Technology Collaboration Programme
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IEAGHG Technical Review
2020-TR01
January 2020

Hydrogen Production with CCS Workshop – 6 November 2019

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

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This report describes the outputs of the "Hydrogen Production with CCS" Workshop held on November 6th 2019, and hosted by EDF and Club CO2. The Carbon Sequestration Leadership Forum (CSLF) decided to map activities on hydrogen production with CCS in member states and elsewhere. One conclusion of that exercise was to hold a workshop with other organisations. A steering committee was formed to organise this workshop, including representatives from CSLF (Lars Ingolf Eide), IEA-GHG TCP (Monica Garcia Ortega), IEA- Hydrogen TCP (Mary-Rose de Valladares), and Equinor (Christoph Schäfer).

This report was prepared by Monica Garcia Ortega, with contributions from Lars Ingolf Eide, Christoph Schäfer and Mary-Rose de Valladares.

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The report should be cited in literature as follows:

'IEAGHG, "Hydrogen Production with CCS" Workshop outputs, 2020-TR01, January 2020.'

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WORKSHOP HYDROGEN PRODUCTION WITH CCS- 6TH NOVEMBER 2019

BACKGROUND

Hydrogen is a key raw material to other energy intensive industries. Globally, nearly 90% of the hydrogen produced industrially is consumed by the ammonia, methanol and oil refining industries. Moreover, hydrogen could soon play a significant role in the decarbonisation of power, space heating (i.e. industrial, commercial, building and residential heating) and transport fuel (i.e. use of fuel cell vehicles).

Although the steam methane reformer route (SMR) is the leading technology for H_2 production from natural gas or light hydrocarbons, there are other mature and emerging alternatives. Similarly, while increasing the process efficiency has shown a CO_2 emissions reduction of nearly 10%, CCS has been identified as a key strategy to cut down CO_2 emissions from hydrogen production.

Against this background the Carbon Sequestration Leadership Forum (CSLF) decided to map activities on hydrogen production with CCS in member states and elsewhere. One conclusion of that exercise was to hold workshop with other organisations.

A steering committee was formed to organise this workshop, held on November 6th 2019, and hosted by EDF and Club CO_2. Steering group members included representatives from CSLF (Lars Ingolf Eide), IEA-GHG TCP (Monica Garcia Ortega), IEA- Hydrogen TCP (Mary-Rose de Valladares), and Equinor (Christoph Schäfer). Prior to the workshop, the following objectives were delineated:

1. Define the Research, Development & Demonstration (RD&D) needs for decarbonised hydrogen
2. Identify the role that decarbonised hydrogen can play in a future low-carbon society
3. Provide recommendations on decarbonised hydrogen to policy-makers
4. Lay a foundation for further co-operation

This workshop was held for one day, devoted to a plenary session addressing three general topics, and including 90 attendees from 19 countries. Each session included several invited presentations, followed by a discussion among the workshop attendees.

This document presents brief summaries of the three plenary sessions topics and one break-out session where all attendees were able to contribute.

<u>Immediate actions:</u> Cooperation between countries, different industries, and between industry and academia; Regulatory framework as a driver of the research, development, and innovation, which will catalyse the blue hydrogen deployment

<u>Medium-term actions</u>: Application and deployment of hydrogen to niche opportunities for industry

<u>Long-term actions:</u> Implementation of a complex infrastructure for hydrogen and CCS. Experience on long testing campaigns (e.g. safety, materials) and large-scale deployment

Agenda Workshop on Hydrogen Production with CCS

Organised by CSLF, IEAGHG, IEA Hydrogen TCP, and Equinor
Hosts: EDF and Club CO_2

Date and time:
November 6, 2019, 08:00 – 17:30

Place:
CAMPUS EDF CHATOU
Bâtiment B / “B” Building
6 Quai Watier
78400 CHATOU
FRANCE
Meeting room “Renoir & Caillebotte” room, on the 1st floor.

Programme

08:00 Registration

09:00 Welcome, background of workshop, and safety moment

09:10 *Session 1: Role of hydrogen in a low-carbon economy – long-term perspective. Chair Lars Ingolf Eide, Research Council of Norway*

- 09:10 Global Perspectives on hydrogen and IEA hydrogen activities. **Paul Lucchese, IEA Hydrogen TCP**
- 09:30 A national view. **Marten Hamelink, Ministry of Economic Affairs and Climate, the Netherlands**.
- 09:50 Safety aspects. **Y. John Khalil**, **IEA Hydrogen TCP Task 37**
- 10:10 The CCS chain – example of Northern Lights Project. **Per Sandberg, Equinor**

10.30 Break

10:50 *Session 1* - Views from industry

- 10:50 Maritime. **Dr. Jacques Saint-Just, H2 Plus Ltd**
- 11:05 Refining. **Damien Valdenaire, Concawe**

11:15 Questions and discussions

11:45 *Session 2: Case studies Chair Mary-Rose de Valladares, IEA Hydrogen TCP*

11:45 H21. **Anna Korolko, Equinor**

12:05 Hydrogen Energy Supply Chain (HESC). **Hiroshi Ohata, J-POWER, Japan**

12:25 Overview of Carbon Capture, Utilization and Storage (CCUS) and opportunities for Hydrogen in USA. **Mark Ackiewicz, US DOE** (Presented by **Richard Lynch, DOE)**

12:40 Key learnings from recent UK activities. **Emrah Durusut**. **Elementenergy**

12:55 Questions and discussions

13:15 Lunch

14:15 *Session 3: Technology status hydrogen production from fossil fuels w/CCS. Chair Christoph Schäfer, Equinor*

14:15 Overview of hydrogen production methods. **Mary-Rose de Valladares, IEA Hydrogen TCP**

14:30 Status of hydrogen production with CO_2 capture. **Sigmund Størset, SINTEF**.

14:55 Views from hydrogen producers and technology vendors (10 min each):

- **Fabrice Del Corso, Air Liquide**
- **Vince White**, **Air Products**
- **Markus Lesemann, GTI**

15:35 Breakout in groups

Questions to answer:

a. Where to go from here - opportunities for and approaches to cooperation (e.g. common task force)?
b. RD&D needs for hydrogen production from fossil fuels w/CCS, with a view to bring down cost and carbon footprint?
   i. Gaps
   ii. Bottlenecks
   iii. Analysis
c. Creating a market for hydrogen w/CCS – incentives, policy and regulatory aspects?

16:45 Report out – breakout groups

17:15 Conclusions, wrap-up, the path forward

SESSION 1: ROLE OF HYDROGEN IN A LOW CARBON ECONOMY- LONG TERM PERSPECTIVE

Key points

- Hydrogen is essential for the decarbonisation of the industrial sector (production and consumption), and may play a significant role for the power sector (pure and blended with natural gas) as well as in transport, buildings, portables and appliances. The use of hydrogen for energy storage is expected to play an important role in the future integrated energy system
- The market and business models should be seen as main objectives in the following years
- Compared to green hydrogen (hydrogen produced from renewable sources), blue hydrogen (hydrogen from fossil fuels with CCS) has the additional challenge of public acceptance of CCS
- Collaboration is key for the implementation of new infrastructure and clusters. Those topics must be studied from a technical and policies perspective
- Harmonisation of safety standards could be key for the further H_2 deployment

Paul Lucchese, IEA Hydrogen TCP Chair, focused on the long-term perspectives for hydrogen in the energy transition and Paris agreement objectives. He explained the individual and cooperative EA and IEA-hydrogen TCP approaches to these issues. There has been an unprecedented international focus and momentum on hydrogen over the last few years. Identified drivers are renewables, maturity of hydrogen technologies, flexibility of its application to several sectors, and decarbonising goals. The energy transition needs a big-picture approach that combines the economic growth, climate goals, universal energy access, and energy security. Paul Lucchese mentioned relevant areas where hydrogen can be applied, such as in the industrial, power and transport sectors, and in combination with renewables, low carbon technologies, bioenergy, nuclear energy, all and/or together with CCS/CCUS (CO_2 capture and storage/CO_2 capture, utilization and storage). He also mentioned the IEA report delivered in June [1], where key recommendations on hydrogen and the opportunities for the next 10 years were included. Infrastructure was identified as one of the main parameters to take into account, including not only the grid but also industrial ports and international shipping routes. Additionally, industrial clusters provide the opportunity for synergies between different facilities to provide and use hydrogen. Although there is a significant momentum, there are still challenges to overcome. Hydrogen production is currently based mainly on fossil fuels[1]. The replacement of that process by electrolysis would mean a significant increase on the cost of hydrogen and will need a significant electricity input, which also needs to be decarbonised. Paul mentioned the application of pure hydrogen to several industrial sectors, and the different roles between regions (hydrogen production, application, costs).

Marten Hamelink, from the Ministry of Economic Affairs and Climate in The Netherlands, presented the mission national climate agreement industry, setting up the 59% CO_2 reduction by 2030 and aiming to ensure the competitiveness of this sector. In this region, CO_2 emissions are heavily concentrated in clusters: 12 companies are responsible of the 75% of the CO_2 emissions from the industrial sector. Netherlands is focused on subsidies to accelerate the advancement, CO_2 levy and the implementation of a regional/cluster approach, but also linked to European policies. Marten Hamelink described the

[1] Electrolysis currently accounts for 2% of global hydrogen production. 76% of the hydrogen is produced from natural gas, and almost the rest from coal (Source: https://www.iea.org/topics/hydrogen/production/). To note that those estimates might vary per source and/or region.

policy subsidies and technologies needed to reach the decarbonisation goals. In regard to the hydrogen production, the Ministry of Economic Affairs and Climate in The Netherlands have commissioned several reports linked to the hydrogen roadmap and identifying next steps and actions for several sectors (mobility and transport, industry, agriculture and land use, and electricity). The estimated reduction in 2030 by CCS is 7 Mton, within a total of 20Mton reduction by the combination of all the measures. He mentioned the discussions in The Netherlands on blue and green hydrogen, produced from fossil fuels with CO_2 capture or from renewables, respectively. Due to the issues on public acceptance of CCS, the integration of blue hydrogen becomes more difficult. Moreover, the infrastructure was identified as a key factor, while other key elements are identified in the EU Hydrogen strategy, such as targets on industry, transport, gas grid, common standards, R&D needs, and a strong EU presence.

Y. John Khalil, who represented the IEA Hydrogen TCP Task 37, discussed the different aspects linked to the safety on the production and use of hydrogen. Y. John Khalil described the hydrogen production routes and key applications, including the intermediate hydrogen storage step. He described further information on the P2G concept (power-to-gas), which enables storage of renewable electricity surplus in the form of hydrogen injected into natural gas pipelines. This blending strategy offers benefits on decarbonisation and integration, depending on the level of hydrogen content and infrastructure (internal gas pressure and pipeline material). However, risks and safety must be monitored. With regard to safety issues, some characteristics of hydrogen must be considered, such as its lower density, higher flammability and lower minimum ignition energy, compared with natural gas. Specific risk quantification strategies are recommended to assess the hazards on particular cases of hydrogen production, transport, and utilization. Moreover, he suggested the harmonization of hydrogen safety standards, and the use of credit trading mechanisms for blended hydrogen with natural gas.

Per Sandberg, from Equinor, described the Northern Lights project. He mentioned the complexity of such an initiative because it not only involves CO_2 capture and storage, but also shipping. A notable feature of this project is that while the storage site is in Norway, the real value is applied to Europe. The first project phase includes 1.5 MTPA (million tonnes per annum) capacity, to reach 5 MTPA capacity in the second phase, and with the start-up expected in 2023. Up until then, the project is developing the technical and commercial studies, with parallel activities including company and parliament decisions, and investments resolutions. The potential application of the Northern Lights solution is linked to several industrial sectors, such as hydrogen and power from natural gas, WtE (Waste-to-energy), cement, biomass and biofuel, steel, and refineries, amongst others. Currently, the team is identifying candidates for a future scheme of 300 MTPA.

Views from Industry

Jaques Saint-Just, from H_2 Plus LtD, presented the IEA Hydrogen TCP Task 39, on hydrogen in maritime transport (2017-2019). This initiative identified that the current deployment of hydrogen technologies in the maritime transport sector is not enough. The objectives of the Task 39 are to evaluate available concepts, initiate research and demonstration projects, and provide new know-how. He commented on the outputs from their recent white paper, which covers logistics, H_2 supply and port development, safety, and on-board technology. Moreover, Jaques Saint-Just presented the ongoing demonstration activities in Los Angeles and Long Beach, and funded projects by the European Commission. Other initiatives, including hydrogen from brown coal with CCS and transport by ship within the collaborative agreement between Japan and Australia, as part of which hydrogen will be transported on ships, were mentioned. He highlighted that H_2 has a way to go before being implemented in the maritime sector but that it may play a major role in the long-term perspective, following the short-term niche opportunities for industry and development of regulatory framework.

Damien Valdenaire, from Concawe, commented on the importance of the refining industry but also the final use of the products, covering a big-picture approach within the assessment of the total CO_2 emissions. Based on the Concawe vision towards the 2050 refining sector, the refinery as an energy hub within an industrial cluster, is key to the strategy for the future of this sector. This two-pathways reduction approach, production and products, will decrease the CO_2 emissions, aiming to achieve negative emissions by 2050 by the integration of BECCS (biomass as feedstock of the refineries with CCS). Concawe is looking at the technologies behind this modelling work, but also at the business case linked to those future scenarios. Carbon capture has been identified as one of the tools in the mix of measures to decarbonise the refining sector, for which the capture costs for dedicated streams is expected to drop well below 100$/t$CO_2$ avoided.

SESSION 2: CASE STUDIES

Key points

- Sequential scale up is key to de-risk the H_2 supply chain deployment
- Parallel demonstration projects are essential to increase the range of available production pathways, promote the knowledge transfer, and catalyse the learning by doing

Anna Korolko, from Equinor, described their United Kingdom (UK) plan on hydrogen production from natural gas with CCS as part of the H21 project (2019-2023), which includes salt caverns for hydrogen storage. Based on the literature [2], the need for 270 TWh of hydrogen was identified, where 225 TWh is from natural gas from CCS. 2020 has been identified as the year that this large scale project starts, and, by 2030, the hydrogen production should start at significant scale at each of the industrial CCS clusters. Equinor's strategy includes project implementation in a 7 years period, followed by start-up two years later, and with minimum disruption to the public. The plan includes the production of hydrogen via autothermal reforming (ATR reactor), which they identified as the optimum pathway, and it considers inter-seasonal hydrogen storage. Anna Korolko highlighted several projects, including: the Zero Carbon Humber, where the Drax power station is involved within a scheme to produce hydrogen for its investment in the industrial sector; the Magnum project, which is exploring the hydrogen production plant on based load; and H2morrow, where hydrogen is used for steel production. H2morrow is also linked to the Northern Lights solution.

Hiroshi Ohata, from J-Power, explained the low carbon energy supply as part of the plans towards FY2050. Within the Japanese context, hydrogen has significant potential due to its application in generation, transport, and industry, and the current reliance on the importation of fossil fuel for 90% of primary energy. Hiroshi Ohata reviewed the different options within the hydrogen supply chain and the pathways to develop CO_2-free hydrogen routes for transport, power, and industrial applications.

In particular, he described the planned Australian-Japanese chain where hydrogen will be produced by gasification of coal with CCS in Australia and transport by ship to Japan. Moreover, he presented the Oxygen blown entrained flow two-stage spiral-flow (EAGLE) gasifier, a technology that is being demonstrated at Osaki (166 MW output) and which includes partial CO_2 capture. In addition, Hiroshi Ohata presented other initiatives in collaboration with Australia towards the production of blue hydrogen.

Richard Lynch, from US Department of Energy (DOE) and Carbon Sequestration Leadership Forum (CSLF) Secretariat, presented the opportunities for hydrogen in USA, together with techno-economic information on blue hydrogen. USA has the experience of major CCUS projects (e.g. Port Arthur, Petra Nova, ADM ethanol facility) and current policy incentives (e.g. 45Q tax credits), which has meant a technology push matched with a market pull. Moreover, hydrogen was identified in 2014 as the second main CO_2 emitter in USA which, together with the growing industrial interest on CCUS, has placed it within the future USA strategy.

The session was closed by Emrah Durusut, from Element Energy, who presented the UK key learnings on blue hydrogen, based on their recent studies and activities. Hydrogen has been identified as a key aspect in the UK's economic growth, which considers not only the economics (investments and economic strategy) but the value of such pathways (environmental and employment benefits). In their work, the hydrogen production was linked not only to CCS but also to bioenergy with CCS (BECCS), regional clusters, and the industrial sector. Remarkably, their studies covered potential business models for hydrogen production with CO_2 capture, reviews of comparable existing supportive policies, and shipping as a way to unlock opportunities within the blue hydrogen chain.

SESSION 3: TECHNOLOGY STATUS OF HYDROGEN PRODUCTION FROM FOSSIL FUELS WITH CCS

Key points

- There is plenty of experience on hydrogen production with CCS, mainly on SMR
- There is a wide range of decarbonised hydrogen production pathways. Emerging technologies could be key to decrease hydrogen production costs in the near future
- The rapid decline in renewables costs, such as in photovoltaic and some wind technologies, have decreased the green hydrogen production cost in some areas
- Current hydrogen production technologies focus on maximizing H_2 production and venting/ capturing the CO_2 after. Emerging technologies focus not only on H_2 production but also CO_2 capturing during the process phase, increasing its efficiency

Mary-Rose de Valladares, from IEA Hydrogen TCP, presented the hydrogen production pathways and their interaction with CCS. She covered conventional and innovative pathways via fossil fuels, renewables, nuclear, and electrolysis. She highlighted technologies beyond electrolysis, photo-electrochemical water-splitting, and solar thermos-chemical water-splitting. Nowadays, there are more than 20 demonstration projects with hydrogen in grid around the world, and it is expected that hydrogen will become a key element in the energy system. Within the hydrogen supply chain, Mary-Rose de Valladares highlighted 4 opportunities for scale-up identified in the Future of Hydrogen: gas grids; industrial hubs; mobility; and international trade. As on CCS plants, she mentioned the regional differences on hydrogen production costs. Moreover, she highlighted the impact of the cost reduction of renewables, notably photovoltaic and wind, within the H_2 cost model, and the role of electrolysis as a key enabler technology on the energy transition and the scale-up. Hydrogen could serve as storage, becoming an alternative to absorb the renewable electricity surplus. Other technologies will contribute to the decarbonisation of energy and fuels production via hydrogen production.

Sigmund Størset, from SINTEF, introduced the attendees to the integrated syngas production and gas separation technologies. He presented the different technologies based on the desired hydrogen purity, CO_2 transport quality, and fossil fuel. Sigmund Størset explained more detailed information on characteristics of emerging hydrogen production and CO_2 separation technologies, including Protonic Membrane Reformer (PMR) technology, low temperature CO_2 separation (such as membrane combined with liquefaction), and Vapour Pressure Swing adsorption (VPSA). In addition, he presented the ELEGANCY project, including lab pilot tests on SMR, ATR, HT-WGS (high temperature water gas shift), and LT-WGS (low temperature water gas shift). Apart from that, Sigmund Størset also discussed the differences between CO_2 emissions delivered by the blue and green hydrogen production pathways, and how the regional context will be a significant parameter to consider. At the end of his presentation, Sigmund Størset gave a brief overview of the newly started project "Hydrogen for Europe".

Fabrice del Corso, from Air Liquide, presented different syngas ($H_2/CO/CO_2$) generation technologies (Steam Methane Reforming (SMR), Autothermal Reforming (ATR), and natural gas Partial Oxidation (POX)) and the Air Liquide's approach through their active projects within their energy transition. Examples of their collaborative activities are the Porthos CCS project, H-vision study, and Northern Lights project. Fabrice del Corso presented an overview of CO_2 capture technologies for SMR plants, such as amines for the flue-gas/syngas, and Cryocap™ , and examples of their successful applications. He also mentioned technologies involving membranes and adsorption. For ATR plants, Air Liquide has also patented Lurgi Rectisol™, which was identified as a more compact process carried out in one unit. Remarkably, they have tested their technologies at a significant scale.

Vince White, from Air Products, showed their experience on hydrogen supply since 1975 (> 3.7 million Nm3/h), with more than 80 hydrogen plants located globally. Air Products has a complete technology portfolio on hydrogen, CO, and syngas equipment, including proprietary separation systems (membrane, PSA, and cold boxes) and a global alliance with TechnipFMC for reforming technology. Moreover, Air Products builds and operates hydrogen plants of all sizes (from 1 to >170 kNm^3/h), as standalone facilities or linked to pipelines. As an example, Vince White mentioned the Port Arthur project: CCS in the SMR, captures more than 90 % of CO_2 from the syngas, and operating at full capacity since 2013 (1million tonnes CO_2 captured/year). From a financial perspective, the project receives tax credits from the 45Q incentive (CO_2 is stored via EOR (enhanced oil recovery)), as well as US government grant from the Recovery Act, and Denbury payment for CO_2 use in EOR applications. Vince White described the gasification technologies with CO2 capture, and the differences between grey (hydrogen from fossil fuels), blue, and green hydrogen. Blue hydrogen is identified as a pathway to expand the infrastructure and experience towards green hydrogen.

Markus Lesemann, from GTI, presented their work on hydrogen production with CO_2 capture via SMR. This technology (compact hydrogen generator with CO_2 capture, CHG) is based on sorbents and catalysts (one-step conversion of natural gas to H_2 for power or high purity H_2). The process is currently tested under a $6 million DOE contract and could mean, at large scale, a cost reduction on the production of low carbon electricity (15-30% lower H_2 product cost compared with current benchmark, and 40-50% lower CAPEX) at capture rates higher than 97%. The commercialization plan includes a commercial plant (10 MW) in 2024. Moreover, CHG can be applied to the industrial sector, such as the refining, ammonia, and power sectors, or within a H_2 infrastructure.

BREAKOUT IN GROUPS

Key points

- Cooperation between countries to implement the entire hydrogen supply chain, and between industries and academia, and those with international organisations, is key to accelerate the deployment and market penetration
- Research and development to enhance current and emerging technologies are still needed. However, it should not inhibit the deployment process
- Policies are still needed to provide economic support, de-risk deployment projects, and implement standards for hydrogen production and greener products. In summary, those will be key to create the hydrogen market

During the last session of this workshop, the attendees split into smaller breakout sessions. The objective was to further discuss three questions proposed by the organisers, linked to the aims of this workshop, and in order to identify the next steps on hydrogen production through fossil fuels with CCS.

1. Where to go from here: opportunities for and approaches to cooperation

Blue hydrogen (hydrogen production via fossil fuels with CCS) was identified as a pathway which includes several techno-economic individual challenges: hydrogen production, CO_2 capture, transport, and storage.

Attendees identified the opportunity for industries to cooperate via a common **task force**. That could include **knowledge transfer, and cooperation** amongst different parts of the hydrogen chain. Moreover, collaborations of academia and industry, and those with governments, can accelerate the optimization of existing technologies and, consequently, the deployment. Cooperation between sectors could be key to complete the entire H_2 supply chain. In addition, the production of **blue hydrogen can be a route to accelerate the green hydrogen** production.

From a technical perspective, synergies for the **development of novel technologies** for compact and low capex methane-to-hydrogen, including decentralized production based on biomethane, could speed up the near-future hydrogen deployment. In this regard, an open source approach to technology components, and sharing learnings would be essential. Moreover, joint efforts for a common **infrastructure for transportation and storage**, for either hydrogen and/or CO_2, was considered as a key element for the deployment of a complex hydrogen supply chain. **Regional clusters** could offer an optimum element for the industrial sector, while

collaborations between countries could catalyse the implementation of an international hydrogen supply chain for countries which are not able to do it by themselves.

From the regulations and policies perspectives, attendees identified the need of **standards** for hydrogen production and **safety/risks** assessments (including the use and storage of hydrogen blended with natural gas), and the distinction of grey (hydrogen production from fossil fuels)/blue/green hydrogen. For blue hydrogen production, the development of **policy packages** including both hydrogen and CCS is essential within government strategies. Moreover, further descriptions such as **"light/dark blue"** which would include definitions of capture rates and its impact on the decarbonised levels should be considered. That would contribute to the better understanding of suitable technologies and processes for greenfield or brownfield plants.

From a social perspective, the end-users perspective should be incorporated within cooperation initiatives, including efforts to reach **public acceptance** and **stimulating low carbon end-products**. Moreover, that could benefit the research and technology communities on identifying obstacles, needs, and/or requirements.

2. RD&D needs for hydrogen production from fossil fuels w/CCS, with a view to bring down cost and carbon footprint

In this workshop, speakers showed the available hydrogen production routes. Attendees heard about current pilot and large projects, and the experience over the years, which proves the technical viability of hydrogen production from fossil fuels with CCS. However, the cost and net carbon footprint is still under debate.

Scale-up and deployment projects were recognised as the main RD&D need able to cut down costs. However, attendees identified specific areas for further development, as current technologies are still far away from the optimum arrangement, in terms of performance and cost. Examples of identified needs are **technologies for ammonia utilization in energy, better processes and catalysts for liquid organic hydrogen carriers (LOHC), gas turbines** (increasing hydrogen content maintaining high efficiency), **long-term safety tests**, and the use/storage of **blended hydrogen with natural gas**. Other general needs would be focused on CO_2 capture and storage separately, energy efficiency, and artificial intelligence. From a supply chain perspective, attendees claimed the need to analyse the **delivery of hydrogen**, which includes not only the production but the transport, and storage. Moreover, analyses from a Life Cycle Assessment (LCA) perspective, would be beneficial to know the net emissions impact. However, even though there is a need to improve current technologies and develop new ones, the further deployment of hydrogen should **not wait for the perfect technology** in order to increase experience and learnings by doing.

In addition to general RD&D needs, attendees also recognised the need to identify **tailored solutions** for production plants, which will be function of the specific needs, capture rates, and hydrogen and CO_2 purity. Moreover, the need of linking those to the **market** would be essential.

3. Creating a market for hydrogen w/CCS- incentives, policy and regulatory aspects

Research from different markets and stakeholders can support highlighting the perspective on the importance of using hydrogen. Moreover, as in CCS itself, the need of a wide range of incentives, policies, and regulations is still significant in order to create a market for blue hydrogen and address different end-users. Tailored incentives can be based on identified needs at regional scale.

Attendees recognised the need of a **funding roadmap**, from which main actors will be able to analyse and learn about different funding schemes, such carbon tax, or cost incentives. In addition, not only explicitly economic support, but **de-risking** strategies would support the deployment. However, as in the technical perspective, the deployment should not wait for the perfect funding scheme.

Apart from funding, policies would be essential for enabling infrastructures for transport and storage and for **standardization**, which also contributes to the challenging deployment of hydrogen. That would include regulatory restrictions and barriers, such as for the flexibility for blending hydrogen with natural gas. Support on the creation of a competitive market for **"greener" products** was identified as a key aspect for producers. Similarly, policies and regulations could contribute to the implementation of **cluster**s.

CONCLUSIONS

The main key elements from this workshop were the current momentum and the emerging opportunity to decarbonise several emitting sectors such as power, industry, and transport, through the use of hydrogen as part of the mix of decarbonising measures.

The invited speakers showed the experience and success on hydrogen production via different pathways at large scale. In addition, blue hydrogen (hydrogen from fossil fuels with CCS) is emerging and incorporating new advances on CCS. However, not only production, but transport, storage, and use should be analysed.

While it is recognised that there is potential for blue hydrogen in the future economy, there is still a number of challenges to overcome: improvement of its techno-economic performance; further deployment at large-scale; social acceptance; and its integration within a regional or international supply chain. For these reasons, research and development is still needed, together with collaboration initiatives, and support from regulations and policies, which will enable the presence of blue hydrogen in the future market. However, those challenges should not stop the deployment. The technology for "blue" hydrogen exists and can be implemented in a short -to mid-term perspective, thus forming a bridge to "green" hydrogen.

IEAGHG RECOMMENDATIONS

This was the first workshop on hydrogen production with CCS. It is recommended that IEAGHG should continue to maintain a watching brief of the developments linked to hydrogen production technologies, their integration with CCS, supply chain (transport, use and storage), policies, and market.

Based on the outputs from this workshop, previous IEAGHG studies [3]-[5] and collaborative reports [6]-[7], it is recommended that current and emerging blue hydrogen production processes should be explored. These are technologies that are different to steam methane reforming (SMR) with CCS systems.

In addition, based on the broad interest from governments, industries and academia, and the success of this workshop, it is recommended that this event should be repeated in the near future to monitor the regional and collaborative R&D strategies, results from demonstration projects, and new technologies.

These recommendations are supported by IEA Hydrogen TCP, CSLF, and Equinor, who also have expressed clear interest in cooperation with IEAGHG and encourage further collaboration.

FURTHER READING

[1] IEA, The Future of Hydrogen, June 2019

[2] Committee on Climate Change, Net Zero. The UK's contribution to stopping global warming, May 2019

[3] IEAGHG 2017-02- Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS

[4] IEAGHG 2017-03 Techno-Economic Evaluation of HYCO plant integrated to ammonia/urea or methanol production with CCS

[5] IEAGHG 2017-TR3 Reference data and supporting literature reviews for SMR based hydrogen production with CCS

[6] Mission Innovation. Accelerating the Clean Energy Revolution, Report of the Mission Innovation Carbon Capture, Utilization and Storage Experts' Workshop, October 2019

[7] Carbon Sequestration Leadership Forum. Technical Group. Task Force on Industry CCUS. Carbon Capture, Utilisation and Storage (CCUS) and Energy Intensive Industries (EIIs). From Energy/Emission Intensive Industries to Low Carbon Industries, September 2019

Evaluating technology options to mitigate greenhouse gas emissions

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