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Toolkit on Nuclear Hydrogen Production

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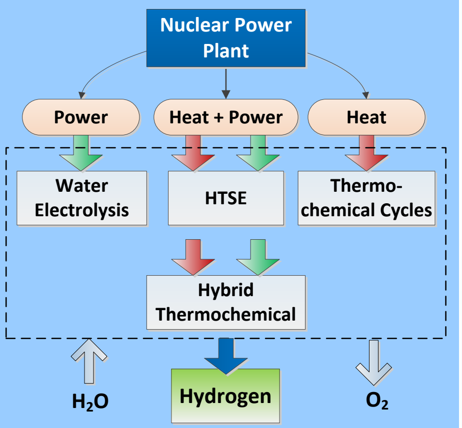
Toolkit on Nuclear Hydrogen Production

HYDROGEN PRODUCTION AND NUCLEAR ENERGY



Non-Carbon Nuclear Hydrogen Production Technologies

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The worldwide interest in hydrogen as a clean fuel has led to comprehensive research, development and demonstration activities. The current hydrogen demand is about 2% of the world energy consumption which has expected annual growth of 4-10%. Currently, the main markets for hydrogen are fertilizers and petrochemical industries. According to projections made by EU, the largest mid-term market for hydrogen will be the petrochemical industry which is to be used to upgrade heavy oils, tar sands and other low grade hydrocarbons to cover the transition period of oil prices increase. Another potential market for hydrogen is to be utilized as a means of storing electrical energy produced by intermittent renewable sources. This is possible since hydrogen can be used to store this 'intermittent energy' during weak consumption via electrolysis and restore electricity using fuel cells during peak power demand.

Hydrogen is widely recognized as an environmentally friendly energy carrier and can be used as a clean fuel for transportation without contributing to global warming. Yet, nuclear generated hydrogen can be even more benign to the environment as it has important potential advantages over other sources that will be considered for a growing hydrogen share in a future world energy economy.

Hydrogen production can be acquired via many paths. Selection of the most appropriate hydrogen production path depends on various factors including:

- Available resources such as water, natural gas and coal
- Available energy resources including cost of energy
- Plant capacity and expected availability
- Environmental impact assessment of the process.

Nuclear energy is poised to be the future alternative for a hydrogen economy. It can produce hydrogen not only in large quantities but also at high quality at a relatively low cost without any GHG emissions. All types of nuclear reactors can be used for the production of hydrogen as they can provide electricity and process heat. An important factor to be considered when selecting a reactor for hydrogen production is the power size. Large reactors are more suitable for cogeneration of electricity and hydrogen production. Whereas small sized plants are more suitable for hydrogen production only as a single purpose plant. Current light water reactors can be used for hydrogen production, especially using off-peak power or cogeneration for better economics. Small and medium power reactors based on high temperature gas cooled reactors are an attracting option for hydrogen production.

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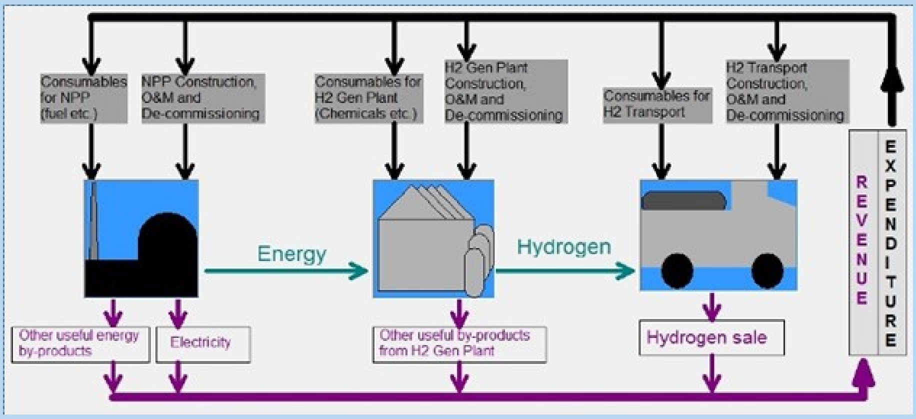
IAEA ACTIVITIES ON NUCLEAR HYDROGEN PRODUCTION

IAEA Hydrogen Economic Evaluation Program (HEEP)

[Download HEEP]

To support Member States assessing options for hydrogen production, the IAEA has released the HEEP program, which can be used for the economic assessment of most promising hydrogen production technologies. Hydrogen economy is believed to play an important role in the future of energy systems with great potential to substitute fossil fuel. This brought great interest in more understanding of the economic aspects of all conventional and innovative hydrogen production technologies. The Beta version of HEEP was first released in November 2009. Subsequently, based on the professional users feedback, the beta version of HEEP was modified and updated in November 2012 to the present version.



Main features of HEEP:

- Considers different promising hydrogen production technologies; conventional and high temperature electrolysis, thermochemical processes, hybrid cycles and steam reforming
- Includes various aspects of hydrogen economy including storage and transport.
- Allows for user-specified input data as well as reading saved cases.

[Main Page]

Documentation regarding HEEP can be found in the following links:

1. Guide for data collection
2. Preprocessor
3. Post processor
4. An overview of the IAEA HEEP software and international programmes on hydrogen production using nuclear energy, I. Khamis, Int. J. of Hydrogen Energy, 36 (2011) 4125-4129
5. HEEP: A new tool for the economic evaluation of hydrogen economy, I.Khamis, U.D. Malshe, Int. J. of Hydrogen Energy, 35 (2010) 8398-8406

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HYDROGEN PRODUCTION AND THE ENVIRONMENT

Hydrogen production using nuclear energy has potential advantages over other production paths. The benefit of this bath can be described in two main aspects: quality, as the process results in lower greenhouse gas emissions, and quantity, cause of the potential for large-scale production.

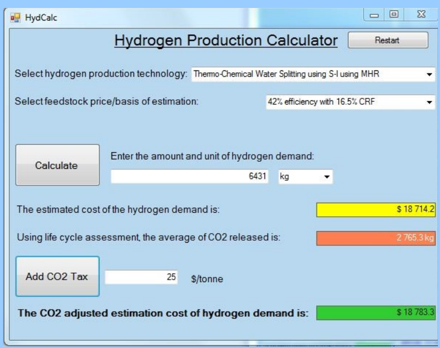
In 1874, Jules Verne wrote in his book, L'Ile Mystérieuse (or The Mysterious Island), that in the future, water would replace coal as an energy source. With the 1973 Oil Crisis, the need for a future energy carrier was even more realized than before and the "Hydrogen economy" started to arise to describe the future of a promising alternative. One important thing to remember is that hydrogen is an energy carrier, not an energy producer. So for a sustainable hydrogen economy, there is a need to produce hydrogen in a way so that the environmental impact is not a major issue.

The first commercial technology of producing hydrogen, developed back in 1920s, was electrolysis of water. During 1960s, hydrogen production started to shift towards fossil sources. Currently, almost 97% of the produced hydrogen originates from fossil sources. Hydrogen production through fossil fuels releases about 10 kg of CO_2 per kg of hydrogen in case of steam methane reformatting, and this amount is doubled when using coal gasification technology for generating hydrogen. Due to the increasing awareness of global warming, the world became more interested to shift towards hydrogen production technologies that help in greenhouse gases reduction. There are incentives to try to shift away from CO_2 emitting sources for hydrogen. This can be done by either using electrolysis, thermal splitting of water, or a carbon capture scheme for the fossil fuel reformation plant.

An important factor to be considered when deciding on nuclear hydrogen production is the size of the reactor. Larger reactors are more suitable for co-generation while smaller and modular reactors are more appropriate hydrogen generation as a single commodity. Economics of hydrogen production is another deciding factor that becomes more effective with the Carbon tax in effect. **HydCalc** is a simple program to get estimates on the price of a certain hydrogen production technology. It is a single window calculator that uses hydrogen production prices based on the data from recent peer reviewed articles and publications. A user guide can be read here.

HydCalc is developed to make estimations of hydrogen production cost utilizing different technologies. It uses price estimations from publications and articles in the literature. It provides the cost of hydrogen production and an average estimated CO_2 release. It also considers the effect of CO_2 tax on the production cost.

To use HydCalc, please download 'Hydcalc.zip' and save it on your computer. Unzip the folder and use HydCalc.exe to run the program.



Download HydCalc

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IAEA ACTIVITIES ON NUCLEAR HYDROGEN PRODUCTION

Coordinated Research Programs (CRPs)

Technical Meetings (TMs)

Consultants Meetings (CMs)

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The IAEA has organized several activities on nuclear hydrogen production, some of which are listed below:

New Coordinated Research Project on Assessing technical and economic aspects of nuclear hydrogen production for near-term deployment *(2018)*

The overall objective of this CRP is to: assess gained experience from R&D on nuclear hydrogen production in MSs; and potential near-term deployment of nuclear hydrogen production. The CRP is expected to develop a roadmap for upscaling and commercialization of nuclear hydrogen production and establish milestone recommendations to MSs on nuclear hydrogen production aiming at providing a better understanding of the feasibility of nuclear hydrogen as part of the future hydrogen economy.

Research Coordination Meetings on the CRP entitled: Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software
(*1st Report*) (*2nd Report*) (*3rd Report*) (*4th Report*)
The aim of this CRP was to improve Member States' analytical capabilities in the field of the economic evaluation of hydrogen production using nuclear energy and to perform benchmarking of the IAEA HEEP with a view to further improvement and updating of the software. This CRP was successfully concluded in 2016.

Technical Meeting on the Role of Nuclear Hydrogen Production in a Low Carbon Economy *(Report)*

Technical Meeting to Assess the Prospects of Coupling Non-Electric Applications to High Temperature Nuclear Reactors *(Report)*

Technical Meeting to Examine the Role of Nuclear Hydrogen Production in the Context of the Hydrogen Economy *(Report)*

Consultants Meeting on Reviewing the Outcome of the CRP, Updating HEEP and Integration of Magnesium Chlorine Cycle for Hydrogen Production in HEEP Library *(Report)*

Technical Meeting on Users of the Hydrogen Economic Evaluation Program (HEEP) *(Report)*

Technical Meeting on Advances in Non-Electric Applications of Nuclear Energy and on Efficiency Improvement at Nuclear Power Plants" *(Report)*

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IAEA RELATED PUBLICATIONS ON NUCLEAR HYDROGEN PRODUCTION

The IAEA has published a long list of publications related to nuclear hydrogen production including the following:

Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software
(IAEA TECDOC Series No. 1859)

Hydrogen Production using Nuclear Power
(*IAEA Nuclear Energy Series NP-T-4.2*)

Hydrogen as an Energy Carrier and its production by Nuclear Power
(*IAEA TECDOC Series No. 1085*)

Safety Related Design and Economic Aspects of HTGRs
(*IAEA TECDOC Series No. 1210*)

Design and Evaluation of Heat Utilization Systems for The High Temperature Engineering Test Reactor
(*IAEA TECDOC Series No. 1236*)

Advances in Nuclear Power Process Heat Applications
(*IAEA TECDOC Series No. 1682*)

Role of Nuclear Based Techniques in Development and Characterization of Materials for Hydrogen Storage and Fuel Cells
(*IAEA TECDOC Series No. 1676*)

Market Potential for Non-electric Applications of Nuclear Energy
(*Technical Reports Series No. 410*)

Advances in High Temperature Gas Cooled Reactor Fuel Technology
(*IAEA TECDOC Series No. 1674*)

Advanced Applications of Water Cooled Nuclear Power Plants
(*IAEA TECDOC Series No. 1584*)

International conference on "Non-electrical Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications", Orai, Japan 2007
(*Proceedings*)

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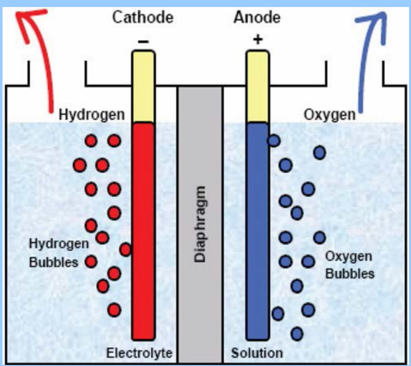
HYDROGEN PRODUCTION USING CURRENT TECHNOLOGIES

Low Temperature Electrolysis



Low temperature electrolysis, or water electrolysis, is the most currently available straightforward approach to produce hydrogen directly from water. Theoretical calculations show that minimum cell potential required for this process is 1.229 V at 0.1MPa which is equivalent to a minimum energy of 3.56 kWh/Nm^3 or 39.61 kWh/kg of hydrogen produced. However, practical values are around 1.7 ~ 2.1 V with energy of 44.5 ~ 50.1 kWh/kg of H_2. Water resource needed is about 11.1 liter/kg of H_2. Hydrogen can be produced at atmospheric or higher pressure, however the latter option causes lower efficiency. These are a few of the different types of electrolysers:

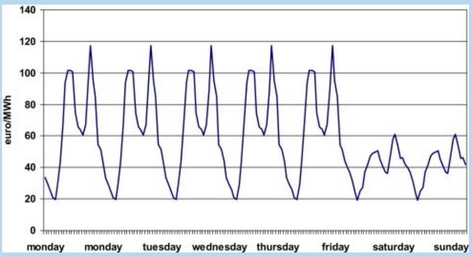
- Alkaline (<150°C but normally around 90°C)
- Inorganic Alkaline (90-120°C)
- Solid polymer (80-150°C)
- PEM (200-400°C).

For more information on Low temperature electrolysis:

1. Current 2009 State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis.
2. Summery of Electrolytic Hydrogen Production, Johanma Ivy, NREL/TP-560-36734, National Renewable Laboratory, Sept 2004.

Off-peak production of hydrogen allows for enhancement in economics of nuclear hydrogen production. The idea is to use off-peak electricity to produce electrolytic hydrogen, which can later be utilized in fuel cells or combustion engines to produce power during high demand. This is available for countries/electricity grids with high-share of nuclear energy. One of the drawbacks is the cost of electrolysers during peak hours, when they are not in use.

Off-Peak Production



Below are some links about Off-Peak Hydrogen Production:

1. C. Mansilla, J. Louyrette, S. Albou, C. Bourasseau, S. Dautremont, Economic competitiveness of off-peak hydrogen production today – A European comparison, Energy, 55, (2013).
2. G.F. Naterer, M. Fowler, J. Cotton, K. Gabriel, Synergistic roles of off-peak electrolysis and thermochemical production of hydrogen from nuclear energy in Canada, Int. J. of Hydrogen Energy, 33 (2008).
3. P-H. Floch, S. Gabriel, C. Mansilla, F. Werkoff, On the production of hydrogen via alkaline electrolysis during off-peak periods, Int. J. of Hydrogen Energy, 32, 18 (2007).

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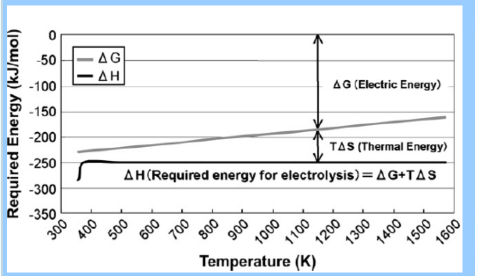
HYDROGEN PRODUCTION USING FUTURE TECHNOLOGIES

High Temperature Electrolysis



High Temperature Electrolysis (HTE) uses electrolysis of steam instead of water, hence it is referred to as High Temperature Steam Electrolysis (HTSE). The process uses thermal and electric power. This results in higher potential to be more efficient compared with low temperature electrolysis. The amount of energy required to break water molecule bindings is constant, but in HTE, part of the provided energy is in thermal form which avoids energy loss in the process converting thermal energy to electricity. The relationship between amounts of energy needed is illustrated in the figure.

There are different options for HTE, for instance:

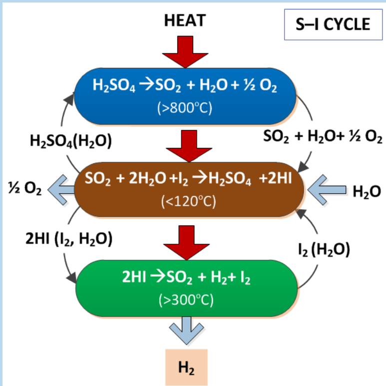
- Molten carbonate (300-600°C).
- Solid oxide fuel (800-1000°C).

For more information about HTE:

1. Hydrogen production by High Temperature Electrolysis with nuclear reactor, 2008.
2. High-Temperature Electrolysis for large-scale hydrogen and syngas production from nuclear energy, summary of system simulation and economic analyses, 2010.

Thermochemical Water Splitting

Thermochemical water splitting offers an efficient and economical way for hydrogen production. Different chemical reagents gets into different chemical reactions resulting in water splitting. The reagents are recirculated and regenerated so that the net reaction will be heat and water as input and hydrogen and oxygen as output. Extensive research started in late 1960s and over 100 publications regarding thermochemical cycles were published by early 1970s. Different cycles was purposed during this period, but lately the research is focused on a few cycles.



Among the most promising cycles are the sulfur family cycles, this is due to the high efficiency potential and low level of complexity in terms of reactions and separations. Sulfur-Iodine (*S-I*) cycle is one of the most studied cycles which utilize heat as input.

For further information:

1. Marc A. Rosen, Advances in hydrogen production by thermochemical water decomposition: A review, Energy, 35, 2, (2010).
2. S. Abanades, et al., Screening of water-splitting thermochemical cycles potentially attractive for hydrogen production by concentrated solar energy, Energy, 31 (2006).
3. Shinji Kubo, et al., A demonstration study on a closed-cycle hydrogen production by the thermochemical water-splitting iodine–sulfur process, Nuclear Engineering and Design, 233(2004).

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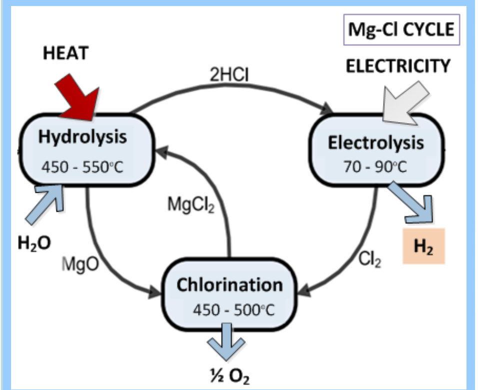
OPTIONS FOR HYDROGEN PRODUCTION USING FUTURE TECHNOLOGIES

Hybrid Thermo-chemical Cycles



Another cycle that is extensively studied is the Copper-Chlorine (***Cu-Cl***) cycle which is a **Hybrid Thermochemical Cycle**. These cycles are governed by thermal-driven reactions, at around 500°C, and electrical-driven processes. For Cu-Cl cycle, there are 3, 4 or 5-step cycles. Hybrid Sulfur (***HyS***) and Magnesium-Chlorine (***Mg-Cl***) cycles are examples of other promising hybrid thermochemical cycles. Generally talking, the benefits of thermochemical cycles is the use of heat, which is a lower grade energy form compared with electricity, and most of nowadays nuclear power plants operate at about 35% thermal efficiency. The challenging part with thermochemical cycles is the high temperature required. Steam in currently available nuclear reactors is about 300°C, which is not high enough for thermochemical cycles. However, high and very high temperature reactors are good candidates for thermochemical and hybrid cycles for nuclear hydrogen production.

Hydrogen Production from Fossil Resources

Currently, hydrogen production schemes are based on either splitting the water molecule or fossil fuel sources. The most common method for hydrogen production is **steam reforming of natural gas**. In this process steam at temperature of 500 ~ 900°C is reacting with natural gas in the presence of a nickel catalyst. The chemical reaction can be described as:

$$\mathbf{CH_4 + H_2O + heat \longrightarrow CO + 3H_2}.$$

This process could be supported by either HTR or even conventional reactor using additional heaters. However, as of today, this high heat process is fueled by huge amounts of fossil fuel.

In practice, the above reaction is usually accompanied by a lower temperature gas shift reaction which can be described as:

$$\mathbf{CO + H_2O \longrightarrow CO_2 + H_2 + heat}$$

where the heat released is much lower then heat fed in the first step.

Coal gasification is another fossil fuel based technology which represents about 18% of the worldwide hydrogen production, which comes in as a component of the produced syngas. Syngas passes through gas shift reaction, as described above, for pure hydrogen production.

For more regarding nuclear-assisted fossil-based hydrogen production:

1. HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Process Analysis.
2. HTGR-Integrated Hydrogen Production via Steam Methane Reforming -SMR- Economic Analysis.
3. Coal Gasification for Hydrogen Production Using Nuclear Energy.

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