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HEEP: A new tool for the economic evaluation of hydrogen economy

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ARTICLE INFO

Article history:
Received 25 February 2010
Received in revised form
26 April 2010
Accepted 27 April 2010
Available online 9 June 2010

Keywords:
HEEP
Software
IAEA
Hydrogen production
Nuclear energy
Economics

ABSTRACT

Under agreement and in collaboration with the Indian BHABHA Atomic Research Centre (BARC), the International Atomic Energy Agency (IAEA) has just released the newly developed Hydrogen Economic Evaluation Programme (HEEP) software, which can be used to perform economic analysis related to large scale hydrogen production. The software could be used to analyse economics of the most promising processes for hydrogen production. These processes are: high and low-temperature electrolysis, thermo-chemical processes including Sulphur–Iodine (S-I) process, conventional electrolysis and steam reforming. The IAEA-HEEP software is also suitable for comparative studies not only between nuclear and fossil energy sources for hydrogen production but also for solely hydrogen production or cogeneration with electricity. The HEEP models are based on economic, technical as well as chronological inputs, and cost modelling. Modelling will include various aspects of hydrogen economy including storage, transport, and distribution with options to eliminate or include specific details as required by the users.

Similar in principles to the IAEA DEEP software, HEEP can be used to perform economic analysis and feasibility studies related to hydrogen production using nuclear energy. Preliminary benchmarking of the beta-version of HEEP with open literature has revealed that the software could indeed be used for the investigation of complex systems for hydrogen production including the nuclear power plant, the hydrogen production plant and the hydrogen distribution systems. The development of HEEP will continue in future to ensure that various major processes and technologies are incorporated in HEEP. The beta-version of HEEP can be downloaded free of charge from the IAEA web site.

1. Introduction

Nuclear power is the only large-scale carbon-free energy source that has, in the near and medium term, the potential to significantly contribute to the global energy sector. Moving beyond its historical role as solely a producer of electricity to other non-electric applications, nuclear power is expected to play an important role in replacing the limited and uncertain fossil fuels. These applications include seawater desalination, district heating, heat for industrial processes, and electricity and heat for hydrogen production. Such applications have tremendous potential in future ensuring worldwide energy and water security for a sustainable development [1] and [2].

In recent years, various agencies which are already involved in nuclear energy development programmes have carried out studies on non-electric applications of nuclear

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0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2010.04.154

power. Similarly, the International Atomic Energy Agency (IAEA) launched a programme on cogeneration applications in the nineties where a number of Member States have been and continue to be actively involved. More recently, the scope of the IAEA's programme has been widened to include other more promising applications such as nuclear hydrogen production and higher temperature process heat applications. OECD/NEA, Euroatom and GIF have also evinced interest in the non-electric applications of nuclear power based on future generation of advanced and innovative nuclear reactors [3].

As an alternative path to the current fossil fuel economy, hydrogen economy is envisaged in which hydrogen would play a major role in energy systems and serve all sectors of the economy, substituting for fossil fuels [4] and [5]. As an energy carrier, Hydrogen can be stored in large quantities and converted into electricity in fuel cells with only heat and water as by-products [6] and [7]. It is also compatible with combustion turbines and reciprocating engines to produce power with near-zero emission of pollutants. The production of clean hydrogen is a key component of the energy chain (i.e. from production to the final uses). However, various in-depth studies might be needed to evaluate the competitiveness of hydrogen chains to serve the future growing markets along with other energy sources. A greater appreciation is emerging of the economic and financial aspects of hydrogen production [8] particularly the suggestion that the ability to switch between two possible product streams e.g. electricity and hydrogen; heating and desalination may improve economics. The economics of an integrated complex of nuclear production of electricity, hydrogen, and fresh water may look further more attractive.

The current worldwide hydrogen production is roughly 50 million tonnes per year [7]. Although current use of hydrogen in energy systems is very limited, its future use could become enormous, especially if fuel-cell vehicles would be deployed on a large commercial scale. Meanwhile in near term, the developments on plug-in-vehicles and hybrid vehicles could provide enough experience on the hydrogen use in transport sector. The hydrogen economy is getting higher visibility and stronger political support in several parts of the world. A range of different combinations exists among sources of heat, various processes generating hydrogen, and different methods to store and distribute hydrogen for its end application as clean source of energy [9], [10], and [11].

Nuclear-generated hydrogen has important potential advantages over other sources that will be considered for a growing hydrogen economy. Nuclear hydrogen requires no fossil fuels, results in lower greenhouse-gas emissions and other pollutants, and lends itself to large-scale production. These advantages do not ensure that nuclear hydrogen will prevail, however, especially given strong competition from other hydrogen sources. There are technical uncertainties in nuclear hydrogen processes, certainly, which need to be addressed through a vigorous research and development effort. The hydrogen storage and distribution are also important area of research to be undertaken for bringing in a successful hydrogen economy regime in future.

As a greenhouse-gas-free alternative, the U.S., Japan, and other nations are exploring ways to produce hydrogen from water by means of electrolytic, thermo-chemical, and hybrid processes. Most of the work has concentrated on high-temperature processes such as high temperature steam electrolysis (HTE) and the sulphur–iodine (S-I) and calcium–-bromine cycles. These processes require higher temperatures (>750 °C) than can be achieved by water cooled reactors. Advanced reactors such as the very high temperature gas cooled reactor (VHTGR) can generate heat at these temperatures, but will require several years before they are commercially deployed. There are estimates that for SI or even for HTE process, the hydrogen production cost can be brought to \$2/kg levels, if oxygen credit is also taken in to account. If the natural gas price ranges between \$6–8/MBtu and carbon dioxide sequestering costs are also included, hydrogen by steam methane reforming (SMR) would cost more than nuclear hydrogen [2].

Competitive economics is going to be one of the important considerations among others like national energy policy, availability of resources etc. in selection of the pathway to produce hydrogen and distribute it to the user. The IAEA is taking the first step towards the development of a common cost assessment software for nuclear hydrogen i.e. HEEP, similar to the Desalination Economic Evaluation Programme (DEEP) [12] and [13]. Fig. 1 shows hydrogen production and distribution stages considered while developing software tool HEEP. For HEEP development, there are some technologies that can be considered mature for such economic assessment models like steam reforming and low-temperature electrolysis. Promising processes such as thermo-chemical water splitting and high temperature steam electrolysis need to be considered. Hydrogen production from biomass or waste is expected to take place but not on a large scale.

2. Previous work towards estimation of hydrogen cost

In several countries, activities on hydrogen production and cost assessments within the hydrogen economy were initiated and are still going on. Some countries have either already developed their own models such as the German-French

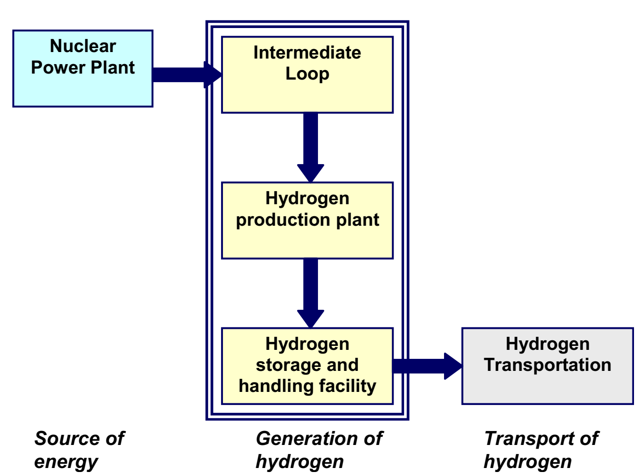

Fig. 1 – Processes considered in HEEP.

E3-database, the hydrogen cost analysis model in Canada, and other models in the USA or appropriately modified existing models estimating levelized unit energy cost to evaluate cost of hydrogen generation [14][15]. The Idaho National Laboratory have carried out hydrogen cost analysis of high temperature steam electrolysis based hydrogen producing plant driven by high temperature helium cooled reactor [14]. In this study the Hydrogen Analysis (H2A) production model developed by the U.S. Department of Energy Hydrogen Programme was used. The H2A methodology is an excel spread-sheet based tool using a standard discounted cash flow rate method for estimation of hydrogen. The H2A Production models has been developed for estimation of hydrogen production cost and H2A delivery models can be used for estimation of hydrogen transportation and distribution cost.

The Korean Atomic Energy Research Institute (KAERI) has also published a report on the estimation of cost of hydrogen production by S-I thermo-chemical based plant coupled to high temperature reactors [15]. In this study, the G4-ECONS methodology which gives levelized unit energy cost was appropriately modified to evaluate levelized cost of hydrogen.

3. HEEP structure and formulation

As seen in Fig. 1, the new software HEEP is single-window based software which can be used to analyse the hydrogen economy, addressing the economic aspects starting from the source to end-user. Like any other software tool, the structure of the computer programme HEEP consists of three modules (see Fig. 2.) viz. (i) pre-processing module (ii) executing module, and (iii) Post -processing module. The Graphical User Interface (GUI) provides user-friendly feature to the pre-processing and post-processing modules of HEEP.

The pre-processing module provides user-friendly interface to enter technical details, chronological inputs and cost components of each utility (a) nuclear energy generation, (b) hydrogen generation and storage, and (c) hydrogen transportation. The execution module calculates levelized cost for generation, storage and transportation of hydrogen. The post-processing module is programmed to display results delivered by execution module in pie chart and tabulated form.

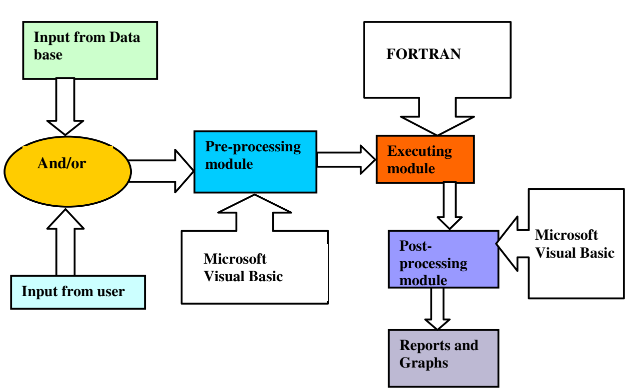

Fig. 2 – Structure of HEEP.

4. Important features of HEEP

HEEP considers several reactor concepts including water reactors such as the PWR and PHWR for the lower temperature range, the very high temperature reactors (VHTR), Fast Breeder Reactors (FBR) and molten-salt cooled reactors for the high temperature range, and Super-Critical Water Reactor (SCWR) capable of output temperatures up to around 625 °C for the medium range of temperature, hence covering full energy spectrum for the production of hydrogen, electricity and potable water etc. The present version of HEEP can consider nuclear power plant delivering thermal energy alone or delivering electricity alone or delivering both thermal energy as well as electricity to hydrogen generation plant. Indeed, the use of nuclear technology for non-electricity related applications, particularly for hydrogen production, is an important aspect of the proposed Generation IV nuclear systems [7].

HEEP considers different methods of hydrogen production such as: high temperature thermo-chemical cycles (e.g. S-I, hybrid-sulphur), moderate temperature thermo-chemical cycles (e.g. Copper-chlorine and Hybrid Hydrogen process in the Lower Temperature HHLT) and high temperature steam electrolysis to be compared with conventional electrolysis and steam reforming, etc. Due to both high temperature (more than 750 °C) and strongly corrosive environment, selection of suitable material for the thermo-chemical components of the sulphuric acid decomposition is still an issue in case of S-I and hybrid-sulphur cycles. Development of high performance materials for the S-I process is still being investigated worldwide. The hydrogen generation process plant may be co-located with the power plant or can be isolated from power plant and receiving energy from the commercial grid.

After production, hydrogen will be transported to the user. Storage system is required for absorbing surges produced due to the mismatch in production and consumption rates. The storage system plays an important role in accommodating plant outages on account of routine short-term repair and maintenance. The storage and transportation system could increase the cost of hydrogen by significant factor [6]. This factor will vary depending on the design of the storage system and method of transportation selected. The choice of storage type depends mainly on storage duration, quantity to be stored, type of delivery system etc. Similarly, transportation method depends mainly on the distance of transportation and quantity to be transported. Cost assessment using HEEP includes storage (liquefied or gaseous or in the form of metal hydrides) as well as transport and distribution of hydrogen. Detailed transport model may include distribution centres in the software at a later stage.

The concept of nuclear hydrogen economy is expected to include components starting from hydrogen generation using nuclear power, to the transport of energy stored in the hydrogen, and to final application. The production facility will consist of a nuclear reactor as a source of heat combined with the hydrogen generating plant. The high temperature heat will be converted directly into chemical energy mainly hydrogen. Transport and distribution will also be considered in HEEP. Large and small scale storage tanks may serve as options for long term and short-term energy demand balancing. Such cost assessment will be developed on step-by-step approach as new R&D concepts are developed. The HEEP development/update will continue to include future possible technological changes so as to assess economic viability of hydrogen generation using different possible combinations among various options including presently developed as well as future development of heat energy sources, methods of hydrogen generation, storage and transportation.

4.1. *Input variables to be provided for execution of HEEP*

Plants and facilities for generation of hydrogen are grouped in thee categories viz. (i) nuclear power plant forming source of energy, (ii) hydrogen generation and storage plant producing hydrogen and storing in appropriate form, and (iii) facility for hydrogen transportation. The parameters affecting hydrogen economy are further categorised in the following three groups:

- Technical features of plants and facilities
- Time periods of various activities during life cycle of these plants
- Elements of cost

4.1.1. *Technical features of plants and facilities*

The economy of hydrogen production will depend on a number of technical features of the plant such as its availability factor as well as the efficiency of the hydrogen generating process. For example, hydrogen generation plants operating on high temperature thermo-chemical process have higher efficiency, however the systems are subjected to very aggressive environment. This may lead to more outages on account of repair and maintenance resulting into lower availability factor. In order to maintain rate of higher hydrogen supply, redundant components or units may have to be incorporated in the system. Alternatively, capacity of storage facility has to be larger to maintain the hydrogen supply during plant maintenance outage. Whereas a plant operating on matured electrolysis process will have higher availability factor. Yet, the process itself has lower efficiency. The cost of hydrogen will also depend on the form in which hydrogen will be stored and transported to end-user. Apart from some of these descriptive examples of technical features, many other technical features affecting hydrogen economy are considered in HEEP. These important technical features of different categories of plants and facilities are listed in Table 1.

4.1.2. *Time periods considered in HEEP*

The time period required by various activities during life cycle of these plants and facilities is an important variable that affects the cost of hydrogen generation. For example, a higher number of refurbishment may be required in the case of hydrogen generation plant based on thermo-chemical processes. Another example is the construction period of nuclear power plant affecting the interest during construction. Most of these activities have been considered in HEEP (see Table 2).

4.2. *Cost components*

Cost components considered in HEEP have been grouped in three categories viz. (i) Capital cost or fixed cost, (ii) running cost, and (iii) decommissioning cost. Fig. 3 shows the cost components considered in the beta -version of HEEP. Constant price analysis methodology has been adopted for obtaining the levelized cost of hydrogen in real discount rate excluding the inflation rate. All cost components are calculated relevance to the value corresponding to the reference year at the specified discount rate. Furthermore, HEEP considers aspects of capital investments which eventually affect the cost of hydrogen. The capital investment; which is the sum of all

Table 1 – HEEP important technical features.

Nuclear power plant	Hydrogen generation and storage plant	Hydrogen transportation and distribution
• Number of units • Rated installed capacity per unit • Capacity and availability factor of unit • Thermal power available for hydrogen generation • Thermal efficiency of unit (if electricity is generated)	• Hydrogen generation plant • Number of units • Rated annual hydrogen generation rate • Process efficiency • Capacity and availability factor of unit • Maximum thermal power required for process by each unit • Maximum electricity required for process by each unit • Non-process electricity required by each unit • Location of plant (Co-located with NPP or isolated) • Hydrogen storage facility • Type of hydrogen storage (Gaseous or Liquid or Metal hydride) • Capacities, power and auxiliary requirements of storage devices	• Method of transportation of hydrogen (Pipe line of vehicular transportation) • Pipeline transportation • Transportation distance • Technical parameters affecting power required to overcome losses in pipeline transportation • vehicular transportation • Transportation distance • Mileage of vehicle • Vehicle capacity • Speed of vehicle • Preparation time for each trip of the vehicle

Table 2 – Various activities considered in HEEP.

Description of activity	Nuclear Power Plant	Hydrogen generation plant	Hydrogen transportation
Construction	✓	✓	✓
Operation	✓	✓	✓
Decommissioning	✓	✓	✓
Cooling before decommissioning	✓	✓	✓
Refurbishment	✓	✓	✓
Spent fuel cooling	✓	X	X
Reprocessing of fuel	✓	X	X
Waste storage period.	✓	X	X

✓: Applicable for relevant plant/facility.
X: Not applicable for relevant plant/facility.

expenditures incurred in design, licensing, manufacturing and erection, construction and commissioning of the plant; can be raised at a given equity to debt ratio (i.e. the funding of the project can be raised through equities or can be raised through market borrowings or combination of both). The user has to arrange the return on equity in case of funds is raised through equity or must keep provision to return the borrowings in specified period along with the interest. Another important parameter is the cash flow during construction which affects the interest during construction. This is particularly prominent in case of nuclear power plant that needs high capital investments with longer construction period.

The running cost comprises of operational expenditures like wages, salaries, rents to be paid etc., as well as routine maintenance, refurbishment expenditures, and cost of consumables. The routine operation cost consists of charges for energy needed to operate various systems of plants and facilities. If hydrogen-generating plant is co-located with nuclear power plant, the thermal energy as well as electricity needed for operation is received directly from nuclear power plant. Thus, energy charges forming component of operational expenditures of hydrogen generating plant will be lower and may become zero.. However, if hydrogen generation were not produced from nuclear power plant, the hydrogen generation plant may receive electricity from the grid at market rate. In such cases operational expenditures of the hydrogen generating plant will include the cost of electricity.

Similarly, in the case of having a facility to transport and distribute hydrogen, the cost of front and back end of fuel cycle in nuclear power plant can be treated as a component of operation and maintenance cost. If the back end of the fuel cycle is using reprocessing of spent fuel, the recovered fissile component can be considered for revenue generation. Decommissioning cost of the nuclear power plant may have significant contribution towards the cost of hydrogen production compared to decommissioning cost of hydrogen generation, storage and transport facility. Therefore, HEEP expects the user to provide cost values with respect to a reference year after appropriately adjusting for escalations resulting from inflation and other factors. For example, if the user provides cost figures using the year 2010 as a basis and the project starts on 2020, then the user has to provide escalated cost figures adjusted to the year 2020, since HEEP uses constant price methodology.

4.3. *HEEP expandable database*

The GUI of the pre-processing module has provided user-friendly feature for entering data needed to build a case for evaluating cost of hydrogen. Different options for providing this data are available in the current version of HEEP, namely:

- Provide new inputs to perform assessment,
- Build new case based on previously generated library files, and
- Read previously evaluated and stored cases.

Currently, sufficient information needed for economic evaluation of hydrogen production and distribution using established technologies is well known. However, many processes and technologies are being developed world wide to enhance hydrogen production at economical terms. Hence, it was clear that HEEP needs to incorporate an expandable

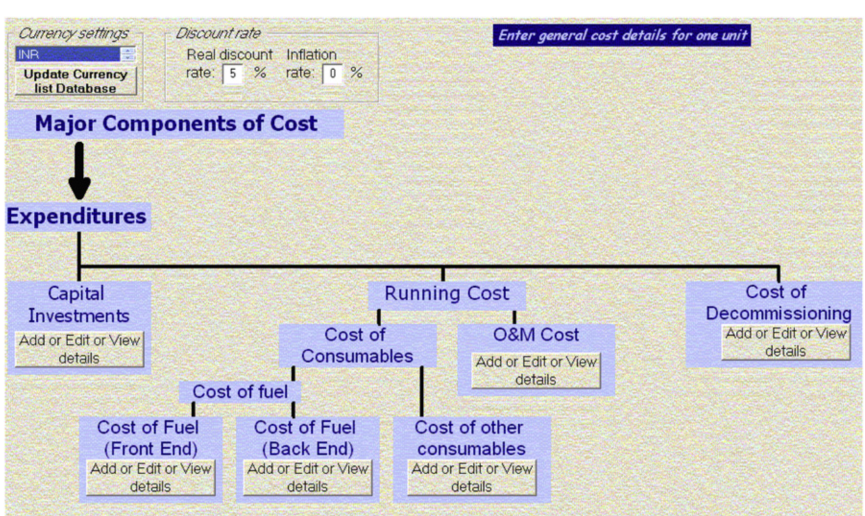

Fig. 3 – Major cost components in HEEP.

database so as to generate new library files for such processes and technologies and append them to the existing database. In addition, another necessity to analyse and compare economic aspects of multiple routes of nuclear hydrogen generation and distribution, arising out of different combination between source of heat energy, process of hydrogen generation and distribution of hydrogen was obvious. The abovementioned different methods of creating case file for estimation of hydrogen cost can fulfil these requirements.

4.4. *Execution module of HEEP*

The execution module of HEEP reads processed inputs from the pre-processing module. This module calculates levelized cost of hydrogen generated by dividing sum of present value of all expenditures during entire life span with sum of present value of hydrogen generated during entire life span. The formula used for calculation of levelized cost of hydrogen generation is:

$$C_{H2} = \frac{E_{NPP}(t_0) + E_{H2GP}(t_0) + E_{H2T}(t_0)}{G_{H2}(t_0)}$$

Where, C_{H2} = Levelized cost of hydrogen generation; $E_{NPP}(t_0)$ = Present value of expenditures of nuclear power plant at time t_0; $E_{H2GP}(t_0)$ = Present value of expenditures of hydrogen generation and storage plant plant at time t_0; $E_{H2T}(t_0)$ = Present value of expenditures of hydrogen transportation facility at time t_0; $G_{H2}(t_0)$ = Present value of gross hydrogen generation at time t_0

The present value of expenditures are calculated using following fundamental formula:

$$E(t_0) = \sum_{t=t_{START}}^{t_{END}} \frac{CI_t}{(1+r)^{t-t_0}} + \sum_{t=t_{START}}^{t_{END}} \frac{R_t}{(1+r)^{t-t_0}} + \sum_{t=t_{START}}^{t_{END}} \frac{DC_t}{(1+r)^{t-t_0}}$$

Where, CI_t = Capital Investment expenditures at year t; R_t = Expenditures towards running the facility in the year t; DC_t = Decommissioning expenditures at year t; t_0 = Base year of comparison; r = Real discount rate.

The present value at time t_0 of gross hydrogen generation is calculated using similar formula:

$$G_{H2}(t_0) = \sum_{t=t_{START}}^{t_{END}} \frac{G_{H2}(t)}{(1+r)^{t-t_0}}$$

Where; $G_{H2}(t)$ = Hydrogen generation in the year t

When part of thermal energy generated by nuclear power plant is diverted for production of electricity, there is a need to estimate cost of thermal energy as well as cost of electricity generation. The "Power Credit Method" adopted in DEEP [13] has also been adopted in HEEP to arrive at the cost of electricity produced.

4.5. *Post-processing module in HEEP*

The post-processing module is also developed with GUI to provide user-friendliness while displaying results calculated by execution module. The cost of hydrogen evaluated by execution module is processed in post-processing module to display results of the analysis in the form of navigable pie charts. The navigable pie chart helps user to visualise components of hydrogen cost at different levels. The pie chart can display contribution of nuclear power plant, contribution of hydrogen generation and storage plant and contribution of transportation facility. The next level components like components of capital investment, running cost and decommissioning cost for each of these facilities can also be viewed. This module can display results in the tabular formats also. The post processor also facilitates in generating reports in the "html" format.

4.6. *Future versions of HEEP*

As the safety considerations may affect the final cost of hydrogen, inputs pertaining to safety of nuclear hydrogen production can be provided in the present version of HEEP as part of nuclear power plant or hydrogen generation plant inputs. Major guidelines for the set up of such consideration will be established based on the available information of HTGR plant. Later development may also include various safety related layout of other HTR such as the Japanese HTTR. The product hydrogen may represent no major risk to the nuclear plant if transported away directly after production from the place of generation to liquefaction and storage site. For a chemical plant based on the S-I thermo-chemical cycle, the hydrogen producing section (HI decomposition) is expected to be located away from the nuclear buildings for maintaining sufficient safety distance. It is also expected that HEEP will include, may be later in future versions, the feature to calculate and display the contribution of some important safety measures such as specific activity enclosure (i.e. intermediate loop), facility for maintenance of primary circuit surfaces, measures to reduce the hydrogen and tritium permeation ...etc as a separate entity. Further risk reducing means are to be anticipated as part of the overall safety aspects of hydrogen production.

5. Preliminary benchmarking of HEEP

As described earlier, some work has already been initiated to estimate cost of hydrogen production. Results of a lifecycle cost analysis of the reference design for a commercial-scale high-temperature electrolysis plant driven by high temperature gas cooled nuclear reactor are provided in the report published by the INL [14]. KAERI has also published results of the preliminary study on cost estimates for hydrogen generated by S-I thermo-chemical process coupled with the modular nuclear reactors generating very high temperature as source of thermal energy [15]. The hydrogen production cost using the information provided in the KAERI publication is re-calculated using HEEP and results are compared with those reported in the publication to carry out benchmarking of the HEEP. This preliminary benchmarking has demonstrated that the elements of hydrogen cost reproduced by HEEP were comparable with the estimates of earlier studies.

5.1. *Inputs and assumptions in HEEP benchmarking*

The economic assessment performed by KAERI for the nth-of-a-kind hydrogen generating plant coupled with high

Table 3 – Summary of various components and configurations used for HEEP Benchmarking.

CASES	CASE-I	CASE-II	CASE-III	CASE-IV
Discount rate	5%	5%	5%	5%
Nuclear power plant details				
Nuclear power plant configuration	4 × 600 MWth PMR	4 × 200 MWth PMR	10 × 250 MWth PBR	4 × 200 MWth PBR
Capacity factor	90%	90%	90%	90%
Availability factor	100%	100%	100%	100%
Construction period	3 years	3 years	3 years	3 years
Operating life	60 years	60 years	60 years	60 years
Cooling before decommissioning	1 year	1 year	1 year	1 year
Decommissioning period	9 years	9 years	9 years	9 years
Spent fuel cooling period	2 year	2 year	2 year	2 year
Waste cooling period	2 year	2 year	2 year	2 year
Capital cost	1835.8 M$	867.575 M$	2944.45 M$	1088.75 M$
Annual fuel cost	120.6 M$	40.2 M$	112.5 M$	36 M$
O&M Cost	38 M$	16.8 M$	56.4 M$	19.5 M$
Decommissioning cost	10% of total capital cost	10% of total capital cost	10% of total capital cost	10% of total capital cost
Hydrogen generation plant				
Rated hydrogen generation	216 000 te/yr	72 000 te/yr	225 000 te/yr	72 000 te/yr
Non-process electricity	815 MWe	272 MWe	849 MWe	272 MWe
Construction period	3 years	3 years	3 years	3 years
Operating life	60 years	60 years	60 years	60 years
Cooling before decommissioning	1 year	1 year	1 year	1 year
Decommissioning period	9 years	9 years	9 years	9 years
Capacity factor	90%	90%	90%	90%
Availability factor	100%	100%	100%	100%
Capital cost	1410 M$	673.325 M$	1564.75 M$	693.15 M$
O&M cost	77 M$	37 M$	77 M$	37 M$

temperature reactor. This study considered two-different core types viz. prismatic core (PMR) and pebble bed core (PBR) of the nuclear reactors. Four different cases resulting from four different configurations of nuclear plants delivering thermal energy to S-I thermo-chemical process were analyzed: (i) 4 modular units of 600 MW(th) PMR, (ii) 4 modular units of 200 MW(th) PMR, (iii) 10 modular units of 250 MW(th) PBR and (iv) 4 modular unit 200 MW(th) PBR.

The capital costs for PMR and PBR were taken from the references for the Gas Turbine- Modular High temperature Reactor (GT-MHR) and Pebble Bed Modular Reactor (PBMR), respectively and corrected to the Korean specific cost values. The capital costs for hydrogen generating chemical plant were taken from the references for the H2-MHR based plant. The relevant capital cost values of reference plants were appropriately modified to account for size of plant (scale factor), as well as for the use of material to withstand higher temperatures. Capital costs values were also escalated to the value of the US 2005 dollars.

Input data required for execution of HEEP was prepared based on the information provided in the KAERI report including technical features of plants, time and cost required for construction and operation of plants, real discount rate assumed etc. Table 3 gives various technical features, time periods and cost components of different configurations considered for HEEP benchmarking.

5.1.1. *Assumptions for HEEP benchmarking*

In this HEEP benchmarking exercise, it was assumed that nuclear power plant would generate no electricity and entire heat produced by nuclear reactor would be utilised by thermo-chemical process generating hydrogen. In the KAERI publication availability factor for both plants was not indicated, but for HEEP benchmarking, a 100% availability of the nuclear power plant and hydrogen generating station was assumed. The S-I thermo-chemical plant coupled with 4 × 600 MW(th) nuclear power plant is assumed to be generating 216 000 tonnes of hydrogen annually at efficiency of 45%. Hydrogen generation capacity of plants coupled to other configurations of nuclear power plant is assumed to be directly proportional to the thermal energy generated. Time periods for cooling before decommissioning (period between end of plant operation to start of decommissioning), spent fuel cooling, decommissioning period indicated in the Table 3 are assumed numbers for this exercise, as these time periods were not mentioned in the Korean study.

Table 4 – Summary of various components of hydrogen transportation as used for HEEP Benchmarking.

Vehicle capacity	180 kg
Average speed of vehicle	40 km/h
Mileage of vehicle	2.5 km/lit
Loading-unloading time per trip	2 h
Procurement period of vehicle	3 years
Life of vehicle	15 years
Refurbishment cost	100%
Number of refurbishments	4 nos.
Capital cost per vehicle	100 000 $
Annual salary of driver	5000 $
Price of fuel	0.75 $/lit
Routine maintenance of vehicle	1% of total cost

Table 5 – Comparison of levelized cost of hydrogen.

CASE	Levelized cost of Hydrogen ($/kg)					
	HEEP results					KAERI results
	Total levelized cost of hydrogen	Nuclear power plant component	Hydrogen generation & storage component	Hydrogen transportation cost component	Nuclear power plant + hydrogen generation & storage	
CASE-I	5.07	1.23	3.02	0.83	4.25	4.06
CASE-II	5.82	1.62	3.38	0.83	5.00	5.56
CASE-III	5.36	1.50	3.03	0.83	4.53	4.48
CASE-IV	6.02	1.79	3.40	0.83	5.19	5.86

As indicated in the publication that annual non-process electricity cost of hydrogen generating plant coupled to four modular units of 600 MW(th) nuclear power plant is 428.4 M$, the non-process electric power given in the Table 3 have been worked out for electricity charge of 0.06 $/kWh and plant capacity factor of 90% as indicated in the KAERI publication. Since nuclear power plant is not generating electricity, it is assumed that the electricity required by hydrogen generating plant would be supplied from the grid at market rate of 0.06 $/kWh. The electricity required for hydrogen plants coupled to other configuration is assumed to be directly proportional to the total thermal energy and thus annual hydrogen generation.

The KAERI publication gives capital cost for six major sub systems of both plants, i.e. nuclear power plant and hydrogen generating plant. The capital costs for the primary and secondary heat transport system was given separately as a common cost component among nuclear power plant and hydrogen generating plant. It also presents cost for the supplementary capitalised support and contingency requirements as common cost for nuclear power plant and hydrogen generation. However, for HEEP benchmarking calculations, primary and secondary heat transport system cost is considered as component of capital cost of nuclear power plant. The 75% of contingency and capitalised supplementary cost has been considered as part of nuclear power plant capital cost and remaining 25% as part of capital cost of hydrogen generating plant. The real discount rate of 5% is assumed as indicated in KAERI publications.

Inputs pertaining to the hydrogen storage facility needs to be provided for execution of HEEP. However, hydrogen storage was not considered in the Korean study. Hence, while estimating hydrogen cost by HEEP, the storage period is assumed to be zero and storage pressure of hydrogen storage system is assumed to be atmospheric pressure. Even though decommissioning period is assumed to be 9 years, the decommissioning cost is assumed to be nil, as the same was also not considered in the Korean study.

HEEP is used to estimate the comprehensive cost of hydrogen from its generation to its delivery to the end user including the hydrogen transportation cost. In this benchmarking study, vehicular transportation of gaseous hydrogen has been assumed. The output of HEEP includes contribution of nuclear power plant, hydrogen generation and storage cost and hydrogen transportation. To compare results of HEEP with that reported in the Korean publication, the contribution of hydrogen transportation has to be deducted from the total levelized cost of hydrogen. Table 4 presents a summary of technical features, various time periods and cost components for vehicular transportation of hydrogen considered for HEEP benchmarking.

Based on the technical features of the vehicle, in-built functions in the HEEP calculate total number of trips required for hydrogen produced annually. Depending on the total time required for one trip, total number of vehicles required was estimated. This number is used for the calculation of the total capital cost, routine maintenance and operating cost of the vehicle. The vehicle purchase time is entered as construction period. Since the life of vehicle is considered to be only 15 years, refurbishment cost is considered to be 100% of capital cost i.e. cost of vehicle. This cost is considered as operating cost after every 15th year.

5.2. *Results of HEEP benchmarking*

Table 5 presents the levelized cost of hydrogen for the four cases described earlier. The second column in Table 5 presents the total levelized cost of hydrogen. Next three columns give components of three facilities viz. nuclear power plant, hydrogen generation as well as storage and hydrogen

Table 6 – Comparison of HEEP results with reported KAERI publication.

Cost component	CASE-I		CASE-II		CASE-III		CASE-IV	
	HEEP	KAERI	HEEP	KAERI	HEEP	KAERI	HEEP	KAERI
NPP capital	12%	10%	15%	10%	17%	19%	19%	9%
NPP fuel	13%	16%	12%	11%	11%	12%	10%	15%
NPP O&M	4%	5%	5%	5%	5%	6%	6%	5%
SI plant capital	10%	8%	12%	8%	10%	9%	12%	8%
SI plant O&M	61%	62%	56%	66%	57%	54%	54%	63%

transportation. Since hydrogen transportation was not considered in the KAERI study, sum of cost indicated in third and fourth column should be used for comparing results. All previous results could also be displayed in HEEP as pie charts. The overall comparison of results reported in the KAERI publications and HEEP are presented in Table 6.

6. Conclusion

Interest in nuclear hydrogen production has been growing in several Member States over the past decade. Nuclear power can play a significant role with respect to a large scale hydrogen production. Different reactor types and thermo-chemical cycles are seen as promising technologies for nuclear hydrogen production. The IAEA is taking the lead in the development of HEEP, which will reflect all stages of the hydrogen production technologies, transport, storage, and economy. The HEEP software development may take several years to reach a mature status so long as the technologies and process involved are still under R&D. Yet, results of the benchmarking of the Beta -version of HEEP are encouraging. This version of HEEP has just been released and further update will be released free of charge and can be downloaded from the IAEA web site.

Acknowledgement

The Authors would like to express their gratitude to other members of the HEEP development team from BARC, Mumbai, India. Mr. I.V. Dulera has compiled technical inputs related to various pathways being developed for hydrogen generation. Mr. P.P. Kelkar has prepared the models required for HEEP, Mr. A. Antony has developed the execution module of HEEP, and Mr. A. Basak was involved in developing the post-processing module.

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