NHI economic analysis of candidate nuclear hydrogen processes

Daniel Allen
Technology Insights, San Diego, California, USA

Paul Pickard
Sandia National Laboratories, Albuquerque, New Mexico, USA

Mike Patterson
Idaho National Laboratory, Idaho Falls, Idaho, USA

Carl Sink
Office of Nuclear Energy, US Department of Energy, Washington DC, USA

Abstract

The DOE Nuclear Hydrogen Initiative (NHI) is investigating candidate technologies for large scale hydrogen production using high temperature gas-cooled reactors (HTGR) in concert with the Next Generation Nuclear Plant (NGNP) programme. The candidate processes include high temperature thermochemical and high temperature electrolytic processes which are being investigated in a sequence of experimental and analytic studies to establish the most promising and cost effective means of hydrogen production with nuclear energy. Although these advanced processes are in an early development stage, it is important that the projected economic potential of these processes be evaluated to assist in the prioritisation of research activities, and ultimately in the selection of the most promising processes for demonstration and deployment.

The projected cost of hydrogen produced is the most comprehensive metric in comparing candidate processes. Since these advanced processes are in the early stages of development and much of the technology is still unproven, the estimated production costs are also significantly uncertain. The programme approach has been to estimate the cost of hydrogen production from each process periodically, based on the best available data at that time, with the intent of increasing fidelity and reducing uncertainty as the research programme and system definition studies progress. These updated cost estimates establish comparative costs at that stage of development but are also used as inputs to the evaluation of research priorities, and identify the key cost and risk (uncertainty) drivers for each process. The economic methodology used to assess the candidate processes are based on the H2A ground rules and modelling tool (discounted cash flow) developed by the DOE Office of Energy Efficiency and Renewable Energy (EERE).

The figure of merit output from the calculation is the necessary selling price for hydrogen in dollars per kilogram that satisfies the cost inputs and economic parameters. The NHI implementation decouples the hydrogen production process costs from the HTGR energy source so that the cost of energy (thermal and electric) is treated parametrically. A later stage of the study will address reactor specific optimisation when candidate reactor costs are available. The H2A modelling tool also allows for uncertainty factors to be applied to the inputs for sensitivity analyses. Cost information (capital, operating and energy costs), performance (efficiency, durability), technical readiness and uncertainty/ risk assessments are being compiled in an updatable database for the NHI systems – to serve as the starting point for the next iteration and update. These integral cost metrics provide one of the key inputs to support near-term R&D decisions.

The initial application of this cost methodology to the NHI processes was based on early versions of the thermochemical and high temperature electrolytic processes being evaluated by NHI. These estimates, which had to be based on preliminary data and therefore, contained a higher level of *uncertainty, showed that the cost of hydrogen was comparable for all NHI processes within the uncertainty bounds. At that stage the cost of energy was estimated to be the largest single component and efficiencies for all candidate processes were projected to be in the range of 40%. These initial results are now being updated based on the results of a recent industry assessment performed by Westinghouse/PBMR/Shaw Team under the sponsorship of the NGNP programme. This paper will provide an update on the status of the cost estimates based on the latest information from the NHI research programme and the industry cost study.*

Introduction

DOE NE's Nuclear Hydrogen Initiative (NHI) is investigating several promising methods for hydrogen production with nuclear energy as part of DOE's overall hydrogen programme activities. The primary candidates under development are high temperature thermochemical-based processes and high temperature electrolytic-based processes. There are several other alternative candidates under evaluation with the intent of establishing the most promising and cost effective means of hydrogen production with nuclear energy but these technologies are not as mature and are not considered here. The nuclear reactor heat source utilised in the NHI designs is the high temperature gas-cooled reactor (HTGR) system, which is being advanced by the DOE's Next Generation Nuclear Plant (NGNP) Project.

Although these advanced processes are in an early development stage, it is essential that a consistent framework and methodology of evaluating the economic potential of these processes be established to assist in the prioritisation of limited development funds and the selection of the most promising processes for demonstration and deployment.

NHI framework for economic evaluation

Ultimately the objective of the evaluations is to compare the costs of hydrogen production between processes as a critical component in technology selection decisions and to determine which of these processes are potentially the most cost effective and therefore should be considered for development priority. Comparing these processes is difficult as they are in early stages of development, technology is still uncertain and costs are very uncertain.

The development of a framework for data and analysis leverages the experience gained in hydrogen production cost studies co-ordinated through the H2A Production Analysis Program of the DOE Office of Energy Efficiency and Renewable Energy (EERE). The framework takes as input capital and operating cost estimates for a given hydrogen production process, and it convolutes this technical input with set economic parameters. The figure of merit output from the calculation is a necessary selling price for hydrogen in dollars per kilogram that satisfies the cost inputs and economic parameters.

The initial adaptation and application of this framework to NHI processes was based on early versions of the thermochemical and high temperature electrolytic processes being evaluated by NHI. Those results provided a starting point that is intended to be updated on a continuing basis as results become available from the research programme or other sources. Although it is still early in the development process, these ongoing efforts to provide an integral cost metric are one of several key inputs needed to support R&D decisions in the near term.

Objectives of NHI framework

The objective of the effort is to provide a consistent and transparent framework and methodology for economic assessments of the NHI technologies. Intended applications include:

- to assess the comparative costs of hydrogen production processes to support technology demonstration sequence and/or down-select decisions;
- to support trade-off studies to optimise the design and the allocation of limited R&D resources;
- to understand relative cost and risk (uncertainty) drivers as guide to R&D resource allocation;
- to assess pertinent market issues and uncertainties as a further guide to R&D.

The nuclear hydrogen production framework can also be used to assess trade-offs between component cost, performance, O&M cost, fuel cycle cost, lifetime and other factors affecting the cost of hydrogen and hence guide related R&D funding priorities. Further, market entry challenges associated with product introduction and higher initial costs and risks will be assessed to gain insights for mitigating strategies for such challenges.

The H2A Production Analysis Program

In 2005, DOE EERE organised the H2A Production Analysis Program. The primary objectives of that effort were as follows:

- to improve the consistency and transparency of the ground rules and assumptions for the economic analyses of hydrogen systems within the DOE hydrogen programmes, as well as within related industry programmes;
- to develop a tool for consistent analyses and reporting of the economics of hydrogen production and delivery systems, as well as for R&D direction and portfolio analyses;
- to validate the consistent ground rules, assumptions and analyses methodology through deliberations with a select group of key industrial collaborators, including nuclear utility and vendor representatives.

The H2A model is a spreadsheet-based (Microsoft Excel®) calculation tool which gives the required selling price of hydrogen for the input capital and operating cost factors for a hydrogen production plant and for the specified economic parameters, including the rate of return on investment. The units of the resultant price are dollars per kilogram, which serves to normalise the comparisons and happens to be approximately equal to the price of gasoline with the same energy content on a lower heating value basis. The results of H2A have been published on the DOE website [*www.hydrogen.energy.gov/h2a_analysis.html*]. While the tool includes agreed-upon H2A reference values for several financial parameters, the user is also given the opportunity to vary parameters such as internal rate of return, plant life, feedstock costs and tax rate, to examine the technology using their own basis. The calculation part of the tool uses a standard discounted cash flow rate of return analysis methodology to determine the hydrogen selling cost for the desired internal rate of return. Some advantages of this method are that construction time and plant start-up phase can be modelled with proper accounting for interest during construction, and over the life of the plant replacement of significant capital items can be scheduled. Inflation can be input to the model, but in the discounted cash flow analysis the effect of inflation is nullified except for a small impact on the tax depreciation. For this reason, the calculated selling price for hydrogen is the fixed or levelised price over the plant life in reference year dollars.

The major categories of input to the H2A computer model are as follows:

- Plant capital costs (USD)
  - Direct
    - Equipment
    - Installation (field material & labour)
  - Indirect
  - Replacement capital

- Plant operation and maintenance
  - Fixed (USD/yr)
    - Staff
    - Other labour costs
    - Materials and services for maintenance and repair
  - Variable (USD/kg H_2)
    - Thermal power consumption and costs
    - Electric power consumption and costs
    - Feedstock: water; chemicals; catalyst
  - Performance
    - Efficiency
    - Capacity factor

Specifically, the model may be applied for the integrated energy supply and process plant for hydrogen production, or the input energy to the plant may be generalised in terms of costs for heat in USD/MWt-h and costs for electric power in USD/MWe-h. For the H2A analyses the heat and electric power were modelled as costs per unit energy inputs. Thus, the nuclear reactor economic detail is decoupled in the analysis so that the evaluation concentrates on the process plant.

Candidate systems

The DOE NHI presently focuses on three hydrogen production technologies that potentially can be coupled with HTGR heat sources to supply the energy to split water into hydrogen and oxygen. These are sulphur-iodine thermochemical water-splitting (S-I) cycle, high temperature (steam) electrolysis (HTSE) cycle and the hybrid sulphur thermo-electrochemical water-splitting (HyS) cycle.

Earlier analyses

The initial analyses utilising the framework were complete two years ago. The input costs for developmental items were estimates based on the technologists concerned with the given processes. Costs were itemised for the main unit operations. (In chemical engineering and related fields, a "unit operation" is a basic step in a process.) The conventional parts of the plant were subject to a mix of cost-estimating approaches, scaling factors and installation factors. Bulk costs were not necessarily based on actual layouts. Performance was based on the flow sheet mass and energy balances, which were in early stages of development.

Four cases were evaluated, since there was interest in the comparison of two alternate methods for HI separation. Required selling prices for hydrogen were calculated to be between about USD 3.00/kg and USD 3.50/kg, and efficiencies were from 39 to 44%. This result is shown in Table 1.

Table 1: Results from 2007 evaluation

Hydrogen process	Efficiency	H_2 selling price
Sulphur-iodine HI section: extractive distillation	40%	USD 3.41/kg
Sulphur-iodine HI section: reactive distillation	39%	USD 3.05/kg
High temperature electrolysis	44%	USD 3.22/kg
Hybrid sulphur	43%	USD 2.94/kg

Recent work

In 2008, the US Department of Energy's NGNP programme initiated an evaluation of the three NHI hydrogen technologies by the Westinghouse/PBMR/Shaw Team. The evaluation was led by Shaw, and interacted with all the technology constituents within the NHI. Shaw is a world-wide engineering, construction and industrial services company. An objective of the study was to take advantage of Shaw's expertise in chemical process design, deployment experience and depth of capability in cost estimating from actual projects. The Hydrogen Plant Alternatives Study has only recently been completed.

The study evaluates the three hydrogen production technologies and processes – S-I, HyS and HTSE – on consistent technical and economic bases. This would be the first such systematic comparison.

The economic viability of each technology was assessed based on capital costs, operating costs, technical risk, safety and operability. Standard industry practice with respect to process engineering and cost estimating were used to assess the economic viability of each technology for commercial implementation. Only limited credit was given for cost improvements from technology breakthroughs. All of these technologies are at an early stage of development, but the effort was to estimate a commercially operable plant that could be deployed (technology development through design and construction) in only ten years.

Three flow sheets with consistent assumptions, and using commercially available equipment where possible, were developed. The flow sheets and mass and energy balances were used to generate sized equipment lists. Estimated costs for unit operations are based on industry databases for materials and labour, and on the estimates of technical experts from associated research and development programmes. Installation costs, including labour and field bulk materials, were estimated on a subsystem basis.

Final hydrogen selling price was calculated using the capital and operating cost results from the hydrogen alternatives study and the H2A analysis tool. The cost data was subsequently entered into the NHI analysis framework database, and further calculations have been done using the data from the Shaw base cases. Results of those calculated hydrogen prices are reported below.

Reference designs

Choice of a basis for plant design, particularly plant sizing and interface with the nuclear heat supply system, can be approached differently with different results. One can choose to size the hydrogen process plant to fit one nuclear reactor unit and then increase plant scale by adding nuclear units. In this evaluation, the choice is to set the size of the hydrogen plant at about the output level of the largest hydrogen plant that users would want or that suppliers would build considering present norms of the petrochemical industry. That plant size is approximately 175 000 Sm^3/h (150 MMSCFD, 365 t/d, 4.2 kg/s). For that level, depending on the hydrogen process, the HTGR nuclear units are applied in integer numbers to provide the necessary high temperature heat input according to each process. In the model, additional heat available from the HTGR units is converted into electricity in a Rankine cycle with a condensing steam turbine generator system. This electric power is provided to the hydrogen production system. Excess electric power for the hydrogen process is imported from the electric grid.

For the HTGR, a generic nuclear heat supply system (NHSS) was assumed to generate a nominal 550 MWt of heat and deliver helium at 910°C to the process coupling heat exchanger(s) of the process plant. Helium returns to the NHSS in the range of 275 to 350°C. The three hydrogen production technologies from the NHI were as follows:

- The sulphur-iodine (S-I) cycle includes the feature of a H_2SO_4 decomposer with silicon carbide tubes, as has been developed at Sandia National Laboratories (Moore, 2007). For this decomposer the Shaw model takes the design and costing from a variant of the design by Westinghouse (Hu, 2008). The HI section utilises the reactive distillation option. The process plant is coupled with three NHSS and produced 4.4 kg/s of hydrogen. Oxygen is sold as a by-product. The process plant used all of the nuclear heat and so no electricity was generated on-site. The amount of grid power consumed was 330 MWe.
- The hybrid sulphur (HyS) cycle utilises the same H_2SO_4 decomposer and acid concentration section as the S-I plant. The SO_2 electrolysers are polymer electrolyte membrane (PEM) technology. The hydrogen plant is coupled to two NHSS and produces 4.0 kg/s of product. Oxygen is sold as a by-product. The Rankine “bottoming” cycle generates 133 MWe for the electrolysis section and an additional 198 MWe is imported.
- The high temperature (steam) electrolysis (HTSE) cycle is the variant utilising air sweep on the anode side of the cells. It takes heat from only one NHSS and puts out 4.0 kg/s of hydrogen. The Rankine “bottoming” cycle generates 176 MWe. The oxygen by-product is not sold, and 365 MWe is taken from the grid.

Databases

Shaw’s estimating organisation used their FACES system, which is regularly updated from purchase order data. However, a significant factor in the results of the study come from the timing of the cost estimating, which was mid-2008, at the time commodity prices and other factors in the cost calculations were at recent peaks.

Input heat and power sources

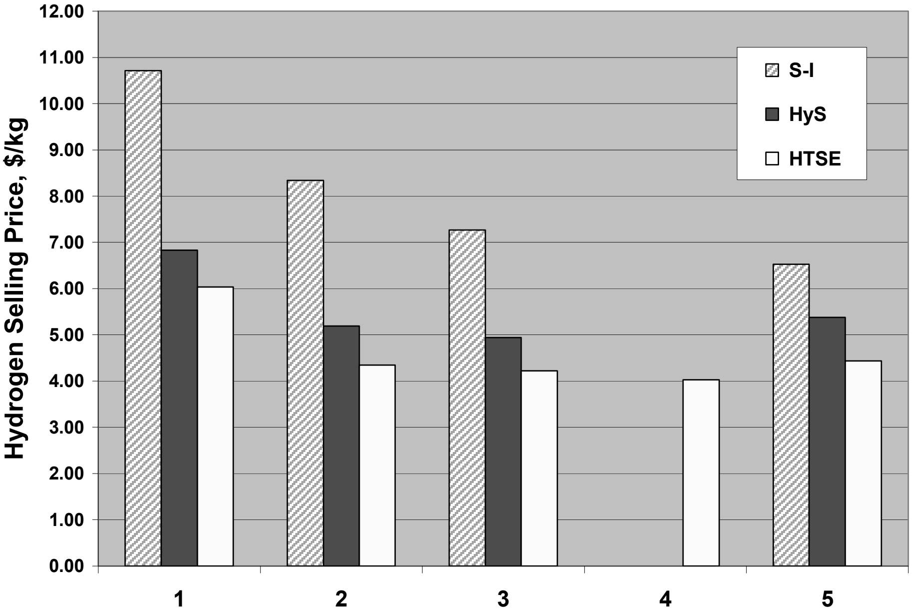
Without reference to a particular HTGR, an input parameter of USD 30/MWt-h was used for the cost of nuclear heat was. Electricity cost was set based on a 2008 price of USD 75/MWe-h. The H2A modelling tool, as published, is based on an assumption that all costs and the selling price have the same rate of inflation. However, for the Shaw assessments, energy costs are projected to rise more rapidly than general inflation, and so a modification to the H2A model was been made to add this analysis capability. For the analysis, real escalation, over and above any inflation, is included at 1%/yr over the plant life for the electric power bought or sold. The assumed reactor outlet temperature for evaluating component costs and process efficiencies was 950°C.

Results

Resulting hydrogen selling prices from the Shaw analysis were high compared to earlier estimates, particularly the 2007 NHI framework cases. The high price is the result of conservative assumptions in the development of the three process flow sheets, in the cost-estimating process and in the energy cost parameters input to the cost calculations.

As a starting point for further evaluations of the NHI technologies, a series of changes to the cost inputs were made. The NHI process development teams were asked to review the Shaw study and to suggest areas where there might be alternative assumptions or configurations. Without altering the systematic approach to the parallel evaluation of the technologies, these adjustments were made to enable exploration of sensitivities. The Shaw results and the varying hydrogen price with these changes are plotted in Figure 1. The rightmost set of bars (above "1") shows the Shaw base case results. A first adjustment to the Shaw results is made to the energy cost inputs. The nuclear heat cost and electric power costs are reduced to the same values used in the 2007 analyses, and so nuclear heat cost is reduced from USD 30/MWt-h to USD 20/MWt-h and electricity cost from USD 75/MWe-h to USD 60/MWe-h. Also, the escalation in the cost of imported electric power is taken out to provide a consistent comparison with earlier studies and to be more in line with current economic realities. The resulting lower hydrogen prices are shown in the next set of bars in Figure 1 (above "2").

Figure 1: Varying hydrogen price for cost model variations



To adjust for the cost estimating having been done at around the time of the peak in the commodity "bubble", three cost factors were considered. In mid-2008 the price of carbon steel plate as an index was up a factor of 1.7 from its average in 2005 to 2007. The price of nickel, which is reflected in the cost of stainless steel and might more accurately track the cost of the process plant capital equipment was up by 1.4 over 2005-2006 (nickel peaked in late 2007). The *Chemical Engineering* Plant Cost Index (CECPI), which is a composite of equipment, site material, labour and engineering costs in the industry, peaked at 1.3 times the 2005-2007 value. In consideration of these indices, a factor of 1.5 is taken to be the approximate excess capital cost due to the cost estimating at the cost peak. The third set of bars in Figure 1 (above "3") shows the hydrogen selling price for the three technologies with this additional adjustment to the equipment and bulk materials costs.

In the analysis of the HTSE hydrogen plant, the anode air sweep option was used as the reference, and when diluted with air, by-product oxygen is not likely to be saleable, whereas in the S-I and HyS flow sheets there is a pure oxygen by-product. A further revision to the HTSE case is plotted next in Figure 1 (above "4") for the HTSE case of no air sweep equipment and adds sale of by-product oxygen.

Two additional adjustments are made to attempt to bring the S-I, HyS and HTSE evaluations to a common level of capital cost uncertainty. In the HI section of the S-I process, the highly corrosive fluids require vessels, piping and equipment specially lined with either tantalum or niobium alloy, which for the process industry are exotic materials. The technologists familiar with the S-I Integrated Laboratory Experiment were of the opinion that the extent of this corrosion resistant material was excessive in the Shaw design, and so for the last bar for S-I in Figure 1 (above "5") the amount of exotic material lining is reduced (by approximately 30% in the HI feed and distillation equipment and by 50% in the iodine recovery portion) and replaced with glass or Teflon® lining.

The second adjustment is to a non-conservative cost input to the Shaw evaluation. The equipment capital costs for the SO_2 electrolyser in HyS and the steam electrolyser in the HTSE are based on projected cost targets. For both electrolyser technologies the cost targets were adopted from the development programmes for the associated fuel cells, and those targets appear to be far from being achieved. To show the effect of a more realistic outcome to compare with the S-I case the last bars for HyS and HTSE Figure 1 (above "5") show the price if the uninstalled costs of these components were doubled.

There is a trend in Figure 1 for the costs of the three technologies to converge in a range of USD 4.50/kg to USD 6.00/kg, which is 50 to 75% higher overall than the costs calculated in the 2007 evaluation. A comparison of the earlier and recent capital cost summaries is insightful. The largest factor in the increase in hydrogen cost, after adjustments from the Shaw base cases, is the cost of the conventional parts of the plant and not of the new technologies. For example, in the 2007 calculations the capital costs for the electrolysers in the HyS and HTSE plants were, respectively, 66 and 82% of the total capital cost of the plant. In the recent analyses the fractions are 24 and 35%.

Another notable element of the cost increases is the inclusion in the Shaw flow sheets of subsystems for hydrogen product purification and for feed water purification. For S-I and to a lesser extent for HyS, concern with the carry-over of sulphur to the product necessitated a significantly costly purification subsystem on the product end of the cycle. For HTSE, the issue is uncertainty in the purity of input steam and effects on the electrolysis cells, and so a large feedwater purification subsystem impacts the overall capital cost. In the earlier evaluations these subsystems were not considered significant enough to include.

The data in Figure 1 do not take into account the conservative efficiencies resulting from the Shaw flow sheet mass and energy balances. Technologists developing the S-I, HyS and HTSE processes offered suggested improved mass and energy balances to consider along with the adjusted energy and capital cost cases.

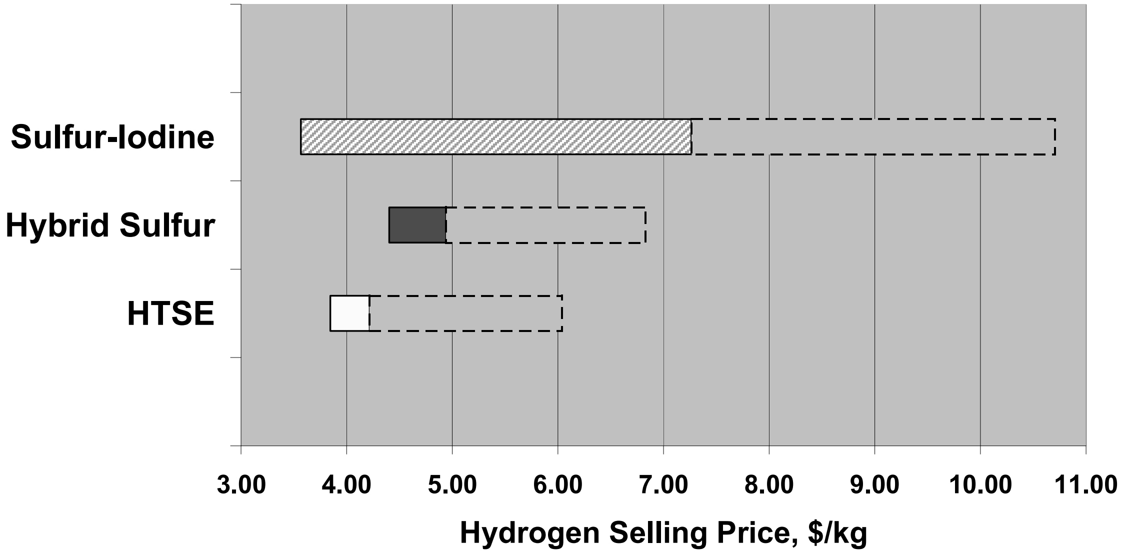
For S-I, the H2A model was re-run with the "Mathias" model flow sheet (Mathias, 2003), which has increased heat recovery in the HI section and other thermodynamic modelling features that result in a large increase in process efficiency. For the HyS cycle the model was further adjusted with improvements of lower cell voltage (525 vs. 600 mV) and reduced thermal demand in the acid concentration step. For HTSE the improvement was to eliminate the air sweep subsystem. The before and after efficiencies for these improved cycles and the resulting hydrogen selling prices are in Table 2 (the costs in the third column of Table 2 correspond to the set of bars in Figure 1 above "3".)

The ranges of hydrogen selling prices from Table 2 are plotted as the solid bars in Figure 2. The bars with dashed lines extend the range to include the unadjusted Shaw base case (the leftmost bars in Figure 1). This is not a sensitivity plot, but the relative sensitivity of the S-I technology to capital cost and efficiency is demonstrated by the large band of hydrogen price, which spans a factor of two.

Table 2: Results with revised capital costs and efficiencies

	Shaw results adjusted for energy and capital costs		Further adjusted for efficiency	
Hydrogen process	**Efficiency**	**H_2 price**	**Efficiency**	**H_2 price**
Sulphur-iodine	25%	USD 7.27/kg	42%	USD 3.57/kg
Hybrid sulphur	35%	USD 4.94/kg	38%	USD 4.40/kg
High temperature electrolysis	33%	USD 4.22 /kg	37%	USD 3.85/kg

Figure 2: Hydrogen selling price range



The range of accuracy generally accepted for preliminary, pre-conceptual categories of cost estimates (estimates based on less than 10% design progress) is ±40%. Given that additional factor, one cannot conclude a cost advantage for any one production cycle.

Conclusions

The results of our work in the investigation of nuclear-heated, high-temperature hydrogen production technologies show significant quantitative uncertainty. The causes are understood and are outlined in this paper. Resolution will require significant additional development, refinement of designs and confirmation of system performance. The economic analysis work is a continuing process as part of the DOE's NHI, and the product price range can be narrowed as available input data is updated from the development programme.

Within hydrogen production technologies

The earlier and more recent evaluations have shown which various parts of the process plants are the "cost drivers" within each of the three hydrogen production technologies. These have been used as indications for prioritising R&D efforts in the NHI programme.

Between hydrogen production technologies

The formal approach taken to evaluate nuclear hydrogen technologies provides useful results for comparison of the various technologies. The range of relative variation in product hydrogen price in the evaluations is the result of several factors. One of the most significant is the uncertainty of new technology performance in flow sheets and simulation models that drive the process efficiency. These uncertainties are expected at the early development and demonstration phase, but the technology must mature further and simulation models need to be better supported before the uncertainties in product price can converge.

For the unique and high-technology equipment in the systems – the sulphuric acid decomposer in S-I and HyS and the two different electrolysers in HyS and HTSE – costs of equipment in the eventual commercial plant are based on development targets and only weakly derived from examination of fabrication technologies and manufacturing details. This is a manifestation of the immaturity of the designs, which require further iteration and refinement within the current development and demonstration phase.

One additional factor not directly covered in this paper is the issue of performance stability and the associated costs for refurbishment, repair or replacement of components with lifetimes shorter than the overall plant. None of the laboratory experiments to date for S-I, HyS or HTSE has run long enough and provided data that can be used to quantify degradation factors or lifetimes. Performance variation with time and limited lifetimes of components can be factored into the analysis, particularly as operating cost and replacement capital inputs.

As the NHI hydrogen technology development proceeds, distinctions between the economics of the technologies should become more apparent.

Comparison to alternatives

Comparisons of the calculated hydrogen prices from the current NHI technologies to prices from other sources of hydrogen are problematical. The most significant uncertainty is the cost of input energy, which comes as nuclear heat or as electricity, in varying ratio for the different technologies. The cost of heat depends on the costs of building and operating the HTGR, which is uncertain at this point. The cost of electricity is either dependent on the same uncertain HTGR cost if the electricity is to be generated at the site of the hydrogen plant using the same reactor heat source, or it is dependent on the price of grid electricity if imported. In most of the cases in the NHI evaluation, the electric power is both generated on site and imported. Any prediction of grid electricity prices in distant future years is speculation, considering energy resource issues and the likely imposition of significant constraints on carbon combustion.

Another precaution in making comparisons of hydrogen price to other technologies is that cost models for the NHI technologies assume all would be deployed as very large chemical process plants. In the present conceptual design phase, there is appropriately little focus on the optimisation of the systems of conventional piping, valves, instrumentation, structural works and other bulk components. For those in the process industry familiar with such large, complex plants, the hydrogen technologies are similarly unfamiliar. The interaction with established process industry engineers at Shaw is a first iteration to mutually instruct and provide familiarity that can lead to optimised design. Certainly the "high-tech" portions of the process need the greatest attention to advance the overall development. However, so much of the plant cost is in the conventional portion that overall optimisation is essential for a nuclear hydrogen plant to deliver product at a competitive price. This suggests that the process design must mature to improve the cost basis for the conventional portion for the plant.

These conclusions justify continuing the periodic evaluation of the candidate process hydrogen prices and maintenance of the NHI framework with a database of cost input factors as the technologies and designs mature.

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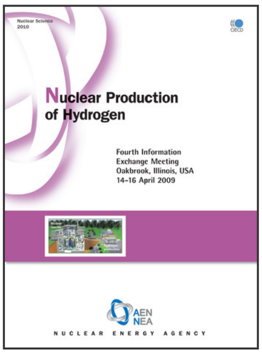

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