Economic Assessment of Nuclear Hybrid Energy Systems: A Framework Demonstration

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INTRODUCTION

One of the goals of the HYBRID modeling and simulation (M&S) project initiated by INL [1] is to assess the economic viability of Nuclear Hybrid Energy Systems (NHES) in a market that contains renewable energy sources like wind. The NHES includes a nuclear reactor that not only generates electricity, but also produces by-products utilizing excess heat/electricity, like hydrogen or desalinated water. The idea is that the possibility of selling non-electric energy provides cushion to the volatility in the electricity demand introduced by the renewable energy sources [2]. The problem to solve is to find the optimal configuration of an NHES that will minimize the cost of electricity or maximize its profit, depending on the electricity market type the NHES will operate in.

The HYBRID M&S project is a multi laboratory effort, led by the Idaho National Laboratory (INL) and supported by the Argonne National Laboratory (ANL) and the Oak Ridge National Laboratory (ORNL).

The software framework development for the HYBRID project is ongoing. The status of the framework has been presented in detail at the ANS summer meeting in 2017 [3]. In summary, the HYBRID software framework includes:

- The RAVEN (Risk Analysis Virtual ENvironment) code developed at INL [4] that drives the problem and manages the data exchange between the different codes involved in the HYBRID framework. Furthermore, RAVEN is used to do the optimization, as well as all sensitivity and statistical analysis needed.
- The CashFlow plugin for RAVEN developed at INL, which computes the cash flows and desired economics indicators such as the Net Present Value (NPV) or the Internal Rate of Return (IRR) in the HYBRID framework.
- The modeling language Modelica [5] (the Dymola compiler is used) to compute the dynamics of the NHES.

The HYBRID framework is very flexible. It allows studying modular systems made of an assembly of components, e.g. a nuclear reactor, a gas turbine, a battery, a by-product production subsystem and, possibly, renewables.

In this paper, as a demonstration of the HYBRID framework, the economic viability of a demonstration case NHES is analyzed. The system presented includes a nuclear reactor and an Industrial Process (IP), in this case the High Temperature Steam Electrolysis system for hydrogen production.

NHES SYSTEM CAPACITY OPTIMISATION

First, hourly time resolution was selected for the demonstration case. At this time scale, none of the components of the hybrid system [1] (in hot standby) have an issue reaching any prescribed level of power (no inertia) within their capacity (the current analysis assumes that the reactor operates at constant power).

Moreover, it was decided to perform a penetration (i.e., profitability) analysis of a hybrid system for a given, existing market. The assumption made is that the hybrid system is considered to be a price taker without the capability to influence the market (neither electrical, nor hydrogen). A constraint must be defined to limit the components of the hybrid system, such that the system optimization does not diverge. The choice here is to consider the reactor to be fixed in capacity and operating at a steady thermal energy level (not electricity production). In this way it is expected that the direct heat coupling between the reactor and the IP creates a maximum for the economic efficiency. Another condition to avoid the system divergence is to use the IRR as the goal function versus the NPV. The NPV would drive the optimization to increase the size of the IP as long as the IRR is positive, even if the IRR is decreasing.

It is not useful to add other components than the nuclear power plant and the IP to the simulation since the lack of inertia of the system would set their optimal size either to zero or infinity depending on a positive or negative economy of scale. In addition, the lack of inertia of the system, i.e. the fact that the system can reach any prescribed level of power within their capacity within the one hour time resolution eliminates the need to run the Modelica model to asses the dynamics of the system.

For such a “copper plate” model, it can be proven that the most efficient, economical way to supply the electricity demand is based on the least marginal cost (as occurs in current deregulated markets). In a hybrid system, the marginal cost should consider not only variable cost but also variable opportunity cost derived from selling/not selling the co-product (hydrogen).

In conclusion, the test case is composed as follows:

- Goal function is the IRR.
- Copper plate model (no inertia, no Modelica needed).
- Dispatching (electricity or process heat) based on marginal cost.
- Size of nuclear plant is fixed.
- Variable size of hydrogen plant (optimization variable).

Price Data

The optimization uses one year of hourly price of electricity. The optimization is not done on one historic price history (which is equivalent of optimizing the problem assuming perfect knowledge of the future), but averaged over a lot of synthetic price histories, each for one year. In this case, one can claim to do an optimization for a given scenario taking into account the stochastic nature of the problem. RAVEN has the capability to produce such synthetic time histories. The generated time series are prepared to statistically conform to the actual measurement but possess different temporal profiles. In particular, a combined model with Fourier series and autoregressive moving average (ARMA) [6] is utilized to de-trend the yearly measurements and to characterize the autocorrelation of the residues.

For the present study, the Fourier & ARMA model has been trained with electricity price data from a region where a hydrogen market exists as well. The data used in the evaluation is from the MISO [7] database using the EES (and EES.DOWCHEM) aggregated data available for the years 2012 and 2013. The 5-minute data is then collapsed into hourly data and used to train the ARMA model.

The hydrogen price in this study is assumed to be constant. A recent literature study [8] suggests hydrogen prices between ~\$1/kg and ~\$3/kg. A parametric study has been performed in this interval.

Dispatch Rules

The IP can cover up to ~10% of its energy needs by steam. It is assumed in this demonstration, that the IP gets steam and electricity form the nuclear plant, but when the nuclear plant is at its capacity, it can buy additional electricity form the grid.

For every hour of the simulation, the dispatch rules decide what the nuclear plant and the industrial process are going to do, i.e. first, is steam used to produce electricity or diverted to the hydrogen plant as process heat and second, is the industrial plant buying more electricity form the grid or not. The dispatch is based on marginal profit, as discussed in the previous section. The decision logic is depicted in Figure 1. Depending on the capacity of the industrial plant, 4 different scenarios are possible:

1. The marginal profit analysis dictates using all steam to produce electricity. In this case, it is never profitable for the industrial process to buy electricity from the grid. Therefore, no hydrogen is produced.
2. The marginal profit analysis dictates steam production. Three different cases can emerge:
   a. The capacity of the hydrogen plant is small. In this case, the reactor provides all steam and electricity needed to the industrial process. Leftover electricity is sold to the grid. The industrial process works at 100% without the need to buy electricity from the grid.
   b. The capacity of the industrial process is large. In this case, the reactor provides the maximum fraction of steam that the hydrogen plant can handle. The corresponding electrical energy needed is partly provided by the reactor and whatever part the reactor cannot provide (since it reached its capacity) is purchased from the grid. No electricity is sold from the reactor to the grid. The maximum case that can result is that the reactor provides all of its energy as steam to the hydrogen plant. All the corresponding electricity is then purchased from the grid.
   c. The industrial process is even larger than in (b). In this case, if the reactor only provides steam and the corresponding electricity is purchased from the grid; the industrial process still does not reach its maximum capacity. In that case, the dispatch function evaluates whether it is profitable for the hydrogen plant to buy even more electricity from the grid to satisfy its maximum capacity. If the answer is no, the hydrogen plant will only buy the amount of electricity needed to utilize the steam coming from the reactor and the hydrogen plant will not run at full capacity. If the answer is yes, the hydrogen plant will buy (in addition to the amount of electricity needed to utilize the steam coming from the reactor) as much electricity is required to run at full capacity.

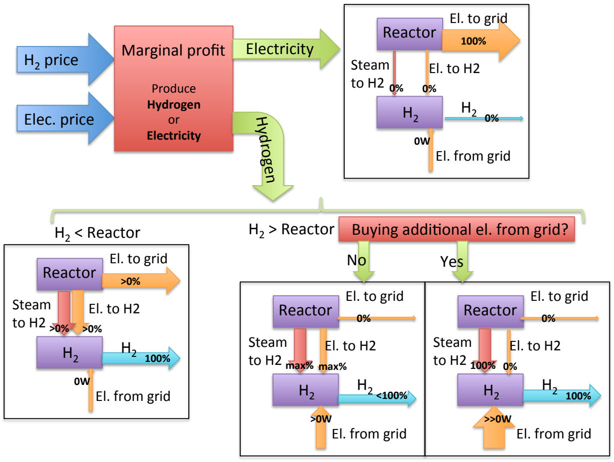

Figure 1. Dispatch rules.

Economics Data

The presented case considers a fixed nuclear reactor capacity of 300 MWe and the capacity of the hydrogen plant is to be optimized. To compute the IRR, the Free Cash Flow to Firm (FCFF) with real discounting [8] is considered.

The following different components of the cash flow have been defined in the CashFlow software as presented in Table I. For the IP, the economy of scale, i.e. the exponent 'X', with which the capital cost and the fixed O&M are scaled is not known very well. Therefore, as a parametric study, two cases have been computed, one where X=1 (linear scaling) and one where X=0.64 (economy of scale similar to nuclear plants). It is worth mentioning that it has been assumed that the IP, when buying electricity form the grid, in addition to paying the electricity price (generated by the ARMA), the IP has to pay an additional CO_2 tax (since the electricity may not come from the CO_2 free reactor anymore). A parametric study on this fictitious CO_2 tax has been preformed.

TABLE I. Table Name

	Nuc. Reactor	IP
Lifetime [y]	60	40
Tax [%]	39.2	
Inflation [%]	4.0	
Overnight capital cost	\$1.96 bio.	\$153 mio./231MW
Revenue	Dispatch * el. price from ARMA	Dispatch * fixed H_2 price
Fixed O&M	\$40.71 mio./y	\$3.5moi./y/231MW
Variable O&M	0.5 \$/MWh	0.048 \$/kg of H_2
Fuel cost	8.4 \$/MWh	electricity from grid & CO_2 tax
Depreciation	15 year Modified Accelerated Cost Recovery System (MACRS)	

Results: Find the Optimum IP Capacity for a Fixed Reactor Capacity

Figure 2 shows the base case for the problem. The plot shows the IRR as a function of IP capacity and hydrogen price (colors of the points) for X(IP)=0.64 and CO_2 tax=0\$/tonCO_2. One can see for this base case:

- For the IP capacity equal zero, i.e. if the hydrogen plant is not built and the reactor just sells all of its electricity to the grid, the IRR does not depend on the hydrogen price and is negative. This means the 300 MWe reactor on its own is not profitable assuming the above economic numbers.
- The IRR is monotonically growing with the IP capacity due to the economy of scale coefficient 0.64 < 1 (the bigger is the plant the cheaper is the hydrogen production). The slope increases as the hydrogen price increases.
- The optimum points computed by RAVEN are shown as bigger points in the figure. The optimizer correctly finds the optimum hydrogen plant capacities to be at the upper bound set.

From the dispatch rules and the heat utilization schema by the IP, the IRR as a function of IP capacity is expected to have three regions with a different slope (i.e. two points were the slope changes):

- The first change point should occur for an IP capacity such as the reactor can supply all the steam and all the electricity needed for the IP to run at nominal capacity and no electricity has to be bought from the grid. Due to the penalty from the CO_2 tax, as soon as the IP capacity exceeds the reactor capacity, the slope in IRR is expected to decrease given the CO_2 tax penalty. This inclination point should happen for an IP size similar to the reactor. This point is where a realistic optimum of IP capacity could be found.
- The second slope changing point should occur when the IP capacity exceeds the capacity where it can absorb all power generated by the reactor in the form of steam. The ratio of maximum steam to electricity ratio for the hydrogen plant is ~1:3. This means that for a 300 MWe nuclear reactor this point is at an IP capacity of ~4 GW (300 MWe corresponds to ~1 GW thermal; to absorb 1 GW thermal, the IP capacity has to be 4 GW to satisfy the 1:3 ratio). If the IP capacity is still larger, the benefit of using steam from the reactor does not exist anymore and all heating has to be done with (more expensive) electricity. The slope of the IRR should decrease at an IP capacity of 4 GW. Obviously, this possible optimum point is not realistic, since typical hydrogen plants are in the range of several 100 MW, not GW. Nevertheless, to show the correct operation of the economical framework, this point is included in the study.

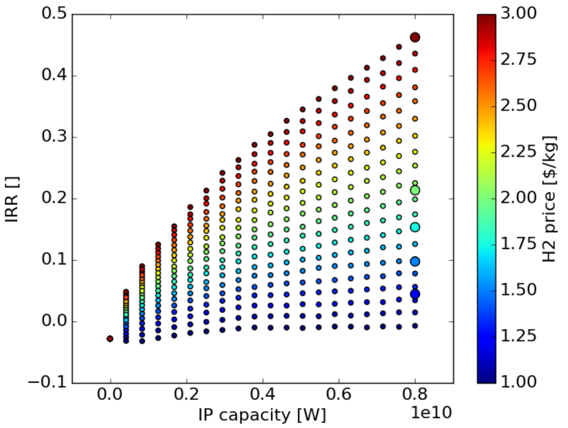

Figure 2. X(IP)=0.64, CO_2 tax=0\$/tonCO_2, IRR as a function of IP capacity and hydrogen price.

Figure 3 and Figure 4 show the same information as Figure 2, but for a CO_2 tax of 15 and 75 \$/tonCO_2. One can se that:

- For low hydrogen prices around \$1.25/kgH_2:
  - The 15\$/tonCO_2 shows the maximum occurring at the first inclination point. The hydrogen price is too low to overcome the CO_2 tax for bigger IP capacities and the IRR is decreasing or flat after the first inclination point. The optima found for \$1.75/kgH_2 and 2\$/kgH_2 are in the flat part of the IRR. The end point for these depends on the applied convergence criteria in the optimizer.
  - The high CO_2 tax case (75\$/tonCO_2) shifts this to higher hydrogen prices, i.e. the hybrid system is unprofitable up to a hydrogen price of about \$2/kgH_2. Above that, for prices around \$2.5/kgH_2, the maximum is at the first inclination point.

- For high hydrogen prices around \$3/kgH_2:
  - If the CO_2 tax is low, the IRR slope after the second inclination point is still positive and the optimum IP capacity is at the maximum boundary for the optimization.
  - If the CO_2 is high, the IRR slope after the second inclination point is negative. This leads to the optimum IP capacity at that point, which we know from the theoretical examination above, is around 4GW.

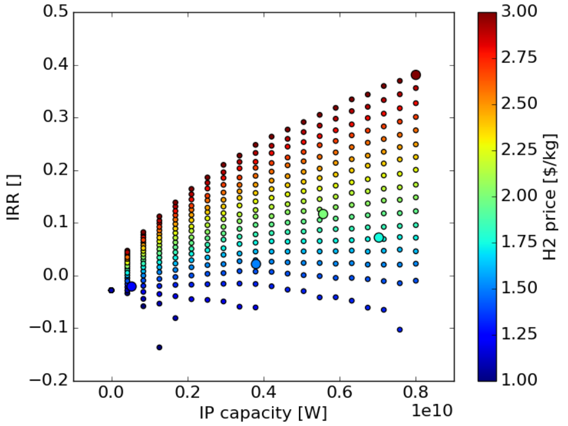

Figure 3. X(IP)=0.64, CO_2 tax=15\$/tonCO_2, IRR as a function of IP capacity and hydrogen price.

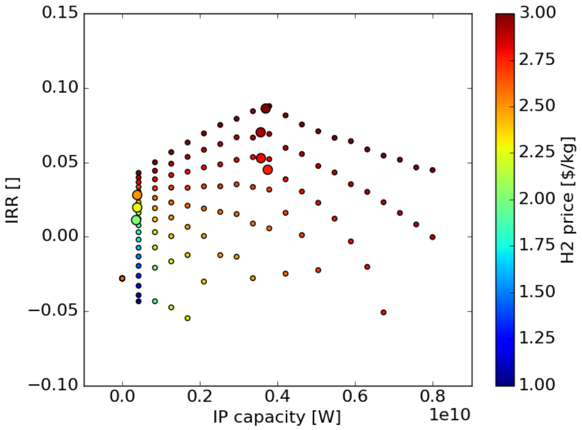

Figure 4. X(IP)=0.64, CO_2 tax=75\$/tonCO_2, IRR as a function of IP capacity and hydrogen price.

Moving from the economy of scale (X=0.64) for the industrial plant to a linear one (X=1) increases the capital cost (proportionally) for larger capacity hydrogen plants, which makes them less profitable. As one can see in Figure 5 the IRR slope change at the two inclination points is larger than for the case with X=0.64. The result is that the optimizer finds the optimum at the beginning of the flat part of the IRR (still around 4 GW) for the low CO_2 tax case and finds the first inclination point as the maximum for high CO_2 tax (high CO_2 tax case not shown).

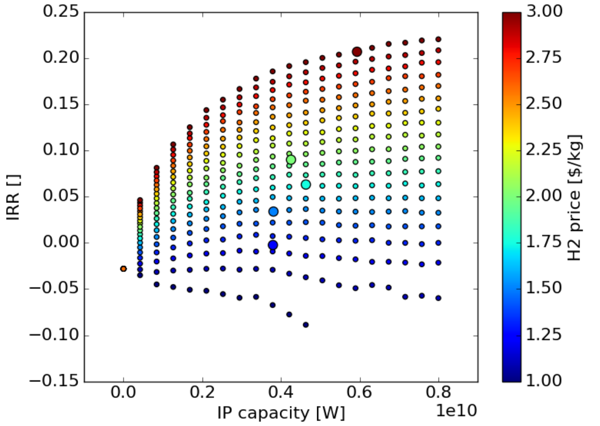

Figure 5. X(IP)=1.0, CO_2 tax=0\$/tonCO_2, IRR as a function of IP capacity and hydrogen price.

CONCLUSIONS

The framework for the economical analysis of NHES is reaching the maturity level necessary to begin analysis of realistic cases.

The optimization algorithm was demonstrated to converge quickly for IRR optimization under stochastic response of the system. The analysis confirmed the qualitative expectations, providing exact numbers that could not be found without the usage of the implemented framework.

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