THE VALUE OF PRODUCT FLEXIBILITY IN NUCLEAR HYDROGEN TECHNOLOGIES

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Economic studies of nuclear hydrogen technologies tend to focus on levelized hydrogen costs without accounting for risks and uncertainties faced by potential investors. To address some of these risks and uncertainties, we develop a financial model based on real options theory to assess the profitability of three nuclear hydrogen production technologies in evolving electricity and hydrogen markets. The model uses Monte-Carlo simulations to represent uncertainty in future hydrogen and electricity prices. It computes both the expected value and the distribution of discounted profits from a production plant. It also quantifies the value of the option to switch between hydrogen and electricity production, depending on what is more profitable to sell. Under these assumptions, we conclude that investors will find significant value in the flexibility to switch plant output between electricity and hydrogen.

I. INTRODUCTION

The Department of Energy's Office of Nuclear Energy is supporting system studies to gain a better understanding of nuclear power's potential role in a hydrogen economy. This assessment includes identifying commercial hydrogen applications and their requirements, comparing the characteristics of nuclear hydrogen systems to those market requirements, evaluating nuclear hydrogen configuration options, and identifying the key drivers and thresholds for market viability of nuclear hydrogen options. In this paper we present results from a profitability evaluation of different nuclear hydrogen technologies, focusing on how the flexibility to switch between hydrogen and electricity production can add economic value to a nuclear hydrogen plant.

The paper expands on previous work by moving beyond levelized cost calculations. Potential investors in nuclear hydrogen production will have to operate in a market environment that is different from the traditional regulated regime the nuclear industry used to operate in. While costs will remain an important decision variable, investment decisions are likely to be driven primarily by profit expectations and risk management considerations. Therefore, we develop a financial model based on real options theory, which analyses profitability, risk, and uncertainty from an investor's perspective.

The paper has the following structure. In the next section we give a brief introduction to real options theory. Section III gives a mathematical description of the stochastic model for profitability analysis. In section IV, we use the model to assess the profitability assessment of three nuclear hydrogen technologies. Finally, we discuss the analysis results and provide conclusions and directions for future work.

II. REAL OPTIONS THEORY

According to traditional finance theory the net present value (NPV) is the best indicator for evaluating an investment project. The static form of the NPV rule states that a project should be undertaken as long as the sum of discounted cash flows from the project (i.e., the NPV) is positive, while projects with a negative NPV should be rejected. However, it has become apparent that the traditional static discounted cash flow techniques have severe shortcomings. First of all, the static assessment compares the value of investing today with not investing at all. In most cases the decision maker has the choice of deferring an investment, and then to invest later in the event of favorable investment conditions. Furthermore, the investor has the flexibility to make investment and operational decisions in the future, depending on how uncertainties unfold.

A new direction within investment theory emerged in the 1980s and 1990s to mitigate the shortcomings of the static discounted cash flow techniques. The new approach, frequently referred to as *real options theory*, is based on a dynamic analysis of investment projects. In the real options theory it is recognized that an investment project can have several embedded properties that can be viewed as options. The most common options for investment projects are the option to defer an investment, the time to build option (for staged investments), the option to alter operating scale, the option to abandon a project, the option to switch inputs or outputs from a process, and different forms of growth options (e.g. investments in R&D). In some projects there are interacting effects between several of these options. In mathematical terms, real options valuation is based on a stochastic dynamic analysis. Compared to a simple static NPV evaluation of the cash flows from an investment, the real options paradigm adds two important analytical dimensions to the problem. First, a flexible and dynamic representation of future managerial operational and investment decisions is used. Second, important uncertain variables are represented as stochastic processes. Under certain assumptions about the underlying stochastic processes, real options models may be solved analytically. However, for complex investment problems with several sources of uncertainty it is more common to use discrete mathematics or stochastic simulations to find the optimal investment strategy. The theoretical foundation for real options theory and its application to investment under uncertainty are covered in detail by Dixit and Pindyck (1994)[1]. A less theoretical description with focus on real world applications is given in Copeland and Antikarov (2003)[2].

The model for profitability assessment of nuclear hydrogen plants presented in this paper focuses on the value of the option to switch output product. We represent uncertainties in hydrogen and electricity prices as stochastic processes. Monte Carlo simulations are used to quantity the value of a plant's potential flexibility to switch between hydrogen and electricity production depending on what is more profitable. The stochastic investment model is outlined in the next Section.

II. A STOCHASTIC PROFITABILITY MODEL

This section describes a model that is under development at Argonne National Laboratory for appraisal of the profitability of nuclear hydrogen technologies (Botterud et al. 2007)[3]. The model calculates the discounted profits from investing in a new production facility. Three different types of nuclear plants can be evaluated with the investment model:

1) H2: Inflexible plant, producing hydrogen only
2) EL: Inflexible plant, producing electricity only
3) FLEX: Flexible plant, producing hydrogen or electricity, depending on what is more profitable

The model uses an annual time resolution. Three price sub-periods are assumed within the year for electricity: base, medium, and peak. The price sub-periods have fixed duration and represent seasonal, daily, and weekly fluctuations in electricity price. The hydrogen price is assumed to be constant within each year.

II.A Cash Flow Analysis

We use the same structure as Technology Insights (2006)[4] in profit calculations and cash flow analysis. The total profit for the plant, Π, is equal to the sum of free cash flows, FCF_t, over the planning horizon (i.e. plant lifetime + construction time), T, and the final salvage value, SV, as shown in Eq. (1). A real risk-adjusted interest rate, r, is used discounting.

$$\Pi = \sum_{t=0}^{T} \frac{1}{(1+r)^t} \cdot FCF_t + \frac{1}{(1+r)^{T+1}} \cdot SV \qquad (1)$$

Earnings before tax, EBT_t, and free cash flows, FCF_t, are calculated as shown in Eqs. (2) and (3).

$$EBT_t = R_t - FOM_t - VOM_t - D_t \qquad (2)$$

$$FCF_t = EBT_t \cdot (1\text{-}tax) + D_t - WC_t - IC_t \qquad (3)$$

where

R_t	Revenue from EL and/or H_2 sales, year t	M $
FOM_t	Fixed O&M cost, year t	M $
VOM_t	Variable O&M cost (incl. fuel), year t	M $
D_t	Depreciation, year t	M $
tax	Tax rate	%
WC_t	Change in working capital, year t	M $
IC_t	Investment cost, year t	M $

The annual revenue, R_t, in Eq. (2) depends on the type of plant being analyzed and could be equal to either $RH2_t$, REL_t, or $RFLEX_t$. The annual variable and fixed O&M costs, the depreciation, the change in working capital, the investment cost, and the salvage value are all deterministic parameters. For the flexible plants, the operating costs are assumed to be independent of the output product. The switching between hydrogen and electricity production is assumed to take place instantaneously at zero additional cost and with no losses.

A key part of the model is the representation of revenue from sales of hydrogen and electricity. The total annual revenue depends on the type of plant, as shown in Eqs. (4)-(6). For the hydrogen plant the revenue is simply the annual hydrogen output times the hydrogen price, adjusted for the plants availability factor. Likewise, for the electricity plant the revenue equals the sum of electricity generation times price over the three electricity price sub-periods. Finally, the flexible plant generates either hydrogen or electricity in each of the three price sub-periods, depending on what is more profitable. With a flexible plant, the option to switch between output products can have considerable value for the investors, especially when there is large uncertainty in electricity and hydrogen prices.

$$RH2_t = af \cdot QH2_t \cdot PH2_t \qquad (4)$$

$$REL_t = af \cdot \sum_{i=1}^{3} QEL_t \cdot PEL_t \cdot pf_i \cdot \frac{d_i}{8760} \qquad (5)$$

$$RFLEX_t =$$
$$af \cdot \sum_{i=1}^{3} \mathrm{MAX}(QH2_t \cdot PH2_t, QEL_t \cdot PEL_t \cdot pf_i) \cdot \frac{d_i}{8760} \qquad (6)$$

where

$QH2_t$	Max annual H_2 production, year t	kg/year
QEL_t	Max annual EL generation, year t	MWh/year
af	Plant availability factor	%
$PH2_t$	Hydrogen price, year t	\$/kg
PEL_t	Average electricity price, year t	\$/MWh
d_i	Duration, sub-period i	hours
pf_i	Rel. EL price factor, sub-period i	

The electricity price in each price period is equal to the average annual electricity price times the relative price factor, i.e. $PEL_{i,t} = PEL_t \cdot pf_i$. Hence, the relative difference between electricity prices in high, medium, and base periods remain constant. The quantity of hydrogen and electricity being produced depends on the simulated realization of the annual hydrogen and electricity prices. The stochastic representation of these prices is outlined below.

II.B Representation of EL and H_2 Prices

In real options analysis it is common to assume that the uncertain variables follows certain stochastic processes. The most common processes are Geometric Brownian Motion (GBM) and Mean Reversion (MR) processes. These two stochastic processes are used to represent uncertainty in electricity and hydrogen price in our investment model. A correlation between the hydrogen and electricity price can also be represented. The model user can decide whether a GBM or MR process is used to represent prices, and can set parameters in the price model accordingly. In this paper we focus on the GBM process, and only present results based on this stochastic process..

Discrete versions of GBM processes with correlation are used to represent hydrogen and electricity prices in the Monte Carlo simulations. Eqs. (7) and (8) show the underlying equations, which are based on Maribu and Fleten (2005)[5].

$$PH2_{t+1} = PH2_t \cdot (1 + \alpha_{PH2} + \sigma_{PH2} \cdot \varepsilon_{PH2,t}) \qquad (7)$$

$$PEL_{t+1} = PEL_t \cdot (1 + \alpha_{PEL} + \rho \cdot \sigma_{PEL} \cdot \varepsilon_{PH2,t} + \sqrt{1-\rho^2} \cdot \sigma_{PEL} \cdot \varepsilon_{EL,t}) \qquad (8)$$

where

α_{PH2}	H_2 price growth rate	%/year
σ_{PH2}	H_2 price volatility	%/year
$\varepsilon_{PH2,t}$	Stochastic variable for H_2 price, year t, Normal distribution (0,1)	
α_{PEL}	EL price growth rate	%/year
σ_{PEL}	EL price volatility	%/year
$\varepsilon_{PEL,t}$	Stochastic variable for EL price, year t, Normal distribution (0,1)	
ρ	Correlation btw. H_2 and EL prices	

With the GBM process the simulated prices at a certain time period in the future will have a lognormal distribution. The upper tail of the distribution tends to drift off to high levels owing to the multiplicative effect. In contrast, with the MR price processes, the width of the distribution tends to be more narrow, depending on the magnitude of a mean reversion factor.

The parameters in the stochastic price model can be based on either historical prices or expert/management opinion.

II.C Monte Carlo Simulations

We use @Risk to run Monte Carlo (MC) simulations for the nuclear plant cash flow analysis and profitability assessment. @Risk is an add-in to Excel developed specifically for risk analysis and stochastic simulations (Palisade 2004)[6]. In each iteration of the MC simulation random numbers are drawn for the random price variables $\varepsilon_{H2,t}$ and $\varepsilon_{EL,t}$ for all future years, $t = 1,2, .. , T$. The number of MC iterations is specified in the @Risk interface. A fixed random number seed can also be defined, so that the same sequence of random simulations can be repeated. Hence, sampling errors can be removed when comparing model runs with different plant configurations.

III. PROFITABILITY ANALYSIS

In this section we analyze the profitability of three nuclear hydrogen production technologies. We first outline the main assumptions about technology costs and prices, before presenting the results from the profitability assessments. A more detailed presentation of assumptions and results can be found in Botterud et al. (2007)[3].

III.A Nuclear Hydrogen Technologies

Several hydrogen production processes supported by advanced nuclear reactors could contribute to the hydrogen supply in evolving energy markets. Nuclear hydrogen processes can range from low-temperature electrolysis to high-temperature thermochemical water-splitting cycles. Each technology has challenges before it can become practically available, as well as different properties – such as the process temperature, modular versus larger installations, and cogeneration versus hydrogen as single product (Yildiz et al. 2005)[7]. Technology Insights[4] reported a levelized hydrogen cost analysis for three possible nuclear hydrogen technologies (Table I). As shown in the table the SI-HTGR technology has the lowest levelized cost for hydrogen production. Although the capital cost and performance input for the levelized cost analysis of these technologies was of a preliminary nature and requires significant refinement by the technology designers, it made a good starting point for our analysis.

We analyze the profitability of the same three technologies using the cost assumptions provided by Technology Insights[4]. Both the low- and high-temperature electrolysis alternatives require electricity production, so they lend themselves naturally to cogeneration of electricity and hydrogen. Pure thermochemical cycles such as SI do not, in themselves, require electricity generation, although the nuclear units could be designed that way. In this analysis, we assume that only the HPWE and HTSE configurations would allow for cogeneration of electricity and hydrogen. The main assumptions for the three technologies are summarized in Table II.

TABLE I. Nuclear hydrogen technologies

Hydrogen Production Process	**Nuclear Reactor Type**	**Product flexibility (H_2/EL)?**	**Levelized H_2 cost[4] [$/kg]**
High-Pressure, low-temp. water Electrolysis (HPE)	Advanced Light Water Reactor (ALWR)	Yes	2.94
High-Temp. steam Electrolysis (HTE)	High-Temp. Gas-cooled Reactor (HTGR)	Yes	2.53
High-temp. Sulfur-Iodine cycle (SI)	High-Temp. Gas-cooled Reactor (HTGR)	No	2.22

TABLE II. Cost and performance assumptions

Para-meter	***HPE - ALWR***	***HTE – HTGR***	***SI - HTGR***	***Unit***
$QH2_t$	245.53	262.58	280.24	M kg/year
QEL_t	11.83	9.00	-	TWh/year
FOM_t	169.1	120.0	118.4	M $
VOM_t	73.5	87.6	111.4	M $
$IC_{initial}$	2201.2	2141.8	1856.9	M $

Common assumptions for all technologies are:

- Construction time 3 years and operating lifetime 40 years (i.e. $T = 43$ years);
- Investment cost split between the three construction years with 25%, 40%, and 35%. Additional non-depreciable investment costs $2M;
- Unplanned replacement costs 0.5% of initial investment cost per year. Some plant-specific replacement costs;
- Salvage value 10% of the investment cost;
- 90% plant availability, 38.9 % tax rate, and 10% discount rate.

III.B Electricity and Hydrogen Price Assumptions

In the results presented in this paper we only use the GBM price processes to represent uncertainty in hydrogen and electricity prices. In the Monte Carlo simulations we used 10,000 iterations (Latin Hypercube sampling) with a fixed seed. The parameters for the stochastic GBM processes were estimated based on our judgment of price outlooks for hydrogen and electricity. For hydrogen we assumed a mean level of 3.0 $/kg. This compares to the DOE target cost for hydrogen of 2.0-3.0 $/kg (Petri et al. 2006) [8]. For electricity we used a mean of 50 $/MWh for the average annual price, which is comparable to the prices in the PJM electricity market the last few years.

Parameters for volatility of annual electricity prices are difficult to estimate. We have used the values in Table III, which give a fairly reasonable range of outcomes for prices. With the GBM assumption the uncertainty range increases in the long run, especially on the more expensive side of the distribution, as is clearly evident from Fig 1. The correlation between hydrogen and electricity prices, ρ, is set to 0.5. The values of the price parameters are, of course, highly uncertain and subject to discussion. It should therefore be stressed that the main conclusions from this analysis are of a qualitative rather than quantitative nature. We do a sensitivity analysis in section III.E for some of the parameters.

TABLE III. Parameters for stochastic price processes.

Parameter	***Hydrogen***	***Parameter***	***Electricity***	***Unit***
$\sigma_{PH2,GBM}$	0.2	$\sigma_{PEL,GBM}$	0.2	%
$\alpha_{PH2,GBM}$	0	$\alpha_{PEL,GBM}$	0	%

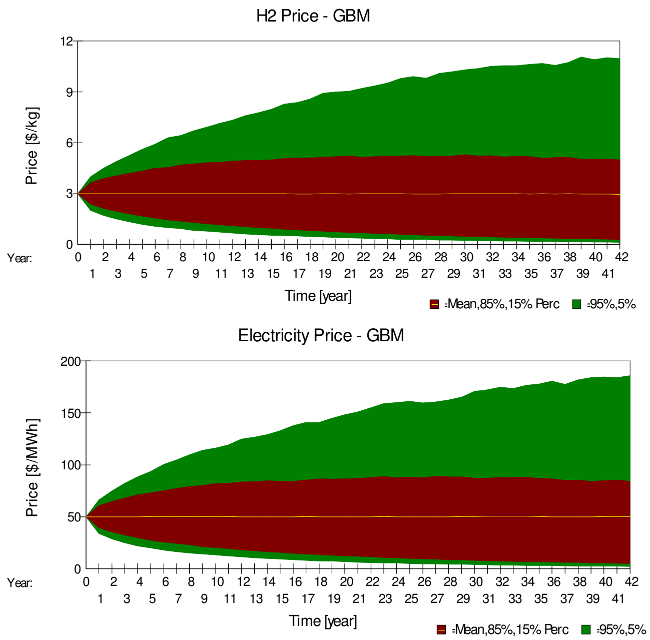

Fig. 1. Simulated distributions for H_2 and EL prices.

The durations of the electricity price sub-periods, d_1, d_2, d_3, are set to 760 hours, 4000 hours, and 4000 hours respectively. The relative price factors, pf_1, pf_2, pf_3, are estimated from hourly prices from the PJM market from 1999-2005, and are set to 2.66, 1.12, and 0.56 respectively.

III.C Results for the HTE-HTGR Technology

Fig. 2 shows the simulated profit distributions for the HTSE-HTGR plant for pure hydrogen production and flexible H_2/EL production. When comparing the two simulated profit distributions we see that operational flexibility decreases the downside of the distribution, and increases the upside. Hence, the plant owner can clearly reduce exposure to economic risk by having the flexibility to switch output product. Moreover, the expected profit is considerably higher with flexibility: the option value of flexibility amounts to 343 M$. Hence, the option to switch output product has significant value for the investor. Table IV compares the results from deterministic and stochastic analyses and shows that a stochastic analysis is necessary to properly evaluate the option to switch output product under uncertainty in EL and H_2 prices. A deterministic analysis gives a much lower profit under output flexibility, since the plant in this case would only produce electricity in the high price sub-period. With stochastic prices, the plant will also produce electricity during medium and low price-periods for some realizations of prices. The results also illustrate that a stochastic analysis is required to assess the investor's potential risk and return from investing in nuclear hydrogen technologies.

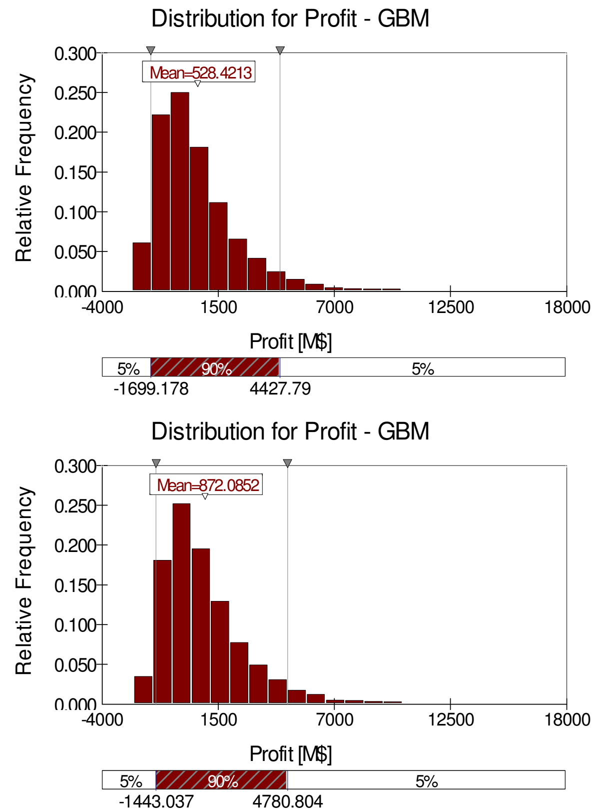

Fig. 2. Distribution of profits (M$) for inflexible ($H_2$ only - upper) and flexible (EL/H_2 - lower) operation.

TABLE IV. Expected profits for HTE-HTGR. M$

	Deterministic	Stochastic
Inflexible: Pure H_2	541	528
Flexible: H_2/EL	691	872
Value of option to switch	150	344

III.D Comparison of Technologies

The same profitability analysis was done for all three technologies described in Section III.A. The expected profits for the different nuclear hydrogen alternatives are summarized in Table V. It is evident from the table that the HPE-ALWR and HTE-HTGR alternatives benefit greatly from their output flexibility. In fact, under stochastic prices the flexible HTE-HTGR plant has a higher expected profit than the SI-HTGR plant, despite having a substantially higher levelized hydrogen cost.

TABLE V. Expected profits. M$

	Deterministic	Stochastic
HPE-ALWR: Inflexible	99	96
HPE-ALWR: Flexible	407	774
HTE-HTGR: Inflexible	541	528
HTE-HTGR: Flexible	691	872
SI-HTGR: Inflexible	874	861

Table VI shows the relative hydrogen production for the two flexible technologies. This can be interpreted as the expected percentage of time the plants produce hydrogen over all scenarios in the Monte Carlo simulation. It is also equivalent to the expected percentage of the maximum hydrogen production the plant will be producing over the lifetime of the plant. The HTE-HTGR technology has a higher expected H2 production than the HPE-ALWR plant. This is because H_2 production is cheaper and therefore more profitable with the HTE-HTGR technology. Note that the current model assumes that the plants have full flexibility to switch between the two output products at any time, without being constrained by firm deliveries of hydrogen.

TABLE VI. Relative Hydrogen Production. %

	Deterministic	Stochastic
HPE-ALWR: Flexible	91.3	63.5
HTE-HTGR: Flexible	91.3	74.5

III.E Sensitivity Analysis

We used the model to perform sensitivity analysis for some of the parameters in the price models: the mean value in the electricity and hydrogen price processes, and the correlation between hydrogen and electricity prices, ρ.

Fig. 3 shows how the simulated expected profit changes as a function of the mean in the stochastic process for electricity price. All other parameters are kept constant with the same values as in the analysis above. We see that the flexible hydrogen plants based on electrolysis benefit from an increasing electricity price level. In fact, the HPE-ALWR plant becomes the most profitable technology when the electricity price level exceeds 60 \$/MWh. The electrolysis based technologies take advantage of the higher electricity price level by producing less hydrogen and more electricity. The expected profits from the SI-HTGR plant does not change as a function of electricity price, since it produces hydrogen only.

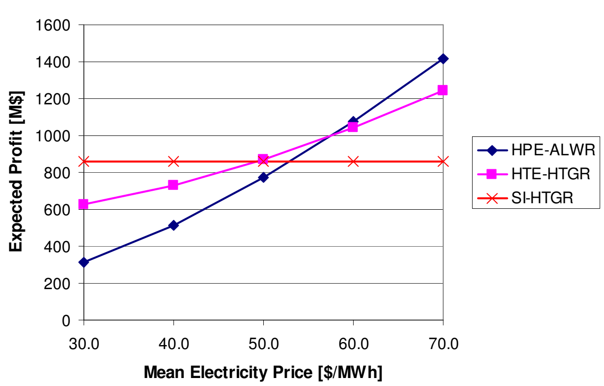

Fig. 3. Sensitivity analysis for mean EL price.

When doing the same type of sensitivity analysis for the mean hydrogen price (Fig. 4), we see that the SI-HTGR plant benefits the most from increasing hydrogen price. However, also the flexible electrolysis plants increase their profits as a function of higher hydrogen prices, since the amount of hydrogen production goes up.

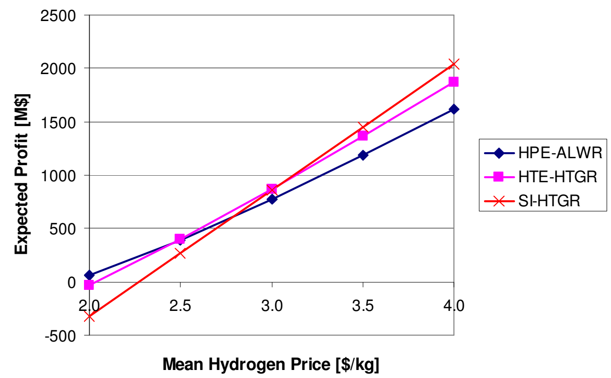

Fig. 4. Sensitivity analysis for mean H_2 price.

The correlation between hydrogen and electricity price also has an important impact on the profitability of the two flexible electrolysis technologies (Fig. 5). For the HPE-ALWR and HTE-HTGR plants it is clearly an advantage with a low or negative correlation between H_2 and EL prices. This is because with low correlation it is more likely that EL prices are high when H_2 prices are low, and these plants can take advantage of these situations, by switching from H_2 to EL production. In contrast, if the correlation is high this advantage disappears, since high EL prices will only occur when H_2 prices are also high. In fact, with a correlation factor of 1 the expected profit for the HPE-ALWR and HTE-HTGR plants drop down to the same level as in the deterministic analysis. The amount of hydrogen production increases as a function higher correlation, and with a correlation of 1 the plant produces electricity in the peak price sub-period only, equivalent to the deterministic case.

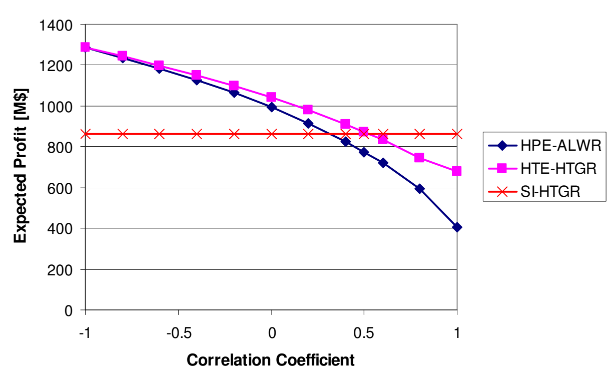

Fig. 5. Sensitivity analysis for H_2/EL price correlation.

All the results presented so far are based on the GBM assumption for H_2 and EL price processes. The GBM processes give a high uncertainty range for prices, as shown in Fig. 1. We repeated the profitability analysis of the three technologies with the MR assumption for prices, resulting in a more narrow uncertainty range due to the reversion to a mean level for both prices. In general, when comparing to the GBM results, the MR assumption gives lower expected profit and a lower option value of switching for the two flexible technologies, because of the lower variability in prices. The expected profit for inflexible plants do not depend significantly on the stochastic processes for prices. The results from the analysis with the MR assumptions are fully documented in Botterud et al. (2007)[3].

IV. DISCUSSION OF RESULTS

The main results from the analysis can be summarized in the following bullets:

- The profitability analysis under uncertainty gives a different picture of the relative viability of the nuclear hydrogen production technologies compared to a standard levelized cost analysis.

- The HPE-ALWR and HTE-HTGR configurations have an advantage in being able to switch between hydrogen and electricity output. Our analysis indicates that the HTE-HTGR plant can be at least as attractive for the investor as the SI-HTGR plant (Table 3), despite having a considerably higher levelized hydrogen cost.

- The option to switch output product adds value for the investor. The added value must be weighed against potential increases in capital and operating costs. For the flexible plants we assumed that they are capable of switching their entire production from hydrogen to electricity instantaneously and frequently without additional cost. In reality, there may be both technical and contractual restrictions for how quickly and often plants can switch their output. The calculated option values of flexibility may therefore be regarded as an upper limit.

- Our findings suggest that research should be directed toward developing better and more durable materials for the hydrogen production processes that are better able to handle switching in production output.

- Plant owners should carefully consider how much hydrogen production to sell on long-term contracts, at the expense of losing the value of the option to switch between electricity and hydrogen production.

- There is high uncertainty concerning the assumptions for the analysis, in terms of performance, cost, and price parameters. The conclusions are therefore qualitative rather than quantitative. Sensitivity analysis was performed for price parameters. However, sensitivity studies should also be carried out for the cost and performance assumptions used for the different technologies.

- The study serves to illustrate the advantage of using a stochastic model for analyzing investments and operational flexibility under uncertainty in future prices. A deterministic model is likely to underestimate the option value of flexibility.

IV. CONCLUSIONS AND FUTURE WORK

Although the potential for hydrogen markets seems promising, there are also substantial risks and uncertainties that will affect how investors will try to enter this market. Economic studies of nuclear hydrogen technologies have so far mainly focused on levelized costs without accounting for these risks and uncertainties The analysis presented in this paper is an important extension to the levelized hydrogen cost calculations and has attempted to identify and address some of the financial risks and opportunities associated with nuclear hydrogen production.

The model we developed is based on real options theory and calculates the discounted profits from investing in a nuclear hydrogen facility. Monte-Carlo simulations are used to represent uncertainty in hydrogen and electricity prices. The model computes both the expected value and the distribution of discounted profits from the production plant. It also quantifies the value of the option to switch between hydrogen and electricity production while trying to maximize facility profits.

We assessed the profitability of three nuclear hydrogen production technologies under price uncertainty in newly emerging markets. Under the assumptions used, we conclude that investors will find significant value in the ability to switch plant output between electricity and hydrogen. This should be traded-off against possible higher capital and operating costs.

The flexibility to quickly react to market signals brings technical challenges related to the durability of the components in the nuclear hydrogen plant. Nevertheless, given the potential significant economic benefit that can be gained from cogeneration with the flexibility to react to market signals, we recommend that R&D be aimed toward developing durable materials and processes that can enable this type of operation.

Our ongoing work is focused on analyzing a wider range of hydrogen production technologies associated with an extension of the financial analysis framework presented here. We are planning to address additional risks and options, such as the value of modular plant expansion (i.e., a modular increase in the hydrogen production capacity in a market with rising hydrogen demand), and contrast that with economies-of-scale of large-unit designs. We are also introducing a more detailed representation of electricity and hydrogen price fluctuations within day, week, and season. Furthermore, we are introducing a firm hydrogen demand, which limits the ability to switch output product from the plant. These extensions will make the model better capable of assessing the commercial viability of various nuclear hydrogen technologies.

ACKNOWLEDGMENTS

The work at Argonne National Laboratory was supported by the U.S. Department of Energy, Assistant Secretary for Nuclear Energy, Office of Advanced Nuclear Research, under contract DE-AC02-06CH11357.

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