Overview: Hydrogen Production
Today and Tomorrow

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Workshop on Hydrogen Production with CCS
EDF Chatou Campus
6 November 2019
Perspectives for Hydrogen production

- **Central**
  - Natural Gas Reforming
  - Biomass Gasification

- **Near-term**
  - Natural Gas Reforming
  - Electrolysis (Grid)
  - Bio-derived Liquids

- **Mid-term**
  - Coal Gasification With CCS
  - Electrolysis (wind)
  - Electrolysis (solar)
  - Microbial Biomass Conversion

- **Long-term**
  - High-temp Electrolysis
  - STCH
  - PEC
  - Photo-biological

- **Estimated Plant Capacity (kg/day)**
  - Up to 1,500
  - 50,000
  - 100,000
  - ≥ 500,000

- P&D Subprogram R&D efforts successfully concluded

*Source US DOE/EERE*
Hydrogen Production & Pathways: Today & Tomorrow

From Fossil Fuel – Natural Gas Reforming and Coal
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- Advanced Electrolysis
- Photoelectrochemical (PEC)
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From Nuclear

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)

Source Graphic: US DOE/EERE
TODAY: Natural Gas Reforming  - Tomorrow with CCS

Central and Distributed Steam Methane Reforming (SMR)

Partial Oxidation POX

Source: Air Liquide

Steam methane reforming

\[
\begin{align*}
    CH_4 + H_2O & \rightleftharpoons CO + 3H_2 & \Delta H_{500^\circ C} = 221.6 \ \frac{kJ}{mol} & \text{(SR)} \\
    CO + H_2O & \rightleftharpoons CO_2 + H_2 & \Delta H_{500^\circ C} = -37.4 \ \frac{kJ}{mol} & \text{(WGS)} \\
    CH_4 + 2H_2O & \rightleftharpoons CO_2 + 4H_2 & \Delta H_{500^\circ C} = 184.2 \ \frac{kJ}{mol} & \text{(OSR)} \\
    CH_4 + CO_2 & \rightleftharpoons 2CO + 2H_2 & \frac{kJ}{mol} & \text{(DR)}
\end{align*}
\]

**Conventional process:**

- Carried out in externally heated (furnace) tubular reactors
- Operating conditions: $T = 700-900 \ ^\circ C$; $P = 10-40 \ \text{bar}$; $S/C = 3-6$
- Downstream of the reformer 1 or 2 WGS reactor(s) ($500-600 \ ^\circ C$)
- 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

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

Source IEA 2019

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

By Q1 of 2017, the realised installed capacity of electrolyzers 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 (H₂) as final product, 23% methane (CH₄) and 15% both hydrogen (H₂) and methane (CH₄). Only one project produces methanol (CH₃OH).

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

Liquefaction, reforming of steam, etc.

Organic hydride

Hydrogen is combined with toluene into methycyclohexane.

→ Hydrogen in this state can be compressed to a volume equal to 1/500 of the volume under normal pressure.

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

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 normal pressure.

Refinement of hydrogen

Conversion into hydrogen carriers

It is necessary to develop hydrogen ships.

Technology has been established.

Transportation under normal temperature and normal pressure

Use of chemical tankers

Use of hydrogen: Hydrogen power generation, fuel cells, industrial gas, etc.

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.

Technology has been established.

Conversion into hydrogen carriers

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

Source: Japanese METI/NEDO

Brown Coal to Hydrogen

CO2 CCS

Turbine Combustion

Source: Japanese METI/NEDO

AN INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME
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- Solar Pathways
- Biomass Pathways
- Near-term
- Mid-term
- Long-term

From Water Electrolysis

Conventional

- 100 years of experience
- Electrolysers available in small and large sizes (now in MWs!)

Advanced

- Low – alkaline and polymer electrolyte membrane (PEM)
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Source Graphic: USDOE/EERE

AN INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME
TODAY: Massive and low cost Hydrogen production from Renewables in some areas

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

Source IEA, 2019
The future of Hydrogen, Webinar
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

Source: The Royal Society, 2019
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Source Graphic: US DOE/EERE
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 consi...](image-url)

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

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

![Fig. 3 Cost projections in the near to long term, for alkaline and PEM electrolysers [2]](http://ieahydrogen.org/pdfs/Brief-ElyData_final.aspx)

References


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

- Scale and learning effects are critical for cost reduction, but uncertain (e.g. CO₂ from air).
- International 100-gigawatts-challenge.
- Investments are not to be expected without political intervention or high CO₂ 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.

Producing ammonia from cheap solar and wind

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
TOMORROW: « Green Hydrogen inside » designer fuels

**Electro fuels: a broad definition**

<table>
<thead>
<tr>
<th>Without carbon</th>
<th>Containing carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gaseous</strong></td>
<td></td>
</tr>
<tr>
<td>Hydrogen gas ($H_2$)</td>
<td>Methane ($CH_4$)</td>
</tr>
<tr>
<td><strong>Liquids</strong></td>
<td></td>
</tr>
<tr>
<td>Ammonia ($NH_3$)</td>
<td>Alcohols ($C_xH_yOH$)</td>
</tr>
<tr>
<td></td>
<td>Hydrocarbons ($C_xH_y$)</td>
</tr>
</tbody>
</table>

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

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


- **Subtask1:** water electrolysis (low+high temperature)
- **Subtask2:** photoelectrochemical water splitting
- **Subtask3:** solar-thermochemical water splitting

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

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

*NEW WORLD RECORD*

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


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

Concentrating solar thermal (CST)

Line-focusing
- Linear fresnel reflectors

Point-focusing
- Central receiver
- Parabolic dish

Static receiver

Moving receiver

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

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Source Graphic: US DOE/EERE
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

IEA Hydrogen overview on hydrogen production – Thank you!

Source US DOE/EEERE
Thank you from IEA Hydrogen
A premier global resource for technical expertise in H2 RD&D

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