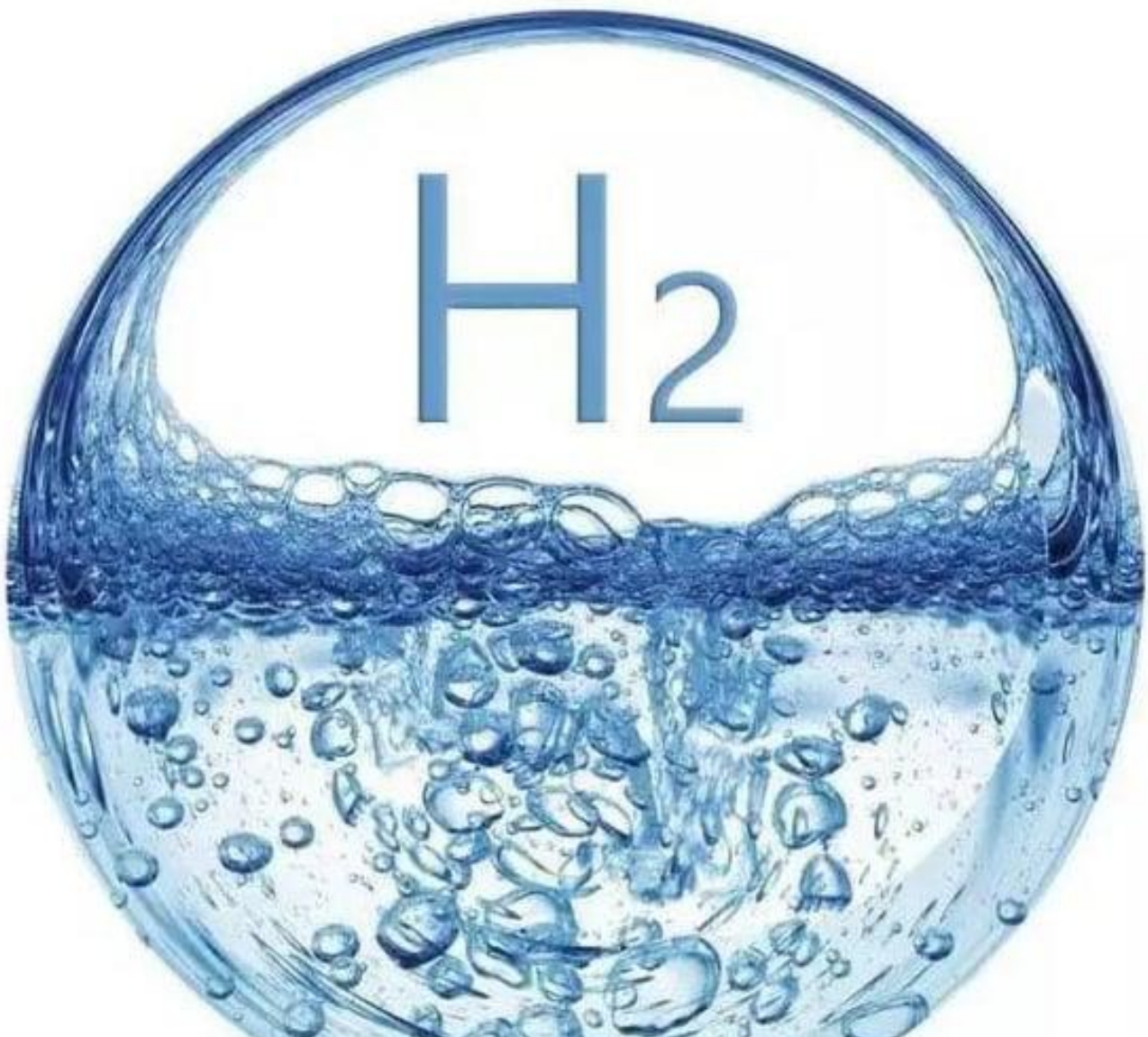


Hydrogen an enabler of the Grand Transition

Future Energy Leader position paper | 2018



Future Energy Leaders Hydrogen Taskforce: Alena Fargere, Bartłomiej Kolodziejczyk, James Carton, Laura Lapeña Martínez, Andrés Pica Téllez, Cansu Karaca, Yena Chae, Lucia Fuselli

ABOUT FUTURE ENERGY LEADERS

The World Energy Council's Future Energy Leaders' Programme – the FEL-100 – is a global and diverse network of young energy professionals. The programme serves as a platform for engaging one hundred ambitious young professionals globally in national, regional and international activities and events. The FEL-100 represent diverse players within the energy sector including government, academia, civil society, industry as well as social entrepreneurs. The objective of the programme is to inspire participants to become the next generation of energy leaders capable of solving the world's most pressing challenges regarding energy and sustainability.

FEL Projects form an integral part of the programme as they shape the development of the FEL community and provide unique opportunities for international cooperation. Through a flexible and interactive system, the programme enables FELs to design projects with valuable and interactive outputs – webinars, events, online tools, case studies, practical projects etc.

Further details at www.worldenergy.org/wec-network/future-energy-leaders/

Copyright © 2018 Future Energy Leaders,
Hydrogen Taskforce

All rights reserved. All or part of this publication may be used or reproduced as long as the following citation is included on each copy or transmission: 'Used by permission of Future Energy Leaders, Hydrogen Taskforce'.

Front cover image: AlkaWay

ABOUT HYDROGEN AN ENABLER OF THE GRAND TRANSITION

Hydrogen has the potential to be a powerful effective accelerator towards a low-carbon energy system, capable of addressing multiple energy challenges: from facilitating the massive integration of renewables and decarbonisation of energy production, to energy transportation in a zero-carbon energy economy, to electrification of end uses.

This report assesses the potential of hydrogen as well as its current deployment status to enable the Grand Transition by addressing the entire energy system by: (1) enabling large-scale, efficient renewable energy integration; (2) distributing energy across sectors and regions; (3) acting as a buffer to increase system resilience; (4) decarbonising transport; (5) decarbonising industry energy use; (6) serving as feedstock using captured carbon; and (7) helping decarbonise building heating.

ABOUT THE WORLD ENERGY COUNCIL

The World Energy Council is the principal impartial network of energy leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all.

Formed in 1923, the Council is the UN-accredited global energy body, representing the entire energy spectrum, with over 3,000 member organisations in over 90 countries, drawn from governments, private and state corporations, academia, NGOs and energy stakeholders. We inform global, regional and national energy strategies by hosting high-level events including the World Energy Congress and publishing authoritative studies, and work through our extensive member network to facilitate the world's energy policy dialogue.

Further details at [@WECouncil](http://www.worldenergy.org) and [@WECFELS](http://www.worldenergy.org)

FOREWORD

The Grand Energy Transition is one of the main challenges of our generation. Due to the cumulative and interactive nature of climate change, if an action can be taken to mitigate against its drastic consequences it should be taken today. We, Future Energy Leaders, believe that a synchronised action of key stakeholders, technology and energy innovation, and strong societal commitment that will make the Grand Energy Transition a common success.

The Energy Transition requires solutions impacting the entire energy system, hydrogen being one of them. Hydrogen facilitates integration and better valorisation of renewable energy systems, allows energy transition in a decarbonated way, and ensures electrification of multiple end users. Hydrogen plays multiple roles and is considered as one of enablers of the Grand Energy Transition.

One of the current challenges of hydrogen technologies is further cost reduction through scaling and addressing wider markets. Hydrogen technologies are being deployed across the globe, primarily in developed countries with low carbon policy framework in place. Hydrogen energy systems should perform further cost reduction in order to address emerging markets, which are shaping the growing energy demand of tomorrow.

This Grand Energy Transition requires consolidated international and multistakeholder approaches, where governments, private sector, research organisations, educational institutions and end customers have a role to play. Clear vision, guidelines, and supportive policies are essential to enabling the transition.

The work assesses the potential of hydrogen to enable the Grand Transition and hopefully contributes to its common success.

Dr. Alena Fargere and Dr. Bartłomiej Kolodziejczyk
Chairs of Future Energy Leaders Hydrogen Taskforce

TABLE OF CONTENTS

Foreword	1
Executive summary	3
Key messages and recommendations	4
Implications for the energy sector	5
FEL Hydrogen task Force Team	6
CHAPTER 1	10
POTENTIAL OF HYDROGEN IN ENABLING THE GRAND TRANSITION	10
1. Grand Transition, its challenges and solutions	11
CHAPTER 2	14
SYSTEMIC ROLE OF HYDROGEN: FROM ENERGY PRODUCTION DECARBONISATION TO THE ELECTRIFICATION OF THE END USES	14
1. Hydrogen enabling large-scale, efficient renewable energy integration	15
2. Hydrogen distributing energy across sectors and regions	19
3. Hydrogen acting as a buffer to increase system resilience	23
4. Hydrogen decarbonising transport	25
5. Hydrogen decarbonising industry energy use	28
6. Hydrogen serving as feedstock using captured carbon	31
7. Hydrogen helping decarbonise building heating	34
CHAPTER 3	36
POWER-TO-X: GLOBAL PROJECTS REVIEW	36
CHAPTER 4	41
KEY MESSAGES AND POLICY RECOMMENDATION TO ACCELERATE THE GRAND TRANSITION THROUGH HYDROGEN VECTOR	41
key messages and recommendations	42
List of Tables and Figures	43
Glossary	44
References	46

EXECUTIVE SUMMARY

A major transformation and redesign of the global energy system is required towards decarbonisation and to achieve the Paris Agreement targets. This Grand Transition is a complex pressing issue where global joint efforts and system solutions are essential; with hydrogen being one of them.

Hydrogen has the potential to be a powerful effective accelerator towards a low-carbon energy system, capable of addressing multiple energy challenges: from facilitating the massive integration of renewables and decarbonisation of energy production, to energy transportation in a zero-carbon energy economy, to electrification of end uses.

1. Hydrogen facilitating the integration of renewables

The increasing role of renewables in the power sector has raised the need of complementary technologies to balance the grid, and, understanding that electricity cannot be stored easily, allows an opportunity for hydrogen technologies. It is important that power systems acknowledge the benefits that stored hydrogen and power-to-X projects can provide, which can also minimize the overall cost of the system. Analysing more than 250 power-to-X projects shows that OECD countries with national and industrial funds available, and with developed gas grid and transport infrastructure, lead the deployment.

2. Hydrogen distributing energy across sectors and regions

Hydrogen technologies can play a significant role in distributing energy in a low carbon energy world. Delivery is a critical contributor to the cost, energy use and emissions. The choice of hydrogen delivery mode, such as road transport or pipelines, depends upon specific geographic and market characteristics. Solar rich Australia plans to ship renewable hydrogen to Japan, which is switching progressively out of nuclear power.

3. Hydrogen acting as a buffer to increase system resilience

Hydrogen can be converted back to electricity to provide constant power when the renewable source is unavailable, helping stabilise the electrical grid and, in addition, the excess can be sold for a variety of other purposes. Hydrogen is a strategically important commodity, both as a primary feedstock to the refining, fertilizer and chemical industries and as a by-product of other industrial processes. Hydrogen can be injected into the natural gas grid to support the distribution of a clean gas at the same time as reducing emissions and stranded assets. City of Leeds in the UK has announced a plan to convert its gas system to 100% hydrogen.

4. Hydrogen decarbonising transport

To achieve the decarbonisation of the transport sector a social change, and technological modifications are needed. Zero-emission vehicles (ZEV); fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV) are being progressively introduced. Today, a number of studies recognise an important contribution of hydrogen mobility to decarbonise the transport sector and to create extra environmental benefits and number of countries adopt FCEV technology. Due to extensive policy framework, Japan and California lead the hydrogen fuel cell passenger car deployment.

5. Hydrogen decarbonising industry energy use

Hydrogen as an energy carrier could offer a climate-friendly solution to decarbonising industry. It is used in the production of carbon steels, special metals and semiconductors in the steel and electronics industries. Hydrogen is used to process crude oil into refined fuels and hydrogen demand is increasing. German steel makers have announced a project to use renewable hydrogen in a DRI (Direct Reduced Iron) plant.

6. Hydrogen serving as a feedstock

Renewable hydrogen can simplify the value chain for many industries and can be used as a feedstock for production of methane, clean chemicals and fertilizers. Synthetic methane can be produced through a power-to-methane process that can be injected into the natural gas grid. In addition, hydrogen is widely used as a feedstock for production of numerous chemicals that are widely used in the industry such as ammonia. Electrochemical ways for producing ammonia can compete with the traditional Haber-Bosch process. A German car manufacturer uses renewable hydrogen to produce bio methane powering the site's vehicles.

7. Hydrogen helping decarbonise building heating

To achieve the decarbonisation target, building heating can use hydrogen as a fuel or leverage hydrogen technologies, or use a combination of both, offering high efficiency for heat and power generation. In homes, hydrogen could be used to power fuel cell micro-CHP systems, direct flame combustion boilers, catalytic boilers and gas-powered heat pumps. CHP devices are widely deployed in Japan.

KEY MESSAGES AND RECOMMENDATIONS

The recommended steps to be considered when enabling the Grand Transition through hydrogen vector, these comprise of:

- Hydrogen technologies are market mature and are being deployed in different sectors all across the globe;
- Hydrogen has a large potential to enable the Grand Transition via its systemic contribution to the entire energy system: from energy production decarbonisation to the electrification of the end uses;
- Industrial global associations (like Hydrogen Council) ensure an aligned industrial vision of hydrogen enabling the Grand Transition and give a strong positive signal to the market to further develop and deploy low-carbon hydrogen technologies;
- Being in an initial market deployment stage hydrogen energy requires the development and implementation of coherent financial and policy framework that enables long-term implementation and profitability of hydrogen economy across different sectors (including transportation, energy storage, etc.); and
- Extensive communication, education and training initiatives are necessary to promote public acceptance of hydrogen and to build skills and workforce to deliver the transition to hydrogen-based low-carbon economy.

IMPLICATIONS FOR THE ENERGY SECTOR

Hydrogen has long been used across a number of industries, including the oil & gas industry where hydrogen is used in a process called hydrocracking, used to convert crude heavy petroleum extracts into lighter, usable forms of fuel. However, the developments leading to use of hydrogen as a transportation fuel, large-scale energy storage medium or in so-called power-to-gas applications to provide a clean and viable energy source to power vehicles or to provide power and heat for households and larger buildings is the potential game-changing solution. Hydrogen derived from water is heralded as an enabler of the Grand Transition into cleaner future. While this Grand Transition will reduce the impacts of climate change, provide economic growth and numerous jobs, there are major concerns and threats, but also opportunities oil revenue-dependent economies.

FEL HYDROGEN TASK FORCE TEAM



Alena Fargere, Paris, France

Passionate about solving energy transition challenges and climate change mitigation, Dr Alena Fargère works as an Economist in the Hydrogen Energy World Business Unit at Air Liquide. She specializes in innovative financial modelling for low carbon infrastructure investments and strategy consulting for the hydrogen energy market to accelerate the energy transition. Alena started her career in the energy transition in 2012 through designing an appropriate policy framework to support Air Liquide top management in defining a strategy for hydrogen mobility market. Alena holds a Ph.D. in Economics from Ecole Polytechnique, France. She published numerous academic papers on dynamic carbon abatement cost, optimal deployment trajectories for green technologies, and policy framework for the zero-emission mobility. Alena also holds Master's degrees in Economics and Public Policy from Ecole Polytechnique and Sciences Po Paris, and in Applied Mathematics from Moscow Institute of Physics and Technology.



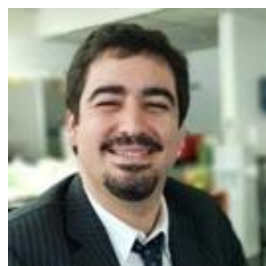
Bartłomiej Kolodziejczyk, Melbourne, Australia

Dr Kolodziejczyk is a Chief Technology Officer of Singapore-based H2SG Energy, an electrolyser manufacturer. In the past he has established two technology startups and three not-for-profit organisations. Kolodziejczyk has advised the United Nations, NATO, OECD, European Commission, G20 and more; on science, technology, innovation, and policy and was named one of MIT Technology Review's Innovators Under 35 for his conductive polymers, which reduce the cost of solar panels and are applied in medicine and bio-sensing. Dr Kolodziejczyk was featured as one of 100 Visionary Leaders by Real Leaders Magazine. Bart has also appeared in numerous publications, including Forbes Magazine, Science Magazine, Business Insider, as well as many newspapers and radio stations in the US, Australia, Poland and elsewhere. Bart holds three master degrees and two Ph.D. in materials engineering and microelectronics. Kolodziejczyk is an active Member of the Global Young Academy and IUCN, Fellow of the Royal Society of Arts and Fellow of the Linnean Society of London.



Laura Lapeña Martinez, Madrid, Spain

With seven years of experience in the energy sector, Laura is currently working for Enagás, a Spanish gas infrastructure operator for transmission, LNG regasification and underground storage. She is currently involved in regulatory development, dealing with analysis of the regulatory framework at the national and international level. Laura is directly participating in the expansion process of the company, taking an active part in the analysis and the due diligence for the acquisition of existing and projected gas infrastructures in Spain and abroad in different countries. In addition, Laura is frequently participating in national and international working groups and for organisations related to the natural gas industry. She has also attended a wide variety of additional energy congresses and fora. Laura has a degree in Mining Engineering, followed by a Masters in Renewable Energy. In addition, she successfully completed an Expert Course on Energy Management and other courses mainly related to the natural gas business and the electricity sector.



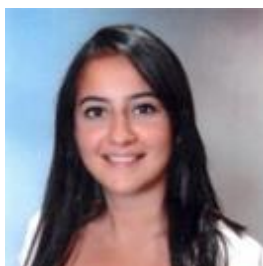
Andrés Pica Téllez, Santiago, Chile

Graduated in Industrial Engineering from the Catholic University of Chile, he holds a Master of Science Degree in Environmental Engineering from the Politecnico di Torino (Italy). Mr. Pica currently is Executive Director in the Global Change Center (Pontificia Universidad Catolica de Chile). The center creates scientific research and provides support to private and public actors to generate information about global change, with special emphasis on climate change. Mr. Pica is a Senior Consultant in Energy, Environment and Public Policy for Government institutions, International Organisations, NGOs and private sector. In 2017 he was selected by the World Energy Council to be part of the Future Energy Leaders Program, that selects 100 young energy leaders in the world. Previously he worked in the Ministry of Environment of Chile as Head of the Air Quality Division; the focus of his work was to promote regulations, projects and programs that helps to control air pollution and mitigate climate change, throw the implementation of new-cleaner technologies that reduces environmental impacts and improves the quality of people's life. Also, he has taught Environmental Economics between other courses at the Catholic University of Chile and at Metropolitan University of Technology.



James G Carton, Dublin, Ireland

Dr James Carton graduated with Bachelor of Engineering in Manufacturing Engineering from Bolton St. Dublin Institute of Technology, Ireland, in 2005 and obtained his Ph.D. from Dublin City University, Ireland, graduating in 2011, focussing on the research, design and development of Hydrogen & Fuel Cell technology. Dr. Carton has gained many years of experience in leading edge technology development, completing projects with many top companies. In 2017, Dr Carton was appointed Assistant Professor in Sustainable Energy in the School of Mechanical and Manufacturing Engineering Dublin City University. Dr Carton is the foremost academic in Ireland with a deep sectoral network in hydrogen, using analysis techniques to develop a clear understanding of the potential opportunity and barriers to deployment of a clean renewable hydrogen society. Dr Carton's research includes the development of advanced functional materials for regenerative fuel cells, for drone applications and electrolyzers for hydrogen production from excess renewable electricity.



Cansu Karaca, Istanbul, Turkey

Cansu Karaca graduated from Istanbul Technical University and University at Buffalo, The State University of New York (SUNY) with a degree in Environmental Engineering DDP (Dual Diploma Program), 2012. She worked as a project engineer in a consulting firm, ENVIS Energy and Environmental Research and Development Company Ltd. for 5 years. She is an enthusiastic energy professional with years of work experience on a diverse spectrum of environmental challenges as well as energy issues. She specialized in energy recovery projects from biomass; life cycle assessment based on energy, water and carbon footprint in different sectors; climate change and GHG emission inventory; environmental sustainability reporting. She holds a master's degree in environmental biotechnology from Istanbul Technical University in energy recovery from biomass with high-temperature pyrolysis and is currently working on her Ph.D. She has been chosen to participate in the Future Energy Leaders' (FEL-100) Programme of World Energy Council since 2015. Cansu has co-authored in several publications on high-temperature pyrolysis, energy conversation, and resource recovery. She is a member of the Turkish Energy Foundation and Chamber of Environmental Engineers.



Yena Chae, Seoul, South Korea

As the Manager of the Global Business department, at Korea Gas Safety Corporation, Yena is a part of sustainable energy developments, official development assistance (ODA) projects that support developing countries, equipping them with gas safety regulations, technologies and standards, and education. Under the Ministry of Trade, Industry and Energy, Korea Gas Safety Corporation is a government testing, inspection and R&D organisation that enacts, revises and enforces High-pressure gas, LPG and City gas related laws, largely ensuring safety of practices. The environment and the ethics of human lives are at the core of Yena's work, so it comes naturally that she understands the importance of implementing the right energy policies. Korea's move towards a nuclear-free energy policy will come at a challenge, however Yena views importing natural gas from abroad could hold the middle-step solution to cleaner energy. Yena hopes her analytical private sector experience together with her current Master's degree in public policy and management with a focus on energy policy will take her a step closer in building a greener tomorrow.



Lucia Fuselli, Italy

As an energy investment specialist at the European Investment Bank (EIB), Lucia Fuselli coordinates the due diligence of some of the largest investment projects focusing on energy and sustainable infrastructure in emerging markets as well as in Europe. In this capacity, she is also involved in the Bank's advisory activities and energy lending policy development. Lucia has also been a research consultant for London Business School, focusing on innovative financing for energy efficiency and, as a subject matter expert, on the Urban Innovative Actions initiative for cities. Previously, she was an external consultant for a EU MP in Brussels, advising on energy, sustainable urban development and innovation. Lucia developed her early career internationally in project development, corporate (Trina Solar), asset management and consulting (RINA). She holds a Master in Finance from London Business School and a Master degree in Civil and Environmental Engineering.

Chapter 1

Potential of hydrogen in enabling the Grand Transition

1. GRAND TRANSITION, ITS CHALLENGES AND SOLUTIONS

A major transformation and redesign of the global energy system is required towards decarbonisation and to achieve the Paris Agreement target of limiting the average increase of global temperature to well below 2 °C above pre-industrial levels.

The Paris Agreement entered into force on 4 November 2016 and to this date 184 Parties have already ratified of 197 Parties to the Convention, representing around 91% of global greenhouse gas emissions (UNFCCC, 2018). Nationally determined contributions (NDCs) are a key element for the achievement of the long-term goals, incorporating each country's efforts to reduce national emissions and adapt to the impacts of climate change.

Meeting the 2 °C scenario requires to decarbonise large parts of the energy systems enabling strong reductions of greenhouse gas emissions. According to the International Energy Agency ("Perspectives for the Energy Transition - Investment Needs for a Low-Carbon Energy System", 2017) energy-related CO₂ emissions have to fall by 70% until 2050 to stay within the carbon budget. The World Energy Council stated that limiting global warming to no more than a 2 °C increase will require an exceptional and enduring effort, far beyond already pledged commitments, and with very high carbon prices. According to the Council the carbon budget is likely to be consumed in the next 30 to 40 years.

The World Energy Council has developed three scenarios looking to 2060 to explore the likely futures and outcomes for the Grand Transition: Modern Jazz, Unfinished Symphony, and Hard Rock. The World Energy Council refers to the Grand Transition as the journey to a different future and a new energy industry panorama, characterised by lower population growth, radical new technologies, greater environmental challenges, and a shift in economic and geopolitical power. Modern Jazz represents a 'digitally disrupted', innovative, and market-driven world. Unfinished Symphony is a world in which more 'intelligent' and sustainable economic growth models emerge as the world drives to a low carbon future. The Hard Rock explores the consequences of weaker and unsustainable economic growth with inward-looking policies (World Energy Scenarios 2016, World Energy Council).

Global joint efforts are essential for attaining the emission reduction goals, increasing energy efficiency in all relevant sectors (mainly transport, industry and buildings), combined with a wide expansion of renewable energies and low carbon technologies. At the same time, the resilience of the system and a reliable and secure energy supply should be ensured.

Hydrogen technologies can play a significant role in this transition and they have proven effective potential for being a powerful accelerator to a low-carbon energy system. Hydrogen is a clean, safe and flexible energy carrier which can be produced from renewable energy and through fossil fuel with carbon capture and storage (CCS) or using bio methane. Indeed today 99% of hydrogen is produced via steam methane reforming (SMR), the cheap but carbon emitting process. It is possible to produce clean (without CO₂ emissions) hydrogen via electrolysis using renewable power, via SMR coupled with CCS or SMR using bio methane.

Hydrogen technology is mature and has been trialed and tested. Presently there are over 30 large scale Power-to-Hydrogen installations operational across Europe (Power-to-X FEL Project, 2018). These systems supply hydrogen for a range of applications from power generation, heating, and mobility, providing great insights of how to decarbonise the grid system.

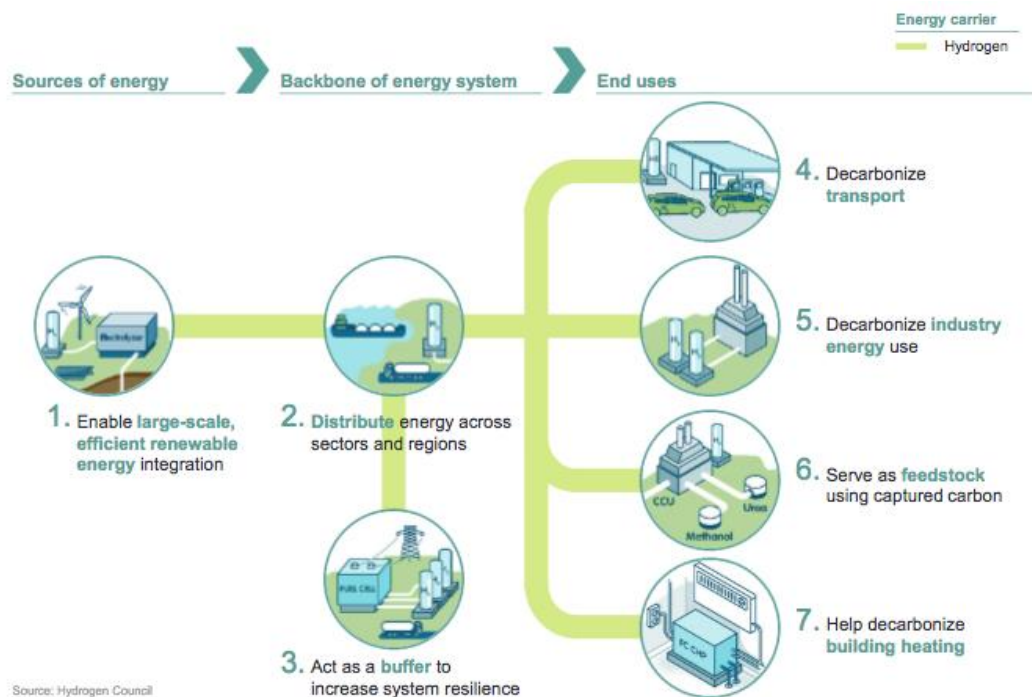
It is possible to produce zero CO₂ emission hydrogen and it can be used in fuel cells, for electric power, fuel for transport or in industry as feedstock. Hydrogen can be transported and stored in liquid or gaseous form and can be converted to other chemicals such as ammonia, methanol, methane, etc, depending on the market needs. Other storage options include underground and pressurized storage.

Transport options include truck transport, ship transport, and grid injection, where the gaseous hydrogen is added/blended with natural gas in the natural gas grid. Blending hydrogen into the existing natural gas pipeline network can significantly contribute to reduce greenhouse gas emissions.

Hydrogen offers a viable solution for some energy uses which are hard to electrify through the grid or with batteries, such as long-range transport, energy-intensive industry and elements of residential heating.

For the deployment of hydrogen technologies the support of policymakers, industry, and society are essential.

Figure 1: Seven roles of hydrogen in enabling the Grand Transition



Source: Hydrogen Council

Source: Hydrogen Council, 2017.

According to a report of the Hydrogen Council (Hydrogen Council, 2017), the energy transition needs to overcome major challenges which come from five areas, and hydrogen has the potential for successfully overcoming all of them:

1. increasing renewables share leading to imbalances of power supply & demand;
2. to ensure security of supply, global and local energy infrastructure will require major transformation;
3. buffering of the energy system through fossil fuels will no longer be sufficient to ensure smooth functioning of the system;

4. some energy end uses are hard to electrify via the grid or with batteries; and
5. renewable energy sources cannot replace all fossil feedstocks in the petrochemicals industry.

In addition, several obstacles need to be overcome before hydrogen can be effectively positioned as an accelerator of the energy transition. The Hydrogen Council finds that there is insufficient recognition of the importance of hydrogen for the energy transition, the absence of mechanisms to mitigate and share the long-term risks of the initial large-scale investments, a lack of coordinated action across stakeholders, a lack of fair economic treatment of a developing technology, and limited technology standards to drive economies of scale.

Hydrogen has an important potential to enable the Grand Transition by addressing the entire energy system by:

1. Enabling large-scale, efficient renewable energy integration;
2. Distributing energy across sectors and regions;
3. Acting as a buffer to increase system resilience;
4. Decarbonising transport;
5. Decarbonising industry energy use;
6. Serving as feedstock using captured carbon; and
7. Helping decarbonise building heating.

These seven roles of hydrogen as well as its current deployment status are assessed in this paper.

Chapter 2

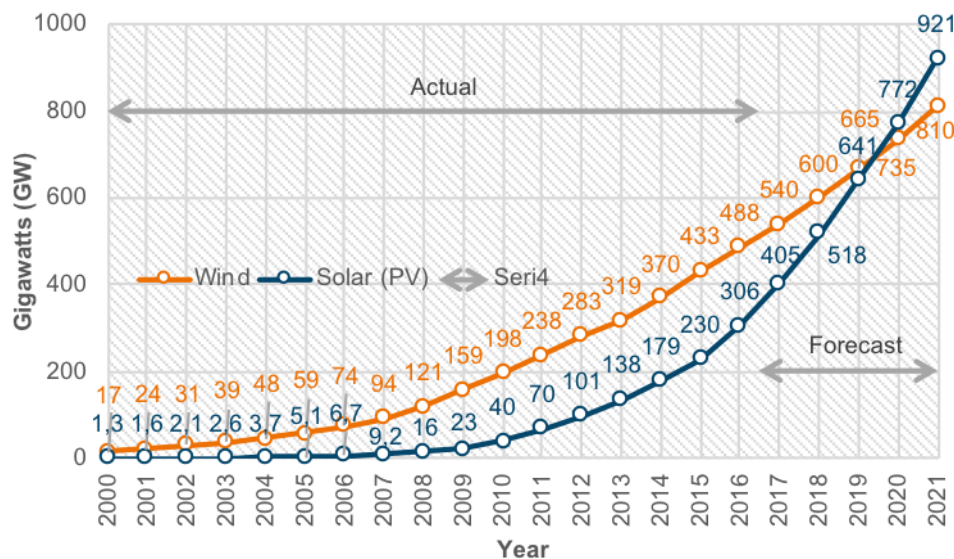
Systemic role of hydrogen: from energy production decarbonisation to the electrification of the end uses

1. HYDROGEN ENABLING LARGE-SCALE, EFFICIENT RENEWABLE ENERGY INTEGRATION

The increasing role of variable renewables (solar and wind power) in the power sector and the need of complementary source of energy

In the last decade the installed capacity of wind and solar power generation had expand rapidly, driven mostly by the market, given that its Levelized Cost Of Electricity (LCOE) has fall dramatically. In 2017 wind and solar power accounted 85% of all new renewable capacity and will continue to increase, according to (IRENA, 2018). In 2013 the world had 319 GW of wind power and 138 GW of solar (PV), while in 2018 wind power is expected to reach 600 GW (88% growth) and solar (PV) 518 GW (375% growth) (PowerWeb, 2018).

Figure 2: Global cumulative renewables installations growth



Source: PowerWeb, 2018.

All types of power plants are subject to variability (e.g. stoppage for scheduled maintenance) and uncertainty (e.g. stoppage due to failure in the system), but the magnitude of these phenomena differ. Unlike conventional technologies (such as coal, gas, diesel and hydroelectric), wind and photovoltaic generation is characterized by being variable and dependent on climatic conditions.

Environmentally, important net benefits associated with wind and solar generation are obvious, however, their renewable energy generation is variable and uncertain and its integration into the electrical system is a great challenge (Bird et al., 2013; Ela & O'Malley 2012).

With an increasing demand for flexibility in the electric system around the world, the electricity storage market faces great challenges. Currently, pumped hydro storage (PHS) represent 96% of current storage electricity capacity (IRENA, 2017), but PHS solutions are quite geographically limited, this opens an opportunity for other storage technologies, such as hydrogen.

Ancillary services that hydrogen can provide in the power sector

Wind and PV projects today have their LCOE as low as half of coal, but with the limitations that they can not provide electricity 24 hours a day and can not respond to variation of demand. This forces the system to respond with other technologies, such diesel and gas power plants, which can increase the overall cost of the system, have a negative environmental impact and also waste some of the electricity produced by wind or PV.

Green hydrogen produced through electrolysis, using renewable energy, needs economic and political signals to develop systems are capital intensive. This makes it necessary that power systems acknowledge the ancillary services that green hydrogen technologies can provide.

Ancillary services markets have existed since 1996 in the USA (Hirst & Kirby 1996) and have expanded in different regions since then, proving to be a solution to improve the reliability of electrical systems and reduce their operating costs by differentiating products.

Generation of electricity is not a single homogeneous product. The same applies to the generation of electricity, each service requires different response times (from seconds to tens of minutes) and periods of service duration (from a few minutes to hours), for this an independent market can be defined, which will decrease the total costs of the system, given that will allow the most competitive technology to deliver the specific service required.

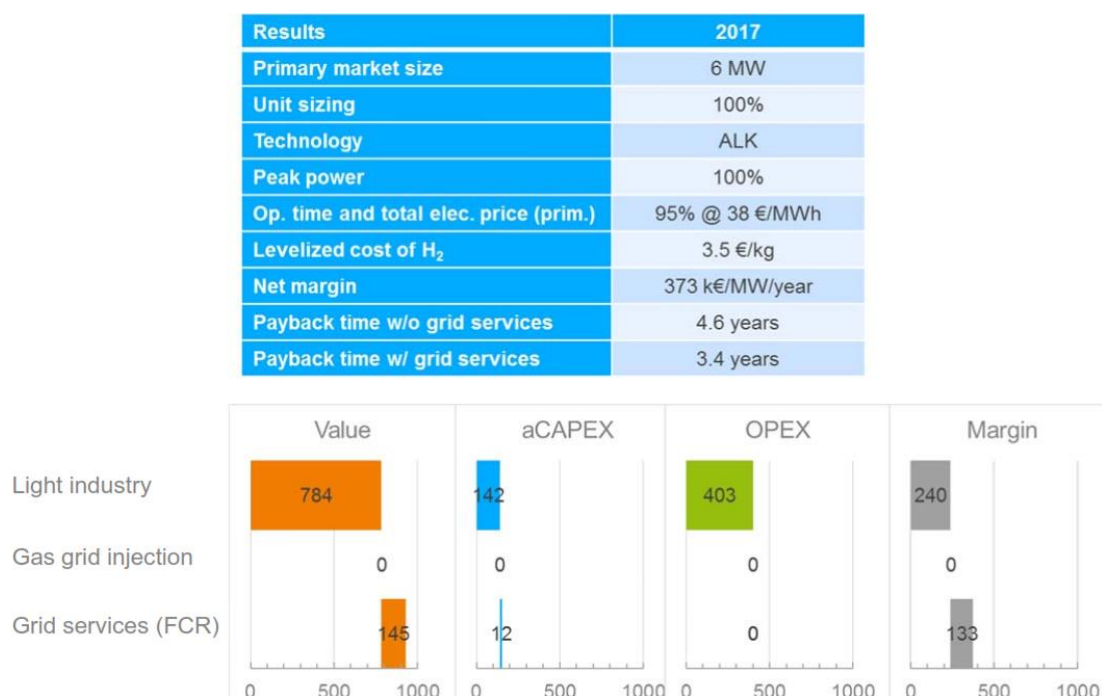
Hydrogen technologies for electrical storage: examples and projects

Hydrogen technologies that can be use to store electricity generated by renewable or other source can be categorized in two main families:

- hydrogen generated by electrolysis, then compressed and stored to be used to generate electricity afterwards through an internal combustion engine; and
- hydrogen generated by electrolysis, then compressed and stored to be used to generate electricity afterwards through a fuel cell.

(Tractebel-Engie and Hincio, 2017) identified in Europe, five regions where power to hydrogen can be profitable today, using the excess of renewable energy at some points of the day to produce hydrogen and then through fuel cell generate electricity when there is a shortage of renewables.

According to (Tractebel-Engie and Hincio, 2017), business models for power to hydrogen, must consider multiple sources of revenue, secondary value streams can represent up to 78% of this margin, making the business case profitable. This can be explained, because the extra cost of hydrogen injection into gas grid allows the system operate more hours, maximizing the use of low cost electricity. An example of a current profitable business model is shown in figure 3, from (Tractebel-Engie and Hincio, 2017), they consider 3 sources of revenue: light industry applications (flat glass, metallurgy, etc.), gas grid injections and grid services:

Figure 3: Power to hydrogen business model

Source: Tractebel-Engie and Hinicio, 2017.

Multi-valorization will play a key role for power to hydrogen, at least in early stages of large-scale projects, initiatives like HyBalance are good examples, the project, using a proton exchange membrane (PEM) electrolyser, will be able to produce up to 500kgH₂/day using cheap electricity from wind turbines. Then uses the stored green hydrogen to provide different electricity services, refilling FCEVs and multiple industry purposes.

Is expected that the cost of power to hydrogen technologies will be reduce in time, the most prominent technology in PEM electrolysers (Hinkley,2016), from the review of perspectives of different institutions and agencies expects that the capital cost (USD/kW) will fall 49% by 2030. (Schmidt et al, 2017) develop an expert elicitation process in order to asses the future cost of different electrolyser technologies (Alkaline, PEM and Solid Oxide electrolysers), most of the experts believe that PEM electrolyser will be the dominant technology by 2030, they also estimates that R&D funding could reduce capital cost up to 24% and scale up alone could get up to 30%.

Policies and regulatory framework needed

As the share of wind and/or solar power increase the electricity system may need levels of electricity storage capacity in order to minimize the overall cost of the system. This will not be produced without explicit measures; this can be achieved by three actions:

- the creation of an adequate ancillary services market, that rewards the investment related to storage technology (electrolyser, compression-storage system and the fuel cell);

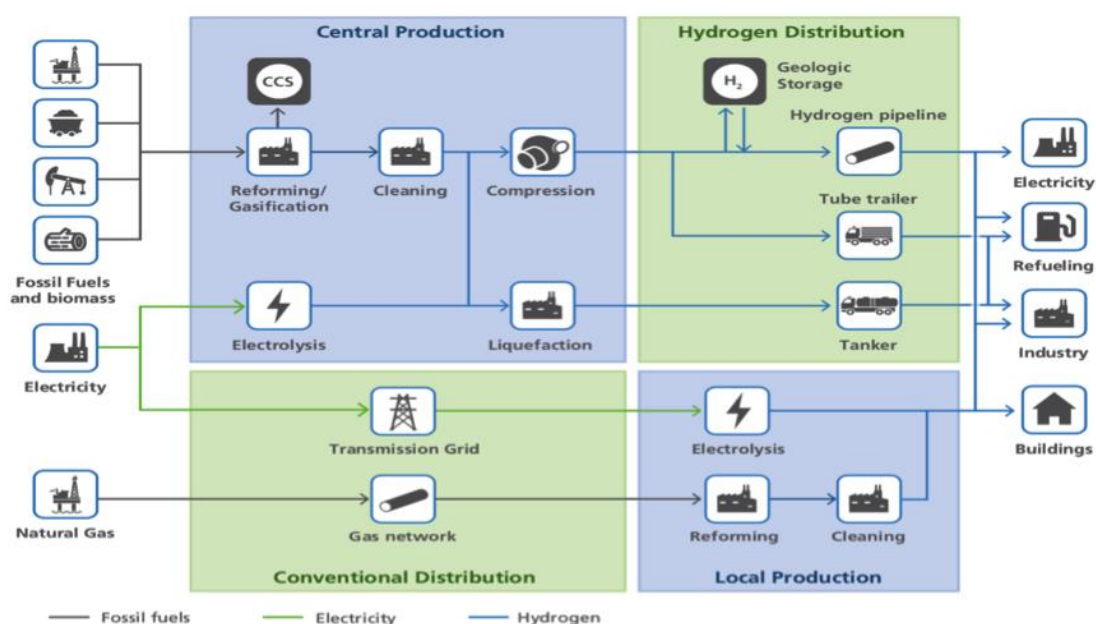
- a regulative framework that force the wind and solar generators to guarantee some level of storage capacity; and
- a government contract that allows to ensure a fixed payment, high enough to pay the upfront investment of the complete storage system.

2. HYDROGEN DISTRIBUTING ENERGY ACROSS SECTORS AND REGIONS

Hydrogen delivery is a critical contributor to the cost, energy use and emissions associated with hydrogen pathways involving central plant production. The choice of the delivery mode is depended upon specific geographic and market characteristics (e.g. city population and radius, population density, size and number of refueling stations and market penetration of fuel cell vehicles). Special cost and safety obstacles at every step of distribution, from manufacture to, ultimately, onboard vehicle storage should be taken into account on the choice of delivery mode. Producing hydrogen centrally in large plants cuts production costs but boosts distribution costs. Producing hydrogen at the point of end-use—at fueling stations, for example—cuts distribution costs but increases production costs because of the cost to construct on-site production capabilities.

There is a multitude of production and distribution pathways for hydrogen, as summarized in the figure below. This diagram serves to highlight the diversity of options at each stage of the system. Two types of hydrogen delivery can be considered: hydrogen transmission (from a central hydrogen production plant to a single point) and hydrogen distribution (from a central hydrogen plant to a distributed network of refueling stations within a city or region). In addition to that, there are typically three hydrogen delivery modes such as liquid storage, compressed truck storage (which are known as road delivery) and pipelines. The suitability of which depends on the size of demand and the transport distance. In this chapter, the routes of hydrogen distribution across sectors and regions will be discussed.

Figure 4: Hydrogen sources, production, distribution and applications



Source: Staffell et al., 2017.

The table below shows the system components for each distribution mode. From the economic point of view, the cost of liquid tanker storage delivery is about 10% of truck storage and pipeline compressed storage shown (see tables below).

Table 1: System components included in delivery pathways

Compressed gas trucks	Cryogenic liquid storage	Pipelines
Compression and storage at hydrogen plant	Liquefaction and storage at hydrogen plant	Compression and storage at hydrogen plant
Compressed gas trucks	Liquefied hydrogen trucks	Gas pipelines

Source: Yang and Ogden, 2007. System components included in delivery pathways.

Table 2: Road delivery comparison

Delivery mode	Storage amount (% of daily flow)	Storage cost (\$/kg)
Cryogenic liquid storage	200	20-40
Compressed truck storage	50	400
Pipelines	50	400

Source: Yang and Ogden, 2007. Road delivery comparison.

Road delivery

The first hydrogen delivery mode considered is compressed gaseous truck transport (i.e. large semi-trucks carrying tube trailers with compressed hydrogen). Commercial tube trailers are made up of 12–20 long steel cylinders mounted on a truck trailer bed. Tube trailers (compressed truck storage) are better suited for relatively small quantities of hydrogen and the higher costs of delivery could compensate for losses due to liquid boil-off during storage. However, high-pressure tube trailers are limited to transport small quantities of hydrogen. Distribution by tube trailer becomes a much less economic option as demand rises (requiring more deliveries) and when transportation over long distances is required as more time and fuel is spent on the road (Hart et al., 2015). An alternative option, particularly for the initial rollout, is distributing hydrogen from centralized production facilities as a compressed gas in tube trailers. This is a well established method, and large trailers specifically for FCEV refueling hold up to 1,000 kg capacity at 200 or 500 bar (Hart et al., 2016). The trailer can be parked at the refueling station to refuel vehicles directly, reducing onsite storage and compression requirements as compression begins from a much higher starting pressure. However, this does take up valuable surface space at the refueling station and delays the trailer's return for its next load.

The volumetric density of hydrogen can be increased significantly by liquefaction. Liquid hydrogen delivery is used today to deliver moderate quantities of hydrogen medium to long distances. Delivery by cryogenic liquid hydrogen tankers is the most economical pathway. They could transport relatively large amounts of hydrogen and reach power plants located in distant geographic areas.

Pipelines

Pipelines are used commercially today for large flows of hydrogen. The cost of hydrogen pipeline delivery depends on the installed capital cost of the pipeline, as well as costs for compression and storage at the central production plant. It has been reported that pipelines are the most efficient method of transporting large quantities of hydrogen, particularly over short distances (Hart et al., 2015). Much of the cost is associated with acquiring right-of-way. The low initial utilization and high upfront costs are also likely to hinder financing. New pipelines would be required for high-pressure hydrogen networks, as existing high carbon steel natural gas pipelines would be affected by hydrogen embrittlement. Likewise, the existing natural gas transmission network will probably be needed for many years to supply gas turbines and industrial users. These high- pressure pipelines are slightly more expensive than for equivalent natural gas pipelines due to the higher material specifications.

Embrittlement is a pressure-driven process and is less of a concern at lower pressures. Additionally, the polythene pipes replacing iron pipelines as part of the Iron Mains Replacement Programme are compatible with hydrogen. These are currently limited to 7 bar, but larger plastic pipes up to 17 bar have been proposed. Hence there is considerable scope for switching the bulk of the lower pressure natural gas distribution system to running on hydrogen. Hydrogen pipelines have long lifetimes, although the rate of embrittlement can make this difficult to predict. Capital cost is often annualized over 30 years for accounting purposes, but pipelines should last at least 50–100 years (Hart et al., 2015).

It has been reported that issues of scale and geography are critical parameters for the costs of developing hydrogen infrastructure systems (Yang and Ogden, 2007). Analysis centers upon hydrogen delivery as it relates to the amounts and distances of hydrogen distribution—large demands that occur at high density are the most economical—but the same trend is also true of scale economies associated with production systems; economical hydrogen production will tend to be associated with large facilities (e.g. steam reformers, gasification plants, and electrolyzers).

Many modern natural gas infrastructure extensions and upgrades replace the metal pipelines with polyurethane, which does not suffer from embrittlement and is hydrogen rated.

Once hydrogen takes foothold in a region and the transport and industry requirements supplied the only option for the hydrogen is to be injected to the gas grid for it to be used in other regions. Regions with developed gas grids, e.g. Europe & US will progress to blend hydrogen mixtures and progress to eventual 100% hydrogen gas grid networks produced by varying sources across the region. Regions and countries with less developed gas grids, e.g. Africa may be reliant on regional central hydrogen production and utilisation rather than the investment cost of a gas grid infrastructure.

Distribution across the regions and continents

Hydrogen and other ‘clean fuels’ such as ammonia are often mentioned in relation to the new industrial revolution, where clean fuels generated using solar or wind energy in countries rich in those resources will be then compressed, liquefied or converted into other chemical compounds; i.e. ammonia, methanol; to be then shipped and utilized in country of destination. This new phenomenon that was made available due to recent technological progress is already discussed by a number of countries. The Australian Renewable Energy Agency (ARENA) is heralding solar fuels as Australia’s next big export industry (ARENA, 2018). Japanese Kawasaki Heavy Industries is currently developing a brown coal gasification project in the

Australian state of Victoria (Lazzaro, 2018). Hydrogen produced from coal gasification will be then liquefied and shipped back to Japan using the special vessel. While this is not a clean hydrogen project, as large amounts of carbon dioxide will be produced in the process, similar approaches using solar, wind or hydropower could be applied. In the matter of fact, a number of countries is trying to compete with Victoria's "grey hydrogen" and are aiming to deliver clean fuel to Japan and other countries. Brunei and neighboring state of Sarawak in the Malaysian part of Borneo, are aiming to develop large-scale solar power plants and produce hydrogen for export via electrolysis (Wong, 2018; Norjidi, 2017). Other countries with great solar conditions are looking at similar options; among them are Saudi Arabia and other states within the MENA region. It is expected that new export opportunities that solar fuels bring to regions with good solar conditions will influence and reshape the global oil and gas industry.

Challenges

In any future hydrogen-based economy, key economic determinants will be the cost and safety of the hydrogen distribution system from the site of a manufacturer to the end user. This is true of any fuel, but hydrogen presents unique challenges because of its high diffusivity, its extremely low density as a gas and liquid, and its broad flammability range relative to hydrocarbons and low-molecular-weight alcohols (NRC, 2004).

Creating an infrastructure for hydrogen distribution and delivery to thousands of future individual fueling stations presents many challenges. Because hydrogen contains less energy per unit volume than all other fuels, transporting, storing, and delivering it to the point of end-use is more expensive on a per gasoline gallon equivalent (per-GGE) basis. Building a new hydrogen pipeline network involves high initial capital costs, and hydrogen's properties present unique challenges to pipeline materials and compressor design. However, because hydrogen can be produced from a wide variety of resources, regional or even local hydrogen production can maximize use of local resources and minimize distribution challenges.

3. HYDROGEN ACTING AS A BUFFER TO INCREASE SYSTEM RESILIENCE

Remarkably for industry, heating and transport, the gradual move from high carbon to low carbon to zero carbon fuel sources can be accommodated via a gaseous strategy, specifically a renewable hydrogen gas strategy (IEA 2017).

Globally today, hydrogen is a strategically important commodity, both as a primary feedstock to the refining, fertilizer & chemical industries and as a by-product of other industrial processes (FuelsEurope, 2018). However, increased deployment of renewable energy technologies combined with global imperative to limit Greenhouse gas (GHG) emissions (not limited to the electricity sector), will be primary drivers for the growth of hydrogen and the implementation of electrolysis / hydrogen technologies into the future.

The hydrogen economy is a proposed system of delivering energy using hydrogen as a zero-CO₂ emitting carrier. The term was coined by John Bockris in the 1970's, and reflects a strong interest in hydrogen as an energy carrier for several reasons:

- It can be distributed, combusted and used in the same way as natural gas (CH₄);
- Electricity can be produced from hydrogen at very high efficiencies compared to traditional generation;
- Hydrogen can be produced from fossil, renewable and biomass sources, facilitating a “bridging” from carbon to a future zero-carbon economy, and this multi-pathway generation of hydrogen can be tailored to local circumstances;
- Hydrogen has zero tailpipe emissions after combustion, which facilitates lower cost CO₂ removal from the atmosphere in the future; and
- Conversion from hydrogen to electricity is reversible, meaning that hydrogen is an analogue to electricity and it can provide an “electricity storage” solution.

Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used: the existing energy grid or renewable resources. Current grid electricity is not the ideal source of energy for electrolysis because most of the electricity is generated using technologies that are fossil intensive and result in greenhouse gas emissions.

Electricity generation using renewable energy technologies, either separate from the grid or as a growing portion of the grid mix, is an option that should be considered more and more for electrolysis. Hydrogen can be produced during off-peak periods or times when there is excess renewable electricity, instead of curtailing it as it is commonly done. Since hydrogen can be converted back to electricity to provide constant power when the renewable source is unavailable, it can be used to stabilise the utility grid and, in addition, the excess can be sold for a variety of other purposes.

Because of their ability to operate at high current densities and variable power supply rates, PEM electrolyzers tend to be more suitable to a system coupled with dynamic energy sources such as wind and solar, which often present spikes in energy. This means a possibility of better efficiency and wider applications, plus higher hydrogen purity for renewable electrolysis. On the other hand, the LCOE of this option would be higher at present due to the fact that PEM is a technology that is not yet as mature and commercially viable as alkaline electrolysis (FCHJU, 2017).

It is clear that injecting hydrogen into this grid could be an excellent opportunity of using existing infrastructure to support the distribution of a clean gas. The H21 Leeds City Gate project has served as a point of reference and inspiration for this idea. The study aims to convert the existing natural gas network in Leeds, in England, to 100% hydrogen. It proposes the production of 150,000 tonnes of hydrogen per annum using four Steam Methane Reformers, which would be fitted with 90% carbon dioxide capture. Intraday and inter-seasonal storages of H_2 would rely on local salt cavern storage – an excellent, waterproof way of storing gases, created by emptying salt caverns. A hydrogen transmission system would also exist to connect the SMRs and salt caverns to the proposed area of conversion.

Figure 5: The H21 Leeds City Gate concept



Source: Northern Gas Networks, 2016.

Power-to-gas (P2G) systems go beyond producing a basic commodity of hydrogen gas (or energy carrier). In particular, grid-balancing technologies are required to maintain grid stability with increased numbers of distributed and intermittent renewable sources. Electrolysers, specifically PEM electrolyser technology can absorb over 100% of its rated energy capacity within seconds, producing renewable hydrogen, and can be shut down as fast. The hydrogen can be directed to industry, transport, gas grid or stored on site and delivered to fuel cells when electricity is required by the grid (although recognising that using fuel cells in this manner is not the most efficient use of the produced hydrogen). According to Hydrogenics, a world leader in pioneering Power-to-Gas and a member of the European Power to Gas Platform, “Power-to-Gas is a highly effective way of integrating renewables. It can provide a rapid, dynamic response to the Independent Grid Operator signal to adjust to the variations in renewable generation output. The siting of a Power-to-Gas facility is not restricted to any geologic formation as it can be deployed wherever the power and gas grids intersect. It is a scalable technology.” Hydrogenics have commissioned a number of MW scale P2G projects across many countries (Germany, Denmark, Italy). One difficulty of Power-to-gas is that it requires for collaboration of different stakeholders from the value chains; electricity production/transmission/ distribution, natural gas transmission, distribution and hydrogen production, delivery and end-users.

4. HYDROGEN DECARBONISING TRANSPORT

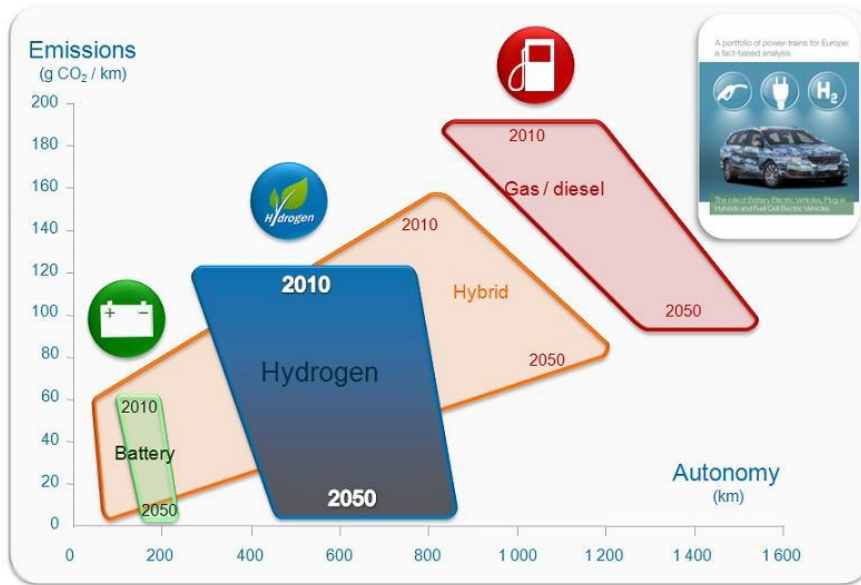
The decarbonisation of the transport system is one of the key challenges in mitigating climate change. Gasoline and diesel account for 96% of total fuel consumption and 21% of global carbon emissions. In Europe the transport sector is the second biggest emitter of GHG emissions after energy industries and contributes about 27% of total GHG emissions, 72.1% of which are from road transport (European Environment Agency, 2018). While other sectors reduce their emissions, emissions of the transport sector continue to increase. Despite the improvements in vehicle efficiency, this increase is mainly due to the growth in personal and freight transport.

Even if according to current trends the European car park is not expected to significantly grow in the future, the number of cars may double worldwide until 2050 due to population and income increases (IEA, 2013). Notably, in Asia experts anticipate six- to eight-fold increase in the number of light-duty vehicles due to population and notably middle-class growth (ADB, 2009).

The decarbonisation of the transport sector can be achieved both through change in commuting habits and technological change. Today, there is a shift towards a more environmental friendly behaviour, which aims to change or even avoid commuting: telework; switch towards transport modes such as bicycles and public transport; car sharing (a model of car rental where people rent cars for short periods of time); carpooling (sharing of car journeys so that more than one person travels in a car), etc. However, a behavioural change alone will not be enough to completely decarbonise transport sector and technological a change will play crucial role in coming decades.

Introduction of ZEVs, which emit zero tailpipe pollutants from the on-board source of power, is a necessary part of the solution to decarbonise passenger transport sector. Recent research shows that both FCEVs and BEVs will play a critical role in decarbonising the transport sector both on global and national levels. The full decarbonisation of the transport sector cannot be achievable only through improvements to the traditional internal combustion engine (ICE), which are bounded by technical limits for engine's efficiency and carbon content of gasoline. Once accounted for the increasing scarcity and cost of energy resources, it appears essential to develop a range of oil free technologies in order to ensure a long-term sustainability of mobility.

Electric vehicles (BEV, FCEV and plug-in hybrid electric vehicles or PHEV in electric drive) have zero tailpipe emissions while driving and significantly improve local air quality. These vehicles also have substantially lower pollution from noise, NO₂ and particles. Moreover, they can reach close to zero well-to-wheel CO₂ emissions, depending on the primary energy source used.

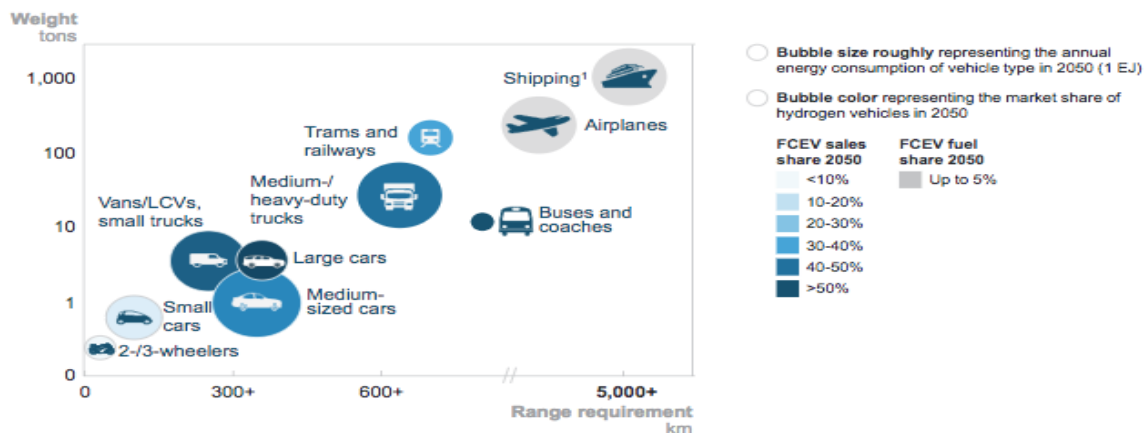
Figure 6: Emissions and autonomy of different powertrains

Source: McKinsey & Company, 2010.

Despite improvements in fuel economy, the capacity of ICE to reduce CO₂ is significantly less than that of BEV and FCEV, which can be CO₂ emissions free due to use of alternative energies in central power and hydrogen production by 2050.

FCEV appears as a promising alternative technology that can ensure a mobility service compared to today's conventional cars: high autonomy range and short recharging time, all at potentially very low lifecycle carbon emissions. Thanks to its large autonomy range (about 500 km), FCEV covers all commuting types: long distance, interurban, and urban.

Hydrogen technology has a greater potential in decarbonising transport segments with longer ranges and more weight:

Figure 7: Hydrogen market potential at different transportation segments

Source: Hydrogen Council, 2017.

The segmentation on the car market is very strong and today FCEV and BEV appear not as direct competitors but rather as complementary solutions. FCEVs cover longer distance and are better positioned to satisfy interurban and urban use within large cars class. As the range of BEV is limited, they are more adapted for smaller cars and shorter trips. However, delays in the development of FCEV infrastructure, possible breakthroughs in battery technology, and promotion of national preferable technological option may change the nature of this competition, making it more intense in the future.

A number of studies recognise an important contribution of hydrogen mobility to decarbonise the transport sector and to create extra environmental benefits such as an increase in domestic employment (Cambridge Econometrics, 2013), a reduction of Europe's dependence on imported oil (EC, 2003), positive impact on public health (Balat, 2008), and an increased use of renewable energy (HyWays, 2008). Hydrogen mobility technology is mature enough and is ready for the market deployment (Roads2HyCom, 2009).

A number of policies was introduced across the globe to encourage ZEV deployment. Programs to ZEVs effectively started in the 2000's through public private partnerships involving government agencies, manufacturers, utilities and fuel companies. These partnerships provided subsidies for research and development, pilot programs and infrastructure. Moreover, technical norms for emissions, global requirements for the portfolio of sales for manufacturers, rebates on the purchasing price for customers as well as various perks (driving bus lanes, free parking, etc.) are now in place. These multiple policy instruments constitute powerful incentives to orient the strategies of manufacturers and to stimulate the demand for ZEV.

The most generous incentives to promote hydrogen vehicles deployment are available in countries using price-based policy instruments design (like subsidies in Japan or tax exemptions in Denmark). These instruments allow maximising short-term FCEV deployment rate (Kotelnikova, 2016). The carbon tax on the distribution of fossil fuels, whenever it exists, remains low and, at this stage, cannot be considered as an important driving force.

The FCEV deployment pace seems to accelerate, with Japan and California leading the deployment effort. There is a number of hydrogen refuelling stations (HRS) deployed in different countries: California (34), Japan (100), South Korea (12), Germany (43), France (5), Denmark (7). The number of vehicles deployed follows progressively: California (1300), Japan (2300), South Korea (150), Denmark (21), Germany (125), France (100).

A detailed analysis of the current national road maps suggests that FCEV has a large potential (Brunet, Kotelnikova, Ponssard, 2015). Targets for the 2025-2030 horizons are significant in particular in Germany (4% in 2030), Denmark (4.5% in 2025) and Japan (15-20% for ZEV new registrations in 2020). The California ARB has recently redefined its program (subsidies and mandates) to provide higher incentives for FCEV. France appears to focus on specialized regional submarkets to promote FCEV (such as the use of hydrogen range extending light utility vehicles). The financing of the hydrogen infrastructure appears as a bottleneck for FCEV deployment. Roadmaps address this issue through progressive geographical expansion (clusters) and a high level of public subsidies for hydrogen refueling stations.

To reach a substantial long-term market share hydrogen mobility should, however, overcome a number of important deployment challenges: decarbonisation of hydrogen production; coordinated deployment of hydrogen distribution infrastructure; and severe cost competition with incumbent gasoline technology.

5. HYDROGEN DECARBONISING INDUSTRY ENERGY USE

Industry accounts for a third of the final energy consumption and a quarter of CO₂ emissions. Two-thirds of all energy in “industries” is consumed by only five industries: aluminum, chemicals, petrochemicals, and refining; cement; iron and steel; and pulp and paper.

With the final energy consumption of the global industry expected to increase, decarbonising industry is also expected to increase. Hydrogen as an energy carrier could be the key to decarbonisation in industries. By 2050, the demand for hydrogen could rise to 70 million tons (10 EJ), driven by the growth in global chemicals production (Hydrogen Scaling up, 2017). If this hydrogen is produced from non-clean sources, it would create emissions of about 500 Mt of carbon dioxide; highlighting the important role of hydrogen in decarbonising industry.

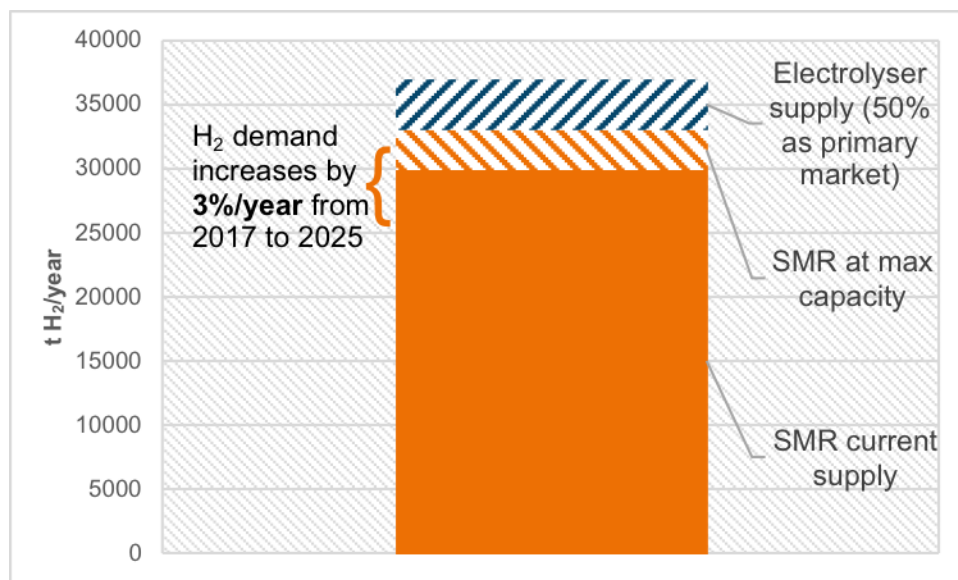
Hydrogen in large industry: refineries

Hydrogen is used to process crude oil into refined fuels, such as gasoline and diesel, and also for removing contaminants, from these fuels.

Due to higher quality requirements on produced fuel and lower input quality of crude oil, hydrogen demand is increasing. Approximately 75% of the hydrogen currently consumed worldwide by oil refineries is supplied by large hydrogen plants that generate hydrogen from natural gas or other hydrocarbon fuels.

In Japan, Osaka University together with Kawasaki, Obayashi, Kansai, Iwatani, Kobe City is working on a project that started in operations from 2018. Operations of a 1,000-kW-class power plant is expected to run on a flexible blend of natural gas and hydrogen (from 0 to 100% hydrogen). This is anticipated to be one of several potential projects in Japan.

According to EIA data, much of the growth in hydrogen use at refineries is being satisfied through hydrogen purchased from merchant suppliers rather than from increased hydrogen production on-site at the refinery. However, the ability of electrolyser to satisfy part of the refinery hydrogen demand is increasing and is further expected to increase. It has a projected growth rate of 3%/year from 2017 to 2025. This represents a cumulated hydrogen increase of approx. 7000 t/year by 2025 in a typical refinery.

Figure 8: Hydrogen demand in refinery

Source: Tractebel, Hincio, 2017.

Hydrogen in large industry: steel manufacturers

Hydrogen is used in the production of carbon steels, special metals and semiconductors. In the electronics industry, it is widely employed as a reducing agent and as a carrier gas. Hydrogen is a very good reducing agent to make steel from iron ore (integrated production route).

Through the following process, a reduction of iron of up to 85% can be achieved. Iron ore could initially be reduced to iron in a direct reduction reactor with the aid of natural gas and a higher volume of hydrogen. A reaction that takes place at 950 °C produces sponge iron. Through an integrated process, gas is introduced in a circular pattern and, after separation of the water produced by the reduction, cleansed of any remaining CO₂ and reused.

The integration of new facilities into existing steelworks is the challenge inherent in direct reduction. Carbon dioxide savings of initially up to 50% are theoretically possible through the gradual implementation of a reactor of this kind. This figure can be raised to as much as 85% in the future, if direct reduction plant of the entire production is achieved.

Beyond the challenges of the integration of new facilities into the existing infrastructure. The flexible use of hydrogen and natural gas and reduction agents in the direct reduction process as well as the flexible hydrogen production based on renewable energies is also a challenge that needs to be met.

Since March 2016, Salzgitter AG together with Sunfire GmbH and other partners have been cooperating in an EU research project: GrInHy (Green Industrial Hydrogen via reversible high-temperature electrolysis) to produce hydrogen. The facilities in Salzgitter also feature the world's currently most powerful reversible high-temperature electrolyser.

Hydrogen in large industry: chemical industry

In the chemical industry, hydrogen is one of the key starting materials used. Hydrogen is used in the manufacture of two of the most important chemical compounds made industrially, ammonia and methanol (the manufacture of many polymers).

The most important hydrogen-nitrogen compound is ammonia (NH_3), also known as azane. Through the Haber-Bosch process, ammonia is able to be obtained on a large scale. This process combines hydrogen and nitrogen together directly by synthesis.

Taking the example of Dutch chemical industry for the potential impact of power to hydrogen in the chemical industry: full replacement of hydrogen production using natural gas by electrolysis would lead to a CO_2 emission reduction in the chemical industry up to 4.1 Mt in the country. However, the production of large amounts of hydrogen would be needed. If this is achieved through electrolysis, it would require large amounts of electricity, leading to a considerable increase in electricity demand and reduction in natural gas demand. Further challenges include the difference in investment viewpoint and actual operations. Investment viewpoint would desire full load operations, but keeping in mind the average amount full load hours of the units for installed capacity of electrolyzers that are often proposed or assumed; this would mean an overcapacity of electrolyzers. At an average of 50% full load hours, twice the required installed capacity of electrolyzers would be required, amounting to six GW for the Dutch chemical industry's power to hydrogen.

6. HYDROGEN SERVING AS FEEDSTOCK USING CAPTURED CARBON

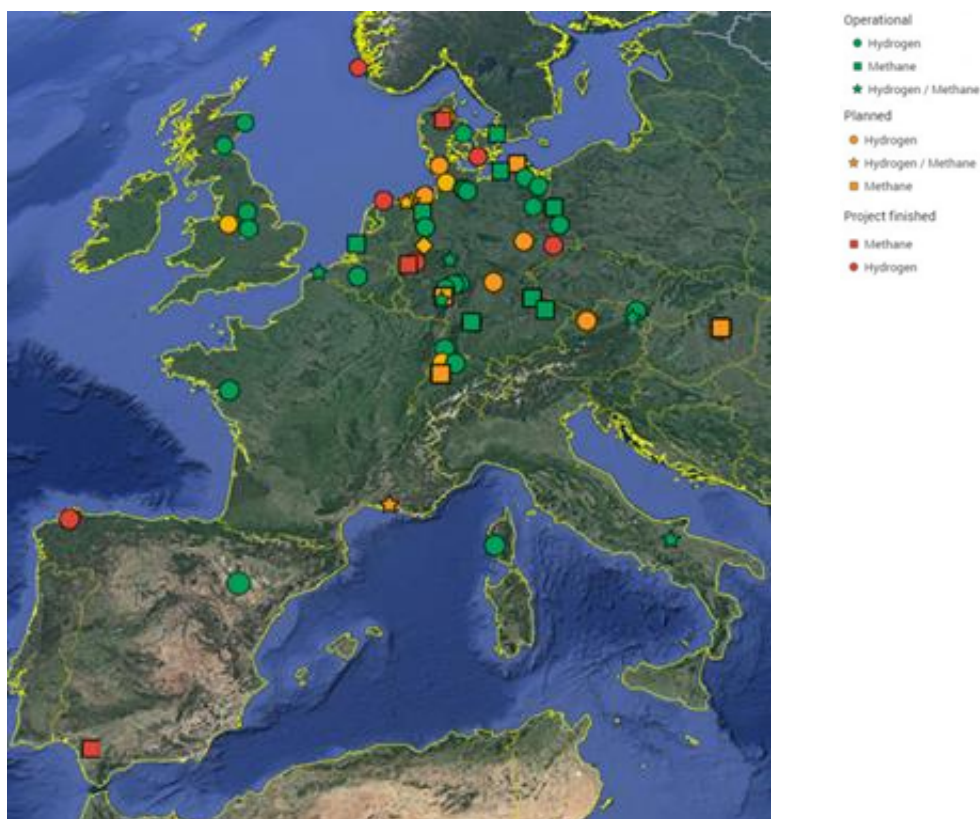
Methane

Hydrogen can be produced using electricity from renewable sources, which can be referred as renewable hydrogen. It is the product of the power-to-gas process described in one of the previous chapters.

Through this process, synthetic methane can be produced (power-to-methane). Hydrogen is produced via electrolysis of water and used to hydrogenate CO₂ in a methanation process. The product is pure methane which can be injected in the gas grid as it is compatible with the natural gas networks specifications and storage infrastructures.

Methanation can be done in biological and catalytic methanation reactors. For catalytic methanation, which is the most extended and developed option, in general fixed-bed reactors are used and different reactor concepts are under development as three-phase methanation and micro reactors. For biological methanation, methanogenic microorganisms serve as biocatalysts. The biological methanation is in principle an option viable for small plant sizes and still faces technical barriers for scale-up. Today several projects with operational testing exist around the world.

Figure 9: Methanisation projects in Europe



Source: European Power to Gas, 2017. Power-to-gas demonstration projects in Europe & FEL Hydrogen Taskforce database.

To give some examples, in Europe in particular the first pilot project of power-to-methane with catalytic methanation was launched in 2009 in Germany. Together with Germany, also countries as Denmark, France, the Netherlands and Spain have developed several projects.

The STORE&GO project focuses on the integration of power-to-gas into the daily operation of European energy grids to investigate the maturity level of the technology. The project counts with three different demonstration sites: Germany (Falkenhagen), Italy (Troia) and Switzerland (Solothurn).

In Denmark a power-to-gas project via biological catalysis, the BioCat Project, was running from February 2014 to October 2016, to produce renewable gas for injection and storage in a local gas distribution grid.

Another example and one of the latest projects is located in France and will be operating in 2019, the Jupiter 1000 project, with a power rating of 1 MWe for electrolysis and a methanation process with carbon capture.

Formic acid, ammonia and hydrogen peroxide production

Hydrogen is widely used as a feedstock for production of numerous chemicals that are widely used in the industry. One example, includes ammonia. Ammonia is one of the most highly produced chemicals worldwide and used predominantly in agriculture as precursor for variety of fertilizers. It is estimated that about 80% of total ammonia produced is applied for agricultural use. Ammonia is also broadly used to manufacture plastics, explosives, fibers, nitric acid, as well as dyes and pharmaceuticals.

Modern ammonia producing plants rely on methane or LPG as a feedstock. The feedstock fuel is converted into gaseous hydrogen applying steam reforming process. Generated hydrogen is then combined with nitrogen via century old process called the Haber-Bosch process. This way of generating ammonia is both inefficient and produces greenhouse gasses such as carbon dioxide.

Thanks to recent technological developments sustainable production of ammonia is achievable. Clean or renewable ammonia uses renewable energy to generate hydrogen by electrolysis of water and then combines produced hydrogen with nitrogen in similar electrochemical ways utilizing renewable energy produced mainly from solar or wind. Practically, methane is still the cheapest source of hydrogen for ammonia production.

Hydrogen peroxide (H_2O_2) is another widely used industrial chemical which can be produced from water via electrolysis. Traditionally, hydrogen peroxide was industrially generated via hydrolysis of the ammonium peroxydisulfate, obtained by the electrolysis of ammonium bisulfate (NH_4HSO_4) solution in sulfuric acid. Nowadays, hydrogen peroxide is produced almost exclusively via anthraquinone process, where reduction of an anthraquinone to the anthrahydroquinone is performed typically via hydrogenation process using palladium catalyst. Multiple attempts have been made to produce hydrogen peroxide electrochemically using various catalysts and renewable energy, however due to the cost, this production method didn't penetrate the market. Hydrogen peroxide finds uses in bleaching and detergent production, disinfection, production of organic compounds, cosmetics industry and many others.

Formic acid (HCOOH) is an important industrial chemical used predominantly as a food preservative and antibacterial agent in livestock feed. Industrially formic acid is produced from methanol. However, niche chemical routes for production of formic acid have been explored. One of which includes electrochemical

hydrogenation of carbon dioxide. In this method hydrogen is feed together with carbon dioxide into special reactor, where under specific temperature and pressure in the presence of catalyst both reactants are turned into formic acid.

Other applications in chemistry

Hydrogenation is a chemical reaction that occurs between molecular hydrogen (H_2) and another compound or element. Hydrogenation reduces double and triple bonds in hydrocarbons. Hydrogenation literally means “to treat with hydrogen”. Hydrogenation usually requires presence of a catalyst. Most industrial hydrogenation processes use predominantly either nickel, platinum or palladium catalysts. Non-catalytic hydrogenation is possible, but it takes place at very high temperatures, and as such is not suitable for many organic compounds.

The hydrogenation process is generally employed to saturate or reduce organic compounds and results in the addition of pairs of hydrogen atoms to a chemical compound or a molecule. The process is widely used in the food industry to saturate vegetable oils. Vegetable oils are exposed to hydrogen gas in the presence of catalyst; mainly nickel based; at temperatures of about 60 °C to speed up reaction. Hydrogenation of vegetable oils changes the oil structure and properties. The carbon double bonds are converted to single bonds allowing for transition from unsaturated fats into saturated fats, same time increasing their melting point. Practically, this often means turning liquid oils into solid form; i.e. margarine; and extending the shelf life of such product. Hydrogenation can be complete or partial.

In 2017/2018, the global production of palm oil reached 66.86 million metric tons. Palm oil extraction is done predominantly in remote areas of Malaysian and Indonesian Borneo, as well as other areas in South East Asia, throughout Central Africa and Central and South America. Remoteness of the operations makes it difficult and very costly to bring large volumes of compressed hydrogen to the extraction and processing site. As such, some palm oil companies are investigating the use of solar hydrogen produced on site via electrolysis using locally available water resources. While palm oil industry is considered to be unsustainable and even damaging to the environment (IUCN report, 2018), this technological innovation adds a degree of sustainability to it.

Hydrogenation is also broadly applied in organic chemistry to convert alkenes, alkynes, as well as aldehydes, nitriles and imines into the corresponding saturated compounds, i.e. alcohols and amines.

Hydrogen and hydrogenation processes are also of a great importance to petrochemical industry, where hydrogenation is used to convert alkenes and aromatic compounds into saturated alkanes (paraffins) and cycloalkanes (naphthenes). Hydrogenation reduces the ability of these compounds to be oxidized, which is of importance to fuels stored for long periods of time in the presence of atmospheric oxygen.

Hydrocracking is another catalytic, hydrogen-heavy process widely used by petrochemical industry. Hydrocracking allows heavy crude oil residues to be converted into diesel, gasoline, kerosene and jet fuel. Generally, hydrocracking converts the high-boiling constituent hydrocarbons to more valuable lower-boiling products. The process takes place in a hydrogen-rich atmosphere at elevated temperatures ranging from 260 °C to 425 °C and pressures between 35 and 200 bar.

7. HYDROGEN HELPING DECARBONISE BUILDING HEATING

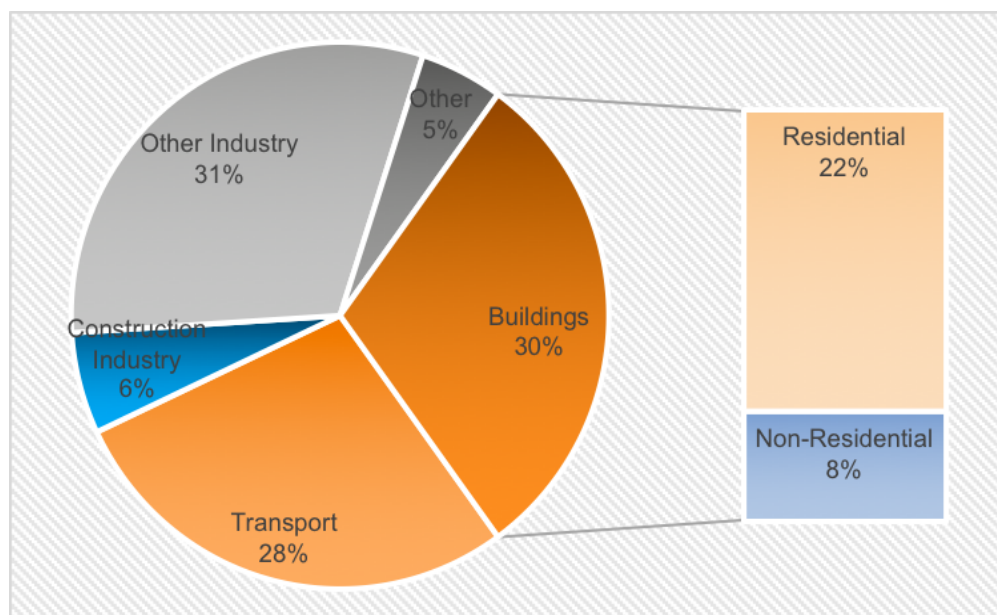
In the last decade the installed capacity of wind and solar power generation has expanded rapidly, decarbonising heat in buildings and industry is challenging. While technology options for low carbon heat are expensive, and require behavioural or technological changes, energy demand for heat is high and varies dramatically over the year. Buildings and construction together account for 36% of global final energy use and 39% of energy-related carbon dioxide (CO₂) in 2016 (UN Environment and International Energy Agency, 2017).

The global buildings sector consumed nearly 125 EJ in 2016, or 30% of total final energy use. Buildings construction, including the manufacturing of materials for building such as steel and cement, accounted for an additional 26 EJ (nearly 6%) in estimated global final energy use (see figure below).

Accounting for upstream power generation, buildings represented 28% of global energy-related CO₂ emissions, with direct emissions in buildings from fossil fuel combustion accounting for around one-third of the total. Buildings construction represented another 11% of energy sector CO₂ emissions.

Globally, fossil fuel use in buildings accounted for 36% of total final energy consumption in 2016, down slightly from 38% in 2010. Yet, that change does not tell the whole story: coal and oil use in buildings has remained practically constant since 2010. Natural gas use grew steadily by about 1% per year.

Figure 10: Carbon dioxide emission by sector



Source: UN Environment and International Energy Agency, 2017.

Building heating can use hydrogen as a fuel or leverage hydrogen technologies, or ideally a combination of both: hydrogen technologies such as fuel cell micro CHPs serve as energy converters. They offer high efficiency for heat and power generation (> 90%). Hydrogen itself can serve as a fuel (Hydrogen Council, 2017).

In homes, hydrogen could be used to power fuel cell micro-CHP, direct flame combustion boilers (similar to existing natural gas boilers), catalytic boilers and gas-powered heat pumps. A variety of larger district heat and CHP devices that use natural gas could also be redesigned to use hydrogen (Chiesa et al., 25). It would also be possible to replace a large number of natural gas processes in industry (IEA, 2005). A direct flame combustion H₂ boiler is functionally identical to the gas boilers installed in Europe and North America to supply residential central heating (DECC, 2011), except that it burns hydrogen instead of natural gas. Like natural gas boilers, direct combustion of the gas produces a series of flame jets that heat water. From a consumer perspective, there is no difference in the appearance or operation of hydrogen boilers when compared to their natural gas equivalents (Dodds et al., 2015).

Most micro-CHPs (>95%) are located in Japan, where about half run on methane combined with a reformer to produce hydrogen. Japan's ENE-FARM program is arguably the most successful fuel cell commercialization program in the world. Japan's "central role" for hydrogen includes targets of 1.4 million residential units by 2020 and 5.3 million by 2030 (about 10% of Japan's homes). Japan is exploring hydrogen pipelines to support these units, hybrid and micro-grid systems to take advantage of generating capacity.

Led by Northern Gas Network (NGN), the H₂ project was launched in 2016 to establish whether the existing gas grid of a UK city could be converted to hydrogen. They chose Leeds as a test area because of its size, location, grid complexity, and high demand. It serves gas to 1.25% of the UK's population alone. A 2016 KPMG report, 2050 Energy Scenarios, found that the cost of converting the UK to hydrogen gas could be at least £150 billion cheaper than electrification.

The Australian Renewable Energy Agency (ARENA) has provided AquaHydrex with \$5 million AUD to develop and test a pilot plant electrolyser in partnership with the Australian Gas Network (AGN). This is the first Australian "power-to-gas" trial to inject hydrogen into the gas grid (IEA Hydrogen, 2016).

Hydrogen is not directly going to assist with decarbonisation of homes. A scenario could be that in our homes we have a CHP from the gas grid and it could contain h₂ from the sources mentioned earlier. The home would use the CHP for balancing power requirements in a smart electrical system and home heating.

Chapter 3

Power-to-X: global projects review

In order to explore the full potential of hydrogen contributing to the energy transition, two parallel processes should take place: first, development of the demand markets for hydrogen energy, described in the previous chapter; and second, progressive decarbonisation of the hydrogen production.

Low-carbon hydrogen can be produced in the three different ways: via electrolysis using renewable power and via steam methane reforming coupled with either biogas or carbon capture technologies. This chapter is focused on the former and provide a global overview of projects for hydrogen production via electrolysis also known as Power-to-Gas. This global review of past and presently active, planned Power-to-X projects / pilots / case-studies / funding streams / government & industry initiatives aims developing an understanding how Power-to-X is presently facilitating the integration of renewables, decarbonisation, grid balancing, integration of mobility, industrial feedstocks and injection to gas grid.

Power-to-Gas / Power-to-X

Power-to-Gas and Power-to-X technologies are very similar but there are key process differences. Power-to-X technology, can convert excess, curtailed, constrained or dedicated renewable electrical power (e.g. wind or solar) to hydrogen at circa 75% efficiency (with zero emissions and zero carbon footprint). The X in Power-to-X technology refers to the further conversion of this produced hydrogen to liquid or gaseous chemicals or carriers or vectors. Therefore if the site just produces hydrogen gas from renewable energy it can be referred to as a Power-to-Gas site, however if the site produces any other chemical or carrier from this hydrogen it is Power-to-X.

Globally today, hydrogen is a strategically important commodity, both as a primary feedstock to the refining, fertilizer & chemical industries and as a by-product of other industrial processes. However, increased deployment of renewable energy technologies combined with global imperative to limit GHG emissions (not limited to the electricity sector), will be primary drivers for the growth of renewable gas / hydrogen and the implementation of electrolysis / hydrogen technologies into the future.

Analysis

A literature review of all hydrogen projects across the world was undertaken. A database of hydrogen projects was created from over 250 referenced documents and a number of existing databases courtesy of national funding bodies (FCH Europa, 2018). The projects were summarised according to 45 key metrics, such as project name, location, size and scale, technology, investment, application, etc. across 4 key geographic regions; Europe, Asia, Americas & Oceania. In total almost 200 projects were reviewed, a summary example of the geographic region of Asia is shown in Table 3.

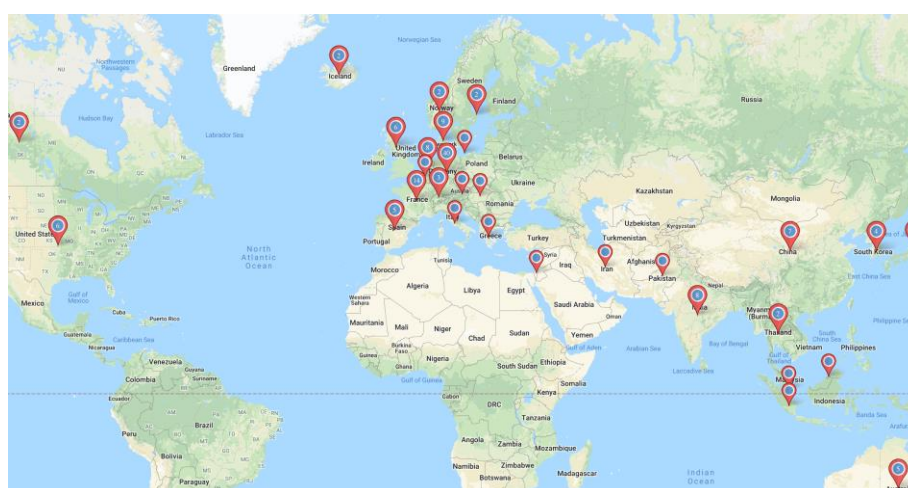
Table 3: Example of part of the P2X database collected for Asia

Project name	Schedule	Geo zone (EU, Asia, Americas)	Country	Location	End product	Scale [kWe]	Size of project (small<50kW, medium<1MW, big>1MW)
Tohoku	1995	Asia	Japan		-	10	small
Solar-hydrogen demonstration project for Pakistan	2003	Asia	Pakistan	Pakistan	Hydrogen	140	medium
Taleghan-Iran solar hydrogen energy system	2011	Asia	Iran	Taleghan	Hydrogen	10	small
Savi Wind-Hydrogen demo project	2013	Asia	India	Savi, Vadadora Gujarat	Hydrogen	5	small
Enstorage Hydrogen Bromine demo project	2013	Asia	Israel	Israel	Hydrogen	50	medium
Gyeonggi Green Energy	2014	Asia	South Korea	Hwasung City and Seoul, South Korea	Hydrogen	19600	big
SmartFuel station pilot project	2015	Asia	India	Delhi	Hydrogen	Mobility	big
MCRC bio-hydrogen facility Chennai	2015	Asia	India	Chennai	Hydrogen	1000	big
Gwalpahari Solar-Hydrogen demo project	2015	Asia	India	Gwalpahari, Gurgaon	Hydrogen	120	medium
Lam Takhong Wind Hydrogen Hybrid Project	2016	Asia	Thailand	Nakhon Ratchasima	e-	1000	big
PEMC demo facility, Chennai	2016	Asia	India	Chennai	Hydrogen	50	medium
Bio-hydrogen facility Kharagpur	2016	Asia	India	Karagpur	Hydrogen	10	small
FCV Taxi Ulsan	2016	Asia	South Korea	Ulsan	Hydrogen	-	-
Hebei	2017	Asia	China	Hebei province	Hydrogen	4000	big
Semakau EnGIE Island self-contained microgrid	2017	Asia	Singapore	Semakau Island	H2 & e-	100	medium
ALCo diesel-fuelling cell battery locomotive	2017	Asia	India	Tughlakabad	Hydrogen	300	medium
Energy Observer	2017	Asia	Japan	Japan	Hydrogen	-	-
Foshan hydrogen city	2017	Asia	China	Foshan, China	Hydrogen	100000	big
Tongji solar hybrid hydrogen	2017	Asia	China	Shanghai	Hydrogen	mobility	big
Kobe Port Island plant	2017	Asia	Japan	Kobe	Hydrogen	1100	big
Yokohama City Wind Hydrogen	2017	Asia	Japan	Yokohama	Hydrogen	2000	big
Hokkaido	2017	Asia	Japan	Hokkaido	Hydrogen	-	-
China Transportation	2018	Asia	China	unknown	Hydrogen	1000	big
South Sumatra hydrogen fleet and infrastructure	2018	Asia	Indonesia	South Sumatra	Hydrogen	c6000	big
Suzhou hydrogen city	2018	Asia	China	Suzhou, China	Hydrogen	100000	big
Wuhan hydrogen city	2018	Asia	China	Wuhan, China	Hydrogen	100000	big

1. Geographical distribution

The distribution of projects across the world was summarised to visually understand the regions where key activities are presently happening. The increasing role of renewables in the power sector has raised the need of complementary technologies to balance the grid, and, understanding that electricity cannot be stored easily, makes a space for hydrogen technologies. Analysing more than 200 Power-to-X projects, with the power demand size from 250kW to 6,300kW within 2012-2018 operational years, shows that OECD countries with national and industrial funds available, and with developed gas grid and transport infrastructure, lead the deployment, as shown in Figure 11.

Figure 11: Geographical Distribution of Power-to-X Global installations (a) Global (b) Europe (c) Asia (Power Demand Size: 250kW to 6,300kW, Years Operational: 2012-2018 inclusive)

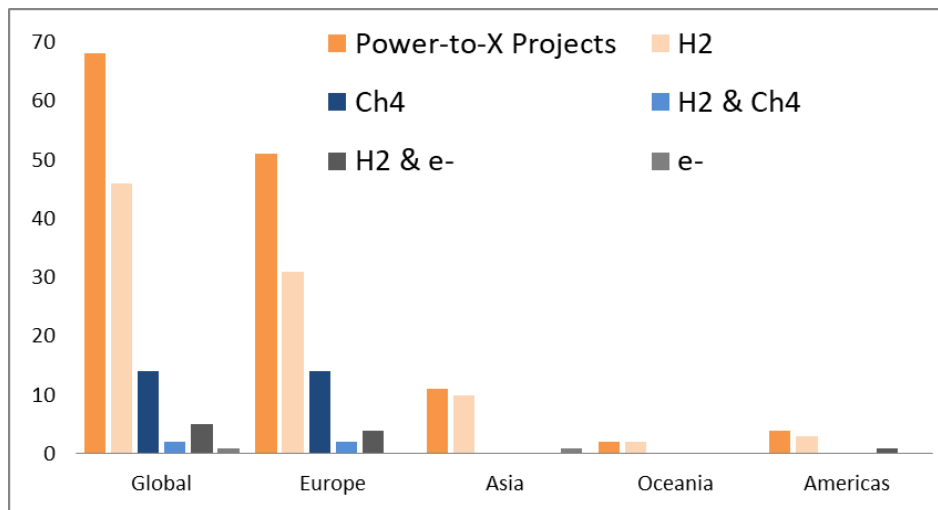


(a)



Further analysis shows that by far hydrogen gas is the most produced end product from all sites and used within many applications such as mobility, industry, oil refining and in more recent projects being injected to the natural gas grid. A minimal number of projects reused the hydrogen to generate electricity and a few demonstration projects convert the hydrogen to methane before it's use in mobility or gas grid injection.

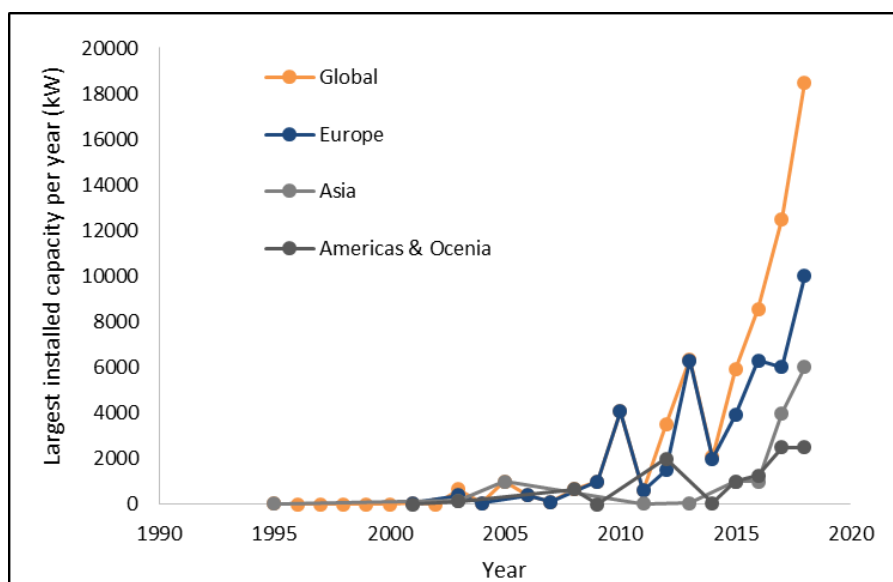
Figure 12: Geographical Distribution of Power-to-X Global installations & Output type (Power Demand Size: 250kW to 6,300kW, Years Operational: 2012-2018 inclusive)



2. Evolution of size of installation through time

Electrolysis technology is beginning to scale up and in the last 5 years bigger systems have been demonstrated across the globe, matching with demand for green hydrogen in mobility and industrial applications, as presented in Figure 13.

Figure 13: Power-to-X installed electrolyser Capacity & Geographical Distribution



Key findings

The aim of this project was to present the existing state of play of Power-to-X technology and understand its Global development path and connection with the rest of the energy sector. Our key messages are:

- Analysis of more than 200 Power-to-X projects shows that OECD countries with national and industrial funds available, and with developed gas grid and transport infrastructure, lead the deployment of Power-to-X technology.
- Power-to-X technology is technologically mature and has been deployed at scale for almost a decade across the globe, with over 70 projects globally operational in the scale of between 250kW to 6,300kW of electrolyser capacity. In addition the average size of Power-to-X installation has grown over time with larger units (6MW - 10MW) being deployed today.
- Hydrogen has an added value to renewables: it can store renewable energy and convert this clean energy into fuel for cars; chemicals for industry, and gas for the grid.

Chapter 4

Key messages and policy recommendation to accelerate the Grand Transition through hydrogen vector

KEY MESSAGES AND RECOMMENDATIONS

Between 2000 and about 2010, hydrogen made a lot of hype as a potential energy source and ultimate solution for transportation, energy storage and other industries. In 2008, President Obama was one of the supporters of hydrogen economy. However, back then both hydrogen generation via electrolysis and fuel cells had not been commercially ready. It took about eight years and vast amount of funding to solve many engineering issues, develop new materials and improve the conversion efficiency.

The hydrogen economy has made a big come back in the last two to three years and it seems that industry is getting more and more convinced about hydrogen. Previous failures can be treated as viable lessons in the next wave of hydrogen economy. However, governmental and industrial support is necessary to make this promising shift happen. Raising community awareness and educating citizens about pros and cons of hydrogen should be an essential part of this transition strategy.

Here we summarize key messages of this report and recommend steps to be considered when enabling the Grand Transition through hydrogen as a vector, these comprise of:

- Hydrogen has a large potential in enabling the Grand Transition via its systemic contribution to the entire energy system: from energy production decarbonisation to the electrification of the end uses;
- Hydrogen technologies are market mature and are being deployed in different sectors all across the globe;
- Being in initial market deployment stage hydrogen energy requires the development and implementation of coherent regulations and policy framework that enables long-term implementation and profitability of hydrogen economy across different sectors (including transportation, energy storage, etc.);
- Current successful project examples show that the implementation of a reward schemes for projects and technologies that meet the above policy objectives, including but not limited to tax incentives and rebates, technology implementation grants and subsidies, long-term state engagement roadmaps etc.;
- Industrial global associations ensure an aligned industrial vision of hydrogen enabling the Grand Transition and give a strong positive signal for market to further develop and deploy low-carbon hydrogen technologies; and
- Extensive communication, education and training initiatives are necessary to promote public acceptance of hydrogen and to build skills and workforce to deliver the transition to hydrogen-based low-carbon economy.

The Grand Energy Transition is a complex global pressing issue (World Energy Council, World Energy Issue Monitor, 2018) and requires system solutions: hydrogen being one of it. Hydrogen is versatile energy vector capable to address multiple energy challenges: from facilitating the massive integration of renewables and decarbonisation of energy production, to energy transportation in a zero-carbon energy economy, to electrification of the end uses. Facing an unfair competition from incumbent carbon-based technologies, hydrogen as other green technologies, requires an alignment of industrial, policy and society actors in order to put in place a coherent deployment framework and allow the Grand Transition happen. This report assesses the potential of hydrogen to enable the Grand Transition and hopefully contributes to make an extra small step towards it success.

LIST OF TABLES AND FIGURES

FIGURES

Figure 1: Seven roles of hydrogen in enabling the Grand Transition	12
Figure 2: Global cumulative renewables installations growth.....	15
Figure 3: Power to hydrogen business model	17
Figure 4: Hydrogen sources, production, distribution and applications	19
Figure 5: The H21 Leeds City Gate concept	24
Figure 6: Emissions and autonomy of different powertrains.....	26
Figure 7: Hydrogen market potential at different transportation segments.....	26
Figure 8: Hydrogen demand in refinery	29
Figure 9: Methanisation projects in Europe	31
Figure 10: Carbon dioxide emission by sector	34
Figure 11: Geographical Distribution of Power-to-X Global installations (a) Global (b) Europe (c) Asia (Power Demand Size: 250kW to 6,300kW, Years Operational: 2012-2018 inclusive)	38
Figure 12: Geographical Distribution of Power-to-X Global installations & Output type (Power Demand Size: 250kW to 6,300kW, Years Operational: 2012-2018 inclusive)	39
Figure 13: Power-to-X installed electrolyser Capacity & Geographical Distribution	40

TABLES

Table 1: System components included in delivery pathways	20
Table 2: Road delivery comparison	20
Table 3: Example of part of the P2X database collected for Asia	38

GLOSSARY

\$:	United States dollar, currency
%:	percent
£:	British pound, currency
°C:	Degrees Celsius, unit of temperature
ADB:	Asian Development Bank
AGN:	Australian Gas Network
ARENA:	Australian Renewable Energy Agency
AUD:	Australian dollar, currency
BEV:	Battery Electric Vehicles
CCS:	Carbon Capture and Storage
CH₄:	Methane
CHP:	Combined Heat and Power
CO₂:	Carbon Dioxide
DDP:	Dual Diploma Programme
DRI:	Direct Reduced Iron
EC:	European Commission
EIA:	Energy Information Administration
EJ:	Exajoule, unit of energy
EU:	European Union
FCEV:	Fuel-Cell Electric Vehicles
FEL-100:	[World Energy Council] Future Energy Leaders
G20:	Group of twenty
GGE:	Gasoline Gallon Equivalent, unit of energy
GHG:	Greenhouse gas
GmbH:	Gesellschaft mit beschränkter Haftung, private entity in Germany
GrInHy:	Green Industrial Hydrogen via Reversible High-temperature Electrolysis, European Union project
GW:	Gigawatt, unit of power
H₂:	Hydrogen
H21:	H21 Leeds City Gate, hydrogen project
H₂O₂:	Hydrogen peroxide
HCOOH:	Formic acid
HRS:	Hydrogen Refuelling Stations
ICE:	Internal Combustion Engine
IEA:	International Energy Agency
IRENA:	International Renewable Energy Agency
IUCN:	International Union for the conservation of Nature
kg:	kilogram, unit of weight
km:	Kilometre, unit of length
KPMG:	Klynveld Peat Marwick Goerdeler, accounting firm
kW:	Kilowatt, unit of power
LCOE:	Levelized Cost of Electricity
LNG:	Liquefied Natural Gas
LPG:	Liquefied petroleum gas

MENA: Middle East and North Africa
MIT: Massachusetts Institute of technology
Mt: Megaton, unit of weight
MW: Megawatt, unit of power
MWe: Megawatt electrical, unit of power
NATO: North Atlantic Treaty Organisation
NDC: Nationsl Determined Contribution
NGN: Northern Gas Network
NGO: Non-Governmental Organisation
NH₃: Ammonia
NH₄HSO₄: Ammonium bisulfate
NO₂: Nitrogen Dioxide
ODA: Official Development Assistance
OECD: Organisation for Economic Co-operation and Development
P2G: Power to Gas
PEM: Proton Exchange Membrane
Ph.D.: Doctor of Philosophy
PHEV: Plug-in Hybrid Electric Vehicle
PHS: Pumped Hydrogen Storage
PV: Photovoltaic
R&D: Research and Development
SMR: Steam Methane Reforming
SUNY: State University of New York
t: ton
UK: United Kingdom
UN: United Nations
US: United Stats [of Amercia]
USA: United States of America
USD: United States Dollar, currency
ZEV: Zero Emission Vehicles

REFERENCES

- Asian Development Bank (ADB) (2009) Rethinking Transport and Climate Change. ADB Sustainable Development Working Paper Series. Retrieved from <https://www.adb.org/sites/default/files/publication/28489/adb-wp10-rethinking-transport-climate-change.pdf>
- Australian Renewable Energy Agency (2018) Hydrogen to become Australia's next big export? ARENA Wire. <https://arena.gov.au/blog/hydrogen-to-become-australias-next-big-export/>
- Balat M. (2008). Potential importance of hydrogen as a future solution to environmental and transportation problems. *Int. J. Hydrogen Energy* 33, 4013–4029.
- Bird L., Milligan M., and Lew D. (2013). Integrating Variable Renewable Energy: Challenges and Solutions (No. NREL/TP-6A20-60451) (p. 14). Golden, Colorado: National Renewable Energy Laboratory (NREL). Retrieved from <http://www.nrel.gov/docs/fy13osti/60451.pdf>.
- Chiesa P, Lozza G, Mazzocchi L (2005). Using hydrogen as gas turbine fuel. *Journal of Engine Gas Turbines Power* 127:73e80.
- DECC (2011). Great Britain's housing energy fact file. London, UK: Department of Energy and Climate Change.
- Dodds PE., Staffell I., Hawkes AD., Li F., Grünewald P., McDowall W., and Ekins P. (2015). Hydrogen and fuel cell technologies for heating: A review. *International journal of hydrogen energy*, 40(5), 2065-2083.
- Ela E. and O'Malley M. (2012) Studying the variability and uncertainty impacts of variable generation at multiple timescales. *IEEE Transactions on Power Systems* 27(3):1324.
- European Environment Agency (2018) Greenhouse gas emissions from transport. Retrieved on 15/12/2018 from <https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11>
- FCH Europa (2018) Database of hydrogen projects <https://www.fch.europa.eu/page/fch-ju-funded-demonstration-projects-transport-and-energy-map>. Accessed Nov 2018.
- FuelsEurope (2018) Vision 2050: A Pathway for the Evolution of the Refining Industry and Liquid Fuels
- Hart D., Howes J., Lehner F., Dodds P., Hughes, N., Birgit, F., and Sabio, N. (2015). Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target. Committee on Climate Change: London, UK.
- Hart D, Howes J, Madden B and Boyd E. (2016). Hydrogen and Fuel Cells: Opportunities for Growth. A Roadmap for the UK. E4Tech and Element Energy.
- Hinkley (2016) Cost assessment of hydrogen production from PV and electrolysis. CSIRO, Australia.
- Hirst E., and Kerby B. (1996) Ancillary-Service Costs for Ten U.S. Electric Utilities, ORNL/CON- 427, Draft, Oak Ridge National Laboratory, Oak Ridge, TN, January.
- Hydrogen Council (2017). Hydrogen scaling up - A sustainable pathway for the global energy transition.
- Hydrogen Council (2017) How Hydrogen Empowers the Energy Transition.
- The Hydrogen Council (2018) <http://hydrogencouncil.com/> Accessed Nov 2018.

- HyWays (2008). The European Hydrogen Energy Roadmap. Brussels. Available at http://www.hyways.de/docs/Brochures_and_Flyers/HyWays_Roadmap_FINAL_22FEB2008.pdf
- International Energy Agency (IEA) (2005). Prospects for hydrogen and fuel cells. Paris, France.
- International Energy Agency (IEA) (2013) International Energy Outlook report. Available at <http://www.iea.org/publications/freepublications/publication/WEO2013.pdf>
- International Energy Agency (IEA) (2015). Technology Roadmap Hydrogen and Fuel Cells Hydrogen and Fuel Cells. Available at <https://webstore.iea.org/technology-roadmap-hydrogen-and-fuel-cells>
- International Energy Agency (IEA) Hydrogen (2016). Global Trends and Outlook for Hydrogen.
- International Energy Agency (IEA) (2017). Perspectives for the Energy Transition: Investment Needs for a Low Carbon Energy System.
- International Renewable Energy Agency (IRENA) (2017) Electricity Storage and Renewables Costs and Markets to 2030.
- International Renewable Energy Agency (IRENA) (2018) The Global Energy Transformation: A Roadmap to 2050.
- International Union for the Conservation of Nature (IUCN) (2018) Oil palm and biodiversity: a situation analysis by the IUCN Oil Palm Task Force. Available at <https://portals.iucn.org/library/node/47753>
- Kotelnikova A. (2016). Analysis of a hydrogen-based transport system and the role of public policy in the transition to a decarbonised economy. Diss. Université Paris-Saclay.
- Lazzaro K. (2018) World-first coal to hydrogen plant trial launched in Victoria. ABC News. <http://www.abc.net.au/news/2018-04-12/coal-to-hydrogen-trial-for-latrobe-valley/9643570>
- McKinsey. (2010). A portfolio of power-trains for Europe: a fact-based analysis - The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. Fuel Cell, (FCEV; BEV), 68. Available at http://www.iphe.net/docs/Resources/Power_trains_for_Europe.pdf
- National Research Council. (2004). The hydrogen economy: opportunities, costs, barriers, and R&D needs. National Academies Press.
- Northern Gas Networks. (2016). H21 Leeds City Gate Report. Available at: <https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf>
- Norjidi D. (2017) Brunei hydrogen plant to fuel cars at Tokyo Olympics. Borneo Bulletin. <https://borneobulletin.com.bn/brunei-hydrogen-plant-to-fuel-cars-at-tokyo-olympics/>
- PowerWeb (2018) Forecast International's Energy Portal.
- Power-to-X the Future Energy Leaders Taskforce; Alena Fargere, James Carton, Lucia Fuselli, Cansu Karaca, WEW Milan 2018.
- Roads2Hycom (2009). Fuel Cells and Hydrogen in a Sustainable Energy Economy. Available at http://www.earpa.eu/docs/2008/roads2hycom_brochure_V5.pdf
- Schmidt O., Gambhir A., Staffell I., Nelson J., Few S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy. 42(52): 30470-30492.

Staffell I., Dodds P., and Scamman D. (2017). The role of hydrogen and fuel cells in future energy systems. H2FC SUPERGEN, London, UK.

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) (2017). Study on early business cases for H₂ in energy storage and more broadly power to H₂ applications.

Tractebel Engie and Hincio (2017) Study on Early Business Cases for H₂ in Energy Storage and More Broadly Power to H₂ Applications.

UN Environment and International Energy Agency (2017): Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report.

United Nations Framework Convention on Climate Change website: Paris Agreement – NDCs

Wong A. (2018) AHEAD to begin world's first international supply of hydrogen from Brunei in 2020. Biz Brunei. <https://www.bizbrunei.com/2018/04/ahead-to-begin-worlds-first-international-supply-of-hydrogen-from-brunei-in-2020/>

World Energy Council (2016) World Energy Scenarios: The Grand Transition.

World Energy Council (2018) World Energy Issues Monitor 2018.

Yang C., and Ogden J. (2007). Determining the lowest-cost hydrogen delivery mode. International Journal of Hydrogen Energy, 32(2), 268-286.