IAEA
International Atomic Energy Agency

Interoffice Memorandum

To:	D. Hahn, DIR-NENP	**From:**	I. Khamis, NPTDS/ 22822
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Reference:	EVT1803517	**Date:**	2019-04-29

Subject: Technical Meeting on the Role of Nuclear Hydrogen Production in a Low Carbon Economy

Place of Meeting:	IAEA Headquarters, Vienna
Date of Meeting:	8-10 April 2019
PTAEO Code:	1000155.2018.06.RBF-MP1-2019.613222.NENP-NPTDS
Scientific Secretary:	Mr Ibrahim KHAMIS
Chairperson:	Mr Sam SUPPIAH

ATTENDING EXPERTS

Name	Country/Organization
Mr C. A. Canavesio	Argentina/INVAP
Mr S. Suppiah	Canada/Canadian Nuclear Laboratories
Mr N. Haneklaus	Germany/RWTH Aachen University
Mr Z. Kerner	Hungary/MTA Centre for Energy Research
Mr E. Börcsök	Hungary/Hungarian Academy of Sciences
Mr S. Bakhri	Indonesia/BATAN

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Name	**Country/Organization**
Mr T. Sainati	Italy/University of Leeds
Mr M. A. Alhengari	Libya/Libyan Atomic Energy Establishment
Mr G. Mustafa	Pakistan/PAEC
Mr I. Iordache	Romania/National Research and Development Institute for Cryogenics and Isotopic Technologies
Ms M. Deaconu	Romania/RATEN ICN
Ms E. Pashina	Russia/Rusatom Overseas
Mr A. Balanin	Russia/NRC "Kurchatov Institute"
Mr N. G. Kodochigov	Russia/JSC "Afrikantov OKBM"
Mr D. Mathers	UK/Department for Business, Energy & Industrial Strategy
Mr J. M. Bermudez Menendez	UK/Department for Business, Energy & Industrial Strategy
Mr F. Aydogan	USA/Jacksonville University
Mr F. P. Dolci	European Commission–Joint Research Centre

1. Background

Currently, hydrogen is predominantly produced using steam methane reforming, a fossil-based technology. To make the system carbon neutral, amongst other things, this process requires the integration of carbon capture and storage plants into the overall system. Studies show that hydrogen can be produced using electricity and high temperature heat through water splitting based on either electrolysis or thermochemical cycle technologies. Both technologies are considered the most promising routes towards large-scale clean hydrogen production for near-term deployment.

Nuclear hydrogen production is viewed as an important clean method for producing hydrogen, serving to mitigate climate change in the short and long term in the power, heat and transportation sectors. The potential of nuclear hydrogen production is continuously growing with continuing progress in research, development, and deployment of pertinent high temperature nuclear reactors and process technologies in several countries, which have a renewed interest in hydrogen economy as part of national sustainable energy strategies. One of the potential paths towards 'greening' district heating and domestic hot water needs is the use of hydrogen as feed for gas grids supplying domestic boilers. In addition, the increased production of hydrogen fuel cell vehicles worldwide is expected to increase interest in nuclear hydrogen production. This will bring a sustainable and ready-to-implement solution to help decarbonize the transportation sector, mainly for light-duty vehicles in the short term, and for long-distance road transport, shipping, and aviation in the long term.

The storage of hydrogen, produced using nuclear energy, is expected to play a key role in balancing supply and demand in future nuclear-renewable hybrid energy systems integrated into smart grids and in load following operations. In the short term, the direct use of nuclear power for hydrogen production through local or decentralized electrolysis can be easily implemented. In the long term, storing hydrogen produced during off-peak times is going to be vital in addressing the seasonal fluctuations in demand, and in stabilizing the energy supply/demand issues when more renewable energy systems are integrated into national and international grids. This requires innovative development in large-scale hydrogen storage methods and technologies. Furthermore, the use of combined heat and power systems that employ hydrogen fuel cells in micro and large-scale applications is another attractive path towards decarbonizing the power and heat sectors. Such systems still require further practical considerations before being ready for commercial use. These disruptive alternative technologies still have a number of challenges to overcome.

The IAEA is organizing this technical meeting as a forum to exchange information on the potential of nuclear hydrogen production to decarbonize the energy, heat and transportation sectors, and to discuss the challenges facing the implementation of such projects. Furthermore, introduction and training on the IAEA’s Hydrogen Economic Evaluation Program (HEEP) tool will be provided.

2. Objectives of the meeting

The purpose of the event is to evaluate the options for nuclear hydrogen production and its role in a future hydrogen economy, taking into account the various climate change scenarios; to examine the cost of nuclear hydrogen production depending on the technologies that are used; and to provide training on the IAEA’s Hydrogen Economic Evaluation Program (HEEP) and collect feedback on the tool for further development

3. Agenda (see Annex 1.)

4. Summary of the work done and results achieved

The participants to the meeting were introduced to activities of the IAEA on nuclear hydrogen production, and the scope of the IAEA project on non-electric applications and the use of nuclear energy for hydrogen generation towards a low-carbon economy. In addition, they also contributed effectively and interacted positively in the fruitful discussions for exchange of experience and information. Below is the summary of the delivered presentations, work done, and discussions during the meeting:

Mr KHAMIS (*IAEA Scientific Secretary*) delivered an introductory presentation on the objectives and expected outcomes of the meeting. In addition, he presented on the ongoing and future activities of the IAEA on non-electric applications and nuclear cogeneration with focus on the ones on nuclear hydrogen production including the successfully concluded and recently started coordinated research projects on the topic. In addition, Mr. Khamis highlighted the recently released IAEA publications produced on nuclear cogeneration and industrial applications of nuclear energy. He also delivered a demonstration on the IAEA HEEP for technoeconomic assessment of nuclear hydrogen production technologies and encouraged the participants to use the and provide feedback to the IAEA for further improvement.

In the following, the input of participating Member States is presented:

Argentina (Mr CANAVESIO) presented a study about nuclear hydrogen production through a novel cobalt-chlorine water splitting thermochemical cycle. The cobalt-chlorine cycle proposed comprises a closed loop of four thermochemical reactions occurring at 700ºC that is a reaction temperature compatible with the present generation of high-temperature nuclear reactors. Thermodynamic calculations and experimental results were presented, and these show the possibility to decompose the water at much lower temperatures than the direct thermolysis of water. Even though theoretical performance assessment and proof-of-principle experimental results obtained for the Co-Cl cycle, more research work will be required in the future to confirm these preliminary findings.

Canada (Mr SUPPIAH) presented on the Canadian advances in nuclear hydrogen production using Copper-Chlorine hybrid thermochemical cycle. He said that Canada is actively involved in the development of the hybrid thermochemical process Copper-Chlorine Cycle, with a plan to have an integrated lab-scale system capable of producing 100 g hydrogen/d (50 L/h) for demonstration by 2021. He stated that significant milestones have been achieved recently in the development of the individual steps involved in the process, and work is in progress to integrate them. The plan also includes establishing collaborations with large-scale hydrogen producers and engineering companies to scale up the production to a 1 ton/d prototype plant. Canada's focus is to decarbonize the transport sector and provide clean energy to remote off-grid communities in Canada over the next decade.

Germany (Mr HANEKLAUS) presented on the nuclear hydrogen production for future energy needs. He mentioned that future power generation will largely consist of intermittent renewables, mainly wind and solar. Nuclear power production will remain constant. Since renewables, in particular wind, will largely be used to generate electricity a chance for high temperature reactors, gas-cooled or other, arise. "Waste heat" or excess power from these reactors can be used to produce hydrogen, increasing the overall efficiency of the employed nuclear power plant.

Hungary (Mr BÖRCSÖK and Mr KERNER) presented on a case study on sustainable nuclear-renewable hybrid energy system for Hungary. They said that the large increase in renewable-based energy generation and the newly installed nuclear units are promising steps towards a low-carbon economy in Hungary in the next decade. Nevertheless, the balancing of daily and seasonal demand profiles and the electricity supply from intermittent sources could pose a substantial challenge to the power system. On the supply side, the downward flexibility can be enhanced by load reduction or by exporting the excess energy at discounted prices. However, the hydrogen production by base-load power plants in the off-peak periods of excess electricity supply could be more promising economically. For making responsible decisions on the national energy strategy, it is essential to study the potential framework for a sustainable hydrogen economy.

Indonesia (Mr BAKHRI) presented on the status of high temperature gas cooled research and development in Indonesia. He stated that a nuclear power plant is a must in Indonesia to deal with shortage of energy especial. Majority people believe and support the nuclear program (around 77.53% in 2016), however the NIMBY, NIMEY and BANANA phenomena are the challenges to be overcome. In case of Climate change, people in Indonesia also believe that clean resources such as hydrogen is one of the solutions. For example, he added, the government expects that in 2025 electric and fuel cell cars will be implemented. Therefore, the nuclear electricity generation with heat application can be a real solution for Indonesia. However, the government is still reluctant to really implement this in near term while the price of the electricity itself is still higher than 7 cent $/kWh. It means that that uncertainty of the price is major concern. If the hydrogen production combines maybe with desalination can offer better and affordable combine price with electricity,

Italy (Mr SAINATI) presented a comparison between the cogeneration of hydrogen production using high temperature reactor and from other sources of energy. Nowadays, he stated, hydrogen is mainly produced by fossil fuels using Steam Methane Reforming, and coal gasification. The Chemical Industry is the main consumer of hydrogen and large installations, like petrochemical refineries, can produce hydrogen endogenously for their specific needs. The presentation introduced providing cost estimations for the coupling of High-Temperature Reactors (HTR) with Pure & Hybrid Thermochemical Hydrogen Production

Processes (P&HTHPPs). Producing hydrogen with HTR is expected to cost between 2.36 and 5.65 $/kg. The cost range seems comparable with the production of hydrogen from the renewables. However, the presentation emphasised that the existing studies fail to recognise two essential aspects: technology readiness levels of technology and the project risk associated with nuclear. Both HTR and P&HTHPPs are less mature than other technologies for hydrogen production; they require significant R&D investments.

Libya (Mr ALHENGARI) presented on the feasibility and needs of nuclear hydrogen production in Libya and contribution in low carbon emission .He stated that Libya's national income depends mainly on oil and natural gas (Libya's natural gas reserves is 1.456 trillion cubic meters, approximately 604 billion metric tons), and that in the case of reduced global demand for these sources, the country should be looking for other areas to invest these sources, one of these fields is hydrogen production. He added that Libya should start away investing in hydrogen production technologies to keep up with the energy market

Pakistan (Mr MUSTAFA) presented on the potential role of nuclear hydrogen production in greenhouse gas mitigation in Pakistan. He introduced Pakistan as a big producer/consumer of hydrogen and its demand is projected to grow significantly in coming decades. He showed that the hydrogen need in Pakistan are for fertilizers, oil refineries, ammonia, hydrogenation for oils and for other industries. He stated that Pakistan has good experience of use of nuclear energy for production of electricity and sea water desalination, and that there is good public acceptance of nuclear power. The country, he added, has big plans to expand nuclear power, however, use of nuclear energy is subject to its techno-economic feasibility

Romania (Ms DEACONU and Mr IORDACHE) presented scientific activities realised in their Romanian research and development institutes. They pointed out the investigations referring to hydrogen storage in hydride and underground large-scale hydrogen storage in salt caverns. The participants have been informed about the existence of the Nuclear Hydrogen Division (NHD) as part of the International Association for Hydrogen Energy (IAHE) since 2010. Romania, through National Center for Hydrogen and Fuel Cell is fonder member of IAHE Nuclear Hydrogen Division and have collaborations with partners from Canada on nuclear hydrogen production with the thermochemical Cu-Cl cycle.

Russian Federation (Mr BALANIN) delivered a presentation on hydrogen production with alkaline electrolysis for energy system optimization, showing that electrolysis could assist to fulfil the function of load following by means of compensating a missing load for nuclear power plants. He added that the application of hydrogen production for optimization of nuclear power plant operation in energy system is environmentally friendly and could assist development of hydrogen transport due to production of pure hydrogen as a clean fuel for future transport. He also presented that a reduction in polluting emissions occurs in comparison with fossil power plants and in case of using of produced hydrogen as fuel for transportation. He added that capacity factor of hydrogen production could be higher if the facilities operate with constant component of power, which is reflected on unit cost of hydrogen. Geological storing in salt caverns was proposed for large-scale hydrogen storage which proposes safety, low losses, fast issue and attractive economics.

Russian Federation (Mr KODOCHIGOV) delivered a presentation on HTGR for clean hydrogen production using the method of adiabatic methane conversion which is tested in Russia for methane-hydrogen mixture production. He illustrated that the system source of heat is HTGR with a thermal capacity of about 200 MW with reactor core of prismatic fuel assemblies, and helium at the outlet of the reactor is at 750-800°C. He added that nuclear power plant with thermal power 4x200MW can produce approximately 280 thousand ton of hydrogen per year without CO_2 emissions, and recycled CO_2 is considered as a raw material for industry application. He also stated in his presentation that Russia has great reserves of natural gas and high TRL of HTGR technology, as well as knowledge and experience in the field of hydrocarbon conversion.

Russian Federation (Ms PASHINA) delivered a presentation on Rosatom view on clean hydrogen market and technological perspectives. She stated that Rosatom considers hydrogen energy as one of the key priorities for its technological development; and it has a large potential to become a leader in GHG-free hydrogen production. Ms Pashina added that hydrogen production through electrolysis with the excess power from Russian Leningrad and Kola nuclear power plants is considered as first stage (near-term), and the second stage (mid-, long-term) implies using HTGR and with adiabatic steam methane reforming to produce and supply hydrogen for global commercial hydrogen market. She also said that the key role of the hydrogen supply chain belongs to hydrogen production; however it is important to have the whole hydrogen supply chain developed, hydrogen production being the key part, but other parts have to be considered, including storage, transportation and the demand side. She concluded with stating that Rosatom acknowledges the importance of global hydrogen supply chain and value chain development.

United Kingdom (Mr MATHERS and Mr BERMUDEZ MENENDEZ) For the Hydrogen market to be fully realised, the full supply chain, concluding supply, storage, transport and end use applications all need to be developed. Working with the IAEA can help to develop a perspective on these aspects in support of decision making on commercial or government backed R&D and policy developments. The IAEA can help to focus needs primarily on the technologies that enable nuclear power to produce hydrogen (e.g. electrolysis or thermal cycles and coupling these with nuclear plants) and then secondly on aspects of the nuclear reactor and fuel cycle technology itself. This focus needs to consider technical maturity, key challenges to commercialise, costs for R&D, capital plant costs and operational costs and uncertainties around cost estimates.

United States of America (Mr AYDOGAN) presented various technologies for nuclear hydrogen generation. In this presentation, different nuclear power plants that can be the options of nuclear hydrogen production are defined. For the selection of a nuclear power plant for hydrogen generation, selection criteria have been defined to prioritise and to eliminate the nuclear power plants. Since Light Water Reactors are the most commonly used reactors in the world, the reactor configuration updates of LWRs was defined and discussed to increase the reactor core coolant temperature to 550^{o}C level. Thermo-cycles for nuclear hydrogen generation were compared to highlight cycle efficiencies to decrease the overall cost of Hydrogen production. To help of calculation of economic evaluation of nuclear hydrogen production, a cost estimate of a power plant has been demonstrated as an example. Lastly, nuclear hydrogen generation system's integration to overall energy systems of a country discussed. Since there is an oscillation on power load, how nuclear power level can be defined to decrease the cost of nuclear hydrogen generation by using off-peak power has been discussed.

EC/JRC (Mr DOLCI) presented a summary of the publicly available report 'Green hydrogen opportunities in selected industrial processes'. This document summarises the contributions to the workshop with the same title organised in June 2018 in Brussels (B). The main aim of this workshop was to objectively assess the technical limitations and the potential benefits for the direct use of "green hydrogen" as feedstock in three specific energy-intensive industrial processes: Ammonia production, Steelmaking, and Oil Refining. A brief overview of the legislation which is expected to be fostering the use of green hydrogen as chemical feedstock, its role in a possible future decarbonisation scenario, and the dimensions of the challenge based on the current European industrial status were given. The technical feasibility of substituting fossil-derived hydrogen feedstock with a sustainable alternative in the three considered chemical processes is achievable, but the large CAPEX, legislative shortcomings, viable supply of the required power, and currently unfavourable business models are still obstacles.

5. Conclusions

The participants are recognizing the value of the IAEA convening a meeting under the theme of this topic. In addition, the participants confirm that the non-electric application of nuclear energy for hydrogen production can lead to low-carbon economy.

1. There is an opportunity for hydrogen to decarbonise significant sectors of the global economy. The deployment of hydrogen to mitigate global warming requires not only the ability to produce hydrogen economically and sustainably in large scale, but also to demonstrate methods for storage and distribution (centralized or otherwise), legal and regulatory framework for safety, and political and public acceptance.
2. Based on several country presentations, an increased role for hydrogen in decarbonising the economy is predicted, specifically in the areas of industrial feedstocks, thermal and electric power production, energy storage and transportation. Canada, USA, Russia, Hungary, Indonesia, Argentina, Germany, Romania, Pakistan and Libya, Italy and UK all recognise aspects of this opportunity and are actively progressing R&D. Some countries are already demonstrating some aspects of the above.
3. Participants to the meeting agree that the uncertainties related to nuclear hydrogen technologies and economics can be a barrier to their development. However, there is a potential for nuclear power plants to produce hydrogen using the heat that they produce. Such processes require a higher temperature output than that of today's commercial plants (<350^{o}C). Some of the advanced high-temperature reactors being developed can support the high-temperature requirements of these processes. Some countries are designing these technologies for hydrogen production. High confidence level of the participants from reactor vendor countries reflects that R&D on nuclear hydrogen production technologies is progressing to the point of entering demonstration phase in some countries.
4. High temperature reactors are the leading technology being developed for future nuclear hydrogen production.
5. For the hydrogen market to be fully realised, the full supply/value chain, including supply, storage, transport, distribution and end use applications all need to be developed.
6. Nuclear-renewable hybrid energy systems can enhance the decarbonization initiatives through hydrogen production.

6. Recommendations

The participants to the meeting recommend the IAEA to:

1. Develop a perspective of the role of nuclear hydrogen production as part of the whole hydrogen supply chain/lifecycle developed, including demand, production, storage and distribution in support of decision making on commercial or government backed R&D and policy developments. There are already several ongoing initiatives (e.g. FCH2JU EU, IEA, Fuel Cell & Hydrogen program by DoE, …etc) that the IAEA could be engaged with and publish a topical report on the subject.
2. Increase focus on the technologies that enable nuclear power to produce hydrogen (e.g. electrolysis or thermochemical processes/cycles and coupling of these with nuclear plants). This focus needs to consider technical maturity, key challenges to commercialisation, costs for R&D, capital plant costs and operational costs and uncertainties around cost estimates. Participants to the meeting recommends that a sensitivity analysis model to be developed and incorporated in HEEP for technoeconomic assessment.
3. Maintain a perspective (e.g. roadmap) on the opportunities and relative benefits for nuclear hydrogen production advanced systems (compared to near to market HTGRs with 550^{o}C output), an understanding of technology challenges (e.g. qualification of heat exchangers), timescales for commercialisation and aspects that affect cost uncertainties 'that are nuclear specific' e.g. regulations, long timescales for development (siting process, regulation, licencing, factory build, construction programme.

4. Support the submission of a paper based on the outcome of this meeting to the IAEA conference on Climate Change and the Role of Nuclear Power.

Annex 1.

IAEA

Technical Meeting on the Role of Nuclear Hydrogen Production in a Low Carbon Economy

Vienna, Austria
08 – 10 April 2019

Meeting Agenda

	Monday, 08 April 2019	
09:30	Welcoming and opening remarks	Mr. I. Khamis IAEA
09:40	Introduction of participants, selection of chairperson and adoption of the Agenda	All participants
10:00	Overview and objectives of the meeting IAEA Conference on Climate Change & the Role of Nuclear Power IAEA Activities on Nuclear Hydrogen Production	Mr. I. Khamis IAEA
10:30	*Coffee Break*	
11:00	Hydrogen production: comparison between HTR cogeneration and alternative sources	Mr. T. Sainati Italy
11:30	Canadian Advances in Nuclear Hydrogen Production Demonstration by Copper Chlorine Hybrid Thermochemical Cycle	Mr. S. Suppiah Canada
12:00	Nuclear Hydrogen Production for Future Energy Needs	Mr. N. Haneklaus Germany
12:30	*Lunch Break*	
14:00	Sustainable Nuclear-Renewable Hybrid Systems: A Case Study for Hungary	Mr. E. Börcsök Hungary
14:30	The Current Status of High Temperature Gas Cooled Research and Development in Indonesia	Mr. S. Bakhri Indonesia
15:00	Nuclear Hydrogen Production Through a Novel Cobalt-Chlorine Water-Splitting Thermochemical Cycle	Mr. C. A. Canavesio Argentina
15:30	*Coffee Break*	
16:00	Green Hydrogen Opportunities in Selected Industrial Processes	Mr. F. Dolci JRC/EC
16:30	**Brainstorming Session I:** Added Value of Hydrogen Production using Nuclear Energy towards Climate Change Mitigation	All participants
17:30	**End of Day 1**	

Tuesday, 09 April 2019		
09:00	IAEA HEEP	Mr. I. Khamis
09:30	The Technologies to Decrease the Cost and Increase the Efficiency of Nuclear Hydrogen Production	Mr. F. Aydogan USA
10:00	The Evaluation of Hydrogen Storage Systems in the Context of a "Hydrogen Economy"	Ms. M. Deaconu Romania
10:30	*Coffee Break*	
11:00	Rosatom View on Clean Hydrogen Market and Technological Perspectives	Ms. E. Pashina Russian Fed.
11:30	Nuclear Hydrogen Perspectives in Romania	Mr. I. Iordache Romania
12:00	HTGR for Clean Hydrogen Production	Mr. N. G. Kodochigo Russian Fed.
12:30	*Lunch Break*	
14:00	Potential Role of Nuclear Hydrogen Production in GHG Mitigation in Pakistan	Mr. G. Mustafa Pakistan
14:30	Feasibility and Needs of Nuclear Hydrogen Production in Libya and Contribution in Low Carbon Emission	Mr. M. A. Alhengari Libya
15:00	Hydrogen Production with Alkaline Electrolysis for Energy System Optimization	Mr. A. Balanin Russian Fed.
15:30	*Coffee Break*	
16:00	**Brainstorming Session II**: Assessment of the cost & technologies for Near-Term Deployment of Nuclear Hydrogen Production	All Participants
17:00	**End of Day 2**	

Wednesday, 10 April 2019		
09:00	Drafting the meeting report: • Conclusions and Recommendations • Collecting Feedback and Summary of the Meeting	All participants
10:30	*Coffee Break*	
11:00	Finalizing meeting report	All participants
13:00	**Closing Remarks**	