The Hydrogen Economy: An Assessment of the Technologies, Markets, and Investment Landscape for Hydrogen Production, Storage, and Transportation

Updated Multi-Client Study Proposal

March 2022
I. ABSTRACT

In this proposed multi-client study, The Catalyst Group Resources (TCGR) will compile a comprehensive review of commercial and R&D progress towards hydrogen production, storage, and transportation technologies, while addressing the most significant unanswered questions. Numerous roadmaps and strategy scenarios to build out the hydrogen economy exist, but they typically stop short of comparing technology offerings by licensor (whether it’s blue, green, grey, or other) and identifying strategic commercial opportunities. TCGR is especially capable at benchmarking these advancements by connecting catalytic and process technology to hydrogen economy scenarios, allowing subscribers to develop their present and future strategies. Subscribers will be able to understand the competitive offerings and reconcile these against the challenges that they will face as the global hydrogen market is projected to grow nearly tenfold over the next three decades.

TCGR’s study will appeal to multiple stakeholders in the hydrogen economy, such as hydrogen producers, catalyst/materials manufacturers, and technology licensors, and those looking to have a better understanding of the investment landscape. Each stakeholder will have similar drivers in mind: decarbonizing and reducing CO\textsubscript{2} emissions, placing their bets on the right R&D and investment pathways, and ensuring that they can uncover the industry’s most immediate and long-term
opportunities. TCGR will assess and develop technoeconomic and life cycle assessments (LCAs), which will include the levers to reduce production costs (see Figure 1), energy and material requirements, and associated CO₂ emissions for the leading hydrogen technologies. Subscribers will understand the relative technological strengths and weaknesses of the full spectrum of production technologies, but will also be able to assess storage and transportation options which include things like liquid organic hydrogen carriers (LOHCs) and inorganic solutions, including ammonia, as a hydrogen carrier.

Unique to this study will be a market potential assessment, based on the various projected hydrogen demand scenarios, to uncover the needed capital investment for blue, green, and other hydrogen production technologies. Depending on the relative technology development curves, the study will evaluate how different scenarios impact the near vs. long term-need for blue vs. green technologies, answering the important question of how much of each technology type will be needed and when. TCGR will help subscribers identify the actions required to reduce these cost curves, the likelihood of doing so, and what further challenges exist.

In answering the critical question “what should our organization be doing in the hydrogen economy,” subscribers will better understand which investment options have the best short-term ROI, which are more or less risky, and for those that are risky, what technology improvements are needed to bring down costs. Another crucial element that will be provided surrounds the greater attention and understanding that’s needed of the full regulatory landscape – how various financial, tax, and government incentives and programs, by country/region, will impact technology development and investment.

TCGR will document how companies can/should address the following challenges:

- The benchmarking of commercial/near-commercial fossil based blue hydrogen technologies. Who is best positioned to succeed? What separates these different technologies? Which is best for your plant or operation?
- What other methods are available, besides reforming and electrolysis, for hydrogen production and how do these compare?
- What is the pathway to scale-up for different electrolyzer technologies? What technological developments (catalysts, electrolyte, processes, engineering, etc.) are being investigated and what’s needed to bring costs down?
- How do hydrogen separation and CO₂ capture technologies fit into the growing hydrogen economy? What novel technologies are being developed and where do they make the most sense?
- Based on the location of production assets, which transportation vector has the most cost-effective solution (e.g., pipeline, in LOHC/ammonia, other)?
- What governmental and regulatory involvement and public/private investment are needed to support the hydrogen economy, or make given technologies both technologically and financially possible?
As is the case with all TCGR multi-client studies, charter subscribers will contribute their most urgent and important questions so that the study is truly “For the Industry, By the Industry.” If you and your team are in need of answers in any of these areas, TCGR will help uncover solutions and clear the confusing landscape ahead in this new and innovative report.

II. INTRODUCTION

There are five main areas where zero to low carbon hydrogen could have a net positive impact on lowering GHG emissions and possibly even compete economically with conventional technologies in the future (see Figure 2):

1. Power generation and grid balancing/variable renewable energy storage
2. Transportation
3. Fuel for industry
4. Feedstock for industry
5. Fuel for residential and commercial buildings (heat generation)

![Figure 2 – Global Energy Demand Supplied by Hydrogen (EJ), Projections Until 2050](source: Hydrogen Council, 2017)

Current global hydrogen production is around 70 Mt/yr, with steam methane reforming (SMR) the largest source of hydrogen generation (~95%). A fully imagined hydrogen economy (like in the 2050 projection from the Hydrogen Council) will require over 600 Mt per year. Since current hydrogen production methods lead to around 830 Mt of CO₂ emissions each year (per the IEA), which is roughly 2-3% of global anthropogenic emissions, a suite of technologies that are either CO₂-neutral that capture/store CO₂ (blue hydrogen) or CO₂-free (green hydrogen) will be required to meet energy demands and emission reduction goals. While green methods like electrolysis make perfect sense, utilizing two seemingly endless resources – energy from the sun and water – to produce hydrogen, they will face economic and engineering challenges in the coming years and likely even decades.
This makes blue and grey hydrogen crucial for global decarbonization and the growing hydrogen economy. Predictions, like by the IEA (see Figure 3), show that it will still be some time before either renewable or grid electrolysis will reach the production cost levels of grey and blue hydrogen. Despite these truths, the coming decade will see a mixture of green and blue projects to scale up the hydrogen economy.

Regional differences between the costs and availability of types of electricity and fuels, along with current in-place infrastructure, are some of the major reasons for the variety of projects and strategies. For places where carbon capture equipment can be bolted onto existing SMR units, blue hydrogen likely makes the most sense. In areas with plenty of cheap renewable energy, green hydrogen might be more economic. Regional regulations about carbon storage could be a deciding factor, as will be individual corporate sustainability and net-zero objectives. The hydrogen economy will additionally require innovative separation and purification technologies, a robust transportation and distribution network, and government support to for research, investment, and supporting regulations.

Figure 3 – Hydrogen Production Costs in 2030 for Different Production Technologies

Since very little hydrogen produced today avoids CO₂ emissions, there is much investigation into technologies that improve upon existing production infrastructure and scale up proposed low carbon concepts, as well as novel technologies that are still far from commercialization. TCGR’s report will benchmark individual commercial offerings and uncover the approaches being developed in the pipeline to help companies throughout the hydrogen value chain chart a course forward for the next decade and beyond.

Combining carbon capture with mature reforming technologies to make blue hydrogen is a rather new endeavor and there are several options that currently exist in this market. To understand novel hydrogen production technologies, these traditional ones with carbon capture will need to be first explored and benchmarked. A handful of the options available today include Johnson Matthey’s Low
Carbon Hydrogen (LCH™) solution, Shell Catalyst & Technologies Shell Blue Hydrogen Process, Haldor Topsoe’s SynCOR Hydrogen™ process (Topsoe is also working with Aker Carbon Capture’s post-combustion technology), and Air Liquide’s Cryocap™. **To our knowledge, never have these technologies been compared against one another and alternatives in a proposed report such as this one.**

Renewable, or at least more sustainable, hydrogen production technologies include thermo and photochemical water splitting, bio-based reforming (ethanol/glycerol) and gasification, and water electrolysis, which is what is typically being referred to by the term “green hydrogen.” Biomass from agricultural waste and landfills can produce biogas, which can be converted to hydrogen. Dry reforming, with CO$_2$ as the oxidant, along with ATR and autothermal cyclic reforming (ACR) are several methods that could valorize biogas into renewable hydrogen. Alkaline electrolysis (AE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE) are the three most investigated electrolysis methods. Depending on the source of electricity, greenhouse gas warming potential (GWP), measured in kg of CO$_2$ per kg of H$_2$, range from 1 to 40, whereas SMR is about 6-13 depending on the hydrocarbon source (TCGR, 2017). The three are at different stages of development, with alkaline electrolysis being the furthest along commercially.

Essential to many of these production methods are efficient and economic separations technologies. Pressure swing absorption (PSA) and solvent based methods have been the primary techniques for hydrogen separation and purification for many decades. Both are generally considered very mature technologies and advancements are marginal and incremental at this stage. PSA is generally used for large applications that also require high hydrogen purity. Solvent methods are typically best when a pure stream of CO$_2$ is required. Membranes are a third separation method. While they are currently the least used option for large scale production, there is still considerable industrial development taking place.

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**Figure 4 – Chiyoda’s Proposed Hydrogen Storage and Transportation System**

Source: Chiyoda, 2018

*Key Technology is New Catalyst of Dehydrogenation.*
To close out the hydrogen production process, robust distribution and transportation methods will need to be developed, or at least expanded upon, for the levels of hydrogen required for large-scale decarbonization. Presently, only small amounts of hydrogen are transported over long distances, as most of it is generated and utilized close to production facilities. Longer term, pipeline transportation over short distances has been proposed as the most economical solution, especially for blending into natural gas pipelines; ultimately longer distance transportation will be required (IEA, 2019). Due to hydrogen’s low energy density, conversion into ammonia or liquid organic hydrogen carriers (LOHC) have been proposed. The development of carrier molecules and catalyst and process technologies that fulfill these requirements are thus a crucial area for development for the catalyst industry.

References


III. THE NEED FOR THE STUDY

The energy transition is well underway, with nearly 200 different nations having committed to the Paris Agreement and companies across industries setting decarbonization and net-zero goals. Hydrogen will need to play a major role in this transition, whether it’s all green, all blue, or some combination of both. The information available on these topics is high-level and scattered, and thus a report that can sift through the cracks, analyze the details, and condense these projections and technology options in a single place is much needed.

A recent publication by Hydrogen Europe listed the production and distribution of clean hydrogen to both traditional and new end-use applications as their most essential pillars of focus for an expanded hydrogen economy (Hydrogen Europe, 2020). Blue hydrogen projects are most likely to develop in regions of the world with low price and high availability of gas, along with access to CO\textsubscript{2} storage and transport/pipeline hubs. In regions without these conditions, blue hydrogen may be less economical without further incentives (Gaffney-Cline, 2020). Identifying the methods to analyze the available technologies and understanding the future pricing of natural gas, hydrogen, and electricity, will be essential for all members of the hydrogen economy to maximize their value.

Downstream purification and post-processing still require development. Cheaper/better membrane and solvent technologies to capture CO\textsubscript{2} and separate H\textsubscript{2} would bring down costs and could provide a clearer picture of where and how to invest. There is still a need to understand how to most effectively and economically store and transport hydrogen. This means better understanding the storage and transportation options, which include pipelines and conversion into other energy carriers, and how the end-use impacts these considerations. Lastly, the full carbon impact that these projects have will be calculated to find areas for improvement to ultimately meet corporate and/or national sustainability goals. The emissions related to construction and operation of plants and the distribution and transportation of products, as well as fugitive methane leakages, need to be fully understood.
Subscribers will benefit from TCGR’s deep industrial knowledge, having been producing techno-economic assessments on syngas production for nearly 40 years and issues related to decarbonization and CO$_2$ capture/conversion more recently in the last decade (through its CO$_2$CC Program). As is the case in all TCGR multi-client studies, this will be a highly client-centric approach. Charter subscribers will be essential in submitting their most pressing questions, thus making this a document that reflects the needs of the industry.

IV. SCOPE AND METHODOLOGY

TCGR’s study will document a broad collection of hydrogen production technologies, from commercial installations and licensable offerings, down to lower TRL R&D efforts, all of which must meet the goal of decarbonizing end-use sectors with the use of low-carbon or zero-carbon hydrogen. Subscribers will benefit from TCGR’s timely insights and analyses.

As can be seen in the preliminary Table of Contents (depicted on p. 8), Section III of the report will begin with a summary of the collective “roadmaps” for the hydrogen economy that have been generated over the last 3-5 years. This will include demand projections, cost estimates for various processes, and a review of the regulations in place that will help expand the hydrogen economy. Additionally, in this section, TCGR will identify the most pressing challenges that subscribers need to solve to make sustainable and profitable businesses in hydrogen.

Section IV will document the collection of hydrogen production technologies, with techno-economic assessments and associated carbon emissions and analysis. TCGR will benchmark these options against each other, highlighting the key areas that still need improvement, whether it be through better catalyst or process development. Section V will cover CO$_2$ capture and CO$_2$/H$_2$ separation and purification options. Section VI will highlight the status of electrolytic hydrogen production and chart a roadmap for its scale up and commercial development. Section VII will focus on the ways in which hydrogen can be stored and transported, with the possibilities for conversion into other energy carriers. Lastly, TCGR will offer its recommendations in the concluding Section VIII.

TCGR’s unique background and established global Dialog Group® ensures expert capability and skill level in this study area. TCGR will utilize numerous deeply experienced experts in membranes and separations to assist us to provide insights beyond what other sources that do not have the reach and industrial experience can provide.

As it does in each of its industrially-focused multi-client studies, TCGR will seek input from “charter” subscribers to help shape the report’s final scope/ToC so that it covers and emphasizes the most pertinent content due to the large volume of research and the numerous hydrogen production routes and application areas that might be of interest.
Preliminary Table of Contents *
(March 2022)

The Hydrogen Economy: An Assessment of the Technologies, Markets, and Investment Landscape for Hydrogen Production, Storage, and Transportation

I. Introduction
II. Executive Summary
III. Roadmap Summary
   A. Hydrogen Demand Projections & Market Potential Assessment
   B. Current and Future Production Costs
   C. Natural Gas and Electricity Cost Projections
   D. Regional Regulatory and Policy Support
   E. Future Challenges
IV. Fossil Based and Low Carbon Hydrogen Production Technology (techno-economic benchmarking, LCA, and emissions analyses)
   A. Commercial Blue Hydrogen Offerings (e.g., JM, Shell, Topsoe, Air Liquide, UOP)
   B. Novel & Alternative Methods for Natural Gas/Methane to Hydrogen (e.g., chemical looping, pyrolysis, membrane reactors)
   C. Biomass, Biogas, Coal Reforming, and Waste Gasification
V. Capture and Separations Technology – CO₂ Capture and H₂/CO₂ Purification (techno-economic benchmarking, LCA, and emissions analyses)
   A. Cryogenics (e.g., Cryocap™)
   B. PSA Adsorption (e.g., UOP, Linde, Air Products technologies)
   C. Solvent (Chemical and Physical) Absorption (progress made in amine/non-amine, solvent blends, ionic liquids, water-free solvents, others)
   D. Membranes (e.g., UOP, Air Liquide, Evonik technologies)
VI. Green Hydrogen Roadmap and Challenges (techno-economic benchmarking, LCA, and emissions analyses)
   A. Technology Status (AE, PEM, SOE; development of new catalysts/electrodes, membranes, and cell designs; progress towards reducing PGMs; benchmarking of licensed technology)
   B. Current Commercial Projects (Project statuses, capacity by region, technology & players involved)
   C. Cost Reduction Pathways (Development of high-pressure systems, improved efficiency and engineering design, lowered CAPEX/OPEX concepts)
   D. Challenges and Framework for Further Scale-up/Commercialization
VII. Storage, Transportation, & Distribution (Improvements in storage technology, sorption kinetics, reaction thermodynamics, costs, etc.)
   A. Compression, Liquefaction, and Solid Storage (e.g., MOFs and carbon materials)
   B. Chemical Storage/Hydrogen Carriers (e.g., LOHCs, NH₃, metal hydrides, ammonia borane)
   C. Distribution and Storage Networks/Hubs (proposed projects and development status)
VIII. Recommendations and Conclusions
   A. Leading Commercial/Industrial Strategies
   B. Investment Landscape
   C. Remaining Hurdles

* Charter subscribers (those who sign up for the study prior to launch) will have the opportunity to work with TCGR to further refine the scope of the report by delineating areas of particular interest, notably in Sections IV-VII, for inclusion in the assessment.
V. QUALIFICATIONS

The Catalyst Group Resources, a member of The Catalyst Group, works with clients to develop sustainable competitive advantage in technology-driven industries such as chemicals, refining, petrochemicals, polymers, specialty/fine chemicals, biotechnology, pharmaceuticals, and environmental protection. We provide concrete proven solutions based on our understanding of how technology impacts business.

Using our in-depth knowledge of molecular structures, process systems, and commercial applications, we offer a unique combination of business solutions and technology skills through a range of client-focused services. Often working as a member of our clients’ planning teams, we combine our knowledge of cutting-edge technology with commercial expertise to:

- Define the business and commercial impacts of leading-edge technologies
- Develop technology strategies that support business objectives.
- Assess technology options through strategy development, including:
  - Independent appraisals and valuations of technology/potential
  - Acquisition consulting, planning and due diligence
- Provide leading-edge financial methodology for shareholder value creation
- Lead and/or manage client-sponsored R&D programs targeted through our opportunity identification process.
- Provide leading information and knowledge through:
  - World-class seminars, conferences and courses
  - Timely technical publications

The client-confidential assignments conducted by The Catalyst Group include projects in:

- Reinventing R&D pipelines
- Technology acquisition
- Technology alliances
- Market strategy

We have built our consulting practice on long-term client relationships, dedication, and integrity. Our philosophy is clear and focused:

We Provide the "Catalysts" for Business Growth by Linking Technology and Leading-Edge Business Practices to Market Opportunities
VI. DELIVERABLES AND PRICING

This report is timely and strategically important to those industry participants and observers both monitoring and investing in the development and implementation of technologies for hydrogen production. TCGR’s report, based on technology evaluations, commercial/market assessments and interviews with key players will go beyond public domain information. As a result, subscribers are requested to complete and sign the “Order Form and Secrecy Agreement” on the following page.

The study, “The Hydrogen Economy: An Assessment of the Technologies, Markets, and Investment Landscape for Hydrogen Production, Storage, and Transportation,” is expected to be available 3-4 months after launch.

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<th>Participation</th>
<th>Deadline</th>
<th>Price</th>
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<td>“Charter” subscribers*</td>
<td>prior to launch</td>
<td>$24,500</td>
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Post-launch subscribers after launch $27,000

The Hydrogen Economy: An Assessment of the Technologies, Markets, and Investment Landscape for Hydrogen Production, Storage, and Transportation

Report in PDF format, in addition to subscription price $1,000

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Notice to Subscribers

Due to the complementary nature of this study to TCGR’s multiclient report completed June 2021 in this area (“Power-to-X: Techno-economic, Commercial and Strategic Developments for Production of Energy Carrier Chemicals, Petrochemicals and Sustainable Fuels”), TCGR is offering a discount of $1,000 off subscribers to that study. Subscribers are requested to contact Chris Dziedziak at +1.215.628.4447 or cdziedziak@catalystgrp.com if further details are required or to determine if your organization is entitled. When completing the order form, please make sure to indicate your company’s subscription to the earlier report.
ORDER FORM AND SECRECY AGREEMENT

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