Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems

Preprint

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Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems

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1. ABSTRACT

Tightly coupled nuclear-renewable hybrid energy systems (N-R HESs) are systems that link subsystems to generate dispatchable electricity and produce at least one industrial product from two or more energy resources. Because N-R HESs are designed to produce different products based on the value of those products in markets, their optimal designs and operations can be complex. This paper summarizes some key conclusions from a set of economic analyses of N-R HESs. Each N-R HES use case analyzed includes a nuclear reactor, a thermal power cycle to convert nuclear energy into electricity, either a wind or photovoltaic solar subsystem producing electricity, and an industrial process producing an energy or an industrial product. The analyses focused on identifying the optimal configuration and hours of operations for each N-R HES within ranges of hypothetical future electricity price profiles and industrial product prices. Four important insights are drawn from the results of those analyses.

2. INTRODUCTION AND MOTIVATION

Energy generation and use across all sectors of the economy is rapidly evolving. The market share of wind and solar photovoltaics (PV) in the electricity sector is growing. At the same time, the surge in natural gas production in the United States has driven down the cost of power generation using natural gas turbines and combined gas turbine/steam cycle power plants that have the flexibility to provide operating reserves as well as energy to the grid. That flexibility supports higher penetrations of wind and PV. Commercial and residential buildings are becoming more energy efficient and now require less energy to provide the same level of comfort. Advances in efficiency of appliances and electronics have also limited the increase in energy consumption in the residential and commercial sectors. The transportation sector is both becoming more efficient and more technologically diverse. The industrial sector is finding ways to improve energy efficiency including utilizing combined heat and power and process intensification measures that improve process heating rates and reaction conversions [1]. These trends—coupled with a renewed focus on energy resiliency and security—are motivating investment and utilization strategies for innovative energy generation and delivery assets.

Tightly coupled nuclear-renewable hybrid energy systems (N-R HESs) are a technology opportunity that can generate dispatchable electricity while shifting uncommitted thermal or electrical energy to an energy-intensive industrial process that uses heat, steam, and/or electricity to produce fuels, chemicals, minerals, or another commodity. In this paper, as elsewhere, N-R HES are defined as individual facilities which take two or more energy resources as inputs and produce two or more products, with at least one being an energy commodity such as electricity or a transportation fuel [2]. FIG. 1 depicts a conceptual tightly-coupled N-R HES.

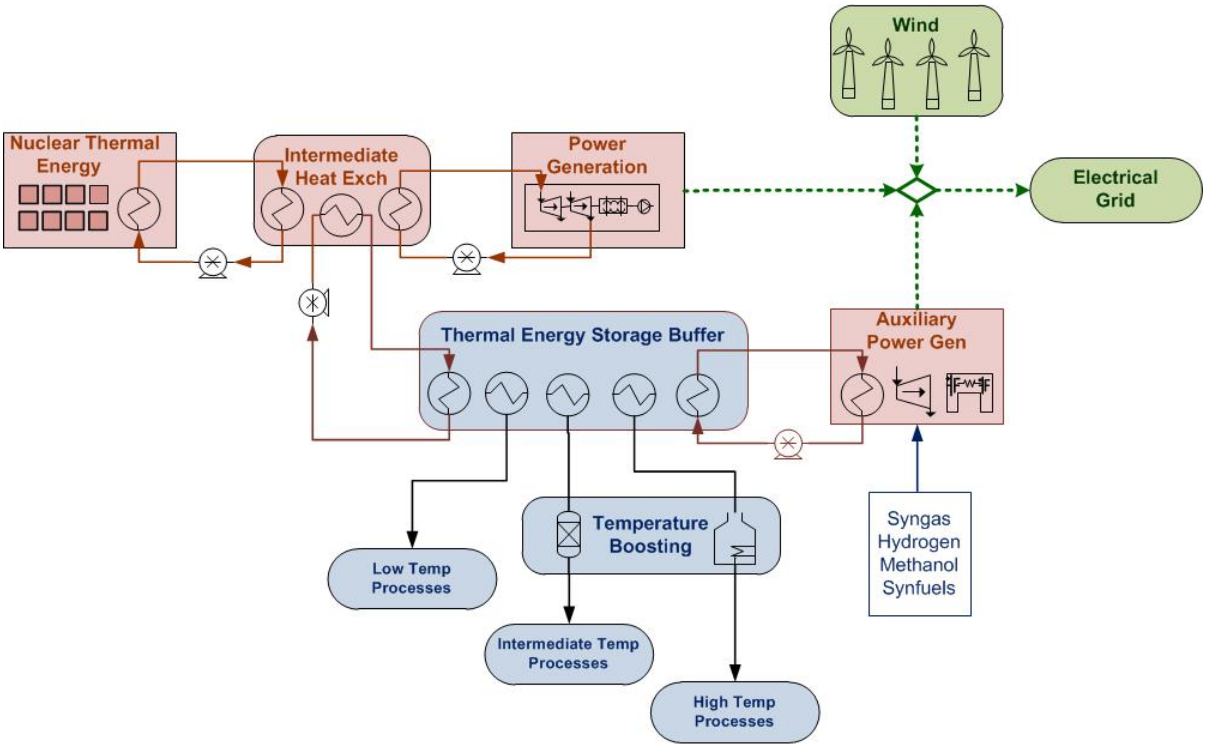

FIG. 1. Schematic of a light water nuclear-renewable hybrid system utilizing wind energy, coupled with generalized industrial processes classified by operational temperature [2].

N-R HESs have been proposed as opportunities that provide a number of potential economic and societal benefits [3]:

1. Dispatchable, flexible, zero-pollutant, and very low-carbon electricity generation that supports the grid's needs for energy, capacity, and ancillary services. Because the energy dispatch between electricity production and the industrial process can be controlled, N-R HESs can maximize electricity production when the net demand for electricity is high, thus supporting grid reliability especially during extreme events including ones that limit natural gas availability for electricity generation or periods when variable generation is unusually low. When electricity prices are low, N-R HESs can increase energy use for the industrial process to maximize plant revenues.
2. Reduced sulfur oxide, nitrogen oxide, particulate, and carbon dioxide emissions and potentially reduced energy costs in the industrial sector when providing process heat instead of combusting coal or natural gas to provide the same service.
3. Providing ancillary grid services including synchronous electro-mechanical (real) inertia to support the grid, frequency regulation, and voltage and reactive power support. The N-R HES can provide these services by rapidly ramping up or down electricity to amenable industrial subsystems to compensate for grid perturbations.
4. Alleviation of the impacts of electricity price suppression at high penetration of low marginal cost generation (e.g., nuclear and renewables) because they provide a floor for energy prices by diverting an energy source from electricity to the industrial process.

3. ANALYSIS OBJECTIVES

This paper summarizes results and draws conclusions from a series of economic analyses of N-R HESs. The overall objective of the analyses was to quantify the economic potential of some specific N-R HES use cases and configurations, compare those results to uncoupled alternatives that provide the same services, and identify when the N-R HES both meets the required hurdle rate and has the potential to be more profitable than the alternatives. Economic potentials are calculated as the net present value (NPV) of the N-R HESs expenses and incomes. Key expenses include the capital investment and operating costs, including those related to feedstocks, labor , and maintenance. Income includes revenue from selling the industrial product, electrical energy, and the value of providing capacity and ancillary services to the grid. We did not include electro-mechanical inertia [4] or other grid services that are not commonly priced because we could not assign an economic value to them. We only considered revenue from selling the industrial product. Hence, we did not include potential additional revenues such as potentially marketable credits for industrial products under renewable identification numbers – RINs [5].

In some cases, the uncoupled alternatives emit carbon dioxide and results were calculated both without and with a cost of carbon levied on those emissions.

The economic analyses test the following key hypotheses:

- The N-R HES configurations meet a hurdle rate that can be considered a minimum return for investors and that the N-R HES configurations are more profitable than alternatives composed of the same subsystems and uncoupled configurations.
- N-R HESs can be more profitable than uncoupled alternatives because they can generate electricity at times when its price is high and an industrial product at times when the price of electricity is low.
- N-R HESs can support the electricity grid's resource adequacy requirements when needed while maximizing income by producing a higher value industrial product while other grid resources are sufficient, providing market structures support that opportunity.

4. SYSTEMS ANALYZED

The conclusions reported in this paper are based on results from analyses of four different N-R HES use cases reported elsewhere. The four different N-R HES use cases that were analyzed are illustrated in FIG. 2. All four N-R HESs analyzed include four potential subsystems: (1) a light water small modular nuclear reactor generating heat; (2) the balance of plant that converts that heat into electricity; (3) a variable renewable generator (wind or PV); and (4) an industrial energy process that produces an energy product or a commodity. Additionally, a short description of each configuration is provided in following paragraphs.

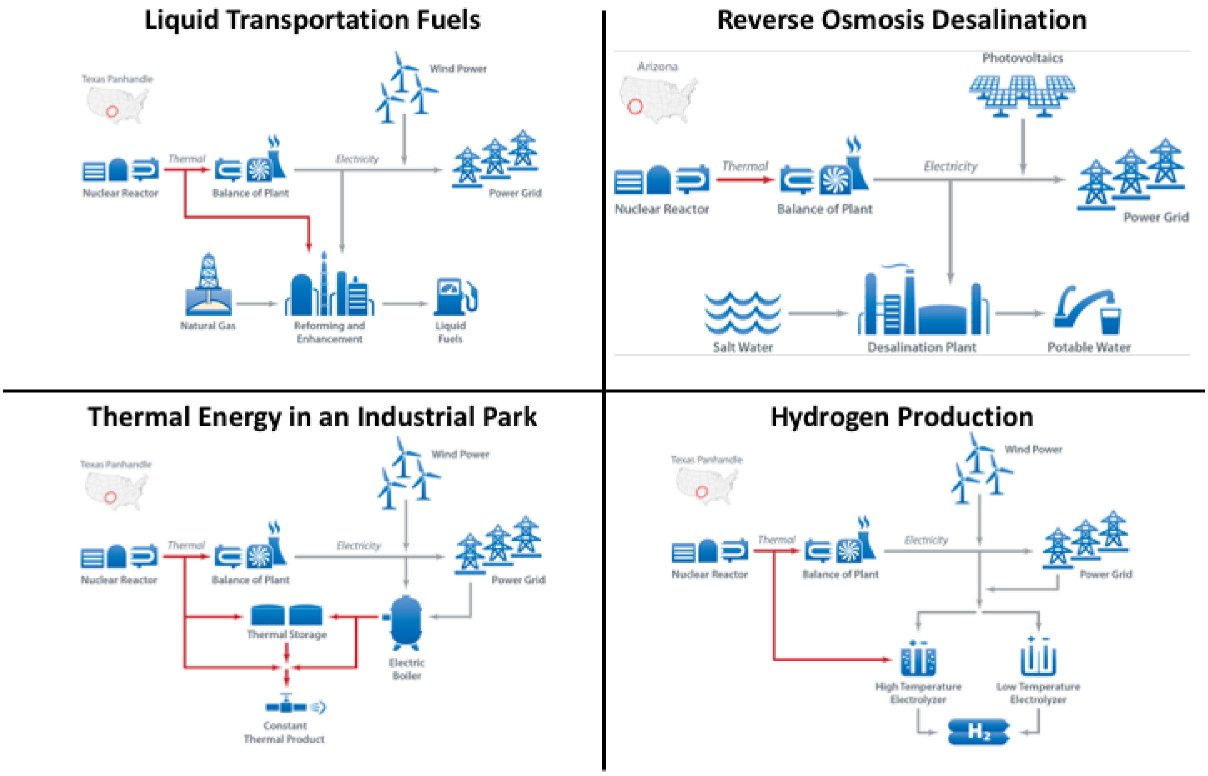

FIG. 2. Graphical depictions of the four N-R HESs that were analyzed [6, 8, 9]

The liquid transportation fuel N-R HES use case includes a subsystem that converts natural gas to a liquid fuel the methanol-to-gasoline process that involves methanol and dimethyl ether (DME) as process intermediates. The analysis assumes that the liquid fuel can be sold on the market at the same price as gasoline. The synthetic fuel production subsystem has a high capital cost and requires both heat and electricity hence the process has both thermal coupling between the nuclear reactor and the industrial process in addition to electrical coupling that can provide either nuclear-generated electricity or wind-generated electricity to the industrial process as needed. The project did not consider any market off-take of methanol or DME, which could reduce the equipment required and hence the capital cost of the industrial process. Site-specific parameters within the analysis are based on a Texas location because Texas has natural gas and wind resources as well as liquid fuel infrastructure [6].

The desalination N-R HES use case includes a reverse osmosis (RO) desalination unit which requires only electricity as the industrial process. Hence, this N-R HES only has electrical coupling. Site specific parameters are based on Arizona data because Arizona has a saline aquifer that can provide water to the RO unit, a growing demand for potable water, and abundant solar resources. An initial report presents the methodology, assumptions, results, and conclusions of the analysis of these first two N-R HESs (liquid transportation fuel and desalination) [6]. It should be noted that RO desalination is based on modular units so capital costs scale nearly linearly with production rate.

The thermal energy N-R HES use case is slightly different than the two described above. Instead of producing an industrial product, it generates a thermal product (either steam or heat transfer fluid) that can be provided to one or more customers. To produce the thermal product at a constant rate, two variants are considered: thermal storage and an electric boiler. The thermal product would not be produced from nuclear generated electricity due to thermal-to-electric-to-thermal energy conversion inefficiencies. Rather, it could be produced from electricity from either the N-R HES's wind subsystem or purchased from the grid depending upon the availability and cost of that electricity when the heat is needed. This N-R HES is situated in Texas because the industrial sector in Texas is large and has a large demand for heat [7]. A second report summarizes the methodology, assumptions, results, and conclusions of the analysis of the thermal energy N-R HES [8].

The hydrogen N-R HES use case involves two variations for the industrial process subsystem. In the first, the industrial process is a high temperature electrolyzer (HTE) that utilizes both heat and electricity to generate hydrogen, requiring both thermal and electrical coupling. In the second, the industrial process is a low temperature electrolyzer (LTE) that requires only electrical coupling but has a lower efficiency. The analysis was performed on each variant individually. In both variants, the electricity used could be nuclear-generated, wind-generated, or from the grid. Another report summarizes the hydrogen N-R HES analyses [9].

The published reports describe the analysis of each N-R HES and communicate the results and conclusions from those analyses. This paper reports general conclusions drawn from all four analyses.

The four use cases and their associated configurations that are analyzed range over the spectrum of types of N-R HESs. That spectrum ranges from N-R HESs that have only electrical coupling as well as those that have both electrical and thermal coupling. It also includes N-R HESs with industrial processes that have high capital costs and those that have very low capital costs. It also includes N-R HESs that only produce energy as well as those that can purchase electricity when at a low price.

5. ANALYSIS METHODOLOGY

The overall objective of the N-R HES analysis was to identify the subsystem sizes and operational decisions (i.e., the internal dispatch strategy) that are most profitable under a variety of electricity and industrial product prices and compare those to other options that provide the same service. For this purpose, profitability is defined as the NPV of the investment – a higher NPV means increased profitability. Given an interest in achieving more generally applicable conclusions, we considered the potential for greenfield (all new) plants only. We recognize that specific opportunities, including reconfigurations of existing nuclear power plants, could result in conflicting conclusions that are appropriate for those specific opportunities but may not be more generally applicable.

The results reported here were generated using National Renewable Energy Laboratory's (NREL's) REopt tool. REopt is an energy-planning platform that offers concurrent, multiple technology integration and optimization capabilities. Formulated as a mixed-integer linear program, REopt identifies optimal subsystem sizes and dispatch strategies for the selected technologies. The model accounts for subsystem costs (capital, fixed, and variable), fuel costs, financial parameters (discount rate, inflation, utility electricity price escalation rates, and incentives), utility prices, and other variables that contribute to a techno-economic analysis of the proposed system. REopt also has the capability to optimize a system for objectives other than those used in this analysis, such as minimum fuel consumption or minimum GHG emissions [10]. For this analysis, we extended REopt to incorporate reduced order models of these industrial processes and associated operational constraints. We then applied REopt to determine the optimal subsystem sizes and corresponding dispatch strategies (i.e., the optimal product mix during each hour of the year that would maximize the net present value of each N-R HES given the capital, feedstock, and other operating costs and the product selling prices. We constrained maximum sizes of all subsystems in each N-R HES to the same value because the purpose of the analysis was to understand the potential of coupled subsystems with full flexibility. We assumed that the presence of each N-R HES does not impact market prices (i.e., it does not reduce the price of electricity or the industrial product by flooding that market).

Capital and operating costs and efficiencies used in REopt are based on published estimates and, due to the limitations of the optimization methodology, scaling is linear (i.e., as the ratio between capacity and capital cost is held constant, the subsystems are not scaled exponentially). That limitation is unlikely to impact most of the sensitivities because in most of the instances when the subsystems are included in the optimal configuration those subsystems are at the maximum size (which is also the size at which the ratio was set). Table 1 reports the values used within the optimization and the sources of those values. We assumed that the N-R HES would begin operations in 2035 so the values are projected costs and performance in 2035 in 2013 U.S. dollars. The nuclear reactor is based on light-water small modular reactor (LW-SMR) technology. Using subjective judgment, we assumed that this technology could potentially be commercialized and several built before 2035 following completion of reactor design certification, development of steam-line combined technology and operating permits, equipment manufacturing supply chain development, and construction and operating experience. That experience is necessary to meet the "nth-of-a-kind" cost estimate used in this analysis. Other reactor technologies are under development and may prove to be more economic than LW-SMRs and future analysis using those technologies may be valuable. Capital costs reflect the total cost for the subsystem – they include indirect costs such as foundations and buildings, control systems, and utility connections.

TABLE 1. SUBSYSTEM CAPITAL AND OPERATING COSTS AND REFERENCES

Subsystem	Overnight Capital Cost	Fixed O&M Cost	Electricity Requirement	Thermal Energy Requirement
Nuclear Reactor [11]	$3,716/kWe	$95/kWe-yr	N/A	N/A
Thermal Power Cycle [11]	$1,305/kWe	-	N/A	N/A
Wind Turbines	$1,689/kWe [11]	$46.75/kWe-yr [12]	N/A	N/A
Solar PV Plant	$1,094/kWe [13]	$8 /(kWe-yr) [14]	N/A	N/A
Liquid Fuel Production [15]	$12,810/(kg/hr)	$1,537/(kg/hr-yr)	Negligible	9,140 Btu/gal gasoline[1]
RO Desalination Plant [15]	$32,894/(kg/s)	$4,841/(kg/s-yr)	1,125 kg water/kWh electricity	N/A
Electric Boiler [8]	$81/kWe	N/A	N/A	1 kWh electricity input / kWh heat product
Electric Thermal Storage Unit [8]	$25/kWht = $125/kW	N/A	N/A	1 kWh electricity input / kWh heat product
Thermal Storage Unit [8]	$15/kWht	N/A	N/A	1 kWh heat input / kWh heat product
High Temperature Electrolysis (HTE) [9]	$662/kWe	$58.69/kWe-yr	35.1 kWhe/kg H_2	11.15 kWht/kg H_2
Low Temperature Electrolysis (LTE) – Higher Capital Cost [9]	$616/kWe	$42.73/kWe-yr	50.2 kWhe/kg H_2	N/A
Low Temperature Electrolysis (LTE) – Lower Capital Cost [9]	$154/kWe	$42.73/kWe-yr	55.2 kWhe/kg H_2	N/A

kWe: kilowatt electric
O&M: operations and maintenance

[1] 171,300 Btu(HHV) natural gas / gal liquid fuel is required as a feedstock for the process in addition to the thermal energy requirement

A key input is the electricity markets and performance. Three types of electricity products were included in the analyses:

1. Hourly electrical energy revenue (dollars per megawatt-hour [$/MWh])
2. Hourly ancillary service revenue from contingency reserves, regulation, and flexibility reserves (dollars per megawatt [$/MW])
3. Annual capacity payments (dollars per kilowatt-year [$/kW-yr]).

Future electrical energy prices and ancillary service prices were projected using the 2036 generation mix in the National Renewable Portfolio Standard (RPS) scenario in a published set of standard scenarios (2036 was used because only even number years are available) [16]. We used areas representative of Northern California, the Public Service Company of Colorado district, and Washington to create a mix of generators. That scenario and those locations were chosen because it resulted in an analysis with a high penetration of variable renewable generation (21% of annual generation from wind and 20% from PV) thus requiring flexibility be provided by other generators and lead to high electricity price volatility. Those conditions are expected increase the economic attractiveness of N-R HESs. In that scenario, natural gas combined cycle (NGCC) units generate 26% of the national annual electrical energy produced; hydropower generates 26%; traditional nuclear power generates 6%; and natural gas combustion turbines generate the remaining 1%. The generation mix for each state analyzed (Texas and Arizona) was entered into the PLEXOS production cost model to estimate the annual electrical energy production and hourly electrical energy and ancillary service price profiles that would be paid to the provider [6]. To avoid site-dependent price volatility, transmission constraints were not included in the PLEXOS analyses. FIG. 3 shows the price duration curves used in the analyses of the liquid transportation fuel, thermal energy, and hydrogen transportation N-R HESs [9]. The price duration curve used in the reverse osmosis desalination N-R HES is available in the report discussing that analysis [6]. Sensitivities were performed to analyze impacts of electricity prices and their volatility. For each sensitivity, a multiplier was randomly generated and the product of that multiplier and each hourly electricity energy price within the profile used as the electricity energy price for that hour.

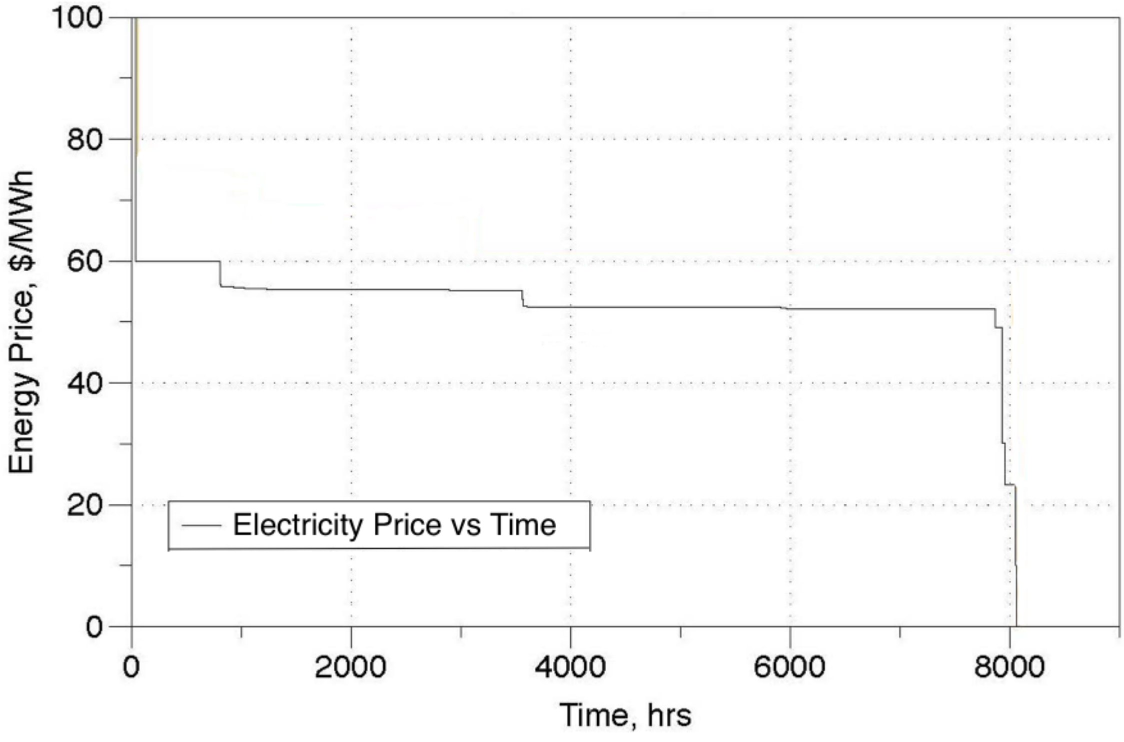

FIG. 3. Price duration curves for electricity energy prices in the Texas location over all hours of the year sorted from highest price to lowest. The price is $0/MWh for 704 hours in the year [6]

Electrical energy purchase prices are estimated as the hourly cost plus $15/MWh. The $15/MWh adder is intended to cover costs associated with the transmission and delivery of electrical energy that regional transmission organizations or independent system operators normally incur but are not included in the locational marginal price estimates (e.g., capacity, reserves, and administration). The $15/MWh adder is based on costs reported by the PJM Interconnection [17].

We included a capacity payment because it is a commonly used economic incentive to provide resource adequacy and set it at $50/kW-yr based on observed values in restructured markets over the last decade [6]. To receive capacity payments, the N-R HES has to provide electrical power to the grid for the 50 highest load hours during the year based on recent history of hours when available supply was limited [8]. Sensitivities with capacity payments of $100/kW-yr and $150/kW-yr are performed to help understand the potential of N-R HESs to support the grid's resource adequacy requirements.

The optimization is based on the NPV of the cash flows for the 25-year project financial life for each N-R HES using the calculation method recommended by Short [18]. Table 2 reports key financial parameters for that calculation. The weighted average cost of capital (WACC) in this analysis is 10% reflecting a debt percentage of 0% and a cost of equity of 10%; however, that WACC can be met with various debt/equity ratios with different discount rates. The analysis did not include state or federal policies with the exception of those that impacted the generation mix.

TABLE 2. KEY FINANCIAL PARAMETERS

Start of operations (year)	2035
Analysis period (years)	25
Tax rate	35%
Cost of equity	10%
Debt percentage	0.00%
Discount rate (nominal)	10%
Inflation rate (electricity/water/gasoline/natural gas)	3.0%

6. DISCUSSION AND CONCLUSIONS

Results of full analyses and results of all the N-R HES use cases shown in FIG. 2 are published in individual reports [See 6, 8, 9]. This section synthesizes overall conclusions and general lessons all of the separate analyses.

The first key conclusion is that the primary driver for whether a subsystem is included in the optimal configuration is whether it would be profitable independently. Under our analytical method and most of our assumptions (economic optimization over a full year; dynamic operations can sufficiently follow economic signals, capital-intensive subsystems), inclusion of each subsystem is not dependent upon whether other subsystems are also present. For example, the variable electricity generation subsystem is generally included if it has an NPV greater than zero and is not included if its NPV is negative.

FIG. 4 supports this conclusion by showing the optimal configurations for ≈2,000 combinations of gasoline price and electricity cost multiplier for the Texas-liquid fuel N-R HES configuration shown on the upper left of FIG. 1. Gasoline wholesale prices are varied between $0.00/gal and $3.00/gal on the x-axis and the electricity price multiplier that is described in Section 4 is varied from 0.1 to 2.0 on the y-axis. Gasoline prices and electricity price multipliers were independently, randomly sampled from a uniform distribution across the above ranges. The resulting figure shows the profitable configurations.

- Given the configuration and supporting assumptions, the electricity price multiplier must be greater than 1.25 to profitably generate electricity and the gasoline price must be greater than $2.09/gal to profitably produce liquid fuel. If the electricity price multiplier is less than 1.25

and the price of gasoline is less than $2.09/gal, no configurations are profitable (i.e., have a positive NPV) so no dots appear in that area in FIG. 4.

- If the electricity price multiplier is between 1.25 and 1.3 and the price of gasoline is less than $2.09/gal (as shown in the dark blue dots), a wind plant has a positive NPV, but the nuclear reactor is not profitable with either a thermal power cycle or the synthetic gasoline process.
- If the electricity price multiplier is greater than 1.3 and the price of gasoline is less than $2.09/gal (as shown in the orange-colored dots), both a wind plant and a nuclear reactor-thermal power cycle combination are profitable. However, since the profitability threshold for both technologies operating together (1.3 price multiplier) is horizontal there appears to be no financial benefit to having both electricity generation technologies co-located and operated together.
- If the electricity price multiplier is less than 1.25 and the wholesale selling price of the liquid fuel is greater than $2.09/gal (as shown in the yellow dots), the nuclear reactor-liquid fuel process is profitable, but neither of the electricity generation subsystems are profitable.
- If the electricity price multiplier is greater than 1.25 and the wholesale selling price of the liquid fuel is greater than $2.09/gal (as shown in the light blue dots), the nuclear reactor-liquid fuel process is profitable based on the value of the produced fuel alone. The wind generation subsystem is also profitable and is included in the optimal configuration.

Similar examples are published for each N-R HES use case.

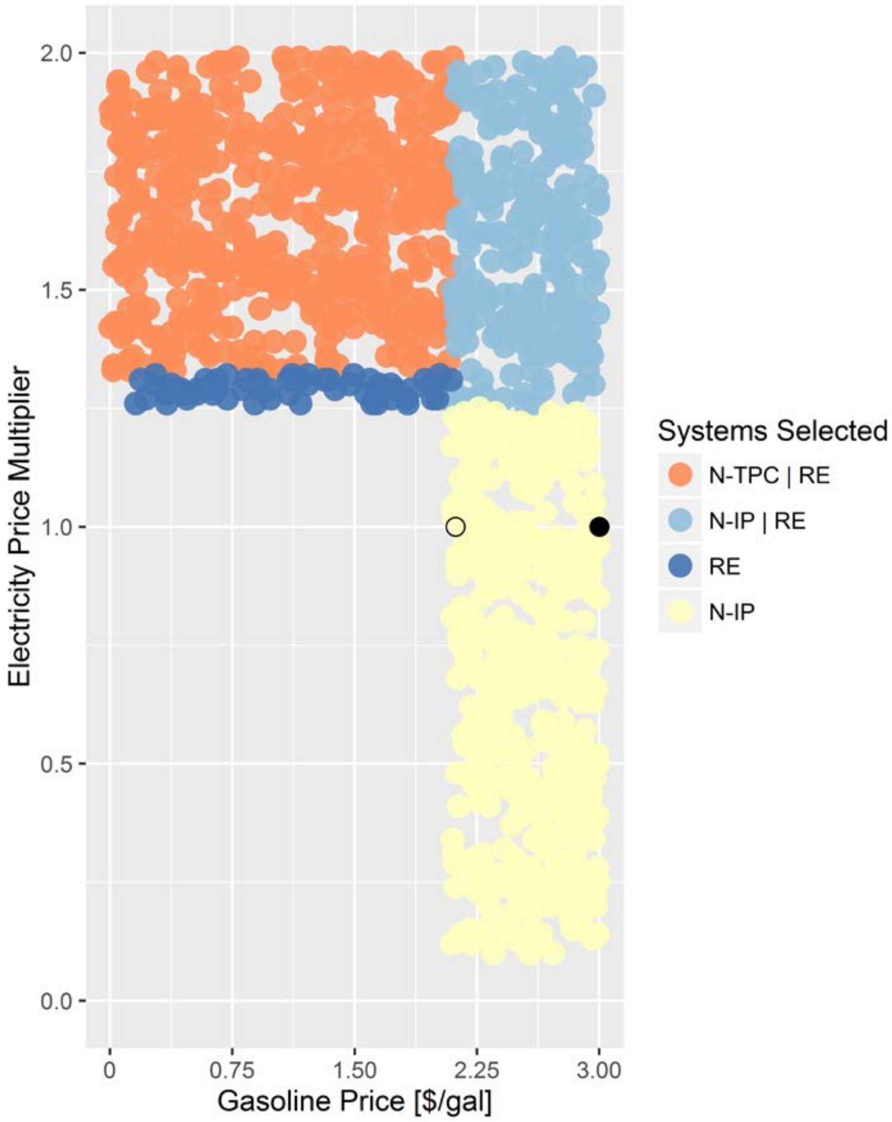

FIG. 4. Optimal configurations for the Texas-synthetic gasoline N-R HES at various gasoline prices and electricity price multipliers [6]

N-TPC: Nuclear reactor and thermal power cycle
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity (wind) generation

Solid black dot at electricity price multiplier of 1.0 and $3.00/gal gasoline price: reference case liquid fuel price projection; reference case electricity price vector
Open black dot: minimum gasoline selling price for a liquid fuel plant using natural gas heating as described on page126 in Ruth, et al [6]; reference case electricity price vector

One key caveat to this first conclusion is that grid interconnection costs are assumed to be negligible. If having a single interconnection for both renewably generated power and nuclear-generated power to the grid is less costly than independent interconnections, then there would be a synergy that makes a configuration with both technologies more profitable than configurations where they are independent. Other factors such as inertia and resilience requirements may also provide additional value for configurations with both forms of electricity generation but those factors are outside the scope of the analysis.

The second key conclusion is that high capital cost equipment is almost always optimally operated the maximum number of hours possible in a year. Because most industrial processes have a high capital cost, industrial processes are usually optimally operated as many hours as possible. FIG. 5 is from the same result set as FIG. 4. The image on the right shows that, when the gasoline price is over $2.09/gal, the synthetic gasoline plant is present and it optimally produces the same amount of liquid fuel no matter what the electricity price is. Hence, the economic optimum is to operate the liquid fuel subsystem at its maximum capacity that uses all the energy produced by the nuclear reactor (i.e., the thermal power cycle is not necessary). The image on the left indicates that electricity is generated when the electricity price multiplier is greater than 1.25. However, in the region with the orange only wind-generated electricity is sold. Electricity generated using energy from the nuclear reactor is only sold at an electricity price multiplier greater than 1.3 and low gasoline price less than $2.25/gal.

This conclusion indicates that electrical pricing is insufficient for optimal N-R configurations to sell electricity when its prices are high and sell an industrial product during the remainder of the year even with high penetrations of renewables resulting in large electricity price swings (as in this analysis) and doubling those price swings by using an electricity price multiplier of 2.0. In this use case, a capacity payment of $50/kW-yr is insufficient for the full N-R HES to produce electricity during hours necessary to receive that payment because the opportunity cost of not producing the liquid fuel during those hours is too high.

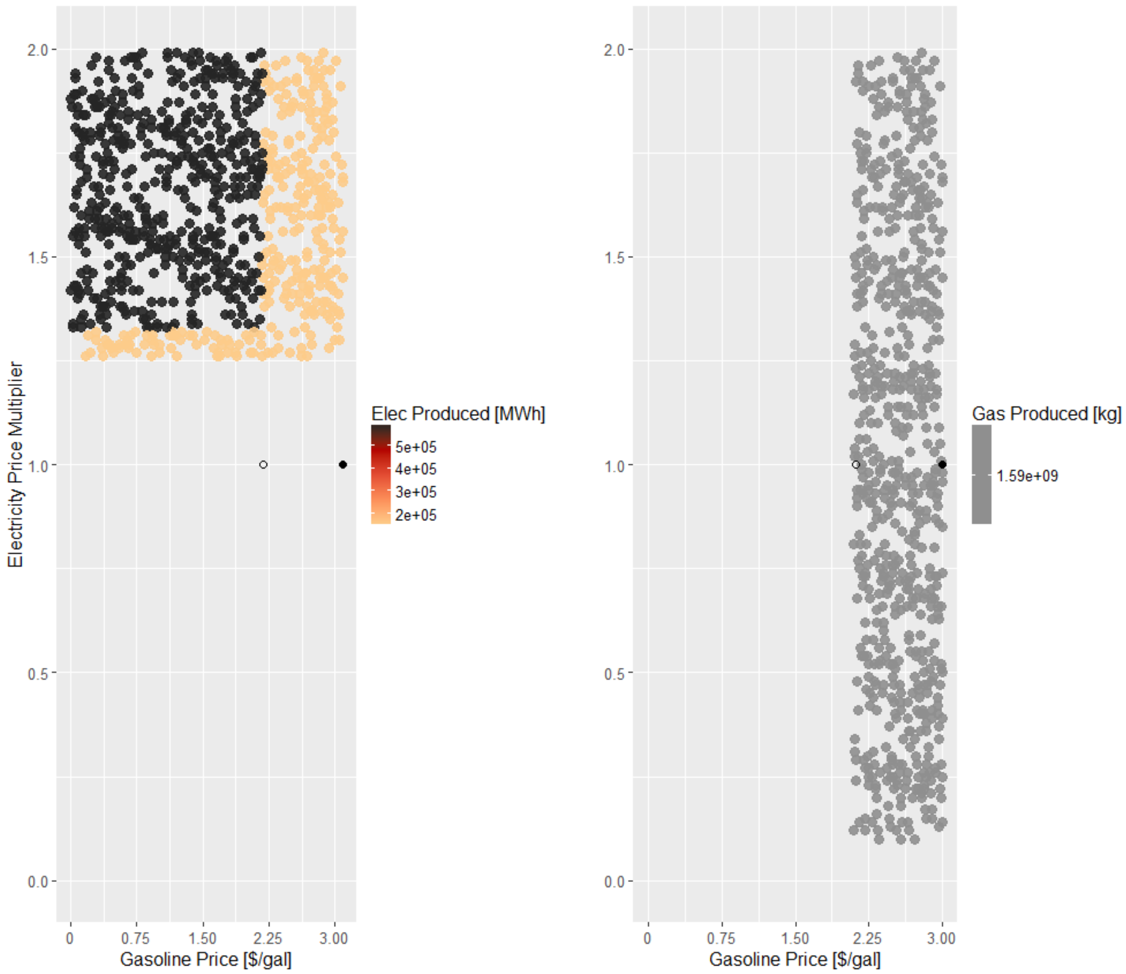

FIG. 5. Optimal annual product generation at various gasoline prices and electricity price multipliers for the Texas-synthetic gasoline N-R HES [6].

Electricity is on the left with greater generation at the darker color. Synthetic gasoline is on the right. Electricity pricing based on AEO reference case and $50/kW-yr capacity payments.

A key caveat to this conclusion is that capacity payments are sometimes sufficient to incentivize the industrial process to be turned down or off for a small number of hours annually (50 hours/yr in this analysis) to enable the N-R HES to receive both the capacity payment and high energy price during those hours. FIG. 6 shows the electricity production (left) and water production (right) of the optimal configurations and operational strategies for the Arizona desalination N-R HES depicted in the upper right of FIG. 2. The dark blue dots shown when water prices are above $3.40/1000 gal and the electricity price multiplier is below 1.40 indicate that the optimal operation is for the nuclear reactor and thermal power cycle to produce electricity that is used desalinate water during all hours of the year. The white dots in the range when the water price is between $1.18/1000 gal and $3.40/1000 gal indicate that the optimal operation is to use nuclear-generated electricity to desalinate water during all but the 50 hours/year necessary to sell electricity to receive the capacity payment. The medium blue and light blue dots are at an electricity price multiplier in conditions where the PV system is included in the optimal configuration. Like the range with the white dots, the light blue dots at water prices the N-R HES optimally sells nuclear-generated electricity to supplement PV-generated electricity during the capacity payment hours. Not desalinating water to receive the capacity payment reduces the overall production of desalinated water from 400,000 acre-feet to 398,000 acre feet but increases income from both electrical energy sales and capacity payment enough to overcome the opportunity cost of not producing those 2,000 acre-feet of water.

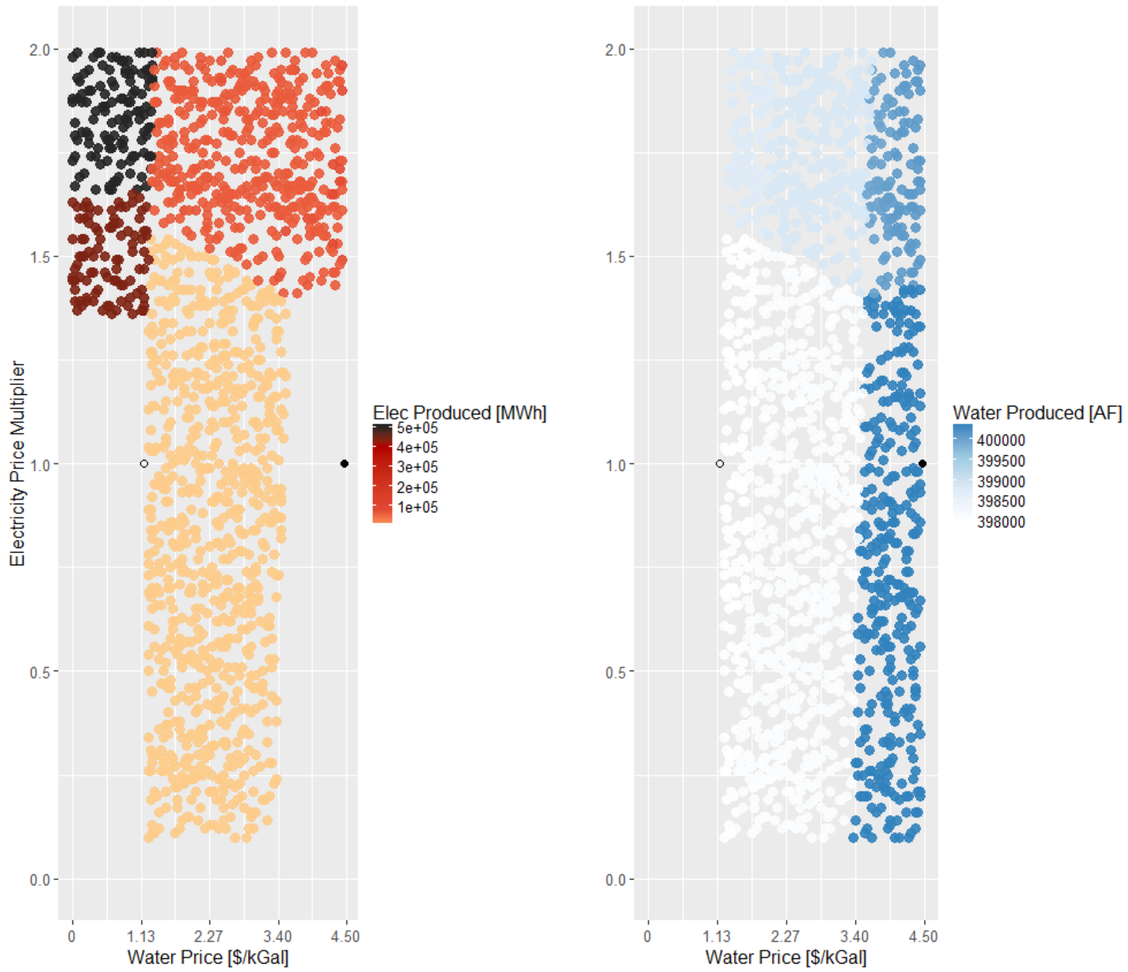

FIG. 6. Optimal annual product generation at various water prices and electricity price multipliers for Arizona-desalination N-R HES [6].

Electricity is on the left with greater generation at the darker color. Synthetic gasoline is on the right. Electricity pricing based on AEO reference case and $50/kW-yr capacity payments.

The third key conclusion is that N-R HESs with lower capital cost industrial processes are more likely to utilize their flexibility to switch between electricity and the industrial product more often than their higher capital cost configurations and that this flexibility increases the instances of profitable situations. The reason is that the cost of capital sitting idle while producing electricity instead of the industrial product is not as high. FIG. 7 compares the optimal configurations of an LTE hydrogen N-R HES with a higher capital cost-higher efficiency LTE (left) and a lower capital cost-lower efficiency LTE (right).[2] The different color dots in the triangles in each image indicate that, at electricity price multipliers greater than 1.4 and hydrogen prices around \$3.85/kg, LTE subsystems with the lower capital and efficiency are included in the optimal configuration whereas those with higher capital costs and efficiencies are not included. The white dots in FIG. 8 that can be found within the red triangle indicate that analysis region has a higher hydrogen production with low-cost LTE parameters but that, with the parameters in that analysis region, the N-R HES is only producing hydrogen during about 20% of the time. Nuclear energy is dispatched to produce the highest value product during each hour in that analysis region; however, that type of dispatch was uncommon within the rest of the analysis because the capital cost of most industrial subsystems was too high for them to be built without running them most hours of the year.

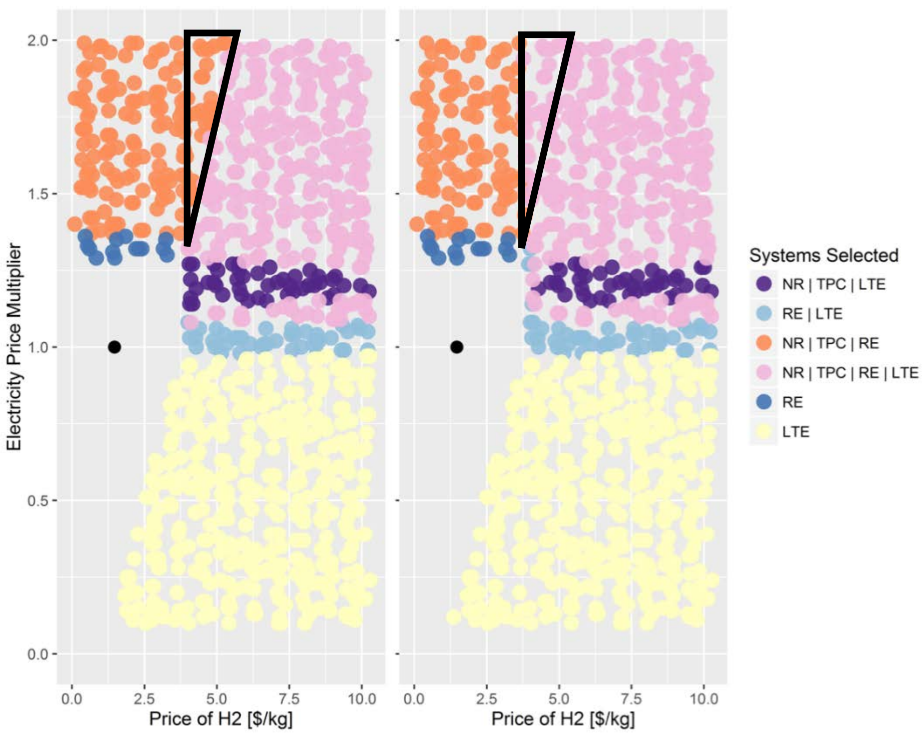

FIG. 7. Optimal configurations for the LTE N-R HES at various hydrogen prices and electricity price multipliers with two different electrolyzer prices and efficiencies[9]. Triangles highlight conditions that result in different optimal configurations.

Projected high cost electrolyzer parameters (left); low cost electrolyzer parameters (right).
\$50/kW-yr capacity payments.

LTE: low temperature electrolysis subsystem
NR: nuclear reactor
RE: renewable electricity generation (wind power plant)
TPC: thermal power cycle

[2] Table 1 reports capital cost and efficiency estimates (reported as electricity and thermal energy requirements). Additional details are in the detailed report [9].

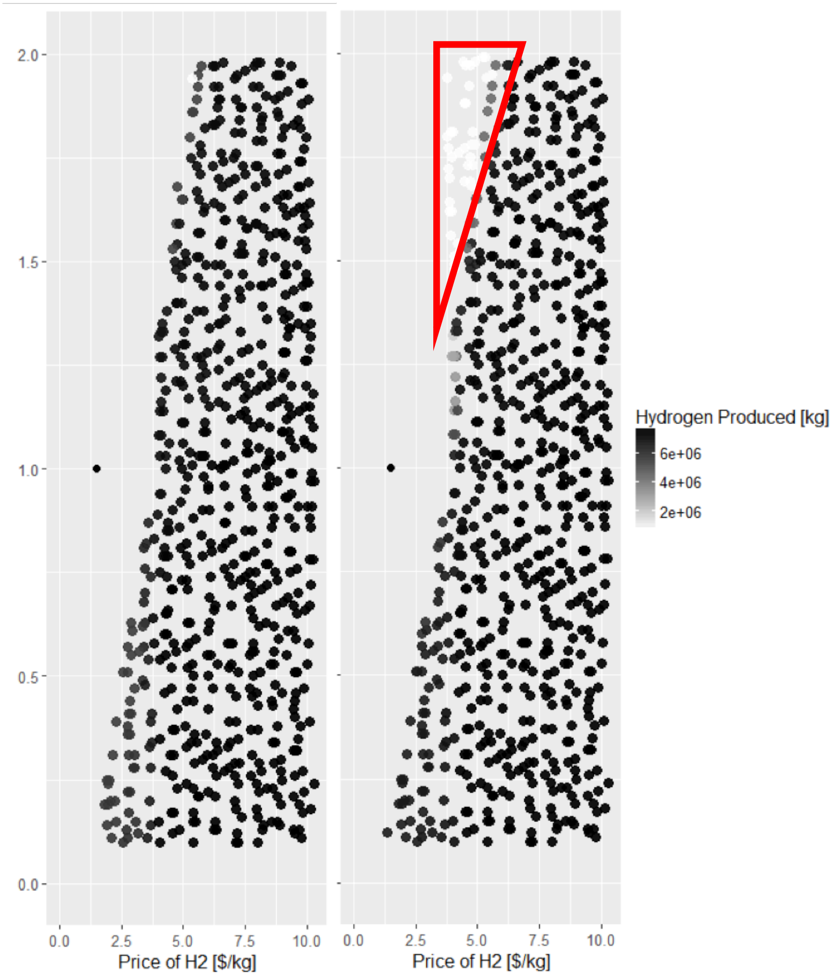

FIG. 8. Optimal annual hydrogen generation for the LTE scenario at various hydrogen prices and electricity price multipliers with two different electrolyzer prices and efficiencies [9]. Triangle highlights conditions that include electrolysis only under low cost electrolyzer parameters.

Projected high cost electrolyzer parameters (left); low cost electrolyzer parameters (right).
$50/kW-yr capacity payments.

Solid black dot at $1.47/kg and 1.0 indicates reference case hydrogen and electricity prices.

The fourth key conclusion is that nuclear reactors may be competitive selling thermal energy if a thermal energy market exists and they can access that market. The primary competition for meeting thermal energy demands in the U.S. is natural gas. FIG. 9 plots the levelized cost of producing steam from both a light water reactor based on pressurized water reactor technology and from a natural gas boiler at various natural gas prices.

Levelized costs of steam from LWRs are shown in the horizontal lines. They are calculated from the levelized cost of producing electricity from the LWRs by backing out the cost of steam. Calculations were made using a HYSYS process and thermodynamic model [19]. The model is based on a 7-stage Rankine power system with high pressure steam (750 psia, 560 F) taken before the first turbine. If only lower pressure steam is required, it could be extracted from several locations throughout the power cycle so that electricity can be generated as well.

The diagonal blue line shows the profile of the cost to produce steam from natural gas. It is based on CAPEX and OPEX estimates, a high combustion efficiency (~85%), and minimal flue gas clean up (i.e., no cost for sulfur, ash, or particulate mitigation) [20]. Three points are highlighted on that line indicating reference case prices in the U.S. Energy Information Administration's 2017 Annual Energy Outlook in current and future timeframes [21].

This plot shows that nuclear generators can provide cost competitive steam. The anticipated levelized cost of electricity from a nuclear reactor is in the range of \$35-\$45/MWh [22], therefore the range between the orange dotted line and the brown dashed line is the anticipated cost of steam generated from nuclear energy. It is less expensive than from natural gas at all natural gas prices above \$2.00-\$3.00/MMBtu depending upon where in the range the nuclear cost of electricity falls. Current industrial natural gas prices in the U.S. are higher than that range as are future price projections.

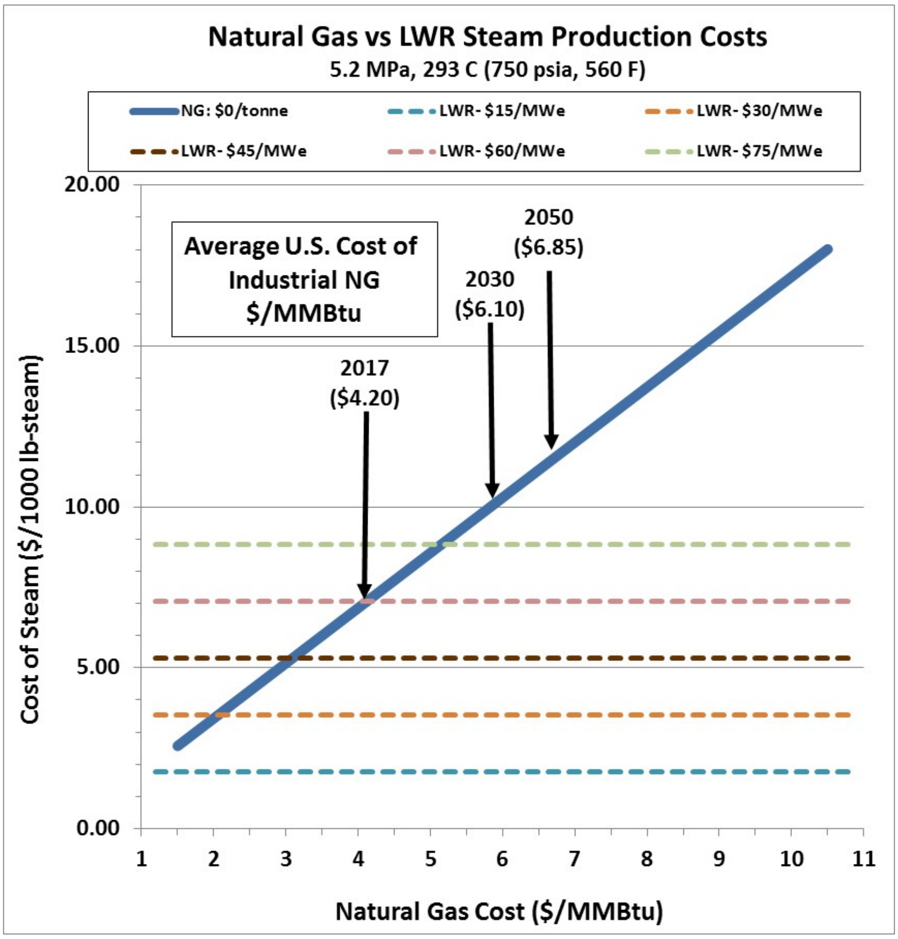

FIG. 9. Comparison of cost to produce steam from nuclear heat and natural gas combustion.

This work shows that N-R HESs can provide benefits to the grid and be economically attractive in situations with high electricity price volatility. They can be especially economically attractive if the industrial process has a low capital cost and be turned on and off easily. N-R HESs with industrial processes that can utilize nuclear-generated heat are also more likely to be economically attractive than those that use electricity exclusively because the overall thermodynamic efficiency is higher.

7. OPPORTUNITIES FOR FUTURE WORK

The Nuclear Innovation: Clean Energy Future (NICE Future) initiative was recently launched under the Clean Energy Ministerial[3] to focus on existing and new opportunities for nuclear energy. The goal of the NICE Future initiative is to initiate a dialogue on the role that nuclear energy can play in bolstering economic growth, energy security and access, and environmental stewardship. In support of that goal, the initiative has several strategic objectives [23]:

[3] The Clean Energy Ministerial is a multinational organization that encourages a transition to a clean energy economy. It provides a forum to promote policies and programs and share experiences. Participants propose and select initiatives based on common interests.

Bring nuclear energy from traditional, nuclear-only fora to broader multilateral discussions on clean energy at both the ministerial and working levels;

1. Engage both nuclear and non-nuclear energy policy makers and stakeholders in a discussion on the role of nuclear energy in integrated clean energy systems of the future; and
2. Ensure energy policy-makers are informed of the opportunities and challenges of the full range of options needed to meet global clean energy goals—covering areas of technology feasibility, economics and financing, and stakeholder perspectives.

Future analysis, research, and development on N-R HESs can support that goal by identifying benefits and challenges for this advanced nuclear energy technology that can support reliability and resilience for both the electricity grid and in the industrial sector. Each specific location will have its own opportunities and challenges. The analyses reported here assume generation mixes that include a high percentage of flexible natural gas power generation and projected U.S. natural gas prices. Locations with higher natural gas prices and less flexible generation may have different opportunities to achieve a reliable and resilient electricity system, and potentially have stronger economic drivers for N-R HESs and their ability to dispatch energy between electricity generation and an industrial process.

Several analysis opportunities would help quantify the benefits of nuclear generation – both independently and as part of N-R HESs. One opportunity is analysis of the level of real inertia required to manage frequency on the grid especially in situations where most of the generation is connected via inverters (e.g., where PV and wind generation is a large fraction of the total). By spinning turbines to produce electricity, nuclear generation inherently includes real inertia and can support those needs. Understanding that value is a first step toward compensating suppliers for it.

A second opportunity is the benefit of having always-operating energy suppliers that do not require frequent supplying of fuels. Most nuclear technologies require fuel deliveries annually or less frequently and wind and PV do not require any fuel deliveries. Therefore, both have a higher likelihood of operating during times of system stress when delivery infrastructures are either constrained or cut off. Understanding that value can be a first step toward markets to provide it. A third opportunity is understanding the benefits of nuclear and renewable technologies, and N-R HESs, to hedge against fuel price uncertainty. Historically, energy prices have been volatile and shart term volatility has put pressure on national economies. Since N-R HESs are designed to adjust the product mixture based on the market prices, they allow the owner to hedge against that volatility. The ability to flex could also benefit market operators and regulators because they would be able to design markets and justify investment decisions recognizing the price ceiling that an N-R HES would provide.

Other opportunities include responsive loads and development of alternative thermal energy sources for industry. The H2@Scale concept involves development of water electrolysis to produce hydrogen as a responsive load that can utilize low-priced electricity to generate hydrogen that can then be used for a variety of industrial and transportation services as well as providing seasonal energy storage for the grid [24].

Alternative thermal energy options could diversify the source of thermal energy for industry. These sources include use of electricity in heat pumps, direct use of solar or geothermal energy, and use of nuclear energy [7]. Examples of industrial processes that use heat include minerals production; concentration, evaporation, and drying; petroleum refining and separations; thermal desorption processes; pulp and paper processes; and forest product drying and pyrolysis. Because many require higher temperature heat, advanced, higher temperature, nuclear reactors including the very high temperature gas-cooled reactor which can delivery hot helium up to 950 C could be beneficial as well as molten-salt reactors that can provide heat at temperatures up to 800 C [7]. In addition, new heat distribution systems, thermal energy storage options, and integrated heat-exchanger chemical reactors could increase thermodynamic efficiency and increase opportunities for integration.

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