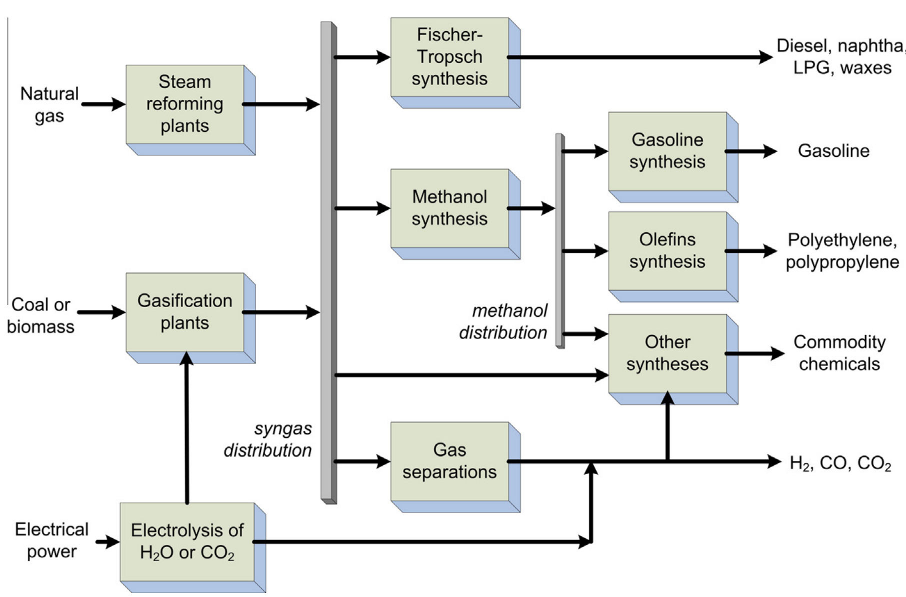

Fig. 3. Production and conversion of syngas into synfuels and chemicals [18].

[75,85]. The heat can be provided by employing high-temperature nuclear reactors, CSP technology, or the combination of a lower temperature nuclear reactor with CSP. R&D needs vary by the T-C cycle. Lower temperature sources might be used instead if temperature-boosting technology in the desired temperature range is developed. Development priorities for the hybrid sulfur process include techniques to control the gas dynamics of sulfur dioxide (SO_2) and improvements to the design of the acid decomposer. For the sulfur-iodine process, priorities include a better understanding of the fundamental kinetics, catalyst development, and improved product/by-product separation operations [76].

Electrolysis is a means by which electrical power is used to separate water into its constituents, hydrogen and oxygen. Of particular interest is high-temperature electrolysis (HTE), which increases the electrical efficiency of hydrogen production by running at temperatures ranging from 100 °C to 850 °C, consuming heat in addition to electricity [77]. High-temperature electrolysis might provide a better interface for combining nuclear with renewables in a hybrid energy system because wind and solar photovoltaic systems generate electricity directly. This allows for the possibility of utilizing heat from a nuclear reactor and most or all of the electricity from renewable sources. One possible arrangement is shown in Fig. 4. Work on dynamic options could supplement current work on steady state HTE [76].

Hydrogen has many possible end uses. It can be sold as merchant hydrogen for applications including transportation fuel and as a feedstock for other industrial chemical processes. Annually, more than 50 million metric tons of hydrogen are used globally, with most used for petroleum refining, ammonia production, and methanol production. That quantity is expected to grow in the near term as the market share of heavier crude oils, such as those from oil sands, increases. Refining sulfur-rich heavy crude oils requires more desulfurization, a process which requires hydrogen [71]. Hydrogen is also used for upgrading some biofuels. Oils produced from biomass via fast pyrolysis require hydrogen for hydrotreating and hydrocracking to convert large hydrocarbon molecules into naphtha and diesel range products [78].

Hydrogen is also under consideration as an energy-carrier for transportation. It can be utilized efficiently in fuel cell electric vehicles (FCEVs), thus helping to make FCEVs a viable option for the future [79]. Because hydrogen is an effective energy carrier and transportation fuels are not required at constant rates, a hybrid energy system producing hydrogen for fuels could potentially produce hydrogen when demand for electricity is lower than potential production.

Hydrogen also can be used for energy storage for the power grid. It can be produced when the net demand is low, stored onsite, and used later in a fuel cell system or combusted to provide additional electricity and heat. If this option is selected, the hybrid system gains flexibility by being able to generate electricity when the bidding price of electrical power is high. However, additional capital costs for hydrogen storage and fuel cells will need to be overcome.

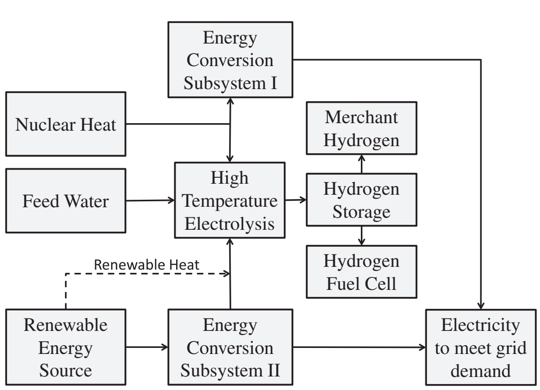

Fig. 4. Generalized schematic of a nuclear-renewable hybrid system utilizing hydrogen interconnections and high-temperature electrolysis.

Additional issues are raised by siting onsite production of hydrogen at a nuclear site. First, hydrogen has its own set of safety codes, standards, best practices and regulations. Second, the presence of a volatile flammable substance invokes more rigorous scrutiny and application of 10 CFR 50 and 52 nuclear power regulations [80,81]. It may be necessary to manufacture the hydrogen away from the nuclear reactor, outside the exclusion area boundary. This poses additional security problems in addition to heat loss concerns and additional concerns pertaining to potential loss of heat sink.

9. Mechanical interconnections

Rotational energy from a turbine in a hybridized system could be transferred directly to a work-performing machine such as a pump or compressor. This may require the custom design of mechanical coupling and gearing to achieve proper transfer of power and torque. A flywheel system could also be employed to store mechanical energy. While flywheels do not typically store large amounts of energy, they are able to absorb or release energy at high rates, which may be advantageous in certain industrial processes, or to quickly smooth out large fluctuations in electrical load if a power electronic converter is also coupled to the flywheel. Mechanical energy could also be used as a supplement or in tandem with electric or gas motors.

Direct mechanical interconnections will need to compete with electric motors. The energy that provides shaft work to directly drive an end-use pump or compressor could be used to generate electricity. The choice between these alternatives is based largely on the relative costs of power and fuel (which includes byproduct purge streams), CO_2 emission penalties, the need for variable speed operation (for which turbines are more suitable than motors), and maintenance costs (which are greater for turbines). Because a significant electric motor is needed to start the end-use device, that capital cost is expended whether the primary drive is electric or mechanical. Thus, mechanical drives are likely to be more expensive than purely electric drives. Additionally, the current trend is toward electric motors in applications traditionally powered by gas or steam turbines [82]. However, mechanical interconnections can be beneficial in special cases such as direct-drive emergency-backup pumps or compressors.

10. Information interconnections

The ready availability of information on the status of the electrical grid and each of the plants in a hybrid system is critical to realize the advantages discussed in this paper. In the absence of such continuous monitoring, a hybrid system behaves like an ordinary market interaction of several buyers and sellers each responding to the price signals they can gather. With near-instantaneous measurement, collection, and distribution of comprehensive information, they can operate as an integrated and optimized entity.

Informatics enables two distinct capabilities. The first is for business and production planning with each subsystem providing information on production plans, needs, and associated prices. Having this information, the overall plan for the hybrid energy system is refined and subsystem operation adjusted. The timeframe of this planning can range from year-ahead plans for major maintenance to daily production plans based on weather forecasts. Optimization tools similar to those used by petroleum refineries and for supply-chain management must be developed to optimize the product slate; thus, maximizing profits and meeting constraints such as production guarantees [83]. Supply-chain management tools that are specifically designed to support facilities meeting rapid dynamics of the electrical grid also are likely to be necessary.

The second level of interaction is on-line monitoring of process performance and, perhaps more importantly, identification, tracking, and control of operational upsets. These upsets, in mild cases, simply are periods of reduced production for which each plant would like forewarning to prepare accordingly. In severe cases—or mild cases where the process units interact in self-reinforcing fashion and become severe—temporary plant shutdowns or damage to equipment might result. Instantaneous access to system information to diagnose and respond to such conditions in coordinated fashion could be an important safety feature.

11. System-level considerations

As with many complex systems, technical, economic, environmental, and social aspects of system integration should be considered to justify the added complexity. Above all, a nuclear-renewable hybrid energy system requires deliberate project selection and optimization so that customer needs are met and the project's profitability justifies the capital expense. Many opportunities are likely to exist for such hybrid energy systems, and many selection criteria are warranted—ranging from project economics to sustainability issues and from national policy to development risks [84]. These criteria will also be affected by whether a hybrid facility is located on a site with an existing nuclear plant.

Each project development team is likely to have its own set of criteria and weighting factors to determine the most promising options for a given situation. Initial heuristics that simplify estimates of key criteria can assist project developers in narrowing the selections to a number manageable for further analysis. Model-centric tools that allow for rapid screening based on resource availability and cost data, environmental conditions and constraints, project goals, and market conditions can help steer technology choices and conceptual hybrid energy system configurations.

Conceptual design and cost-benefit analysis studies can help identify the most promising types of hybrid energy systems and quantify their benefits. Specific challenges for analyzing hybrid systems include construction and operational lifetimes that differ between subsystems. Understanding those differences is necessary to identify when upgrades and renovations should occur, and to identify opportunities for system adjustments to meet the needs of evolving markets.

Project economics will be driven by the dynamic variation of market values for different products; current tools and techniques for design and operation do not encompass the needs of hybrid systems. In design, new tools could improve understanding of tradeoffs, including those between storage capacity (of heat or electricity) and system flexibility/response. New tools also could aid design of systems that are stable and controllable during start up, shut down, and process interruptions.

Because potential nuclear hybrid systems require large initial capital investments, techniques that mitigate project-development risks could be useful. Those techniques are likely to include staged capacity construction and evolutionary development so that certain subsystems (or portions thereof) are built initially, and subsystems are added or expanded during operation when demand increases. Risk mitigation is also likely to involve improved control systems and reduced complexity.

Thorough life-cycle assessments of hybrid energy system options can be used to quantify environmental effects. Metrics should include both emissions and resource utilization. A means for allocating GHG emissions and energy use between operational systems with varying capacity factors will need to be developed to improve the accuracy of the life-cycle assessments. Other factors to be considered include:

- Water use, because linking multiple systems can provide opportunities to reduce water use through re-use, reclamation, and efficiency;
- environmental consequences of material use, especially for materials requiring specialty mining and refining; and
- storage, security, potential reuse, and eventual disposition of used nuclear fuel.

Linking complex processes from multiple industries could result in cross-sectoral issues that need to be addressed. Those issues include communication of technical aspects between groups. They also include reconciliation of regulatory, design, and operational standards between independent industries. One example is safety analysis of nuclear reactors that are connected to other systems where required "stand-off" distances from nuclear operations need to be considered. Another aspect of linking processes from multiple industries is control systems. Techniques are needed to coordinate multiple linked but independent systems with differing dynamic timescales. New schemes for supervisory monitoring and control should be worked out for the complex.

12. Conclusions

Nuclear and renewable energy offer the potential for plentiful long-term supplies of heat and power at prices not subject to the vagaries of fossil-fuel prices, and for producing lower GHG emissions than alternative fossil-fuel sources. Renewable energy sources also have the benefits of strong societal acceptance and the potential for smaller scale, distributed installations. Potentially problematic constraints on availability of these two types of systems—an economic preference for steady high rate operation of nuclear reactors versus unavoidably variable supply rates for many renewables—can be reconciled to their mutual benefit by combining the two energy sources in a hybrid energy system. Such a hybrid system can provide load-following power and, with any transiently excess energy, provide energy services for the production of a second energy-intensive product such as synthetic vehicle fuel or other chemical product.

A large number of these systems could potentially address broader national energy objectives such as sustainability and energy security. To bring hybrid energy systems to practice, technical development, systems analysis, and optimization of the concepts are necessary.

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