

**Power-to-X: Techno-economic, Commercial and
Strategic Developments for Production of Energy Carrier
Chemicals, Petrochemicals and Sustainable Fuels**

MULTI-CLIENT STUDY PRESENTATION

June 2021



Power-to-X: Techno-economic, Commercial and Strategic Developments for Production of Energy Carrier Chemicals, Petrochemicals and Sustainable Fuels

This TCGR multi-client study was launched in February 2021 and completed in June 2021. The study's scope, and specific contents (as depicted in the ToFC on pages 16-26 of this presentation reflect the inputs from a group of "charter" subscribers who have indicated their priorities for coverage, areas to be expanded/deepened and focal points for emphasis in Sections V and VI. These are leading industrial developers, suppliers, and end-users of P-t-X technologies.

ABSTRACT

This recently completed multi-client study from The Catalyst Group Resources (TCGR) addresses the latest commercial and technological progress related to the use of Power-to-X (PtX) technology in the production of energy carrier chemicals (gaseous and liquid), petrochemicals and sustainable fuels. Much of this is encapsulated by the production of green hydrogen from water electrolysis and its downstream value chains but also includes such topics as ammonia cracking. Whether you are a producer or consumer of hydrogen, syngas, methanol, natural gas, ammonia or Fischer-Tropsch hydrocarbons, or have access to excess renewable power, you will want to use this in-depth analysis to inform you of the latest in the state-of-the-art technologies as well as guide you for further investment opportunities. Our study provides an understanding of the market drivers, challenges and opportunities for PtX, a detailed technology review of the green hydrogen value chain (e.g., H₂, SNG, methanol, etc.), techno-economic case studies of the world's current flagship PtX projects and the resulting competitive and strategic implications.

Critical topics this study addresses include:

- Factors enabling PtX deployment including technology robustness and Platinum Group Metal (PGM) requirements
- Markets for PtX by key product including gaseous and liquid energy carriers (e.g., hydrogen, methane, methanol, ammonia, etc.), petrochemicals and sustainable fuels
- Comparison of Steam Methane Reforming (SMR) coupled with Carbon Capture Utilization and Storage (SMR-CCUS) and Water Electrolysis for sustainable hydrogen production
- Techno-economics of flagship PtX projects
- Strategies and trajectory for PtX deployment

With an outlook covering the next 10 years (2020-2030), TCGR considers commercial and technological developments that provide the report's subscribers with expert information for current business operation and future business planning. By focusing on emerging technologies, TCGR details how changes occurring now and expected in the future via the Power-to-X approach will impact the chemical energy carriers, green petrochemicals and sustainable fuels markets of tomorrow. **A key need/justification for this study, and one that TCGR is uniquely capable of delivering, is a comprehensive techno-economic assessment of the commercial implications of increased production of chemicals, fuels and energy storage through Power-to-X methods, and its effect on gas and fuels producers, PGM suppliers, catalyst**

producers and process technology licensors, integrated petrochemicals suppliers and utility companies in such a way that shapes their future plant enhancements. This study documents the commercial opportunities and competitive threats resulting from technology changes – it is a “must have” for future success in commercialization of chemical energy carriers (e.g. hydrogen, methane, methanol, ammonia, etc.), petrochemicals and sustainable fuels production.

I. BACKGROUND

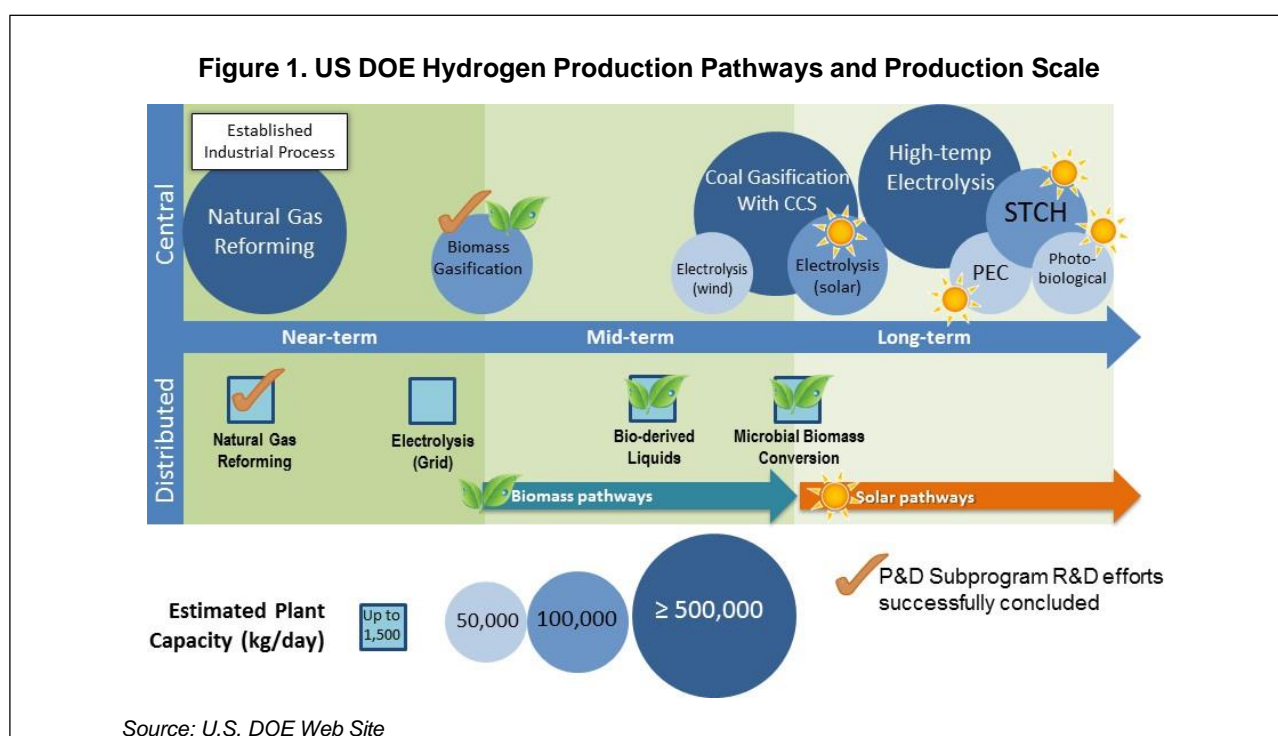
The need to satisfy growing demand for petrochemicals and fuels due to increases in wealth and predicted growth in global population makes reaching climate change targets a very difficult task to achieve. The seemingly incongruent goals of satisfying consumer demand and meeting Sustainable Development Goals (SDG) while keeping to the Paris Climate Agreement goals necessitates simultaneous multi-sector decarbonization. There is also a need to address energy storage (in gaseous or liquid forms) due to intermittent supplies from sources such as wind, solar and hydropower. In order for this substantial task to be realisable in a techno-economic sense, there is a need by-and-large to monopolise on current infrastructure and to deliver existing value chain chemicals while limiting the release of climate-change gases including carbon dioxide (CO₂) and methane (CH₄). There is an additional demand for liquid energy carriers and storage chemicals such as methanol or ammonia, to address the intermittency of renewable power and as potential alternatives to hydrogen and lithium-ion batteries (LIB).

The various decarbonization approaches being taken currently consist broadly of: **a) recycling carbon (e.g. through biomass conversion and pyrolysis of waste plastic); b) removing carbon (e.g. through afforestation and carbon capture, utilization and storage – CCUS); and c) avoiding carbon in the first place (e.g. through CO₂-free chemistries for hydrogen production and use of renewable power).**

There are many obstacles to implementing these methods not least of which are the high costs, project risks, critical material availability, environmental impact, technology readiness, preference of many governments to monetize fossil fuel assets and consequent lack of regulatory support. In order to go forward, so-called “bridging technologies” have been utilized which allow less drastic changes to processes and infrastructure at least to begin with. Electrification of equipment and transportation when combined with renewable power for utilities have been able to lower some of the carbon burden. The major advances in energy conversion and storage solutions e.g. using lithium-ion batteries (LIB), have been instrumental in allowing electrification to happen. This is the first example of PtX, commonly denoted Power-to-Power (P2P). However, PtX can be employed much more broadly in the decarbonization of heat, transportation and the industrial manufacturing of energy carrier chemicals, green petrochemicals and sustainable fuels.

PtX is a relatively simple concept at least when viewed at high level. The main PtX concept currently is one where electricity is transferred directly from a power source, to charge a lithium-ion battery (LIB) or to power water electrolyzers to make “Green Hydrogen” (assuming that the electricity is made from a carbon-neutral process). This allows the sector-coupling between energy production and storage and the production of energy carrier chemicals, green petrochemicals and sustainable fuels.

Green hydrogen is the most visible chemical PtX application heading for large scale deployment and as such hydrogen and its value chain chemicals (e.g., methanol, ammonia) are the key focus of this report. Water electrolysis will likely take at least another 20 years for wide scale deployment, as it cannot yet compete on a techno-economic basis with current hydrogen production techniques, i.e. coal gasification and steam methane reforming (SMR). (See Figure 1).



Nevertheless, as decarbonization becomes a reality, conventional processes will require carbon capture, utilization and storage (CCUS). The low-carbon hydrogen product made via coal gasification or SMR combined with CCUS - “Blue Hydrogen” - can be considered on a closer level in environmental terms with Green Hydrogen from electrolysis. At least it seems reasonable for the techno-economics of Green Hydrogen to be compared with Blue Hydrogen than with hydrogen produced from conventional methods where CO₂ is still emitted. Addition of CCUS is likely to be expensive and is still largely unproven. As such, de-risking strategies are being employed and major hydrogen producers and consumers are devoting resources to developing and integrating more than one hydrogen production method. **Power-to-X is shaping up to be a viable and competitive alternative to fossil fuel conversion approaches and it opens up the ability to use chemicals such as ammonia, methanol and other Liquid Organic Hydrogen Carriers (LOHC) for energy storage.**

TCGR's 2017 report for members of its **Carbon Dioxide Capture and Conversion (CO₂CC) Program, "Progress Towards Sustainable and Cost-Effective Hydrogen Production,"** evaluated the production of hydrogen using Power-to-X strategies. Since that time, this approach has been applied using different technologies to an increasing amount of chemicals, like ammonia, methanol and Fischer-Tropsch hydrocarbons to name a few. **This multi-client report presents the latest technological, commercial, and environmental trends in production of energy carrier chemicals, petrochemicals and sustainable fuels (gaseous and liquid) using Power-to-X strategies with a focus on advances at the pilot and commercial phases.**

II. INTRODUCTION

This report addresses the effects multi-sector decarbonization will have on production of hydrogen, its downstream value chain (ammonia, methanol, syngas, F-T liquids etc.) and chemicals/petrochemicals, including their use "transient" energy carriers.

Currently, the major approaches for making hydrogen are, and will continue to be, Steam Methane Reforming (SMR) and Coal Gasification (CG). In the future, there will be a requirement to reduce or eliminate carbon emissions from these process schemes for instance using retrofit of Carbon Capture, Utilization and Storage (CCUS). CG-CCUS and SMR-CCUS are almost non-existent at present, although they are being considered, but there is little experience with the technology at scale and it is still seen as a risky and expensive approach.

An alternative is to use water electrolysis to make "Green Hydrogen" (c.f. "Blue Hydrogen" from SMR-CCUS). The total deployment of both these approaches in terms of overall hydrogen production is currently <1%. However, the technology choices go beyond a simple techno-economic comparison of SMR-CCUS vs. Water Electrolysis and one must take into account the bigger picture around electricity price trends, emissions pricing, improvements in Lithium-Ion Battery (LIB), fuel cells and electrolyser technologies, critical material availability, new solutions for energy storage and the construction of infrastructure suitable for improving the economics of utilising renewable power.

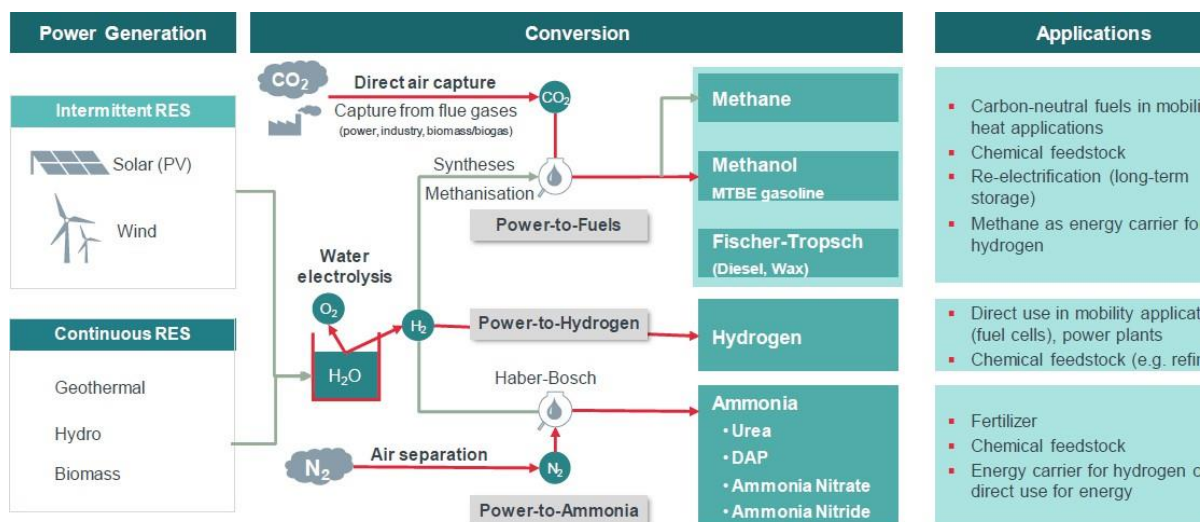
PtX also comes into the picture at smaller scale, where it can increase resource efficiency. By leveraging local excess renewable power, waste heat and industrial off-gases such as those in steel and cement plants, PtX can be employed to make low carbon footprint chemicals, energy carriers and fuels. These are instances where PtX does not have to compete with large-scale chemicals production, but rather it complements it. It is also potentially of great value for local regions to achieve their carbon neutral/sustainability goals.

Consequently, there are opportunities opening up for PtX in the near term. Simultaneously, existing conventional hydrogen process technologies will continue to improve and chemical

industry carbon footprints will be lowered, bridging the transition towards the future decarbonization goals. **This report looks at the way in which hydrogen and its downstream value chains are being disrupted by the increased deployment of Power-to-X and is elaborating on strategies being adopted in a wide range of current pilot and large demonstration projects.**

Green hydrogen can be reacted with CO and/or CO₂ to make natural gas for heat and power, methanol, dimethyl ether (DME) or Fischer-Tropsch (F-T) fuels and with nitrogen to make ammonia. PtX can also be set up to power other electrochemical cells which can reduce CO₂ to CO, or even to convert sugars from biomass into other platform biochemicals. The power can also be used indirectly – for instance to power manufacturing plants and reduce their carbon footprint. As such it has the possibility to be a versatile and flexible technology for production of a range of value-chain chemicals, replacing older chemistries which have higher carbon footprints. Much of the current interest in PtX is for making either hydrogen or “electrofuels” for transportation, in particular aviation and shipping and off-road/heavy equipment. PtX is necessary as an adjunct, or alternative, to electrification which is much harder to do in these systems.

Figure 2. Power-to-X: Conversion of Renewable Power into Chemical Energy Carriers, Petrochemicals and Fuels



Source: Frontier Economics, 2018; “INTERNATIONAL ASPECTS OF A POWER-TO-X ROADMAP: A report prepared for the World Energy Council, Germany”; p. 15

There is an increasing tendency towards sector coupling of the chemical industry with other heavy industrial sectors. For instance, the capture and conversion of power plant, steel and cement off-gases containing carbon oxides (CO/CO₂) into chemicals and fuels. PtX is a key source of hydrogen in these scenarios through water electrolysis.

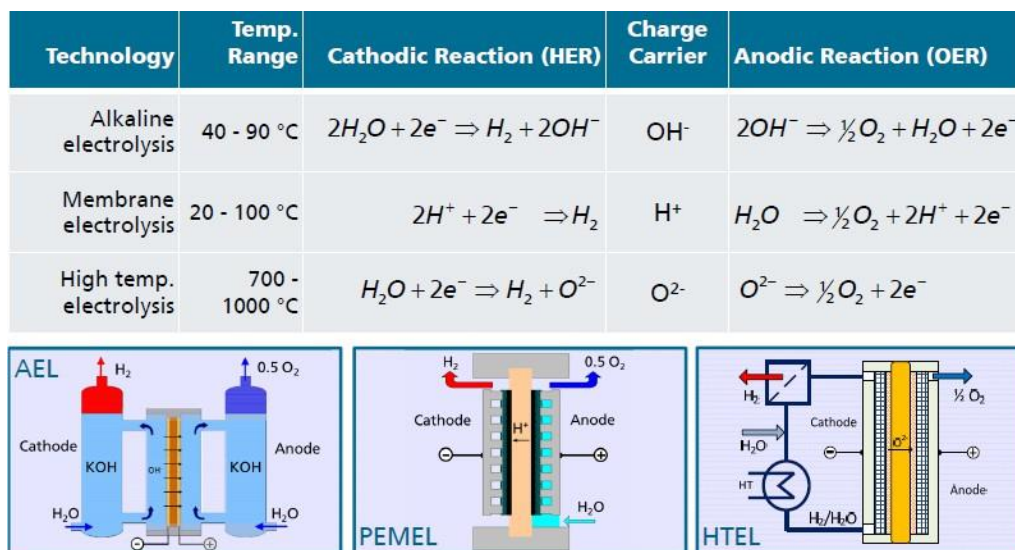
There is also a growing focus on modular production of chemicals, using novel reactors and sophisticated engineering process schemes which reduce the CAPEX, OPEX and carbon footprint such that in future, they can become more viable compared with the large-scale units. Use of combinations of PtX with modular chemical plants is an interesting concept, and one that can be integrated into future Smart, Sustainable Cities. Further down the line, more direct use of PtX in chemical plants is a possibility as many concepts are being researched. These are not limited to electrolysis but also include photocatalysis, photobiological approaches, plasmacatalysis, infra-red, microwave and electromagnetic catalysis, and combinations with thermochemical routes.

Critical to the potential success of PtX is water-splitting. A delineation of the strengths and weaknesses of several approaches provides an indication of the role to be played via technology and techno-economic advancements:

- **Water Electrolysis**

There are currently three key types of water electrolysis technology – Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Electrolysis (PEMEL) and Solid Oxide Electrolysis (SOEL), also known as High Temperature Electrolysis (HTEL). Their respective technologies and characteristics are shown in Figure 3. More recently Anionic Exchange Membranes (AEM) have also been brought to market by Acta in Italy and ITM Power in the UK has an AEM system in development.

Figure 3. Three Main Technologies for Water Electrolysis

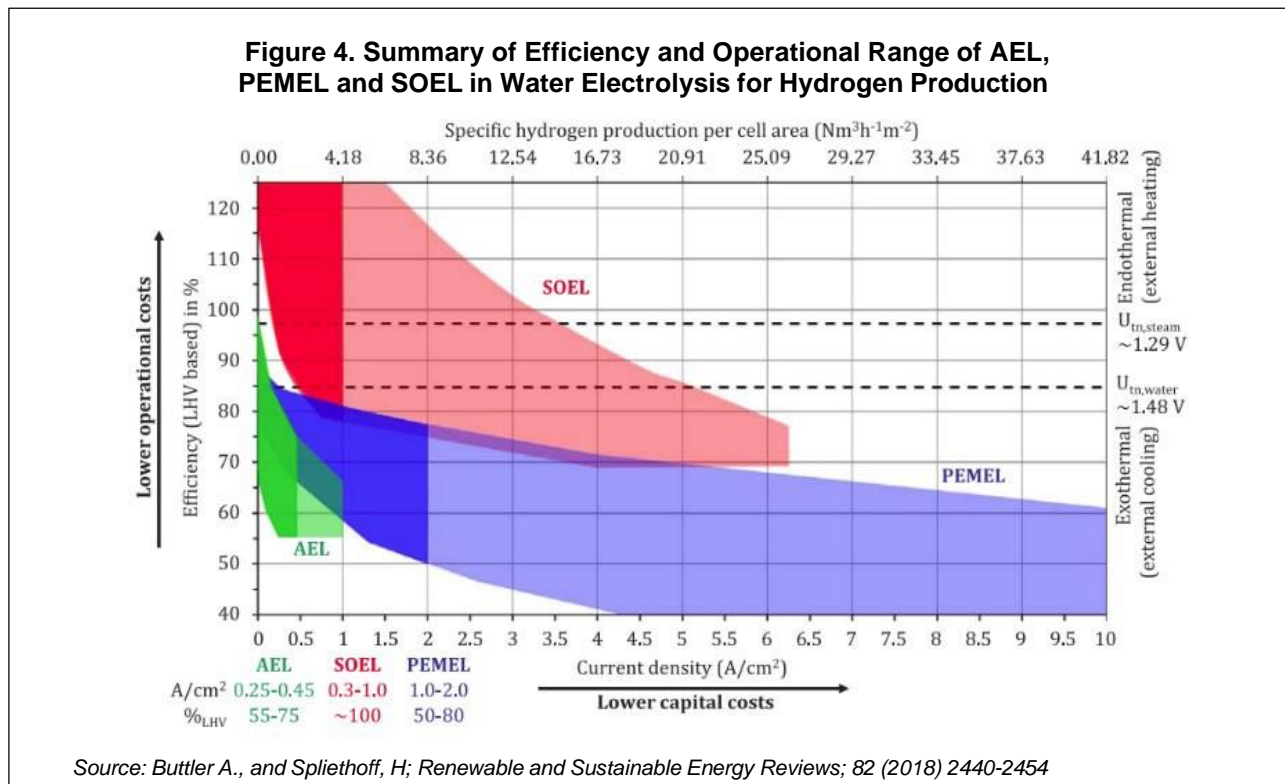


Source: Fraunhofer Institute, 2014

PEMEL is relatively new, although it is growing rapidly in line with the need for hydrogen refuelling stations, where current technology e.g. from ITM Power, UK, can produce high purity hydrogen suitable for fuel cells and industrial hydrogen. ITM's technology benefits from the ability to be ramped up quickly, to operate at high capacity for short periods and to provide a rapid response to power supply and demand fluctuations. PEMEL is expected to be the dominant technology for hydrogen refuelling – as can be seen from Figure 4, it has the widest operating range of the three technologies. Hurdles include the cost of the system, reliability at scale and lowering Platinum Group Metal (PGM) requirements. Currently PEMEL relies on having substantial quantities of platinum and minor metals and these levels need to be thrifted significantly for the PGM supply/demand fundamentals to accommodate wide-scale deployment.

AWE is mature technology and accounts for most of the commercial capacity in operation today. Newer concepts consist of pressurised technology (60-80 bar c.f. 10-40 bar currently). While being a trade off with CAPEX, electrochemical compression is in theory more efficient than systems which require a separate mechanical compressor. Pressurised technology vendors include McPhy, NEL Hydrogen and others. AWE has the benefit of not requiring PGM.

SOEL was originally developed by GE and Brookhaven National Laboratory in the 1970s. It operates at high temperature (700-900 °C) which can achieve higher efficiencies than either AEL or PEMEL whereas material stability remains a challenge. SOEL currently have very short lifetimes (1,000 h) and they need much further development before they can be commercialised. However, their potential is considerable, and they do not rely on PGM, using instead Ni/ceramic electrode technology.



Considerable techno-economic improvements are required before water electrolysis methods can be deployed at large-scale. Five Key Performance Indicator (KPI) targets have been set by the FCHJU for electrolyser flexible performance as part of the European Union Horizon 2020 programme as follows:

- lower construction costs
- lower power consumption
- more stable operation with minimal degradation
- ability to run at part-load (flexibility) and to achieve maximum power from start-up in the shortest time possible
- Increasing stack size and lifetime, with targets to increase to 7 MW stacks with lifetimes of $80\text{-}90 \times 10^3$ hr by 2030 (FCHJU, 2014)

These targets will be considered as part of the techno-economic comparison of water electrolysis against conventional hydrogen production from Steam Methane Reforming (SMR) combined with CCUS as the other main method under consideration for making sustainable hydrogen.

- **Green Hydrogen**

Companies are taking conservative steps towards green hydrogen, with small water electrolyser trials being installed at sites to displace a small proportion of Steam Methane Reforming (SMR) hydrogen. Shell's new green hydrogen plant in Wesseling, will replace 1% of the sites existing hydrogen supply from SMR. Still its 10 MW peak output (5 x 2 MW PEMEL skid mounted technology from ITM Power) makes it the largest of its kind globally. The so-called REFHYNE project represents a significant milestone in moving toward electrolysis as a source of refinery hydrogen.

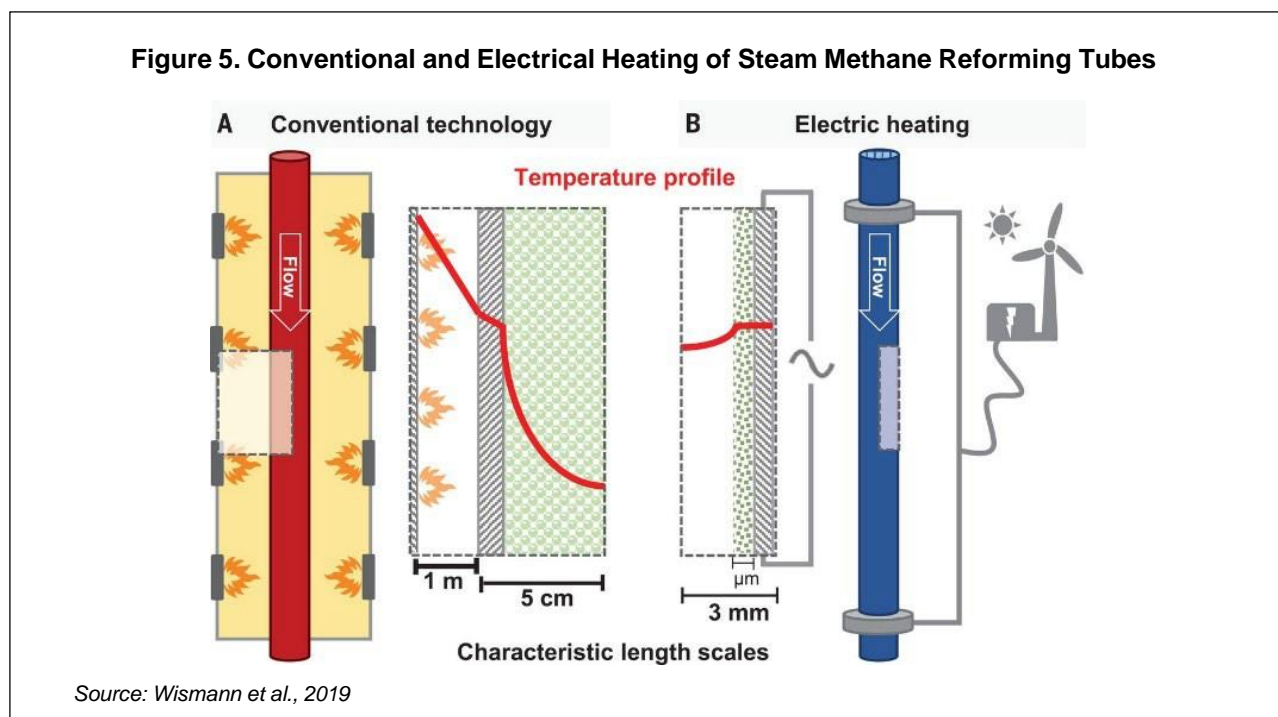
Another key green hydrogen project is the Thyssenkrupp Industrial Solutions (TKIS) Carbon2Chem in Duisburg, Germany. The demonstration has a 2 MW TKIS alkaline water electrolysis (AWE) unit producing $440 \text{ Nm}^3/\text{h}$ of hydrogen. The hydrogen is used as part of a process scheme to make renewable methanol using off-gases from a local steel mill. (see Power-To-Liquids, below).

- **Power-to-Gas (PtG)**

There is interest in developing high-volume applications for green hydrogen as a method of decarbonising multiple sectors including heat and transportation. Various delivery pathways are possible for heat, including injecting hydrogen straight into the natural gas grid and the other is to first methanate green hydrogen with carbon-neutral CO_2 to produce green Substitute Natural Gas (SNG). The choice of injecting hydrogen or SNG comes down partly to the local infrastructure and safety issues. Also, the public may be more willing to accept SNG. PtG is a popular approach in Europe, in particular Germany, driven by the availability of wind and solar energy. Two key projects which are envisioned as case studies in this report are:

- The Audi E-Gas plant at Werlte which is a 6 MW PtG facility providing enough SNG for 1,500 Compressed Natural Gas (CNG) Audi vehicles. CO₂ collected from biogas upgrading is methanated in a reactor system from MAN containing a Clariant methanation catalyst.
- The UNIPER Store-and-Go Power-To-Gas facility at Falkenhagen in Germany which utilises a Hydrogenics electrolyser as well as the Thyssenkrupp Industrial Solutions (TKIS) new catalytic methanation process for conversion of CO₂ to methane. The SNG product is injected into the gas grid for district heating.
- **Syngas & CO**

There are few developed concepts for making Syngas and CO using electrolysis, although Haldor-Topsoe has developed its ECOS system for high purity CO, the bigger prize is in reducing the carbon footprint of its Steam Methane Reforming (SMR) technology. The company is taking an electrification approach for auxiliary components. Electrification of the SMR itself is at the R&D stage. Haldor-Topsoe, together with TU Denmark, the Danish Technological Institute, and Sintex research group, have published recently on electrical resistively-heated Ni catalyst coated FeCrAl alloy SMR reactor tubes. (Wismann et al, 2019). This approach provides more uniform catalyst heating, greater catalyst utilization, reduced byproduct formation and less fuel combustion. It does not use electrolysis, although it can be integrated with a green hydrogen plant and if scaled up successfully, has the potential to achieve lower carbon footprints c.f. standard SMR technologies.



- **Power-to-Liquids**

Most of the remaining PtX scenarios under consideration look to make hydrogen derived liquid transportation fuels and chemical energy carriers. These mainly include methanol, DME, ammonia and Fischer-Tropsch hydrocarbons although formic acid/formate systems have also garnered interest. Methanol is seen as a high-density green alternative to gasoline which can be generated local to the point of use, avoiding transmission losses, and can be blended into the gasoline pool. Such approaches also lend themselves well to decentralised production, helping cities to achieve carbon neutral status through efficient use of their local natural resources and renewable power. Each of these chemistries and products are being considered within the report. Key case studies include flagship projects: CRI MefCO₂ (methanol), Thyssenkrupp's Carbon2Chem (methanol) and Thyssenkrupp's H₂U, Australia (ammonia).

III. THE NEED FOR THE STUDY

Whether you are a producer or consumer of hydrogen, syngas, methanol, natural gas, ammonia or Fischer-Tropsch hydrocarbons, or have access to excess renewable power, you will want to use our in-depth analysis contained in this study to inform you of the latest in the state-of-the-art as well as guide you for further investment opportunities. Our study gives an understanding of the market drivers, challenges and opportunities for PtX, a detailed technology review of the green hydrogen value chain, techno-economic case studies of the world's current flagship PtX projects and the resulting competitive and strategic implications.

With an outlook covering the next 10 years (2020-2030), TCGR considers commercial and technological developments that provide the report's subscribers with expert information for current business operation and future business planning. By focusing on emerging technologies, TCGR details how changes occurring now and expected in the future via the Power-to-X approach will impact the chemical energy carriers, green petrochemicals and sustainable fuels markets of tomorrow. **A key need/justification for this study, and one that TCGR is uniquely capable of delivering, is a comprehensive techno-economic assessment of the commercial implications of increased production of chemicals, fuels and energy storage through Power-to-X methods, and its effect on gas producers, fuels producers, utility companies, PGM suppliers, catalyst producers, and various integrated petrochemicals suppliers in such a way that shapes their future plant enhancements.**

This study documents the commercial opportunities and competitive threats because of technology changes – it is a “must have” for future success in commercialization of chemical energy carriers (e.g. hydrogen, methane, methanol, LOHC etc.), petrochemicals and sustainable fuels production.

The questions for now are:

- What will happen next?
- What will it mean for catalyst producers and manufacturers of chemicals, fuels and critical materials?

- In particular, what can we expect to happen in the next 3-5 years? Where are the best areas for technical development, technology spend, partnerships and investment?

This report focuses on areas where Power-to-X is being used directly to generate at least one of the raw materials in the process. It maps out where in the next 3-5 years, and further along in 10 years, PtX is expected to make inroads and the opportunities, hurdles and techno-economic risks involved. It sets out case studies by each “X” (e.g., hydrogen and other gaseous and liquid chemicals/fuels) to show who is investing the most in each area, which technologies they have pursued and why they have chosen to do so.

IV. SCOPE AND METHODOLOGY

TCGR’s study documents and assesses recent developments in Power-to-X for the production of energy carrier chemicals, petrochemicals and sustainable fuels with the goal to provide insightful, timely advice in both technical and commercial directions.

Topics included are:

- Factors enabling Power-to-X deployment, including technology robustness and critical material availability
- Markets for Power-to-X by key product (e.g. gaseous and liquid energy carriers, petrochemicals and sustainable fuels)
- Comparison of Steam Methane Reforming coupled with Carbon Capture Utilization and Storage (SMR-CCUS) and Water Electrolysis for sustainable hydrogen production
- Power-to-X technology advances and drivers
- Techno-economics of flagship Power-to-X projects
- Strategies and trajectory for Power-to-X deployment

As depicted in the actual Table of Contents which appears on pages 16-26 (and includes “charter” subscriber feedback), TCGR’s study begins by completing an overview of the PtX drivers which consist of a bigger picture around moves toward decarbonization, electrification and local resource efficiency (**Section I**).

Following the Executive Summary (**Section II**), **Section III** provides a synopsis of key legislation, policies, national hydrogen strategies and stakeholder organisations by country or region.

Section IV describes the potential markets which can be addressed using PtX technology, with specific market applications spelled out for individual chemicals.

Section V reviews key electrolyser technologies for making hydrogen, syngas, and CO as well as the research progress for other electrolysis and thermochemical hybrids.

Section VI describes 17 separate PtX projects in key product groups e.g., green hydrogen, ammonia, methanol, hydrocarbon fuels etc. and discusses the technology rationale, development, lifecycle analysis (LCA) factors, justification for further work and remaining hurdles.

Section VII provides strategic insights around the needed technical and market developments for PtX, the milestones it must reach to contribute meaningfully to the “NetZero” carbon approaches and its evolving competitive landscape. The technology landscape risks, hurdles and opportunities for industry participants will be discussed and strategies for the best investments will be identified.

Specific case studies included in the report are summarised in Table 1 below.

**Table 1
Power-to-X Case Studies Included in the Study**

Green Hydrogen	Methane	Ammonia
Haldor-Topsoe SOEC	Audi EGAS	Haldor-Topsoe SOC4NH3
NEL Hydrogen HYBRIT	Edis/GASAG	Siemens/Engie/STFC
Siemens H2Future	Store&Go	Thyssenkrupp H2U
	Electrochaea	
Methanol	Power-to-Liquids	Integrated PtX/Other
CRI MEFCO2	Andes Mining & Energy (AME) HIF	Haldor-Topsoe eCOs™ - CO from CO ₂
TKIS Carbon2Chem	Sunfire Synlink	Westküste 100
	Shell Refhyne	

All TCGR studies are characterized by competitive and strategic insights for industrial and financial companies to evaluate. These include key trends, concerns, and conclusions on the best return on investment (ROI) actions, competitive expectations, and strategic SWOT’s on the players. TCGR is noted for its sound strategic advice in nearly 40 years of experience.

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 PtX, hydrogen and chemical/petrochemical production, and energy storage to assist us in providing insights beyond what other sources that do not have comparable reach and industrial experience can provide.

As it does in each of its industrially-focused multi-client studies, TCGR sought input from “charter” subscribers (i.e., those who signed-up prior to study launch) to help shape the report’s final scope/TofC so that it covers and emphasizes the most pertinent content due to the large volume of research and the numerous PtX approaches and application areas that might be of interest.

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 alliances
- Technology acquisition
- 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

In this assessment, TCGR worked with Enabled Future Ltd. (EFL) which helps its clients to accelerate the profitable deployment of Circular Carbon Pathways in support of Climate Adaptation and future Net Zero manufacturing. It does so by Optimizing Technology Portfolios in line with market trends and environmental targets. The company has four areas of activity organized through separate Market Verticals: EnabledCatalysts which covers the production, use and recycling of process catalysts; EnabledCircular which covers projects aimed at achieving plastic product circularity; EnabledPower which includes projects for the production and recycling of sustainable energy storage and renewable power systems and most recently EnabledSafety which looks after projects relating to chemicals, energy storage and renewable power systems safety during production, use and recycling.

EFL’s Director and Owner, Dr. Michelle Lynch, is a PhD in Chemicals and Catalysis and Fellow of the Royal Society of Chemistry (FRSC). Her 23 years of post-doctoral experience span catalyst R&D, catalyst and precious metals market research, patent analysis and consulting. Prior to setting up EFL, Michelle worked with IHS-Markit, Nexant and Johnson Matthey. She is a regular speaker at conferences and contributor to industry magazines. Her publications to date have included features in IHS Chemical Bulletin, IHS Quarterly, The Catalyst Review, Recycling & Waste World and The Catalyst Group Resources’ Intelligence Report. She lives and runs her consultancy in London, UK. She is passionate about sustainability, pollution abatement and helping to create high impact solutions to tackle climate change.

VI. DELIVERABLES AND PRICING

This report is timely and strategically important to those industry participants and observers considering investment, as well as to technology companies evaluating the Power-to-X markets. TCGR’s report, based on technology evaluations, market assessments and interviews with key players goes beyond public domain information. As a result, subscribers are requested to complete and sign the “Order Form and Secrecy Agreement” on the following page.

“Power-to-X: Techno-economic, Commercial and Strategic Developments for Production of Energy Carrier Chemicals, Petrochemicals and Sustainable Fuels” was completed in June 2021.

<u>Post-production subscriber</u>	<u>Price</u>
Power-to-X: Techno-economic, Commercial and Strategic Developments for Production of Energy Carrier Chemicals, Petrochemicals and Sustainable Fuels	US\$23,500

**Charter subscribers (those who signed up for the study before launch) had the opportunity to work with TCGR in defining the scope of the report by delineating areas of particular interest for inclusion in the assessment.*

* * * * *

Due to the complementary nature of this study to TCGR’s **Carbon Dioxide Capture & Conversion (CO₂CC) Program** techno-economic report entitled **“Progress Towards Cost-Effective and Sustainable H₂ Production”** (completed in 2017 exclusively for members), TCGR is offering a discount of \$1,000 off **“Power-to-X: Techno-economic, Commercial and Strategic Developments for Production of Energy Carrier Chemicals, Petrochemicals and Sustainable Fuels”** to members who elected to receive that study. Subscribers are requested to contact John J. Murphy at +1.215.628.4447, or John.J.Murphy@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 selection of the 2017 **CO₂CC Program** techno-economic report.

ORDER FORM AND SECRECY AGREEMENT

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- Please enter our order for the “**Power-to-X: Techno-economic, Commercial and Strategic Developments for Production of Energy Carrier Chemicals, Petrochemicals and Sustainable Fuels**” (completed in June 2021) delivered in PDF format (site license). The post completion cost of the report is US\$23,500.

Hard copy versions of the study can be made available at cost to subscriber. Please contact TCGR for pricing details.

- We are members of TCGR’s **Carbon Dioxide Capture & Conversion (CO₂CC) Program** and received the 2017 techno-economic report entitled “**Progress Towards Cost- Effective and Sustainable H₂ Production**” and are therefore entitled to the \$1,000 discount off the subscription price.

In signing this order form, our company agrees to hold this report confidential and not make it available to subsidiaries unless a controlling interest (>50%) exists.

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