HYDROGENICS

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COST REDUCTION POTENTIAL FOR ELECTROLYSER TECHNOLOGY

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18 June 2018, Berlin (via conference call)

EUROPEAN POWERTOGAS

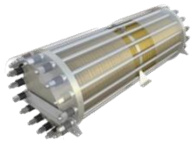
Introduction video

https://youtu.be/UJXhX4dLMtA

Agenda

1. **Hydrogenics & water electrolysers**
2. Actual and future costs of water electrolysers
3. Concluding remarks

Leading Hydrogen **TECHNOLOGY PROVIDER**



Onsite Generation | Electrolysers

H_2O + electricity → $H_2 + ½\, O_2$

Industrial Hydrogen

Hydrogen Fueling

Power Systems | Fuel Cell Modules

$H_2 + ½\, O_2$ → H_2O + electricity

Stand-by Power

Mobility Power

Hydrogenics, a 100% global hydrogen company

Hydrogenics Corporation

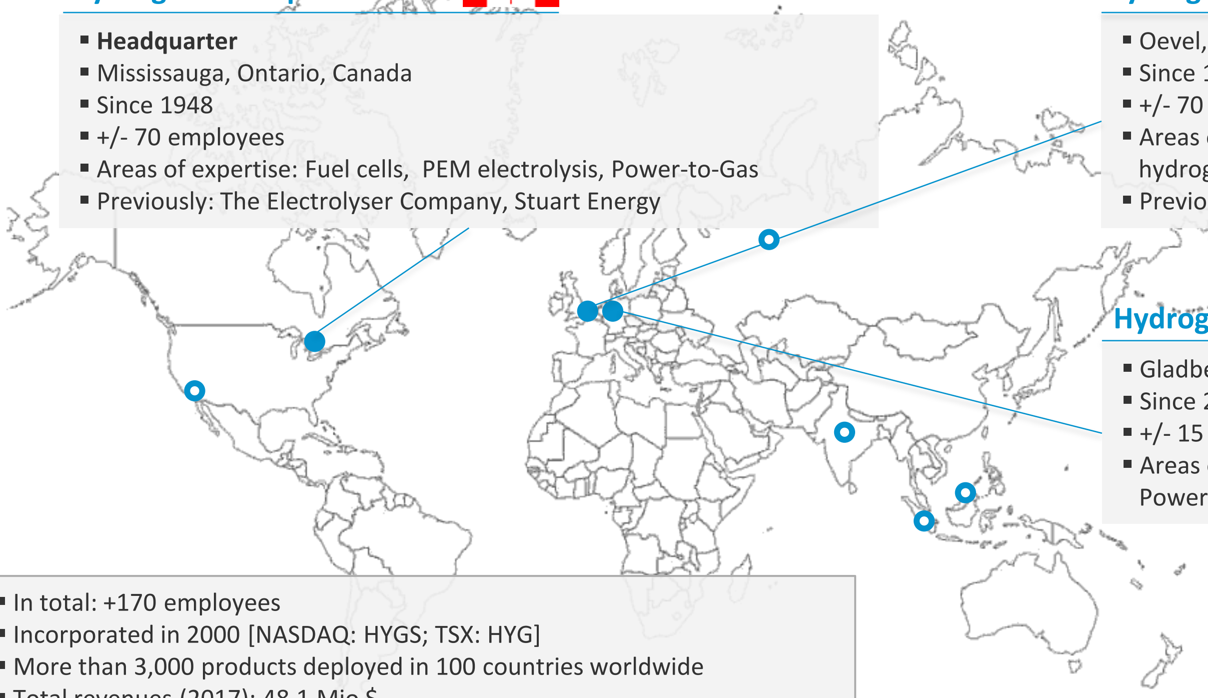
- **Headquarter**
- Mississauga, Ontario, Canada
- Since 1948
- +/- 70 employees
- Areas of expertise: Fuel cells, PEM electrolysis, Power-to-Gas
- Previously: The Electrolyser Company, Stuart Energy

Hydrogenics Europe

- Oevel, Belgium
- Since 1987
- +/- 70 employees
- Areas of expertise: pressurized alkaline electrolysis, hydrogen refueling stations, Power-to-Gas
- Previously: Vandenborre Hydrogen Systems

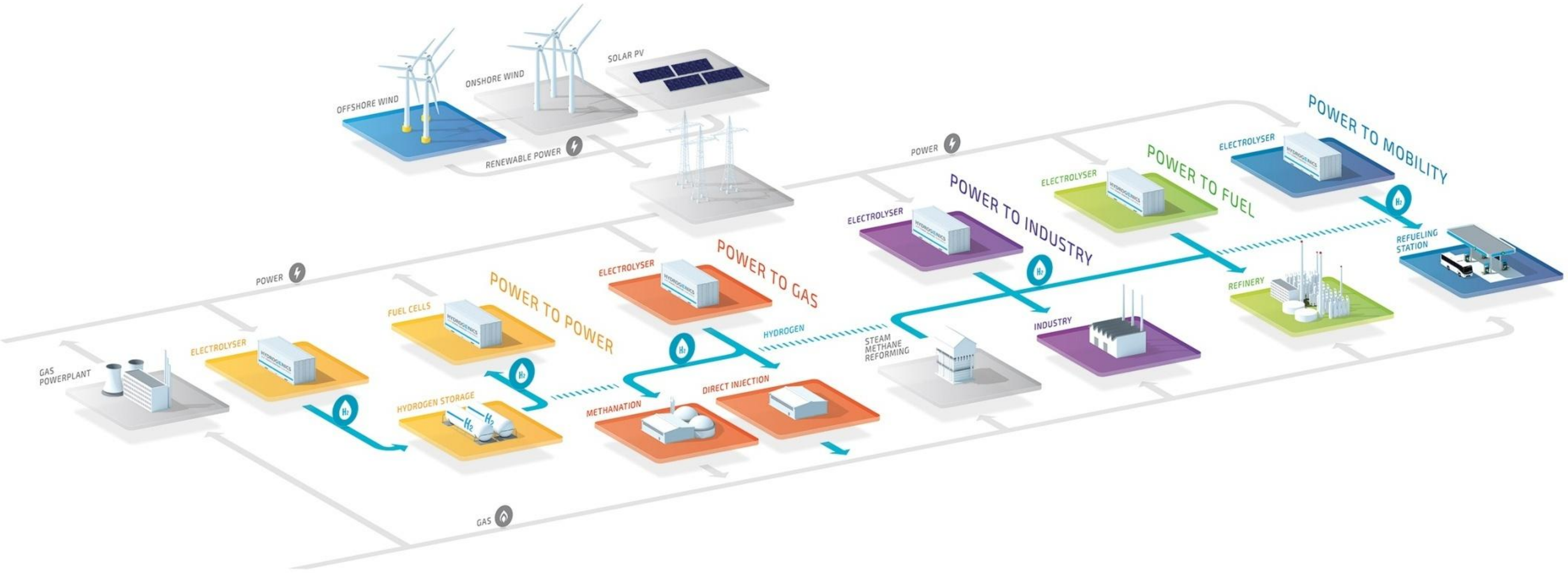
Hydrogenics Gmbh

- Gladbeck, Germany
- Since 2002
- +/- 15 employees
- Areas of expertise: Fuel cells, mobility projects, Power-to-Gas



- In total: +170 employees
- Incorporated in 2000 [NASDAQ: HYGS; TSX: HYG]
- More than 3,000 products deployed in 100 countries worldwide
- Total revenues (2017): 48.1 Mio $
- Over 65 years of electrolysis leadership

Renewable Hydrogen



Selection of our key references

Electrolysis

700 bar Hydrogen Refueling Station
Aberdeen, Scotland (UK)

1,5 MW PEM P2G (direct injection), Hamburg, Germany

1 MW alkaline P2G (methanation)
BIOCAT, Copenhagen, Denmark

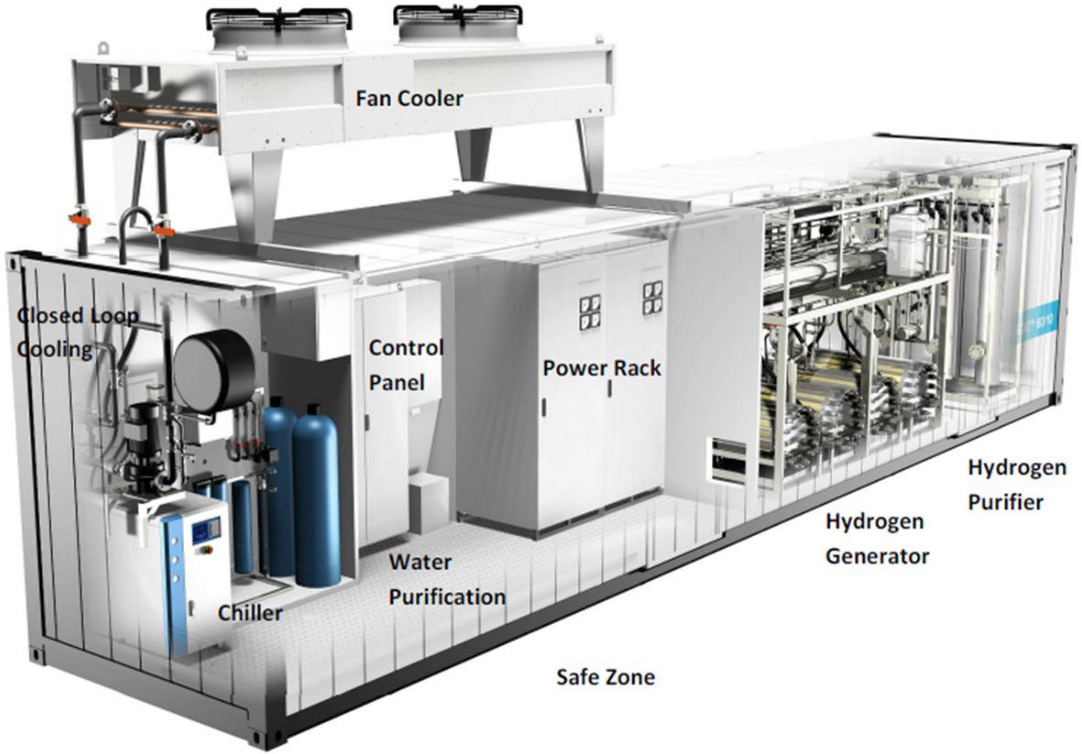
Fuel cells

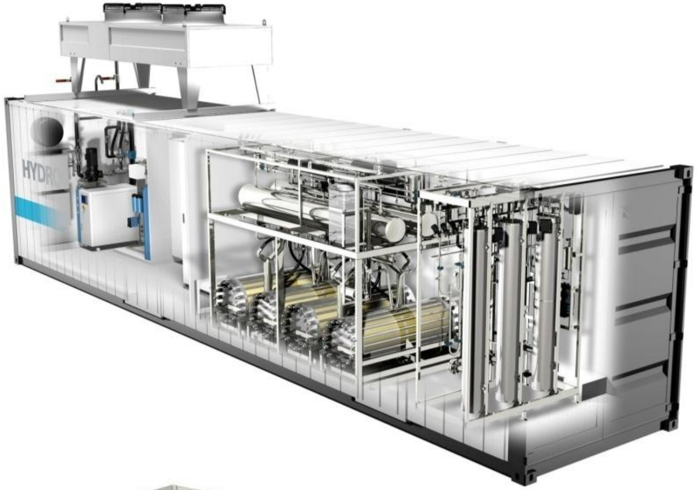
1 MW stationary Fuel cell (H_2 repowering)
Kolon, South-Korea

Fuel cell for mobility (H_2 trains)
Alstom Coradia iLint , Germany

Fuel cell for mobility (H_2 buses), China

HySTAT™ 60 - alkaline electrolyser





Extensive experience with alkaline technology (>30 years)

Saint Gobain, Colombia


Elemash, Russia

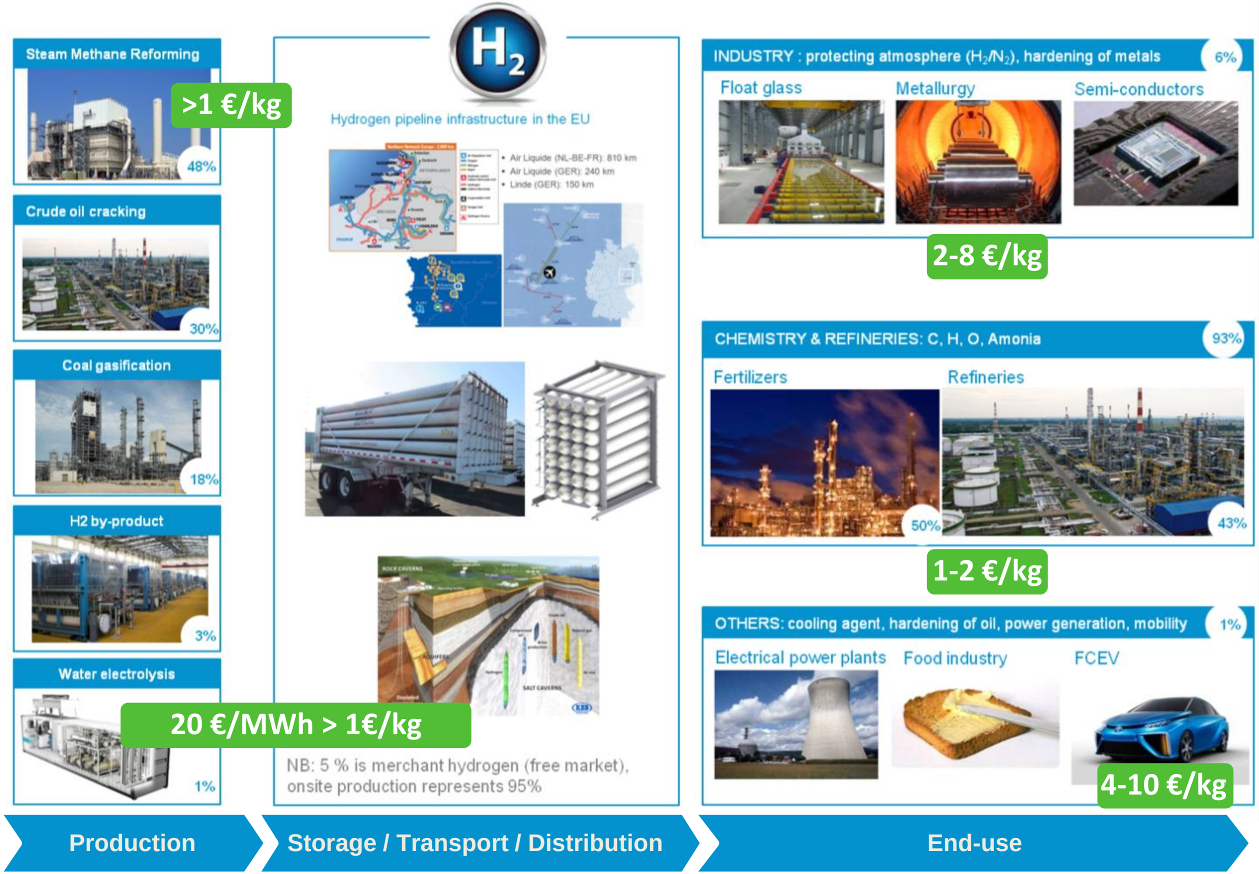

Bushan, India


Camao, Brazil


Nyagan, Russia


Kirovgrad, Russia

World hydrogen market



But most (96%) of the hydrogen produced today is not CO_2-free (from gas, oil, coal)

If produced from renewable power via electrolysis, hydrogen is fully renewable and CO_2-free.

Renewable hydrogen has the potential to decarbonize a large range of applications

Data source: The Hydrogen Economy, M. Ball 2009 & Esprit Associates 2014

HyLYZER® - PEM : key milestones @ Hydrogenics

+15 MW

R&D

Test large stack

Field test 1.5 MW electrolyser

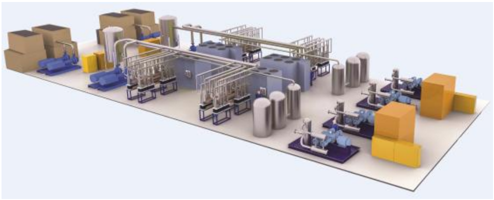
2.5/3 MW cell stack

1999 | 2004 | 2012 | 2014 | 2015 | 2017 | 2018 | ...

Small scale PEM electrolyser

1,5 MW cell stack

Dual cell stack design



Multi MW design

New benchmark in PEM electrolysis HyLYZER®-600
3 MW cell stack from Hydrogenics for multi-MW projects

1
MW Scale Electrolyzer Stack
3.0 MW industry benchmark

2
Reduction of Plant Capital Costs
Achieved target system cost

3
Stack Efficiency Improvements
Leading industry performance

Power Input: **3.0 MW**
Hydrogen Output: 620 Nm^3/h
Design Pressure: 40 bar

Power Input: **1.5 MW**
Hydrogen Output: 310 Nm^3/h
Design Pressure: 40 bar

4
Fast Response and Dynamic Operation
Key IPR established

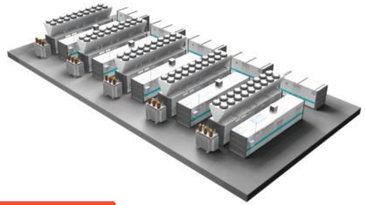
5
Very compact
Lowest footprint on the market

6
Reduced Maintenance
Limited and optimised

Alkaline & PEM electrolysis | Product's line

Alkaline			PEM (Proton Exchange Membrane)		



	HySTAT®-15-10	HySTAT®-60-10	HySTAT®-100-10	HyLYZER® -300-30	HyLYZER® -1.000-30	HyLYZER® -5.000-30
Output pressure		10 barg (27 barg optional)			30 barg	
Number of cell stacks	1	4	6	1	2	10
Nominal Hydrogen Flow	15 Nm³/h	60 Nm³/h	100 Nm³/h	300 Nm³/h	1.000 Nm³/h	5.000 Nm³/h
Nominal input power	80 kW	300 kW	500 kW	1.5 MW	5 MW	25 MW
AC power consumption (utilities included, at nominal capacity)		5.0-5.4 kWh/Nm³			5.0-5.4 kWh/Nm³	
Hydrogen flow range	40-100%	10-100%	5-100%		1-100%	
Hydrogen purity		99.998% O2 < 2 ppm, N2 < 12 ppm (higher purities optional)			99.998% O2 < 2 ppm, N2 < 12 ppm (higher purities optional)	
Tap water consumption		<1.7 liters / Nm³ H2			<1.4 liters / Nm³ H2	
Footprint (in containers)	1 x 20 ft	1 x 40 ft	1 x 40 ft	1 x 40 ft	2 x 40 ft	10 x 40 ft
Footprint utilities (optional)	Incl.	Incl.	Incl.	1 x 20 ft	1 x 20 ft	5 x 20 ft

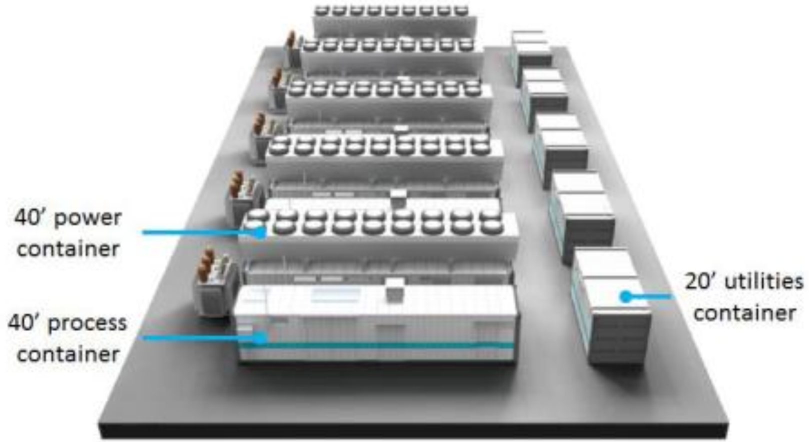
2018

HyLYZER® -1000-30
5 MW PEM Electrolyser

- **Containerized design & compact footprint: 2 x 40 ft**
- **Plug&Play modular design based on 2 x 2,5 MW cell stacks**
- **Fully tested & certified @ Hydrogenics's factory**

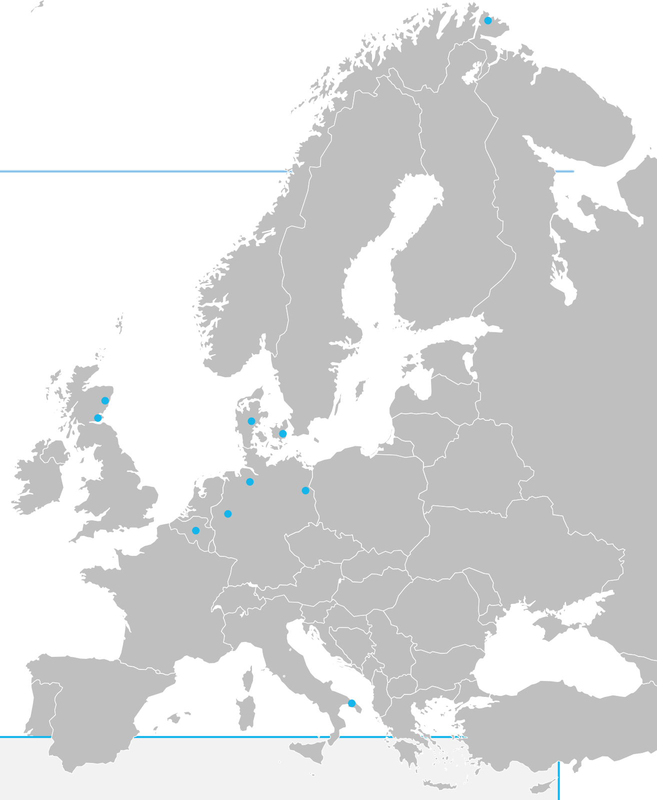
Learnings from demonstration projects

- System cost is coming down faster than expected
- System energy efficiency on track to achieve objectives
- System responsiveness adequate for ancillary grid services
- Maintenance cost trending towards 1% of Capex
- Footprint PEM system adequate for large-scale solutions



Renewable hydrogen
Selection of recent demonstration projects

	Country	Project	Size	Year	Electrolyser technology	Power	Gas	Industry	Mobility	Fuel
	Norway	Haeolus	2 MW + 100 kW FC	2018	PEM	•				
+ CO_2	Germany	MefCO2	1 MW	2018	PEM					•
	Germany	WindGas Brunsbuttel	2.4 MW	2017	PEM		•			
	Thailand	EGAT	1 MW + 300 kW FC	2017	PEM	•				
	Canada	Embridge P2G	2.4 MW + 100 kW FC	2017	PEM		•			
	Denmark	HyBalance	1.2 MW	2017	PEM			•	•	
+ CO_2	Denmark	BioCat	1 MW	2016	Alkaline		•			
+ CO_2	Italy	Ingrid	1 MW + 100 kW FC	2016	Alkaline	•	•	•		
	UK	Aberdeen	1 MW	2016	Alkaline				•	
	Germany	WindGas Reitbrook	1.5 MW	2015	PEM		•			
	Belgium	DonQuichote	150 kW + 100 kW FC	2015	Alkaline + PEM	•			•	
+ CO_2	Germany	WindGas Falkenhagen	2 MW	2014	Alkaline		•			

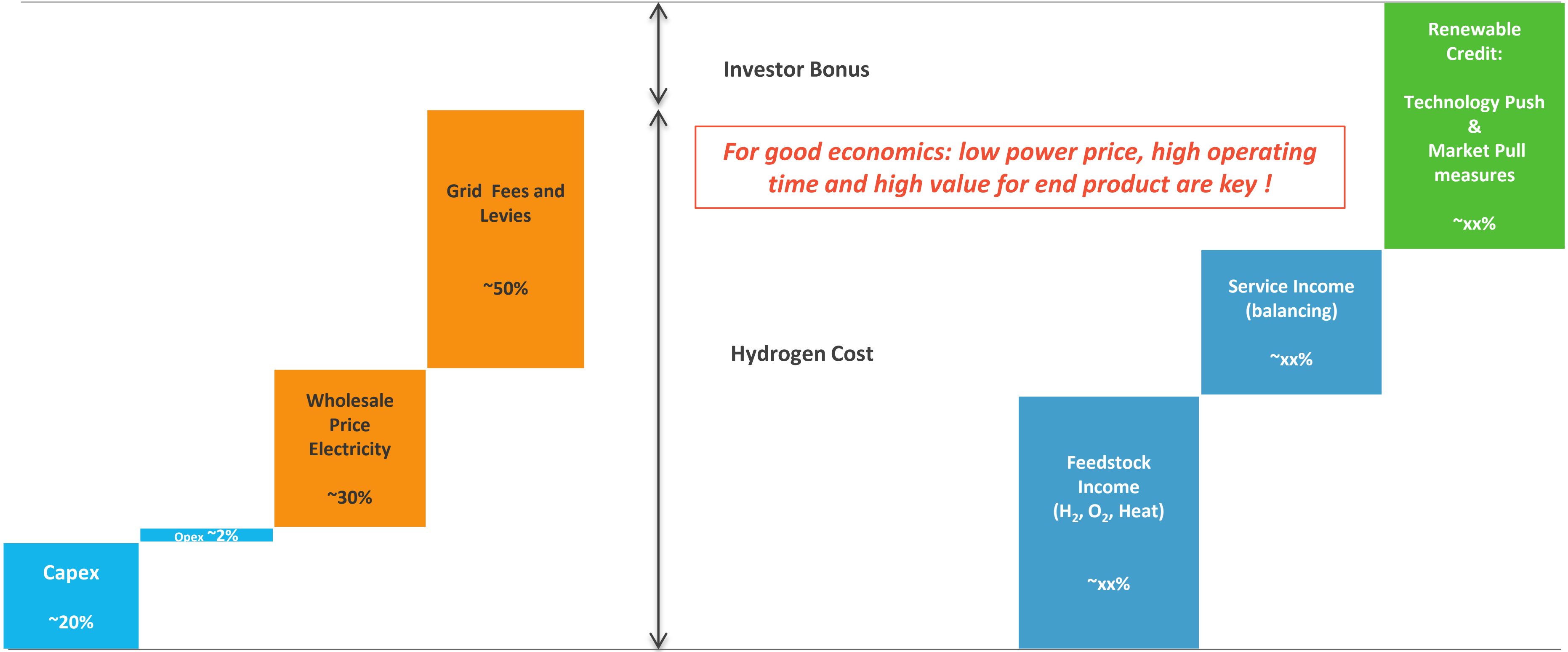


Main conclusions from these projects:

1. Hydrogen **technologies work fine** and deliver according to expectations.
2. There is still room for further technical improvement but **no technology breakthrough is expected**.
3. There is a important potential for further **cost reduction**: going from project manufacturing to product manufacturing
4. Energy **regulatory framework is no suited** for these applications and **business operation** of these projects **remains very challenging**

Business Case Drivers

For more information on the economics, consult the Power-to-Gas Roadmap for Flanders: www.power-to-gas.be/roadmap-study



For good economics: low power price, high operating time and high value for end product are key !

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System boundaries for key performance indicators and techno-economic analysis

Electrolyser system boundary for Key Performance Indicators (KPI)

- Electrolyser stack
- Gas water separators, demisters, gas drying
- Water Management (Inlet pump, treatment, heat exchanger, Circulation pump
- Lye system (Alkaline)
- System control (incl. safety devices)
- Power supply (Transformer, rectifier)

Covered in Techno Economic Analysis (TEA)

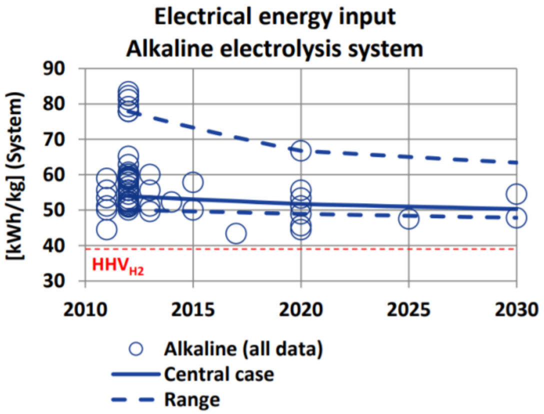
- Hydrogen storage
- External compression
- Grid connection cost

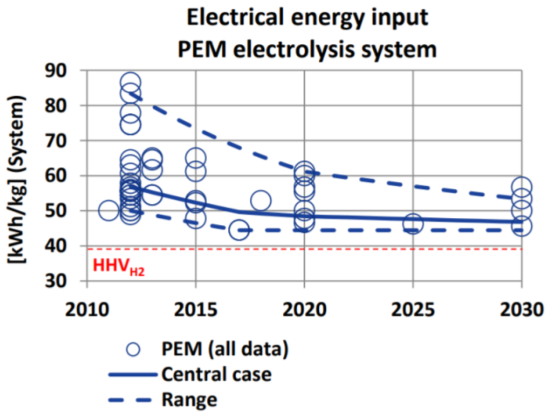
Not included in this study

- Civil works and installation
- Land use cost
- Selling, general and administrative expenses, margins and project cost

Source: FCH-JU, Development of Water Electrolysis in the European Union, February 2014, http://www.fch.europa.eu/node/783

Efficiency → cost of electricity





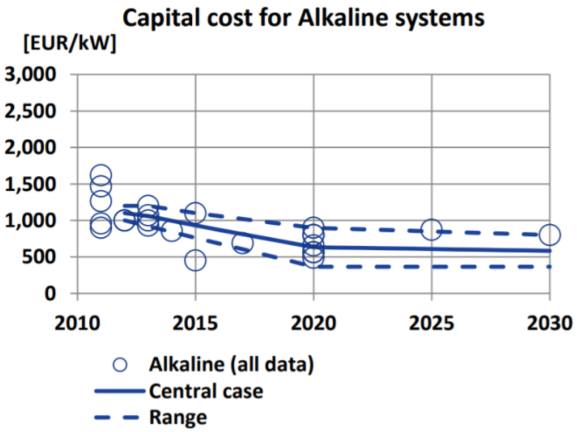
Electricity input [1]			Today	2015	2020	2025	2030
kWh_{el}/kg_{H2}	Alkaline	Central	**54**	**53**	**52**	**51**	**50**
		Range [2]	50 - 78	50 - 73	49 - 67	48 - 65	48 - 63
	PEM	Central	**57**	**52**	**48**	**48**	**47**
		Range [2]	50 - 83	47 - 73	44 - 61	44 - 57	44 - 53

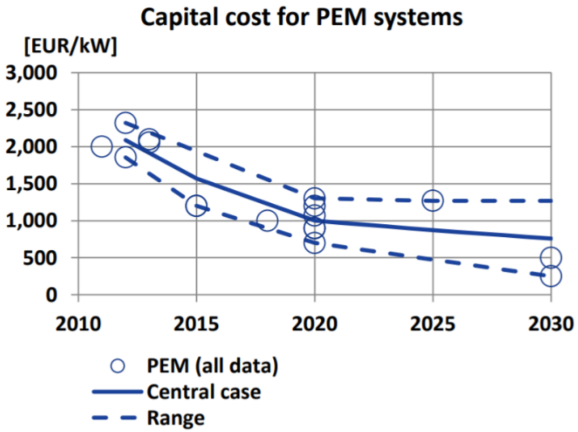
[1] at system level, incl. power supply, system control, gas drying (purity at least 99.4%). Excl. external compression, external purification and hydrogen storage

[2] some outliers excluded from range

Source: FCH-JU, Development of Water Electrolysis in the European Union, February 2014, http://www.fch.europa.eu/node/783

CAPEX → driver for high operating time





System cost [(1)]			Today	2015	2020	2025	2030
EUR/kW	Alkaline	Central	**1,100**	**930**	**630**	**610**	**580**
		Range	1,000 - 1,200	760 - 1,100	370 - 900	370 - 850	370 - 800
	PEM	Central	**2,090**	**1,570**	**1,000**	**870**	**760**
		Range	1,860 - 2,320	1,200 - 1,940	700 - 1,300	480 - 1,270	250 - 1,270

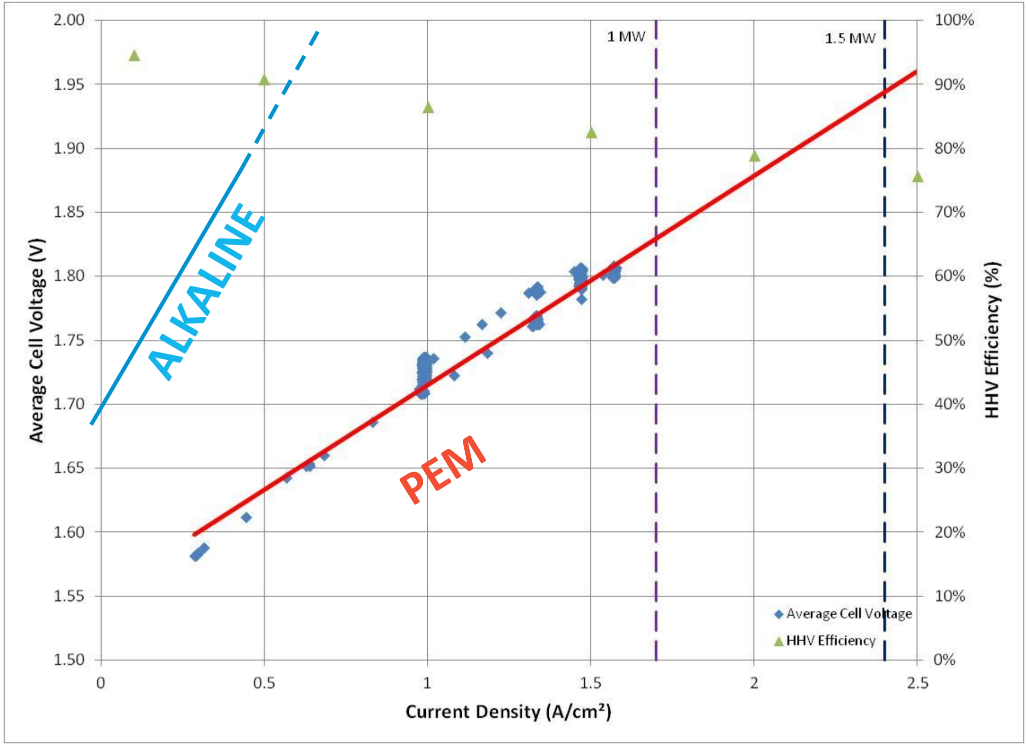
[(1)] incl. power supply, system control, gas drying (purity above 99.4%). Excl. grid connection, external compression, external purification and hydrogen storage

Source: FCH-JU, Development of Water Electrolysis in the European Union, February 2014, http://www.fch.europa.eu/node/783

Relationship between cost and efficiency

First “MW” PEM Stack Measured Efficiency

Increase efficiency
↓
Reduction of operational cost (€/kg)



Example: 1.5 MW PEM Electrolyser, WindGas Reitbrook, Hamburg

Increase current density → Reduction of capital cost (€/MW)

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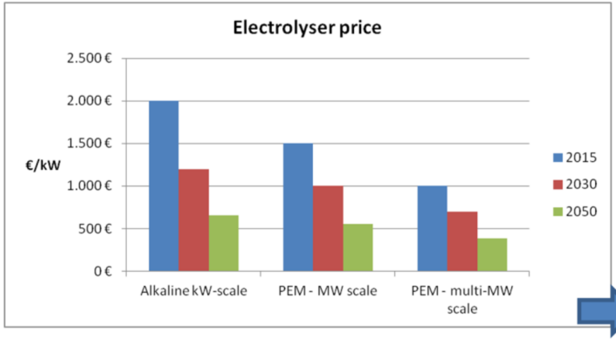
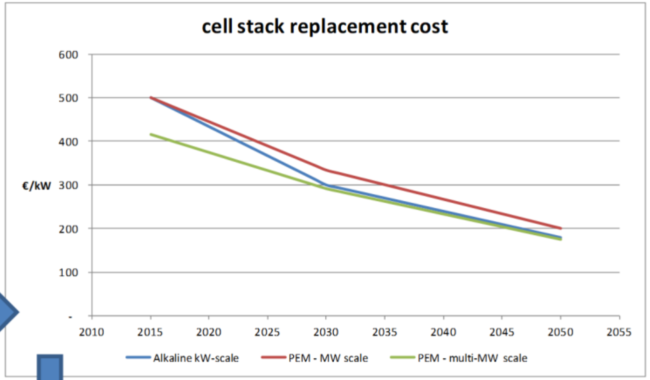
Size effect, output pressure, lifetime, maintenance

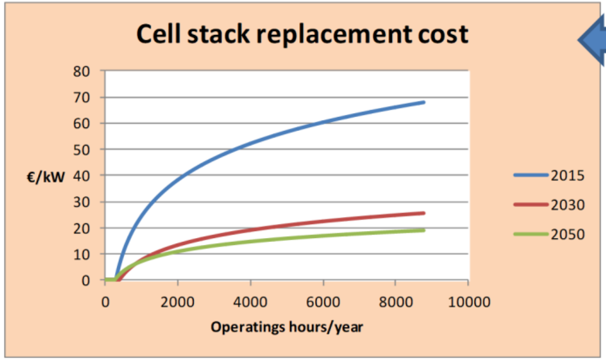
Item	Unit	2015	2030	2050
Alkaline kW-scale				
H_2 nominal production capacity	*Nm³/h*	60	300	300
Efficiency	*kWh/Nm³ H_2*	5,2	5,1	5
Electrical power	*kW*	312	1.530	1.560
Output pressure	*barg*	10	60	60
Water consumption with R/O	*liter / Nm³ H_2*	1,3	1,3	1,3
Price	*€*	624.000	1.836.000	1.029.600
Price/kW - SYSTEM	*€/kW*	2.000	1.200	660
OPEX	*€/kW/year*	80	64	56
Expected cell stack expected lifetime	*hours*	60.000	60.000	60.000
Cell stack cost / electrolyser cost		30%	30%	30%
PEM - MW scale				
H_2 nominal production capacity	*Nm³/h*	200	200	200
Efficiency	*kWh/Nm³ H_2*	5,2	5,1	5
Electrical power	*kW*	1.040	1.020	1.040
Output pressure	*barg*	30	30	30
Water consumption with R/O	*liter / Nm³ H_2*	1,3	1,3	1,3
Price	*€*	1.560.000	1.020.000	572.000
Price/kW - SYSTEM	*€/kW*	1.500	1.000	550
OPEX	*€/kW/year*	60	48	42
Expected cell stack expected lifetime	*hours*	40.000	50.000	60.000
Cell stack cost / electrolyser cost		40%	40%	40%
PEM - multi-MW scale				
H_2 nominal production capacity	*Nm³/h*	3120	3120	3120
Efficiency	*kWh/Nm³ H_2*	5	4,9	4,8
Electrical power	*kW*	15.600	15.288	15.600
Output pressure	*barg*	30	30	30
Water consumption with R/O	*liter / Nm³ H_2*	1,3	1,3	1,3
Price	*€*	15.600.000	10.701.600	6.006.000
Price/kW - SYSTEM	*€/kW*	1.000	700	385
OPEX	*€/kW/year*	40	32	28
Expected cell stack expected lifetime	*hours*	40.000	50.000	60.000
Cell stack cost / electrolyser cost		50%	50%	50%

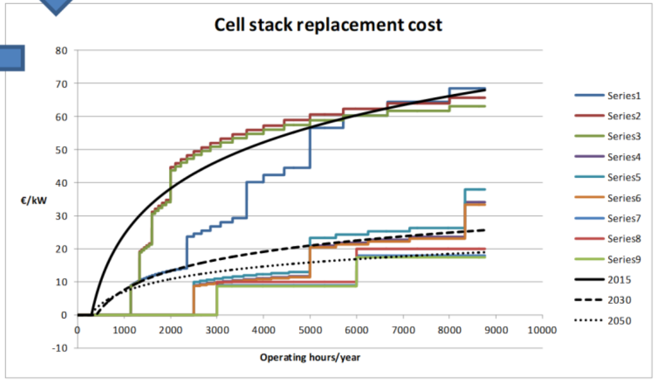
Power-to-Gas Roadmap for Flanders; Brussels, October 2016, http://www.power-to-gas.be/roadmap-study

Cell stack replacement cost









Power-to-Gas Roadmap for Flanders; Brussels, October 2016
http://www.power-to-gas.be/roadmap-study

IEA HIA Task 38 – Brief ‘Electrolysis: What are the investment costs? State of the art and outlook’

iea hydrogen

Task 38 Brief

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.

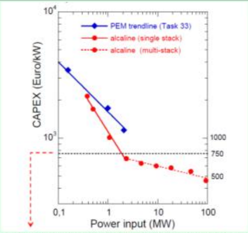


Fig. 1 CAPEX data for both PEM and alkaline electrolysers, plotted as a function of the power input. Data for alkaline systems are based on a single stack of 2.13 MW considering 230 cells, 2.6m² size. Note that change in slope for alkaline electrolysers corresponds to the use of multi-stack systems.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

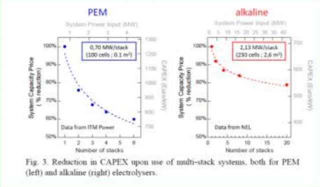
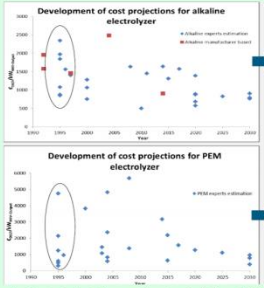


Fig. 2 Reduction in CAPEX upon use of multi-stack systems, both for PEM (left) and alkaline (right) electrolysers. [1]

KEY FINDINGS (continued)



- **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]

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].

References

[1] J. Proost, *State-of-the-art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings*, European 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.

Key takeaways:

- 750 €/kW is reachable today for atmospheric alkaline electrolysers
- 750 €/kW seems achievable today for multi-MW PEM projects
- Alkaline is very mature technology
- Cost reduction potential seems higher with PEM technology (beginning of the learning curve)

Agenda

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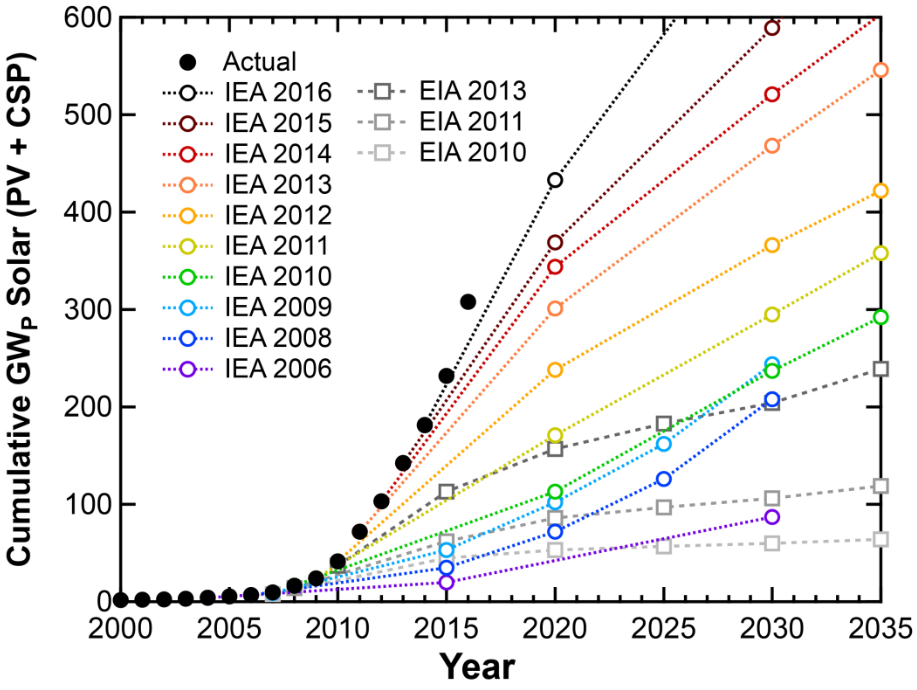
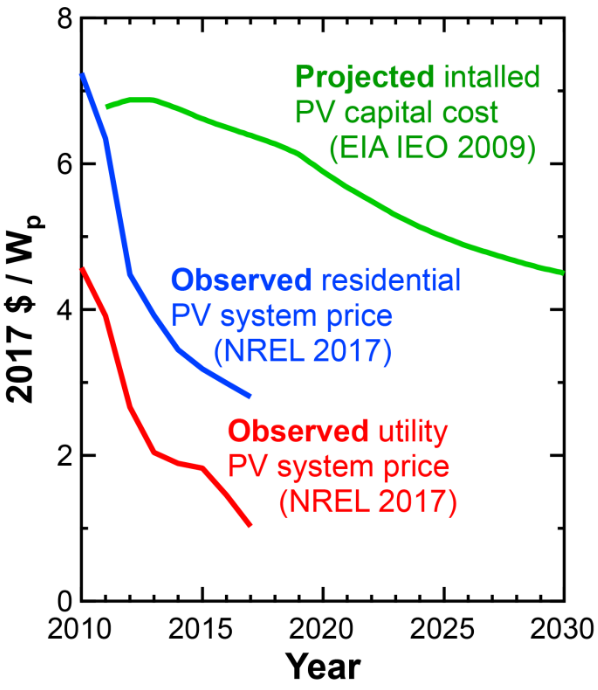
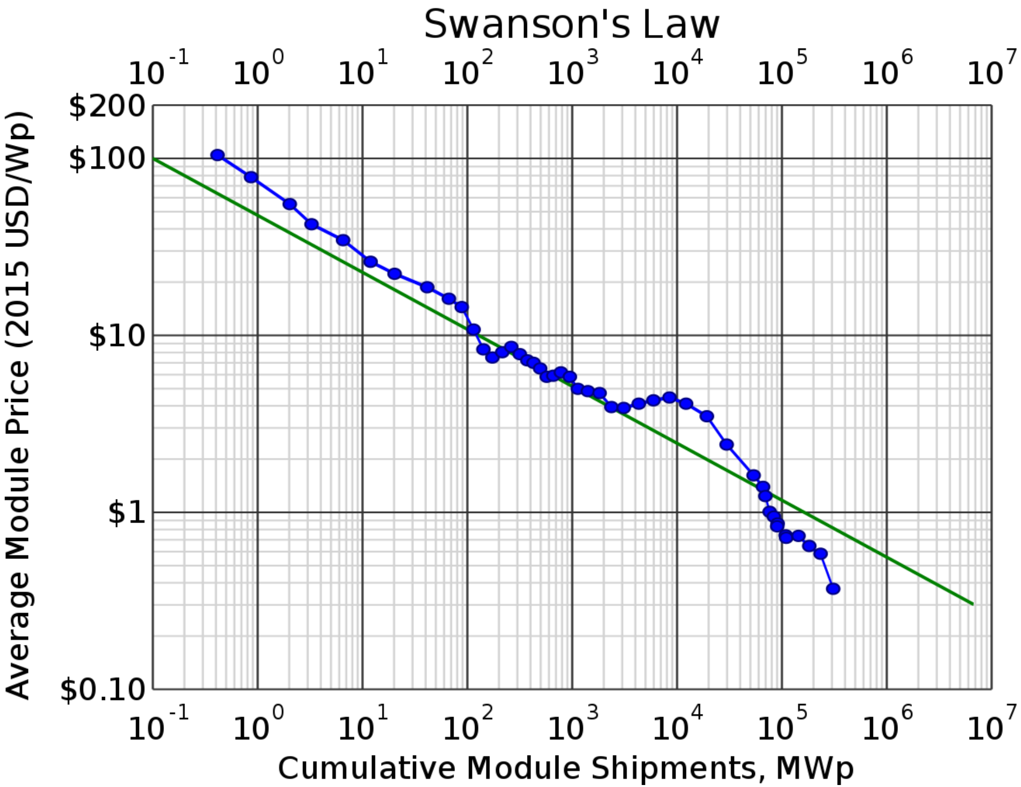
3. **Concluding remarks**

All time-related cost predictions for solar PV have been wrong, because market uptake and technology adoption happened much faster than forecasted !





Experience curves can give a good indication, but such curves for water electrolysis do not really exist yet...



Drivers for cost reduction

- Market uptake → higher volumes → cost reduction
- Improvement of the supply chain: more suppliers
- Higher competition → lower margins → lower prices
- Product standardization
- Better products : quality, efficiency, higher pressure, lifetime…
- Decrease the use of expensive raw material (catalysts)
- Products will be more compact → less BOP, logistics, civil works
- Synergies with PEM fuel cells (volumes are increasing rapidly there already). The cost of PEM electrolyzers will benefit from this synergy (+/- same suppliers).

Final comments

- Compare apples with apples: certainly not only CAPEX (€/kW)

- What matters is the €/kg H2 production cost related to water electrolysis over the entire project lifecycle (Total cost of ownership) which needs to consider at least:
  - Total investment (electrolyser + compression + storage + grid connection + civil works + project costs)
  - Efficiency (incl. degradation)
  - Maintenance
  - Lifetime
  - Warranties

Thank you for your attention

We’re Ready.

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Early business cases for H2 in energy storage and more broadly power to H2 applications

		ALK						PEM					
		2017 @ P atm			2025 @ 15 bar			2017 @ 30 bar			2025 @ 60 bar		
Nominal Power	UNITS	1 MW	5 MW	20 MW	1 MW	5 MW	20 MW	1 MW	5 MW	20 MW	1 MW	5 MW	20 MW
Minimum power	% Pnom		15%			10%			5%			0%	
Peak power – for 10 min	% Pnom		100%			100%			160%			200%	
Pressure output	Bar		0 bar			15 bar			30 bar			60 bar	
Power consumption @ P nom	kWhe/kg	58	52	51	55	50	49	63	61	58	54	53	52
Water consumption	L/kg	15 L/kg											
Lifetime – System	Years	20 years											
Lifetime – Stack @ full charge	hr		80 000 h			90 000 h			40 000 h			50 000 h	
Degradation – System	%/1000 h		0,13%/ 1000 h			0,11%/ 1000 h			0,25%/ 1000 h			0,20%/ 1000 h	
Availability	%/year	>98%											
CAPEX – Total system Equipment	€/kW	1200	830	750	900	600	480	1500	1300	1200	1000	900	700
OPEX – Electrolyser system	%CAPEX	4%	3%	2%	4%	3%	2%	4%	3%	2%	4%	3%	2%
CAPEX – Stack replacement	€/kW	420	415	338	315	300	216	525	455	420	300	270	210

FCH-JU , Early business cases for H2 in energy storage and more broadly power to H2 applications,
June 2017, http://www.fch.europa.eu/publications/study-early-business-cases-h2-energy-storage-and-more-broadly-power-h2-applications

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Future cost and performance of water electrolysis: An expert elicitation study

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Table 1 – Main characteristics of AEC, PEMEC and SOEC systems.

	AEC	PEMEC	SOEC
Electrolyte	Aq. potassium hydroxide (20–40 wt% KOH) [9,32,33]	Polymer membrane (e.g. Nafion) [33,34]	Yttria stabilised Zirconia (YSZ) [37,38]
Cathode	Ni, Ni-Mo alloys [9,32,33]	Pt, Pt-Pd [34]	Ni/YSZ [37,38]
Anode	Ni, Ni-Co alloys [9,32,33]	RuO_2, IrO_2 [34]	LSM[b]/YSZ [37,38]
Current density ($A\ cm^{-2}$)	0.2–0.4 [34]	0.6–2.0 [34]	0.3–2.0 [9,38]
Cell voltage (V)	1.8–2.4 [34]	1.8–2.2 [34]	0.7–1.5 [38]
Voltage efficiency ($\%_{HHV}$)	62–82 [34]	67–82 [34]	<110 [33]
Cell area (m^2)	<4 [33]	<0.3 [33]	<0.01 [33]
Operating Temp. (°C)	60–80 [34]	50–80 [34]	650–1000 [37,38]
Operating Pressure (bar)	<30 [33]	<200 [33]	<25 [33]
Production Rate[c] ($m^3_{H2}\ h^{-1}$)	<760 [33]	<40 [33]	<40 [33]
Stack energy[c] ($kWh_{el}\ m^{-3}_{H2}$)	4.2–5.9 [34]	4.2–5.5 [34]	>3.2 [33]
System energy[c] ($kWh_{el}\ m^{-3}_{H2}$)	4.5–6.6 [16]	4.2–6.6 [16]	>3.7 $(>4.7)_{kWh\_energy}$[a]
Gas purity (%)	>99.5 [32]	99.99 [33]	99.9[a]
Lower dynamic range[d] (%)	10 – 40 [33,34]	0 – 10 [34]	>30[a]
System Response	Seconds [33]	Milliseconds [33]	Seconds[a]
Cold-start time (min.)	<60 [16]	<20 [16]	<60[a]
Stack Lifetime (h)	60,000–90,000 [16]	20,000–60,000 [16]	<10,000[a]
Maturity	Mature	Commercial	Demonstration[a]
Capital Cost (€ kW_{el}^{-1})	1000–1200 [16]	1860–2320 [16]	>2000 [16]

[a] Where no reference is provided, data were derived during expert elicitations.
[b] Perovskite-type lanthanum strontium manganese ($La_{0.8}Sr_{0.2}MnO_3$).
[c] Refers to norm cubic meter of hydrogen (at standard conditions) and respective electrical energy consumption (kWh_{el}) if applicable.
[d] Minimum operable hydrogen production rate relative to maximum specified production rate.

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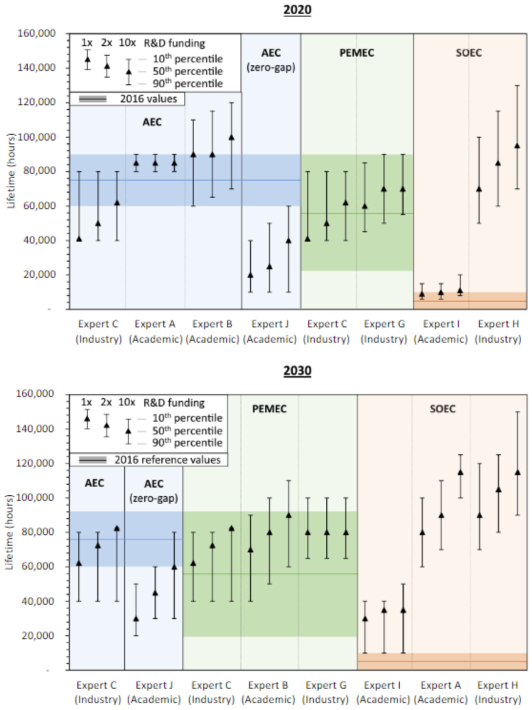

Fig. 5 – Elicited expert estimates for 2020 and 2030 lifetime (in hours) as a function of R&D funding (1x, 2x, 10x). Data points indicate 50th, uncertainty bars 90th and 10th percentile estimates. Expert C made estimates for AEC and PEMEC. Expert J made estimates for AEC zero gap configurations. Results are sorted by technology and in ascending order for 50th percentile estimates. 2016 reference values based on Table 1.

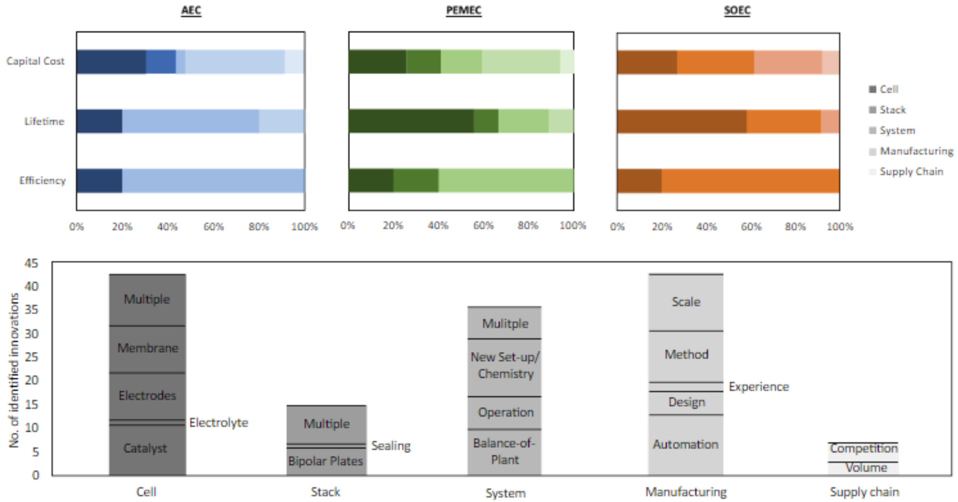

Fig. 7 – Top: Relative share of identified innovations along technology (AEC, PEMEC, SOEC), impact (Capital Cost, Lifetime, Efficiency) and innovation area (From darkest to lightest: Cell, Stack, System, Manufacturing, Supply Chain). No innovation mentioned on stack-level for SOEC. Bottom: Absolute number of mentions of innovations along innovation areas and sub-groups. Includes double-counting of same innovation if mentioned by different experts. Refer to Appendix Table G1 to G6 for detailed breakdown of innovations per technology.