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MULTIMARKET CONTROL AND OPERATION OF AN ADVANCED NUCLEAR REACTOR WITHIN AN INTEGRATED ENERGY PARK

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Abstract

Integrated energy systems (IES) are increasing in popularity and relevance given the heightened penetration of variable renewable energy sources. This variability is causing traditional baseload generators to reconsider their business cases as exclusively electrical generation stations and to instead consider ancillary products (e.g., hydrogen) to remain competitive in the current energy market. This work investigates the coupling, control, and overall viability of IES consisting of an advanced nuclear reactor coupled with a high-temperature steam electrolysis (HTSE) plant and hydrogen storage. The goal of such IES is to produce hydrogen without impacting reactor operations during periods of off-peak electricity demand and then sell electricity to the grid during periods of high demand. To accomplish this, a novel heat exchanger, control scheme, and coupling strategy were needed to ensure that the advanced nuclear power plant could make these transitions. Idaho National Laboratory's open-source Framework for Optimization of Resources and Economics (FORCE) framework was used to develop novel coupling and control schemes that demonstrate the viability of multi-market operation of advanced nuclear reactors to produce both electricity and hydrogen. The results demonstrated the coupled IES could operate without impacting reactor systems while monetizing the electricity market and meeting all contractual hydrogen consumer demands.

1. Introduction

The economic outlook for current and future baseload power generators is increasingly tenuous, with the influx of renewable power generation increasing electricity price fluctuations and decreasing nominal clearing prices, as the marginal price of the solar and wind energy being bid into the grid is extremely low (or even negative). In the U.S., nuclear energy has traditionally served as a baseload generator, but there is increased interest in expanding its role beyond baseload generation in order to take advantage of the large amount of thermal power generated at low marginal costs. Integrated energy systems (IES) introduce alternative heat applications (other than the production of steam to turn turbines) that may be economically attractive when electricity prices are low. Additionally, IES can provide carbon-free generating sources of heat for large heat users in product manufacturing [1].

There are competing methods for generating H_2 for various customers (e.g., low-temperature steam electrolysis, high-temperature steam electrolysis (HTSE), and steam-methane reforming,etc.). Electrolysis is a H_2 production method that creates no CO_2 byproduct. Additionally, by using clean sources of energy (e.g., nuclear power), the entire process can become non-carbon emitting.

In this work, we model and analyze the economics of creating an IES that consists of a high-temperature gas reactor (HTGR), HTSE plant, and hydrogen storage system, providing the customer with a constant stream of H_2 while also taking advantage of high marginal electricity prices to increase overall revenue.

2. Model Development and Theory

The IES is modeled in Modelica using components developed in the HYBRID repository of the Framework for Optimization of Resources and Economics (FORCE) ecosystem. By using an input of the economic price schedule, the controls methods of the overall system/subsystems distribute energy as required to meet a specified H_2 demand. Additional details beyond those given in this brief paper can be found in other publications and reports [2] [3].

2.1 Hydrogen Production via High-Temperature Steam Electrolysis

The HTSE plant uses controlled solid oxide electrolysis cell stacks to calculate the amount of generated H_2 and O_2 given the electric and steam input levels. Actual steam used within the solid oxide electrolysis cell's cathode side is received at temperatures around 750°C and then heated by input steam drawn from outside sources. After the initial heating from the outside steam sources, the final heating is achieved by electrical heaters.

The full electrical load of the HTSE plant is set at a maximum of 36 MWe and a minimum of 9.5 Mwe, for a H_2 production rate of 0.12–0.40 kg/s. When the electrical input decreases to such a low value, the system can be maintained in hot-standby conditions by slightly reducing the heating steam input from 8.2 kg/s down to 7.0 kg/s.

All produced H_2 is directed to a pressurized storage volume without liquefaction. A conservative limit of 40 MPa is imposed on the gaseous H_2 storage.

2.2 Pebble-Bed-Core High-Temperature Gas Reactor

A pebble-bed HTGR that generates electricity via the Rankine cycle was developed in the HYBRID repository [2]. The model was designed to produce power by using pebble-embedded tri-structural isotropic (TRISO) fuel kernels. TRISO fuel encapsulates thousands of small UO_2 fuel pellets in spherical graphite networks (i.e., pebbles). Helium coolant transfers heat from the core to the Rankine system via a heat exchanger. The nominal power ratings of the reactor used in this study were about 124 MWt in the core and 36 MWe generated by the turbine, in addition to the heating supplied to the HTSE plant.

The nominal controlled elements in the HTGR system are the coolant core exit temperature, steam temperature, steam pressure, electric power, and feedwater temperature. These are controlled by control rod movement, feedwater pump speed, primary coolant blower speed, turbine control valve position, and steam extraction valve position. None of these control systems are directly due to the connection of a new heat exchanger to provide HTSE heat.

The model used in this study is an adjustment on the HYBRID repository model NHES.Systems.PrimaryHeatSystem.HTGR.HTGR_Rankine.Pebble_Bed_Rankine_Complex.

2.3 Economic Modeling and Set points

Economic data were obtained from publicly available Electric Reliability Council of Texas (ERCOT) day-ahead market prices [4]. A week of data (collected May 2-8, 2022) was chosen to represent a possible—though certainly not exhaustive—electricity price profile in which to deploy this system. The average electricity price over that week was high ($77.18/MWh), but the resulting demand flexibility from the data helps demonstrate the possible marginal revenue impact of this IES, and stresses the safety implications. By applying the price schedule (see Figure 1) and a $2/kg assumed contract selling price of H_2, a production schedule can be created.

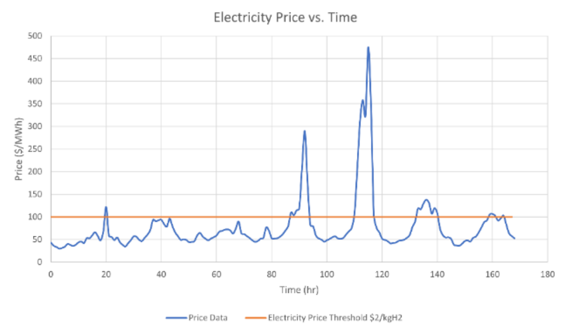

Figure 1. Price data used and example of electricity price threshold.

The modeling results for the HTSE plant indicate that 25 kWh of electricity is required to generate 1 kg of H_2. Thus, the electricity clearing price (i.e., the point at which it is more economical to sell electricity than use it for hydrogen production) in $/MWh is 40 times the assumed $/kg selling point of H_2. Expected H_2 prices range from $1.50/kg - $3.00/kg from the literature were used to set the evaluation range. [2] Preliminary analysis demonstrated that the IES could product 0.12 kg/s of hydrogen at minimum power requirements and could produce 0.4 kg/s of hydrogen at maximum production rates. Given the electricity clearing price, it is possible to determine the approximate total hydrogen production over the analyzed period by calculating the number of hours at which the system would produce maximum electricity and minimum hydrogen or maximum hydrogen and minimum electricity. Taking the average hydrogen production rate over the operating period, a contract size was determined. The storage size is then calculated via parameter sweeping to find a minimum value at which point the contracted supply rate is always met.

Thus, the variables in this study are as follows: the sizes of the HTGR and HTSE, the contracted H_2 flow rate, the contracted H_2 price, and the H_2 storage size. (The first four variables will be fixed to determine the H_2 storage size.)

2.4 System Control

A supervisory control system maintains the energy balance between subsystems and ensures that appropriate safety logic is followed. Each subsystem contains independent control to meet its specific thermophysical requirements or monitor its own limits. Two new controlled elements being introduced into the IES require new control strategies.

The first new controlled element is the H_2 dispatched from storage. A constant demand signal is placed on the storage to ensure that the industrial partner meets its demand at all times. To accommodate this signal, an additional signal is added to the HTSE plant to allow for possible adjustments to the power demand should the storage mass become too low.

The second new controlled element is the provision of HTGR heating feedstock to the HTSE plant. The feedstock heating requirements within the HTSE plant, feedstock being one mixture of water and hydrogen and another of oxygen and nitrogen, are conducted via a closed loop; namely, pumping water through a heat exchanger at the HTSE plant to provide heat, then returning it through a heat exchanger linked with HTSE steam to obtain heat. To maintain HTSE operating conditions, the HTGR steam provided to the heat exchanger must be controlled. The HTSE return steam temperature is used to control the HTGR-provided steam flow rate.

3. Results

The IES control systems were able to maintain core power and fuel temperatures—which are indicators of normal/safe operation—at or near constant values relative to the nominal conditions (see Figure 2). The core power rate decreases are due to reduced steam flow to the HTSE, which thus resulted in less total cooling in the steam generator of the nuclear system. The power is reduced in these instances to maintain the constant outlet coolant temperature. The control systems maintained the fuel centerline temperature within +/- 0.07%. The generator power only slightly fluctuated during times corresponding to thermal power level changes as the secondary control systems responded to system changes.

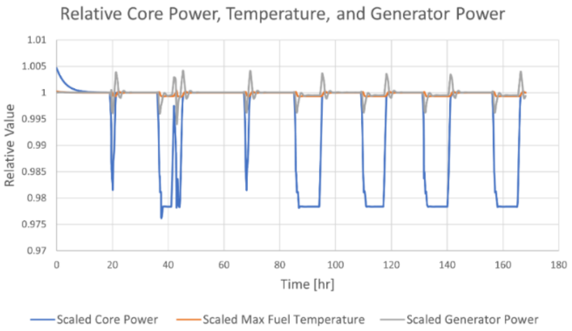

Figure 2. Scaled maximum fuel temperature, core power, and generator power.

As expected, the IES H_2 production contract size increased with the rising contracted selling price of H_2. The non-linearity of the data seen in Figure 3 is caused by the sampled price schedule. As the price of H_2 decreases, the price threshold at which selling electricity is beneficial becomes more frequent—to the point of nearly daily arbitrage. Given the sampled data, it is only with high H_2 prices that electricity would be produced instead of H_2.

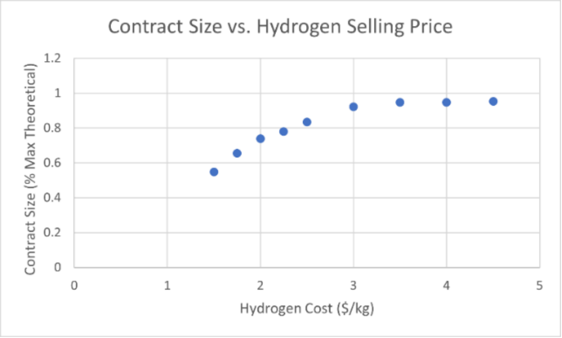

Figure 3. Contracted size as % of maximum flow rate (0.4kg/s) vs. hydrogen price.

By using the sampled electricity price profile to achieve the contracted H_2 production rate (assuming maximum and minimum H_2 storage pressure values), it is possible to calculate the volume of storage such that the system's control systems need not intervene to bypass the set electrical schedule so as to appropriately make up the H_2 generation rate. These values are listed in Table I along with marginal revenue increases when compared to generating only electricity. It is difficult to ascertain a generalized trend regarding storage size requirements. The combination of high and low price frequencies within the electricity price profile seemingly drive the storage size in different directions. Initially, the size increases with price, likely due to the large mass required to meet demand during the long periods of low production, but then the length of demand reduces at dramatically higher prices such that less mass is required—and thus so is a smaller storage volume.

Table I. H2 Storage Size to Meet the Contracted Flow Rate

H_2 Contract Price	H_2 Flow Rate	Storage Size Required	Marginal Revenue Increase	Marginal Effective Electricity Price Increase
$1.50/kg	0.2733 kg/s	220 m^3	-$5,200	-$0.86/MWh
$2.00/kg	0.3250 kg/s	250 m^3	$86,800	$14.36/MWh
$2.50/kg	0.3533 kg/s	480 m^3	$190,700	$31.53/MWh
$3.00/kg	0.3853 kg/s	320 m^3	$302,000	$49.95/MWh

Note that these economic figures are marginal revenue increases only and should not be construed as net present value numbers, as they do not include capital costs of storage or dynamic operation installation costs.

4. Discussion

The strategy for coupling a HTGR with HTSE and hydrogen storage to produce a constant flow of H_2 , shown in Table I, proved successful by meeting demand without greatly impacting reactor operation. Integration controls operated well as additions to nominal controls as opposed to replacement. This promising result indicates that, it will likely be possible to operate the HTGR in nominal operating conditions and methods by adding to standard controls, rather than changing existing methods.

Over a relatively short deployment schedule of one week, the selected data could potentially be inadvertently biased toward either high or low prices. The ERCOT data were selected at random and may not be fully representative of typical operational regimes. With that in mind, future deployments and studies should investigate significantly longer time periods so as to reduce profitability risks. The FORCE framework contains the tools necessary for these lengthier studies once the location, capacity, and generation sources are known.

5. References

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