H2B – Tapping Hydrogen's Potential:
an IEA Hydrogen Perspective

Mary-Rose de Valladares
Paul Lucchese

WKO AFCO

Wien

30 January 2020

Outline for Tapping Hydrogen's Potential

- **Strategic advantages of hydrogen**
- **IEA Hydrogen TCP**
- **IEA report – *The Future of Hydrogen***
- **The Supply Chain/Value Chain; Cost**
- **Trade**

Strategic Advantages of Hydrogen

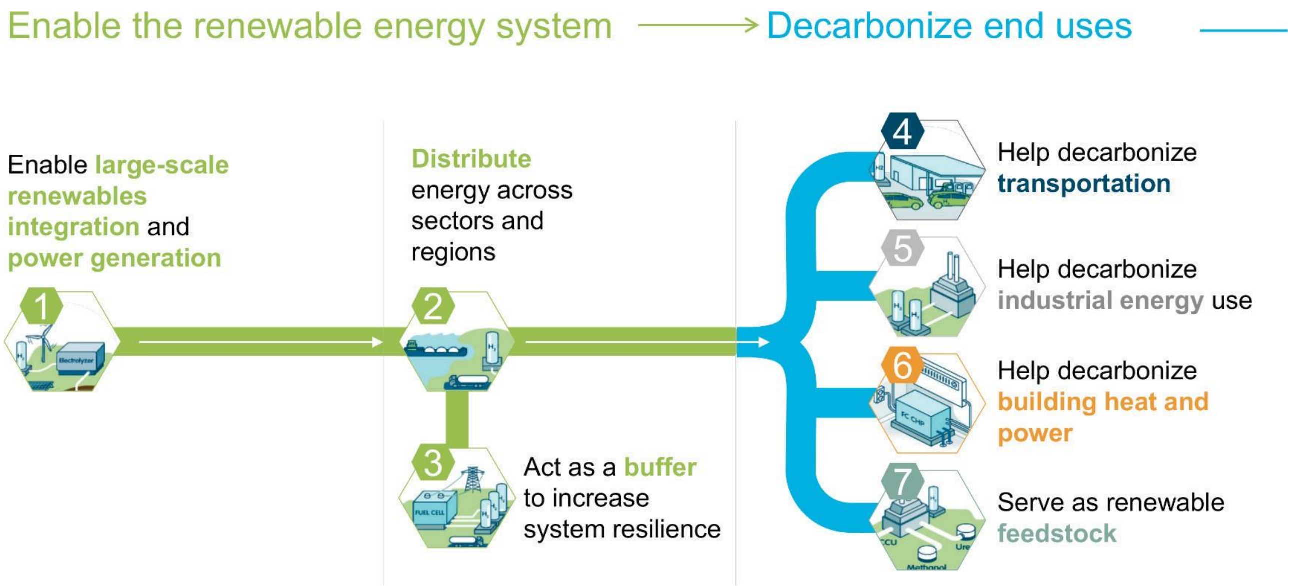
Hydrogen can play a transformative role as a highly flexible energy carrier during the clean energy transition and in an integrated future multi-sector energy system:

- **For Sector coupling - as a bridge between different types of energies**
- **For Storage – utilizing electrical energy that would otherwise have been lost**
- **For Storage – enabling use of massive quantities of renewable energy**
- **For Stability - balancing grid and buffering energy system**
- **For Decarbonization – as a building block of all electrofuels**
- **For Feedstock – using captured carbon**
- **For Certainty – avoiding CO2 capture from air**

Hydrogen is a fuel, an energy carrier and a building block of all electrofuels (power-to-gas/liquids/fuels or synthetic fuels)

HYDROGEN - fuel and energy carrier

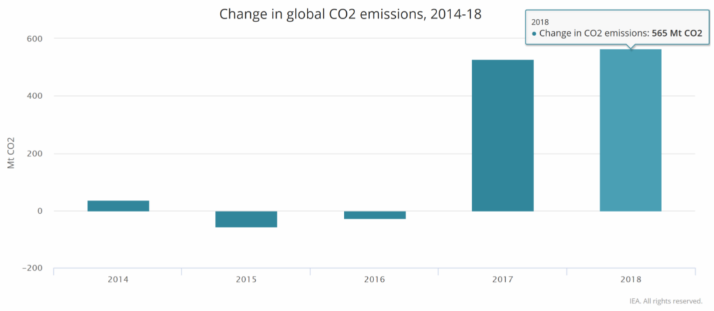
Key to support the energy transition



Source: Hydrogen Council

TODAY: After a 3 year stabilization period, CO_2 emissions rising again

(Fatih Birol Executive Director IEA



Source IEA 2019

China and coal

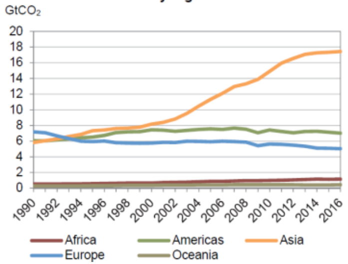


Figure 5. CO_2 emissions from fuel combustion: by region

Despite impressive growth
in Variable Renewables Deployment
(1000GW PV+Wind)
… but for < 1 % World final
energy consumption

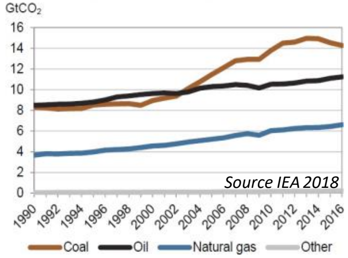


Figure 8. CO_2 emissions by source

Source Wikipedia, BP Statistical review, Irena Renewables Capacity Statistic 2018

IEA Hydrogen TCP – *Global Hub for Hydrogen R,D&D*

Vision – a hydrogen future based on a clean, sustainable energy supply of global proportions that plays a key role in all sectors of the economy

Mission – accelerate H2 implementation and utilization to optimize environmental protection, improve energy security and economic development

Strategy -
Facilitate, coordinate and maintain innovative research, development and demonstration activities through international cooperation and information exchange

Collaborative R,D&D Portfolios
- Production
- Storage
- Integrated Systems
- Integrated Infrastructure

Analysis Portfolios
- Technical
- Market
- Political Decision-making

Awareness, Understanding & Assessment (AUA) Portfolios
- Information Dissemination
- Safety
- Outreach

IEA Hydrogen Members - Executive Committee (January 2020)

European Commission
Dr Beatriz Acosta-Iborra

UNIDO (UN)
Mr Naoki Torii

Europe

Austria
Dr Theodor Zillner

Belgium
Mr Adwin Martens
Dr Joris Proost

Canada
Dr. Jocelyn Millette

Denmark
Mr Jan Jensen

Finland
Dr Michael Gasik

France
Mr Paul Lucchese

Greece
Dr Elli Varkaraki

Germany
TBD

Italy
Dr Alberto Giaconia

Lithuania
Dr R. Urbonas

Norway
Dr. Øystein Ulleberg

Portugal
Dr. Paul Partidario

Spain
Dr M Pilar Argumosa

Sweden
Dr Mikael Lindqvist

Switzerland
Dr Stefan Oberholzer

The Netherlands
Dr Herman Prinsen

United Kingdom
Mr John Foyster

Hychico
Mr Sergio M. Raballo

Shell
Dr C. Patil

Middle East

Israel
Dr Meital Fresher

NOW
Dr Geert Tjarks

Southern Company
Dr N. Meeks

Hydrogen Council
Mr Guillaume de Smedt

Reliance Industries Ltd
Dr Anurag Pandey

Asia - Pacific

Japan
Mr Eiji Ohira

Korea
Dr H-W Lee
Mr. Seok-Jai Choi

PRC
Dr P. Chen &
Dr Lijun Jiang

Oceania

Australia
Dr Craig Buckley

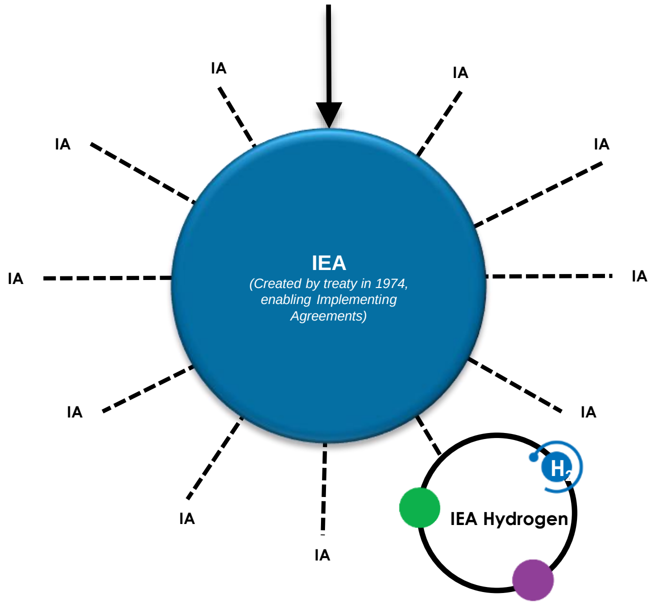
New Zealand
Dr J. Leaver

23 Countries + European Commission + UN + 6 Sponsors (Argentina in accession)

OECD

Organisation for Economic Co-operation and Development

(Created by treaty post war)



International Energy Agency Hydrogen Technology Program
(Created by treaty in 1977)

IEA Hydrogen Strategic Plan 2020-2025 – Overarching Objectives

Overarching Objectives that inform Work Plan for 2020-2025 Term

Special focus	**Place special focus on the role of hydrogen as a facilitator for a smart, sustainable energy system based on renewables: hydrogen as an energy carrier; hydrogen as an energy storage medium; hydrogen as an intermediate for e-fuels and chemicals; hydrogen for smart cities.**
Climate	Elaborate the role of hydrogen in deep decarbonization and sustainability of the energy system for transport, power, heating/cooling and industrial uses, highlighting hydrogen's importance in sector-coupling and energy storage, as well as infrastructure.
Core	Sustain the focus on the Hydrogen TCP's core business of R,D&D cooperation on production, storage, infrastructure, distribution, and safety—enlarging the spectrum of hydrogen applications.
Global analysis	Consolidate reference database and global sector analysis, maintaining a "living document" on technology development and learning experiences, including roadmaps and modeling results.
Outreach	Communicate Hydrogen TCP knowledge and results, as well as hydrogen information from governments, industries and academe to policy-makers, decision-makers, and the greater public.
Demand and trade	Grow global demand for hydrogen and power to gas, while paying special attention to high-growth economies and supporting development of a long-distance supply chain and hydrogen trade.
Hydrogen TCP role	Position Hydrogen TCP as a hub for international collaboration on hydrogen R,D&D within the IEA Technology Network, as well as in the greater energy community, while cooperating closely with the new IEA hydrogen initiative.
Hydrogen TCP capacity	Enlarge Hydrogen TCP expert network and grow Hydrogen TCP membership, thus enhancing resources and capabilities.

Products & Activities

- End of Task Workshops
- External Conference Participation
- IEA Conferences and Events
- IEA Hydrogen Awareness-Building Events
- Social media campaign (growing Twitter following)

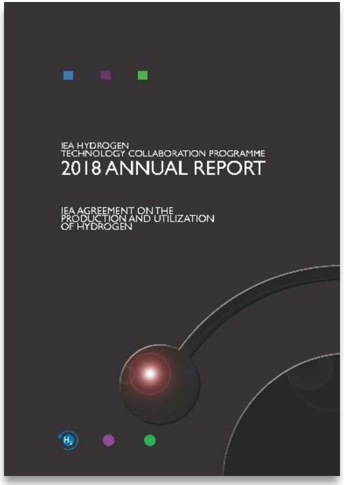
IEA H2 newsletter

IEA H2 Website

IEA H2 Executive Summary

CONNECT WITH IEA HYDROGEN

IEA Hydrogen is an IEA Technology Collaboration Programme (TCP)



Follow us on Twitter @IEA_hydrogen

IEA Hydrogen TCP Tasks – 2015-2020 (January 2020)

Created 6 October 1977

41 tasks approved in whole or part to date – production is most frequent task topic

NR	NAME	15	16	17	18	19	20	21	22	23	STATUS
28	Large Scale Hydrogen Delivery Infrastructure										completed
29	Distributed and Community Hydrogen (DISCO-H2)										completed
32	H2Based Energy Storage										completed
33	LOCAL H2 Supply For Energy Applications										completed
34	BioH2 for Energy & Environment (Successor to Task 21)										completing
35	Renewable Hydrogen (Super Task)										completing
36	Life Cycle Sustainability Assessment (LCSA) (Successor Task 30)										completed
37	Safety (Successor to Task 31; extended 3 years through 2021)										current
38	Power-to-Hydrogen and Hydrogen to X										current
39	Hydrogen in Marine Transport										current
40	Energy Storage and Conversion based on Hydrogen										current
41	Analysis and modeling – a reference database (likely to become a "standing task")										ST C approved others in definition
i	Successor tasks for renewable electrolysis, photoelectrochemical water-splitting (PEC), and solar thermochemical hydrogen production										in definition
ii	Biological production & conversion of H2 for energy and chemicals (Successor Task 34)										in definition
iii	Hydrogen Export Supply Chains										in definition
iv	Hydrogen Applications In Primary Sectors (agriculture, mining and resource)										in definition
v	Industrial Use of Hydrogen in Middle Income Developing countries										proposed new

#	NAME, DATE	FINDINGS/RESULTS, LESSONS LEARNED & SUCCESS STORIES
	Portfolio	PRODUCTS
28	Large-Scale Hydrogen Delivery Infrastructure (2010-2013) *H2 Integration in Existing Infrastructure*	FCEVs are technically ready for market; there are no technical barriers to commercialization; no single blueprint for HRS. Market development is bottlenecked, necessitating involvement of all stakeholders.
		Final report (late 2015) - *Large-Scale Hydrogen Delivery Infrastructure-Final Report Expert Group Task 28*, Weeda and Elgowainy.
29	Distributed and Community Hydrogen (DISCO H2) (2010-2016) *Integrated H2 Systems* and *Analysis*	H2 would be more cost-competitive if more financial value were ascribed to environmental benefits, particularly to climate change mitigation. Homer analysis of techno-economic aspects was performed for each project. Task was seriously disrupted by loss of OA, but rescued by Japan's support of new OA. Task completion is success story, as is development of Market Readiness Level (MRL) template tool.
		Final reports (2017) - *DISCO H2*, Ito; *Subtask 3 - Model Concept Development*, Ito; *Subtask 4 - Replicability and Market Readiness of the Six Case Study Technologies*, Gardiner. Created template tool for Market Readiness Levels (MRL). End-of-task workshop.
32	Hydrogen-Based Energy Storage (2013-2018) *Storage*	World's largest R&D collaboration in H2 storage: 52 experts from 17 Member countries organized in six working groups. Progress with adsorbent-based hydrogen storage; progress with Ni-MH batteries for energy storage as cheaper, safer and simpler than Li-ion batteries (in demo stage); modified Sodium hydride (NaH) shown to be reversible after four cycles. Ferroamp EnergyHub system (using Nilar Ni-MH battery packs) will enter into full-scale production, providing up to 200 kWh energy storage. Case study in efficiency of H2 storage concluded that 28,500 t molten salt could be replaced by 1,100 t MgH2 in Andasol, Spain's concentrated solar thermal energy system. Prolific publication record is success story.
		Final report - Part 1 - final public report organized by working group (in progress); **Part** 2 (special issue of *IJHE*) - Seven papers with 60 affiliations published February 2019. Special issue of *Applied Physics, A Springer* (April 2016) comprised 8 papers with 66 affiliations. Plus, Task 32 experts published >600 other publications.

End of Term Report 2015 – 2020 *Continued*

#	NAME, DATE	FINDINGS/RESULTS, LESSONS LEARNED & SUCCESS STORIES
	Portfolio	PRODUCTS
		Final report - Part 1 - final public report organized by working group (in progress); **Part** 2 (special issue of *IJHE*) - Seven papers with 60 affiliations published February 2019. Special issue of *Applied Physics, A Springer* (April 2016) comprised 8 papers with 66 affiliations. Plus, Task 32 experts published >600 other publications.
33	Local H2 Supply for Energy Applications (2013-2016) *Production, Infrastructure*	80% of participants from industry; created industry electrolyser network. Cooperated with AFC TCP. **ELECTROLYZER** findings/results - Industrial alkaline and PEM electrolyser systems commercially available in containerized units (ca.10-300 Nm3/h per unit), but capital costs for pressurized water-electrolyser systems in new local supply markets require cost reduction. Reduction in stack cost (42-47% of total) expected with mass manufacturing. **REFORMER** findings/results - New generation, small-to-medium (ca. 10-300Nm3/hr per unit) reformers demonstrate flexibility in design, scale-up, and dynamics. New RE system concepts using novel reforming and CO2 capture and/or water electrolysis in development, with 75-80% overall system efficiency. **H2 supply to FCEVs** requires high purity (>99.97%H2). Existing HRS fueling protocols and H2 quality standard are strict, leading to extra costs, but do not represent technical barriers.
34	Biological Hydrogen for Energy and Environment (2014-2017) *Production*	Biohydrogen a viable prospect going forward. Will require consistent direct funding. Key drivers include not only renewable energy demand but also waste treatment, water recovery, and recovery of other valuable resources, such as phosphate. Biohydrogen production from wastes and low-grade biomasses will be important for waste and agro-industry. Progress in both basic and applied biohydrogen production in demonstrating bioH2 production at larger scale in industrial environment. Dark fermentative hydrogen production by integrating extractive technologies is promising.
		Close to 200 publications from H2 TCP Members Proposed successor task will focus on production and conversion of hydrogen for energy and chemicals.

End of Term Report 2015-2020 *Continued*

#	NAME, DATE	FINDINGS/RESULTS, LESSONS LEARNED & SUCCESS STORIES
	Portfolio	PRODUCTS
35	Renewable Hydrogen (2015-2017) *Production*	Combined three large and significant research areas previously organized as discrete tasks, into one super task: renewable electrolysis, photo-electrochemical production, and thermochemical production. Built network of technical experts. Collaborated with two other TCPs: AFC and SolarPACES. New world record at NREL – 16% solar to H2 efficiency in PEC water splitting; high-efficiency III-V semiconductors from Germany; and US achievement of 14% solar-to-H2 efficiency in PEC water splitting.
		Final Report - Task 35: *Renewable Hydrogen Production.* Innovative structure created international network to monitor research.
39	Hydrogen in Marine Applications (2017-2019) *Infrastructure*	Built maritime industry platform - vessels and ports; building "know-how" for sector that is primary means of transportation worldwide (responsible for 90% of all inter-country trade). Supporting development of regulatory framework for hydrogen in the maritime industry.
		Three white papers in progress: 1) "Realizing H2 in the maritime - experience and knowledge gaps;" 2) H2 safety, regulations, codes & standards;" 3) "H2 logistics and ports."
40	Energy Storage and Conversion Based on H2 (2019-2021) *Storage*	Eight working groups, including new working group on ammonia and reversible liquid carriers.
		IEA H2 TCP sponsorship of MH Gordon conference.

End of Term Report 2015-2020 *Continued*

#	NAME, DATE	FINDINGS/RESULTS, LESSONS LEARNED & SUCCESS STORIES
	Portfolio	PRODUCTS
36	Life Cycle Sustainability Analysis (LCSA) 2015-2018	Developed life-cycle costing framework. LCSA is a convenient methodological solution to evaluate the performance of H2 energy systems. LCSA concludes that different calculations associated with conventional LCC, as well as LCC with externalities, influence levelized cost of H2.
		Final report - *Task 36: Life Cycle Sustainability Assessment of Hydrogen Energy Systems.*
38	Power-to-Hydrogen and Hydrogen-to-X 2016-2020	Provided comprehensive assessment of various technical and economic pathways to Power-to-H2 applications in diverse situations as well as the existing legal frameworks. Performed extensive data collection and analysis on techno-economic studies and business cases as well as PtX demonstrations. Regularly held workshops on demonstrations, in conjunction with meetings. Organized WHEC2018 round table "The Role of Hydrogen in Energy Policies" and participated in other WHEC2018 and non-hydrogen conferences. Collaborating with ETSAP project, Task 41c.
		Three technology briefs: 1) "Electrolysis: what are the investment costs?" 2) "Incentives and Legal Barriers;" 3) "Services to the Grid." Produced several journal articles: "Task Force Electrolyser Data," Proost *(IJHE);* "Energy System Models and Hydrogen," *(Nature Energy);* "Task 38," *Research Gate.* Three (3) databases: demonstrations; techno-economic analyses; and national legislation.
41c	Data and Modeling 2020-2023	Subtask 41c – Cooperation with ETSAP (via ETSAP project) – underway. Project aims to better understand and improve modeling of hydrogen, especially within IEA and the IEA network. It is also intended to inform other Task 41 subtasks, providing a sustainable data validation system and enhanced approach to hydrogen modeling. Longer term ambition is to incorporate database as Secretariat function.

End of Term Report 2015-2020 *Continued*

#	NAME, DATE	FINDINGS/RESULTS, LESSONS LEARNED & SUCCESS STORIES
	Portfolio	PRODUCTS
37	Safety 2015-2021	Provided structural and quantitative contributions, including testbed, to HyRam quantitative risk assessment (QRA) platform in dedicated subtask. Held European workshop back-to- back with ICHS. Supported Sponsor Member HySafe on ICHS conferences. Launched *Hydrogen Safety Journal*.
		HyRam QRA tool kit; *Hydrogen Safety Journal*; 2 joint publications in peer-reviewed journal, *Process Safety and Environmental Protection.*

Over the past five years the Landscape for Hydrogen has changed; momentum has accelerated dramatically in the last two years

World Governments

- **2015** **COP21** Paris Agreement
- **2017** Japanese Prime Minister announces **Japan's intent** to become **world's first hydrogen society**
- **2018** Hydrogen adopted as **8th MISSION INNOVATION Challenge** in May
- **2018** European Ministries – **Linz Declaration** on Hydrogen in September
- **2018** **IPCC Special Report** on Global Warming of 1.5° C in October; hydrogen workshop in October
- **2018** **Japan makes voluntary contribution to IEA** for preparation of G20 Report on Hydrogen to be delivered June 2019 at G20 Meeting
- **2018** First Hydrogen Ministerial Meeting in Japan in October produces **"Tokyo Statement"**
- **2019** **FCH2JU Study** Hydrogen Roadmap Europe – published in February
- **2019** Delivery of **IEA Hydrogen Report *The Future of Hydrogen* at G20 Meeting** in June
- **2019** 2nd Hydrogen Ministerial Meeting September

MISSION INNOVATION
Accelerating the Clean Energy Revolution

Multi-lateral Discussions on Energy

Energy Ministerial Meeting:

- **G7 (1976) and G20(1999)** Energy Ministerial meetings>> input for G7/G20 meetings
- **Clean Energy Ministerial**(2010,CEM, 28 countries 9 initiatives) and **Mission Innovation** (2015, 24 countries, 8 challenges) meetings
- **IEA Ministerial meeting** (1976): European Countries, NorthAmerica(*Mexico*), Chile, Japan, Korea, Australia, New Zealand, Turkey, Associate and partners countries (Chine, Inde, Argentina, Russie, Brazil, Indonesia, South Africa, Thailand, Morocco, Singapore…)

International organizations

- OECD (1945)and IEA(1974), ITF (2006), AEN (1958)
- IRENA (2009)
- REN 21(2005, UNEP secretariat)
- ***United Nations(1945), UNIDO(1967), PNUE (1972), World Economic Forum(Davos) (1971)***
- Plus private organization: World Energy Council(1923), WBCSD(1991), Energy Breakthrough Coalition(2015)…
- Thematic Initiative (GBEP, CSLF, IPHE, REEP, H2 ministerial meeting) and Initiative from CEM, COP21(MI, ISA…)

IEA has a leading role in the international energy landscape

–EBC Energy Business Council, EVI, E4, SDG
–CETP programme
–Official secretariat for Clean Energy Ministerial,
–Strong cooperation with Mission Innovation
–Collaboration with IRENA, REN21

"the IEA's unique positioning as the only organization that covers the full energy mix, enabling a holistic perspective on developments and their implications at a time when the global energy system is transforming rapidly, with implications both in the medium and long term on energy security"

Markets and Infrastructure

- 380+ Hydrogen Refueling Stations (HRS) are open to public or fleets worldwide; approximately 6,500 FCEVs have been sold;
- Electrolysers are available in small and large (MW scale) sizes;
- Hydrogen applications are proliferating – for industry, mobility, stationary, “smart grid,” intermediates, and electrofuels/synfuels
- Larger demonstrations and serious debates about “green” hydrogen and “origin” are mainstream;
- Sector coupling and system integration are now recognized as critical to the future energy system; and
- Hydrogen scale-up is a focus everywhere.

TRENDS: Industry and Markets for *flexible, versatile Hydrogen!*

Passenger Cars & Fleets

Toyota Mirai	Honda Clarity	Hyundai Tucson	Hyundai Genesis

- Japanese vehicle production increases dramatically.
- FCEV registration is now being tracked in California.
- Norway anticipates application of FCEVs incentives similar to BEVs.

Buses

- **UC Transit in Oakland**, CA, USA - largest fleet in North America, with 12 fuel cell buses.
- Foshan and Yunfu – $17 million order for 300 fuel cell buses.
- European Union Coordination a national Call for order in progress for a 1000 FC Buses
- South Korea - planning to replace 27,000 CNG buses with FC buses by 2030.

Heavy Duty Trucks

Nikola Motor Company H2 powered **long range tractor trailer**

Logistics Vehicles

UPS - first hydrogen fuel cell electric class 6 delivery van. 17 vans in the U.S. by year end 2018.

Toyota a heavy duty drayage vehicle (class 8), **Amazon** buying $70 million of **fuel-cell forklifts.**

Light Rail Trains

In 2017, **Alstom** unveiled its **Coradia iLint**, which will **replace diesel trains** in the extensive, **un-electrified sections** of rail in Germany.

Airplanes & Drones

Hydrogen-powered Drone
Fuel cell technologies power drones varied applications from lightweight Hycopter to larger military based applications like the Boeing Insitu's ScanEagle drone.

HY4 Hydrogen Fuel Cell Electric Aircraft, World's first 4 seater H2 plane.

Maritime

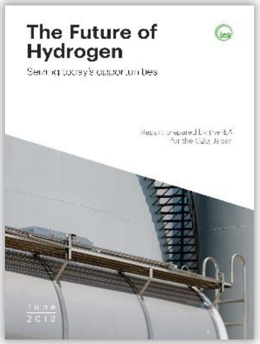
90% of all trade is by ship. Maritime tourism is huge global industry.

The **Red and White Ferry Company** and **Sandia National Laboratory** have teamed up on a feasibility study for designing, building and operating a high-speed hydrogen fuel cell powered passenger ferry and refueling station.

Portables

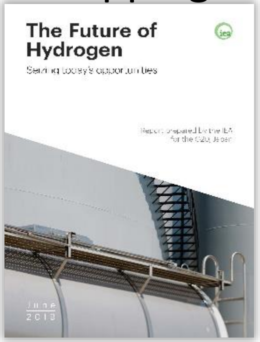
IEA: key recommendations to scale up hydrogen

1. Establish a role for hydrogen in long-term energy strategies.
2. Stimulate commercial demand for clean hydrogen.
3. Address investment risks of first-movers.
4. Support R&D to bring down costs.
5. Eliminate unnecessary regulatory barriers and harmonise standards.
6. Engage internationally and track progress.
7. Focus on four key opportunities to further increase momentum over the next decade.



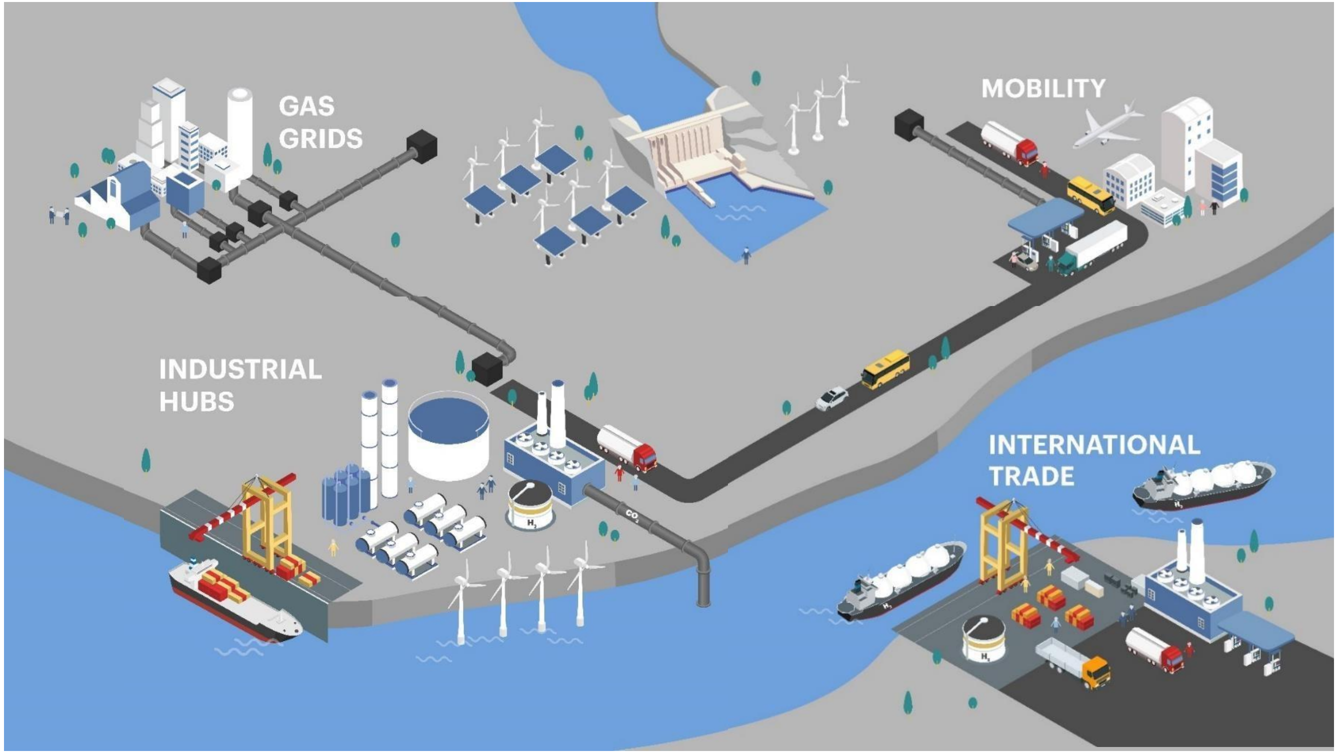
IEA: four near-term opportunities to boost hydrogen on the path towards its clean, widespread use

1. Make industrial ports the nerve centres for scaling up the use of clean hydrogen.
2. Build on existing infrastructure, such as millions of kilometres of natural gas pipelines/grids.
3. Expand hydrogen in transport through fleets, freight and corridors.
4. Launch the hydrogen trade's first international shipping routes.



The Future of Hydrogen:
G20 Report
Released mid-June at G20 in Japan

IEA: 4 opportunities for scale up (*Future of Hydrogen*)



Other Important and relevant IEA reports

- ***Offshore Wind* October 2019**
- ***World Energy* Outlook 2018 *– article on hydrogen***
- ***Energy Technology Perspectives***

IEA Hydrogen report

- ***Global Trends and Outlook for Hydrogen***

http://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_WEB.aspx

SUPPLY CHAIN: H2 Production & Pathways - Today & Tomorrow

From Fossil Fuel –Natural Gas Reforming and Coal

Steam Methane Reforming (SMR)
Partial Oxidation (POX)
Auto Thermal Reforming (ATR)
NG with (with CCS)
Coal Gasification (with CCS)

From Renewables – Conventional

Solar (PV &Concentrated Solar)
Wind
Biomass gasification

From Renewables – Advanced

Advanced Electrolysis
Photoelectrochemical (PEC)
Solar Thermochemical (STCH)

From Nuclear

From Water Electrolysis

Conventional

100 years of experience

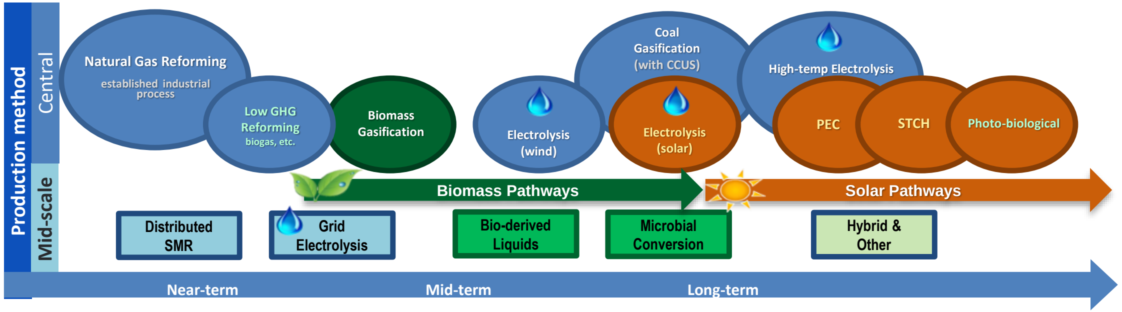
Advanced

Electrolysers available in small and large sizes (now in MWs!)

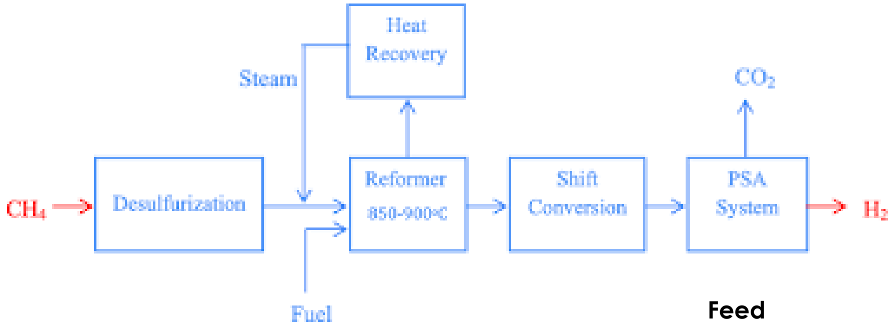
Electrolysers available in low and high temperature technologies:

- **Low – alkaline and polymer electrolyte membrane (PEM)**
- **High – solid oxide electrolyser *(SOEC)***

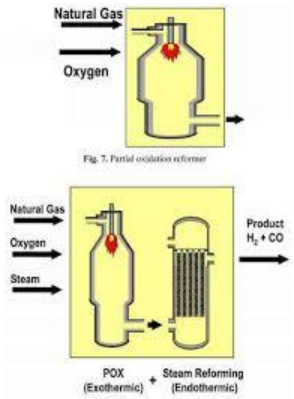
Source Graphic: US DOE/EERE



SUPPLY CHAIN: Production - Natural Gas Reforming Today - *Tomorrow with CCS*

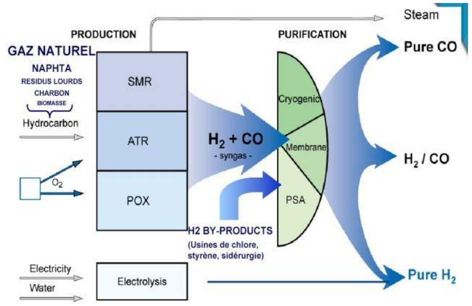


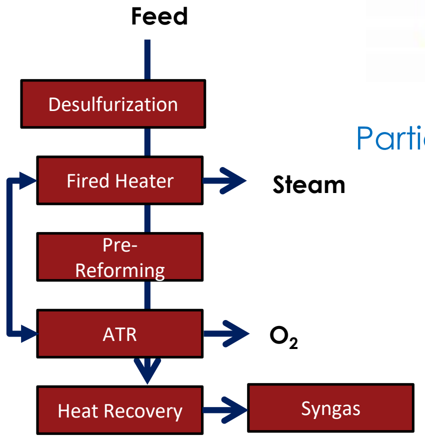
Central and Distributed
Steam Methane Reforming (SMR)



Partial Oxidation POX

Source: Wikipedia

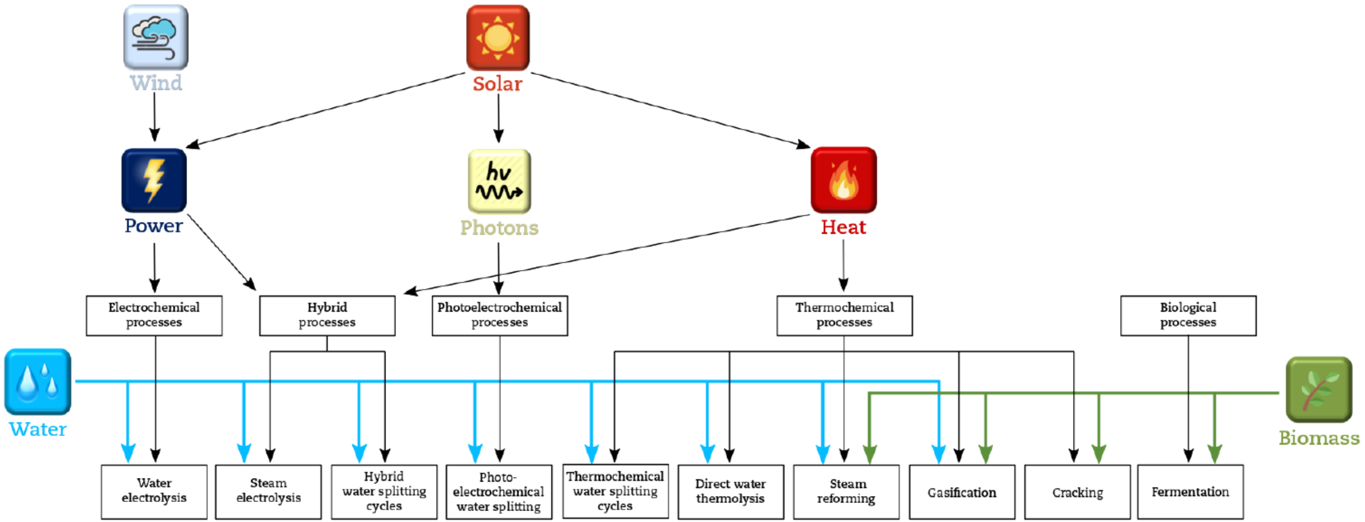




Autothermal Reforming (ATR)

Source: Air Liquide

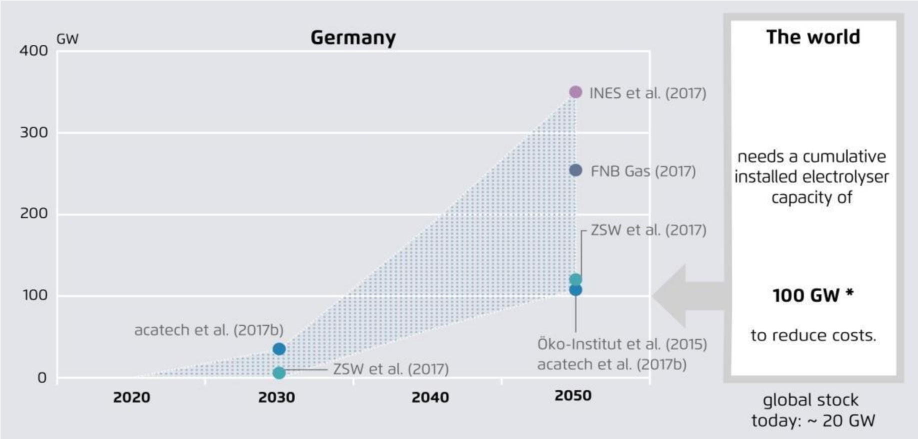
TOMORROW: Green hydrogen production: electrolysis and beyond!



Source: Definition of IEA Hydrogen Task 35 Successor webinar, Turchetti and Della Pietra

SUPPLY/VALUE CHAIN: Electrolyser becoming a Key Technology TODAY for energy transition in scale-up challenge TOMORROW

Installed electrolysis capacity for PtG/PtL in scenarios for Germany in GW



Own illustration based on Frontier Economics (2018) and others

- **Scale and learning effects** are critical for cost reduction, but uncertain (e.g. CO_2 from air).
- International **100-gigawatts-challenge**.
- Investments are not to be expected without **political intervention or high CO_2 price** due to high cost of synthetic fuels.

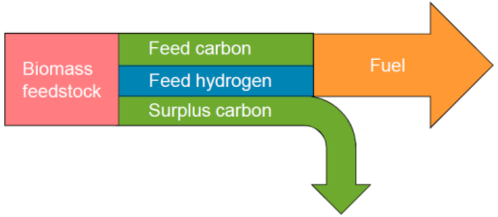
TOMORROW: « Green Hydrogen inside » designer fuels

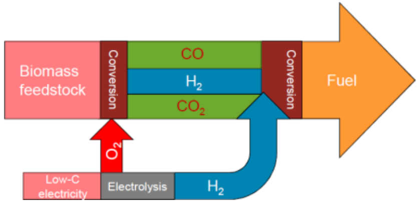
Electro fuels: a broad definition

	Without carbon	Containing carbon
Gaseous	Hydrogen gas (H_2)	Methane (CH_4)
Liquids	Ammonia (NH_3)	Alcohols (C_xH_yOH) Hydrocarbons (C_xH_y)

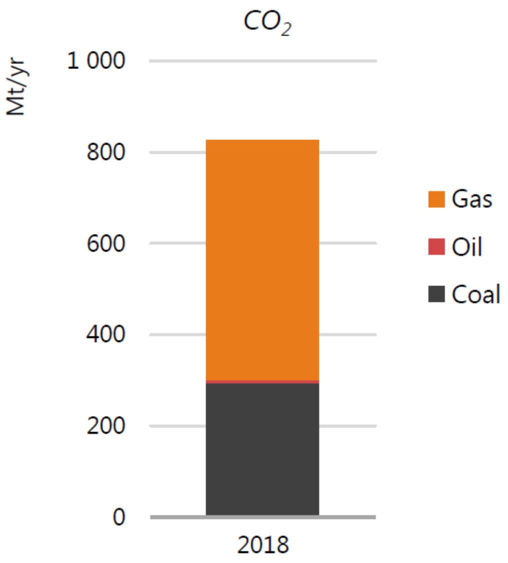
There is a great diversity of options for electro fuels, all based on hydrogen, which may correspond to different needs and uses

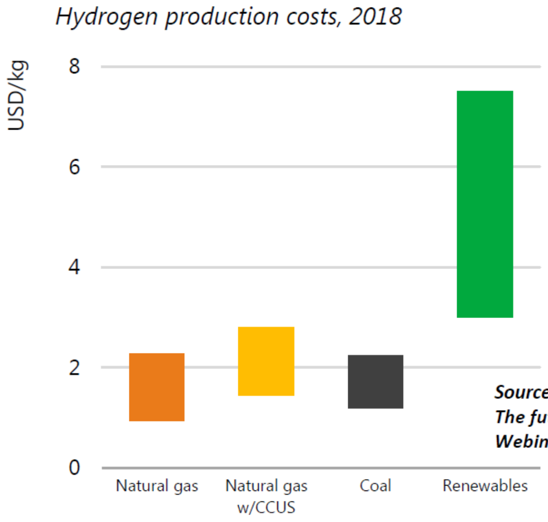
Biofuels and hydrogen synergies





Hydrogen costs today





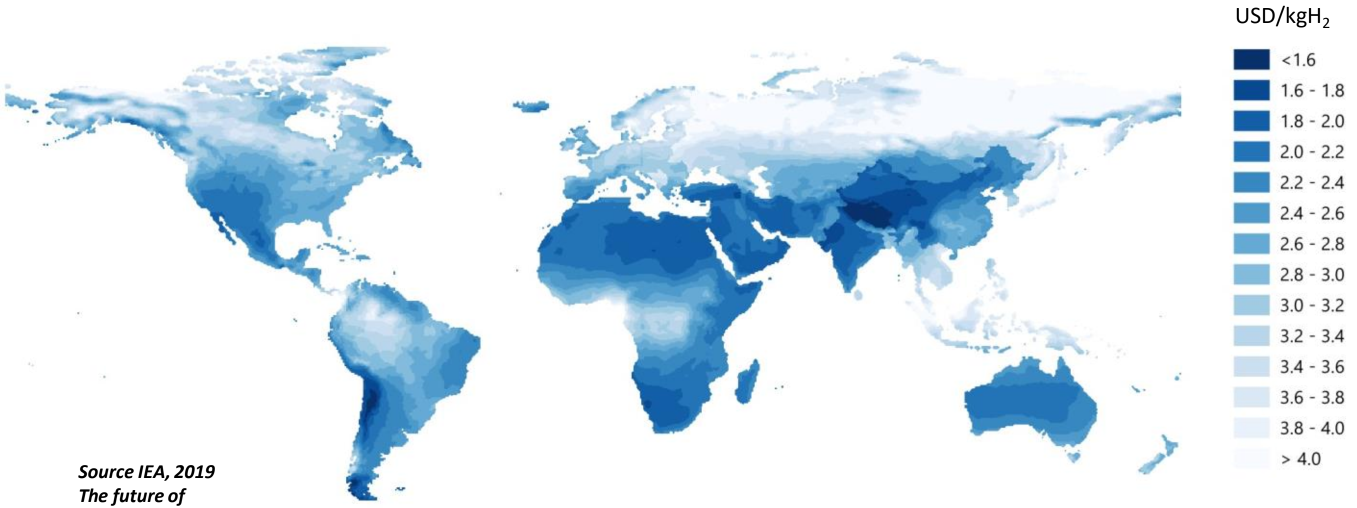
Source IEA, 2019
The future of Hydrogen, Webinar

Virtually all hydrogen today is produced using fossil fuels, as a result of favourable economics

VALUE CHAIN: Production - PV has come down the cost curve and now there is offshore wind
Offshore Wind Outlook 2019 - TODAY

- Standalone IEA report on Offshore Wind released October 25, 2019
- EC has designated wind as key component of long-term strategy for reaching carbon neutrality by 2050
- Current offshore installed capacity in Europe is ~20 GW. Scenarios point to deployment of 450 GW of offshore power
- In 2019, Denmark added 407 GW capacity to its North Sea wind park
- Poised to become a $1 trillion industry

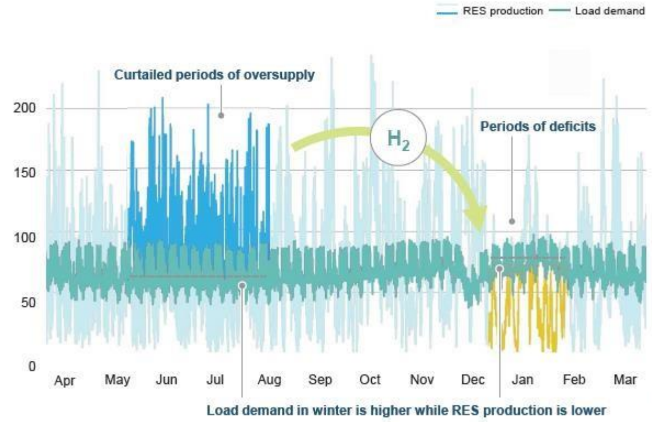
Supply Chain: Massive and low cost Hydrogen production from Renewables in some areas – *TODAY!*



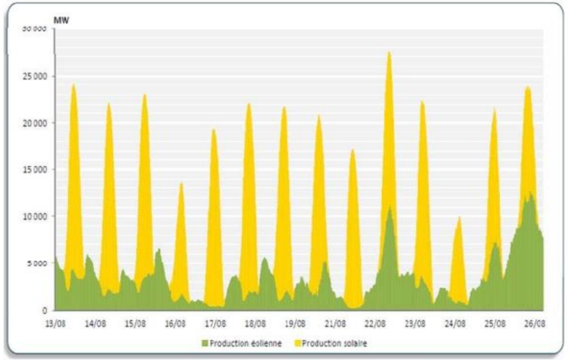
Source IEA, 2019 The future of Hydrogen, Webinar

The declining costs of solar PV and wind could make them a low-cost source for hydrogen production in regions with favourable resource conditions.

SUPPLY/VALUE CHAIN: hydrogen could absorb excess electricity from variable renewables for storage – TODAY AND TOMORROW

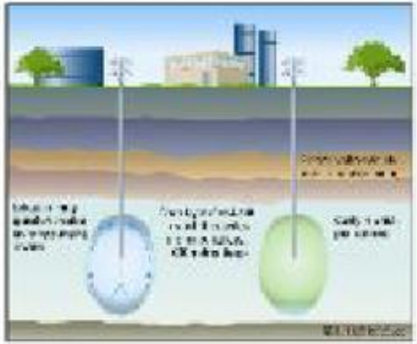


Source: EC 2050 scenario, McKinsey analysis



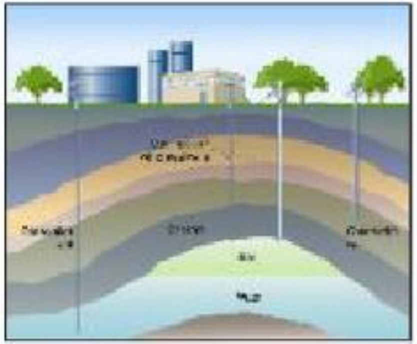
Période du 13 au 26 août 2012 en Allemagne

Hydrogen Storage – Short, Mid, Long Term and Seasonal
(options include underground storage in salt caverns, depleted gas reservoirs)



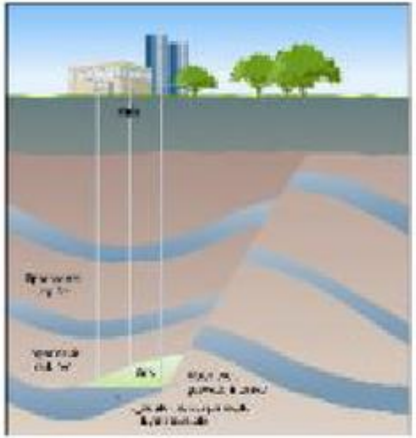
Salt Caverns

- Salt caverns are solution mined cavities within either salt domes or bedded salts that do not match reservoir volume capacity.



Depleted Oil/Gas Reservoirs

- Depleted reservoirs are proven gas reservoirs that are easy to develop and operate due to existing infrastructure.

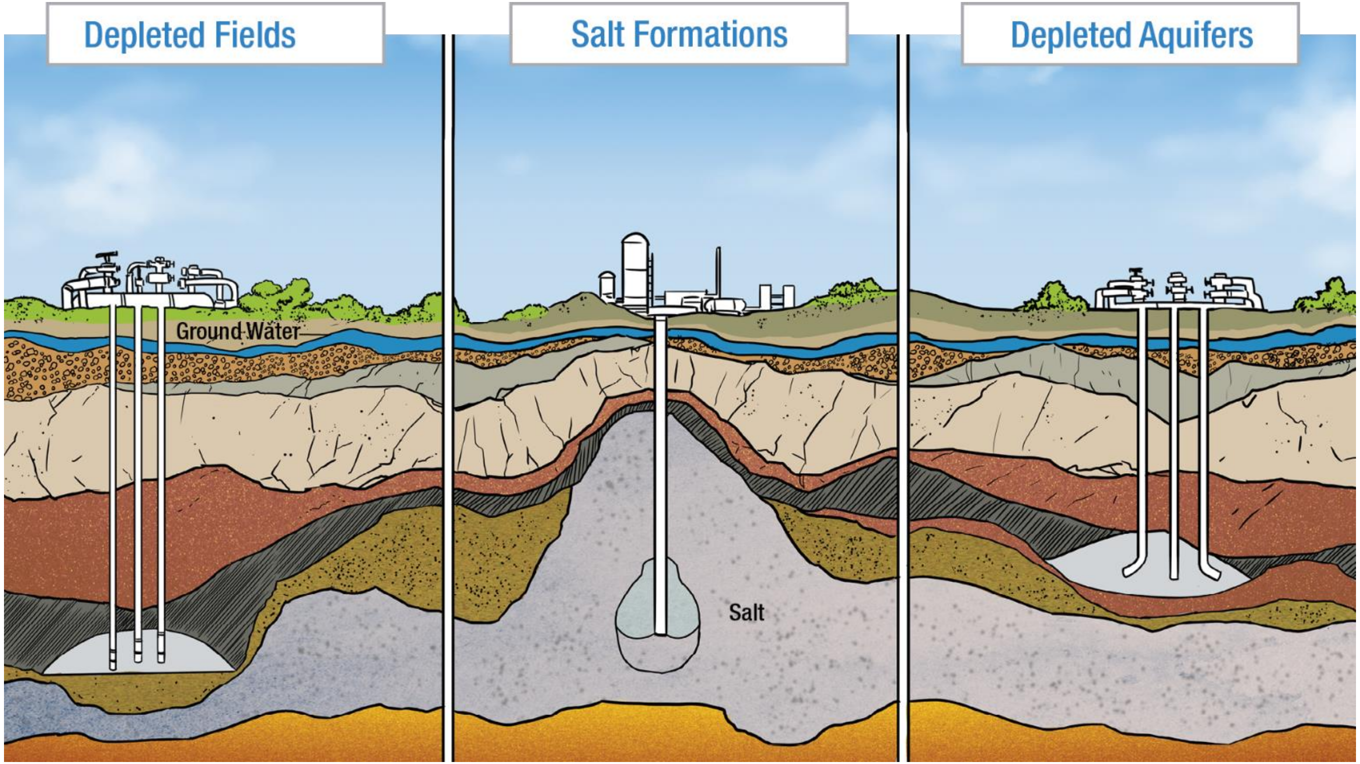


Aquifers

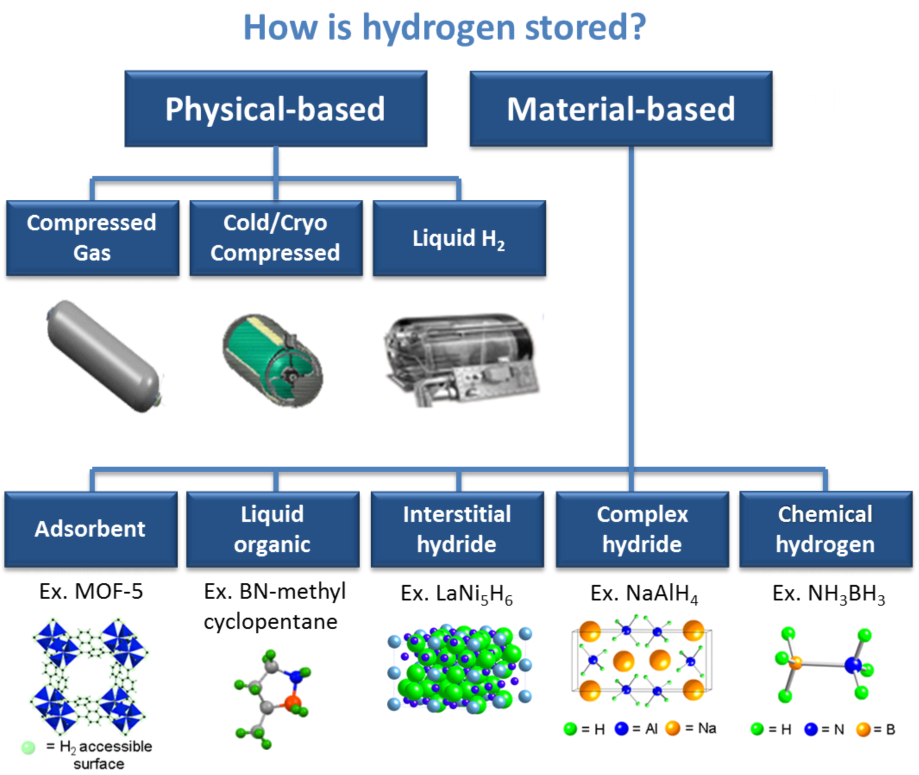
- Aquifers are similar in geology to depleted reservoirs, but have not been proven to trap gas and must be developed.

Researchgate. net: Figure 4- uploaded by Susan M. Schoe

Hydrogen Storage – Short, Mid, Long Term and Seasonal
(options include underground storage in salt caverns, depleted gas reservoirs)



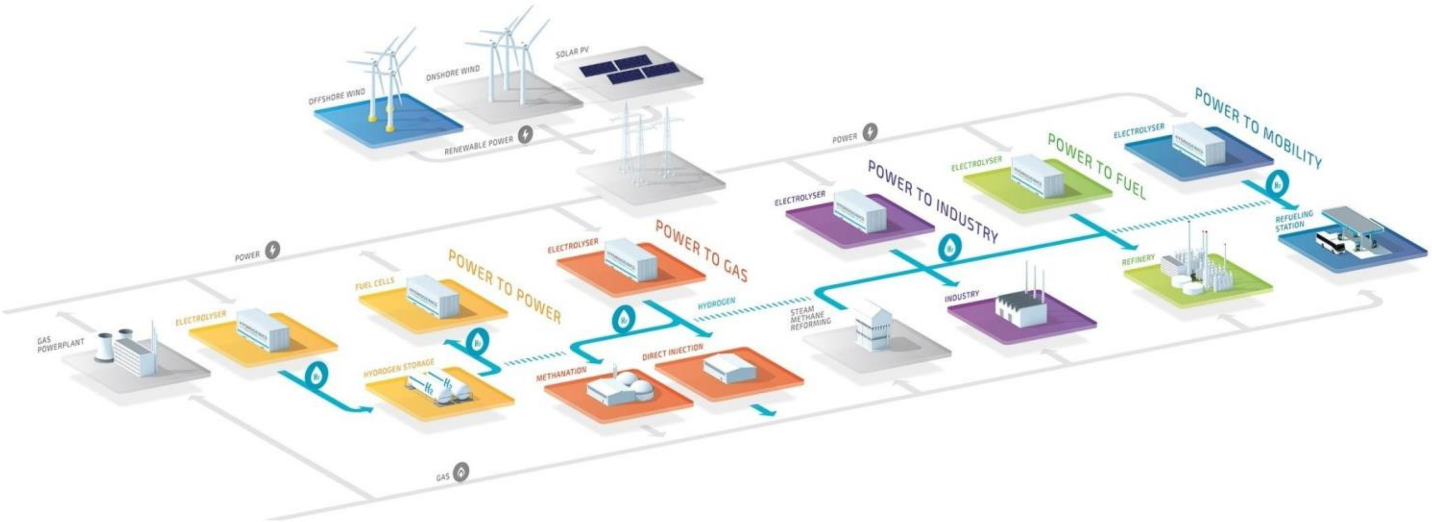
Hydrogen Storage – smaller scale options



Energy.gov: Fuel Cell Technology Office, DOE

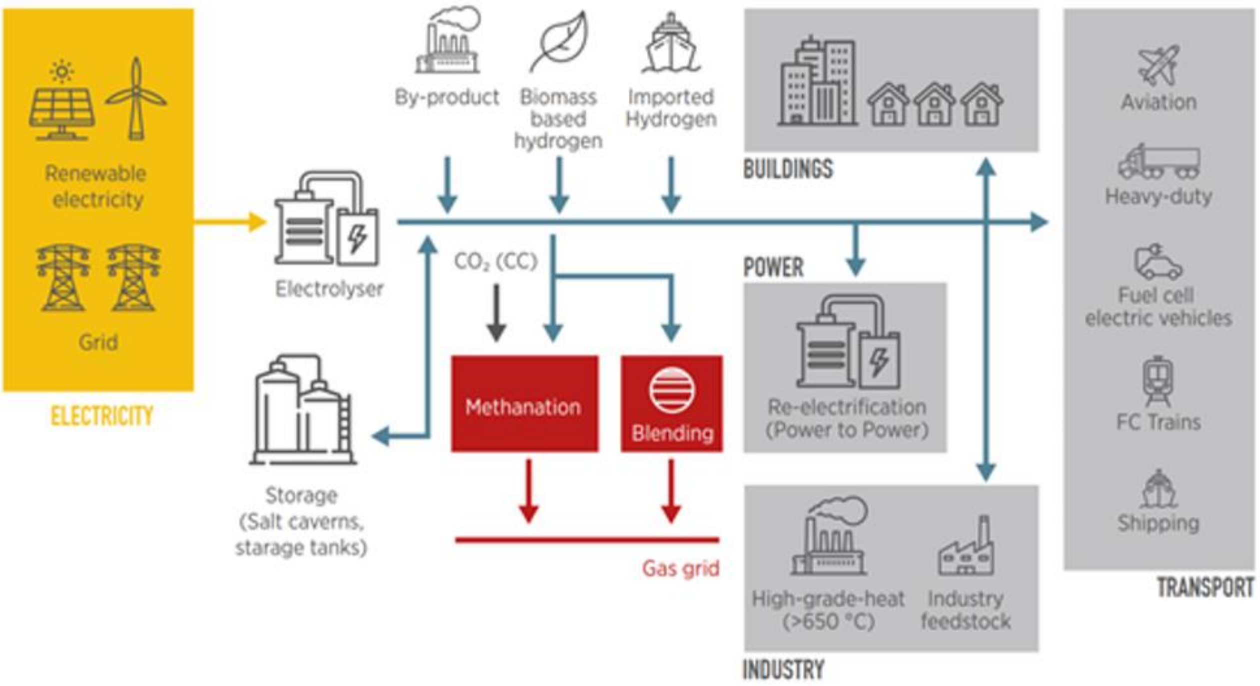
SUPPLY CHAIN: Transmission and Delivery - tomorrow

For Power to Hydrogen, start with renewable electricity

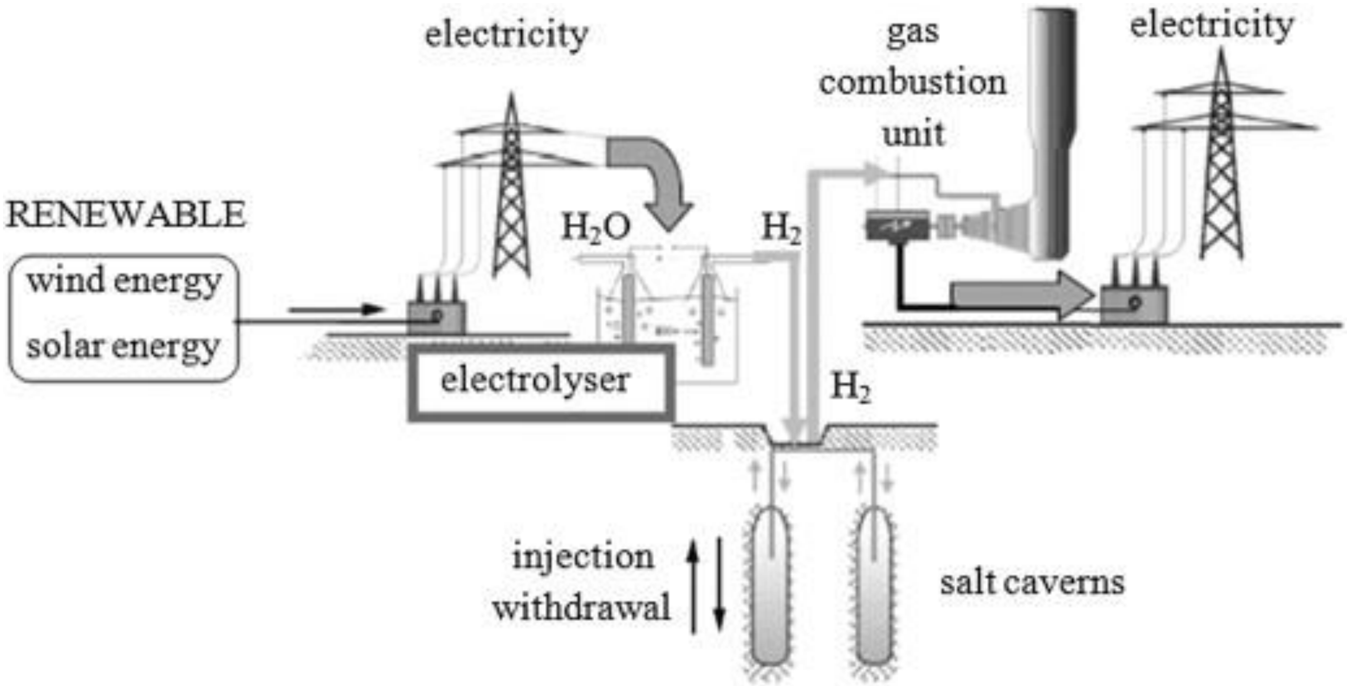


HYDROGENICS
SHIFT POWER | ENERGIZE YOUR WORLD

SUPPLY CHAIN: Electrofuels via Power to gas/liquids/fuels or Synthetic fuels from carbon-based fuels https://theconversation.com/el-hidrogeno-clave-para-gestionar-las-redes-electricas-del-futuro-120837 - TOMORROW



Hydrogen Storage – Short, Mid, Long Term and Seasonal
(options include underground storage in salt caverns, depleted gas reservoirs)



Author: Ahmet Ozarslan
Publication: International Journal of Hydrogen E

Electrolysis: What are the investment costs? State of the art and outlook.

Authors: Joris Proost, Sayed Saba, Martin Müller, Martin Robinius, Detlef Stolten

Topic: Power-to-Hydrogen is the first step of any PtX pathway. Beyond the cost of electricity, the investment costs of the process weighs on the hydrogen production cost, especially at low load rates, which can be characteristic of direct coupling with renewables. Investment costs are investigated in Task 38, in the Task Force “Electrolyser data”.

KEY FINDINGS

- For alkaline systems CAPEX of 750 €/kW is reachable today for a single stack of 2 MW.
- For PEM, such CAPEX should become within reach for 5 MW systems, but currently still require the use of multi-stack systems.
- CAPEX value below 400€/kW have been projected for alkaline systems, but this will require further upscaling up to 100 MW.

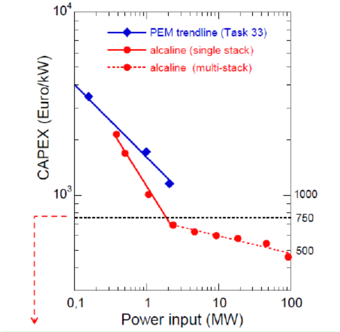


Fig. 1 CAPEX data for both PEM and alkaline electrolysers, plotted as a function of the power input. Data for alkaline systems are based on a single stack of 2.13 MW conside-ring 230 cells, 2.6m² size. Note that change in slope for alkaline electrolysers corres-ponds to the use of multi-stack systems. [1]

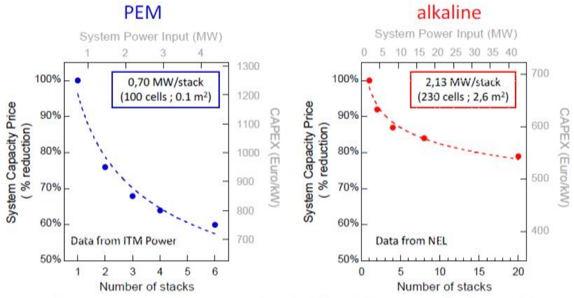
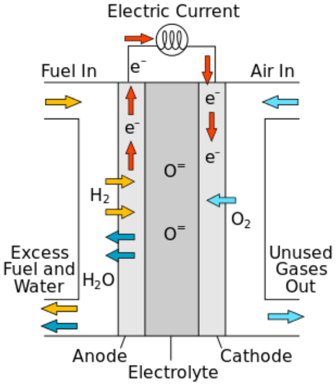
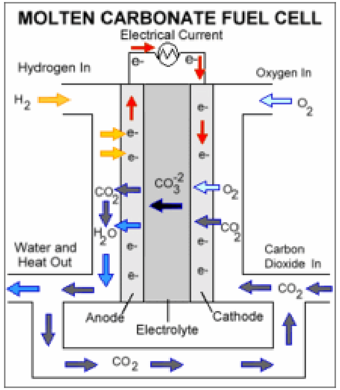


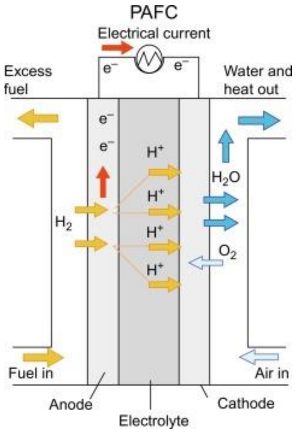
Fig. 3. Reduction in CAPEX upon use of multi-stack systems, both for PEM (left) and alkaline (right) electrolysers.

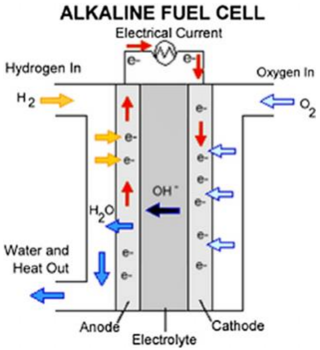
Fig. 2 Reduction in CAPEX upon use of multi-stack systems, both for PEM (left) and alkaline (right) electrolysers. [1]

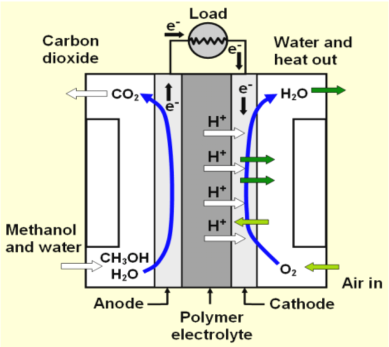
Hydrogen Fuel Cells – Conversion for End Use

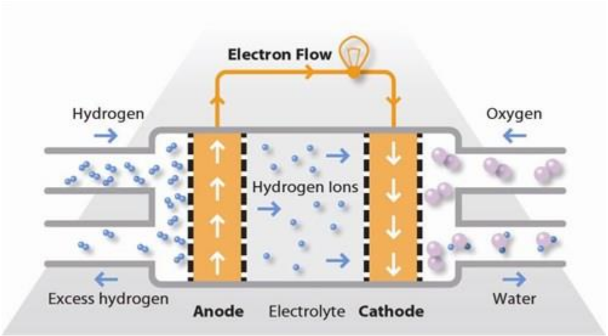












A new and emergent topic: international trade for hydrogen

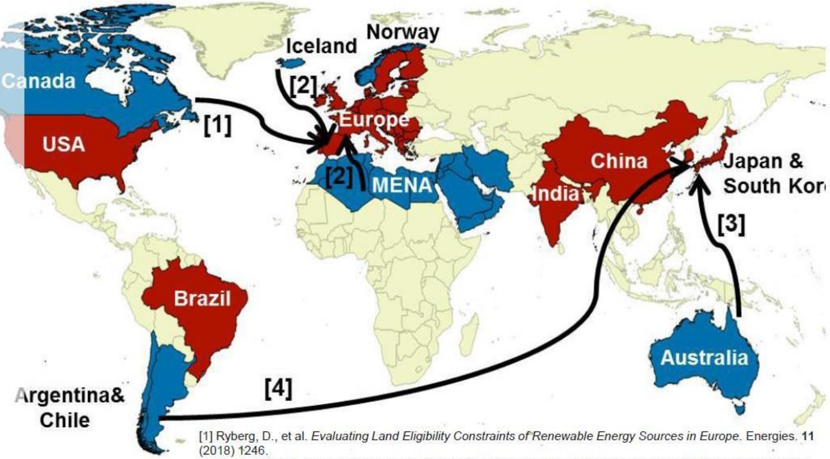
What could be the new trade routes for hydrogen

Renewable hydrogen production – Global perspective

- Due to location boundaries Germany will have the demand for energy import
- High potentials for RE offer the opportunity for green PtX with competitive prizes
- Enable regions to be self-sufficient in energy and potentially chemical feedstocks

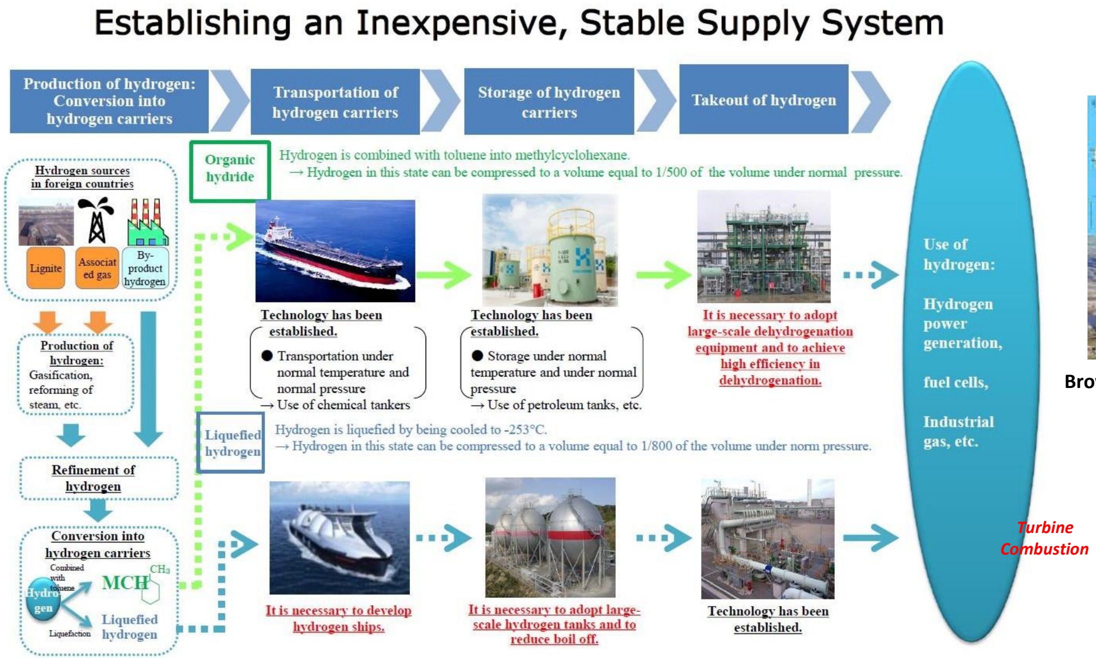
→ Global transport infrastructure

- PtX offers the opportunity of versatile, scalable, intelligent and flexible system integration with high shares of RE



[1] Ryberg, D., et al. *Evaluating Land Eligibility Constraints of Renewable Energy Sources in Europe*. Energies. **11** (2018) 1246.
[2] Reuß, M., et al. *Seasonal Storage and Alternative Carriers: A Flexible Hydrogen Supply Chain Model*. Applied Energy. **200** (2017) 290-302.

SUPPLY CHAIN: Transmission and Delivery - Japanese scheme to import H2 from different countries - TOMORROW



Brown Coal to Hydrogen

CO2 CCS

Source: Japanese METI/NEDO

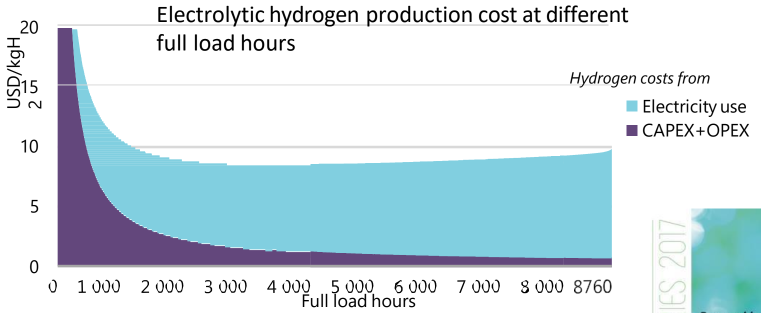
Thank you from IEA Hydrogen
A premier global resource for technical expertise in H2 RD&D

Contact:

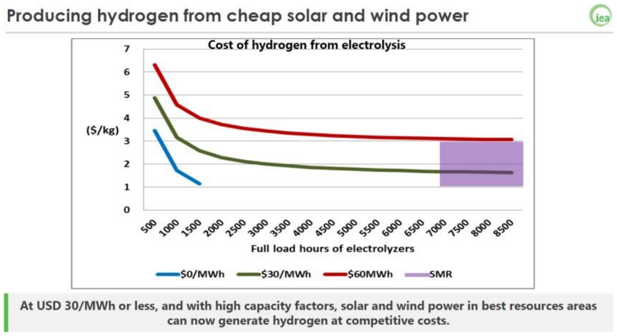
Paul Lucchese
IEA H2 Hydrogen Chairman
Paul.lucchese@capenergies.fr

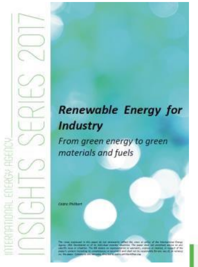
Mary-Rose de Valladares
IEA Hydrogen General Manager
mvalladares@ieahia.org
+1 301 634 7423

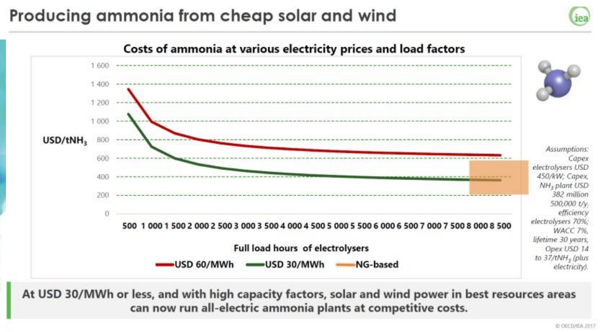
TODAY: Optimal cost versus duration



Source IEA, 2019
The future of Hydrogen,
Webinar

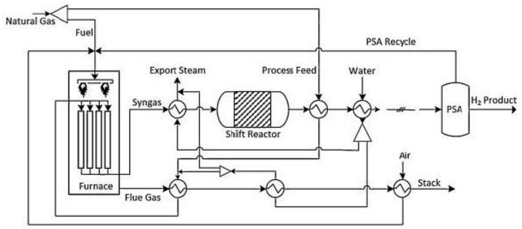






Steam methane reforming

$CH_4 + H_2O \leftrightarrows CO + 3H_2$	$\Delta H_{500°C} = 221{,}6\ \frac{kJ}{mol}$	(SR)
$CO + H_2O \leftrightarrows CO_2 + H_2$	$\Delta H_{500°C} = -37{,}4\ \frac{kJ}{mol}$	(WGS)
$CH_4 + 2H_2O \leftrightarrows CO_2 + 4H_2$	$\Delta H_{500°C} = 184{,}2\ \frac{kJ}{mol}$	(OSR)
$CH_4 + CO_2 \leftrightarrows 2CO + 2H_2$	$\frac{kJ}{mol}$	(DR)

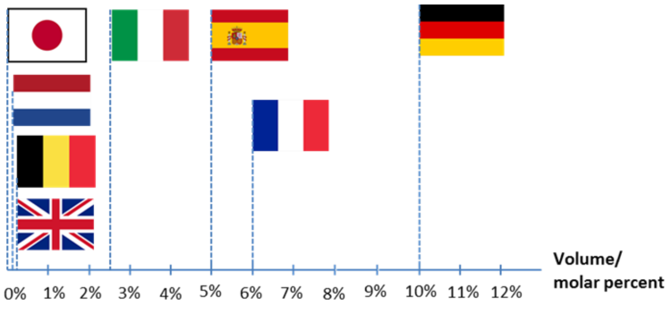


Conventional process:

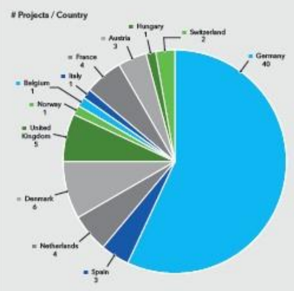
- Carried out in externally heated (furnace) tubular reactors
- Operating conditions: T = 700-900 ° C; P = 10-40 bar; S/C = 3-6
- Downstream of the reformer 1 or 2 WGS reactor(s) (500-600° C)
- About 12 t of CO2 per t of H2
  - From the chemical reaction
  - From combustion

TODAY: H2 in grid > 20 demonstration projects around the world
TOMORROW: in the grid serving the energy system

% Hydrogen in NG Grid permitted



Source Hylaw Project
FCH JU



Overview of pilot projects in Europe (per Q1-2017)

By Q1 of 2017, the (realised) installed capacity of electrolysers totalled approximately 30MW. The vast majority is located in Germany, followed by Spain and the United Kingdom.

More than 60% of the power-to-gas projects have hydrogen (H_2) as final product, 23% methane (CH_4) and 15% both hydrogen (H_2) and methane (CH_4). Only one project produces methanol (CH_3OH).

Power-to-gas (demonstration) projects in Europe; Source: European Power to Gas Platform website[28]

In most of the projects the produced gas finds its destination in the natural gas network (33%). The transport sector and power generation as end users are targeted in 25% of the projects. One single project delivers gas to an industrial user.

Source: IEA Hydrogen Task 38

TODAY: Photoelectrochemical Highlights

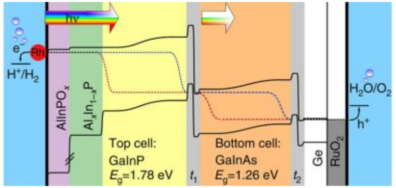
NEW WORLD RECORD

High efficiency III-V semiconductors from NREL achieve a 16% solar to hydrogen efficiency in PEC water splitting.

A new world record for systems with at least 1 semiconductor-liquid junction.

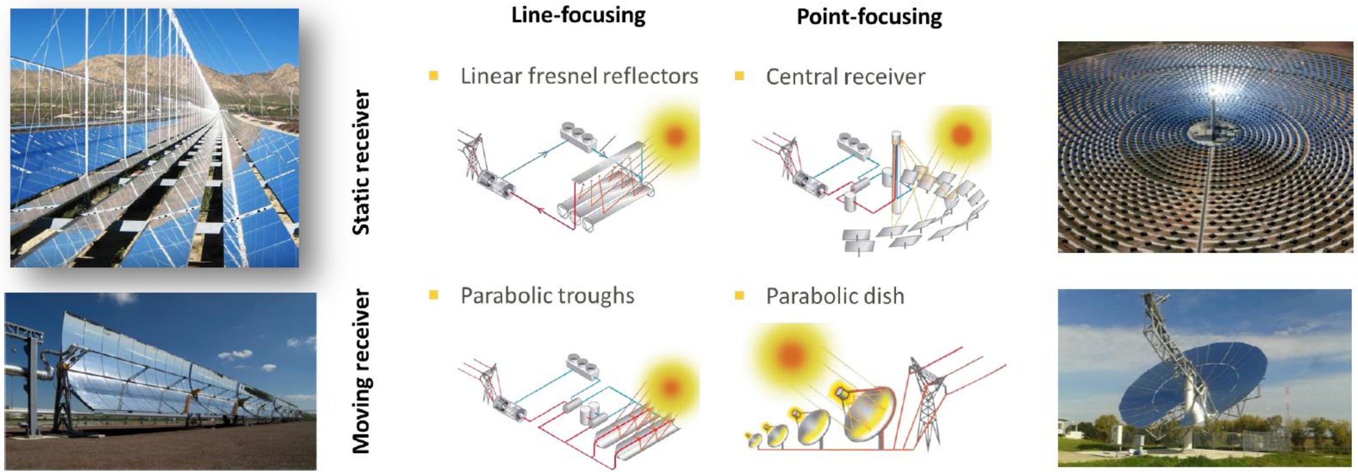
Young, Deutsch, et al. Under Review at Nature Energy

High efficiency III-V semiconductors from International Collaboration (Germany and USA), achieve a 14% solar to hydrogen efficiency in PEC water splitting.



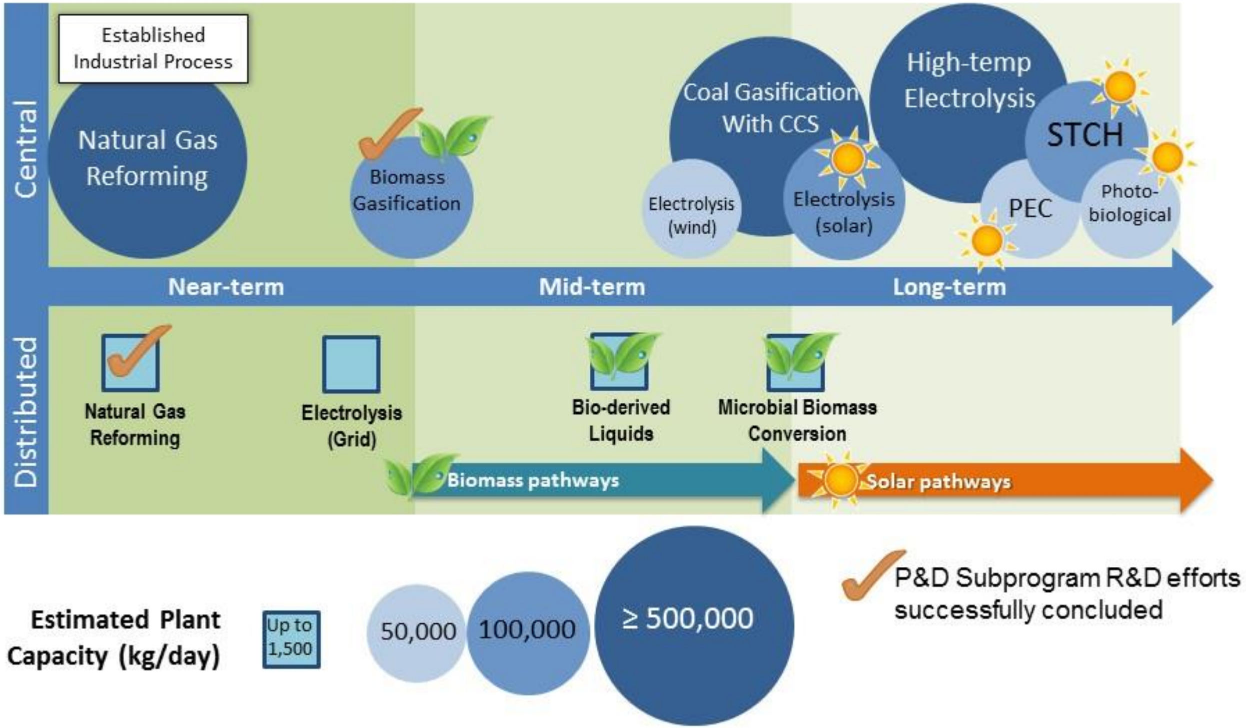
May, M. M. et al.. Nat. Commun. 6:8286 doi: 10.1038/ncomms9286 (2015).

Concentrating solar thermal (CST)



Source: Definition of IEA H2 Task 35 Successor webinar, Turchetti and Della Pietra

Perspectives for Hydrogen production



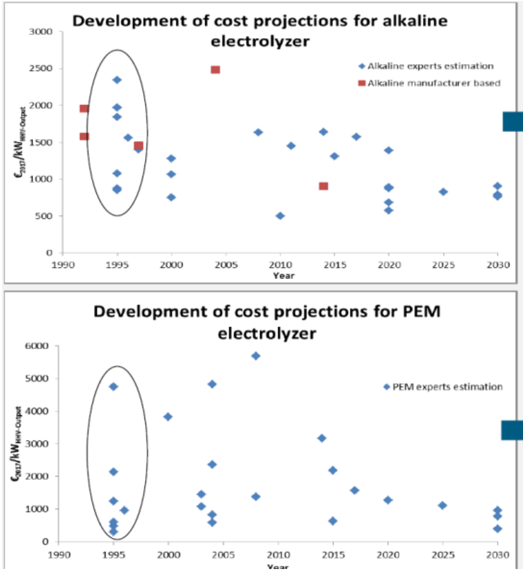
Source US DOE/EERE

Task 38 Brief – continued http://ieahydrogen.org/pdfs/Brief-ElyData_final.aspx

KEY FINDINGS (continued)

Methodology

- This work results from the analysis of data provided by the electrolyser manufacturers members of Task 38 [1], and from the data published in the literature in the last 30 years [2].



- **Range** of estimations **in 1990s for alkaline** was between **~800 and ~2500 €$_{2017}$/kW$_{HHV\text{-}Output}$**
- Today´s expectation for **2030** for alkaline droped to **~700 to ~1000 €$_{2017}$/kW$_{HHV\text{-}Output}$**.
- Alkaline: Reductions more moderate compared to PEM.
- This can be explained with the maturity of the alkaline technology
- **Range** of estimations **in 1990s for PEM** was between **~300 and ~5000 €$_{2017}$/kW$_{HHV\text{-}Output}$**
- Today´s expectation for **2030** for PEM droped to **~400 to ~1000 €$_{2017}$/kW$_{HHV\text{-}Output}$**

Fig. 3 Cost projections in the near to long term, for alkaline and PEM electrolysers [2]

Task 38 Brief – continued - http://ieahydrogen.org/pdfs/Brief-ElyData_final.aspx

References

- [1] J. Proost, *State-of-the-art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings*, Euro-pean Fuel Cell conference & exhibition (EFC17), Naples, Italy, December 12-15, 2017. Oral Communication.
- [2] S. M. Saba, M. Müller, M. Robinius, D. Stolten, *The investment costs of electrolysis—A comparison of cost studies from the past 30 years*, Int J Hydrogen Energ 43(2018) 1209-1223.

Task 38 info:
Entitled: "Power-to-Hydrogen and Hydrogen-to-X: System Analysis of the techno-economic, legal and regulatory conditions", it is a Task dedicated to examine hydrogen as a key energy carrier for a sustainable and smart energy system.
The "Power-to-hydrogen" concept means that hydrogen is produced via electrolysis. Electricity supply can be either grid, off-grid or mixed systems. "**Hydrogen-to-X" implies that the hydrogen supply concerns a large portfolio of uses**: transport natural gas grid, re-electrification through hydrogen turbines or fuel cells, general business of merchant hydrogen for energy or industry, ancillary services or grid services.
The general objectives of the Task are i/ to provide a comprehensive understanding of the various technical and economic pathways for power-to-hydrogen applications in diverse situations; ii/ to provide a comprehensive assessment of existing legal frameworks; and iii/ to present business developers and policy makers with general guidelines and recommendations that enhance hydrogen system deployment in energy markets. A final objective will be to develop hydrogen visibility as a key energy carrier for a sustainable and smart energy system.
Over 50 experts from 17 countries are involved in this Task which is coordinated by the French CEA/I-tésé, supported by the French ADEME. Participating IEA HIA ExCo Members are: Australia, Belgium, European Commission, France, Germany, Japan, The Netherlands, New Zealand, Norway, Shell, Southern Company, Spain, Sweden, United Kingdom, and the United States.