INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 36 (2011) 4125–4129

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

An overview of the IAEA HEEP software and international programmes on hydrogen production using nuclear energy

*I. Khamis**

International Atomic Energy Agency (IAEA), Wagramer Strasse 5, P. O. Box 100, A-1400 Vienna, Austria

ARTICLE INFO

Article history:
Received 15 April 2010
Received in revised form
25 June 2010
Accepted 27 June 2010
Available online 7 August 2010

Keywords:
IAEA
Hydrogen production
Nuclear energy
International programmes
HEEP

ABSTRACT

Recent years have witnessed an increasing interest in hydrogen production using nuclear energy. A number of countries are actively exploring the option of nuclear hydrogen production and have established concrete roadmaps for near and far term achievements. This paper presents a summary of information presented at some IAEA technical meetings on status of nuclear hydrogen production including ongoing related R&D activities in Member States. The paper highlights, in addition, the IAEA hydrogen economic evaluation programme (HEEP) which has recently been developed under agreement and in collaboration with the BHABHA Atomic Research Centre (BARC). HEEP software can be used to perform the economics of the most promising processes for hydrogen production. Current processes considered in HEEP are: high and low temperature electrolysis, thermo-chemical processes including S–I process, conventional electrolysis and steam reforming. HEEP software is also suitable for comparative between nuclear and fossil energy sources, and for solely hydrogen production or cogeneration with electricity. The HEEP modelling includes various aspects of hydrogen economy including storage, transport, and distribution with options to eliminate or include specific details as required by the users.

1. Introduction

Hydrogen could be produced from nuclear energy by several means/processes and through different routes in the near-term, mid-term, and long-term. Nuclear energy could be used for near and mid-term hydrogen production through various approaches/strategies that involves the use of low temperature electrolysis during the off-peak operation of nuclear reactors, or in a cogeneration mode using the high temperature steam electrolysis. Indeed, nuclear hydrogen from electrolysis is a reality now, and the economics need to be improved. Whereas for long-term, high temperature reactors could be seen as the most suitable source for providing heat at various high temperatures as required for hydrogen production using thermal chemical cycles [1]. Numerous cycles have been proposed in the past and investigated in terms of their characteristics like reaction kinetics, thermo-dynamics, separation of substances, stability, processing flow scheme, and cost analysis. Only a few, however, were deemed to be sufficiently promising and worth further investigation. Among those whose partial reactions are being investigated in more detail also with respect to their coupling to High Temperature Gas-cooled Reactor (HTGR) are the sulfur–iodine (S–I) process originally developed in the USA and later pursued and modified by various research groups. The development and deployment of high efficiency high temperature steam electrolysis and thermo-chemical processes are foreseen to play an important role in the long-term prospect of hydrogen production as they are currently under R&D [2–6].

A significant number of countries are involved in research and development on hydrogen production using nuclear energy. In the past few years, the IAEA has organized several technical meetings on hydrogen production using nuclear energy. The

* *Corresponding author*. Tel.: +43 1 2600 22822/22815; fax: +43 1 2600 29598.
E-mail address: i.khamis@iaea.org.
0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2010.06.108

latest meeting was held in Mumbai, India October 2009, preceded by another technical meeting on non-electric applications of nuclear energy in March 2009 in Rep. of Korea, and the International Conference on Non-electric Applications of Nuclear Power held in Japan April 2007. These meetings have helped catalyse current activities in some Member States and opened discussion on advances and challenges to nuclear hydrogen production with emphasis on safety of coupling and future aspects hydrogen economy. Some positive feedbacks were collected during these meetings helped accelerating the development, testing, and the release of the beta version of the HEEP software in early 2010.

2. Highlights of some ongoing national programmes on nuclear hydrogen production

The following brief summary is based on information presented by participants in previous IAEA activities and open publications [7].

Argentina is using domestic capabilities related with both nuclear energy and hydrogen production and applications technologies which has been developed in previous 50 years to support the production of hydrogen using high temperature nuclear reactors. Research activities currently carried out on the water splitting thermo-chemical processes for hydrogen production and focused on the metallic chlorides family of thermo-chemical cycles. Theoretical and experimental investigations are being carried out in order to elucidate the kinetics and mechanisms of thermo-chemical reactions at laboratory scale, and to study optimum conditions for increasing the efficiency of such cycles as a previous step for a future scaling up of the experimental facilities. Moreover, several research activities are planned for near future including: design and construction of a laboratory scale reactor for continuous operation; implementation of separating membrane technology for removing H_2 and O_2 from the gaseous stream, i.e. separation of H_2 and O_2 from HCl and Cl_2 with a ceramic membrane and further separation of H_2 from O_2 with a composite membrane consisting of a ceramic support membrane coated by a metallic palladium layer; and development of catalytic surfaces with rare earth and refractory metal oxides in order to make the reactions faster and to improve the efficiency of the process.

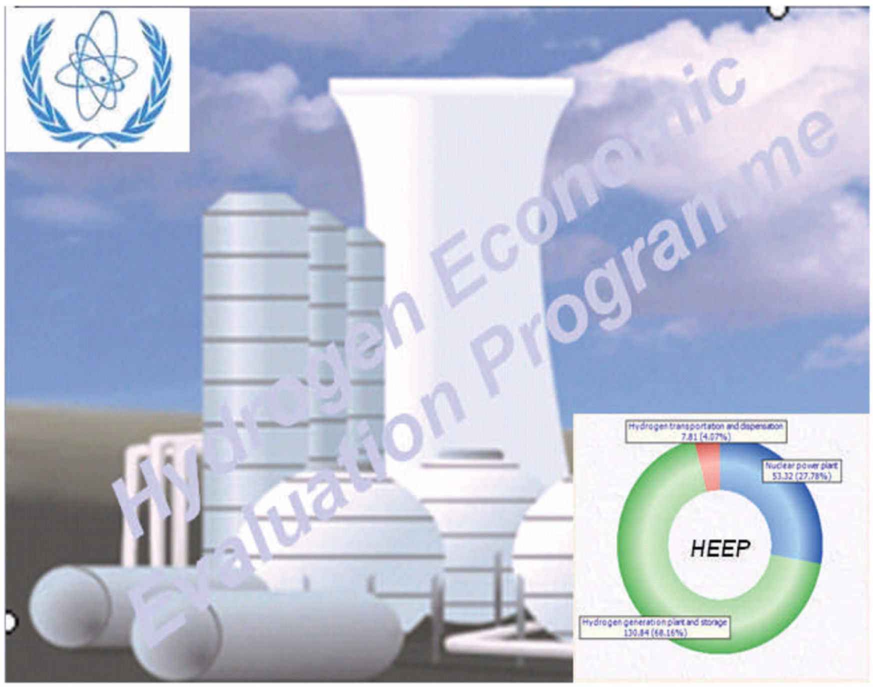
Canada is developing, with cooperation of other nations, the Supercritical Water Cooled Reactor (SCWR) as its Generation IV nuclear reactor system and has also selected the copper–chlorine cycle for the production of hydrogen coupled to the SCWR. The Atomic Energy of Canada (AECL) is coordinating the development of both the SCWR and the copper–chlorine cycle. The University of Ontario Institute of Technology (UOIT), in collaboration with AECL and many other universities and institutes, has set up a program to study all aspects of the cycle with a plan to build an integrated lab facility and eventually a pilot facility. Currently AECL is focusing on this electrochemical step. Indeed, through the understanding of the basic electrode reactions and the performance of the membrane, it has been possible to achieve continuous production of hydrogen at 0.9 V and 429 mA/cm^2. Continuing effort is focused on reducing the voltage at this level of current density. One of the main issues observed in the development of the electrochemical cell is the deterioration of its performance with time. Since maintenance of high level of performance over long periods is a prerequisite for economical hydrogen production. Some of the effort is focused on understanding the deactivation characteristics. Other studies have shown that the passage of copper from anolyte to catholyte through the membrane is one of the electrode deactivation mechanisms. Modification of the properties of the membrane and identifying suitable operating conditions are some of the ways to avoid the passage of copper through the membrane.

In France, the French Atomic Energy Commission (CEA) has for many years established an extensive research and development program to investigate advanced processes which could use directly the nuclear heat and present a better economic potential. In the frame of this program, high temperature steam electrolysis (HTSE) along with several thermo-chemical cycles has been extensively studied. HTSE offers the advantage of reducing the electrical energy needed by substituting thermal energy, which promises to be cheaper. The need for electricity is also greatly reduced for the leading thermo-chemical cycles, the iodine–sulfur and the hybrid sulfur cycles, but they require high temperatures and hence coupling to a gas-cooled reactor. Therefore, interest is also paid to other processes such as the copper–chlorine cycle which operates at lower temperatures and could be coupled to other generation IV nuclear systems. One of the primary goal of the R&D programme is to demonstrate the technological viability of the processes investigated and contribute to their optimization. The program is led in the frame of the Hydrogen Production Project of the Generation IV Very/High Temperature Reactor System which helps mutualise the costs. In addition, techno-economical studies are being investigated aiming at the evaluation of the potential production cost and help the selection of one or two processes for which demonstrators will be built in the next few years.

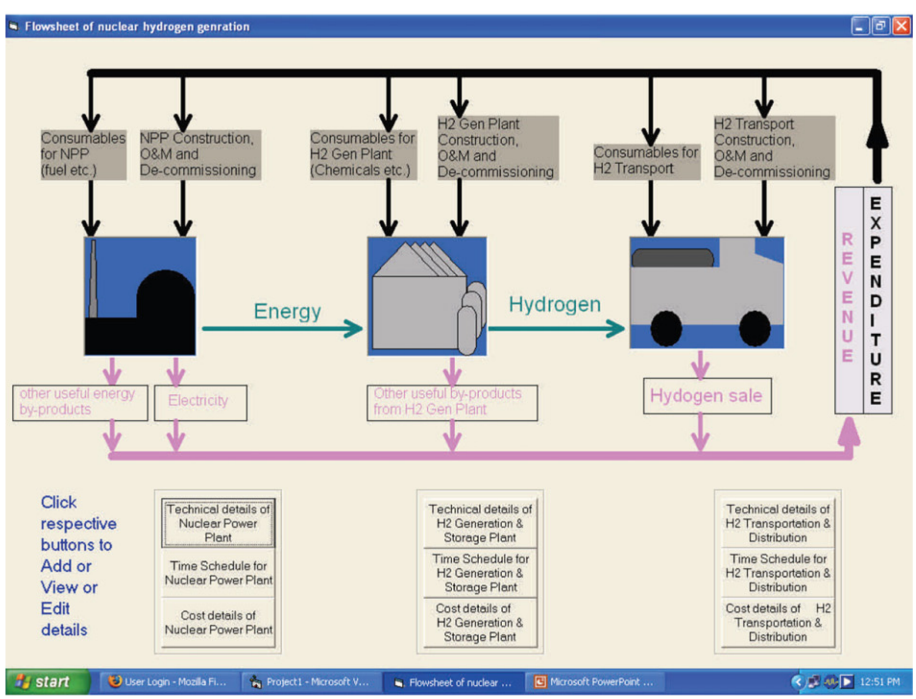
In Japan, has a well established programme on the High Temperature Gas-cooled Reactor (HTGR), which is a graphite moderated, helium cooled reactor, is particularly attractive due to capability of producing high temperature helium gas and its inherent safety characteristics. With the understanding that hydrogen production using HTGR heat is expected to be one of the most promising applications to solve the current environmental issues of CO_2 emission, the Japan Atomic Energy Agency (JAEA) has proceeded with the development studies of the thermo-chemical water splitting I–S process as well as HTGR reactor technology.

In India, has a National Hydrogen Energy Road Map prepared by the Indian Ministry of New & Renewable Energy. The roadmap identifies different routes for hydrogen production during near, mid-term, and long-term. Hence, India is developing technologies for production of hydrogen in large volumes for long-term supplies including envisaged options for nuclear hydrogen production include very high temperature (>850 °C) thermo-chemical processes (e.g. I–S process) with an R&D goal of achieving more than 50 percent energy conversion efficiency, moderately high temperature processes (500–700 °C) with an expected energy conversion efficiency around 35–40 percent, and conventional electrolysis, with an energy conversion efficiency of about 25 percent. The long-term goal is to develop and deploy high efficiency thermo-chemical processes. During the interim period, other less complex processes are proposed to be deployed to meet demands. Currently R&D on Iodine–Sulfur (I–S) process which is reported to be one of the most efficient thermo-chemical process for the production of hydrogen by splitting water. In addition, India has prepared a roadmap for development of reactors for generating nuclear hydrogen. Keeping the focus on the long-term objective, the current R&D activities in the country is targeting technologies for high temperature nuclear reactors and capable of supplying process heat at 1000 °C. Accordingly, technologies for high temperature nuclear reactors using thorium-based fuel are being developed.

In the Rep. of Korea, current R&D is focusing on the nuclear hydrogen development demonstration (NHDD) reactor which will have a 200 MW(th) power, a high exit temperature of



a Main page



b Major cost

Fig. 1 – HEEP: (a) Main page; (b) Representative sheet from HEEP with major cost components.

Table 1 – HEEP important technical features.

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

950 °C, cooled-vessel, indirect loop, coupled to an I–S thermochemical process. The R&D will include: thermal–fluid and safety design aspects, code system for the analysis of the nuclear kinetics, the hydrogen explosion, safety analysis of the very high temperature reactor, the mechanical & seismic analysis, and other related issues.

3. The IAEA hydrogen economic evaluation programme (HEEP)

Among other important considerations, such as the national energy policy, availability of resources …etc, competitive economics is expected to be the frontrunner in the selection of the pathway to produce and distribute hydrogen to users. Currently, wide ranges of pathways are being developed for separating hydrogen from the hydrogen-containing substances using nuclear energy and various international efforts are being made to this regards [8–11]. A comparison from economics perspective is vital to evaluate various hydrogen-producing technologies.

HEEP consists of three modules: (i) Pre-processing module for providing data (ii) Executing module estimating levelized cost of hydrogen generation and (iii) Post-processing module for viewing results generated by HEEP. All three modules are integrated to

Table 2 – Preliminary benchmarking of HEEP compared to published data.

Parameter		Plant combinations			
		Nuclear plant PMR based	H2 plant SI based	Nuclear plant PMR based	H2 plant SI based
Thermal power		4 × 600 MW(th)		4 × 200 MW(th)	
Construction period		36 months		36 months	
Operating period		60 years		60 years	
Capacity factor		90%		90%	
Capital cost		1578 M$	1668 M$	752 M$	782 M$
Fuel cost		121 M$/year	–	40 M$/year	–
O&M cost		38 M$/year	77 M$/year	16.8 M$/year	37 M$/year
O&M (Electricity)		–	457 M$/year	–	220 M$/year
Hydrogen cost	Ref	4.05 $/kg		5.5 $/kg	
	HEEP	4.1 $/kg		5.7 $/kg	

work as single window based application. The pre-processing module and post-processing module are developed in Microsoft Visual Basic© for providing user-friendly Graphical Users Interface. The pre-processing module provides user-friendly interface to enter technical details, chronological inputs and cost components of each of the three expected utilities (see Fig. 1): (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 engine in pie chart and tabulated form.

HEEP can consider several reactor concepts including water reactors such as pressurized water reactors (PWR) and pressurized heavy water reactors (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 Supercritical Water Reactor (SCWR) capable of output temperatures up to around 625 °C for the medium range of temperature. The nuclear system may be satisfying total energy needs of a region in the form 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.

HEEP is programmed to consider different methods of hydrogen production such as: high temperature thermo-chemical cycles (e.g. Sulfur–Iodine, hybrid sulfur), 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. Important technical features of different categories of plants and facilities considered in HEEP are listed in Table 1.

Demonstration of HEEP was made based on the use of parameters reported publications [12]. The preliminary benchmarking of HEEP, as seen from Table 2, reveals that HEEP can be used with reliable accuracy compared to published data [12]. Since time period and chronology of events are important parameter affecting economics of nuclear hydrogen generation, the programme estimates "Levelized Cost of Hydrogen Generation" by bringing down all cost components over the period of life cycle at one level using the method of discounting. Having estimated the levelized cost of hydrogen generation, the post-processing module presents results as components of levelized cost of hydrogen generation in the form of pie chart. User can view the information in tabular form also. The post-processing module has feature to generate report in "html" format.

4. Conclusions

Hydrogen production using nuclear energy is becoming an interesting area of R&D in several countries. At present, several process options for production of nuclear hydrogen are under consideration in different countries. Active information exchange/collaboration among interested nations is vital. The IAEA is taking a leading role in establishing various forums for information exchange on hydrogen production. The IAEA has already released the beta version of the HEEP software which can be used to perform the economics of the most promising processes for hydrogen production. The HEEP modelling includes various aspects of hydrogen economy including storage, transport, and distribution with options to eliminate or include specific details as required by the users. 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. The current HEEP Beta version has been released and could be downloaded free of charge from the IAEA web site.

REFERENCES

[1] Gorensek BM, Forsberg CW. Relative economic incentives for hydrogen from nuclear, renewable, and fossil energy sources. International Journal of Hydrogen Energy 2009;34(9): 4237–42.
[2] Verfondern K. Nuclear energy for hydrogen production. Energy Technology 2007;58. ISBN 978-3-89336-468-8.
[3] International Atomic Energy Agency. Hydrogen as an energy carrier and its production by nuclear power. Vienna: IAEA-TECDOC-1085; 1999.
[4] International Atomic Energy Agency. Non-electric applications of nuclear power: seawater desalination, hydrogen production and other industrial applications. In: Proceeding of an international conference, Oarai, Japan, 16–19 April 2007. IAEA-CN-152; 2009.
[5] Schultz KR, Brown LC, Besenbruch GE, Hamilton CJ. Large-scale production of hydrogen by nuclear energy for the hydrogen economy, GA-A24265. http://web.gat.com/pubs-ext/MISCONF03/A24265.pdf; 2003.
[6] Forsberg CW. Is Hydrogen the future of nuclear energy? In: Proc., Int. topical meeting on the safety and technology of nuclear hydrogen production, control, and management, ANS Embedded Topical; 2007.
[7] Marcus G. An international overview of nuclear hydrogen production programs. Nuclear Technology 2009;166:27–31.
[8] Marcus G. Innovative nuclear energy systems and the future of nuclear power. Progress in Nuclear Energy 2008;50:92–6.
[9] Forsberg CW. Sustainability by combining nuclear, fossil, and renewable energy sources. Progress in Nuclear Energy 2008; 51:1–9.
[10] Balat M. Potential importance of hydrogen as a future solution to environmental and transportation problems. International Journal of Hydrogen Energy 2008;33(15): 4013–29.
[11] Dunn S. Hydrogen futures: toward a sustainable energy system. International Journal of Hydrogen Energy 2002;27(3): 235–64.
[12] Yang KJ, Lee KY, Lee TH. Preliminary cost estimates for massive hydrogen production using SI process. In: the fourth Intl. topical meeting on high temperature reactor technology, HTR2008-58142, Washington, USA; 2008.