The development of the Hydrogen Economic Evaluation Program (HEEP)

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Abstract

The International Atomic Energy Agency (IAEA) is developing software to perform economic analysis related to hydrogen production. The software is expected to analyse the economics of the four most promising processes for hydrogen production. These processes are: high and low temperature electrolysis, thermochemical processes including the S-I process, conventional electrolysis and steam reforming. The IAEA HEEP software is expected to be used for comparative studies between nuclear and fossil energy sources. Therefore, typical conventional methods are also to be included in HEEP to enable comparison with nuclear hydrogen production. The HEEP models will be based on some economic and technical data, and on 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.

Development of HEEP is based on the IAEA's successful programme during the development of DEEP. This IAEA DEEP software has been distributed free of charge to more than 500 scientists/engineers and researchers from 50 countries interested in cost estimation of desalination plants using nuclear/fossil energy sources. DEEP is not a design code. A number of member states engaged in nuclear desalination activities in their countries have used DEEP for conducting feasibility studies for establishing large nuclear desalination projects based on different nuclear reactors types and desalination processes.

HEEP is expected to be similar to the IAEA software DEEP which is being used to perform economic analysis and feasibility studies related to nuclear desalination in the IAEA and other member states. It is expected that HEEP will have similar architecture to DEEP but with the possibility of easy update and future expansion. Various major processes and technologies are to be incorporated in the HEEP programme as the basis for modelling the performance and cost characteristics of hydrogen production plants. The pre-alpha version of HEEP has been completed and the release of the beta version is expected to be in the first quarter of 2009.

The paper will present further details on the IAEA activities towards the development of HEEP and hydrogen production using nuclear energy in general.

Introduction

Nuclear power is the only large-scale carbon-free energy source that, in the near and medium term, has the potential to significantly contribute to the global energy sector, especially in the area of non-electric applications of nuclear energy. Indeed, nuclear power is expected in the future to compensate for the limited and uncertain fossil fuels. However, nuclear power must move beyond its historical role as solely a producer of electricity to other non-electric applications. These applications include seawater desalination, district heating, heat for industrial processes, and electricity and heat for hydrogen production. Such applications have tremendous potential in the future in terms of ensuring world-wide energy and water security for sustainable development (IAEA, 2000b).

In recent years, various agencies which are already involved in nuclear energy development programmes have carried out studies on non-electric applications of nuclear power. Similarly, the IAEA launched a programme on co-generation applications in the 90s in which a number of member states have been and continue to be actively involved. This programme, however, concerns primarily with seawater desalination and district and process heating, utilising the existing reactors as a source of heat and electricity. In recent years, the scope of the Agency's programme has been widened to include other more promising applications such as nuclear hydrogen production and higher temperature process heat applications. OECD/NEA, Euratom and GIF have also evinced interest in the non-electric applications of nuclear power based on future generation advanced and innovative nuclear reactors

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. Hydrogen as an energy carrier can be stored in large quantities, unlike electricity, and converted into electricity in fuel cells, with only heat and water as by-products. 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. A greater appreciation is emerging of the economic and financial aspects of hydrogen production, particularly the suggestion that the ability to switch between two possible product streams *e.g.* electricity/hydrogen and heating/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 (IAEA, 1999). 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.

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. Hydrogen storage and distribution are also important areas of research to be undertaken for bringing in a successful hydrogen economy regime in the future.

As a greenhouse-gas-free alternative, the United States, Japan and other nations are exploring ways to produce hydrogen from water by means of electrolytic, thermochemical and hybrid processes. Most of the work has concentrated on high temperature processes such as high temperature steam electrolysis (HTE) and the sulphur-iodine (SI) 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 cost can be brought to $2/kg levels, if O_2 credit is also taken into account. If the natural gas price ranges between $6-8/MBtu and CO_2 sequestering costs are also included, hydrogen by steam methane reforming (SMR) would cost more than nuclear hydrogen.

In several countries, many activities on hydrogen production and cost assessments within the hydrogen economy are ongoing. Some countries have already developed their own models such as the German-French E3-database, the hydrogen cost analysis model in Canada, and other models in the United States.

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 Program (DEEP). 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 thermochemical 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.

HEEP will be based on basic methods of hydrogen production which are: high temperature thermochemical cycles (*e.g.* sulphur-iodine, hybrid sulphur), moderate temperature thermochemical cycles [*e.g.* copper-chlorine and hybrid hydrogen process in the lower temperature (HHLT)] and high temperature steam electrolysis to be compared to the conventional electrolysis and steam reforming. Due to both high temperature (more than 850°C) and strongly corrosive environment, selection of suitable material for the thermochemical components of the sulphuric acid decomposition is still an issue in case of sulphur-iodine and hybrid-sulphur cycles. Development of high performance materials for the sulphur-iodine process is still being investigated world wide. Figures 1 and 2 show the overall stages to be considered and the structure of HEEP.

Figure 1: Processes considered in HEEP

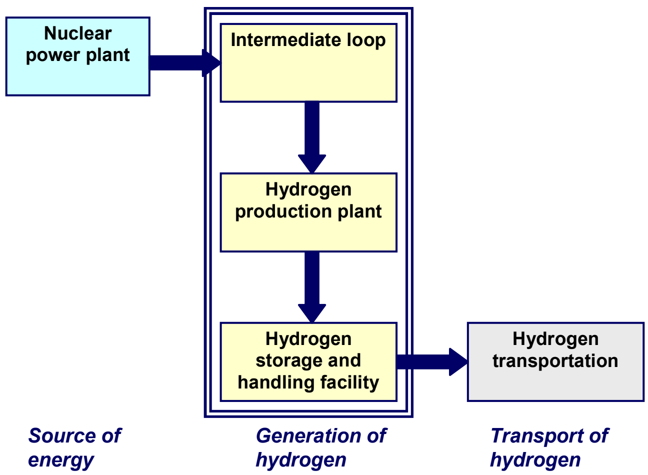
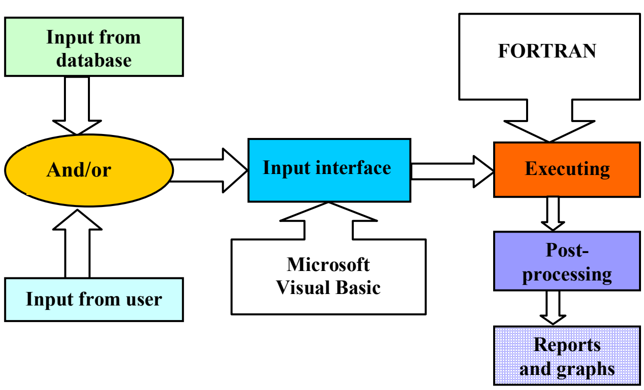


Figure 2: Structure of HEEP

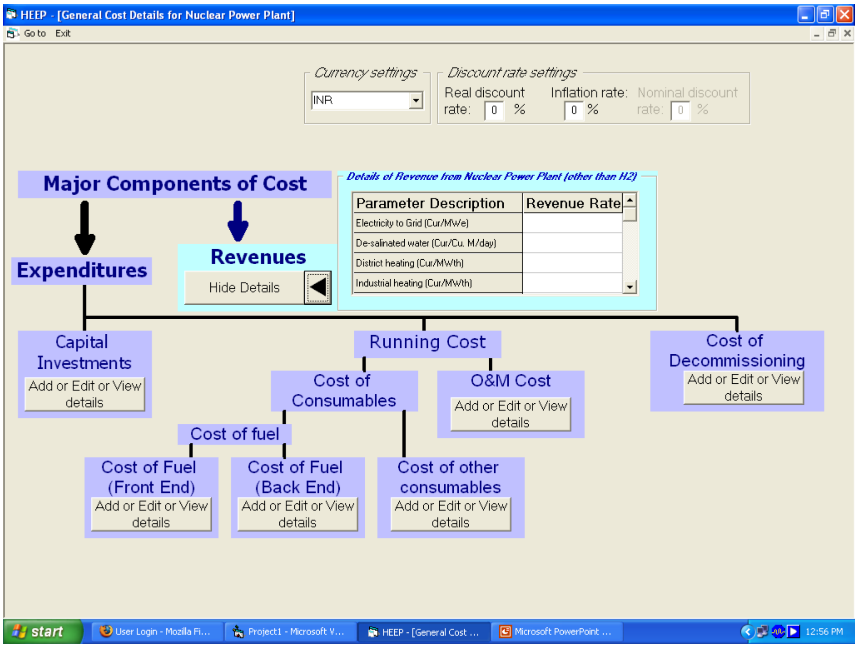


Furthermore, HEEP will consider several reactor concepts including water reactors such as PWR and PHWR for the lower temperature range, the very high temperature reactors (VHTR), fast breeder reactors (FBR) and molten-salt cooled reactors for the high temperature range, and super-critical water reactor (SCWR) capable of output temperatures up to around 625°C for the medium range of temperature.

As more emphasis is placed on developing a hydrogen economy to reduce dependence on fossil fuels, particularly in transportation areas, nuclear systems for producing hydrogen may play an increasingly important role in the overall energy sector. Indeed, the use of nuclear technology for non-electricity related applications is an important aspect of the proposed Generation IV nuclear systems (Verfondern, 2007).

Cost assessment in HEEP is expected to include storage (liquefied or gaseous), transport and distribution of hydrogen. The detailed transport model may include distribution centres in the software at a later stage. The concept of a nuclear hydrogen economy is expected to be based on hydrogen generation using nuclear power, and the transport of energy stored in the hydrogen. The production facility will consist of a high temperature reactor combined with a thermochemical plant. The high temperature heat will be converted directly into chemical energy where basic production is 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. Figure 3 shows the preliminary cost assessment considered in the pre-alpha version of HEEP.

Figure 3: Major cost components in HEEP



Since safety considerations will affect the final cost of hydrogen, they will be included in HEEP. Major guidelines for the set-up of such considerations will be established based on the available information of HTGR plant. Later development may also include various safety-related layouts of other HTR such as the Japanese HTTR. It is also hoped that HEEP will include, perhaps in later versions, some important safety features such as specific activity enclosure (*i.e.* intermediate loop), primary circuit contamination system for maintenance of primary circuit surfaces, measures to reduce the hydrogen and tritium permeation, etc. The product hydrogen may represent no major risk to the nuclear plant if transported away directly after production from the place of generation to its (liquefaction and) storage site. For a chemical plant based on the iodine-sulphur thermochemical cycle, the hydrogen producing section (HI decomposition) is expected to be located far away from the nuclear buildings as it needs only the lower level of process heat. Further risk reducing means are to be anticipated as part of the overall safety aspects of hydrogen production.

The desired features of HEEP are:

- ability to estimate "levelised cost of hydrogen generation";
- user friendly interface to input, view and edit the data required;
- built-in intelligence to avoid run-time error;
- report generation and display results in graphical form.

Contributors to HEEP could be research institutions who are already involved in activities on hydrogen production, and previous developers of DEEP and other related software. The IAEA is contracting some recognised experts to assist in all stages of HEEP development.

Analogy to DEEP

Development of HEEP will mainly be based on the successful IAEA programme implemented during the development of DEEP. Though DEEP is not a design code, this IAEA software has been distributed, and is still being distributed, free of charge to more than 500 scientists/engineers and researchers from 50 countries interested in cost estimation of desalination plants using nuclear/fossil energy sources. A number of member states engaged in nuclear desalination activities in their countries have used DEEP for conducting feasibility studies for establishing large nuclear desalination projects based on different nuclear reactors types and desalination processes.

HEEP is expected to have very similar features and characteristic merits of the IAEA. DEEP comprises modules for several desalination and energy generation options: multi-effect distillation (MED), multi-stage flash (MSF), reverse osmosis (RO), including all possible hybrid combinations. DEEP contains 11 energy modules: five nuclear reactors, three of which are nuclear steam power plants, superheated steam boilers for coal, oil or gas, an open cycle gas turbine, a combined cycle gas turbine, a diesel, used as power-only plant and a boiler (steam or hot water), used as heat-only plant. Steam extraction/condensing turbine models are assumed both for the nuclear and the fossil energy options (IAEA, 2000, 2000a).

DEEP can combine all the above-mentioned technologies for all plant sizes, with a focus on plants of several 10 000 m^3/d or bigger. For each plant option, DEEP calculates power and water production performance and resulting costs for distillation (MED or MSF), for both stand-alone and contiguous RO systems, and for a hybrid plant. The spreadsheet methodology of DEEP is suitable for economic evaluations and screening analyses of various desalination and energy source options. The spreadsheet includes simplified models of several types of nuclear/fossil power plants, nuclear/fossil heat sources, and both distillation and membrane desalination plants. Current cost and performance data have already been incorporated so that the spreadsheet can be quickly adapted to analyse a large variety of options with very little new input data required. The spreadsheet output includes the levelised cost of water and power, breakdowns of cost components, energy consumption and net saleable power for each selected option. Specific power plants can be modelled by adjustment of input data including design power, power cycle parameters and costs.

The spreadsheet serves three important goals:

- enabling side-by-side comparison of a large number of design alternatives on a consistent basis with common assumptions;
- enabling quick identification of the lowest cost options for providing specified quantities of desalinated water and/or power at a given location;
- giving an approximate cost of desalinated water and power as a function of quantity and site specific parameters including temperatures and salinity.

However, the user is cautioned that the spreadsheet is based on simplified models. For planning an actual project, final assessment of project costs should be based on more substantive information including project design and specific vendor data. As a result, HEEP is expected to be similar in many respects to modules for several most promising processes of hydrogen production, energy generation options, and functionality. For several coming years, HEEP will be a living document from the software development point of view. Each development stage will be discussed among experts, and their recommendations will be reflected in another update of the software itself.

IAEA support activities

The IAEA has been supporting these national efforts with the preparation and publication of several guidebooks, TECDOCs, and computer programs as well as the provision of technical assistance through the framework of technical co-operation programmes. In 2007, 5he IAEA launched a Co-ordinated Research Project (CRP) on “Advances in nuclear power process heat applications” with institutes from eight countries in order to share the relevant information, optimise the resources and integrate related R&D efforts. The CRP covers a review of reactor designs suitable for coupling with desalination and hydrogen production systems, the safety consideration of coupling and economic assessments. In addition, the IAEA is planning to hold technical meetings next year on non-electric applications and hydrogen production. The first version of HEEP is hoped to be released early next year.

The HEEP development was initiated following a technical advisory meeting on hydrogen productions in September 2007. The meeting helped catalyse the activities in many countries towards the development and testing of the HEEP software. In addition, the meeting covered major topics related to hydrogen production such as:

- design aspects of high temperature nuclear reactors suitable for hydrogen production;
- most promising hydrogen production processes;
- allocation of cost of hydrogen production using high temperature reactors;
- available models for the production and delivery of hydrogen;
- assessment of hydrogen economy using nuclear power and market viability of nuclear hydrogen options.

Six experts representing six countries attended the meeting. The countries are Canada, France, Germany, India, Japan and Republic of Korea. It was recognised that contributors to HEEP can be research institutions who are already involved in activities on hydrogen production, and previous developers of DEEP and other related software.

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 thermochemical cycles are seen as promising technologies for nuclear hydrogen production. The IAEA is taking the lead to develop software, called HEEP, which will reflect all stages of the hydrogen production technologies, transport, storage and economy. HEEP software development will take several years to reach a mature status so long as the technologies and process involved are still under R&D. The pre-alpha version of HEEP has been completed and the release of the beta version is expected to be in the first quarter of 2009.

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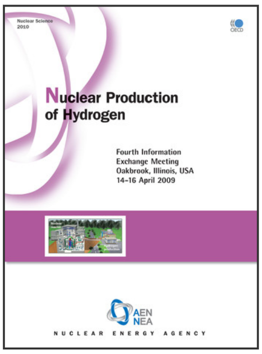

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