Overview: Hydrogen Production

Today and Tomorrow

Mary-Rose de Valladares

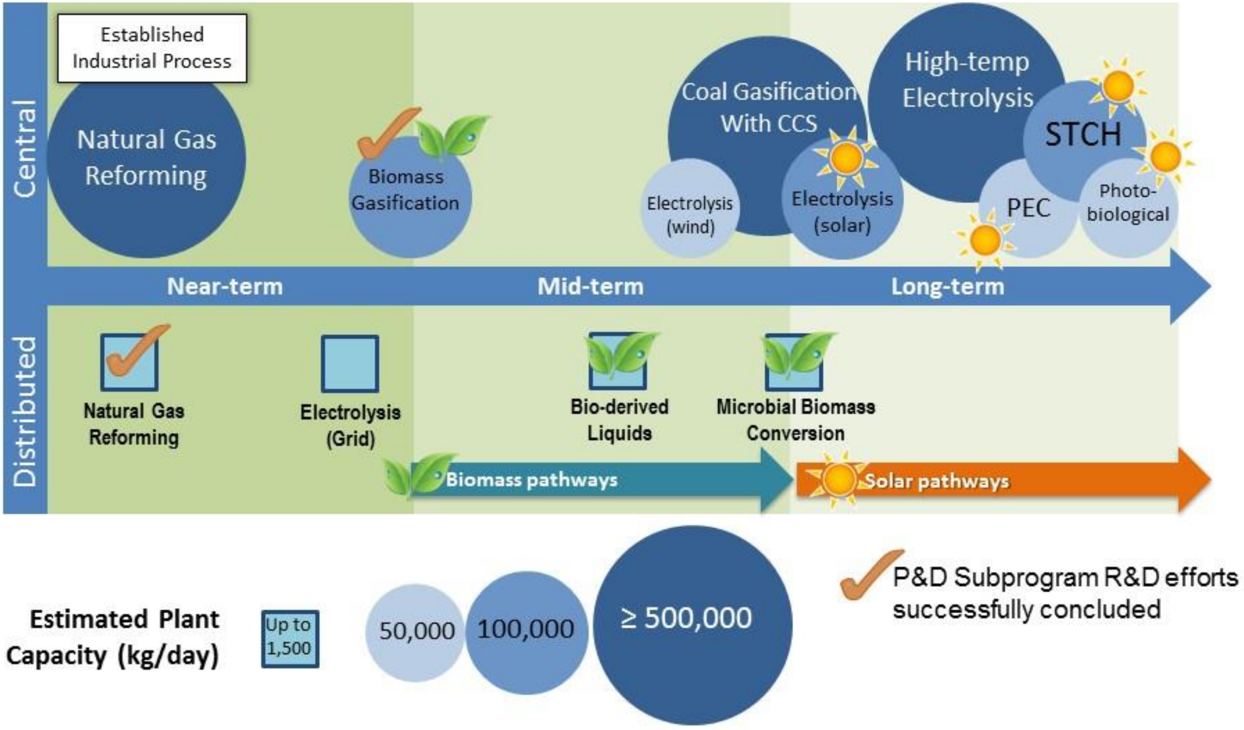
Paul Lucchese

Workshop on Hydrogen Production with CCS

EDF Chatou Campus

6 November 2019

Perspectives for Hydrogen production



Source US DOE/EERE

Hydrogen Production & Pathways: Today & Tomorrow

From Fossil Fuel –Natural Gas Reforming and Coal

- Steam Methane Reforming (SMR)
- Partial Oxidation (POX)
- Auto Thermal Reforming (ATR)
- Blending
- 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 Water Electrolysis

Conventional

100 years of experience

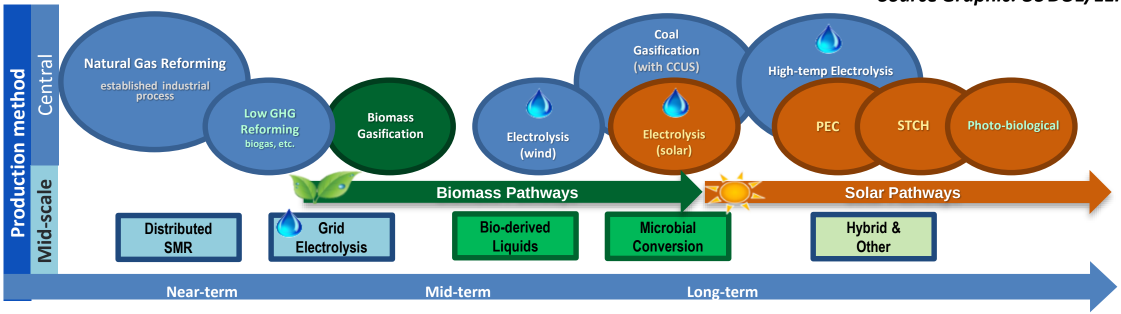
Electrolysers available in small and large sizes (now in MWs!)

Electrolysers available in low and high temperature technologies:

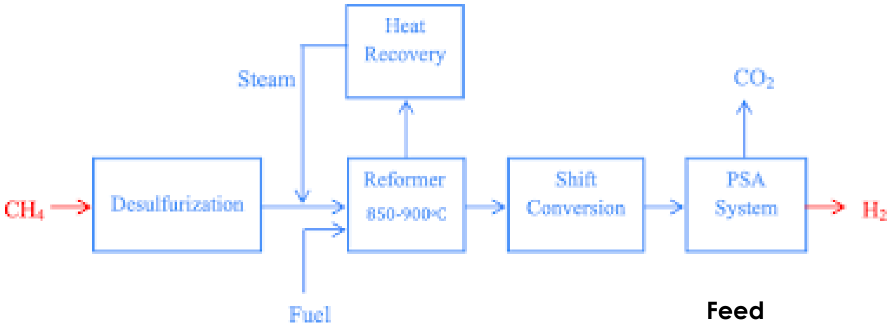
- **Low – alkaline and polymer electrolyte membrane (PEM)**
- **High – solid oxide electrolyser (SOEC)**

From Nuclear

Source Graphic: US DOE/EERE



TODAY: Natural Gas Reforming - *Tomorrow with CCS*



Central and Distributed
Steam Methane Reforming (SMR)

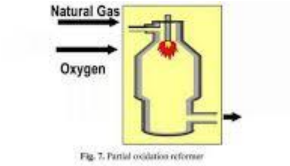
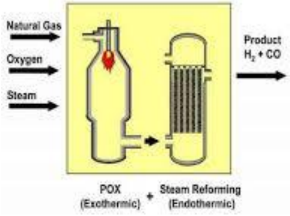
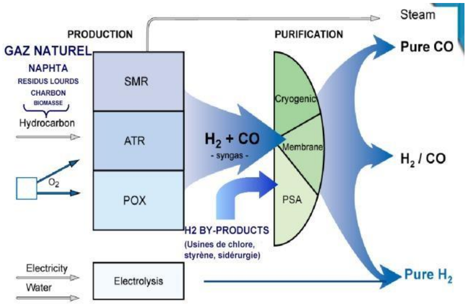


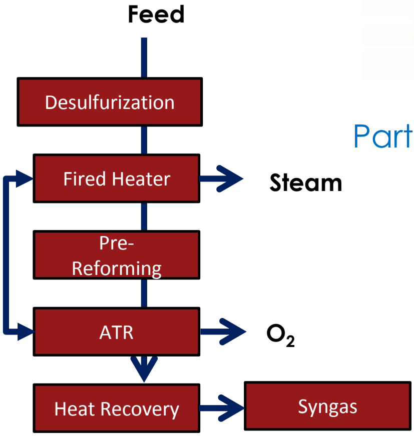
Fig. 7. Partial oxidation reformer



Partial Oxidation POX

Source: Wikipedia





Autothermal Reforming (ATR)

Source: Air Liquide

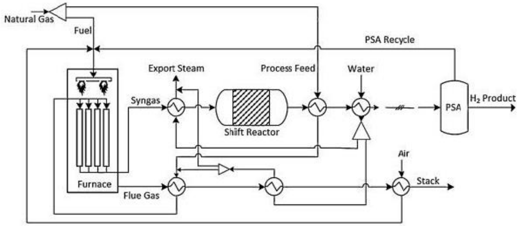
Steam methane reforming

$$CH_4 + H_2O \leftrightarrows CO + 3H_2 \quad \Delta H_{500°C} = 221{,}6 \ \frac{kJ}{mol} \quad \text{(SR)}$$

$$CO + H_2O \leftrightarrows CO_2 + H_2 \quad \Delta H_{500°C} = -37{,}4 \ \frac{kJ}{mol} \quad \text{(WGS)}$$

$$\boxed{CH_4 + 2H_2O \leftrightarrows CO_2 + 4H_2 \quad \Delta H_{500°C} = 184{,}2 \ \frac{kJ}{mol} \quad \text{(OSR)}}$$

$$CH_4 + CO_2 \leftrightarrows 2CO + 2H_2 \quad \frac{kJ}{mol} \quad \text{(DR)}$$

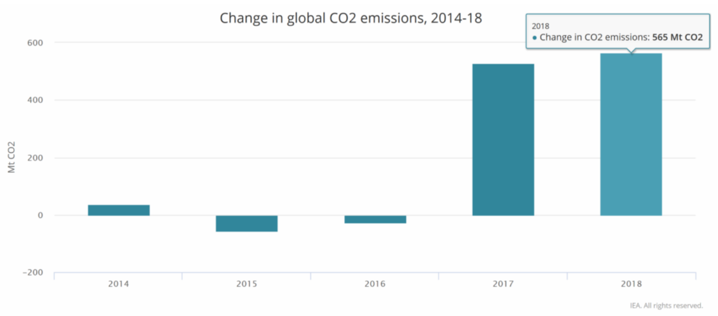


Conventional process:

- 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

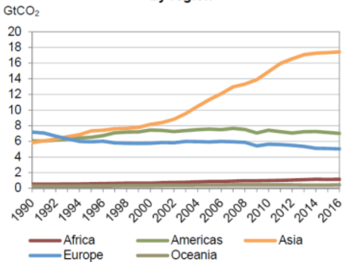
TODAY: After a 3 year stabilization period, CO2 emissions rising again

Fatih Birol Executive Director IEA



China and coal

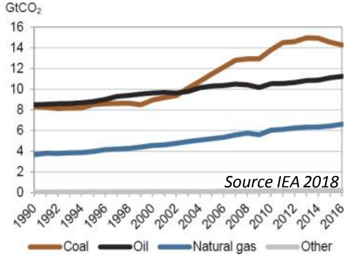
Figure 5. CO_2 emissions from fuel combustion: by region



Source IEA 2019

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

Figure 8. CO_2 emissions by source

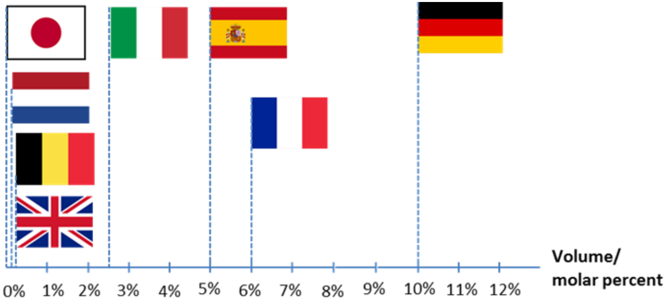


Source IEA 2018

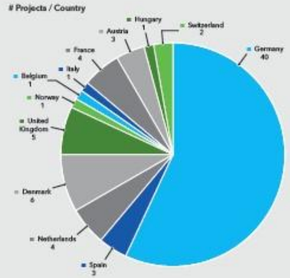
Source Wikipedia, BP Statistical review, Irena Renewables Capacity Statistic 2018

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.

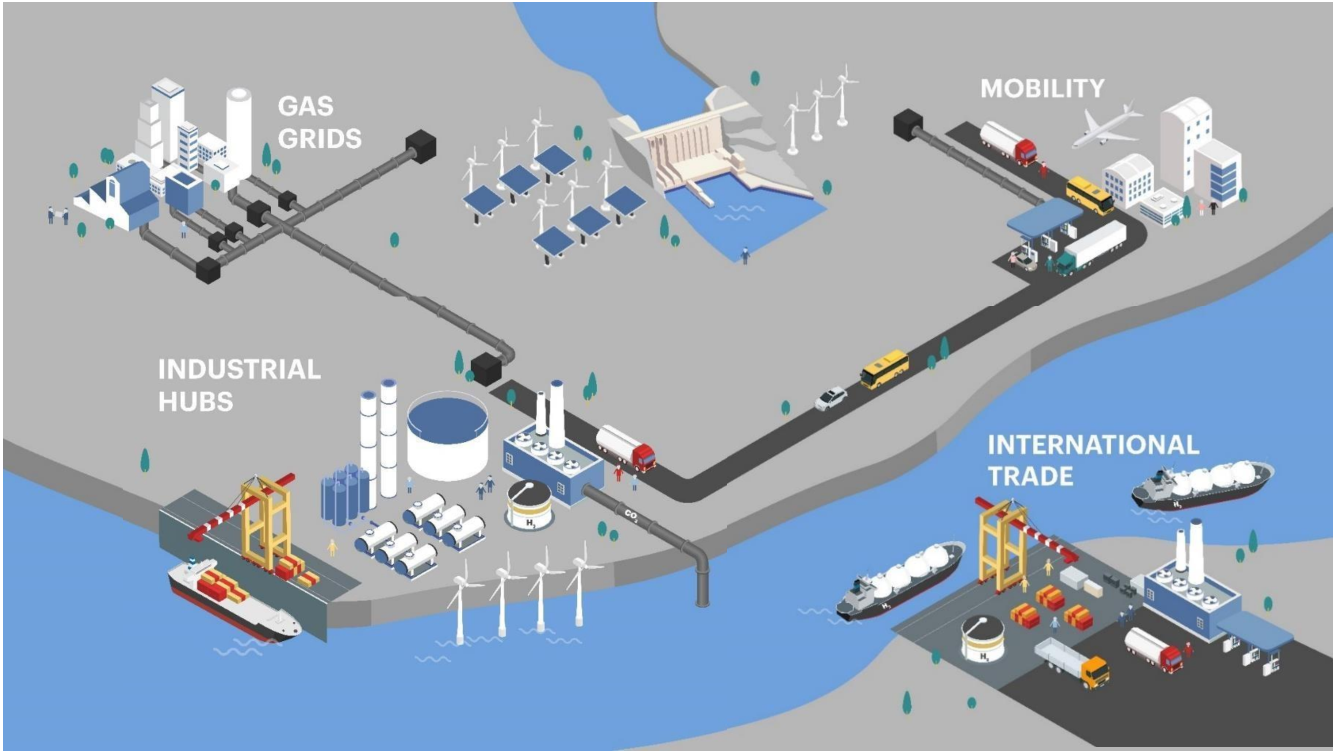
More than 60% of the power-to-gas projects have hydrogen (H_2) as final product, 23% methane (CH_4) and 15% both hydrogen (H_2) and methane (CH_4). Only one project produces methanol (CH_3OH).

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

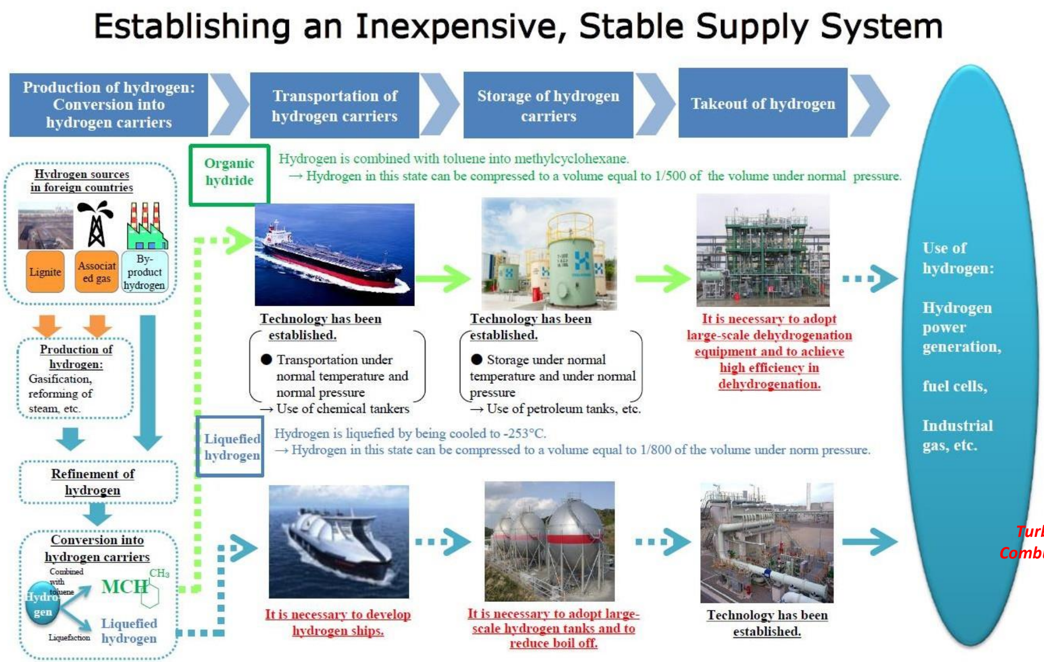
In most of the projects the produced gas finds its destination in the natural gas network (33%). The transport sector and power generation as end users are targeted in 25% of the projects. One single project delivers gas to an industrial user.

Source: IEA Hydrogen Task 38

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



TOMORROW: Japanese scheme to import H2 from different countries



Establishing an Inexpensive, Stable Supply System

Production of hydrogen: Conversion into hydrogen carriers › **Transportation of hydrogen carriers** › **Storage of hydrogen carriers** › **Takeout of hydrogen** ›

Hydrogen sources in foreign countries: Lignite, Associated gas, By-product hydrogen

Production of hydrogen: Gasification, reforming of steam, etc.

Refinement of hydrogen

Conversion into hydrogen carriers

Organic hydride

Hydrogen is combined with toluene into methylcyclohexane.
→ Hydrogen in this state can be compressed to a volume equal to 1/500 of the volume under normal pressure.

Technology has been established.
- Transportation under normal temperature and normal pressure

→ Use of chemical tankers

Technology has been established.
- Storage under normal temperature and under normal pressure

→ Use of petroleum tanks, etc.

It is necessary to adopt large-scale dehydrogenation equipment and to achieve high efficiency in dehydrogenation.

Liquefied hydrogen

Hydrogen is liquefied by being cooled to -253°C.
→ Hydrogen in this state can be compressed to a volume equal to 1/800 of the volume under norm pressure.

It is necessary to develop hydrogen ships.

It is necessary to adopt large-scale hydrogen tanks and to reduce boil off.

Technology has been established.

Use of hydrogen:

Hydrogen power generation,

fuel cells,

Industrial gas, etc.

Turbine Combustion

Brown Coal to Hydrogen

CO2 CCS

Source: Japanese METI/NEDO

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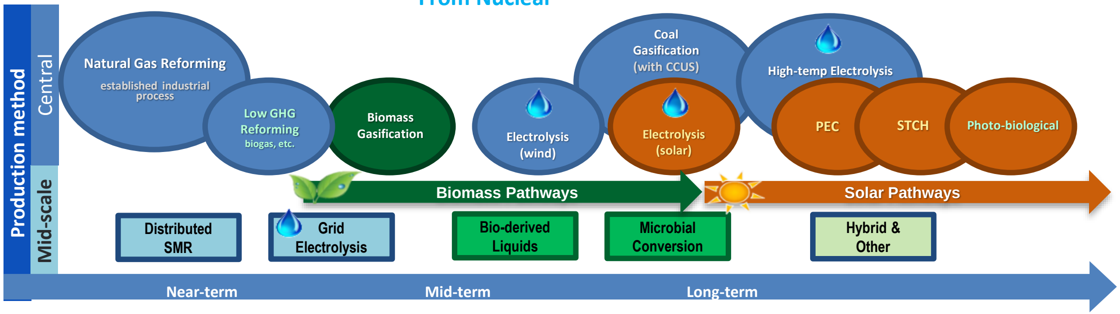
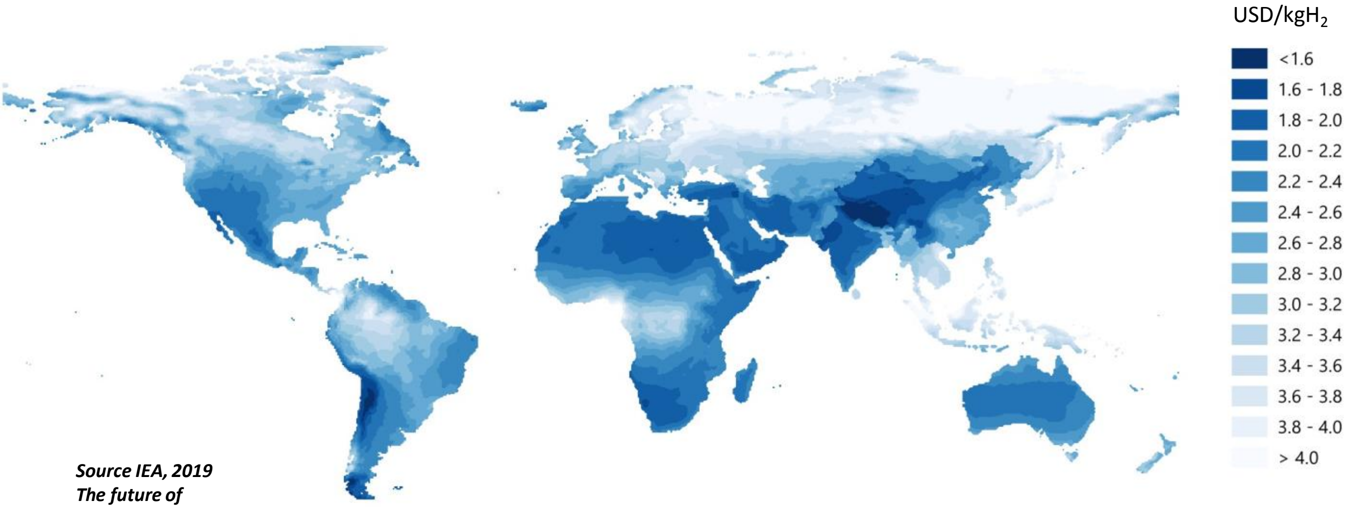


TODAY: Massive and low cost Hydrogen production from Renewables in some areas



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.

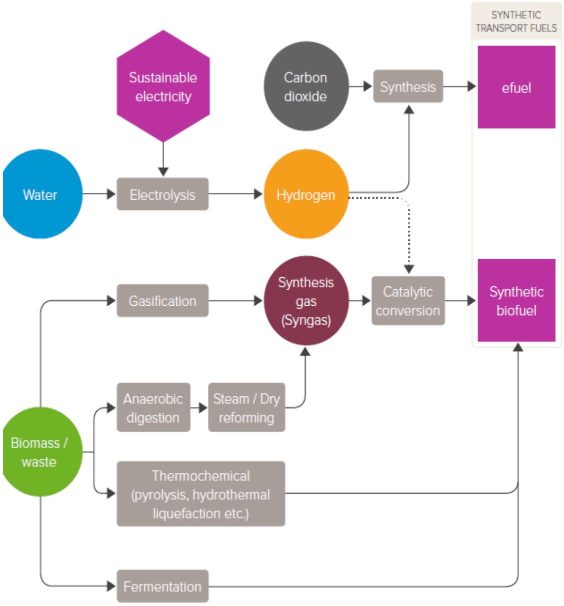
TODAY: PV has come down the cost curve and now there is offshore wind *Offshore Wind Outlook 2019*

- 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

TODAY & TOMORROW: Biomass Gasification – pathway to hydrogen, e-fuel and synthetic biofuel (the Royal Society 2019)

FIGURE 1

Routes to carbon based sustainable liquid synthetic fuels.



Source: The Royal Society, 2019

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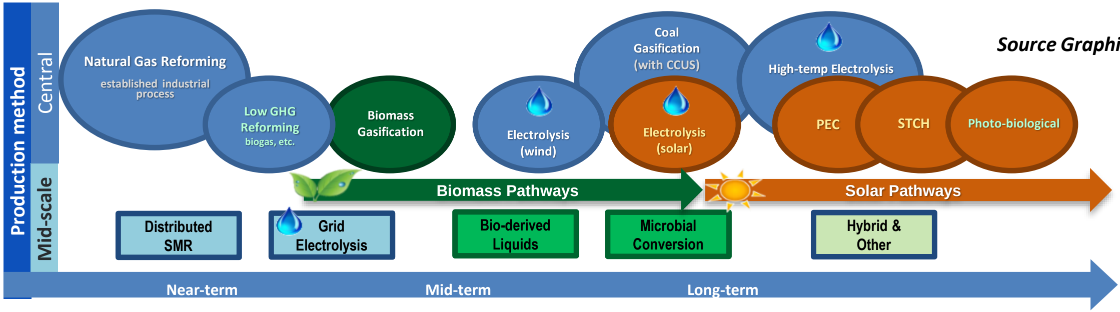


Source Graphic: US DOE/EERE

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

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.

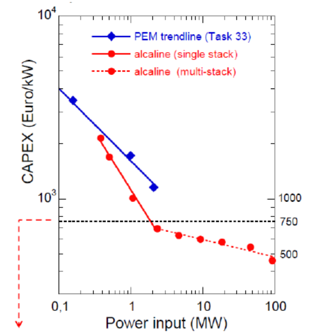


Fig. 1 CAPEX data for both PEM and alkaline electrolysers, plotted as a function of the power input. Data for alkaline systems are based on a single stack of 2.13 MW conside-ring 230 cells, 2.6m² size. Note that change in slope for alkaline electrolysers corres-ponds to the use of multi-stack systems.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

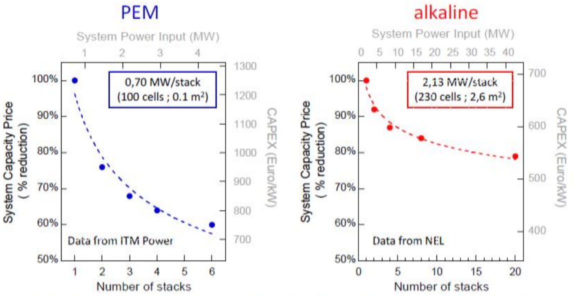


Fig. 3. Reduction in CAPEX upon use of multi-stack systems, both for PEM (left) and alkaline (right) electrolysers.

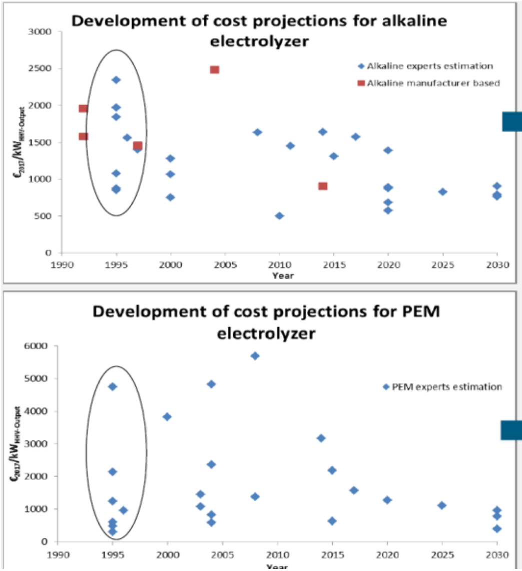
Fig. 2 Reduction in CAPEX upon use of multi-stack systems, both for PEM (left) and alkaline (right) electrolysers. [1]

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].



Development of cost projections for alkaline electrolyzer

Development of cost projections for PEM electrolyzer

- **Range** of estimations **in 1990s for alkaline** was between **~800 and ~2500 $€_{2017}/kW_{HHV-Output}$**
- Today´s expectation for **2030** for alkaline droped to **~700 to ~1000 $€_{2017}/kW_{HHV-Output}$**.
- 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 $€_{2017}/kW_{HHV-Output}$**
- Today´s expectation for **2030** for PEM droped to **~400 to ~1000 $€_{2017}/kW_{HHV-Output}$**

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

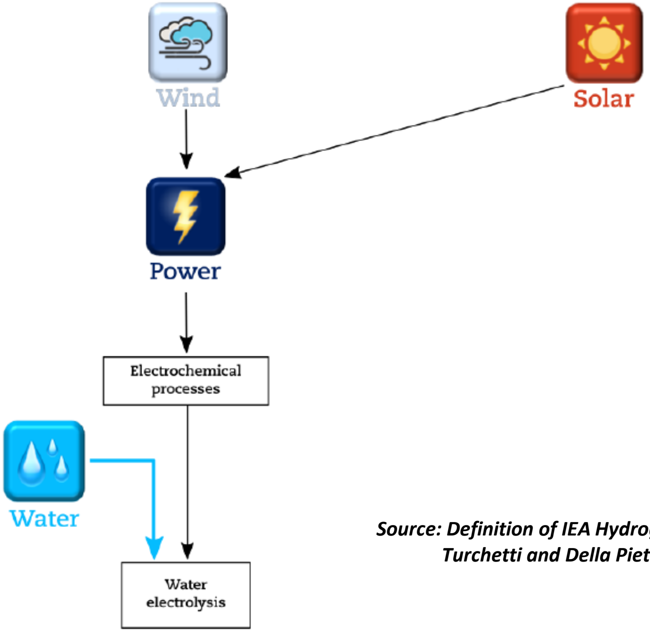
Task 38 Brief – continued - http://ieahydrogen.org/pdfs/Brief-ElyData_final.aspx

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.

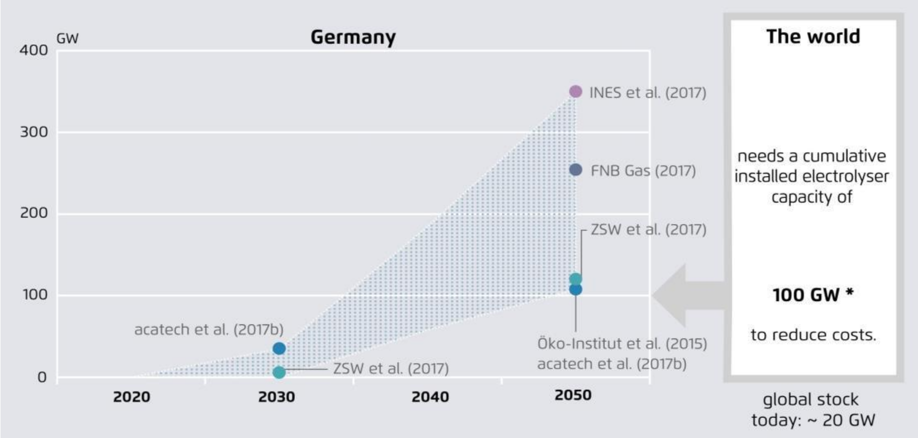
Green hydrogen production via electrolysis:



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

TOMORROW: Electrolyser become a Key Technology for energy transition in scale-up challenge

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



The world needs a cumulative installed electrolyser capacity of

100 GW *

to reduce costs.

global stock today: ~ 20 GW

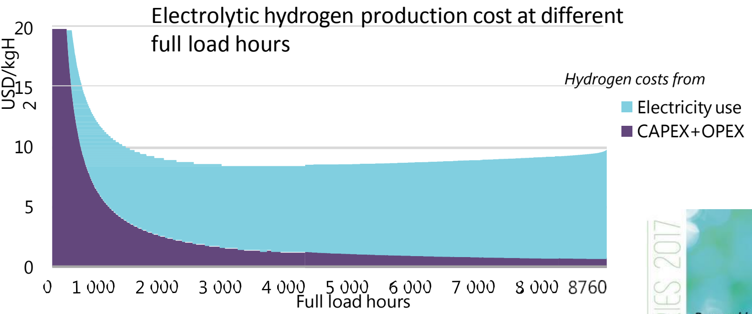
→ **Scale and learning effects** are critical for cost reduction, but uncertain (e.g. CO_2 from air).

→ International **100-gigawatts-challenge**.

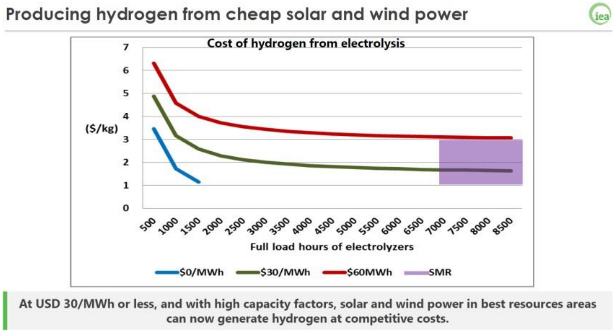
→ Investments are not to be expected without **political intervention or high CO_2 price** due to high cost of synthetic fuels.

Own illustration based on Frontier Economics (2018) and others

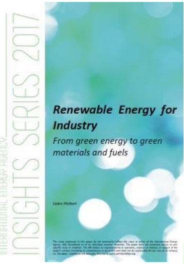
TODAY: Optimal cost versus duration


Electrolytic hydrogen production cost at different full load hours

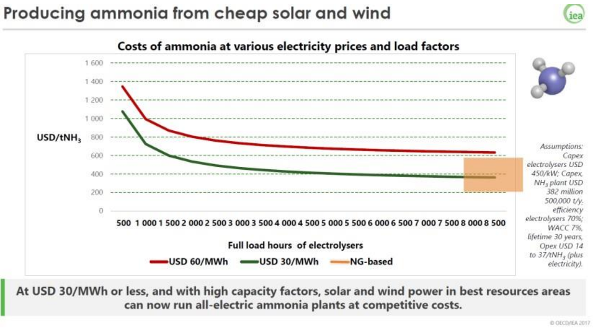
Source IEA, 2019
The future of Hydrogen,
Webinar


Producing hydrogen from cheap solar and wind power

At USD 30/MWh or less, and with high capacity factors, solar and wind power in best resources areas can now generate hydrogen at competitive costs.


INTERNATIONAL ENERGY AGENCY
INSIGHTS SERIES 2017

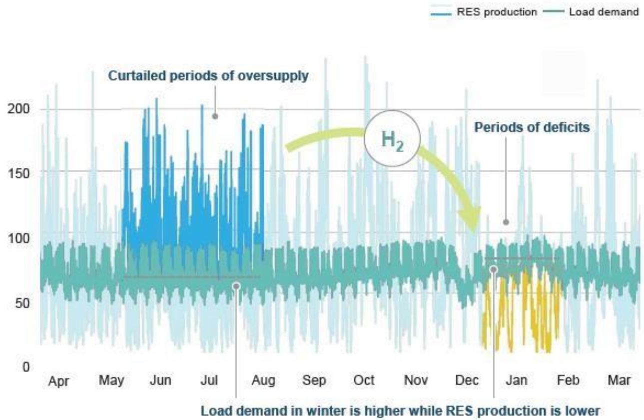
Renewable Energy for Industry
From green energy to green materials and fuels


Producing ammonia from cheap solar and wind

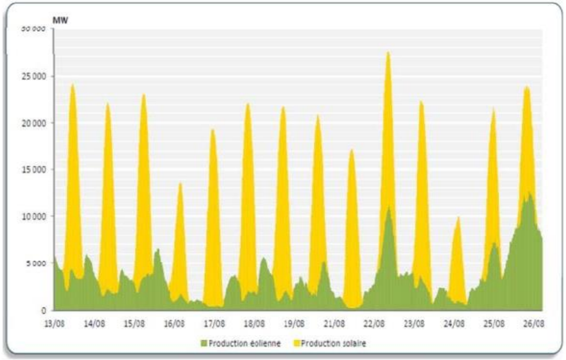
Assumptions: Capex electrolysers USD 450/kW; Capex, NH_3 plant USD 382 million 500,000 t/y, efficiency electrolysers 70%; WACC 7%, lifetime 30 years, Opex USD 14 to 37/tNH_3 (plus electricity).

At USD 30/MWh or less, and with high capacity factors, solar and wind power in best resources areas can now run all-electric ammonia plants at competitive costs.

TOMORROW: hydrogen could absorb excess electricity from variable renewables for storage

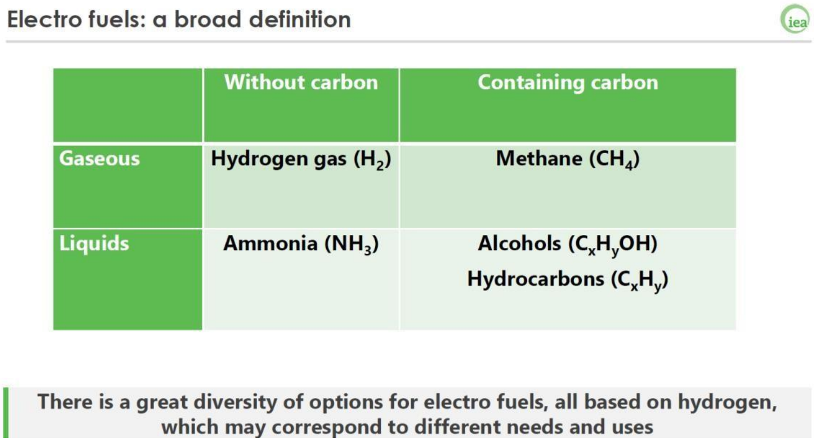


Source: EC 2050 scenario, McKinsey analysis



Période du 13 au 26 août 2012 en Allemagne

TOMORROW: « Green Hydrogen inside » designer fuels

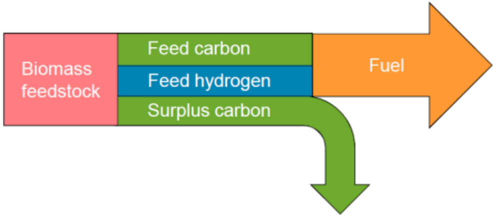


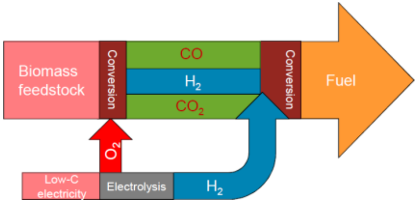
Electro fuels: a broad definition

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

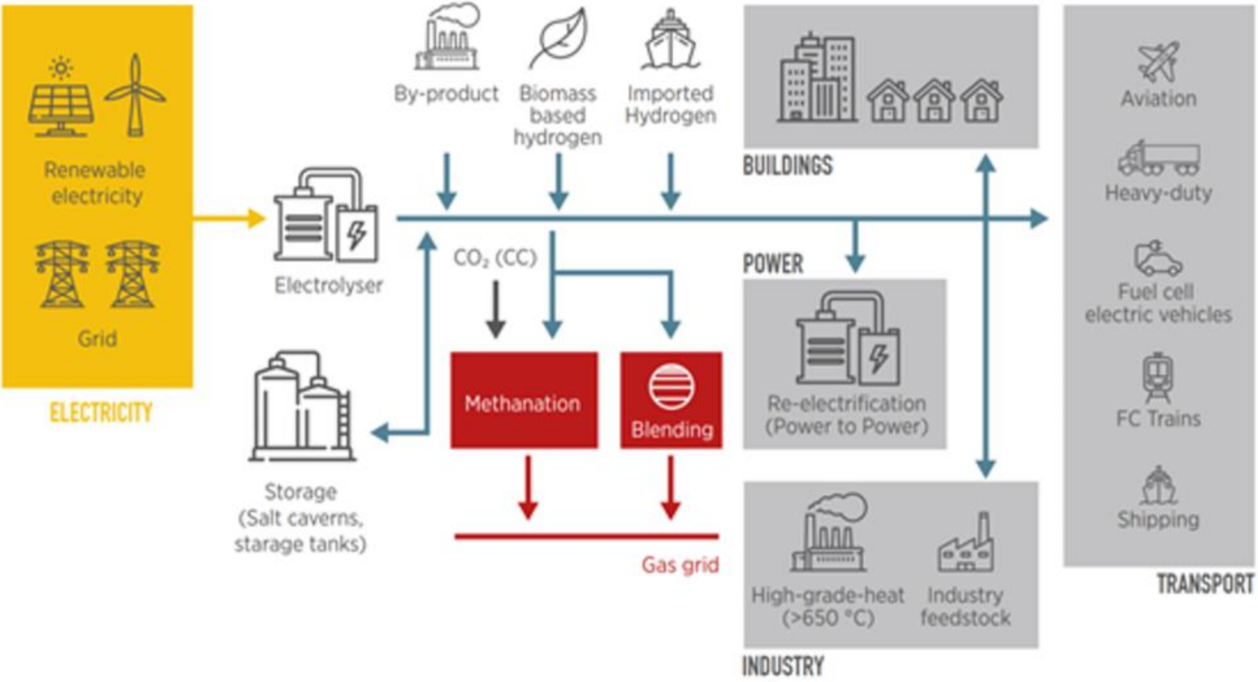
> There is a great diversity of options for electro fuels, all based on hydrogen, which may correspond to different needs and uses

Biofuels and hydrogen synergies





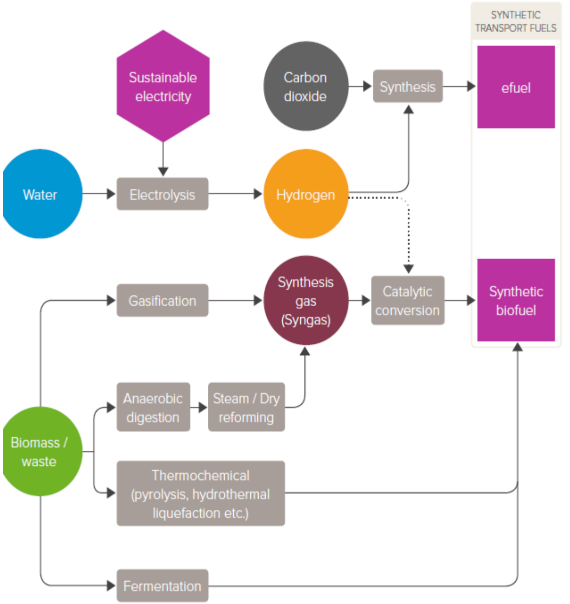
TOMORROW: Electrofuels Carbon-based fuels Power to gas/liquids/fuels or Synthetic fuels https://theconversation.com/el-hidrogeno-clave-para-gestionar-las-redes-electricas-del-futuro-120837



TODAY & TOMORROW: Biomass Gasification – pathway to hydrogen, e-fuel and synthetic biofuel (the Royal Society 2019)

FIGURE 1

outes to carbon based sustainable liquid synthetic fuels.



The Royal Society, 2019

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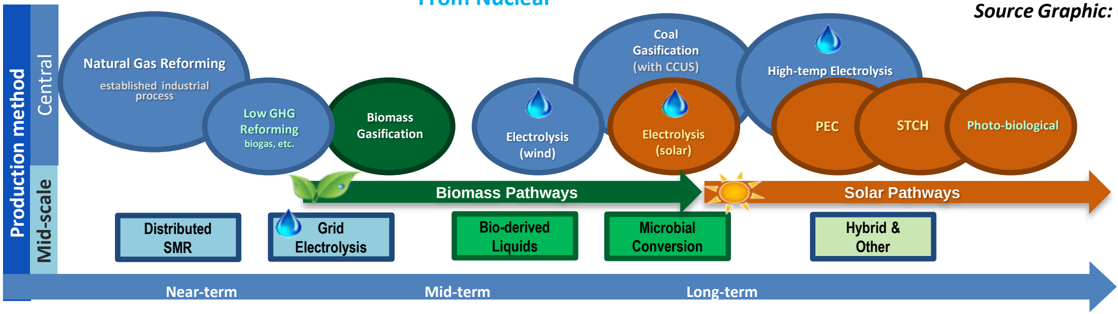
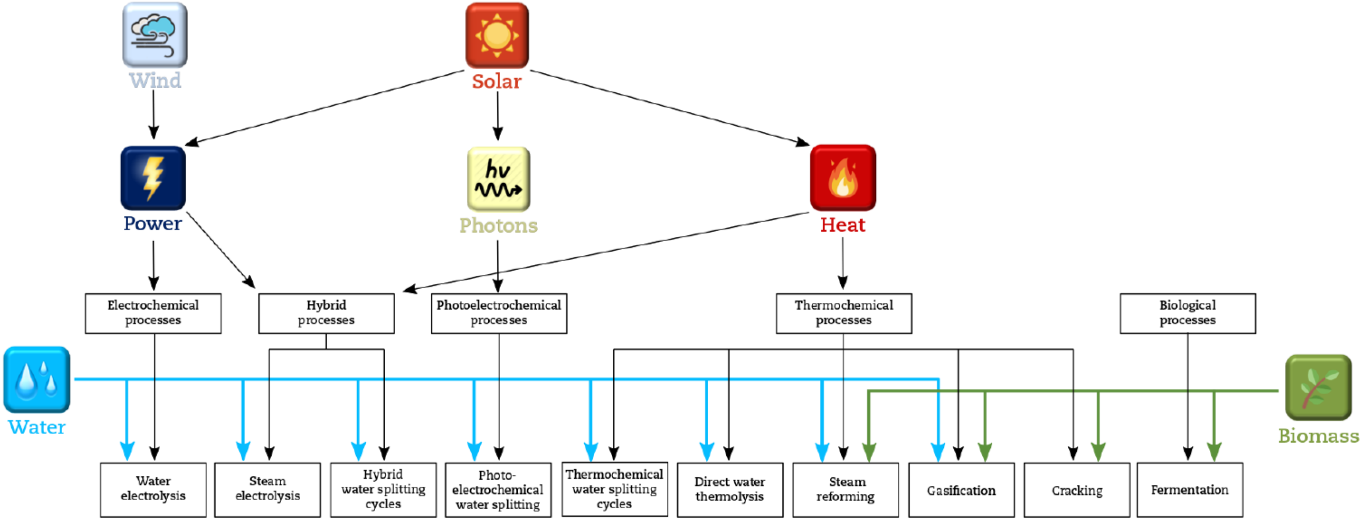


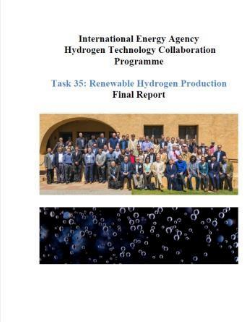
Source Graphic: US DOE/EERE

TOMORROW: Green hydrogen production: much more than electrolysis!



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

TODAY: Preparations for tomorrow



International Energy Agency
Hydrogen Technology Collaboration
Programme

Task 35: Renewable Hydrogen Production
Final Report

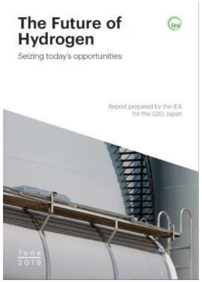
Task 35 final report http://ieahydrogen.org/pdfs/IEA-HTCP-Task-35-FINAL-REPORT_v4.aspx gave a state of the art concerning the most

suitable pathways for a renewable water splitting :

Subtask1: water electrolysis (low+high temperature)

Subtask2: photoelectrochemical water slitting

Subtask3: solar-thermochemical water splitting



The Future of
Hydrogen
Seizing today's opportunities

Report prepared by the IEA
for the G20, Japan

June
2019

Report prepared by the IEA for the G20 held in Japan pointed out how the Integration of the potential linkages between all the sources of supply and demand for hydrogen in energy scenarios can explore the complex trade-offs between competing energy pathways. This would facilitate the decision makers approach to hydrogen as a valuable option in the transition to an integrated energy system.

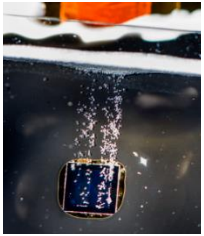
TODAY: Photoelectrochemical Highlights

NEW WORLD RECORD

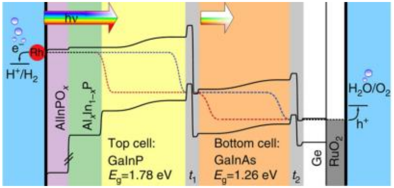
High efficiency III-V semiconductors from NREL achieve a 16% solar to hydrogen efficiency in PEC water splitting.

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

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

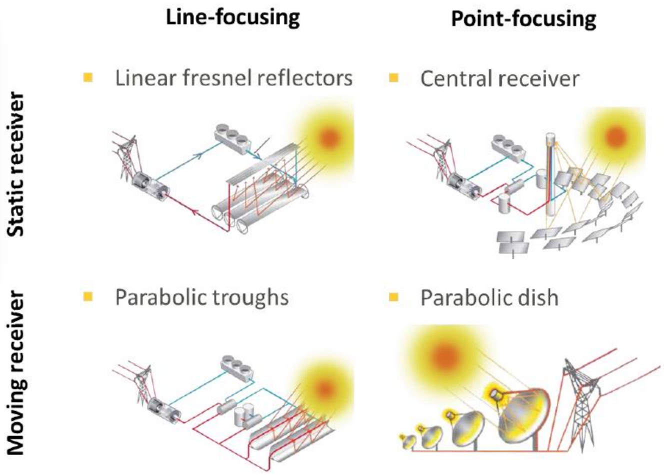


High efficiency III-V semiconductors from International Collaboration (Germany and USA), achieve a 14% solar to hydrogen efficiency in PEC water splitting.



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

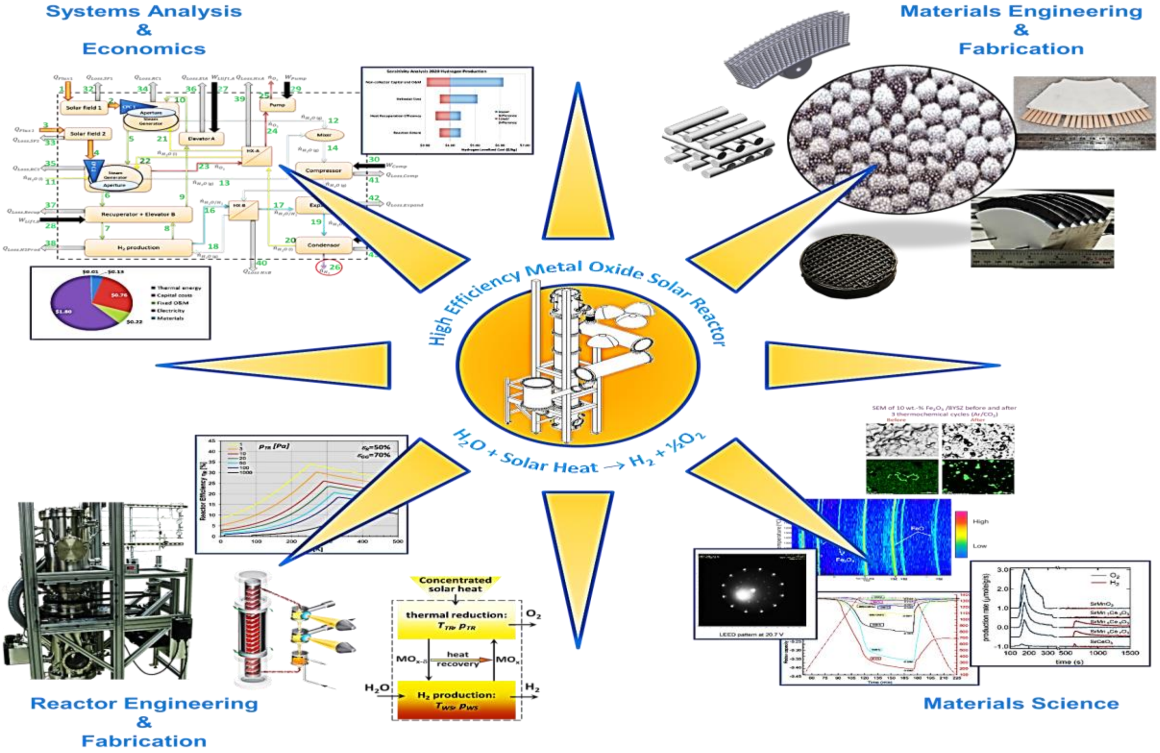
Concentrating solar thermal (CST)



	Line-focusing	Point-focusing
Static receiver	Linear fresnel reflectors	Central receiver
Moving receiver	Parabolic troughs	Parabolic dish

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

TODAY: Solar Thermochemical Highlight

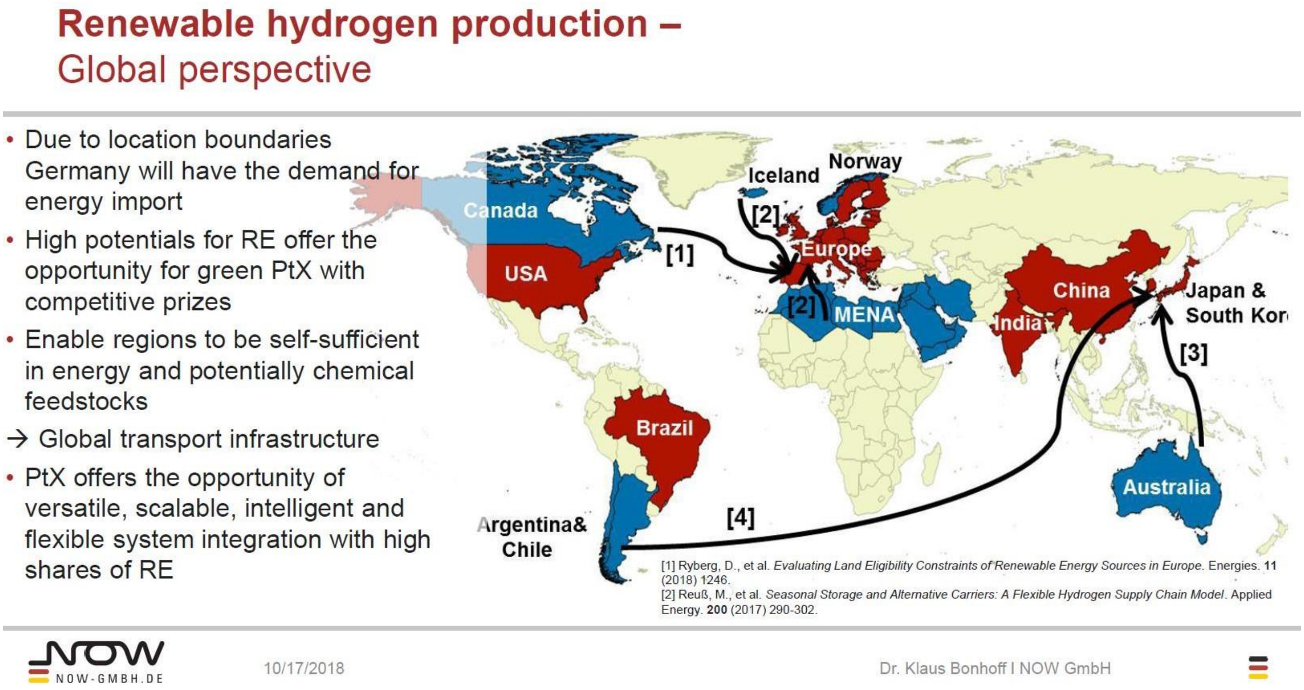


Cascading Pressure Receiver-Reactor built to test RedOx cycles

IEA Hydrogen Technology Collaboration Programme ExCo Oslo Meeting February 2017

A new and emergent topic: international trade for hydrogen

What could be the new roads of 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.

NOW-GMBH.DE 10/17/2018 Dr. Klaus Bonhoff I NOW GmbH

Hydrogen 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

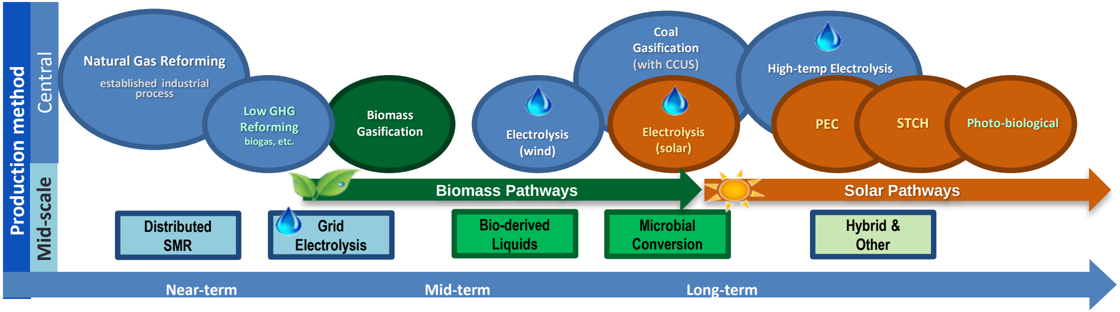
Advanced

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

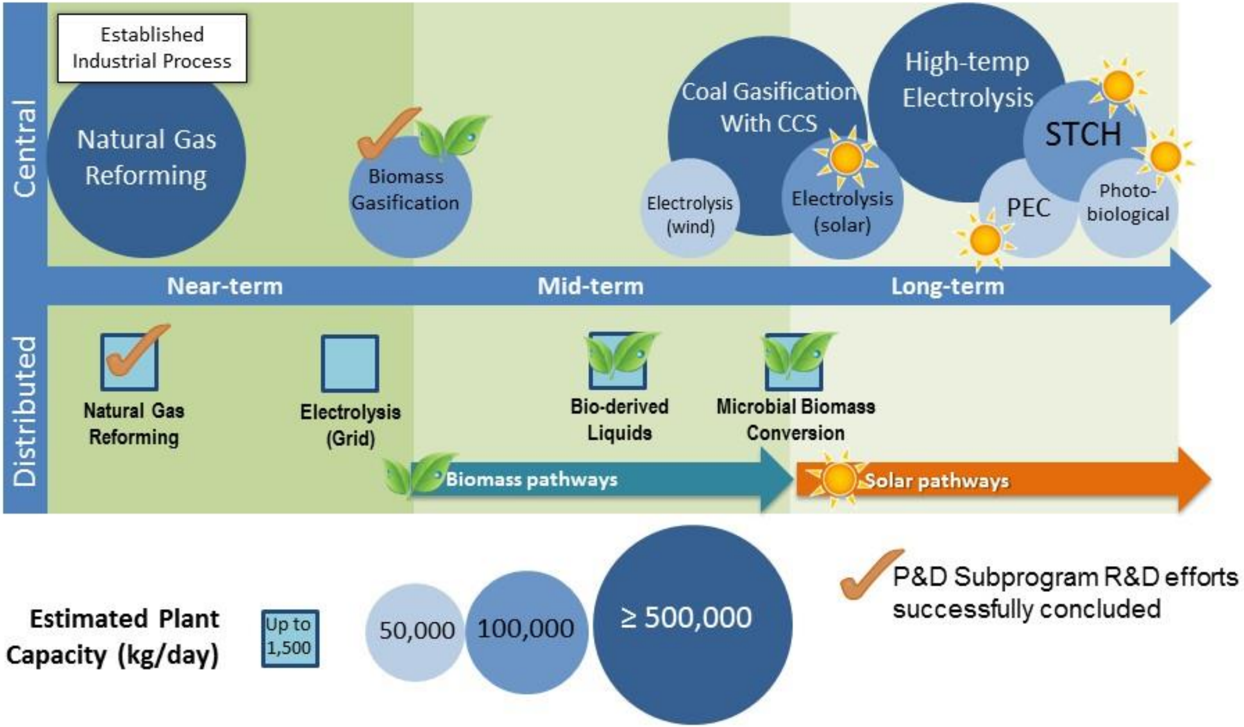


Production method
Central
Mid-scale
Natural Gas Reforming
established industrial process
Low GHG Reforming
biogas, etc.
Biomass Gasification
Electrolysis (wind)
Coal Gasification (with CCUS)
Electrolysis (solar)
High-temp Electrolysis
PEC
STCH
Photo-biological
Biomass Pathways
Solar Pathways
Distributed SMR
Grid Electrolysis
Bio-derived Liquids
Microbial Conversion
Hybrid & Other
Near-term
Mid-term
Long-term

TOMORROW: Nuclear and hydrogen

- **Past R&D on thermochemical cycles, High temperature electrolyser etc….**
- **Plus, wholistic approach of smart electric grid with load based nuclear and VRE**
- **Example of France:** New challenges for Nuclear in France Installed nuclear base
  - ↳ Decrease of the nuclear load factor
  - ↳ Increasing needs for flexibility
  - See IEA HIA Task 25 Nuclear Hydrogen Process Sheet Synopses at http://ieahydrogen.org/PUBLICATIONS,-REPORTS-PRESENTATIONS/Technical-Reports.aspx

IEA Hydrogen overview on hydrogen production – Thank you!



Source US DOE/EERE

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

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