HYDROGEN DERIVED FROM NATURAL GAS WITH CARBON CAPTURE AND STORAGE

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TABLE OF CONTENTS

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The two-day conference on hydrogen derived from natural gas with carbon capture, utilization and sequestration took place on **September 20-21, 2022** at **STANFORD UNIVERSITY**. The event was hosted by the **NATURAL GAS INITIATIVE**, the **STANFORD CENTER FOR CARBON STORAGE**, and the **HYDROGEN INITIATIVE**.

The day brought together leaders and experts from industry, academia, and government. In this report, you will find the key takeaways from the rich presentations and panels throughout the conference.

By way of summary, most presentations and panelists seemed on board with the following conclusions

- While blue hydrogen is far from the perfect solution, amongst other options such as green and turquoise, it will be essential in the industry's evolution toward clean hydrogen
- With the recent increase in the 45Q credit to $85/ton CO_2 as part of the inflation reduction act, blue hydrogen has become significantly more economically viable. This comes with unprecedented momentum in the blue hydrogen industry today. Technology and incentives are there, now it is time to scale.
- In California, the low-carbon fuel standard (LCFS) makes blue hydrogen more cost-effective than grey hydrogen in the mobility market.
- Given its relative ease of transportation, ammonia (NH_3) is expected to play a crucial role in the decarbonization of the shipping industry

Note (*): **BLUE HYDROGEN** is an industry term for hydrogen produced from natural gas and supported by carbon capture and storage (*Estimated carbon emissions: 0.5 - 6 kg CO_2/kg H_2*).

Alternative hydrogen production pathways are:
GREEN HYDROGEN: Hydrogen produced through the electrolysis of water with renewable electricity. (*Estimated carbon emissions: near zero kg CO_2/kg H_2*)
TURQUOISE HYDROGEN: Hydrogen produced through the thermal decomposition of natural gas into hydrogen and solid carbon (*Estimated carbon emissions: near zero kg CO_2/kg H_2*)
PINK HYDROGEN: Hydrogen produced through the electrolysis of water with nuclear energy (*Estimated carbon emissions: near zero kg CO_2/kg H_2*)
GREY AND BROWN HYDROGEN: Hydrogen produced through a steam reforming process of natural gas or coal respectively (*Estimated carbon emissions: 9 kg CO_2/kg H_2*)

TUESDAY, SEPTEMBER 20, 2022

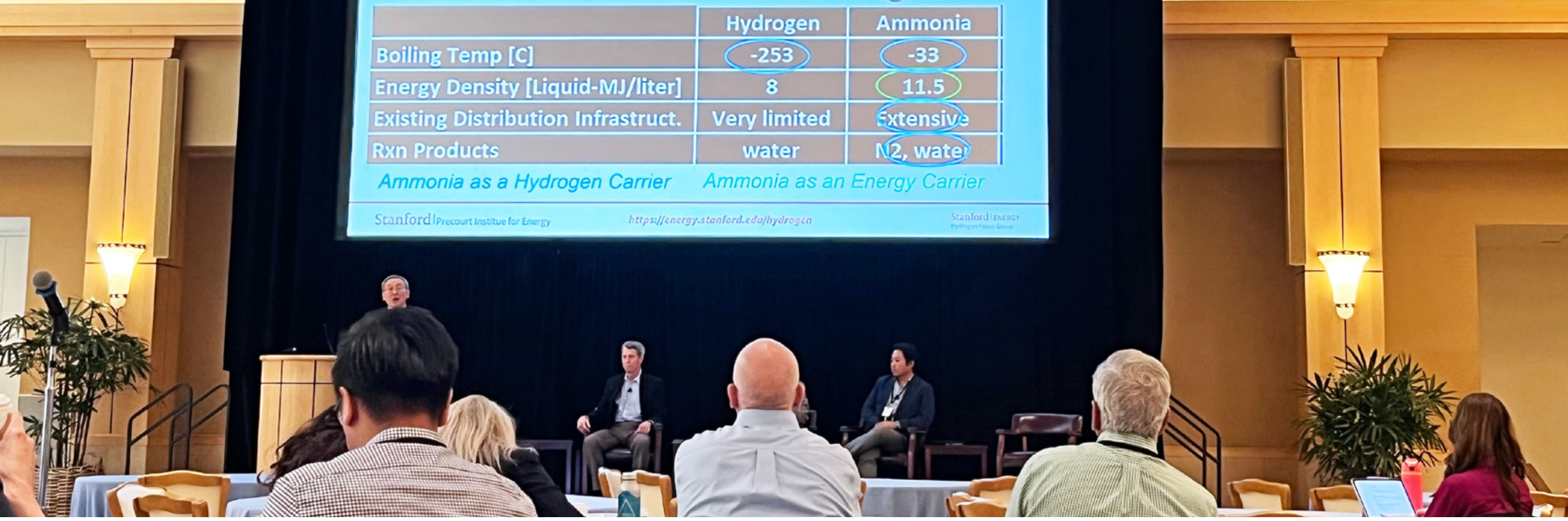
WELCOME REMARKS

To kick off the conference, SARAH SALTZER, Managing Director of the Stanford Center for Carbon Storage and the Stanford Carbon Initiative, welcomed the conference attendees and stressed the importance of sustainable hydrogen production pathways. With a current size of 90 Megatons/year, the hydrogen market is expected to increase sixfold by 2050. Additionally, she shared her excitement about the momentum at Stanford around sustainability, reinforced by this year's opening of the STANFORD DOERR SCHOOL OF SUSTAINABILITY.

KEYNOTE 1: THE VALUE PROPOSITION OF GENERATING HYDROGEN FROM NATURAL GAS

In the day's first keynote NAOMI BONESS, Managing Director of the Natural Gas Initiative and co-Managing Director of the Hydrogen Initiative, highlighted the importance of blue hydrogen as one of the alternatives to grey hydrogen. She shared the following key considerations

- Tomorrow we will need all flavors of hydrogen, with 40% of H_2 in 2050 expected to be blue hydrogen. While blue hydrogen is not a perfect solution it is a step in the right direction and essential in the industry's evolution toward clean hydrogen.
- The optimal hydrogen decarbonization pathway will be geography-dependent given its dependence on the availability and price of renewable electricity, natural gas prices, and regional applications.
- Steam methane reformers (SMRs) and Auto-thermal reformers (ATRs) are well-suited for carbon capture given the high CO_2 partial pressure
- With the recent increase in the 45Q credit to $85/ton, has become significantly more economically viable



TUESDAY, SEPTEMBER 20, 2022

PANEL 1: BLUE AMMONIA & GLOBAL DISTRIBUTION

The first panel was moderated by JIMMY CHEN, co-Managing Director of the Stanford Hydrogen Initiative. The panel included **STEPHEN CROLIUS** (President Emeritus of the Ammonia Energy Association), **SEONGHOON WOO** (CEO and Founder of Amogy), and **RICKY SAKAI** (VP of new business development at Mitsubishi). During the panel, the following key considerations were shared:

- Ammonia (NH_3) is an attractive energy and hydrogen carrier given
  - The ease of liquefaction (-33°C versus -250°C for H2
  - The higher volumetric density than H_2
  - The relative ease of transportation and storage vs H_2
  - The existing global storage and transportation infrastructure given the current use of ammonia as commodity chemical worldwide
- There is a tremendous amount of momentum and investment in the sustainable ammonia production space, with the recent announcement of a wide range of projects run by players such as JERA, Uniper, and OCI
- Both green and blue ammonia are expected to be part of the mix going forward. Estimates of 80% and 10% of NH_3 being green and blue receptively were shared
- Amongst other alternatives such as methanol, ammonia is expected to play a big role in the decarbonization of shipping
- Different pathways for the reconversion of ammonia to energy are being investigated, including ammonia cracking, ammonia combustion, and direct ammonia fuel cells
- Innovative, decentral, modular ammonia production pathways such as Starfire's technology are being developed
- Ammonia is expected to be imported at a large scale in Japan for co-firing of power plants
- Regarding the safety of ammonia in commercial use-cases, not a lot of hazards are expected to arise that haven't already been raised. However, bringing ammonia supply directly out to the "home" is not recommended.

← Back to the Table of Contents

TUESDAY, SEPTEMBER 20, 2022

PANEL 2: BLUE HYDROGEN PROJECTS AND OPPORTUNITIES

The second panel was moderated by **SAM PORTER** from NeuPorter. Panelists included **RAHUL IYER** (KCK Group), **STEVE EVERLEY** (FTI Consulting), and **GREG HINTZ** (Air Liquide). During the conversations, the moderator and panelists raised the following considerations

- With the recent $3/kg production tax credit for clean hydrogen, the US seems to fully embrace hydrogen for decarbonization.
- Blue hydrogen is happening as we speak. While operators are acting and accelerating projects, the financial industry seems to be lagging behind, in part due to a lack of clarity on the rules associated with the IRA incentives.
- New projects include both the retrofit of existing hydrogen production infrastructure as well as greenfield projects.
- While current regulatory incentives (45V, 45Q, LCFS) provide a clear regulatory pull, we should not expect that these incentives will be extended beyond the current scope.

KEYNOTE 2: LIFECYCLE EMISSIONS FOR HYDROGEN PRODUCTION PATHWAYS

In the second keynote of the day, **JUSTIN BRACCI**, a graduate researcher in environmental resources and energy at Stanford, shared his research on the lifecycle emissions for different hydrogen production pathways. Justin shared the following conclusions:

- Given recent regulatory changes, net-zero emissions, fossil-based hydrogen pathways with carbon capture and storage (CCS) become cheaper than grey hydrogen (Pathways without CCS)
- Net-zero electrolytic hydrogen (also known as green hydrogen) could become the most cost-effective carbon-free hydrogen production pathway by mid-century
- Adding a grid connection to solar photovoltaic hydrogen production pathways can be beneficial both from and emissions as well as a cost perspective
- For blue hydrogen to compete on a net-zero basis, mitigation of upstream methane emissions is critical.

TUESDAY, SEPTEMBER 20, 2022

PANEL 3: TECHNO-ECONOMICS AND COMMERCIAL OPPORTUNITY

The third panel of the day was moderated by ADAM BRANDT, Associate Professor in Energy Science and Engineering at Stanford. The panel participants included **TAYLER AMATTO** (Azumith), **ANDREW MARTINEZ** (CARB), **JEFF MAYS** (GTI) and **MATT PITCHER** (Technip Energies). During the panel, the participants covered the following topics

- Repeatability and standardization are crucial to reach economies of scale and advance the blue hydrogen industry
- The hydrogen production tax credit is so valuable that we should think outside the box to reach the 0.45 kg CO_2/kg H_2
- Methane leakage as a potential threat to the hydrogen production tax credit and the potential need to vertically integrate to control the value chain
- "*All models are wrong, some are useful*", and with that the importance of presenting uncertainty (e.g. through sensitivity analysis) for the sake of business decisions
- The blue hydrogen technology is there, we don't have to re-invent it and should focus on scaling up

ROUNDTABLE DISCUSSIONS

The first conference day ended with roundtable discussions where all conference participants were given the chance to share their perspectives on blue hydrogen. While most participants agreed that blue hydrogen is needed in the transition towards zero carbon hydrogen, opinions diverged on whether blue hydrogen would remain part of the mix in the long term. The roundtable discussions were centered around the following questions:

1. Hydrogen: Fuel of the future or just hot air?
2. Is blue hydrogen here to stay or a stepping-stone to a green hydrogen economy?
3. Stuck in the grey zone - What's holding back the conversion to blue for existing hydrogen production

WEDNESDAY, SEPTEMBER 21, 2022

KEYNOTE 1: FUELING THE CALIFORNIA MOBILITY MARKET WITH HYDROGEN FROM NATURAL GAS + CARBON CAPTURE AND STORAGE

After welcome remarks from **NAOMI BONESS**, **SARAH SALTZER** kicked off the second day of the conference. She shared the results of a study evaluating the potential for steam methane reformers (SMRs) with carbon capture In Northern California which led to the following conclusions

- 7 specific sites in northern California have been identified as potentially attractive for the collocation of an SMR-CCS facility with a capacity of around 250 tons per day
- 250 tons/day of hydrogen production is considered mid-case in terms of hydrogen supply and could supply up to 500 refueling stations
- As highlighted in earlier keynotes and panels, the 45Q credit and LCFS play a crucial role in the competitiveness of blue hydrogen compared to grey

PANEL 1: CARBON CAPTURE TECHNOLOGIES FOR SMRS AND ATMS

The first panel of the day was moderated by Stanford's own XIAOLIN ZHENG, professor in mechanical engineering and co-faculty director of the Hydrogen Initiative. The panel included **DAVID DANKWORTH** of ExxonMobil, **ERIK MEULEMAN** of ION Clean Energy, and **ERICA NEMSER** of Compact Membrane Systems. The following conclusions came out of the panel discussion

- Carbon capture is not a new technology and has been demonstrated at scale in many industrial settings, e.g., natural gas processing, ethanol, fertilizer and coal-fired power plants
- Given the high concentration of CO_2 in the exhaust gas of an SMR facility (which makes carbon capture significantly easier), blue hydrogen is often referred to as the "holy grail of carbon capture"
- Separation is a crucial piece of the carbon capture puzzle. Technological advancements aim to allow for cost reductions through separation at high throughput and low pressure
- Retrofitting existing hydrogen plants with carbon capture can be challenging because of the land footprint required, particularly for adsorbent technologies.

PANEL 2: CHALLENGES OF GETTING GEOLOGIC SEQUESTRATION TO SCALE

With the panel on geologic sequestration, we continue to move down the value chain of blue hydrogen. With **ALEXEI VYSSOTSKI** of Chevron as a moderator, the panel included **SHAWN BENNET** of Batelle, **JOHN LITYNSKI** of the Office of Carbon Management at the DoE, **GEORGE PERIDAS** from Lawrence Livermore National Lab, and **MICHAEL WARA** of Stanford. The following themes emerged from the conversation Carbon sequestration technology has been proven and there are currently 27 active projects around the globe sequestering 37 MT/year.

- While there was no commercial case before the inflation reduction act, this has changed with the update of the 45Q production tax credit to $85/ton CO_2
- The challenge ahead of us is identifying sites with multi Mtons/year capacity. As this might seem like an enormous challenge and endeavor, it is important to scale up stepwise and go through the intermediary stages
- There is tremendous value in testing real projects on the ground to understand which potential barriers and challenges are really a cause for concern
- Public acceptance will be crucial to moving forward on projects. Therefore we need to be very careful with the narrative and ensure the public and policymakers are provided with accurate science-based information. We need to work together across states to enable asset operators to advance the industry

PANEL 3: CO_2 UTILIZATION AND END-USE MARKETS

While the captured CO_2 can be sequestered, an alternative is to use the CO_2 to produce valuable goods such as chemical feedstock, fuel… This topic, often referred to as CO_2-to-X, was discussed in a panel moderated by **TOM JARAMILLO**, Associate Professor of Chemical Engineering at Stanford. He was joined in the discussion by **BRENT CONSTANTZ** of Blue Planet, **AQIL JAMAL** of Amarco, **SEAN SIMSON** of LanzaTech, and **SIARI SOSA** of SoCalGas. During the carbon utilization discussion, the following topics were discussed

- While today the CO_2 used is less than 1% of the CO_2 released, a wide range of end products can be produced through both organic and inorganic CO_2 utilization pathways
  - Organic: Thermo-chemical, electro-chemical, photo-chemical, and biochemical pathways to chemicals and fuels
  - Inorganic: Formation of carbonates for usage in cement or aggregates
- It is important to recognize that CO_2 utilization does not necessarily lead to emission reductions as it depends on
  - The source of the CO_2
  - The product being displaced and its carbon intensity
  - How long the CO_2 is retained in the product
- Technological innovations are needed to reduce the cost of CO_2-based synthetic fuels, chemicals, and building aggregates

WEDNESDAY, SEPTEMBER 21, 2022

PANEL 4: PYROLYSIS

The conference was concluded with a panel discussion on pyrolysis. Also referred to as turquoise hydrogen, this production process decomposes methane into hydrogen and carbon black. With MATTEO CARGNELLO, Associate Professor of Chemical Engineering at Stanford as moderator, panelists included **DIETER FLICK** of BASF, **ZACH JONES** of C-zero, and **MATTEO PASQUALI** of Rice University. Key takeaways from the panel were

- Pyrolysis started in the early 1900s, with the first commercial installations operational in 1920. Originally the process was optimized focusing on producing carbon black as the valuable end product
- Going forward, pyrolysis is expected to be part of the mix of hydrogen production technologies and can be a good alternative to blue hydrogen, especially in areas where carbon sequestration is challenging
- Researchers at Stanford are developing catalysts to produce carbon nanotubes (CNTs) instead of carbon black as an end product next to hydrogen
- The key challenges which have inhibited large-scale pyrolysis so far are
  - Removing carbon from the reactor and turning it into a valuable end product or getting rid of the pure carbon black
  - Natural gas (CH_4)- Hydrogen (H_2) conversion rate (Significantly higher in SMR vs pyrolysis)

CONTRIBUTORS

NAOMI BONESS is the managing director of the Natural Gas Initiative at Stanford University, co-managing director of the Stanford Hydrogen Initiative and a coinstructor of a graduate seminar class on the Hydrogen Economy. She is an experienced practitioner in the energy sector with a focus on natural gas, hydrogen and decarbonization in both the developed and the developing world. Prior to Stanford, she held a variety of technical and management positions at Chevron. Naomi is also a Director for a renewable fuels company and an advisor for a hydrogen startup. As an advocate for women and gender equality, she is a member of the organizing committee for the Women in Clean Energy, Education and Empowerment (C3E) Initiative. Naomi holds a Ph.D. in geophysics from Stanford University, a M.Sc. in geological sciences from Indiana University and a B.Sc. in geophysics from the University of Leeds.

JIM CHEN is the managing director of the Stanford Energy Corporate Affiliates at Stanford University, co-managing director of the Stanford Hydrogen Initiative and a co-instructor of a graduate seminar class on the Hydrogen Economy. He is responsible for developing and managing engagements for corporations and other organizations that have an interest in Stanford's research, faculty, and graduate students in energy and energy-related areas. He has a broad background in energy and technology, specializing in technology and product development. He has held technical positions at Lawrence Berkeley Labs, GTE Labs, and AT&T Bell Labs, and technology executive positions at both start-ups and Fortune 500 companies, including FormFactor and Eaton. He received his PhD degree from MIT and his MS degree from the University of California, Berkeley both in materials science and engineering, and his BS degree from the University of California, Berkeley in electrical engineering.

SARAH SALTZER is the Managing Director of the Stanford Center for Carbon Storage and the Stanford Carbon Initiative. Sarah has 25 years of experience at Chevron Corporation where she held a series of scientific, managerial, and executive roles. She has a diversity of experience in geological research and teaching, petroleum engineering on massive offshore fields, leading exploration teams, competitor analysis and business planning, executive responsibilities for all business operations for Chevron's multi-national environmental remediation company, and responsibility for SEC-mandated reserves reporting.

Dr. Saltzer holds a Ph.D. from Stanford University, M.S. and B.S. from the Massachusetts Institute of Technology, and has published her work in peer-reviewed journals and corporate annual reports.

The Stanford Center for Carbon Storage uses a multidisciplinary approach to address critical questions related to flow physics, monitoring, geochemistry, and simulation of the transport and fate of CO_2 stored in geologic media.

Sarah also leads the new Stanford Carbon Initiative with the mission of creating a community of Stanford faculty and industry partners with interest in carbon management to address climate change.

KAREN BAERT is Innovation strategist at the Stanford Hydrogen Initiative while working on hydrogen-related entrepreneurship opportunities. She is devoting her professional life to helping the world to get to net zero, and believes clean hydrogen is a key enabler in that transition. Her work experience includes Management Consulting at Bain & Company and climate tech Venture Capital at Breakthrough Energy Ventures. She holds an MBA from Stanford, a Master's degree in Renewable Energy Engineering from the Technical University Berlin and a Bachelor's degree in Chemical Engineering from the Catholic University in Leuven.

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