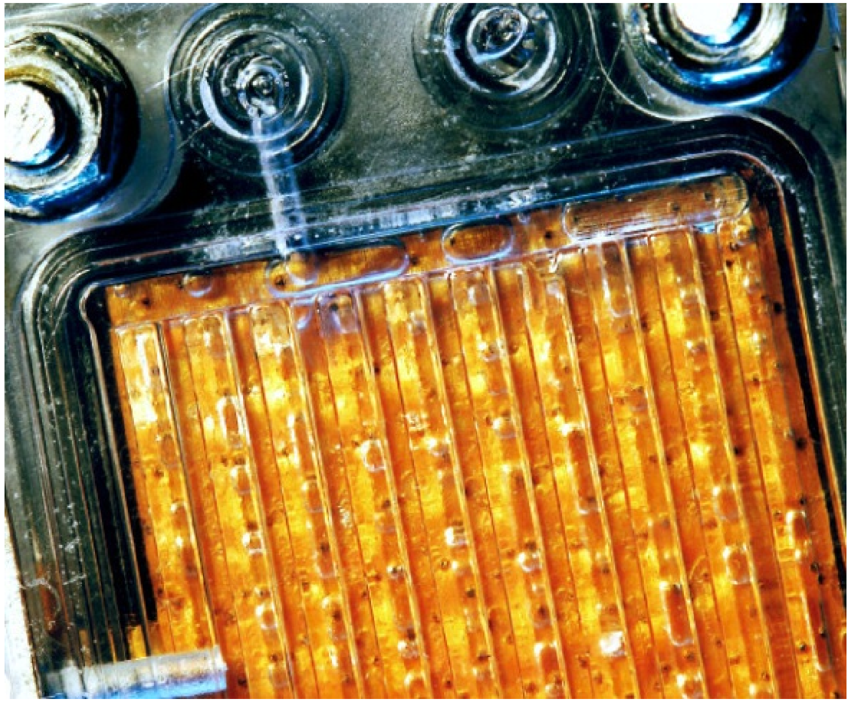
Water Electrolysis:
Status and Potential for Development



Tom Smolinka

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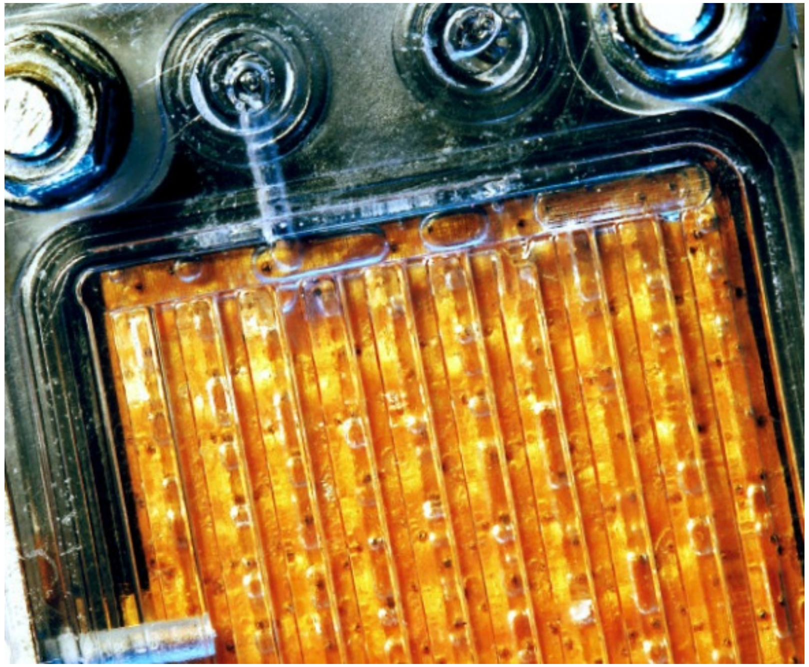
Energiesysteme ISE

Joint NOW GmbH – FCH JU
Water Electrolysis Day
Brussels (BE), April 03, 2014

Fraunhofer
ISE

Agenda

- Short introduction to Fraunhofer ISE
- Applications for water electrolysis
- Key features of different EL approaches
  - Alkaline electrolysis - AEL
  - PEM electrolysis - PEMEL
  - High temperature electrolysis - HTEL
- Discussion of technical challenges:
  - Performance and efficiency
  - High pressure operation
  - Part-load and overload capability
  - Life-time
- R&D demand and summary



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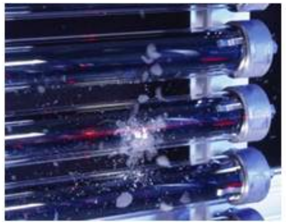
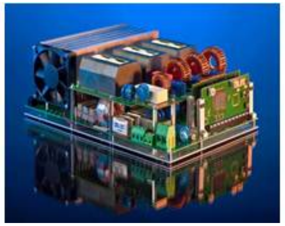
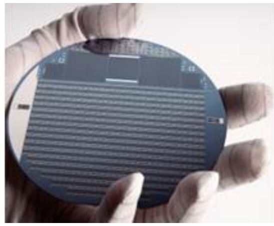
Performing Research for the Energy Transition




12 Business Areas:

- Energy Efficient Buildings
- Silicon Photovoltaics
- III-V and Concentrator Photovoltaics
- Dye, Organic and Novel Solar Cells
- Photovoltaic Modules and Power Plants
- Solar Thermal Technology
- Hydrogen and Fuel Cell Technology
- System Integration and Grids – Electricity, Heat, Gas
- Energy Efficient Power Electronics
- Zero-Emission Mobility
- Storage Technologies
- Energy System Analysis

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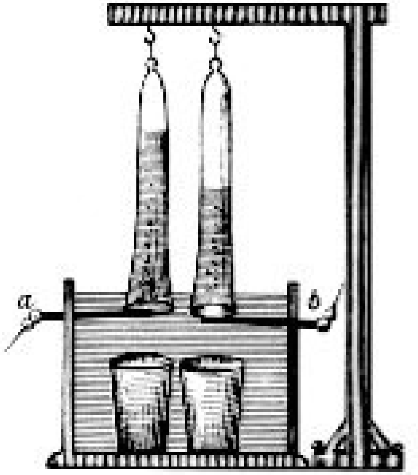
H_2 Refueling Station at Fraunhofer ISE

WASSERSTOFF-ENERGIEKETTE
FREIBURG

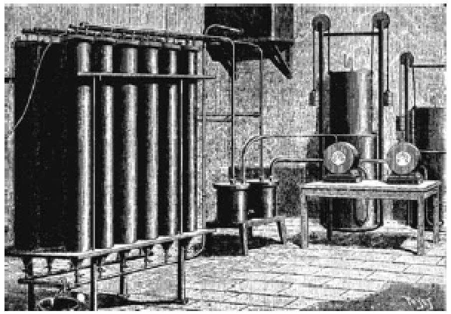
- Publicly accessible refueling station, located at premises of Fraunhofer ISE
- Main components of the filing station:
  - (Membran electrolyser (30 bar / 6 Nm³/h)
  - Mechanical compressor
  - Storage tanks
  - Dispenser units (200/350/700bar)
  - Filling according to SAE J2600
- Integrated container solution
- Coupled with renewable energies:
  - Photovoltaic modules (roof)
  - Certified green electricity
- Two fuel cell cars from Daimler

badenova Freiburg IM BREISGAU Fraunhofer ISE

Hydrogen Production by Electrolytical Water Splitting
Known for more than 200 years.



Test set-up of Ritter



Alkaline electrolyser around 1900

- Invention of voltaic pile (1799) enabled investigations of electrolytic approaches
- Main principle demonstrated around 1800 by J. W. Ritter, William Nicholson and Anthony Carlise
- Today 3 technologies available:
  - Alkaline electrolysis (AEL)
  - Electrolysis in acid environment (PEM electrolysis - PEMEL) (SPE water electrolysis)
  - Steam electrolysis (High temperature electrolysis - HTEL or SOEL)

$$2\,H_2O \rightarrow 2\,H_2 + O_2$$

Johann Wilhelm Ritter (1776-1810)

Picture credits: all www.wikipedia.org

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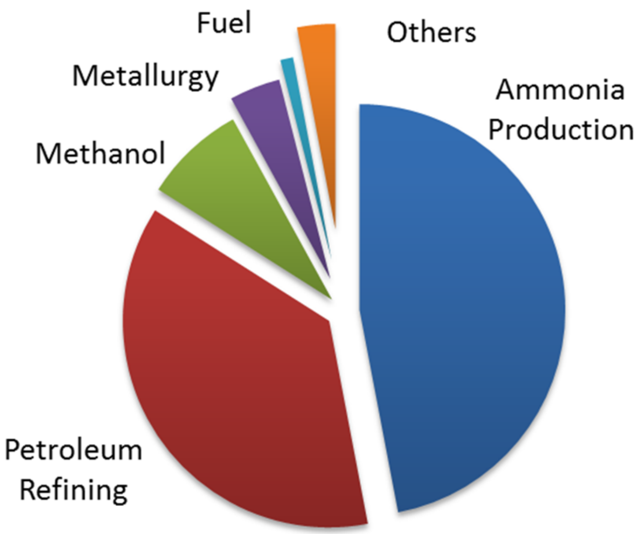
Hydrogen Production by Electrolytical Water Splitting
Today's industrial hydrogen production.

- Global hydrogen production: 600 Bill. Nm³/yr
- Mostly steam reforming
- Less than 1 % by water electrolysis

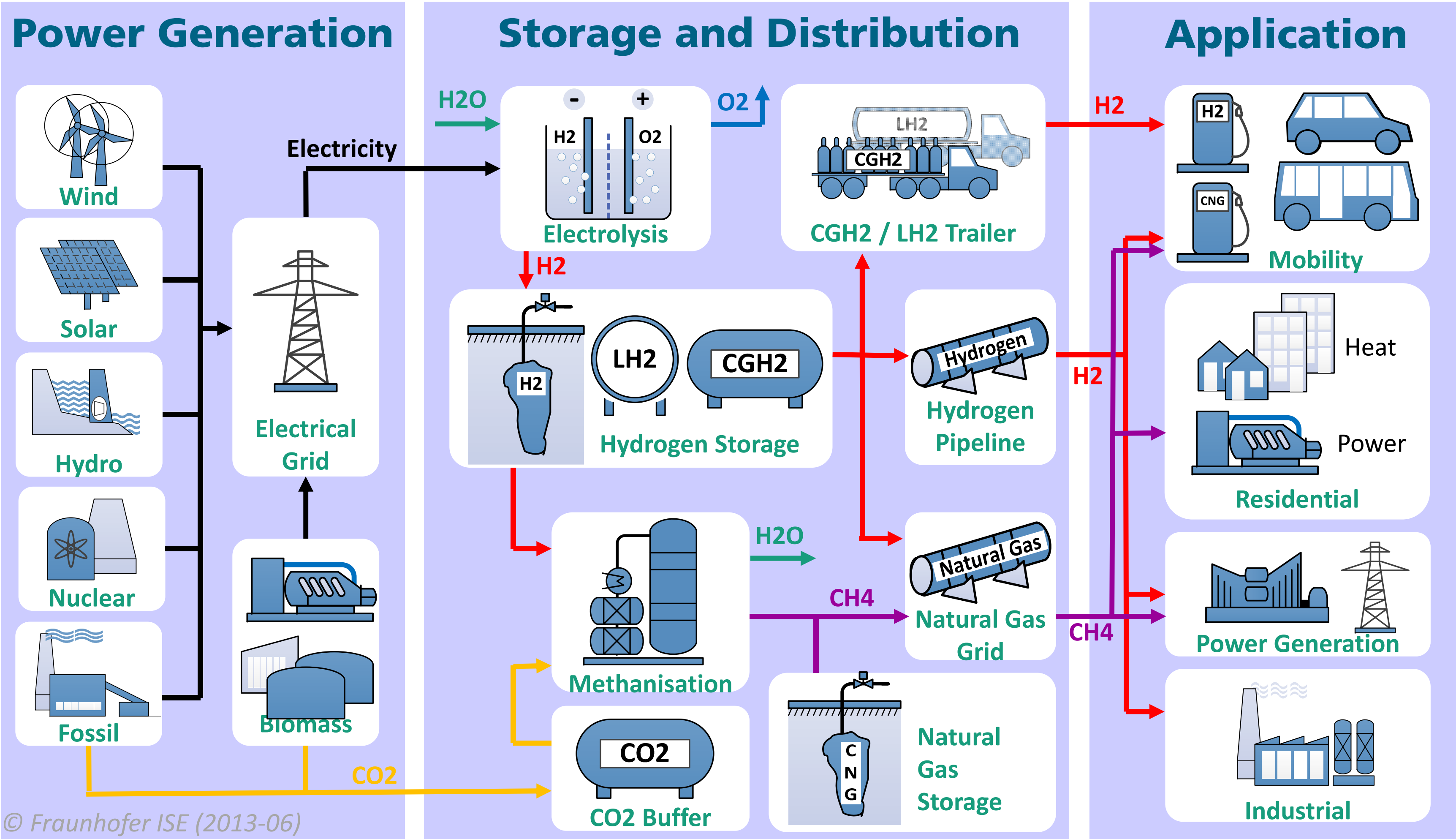


Source: DWV brochure (2006)

Industrial application	Typical size electrolyser
Jewellery, laboratory and medical engineering	5 - 500 Nl/h
Generator cooling in power plants	5 - 20 Nm³/h
Feed Water Inertisation (BWR water chemistry)	10 - 50 Nm³/h
Float glas production (protective atmosphere)	50 - 150 Nm³/h
Electronics industry	100 - 400 Nm³/h
Metallurgy	200 - 750 Nm³/h
Food industry (fat hardening)	100 - 900 Nm³/h
Military und aerospace	< 15 Nm³/h

Coupling Renewable Energies and Water Electrolysis

New market opportunies with power to gas (PtG).



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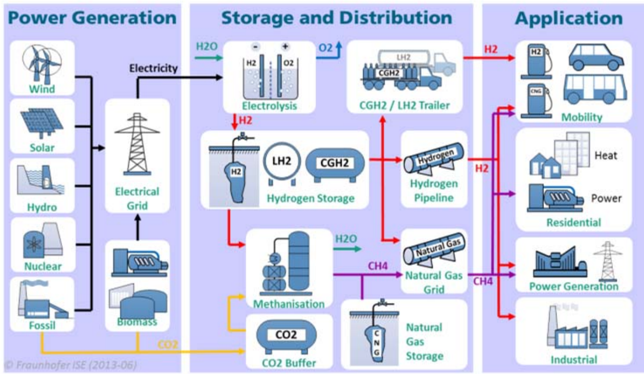
Coupling Renewable Energies and Water Electrolysis

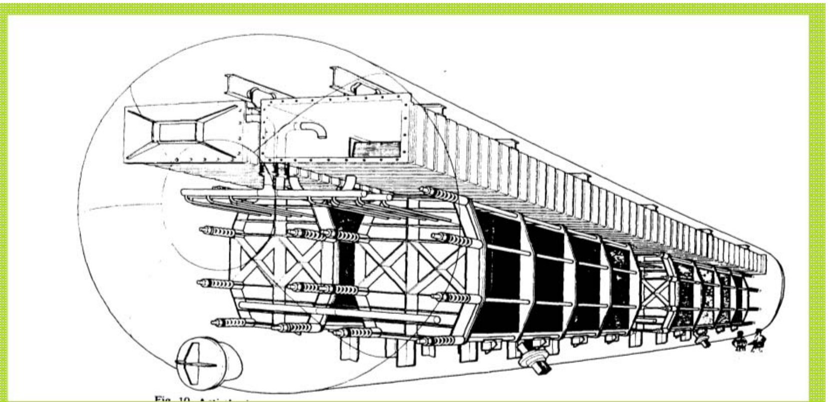
New market opportunies and …



- New tasks for electrolysers in the PtG concept
  - Operating (spinning) reserve for electrical grid (demand site management, load balancing)
  - Hydrogen production as fuel for FCEV
  - Large-scale storage systems by gas injection to the NG grid or underground storage
  - Hydrogen for industrial applications

Coupling Renewable Energies and Water Electrolysis
New market opportunies and new challenges.

- Large EL plants up to x 100MW
  - Scale-up vs. numbering up
  - Optimum pressure level
- Small footprint for on-site H2 production
  - Compact design
  - High-pressure operation
- Highly flexible operation
  - Fast start/stop cycling
  - Efficient part-load operation and efficient stand-by mode
  - Overload capability
- Decrease in CAPEX due to less annual full-load hours → cost pressure!



75 MW AEL module, concept EdF (30 bar, 160 °C) [1]

Definition H2 fueling stations	H2 fueling capacity	Required EL size
HRS Type XS	80 kg/d	~ 40 Nm³/h
HRS Type S	212 kg/d	~ 100 Nm³/h
HRS Type M	420 kg/d	~ 200 Nm³/h
HRS Type L	1.000 kg/d	~ 450 Nm³/h

Definition of HRS size according to H2 Mobility (2012)

[1] *LeRoy 1983, Int. J. Hydrogen Energy)*

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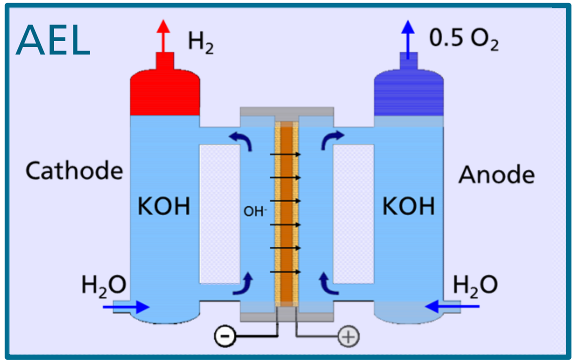
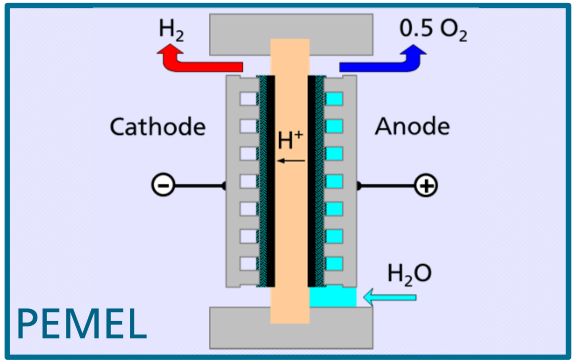
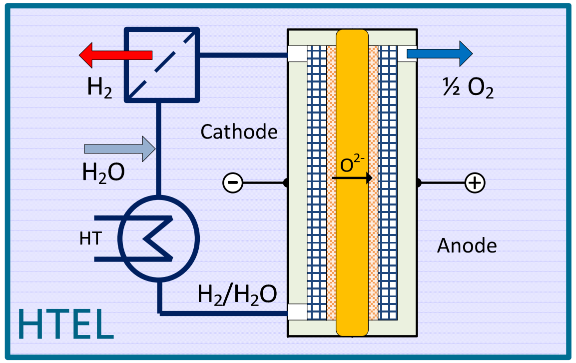
Water Electrolysis

Three approaches for hydrogen and oxygen production

Technology	Temp. Range	Cathodic Reaction (HER)	Charge Carrier	Anodic Reaction (OER)
Alkaline electrolysis	40 - 90 °C	$2H_2O + 2e^- \Rightarrow H_2 + 2OH^-$	OH^-	$2OH^- \Rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$
Membrane electrolysis	20 - 100 °C	$2H^+ + 2e^- \Rightarrow H_2$	H^+	$H_2O \Rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$
High temp. electrolysis	700 - 1000 °C	$H_2O + 2e^- \Rightarrow H_2 + O^{2-}$	O^{2-}	$O^{2-} \Rightarrow \frac{1}{2}O_2 + 2e^-$







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Water Electrolysis

Main technical features - overview

	Alkaline Electrolysis	Membrane Electrolysis	Solid Oxide Electrolysis
Electrolyte	Liquid alkaline KOH	Solid acid polymer	Ceramic metal compound
Electrodes	Ni/Fe electrodes (Raney)	Noble metals (Pt, Ir, ..)	Ni doped ceramic
Temperature	50-80 °C	RT - 90 °C	700 - 1,000 °C
Pressure	< 30 bar	< 200 bar	Atm.
Modul size (commercial)	Max. 760 Nm³ H_2/h ~ 3.2 MW_{el}	Max. 30 Nm³ H_2/h ~ 170 kW_{el}	~ 1 Nm³ H_2/h kW range


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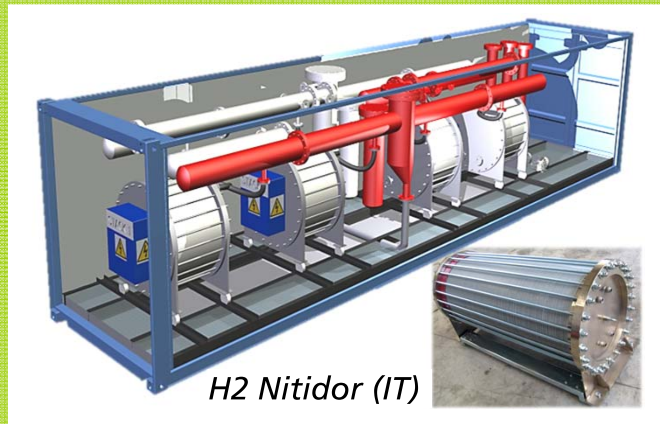
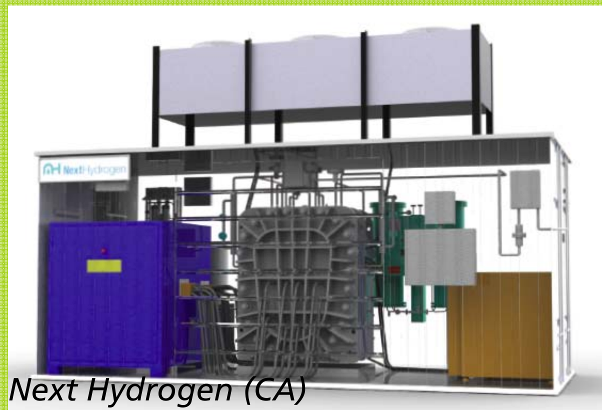
Development Trends in Water Electrolysis
(Pressurised) alkaline electrolysers (re)enter the MW class





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Development Trends in Water Electrolysis
PEM electrolysers entering MW class as well.

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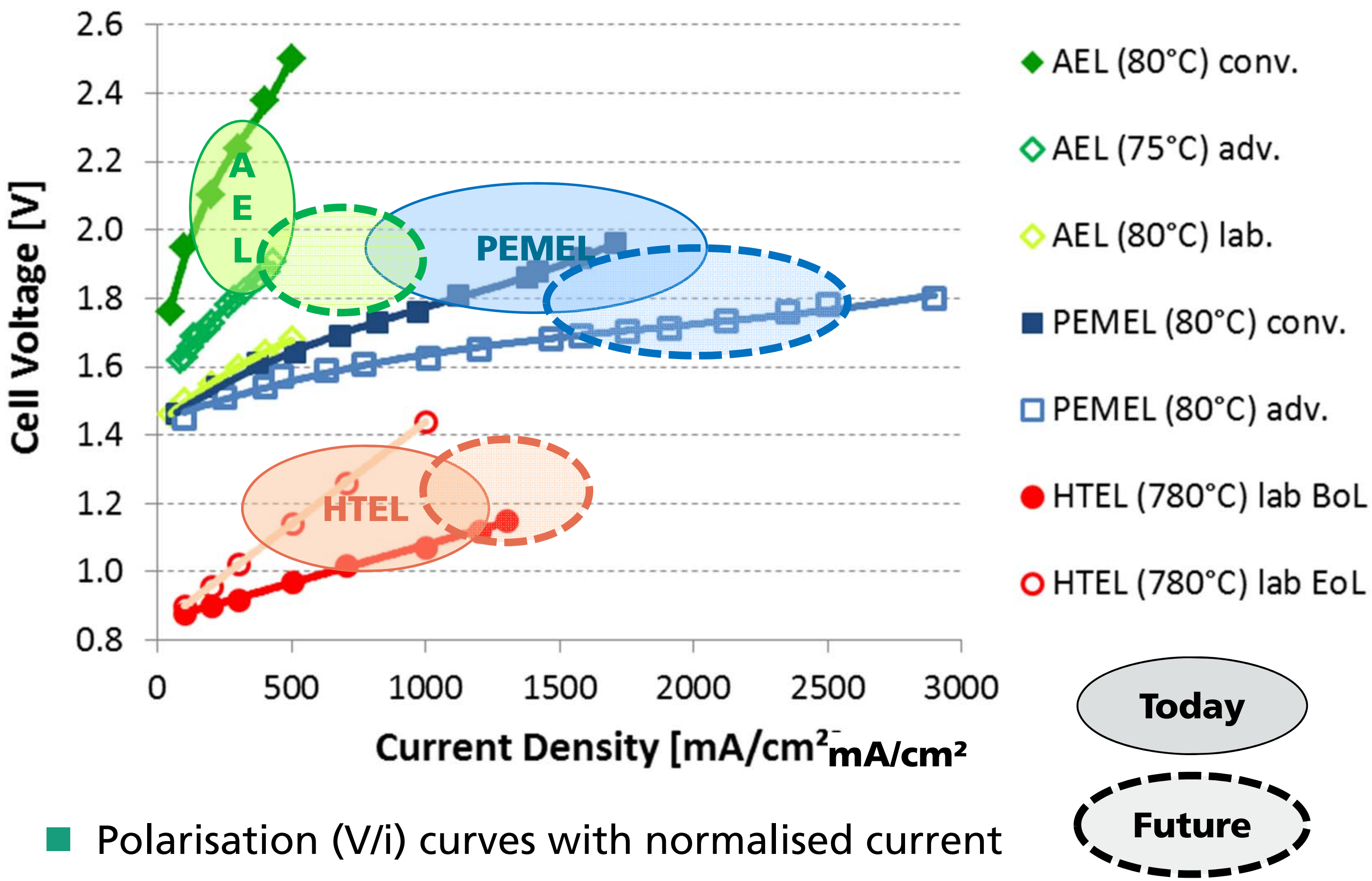
(1) Performance and Efficiency of Water Electrolysis
Comparison of different EL technologies at stack level.



- Polarisation (V/i) curves with normalised current

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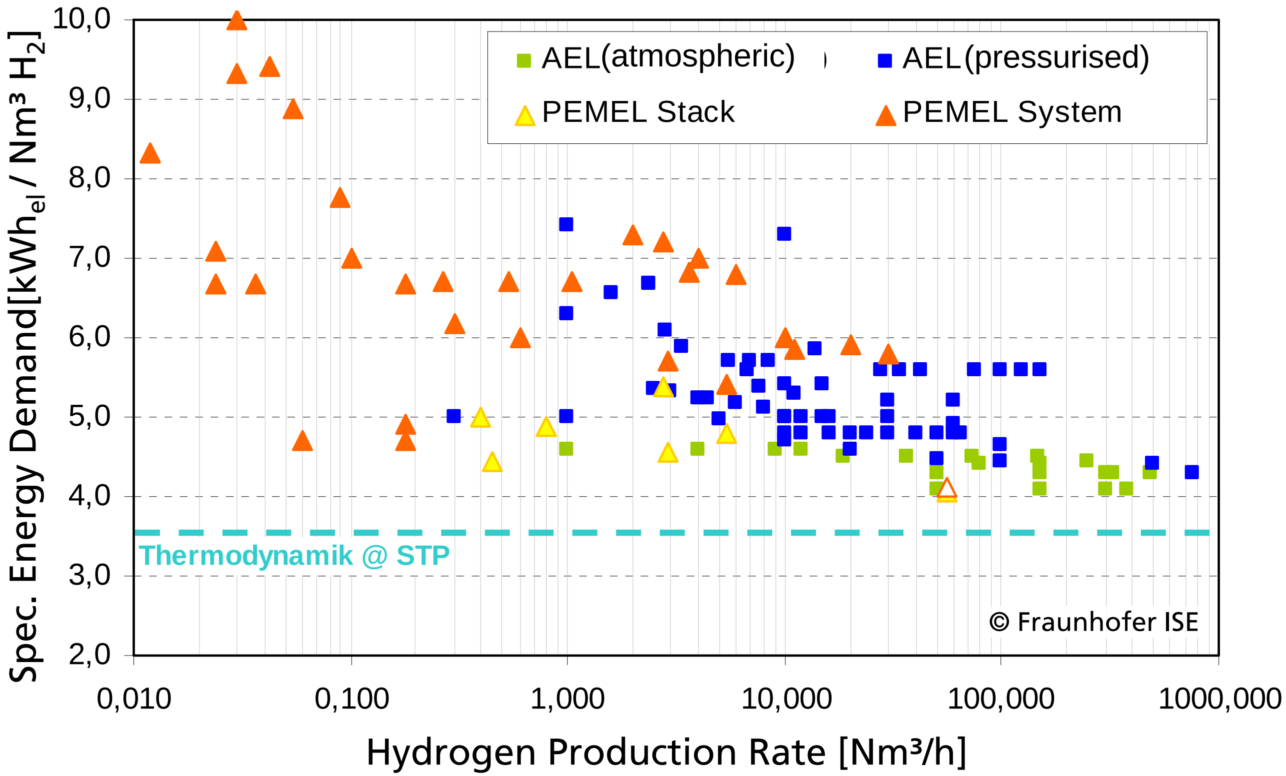
(1) Performance and Efficiency of Water Electrolysis
Attempt to compare the efficiency at system level.

- Specific energy consumption as measure for efficiency
- Manufacturer's data
  - No standardised data
  - Differernt pressure and H_2 purity
  - Specifications for steady state operation



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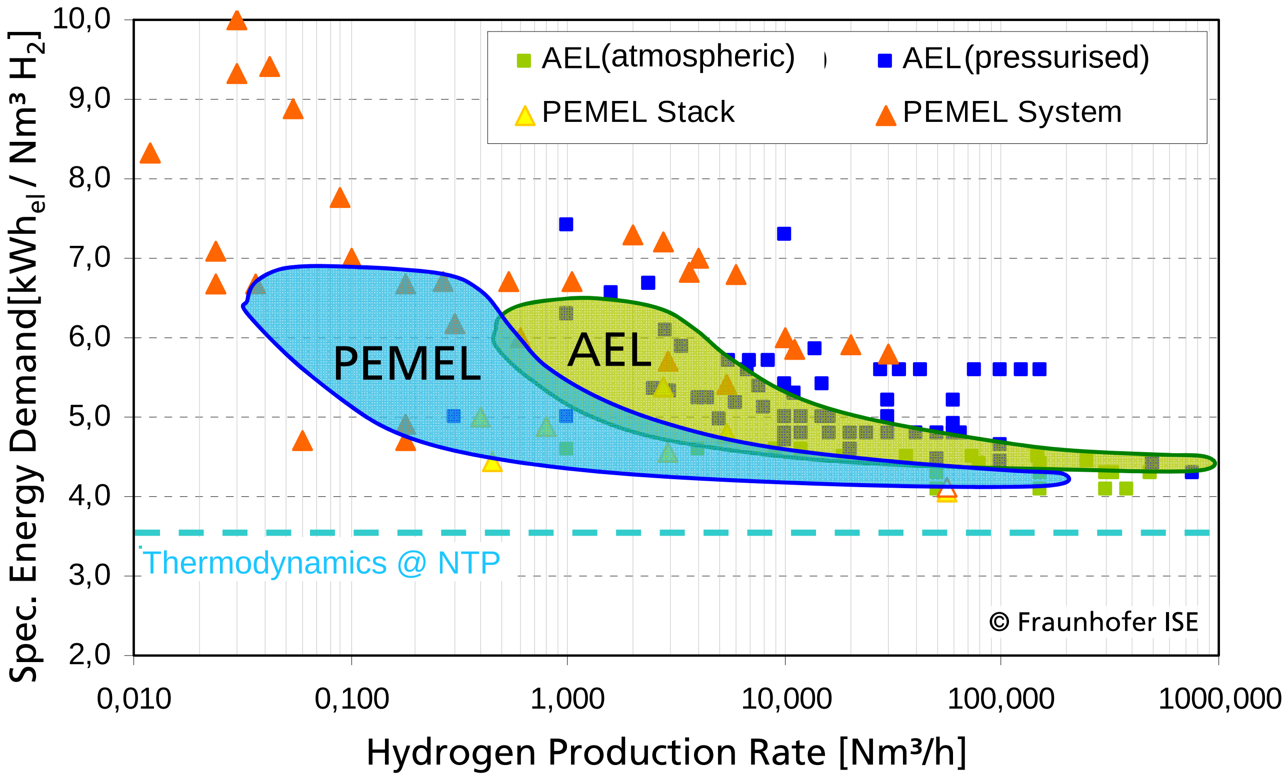
(1) Performance and Efficiency of Water Electrolysis

Attempt to compare the efficiency at system level.

- Energy consumption will not be reduced significantly in the future
  - Higher operating pressure
  - High power densities due to cost pressure
  - Dynamic operation (start/stop, stand-by)



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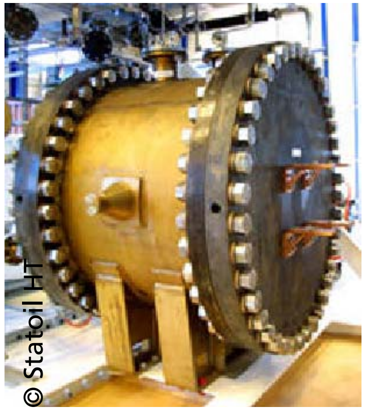
(2) Do We Need High-Pressure Electrolysis?
PEM electrolysis favours high pressure operation.



30 bar AEL stack in pressure compartment

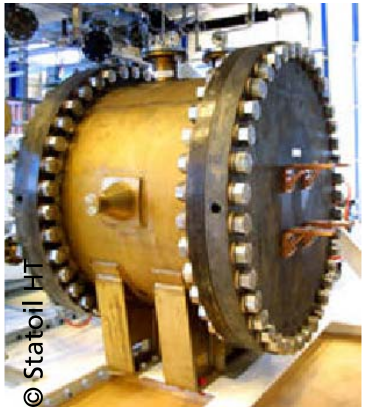
HTEL compartment

55 bar PEM stack

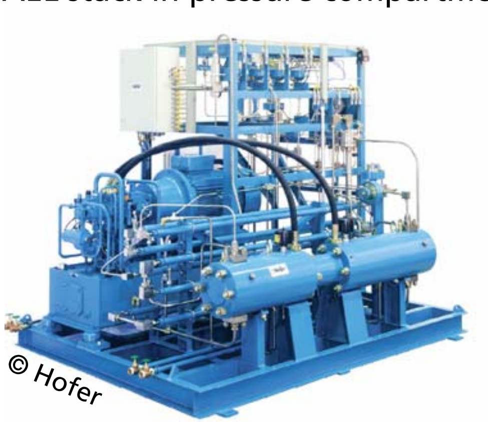
Pressure [bar]	AEL	PEMEL	HTEL
Typically	4 - 15	30	Atm.
Available	60	207	(Atm.)
Demonstrated	~ 345	~ 400	(10)

- AEL (with liquid electrolyte)
  - Pressure balanced design and complex system layout limit HP operation (CAPEX)
- PEMEL
  - Differential pressure system, simpler layout and compact design favour HP operation
- HTEL
  - Restrictions due to HT and HP in parallel

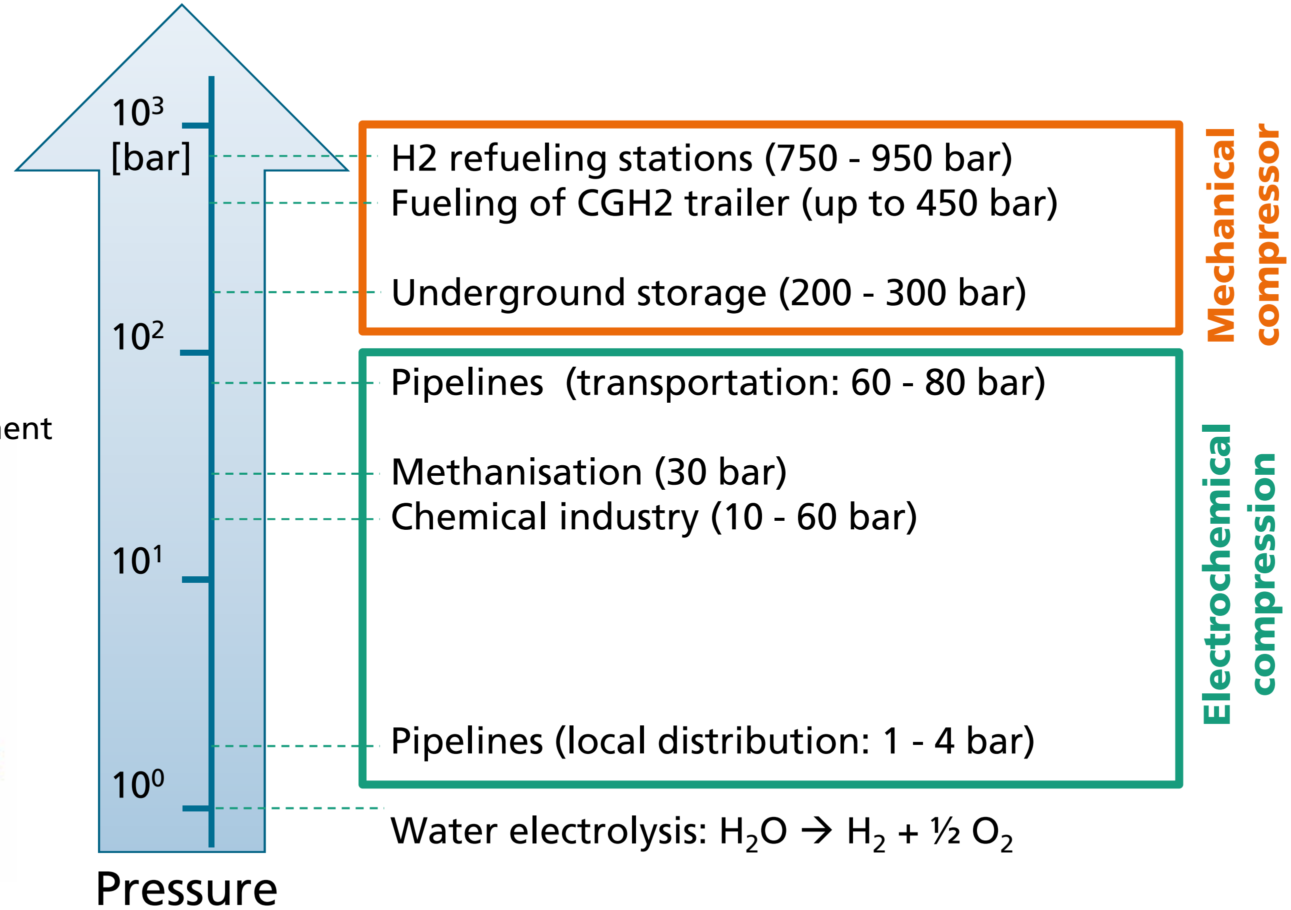
(2) Do We Need High-Pressure Electrolysis?
Typical pressure level of different applications



AEL stack in pressure compartment



Piston compressor



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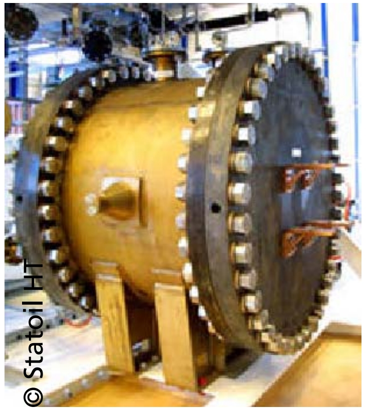
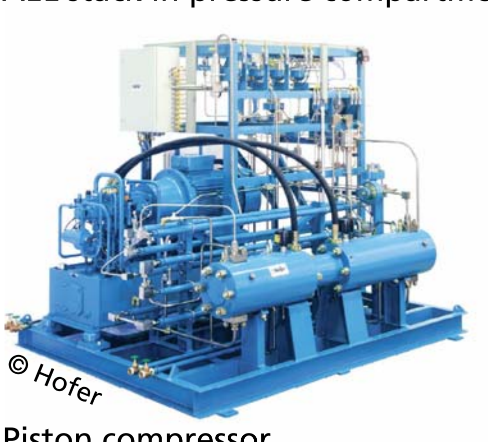
(2) Do We Need High-Pressure Electrolysis?
Electrochemical compression should be the first step!



AEL stack in pressure compartment



Piston compressor

- Hydrogen needs to be compressed for nearly all applications
  - electrochemical compression is more efficient
  - mechanical compression is cheaper at higher P
- Operating pressure of electrolyser is an economical trade-off (CAPEX)
  - today: typically 10 - 40 bar
  - In the future: probably up to 60 - 80 bar
  - Higher pressures only for niche applications
  - Large-scale storage and hydrogen mobility requires mechanical compressors

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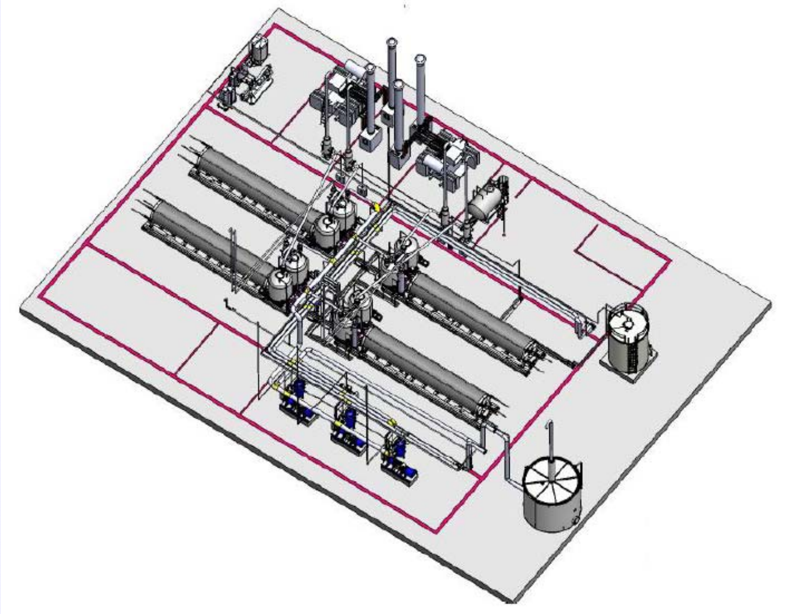
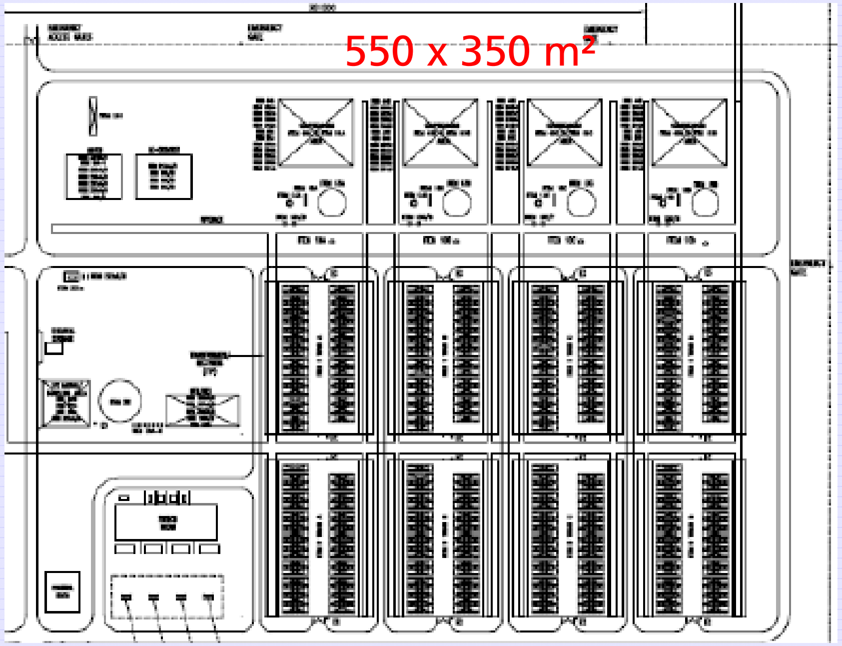
(3) Part-load and Overload Capability

Modularity enables different applications.



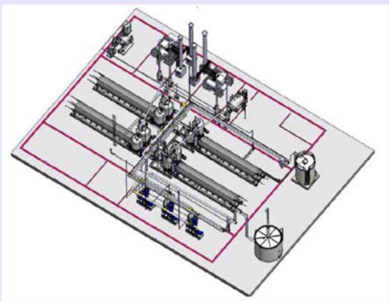
- Decentralised system
  - 4 stacks à 2.3 MW -> 9.2 MW
  - Approx. 2,000 Nm³/h H_2



- Centralised system
  - 248 stacks à 2.3 MW -> 578 MW
  - Approx. 120,000 Nm³/h H_2

Source: Fell - NEL Hydrogen, 2011, NOW-Workshop Berlin

(3) Part-load and Overload Capability
Multi-stack configuration facilitates low part-load limit.



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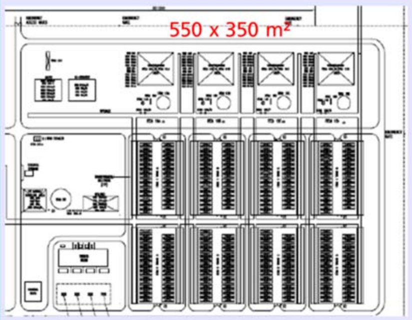

- Centralised system
  - 248 stacks à 2.3 MW -> 578 MW
  - Approx. 120,000 Nm³/h H_2

- Lower part-load limit is defined by
  - Self-consumption of the EL system
  - Gas purity H_2 in O_2 (quality and safety issue)
- New applications in energy sector (PtG)
  - Multi-stack configuration for larger installations
    - part-load non-critical
  - H2 refueling stations with on-site electrolyser
    - capacity small enough for system with single stack
    - H2 demand and buffer tank allows nearly constant operation

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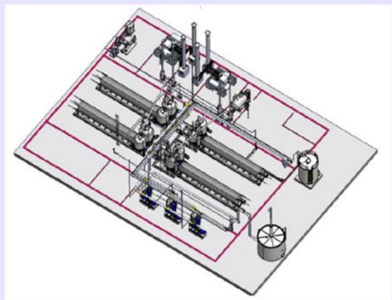
(3) Part-load and Overload Capability
High overload could make sence.



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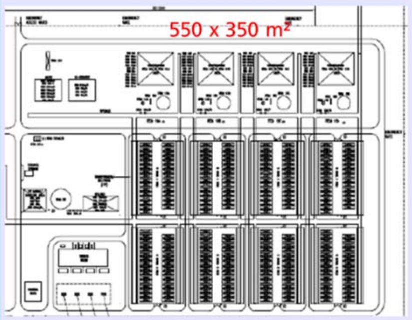

- Centralised system
  - 248 stacks à 2.3 MW -> 578 MW
  - Approx. 120,000 Nm³/h H_2

- Overload capability has to be discussed separately for
  (1) Electrochemical cell/stack
  - PEMEL stack has high overload capability
  - AEL stack is limited by bubble overpotential
  - HTEL stack … ?

  (2) Process part (BoP)
  - Overload for short time possible (<< 1 hour)
  - Thermal management and gas -quality are critical

  (3) Power electronics
  - Rectifier has NO overload capability
- Overload capability is possible but results in higher CAPEX for power electronic and partly for BoP
  - Could be useful for electrical grid services

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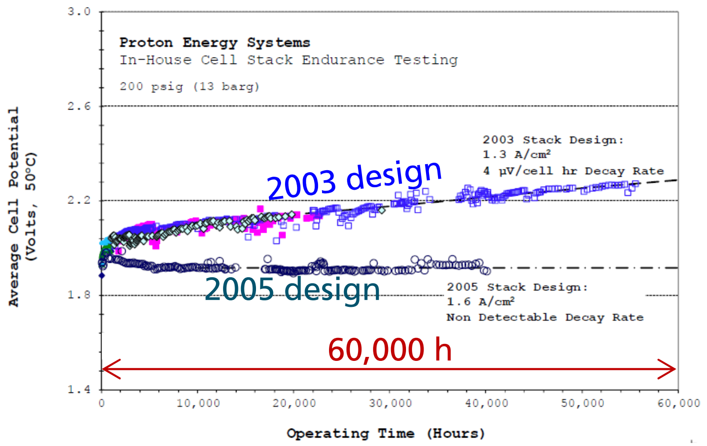
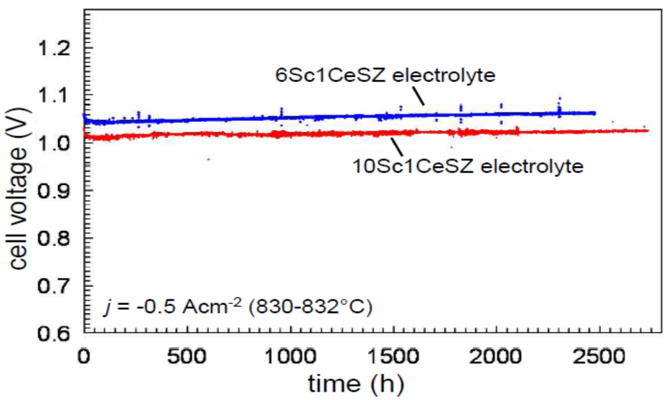
(4) Life-Time of Electrolysis Cells and Stacks
Durability is given for steady state operation at LT



Long-term testing of PEMEL stack at Proton [1]



Long-term test of SOEL cells at EiFER [2]

- AEL life-time
  - Older systems have excellent life-time in steady-state operation > 100,000 h / 9-15 years
  - Newer concepts : 50-70,000 h
- PEMEL life-time
  - Comparable to AEL if well designed
  - But mostly < 40,000 h / 5-10 yrs
  - Degradation mechanism not fully understood
- HTEL life-time
  - Few 1,000 h with decay rate < 1%/1000 h
  - But considerable progress in the last years: 40,000 h should be feasible (cell level)
  - Thermal management is essential for dynamic operation and life-time

[1] Everett / Proton OnSite, Proceedings PEMEL Durability Workshop, 2013-03
[2] Shefold, Brisse / EIFER, Manuscript ICACC 2014

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Where Do We Have R&D Demand in the Next Years?

- AEL
  - Increasing current density
  - (Increasing pressure tightness)
  - Faster dynamics of the complete system (BOP)
  - Higher part load range
  - Decreasing production costs through economies of scale

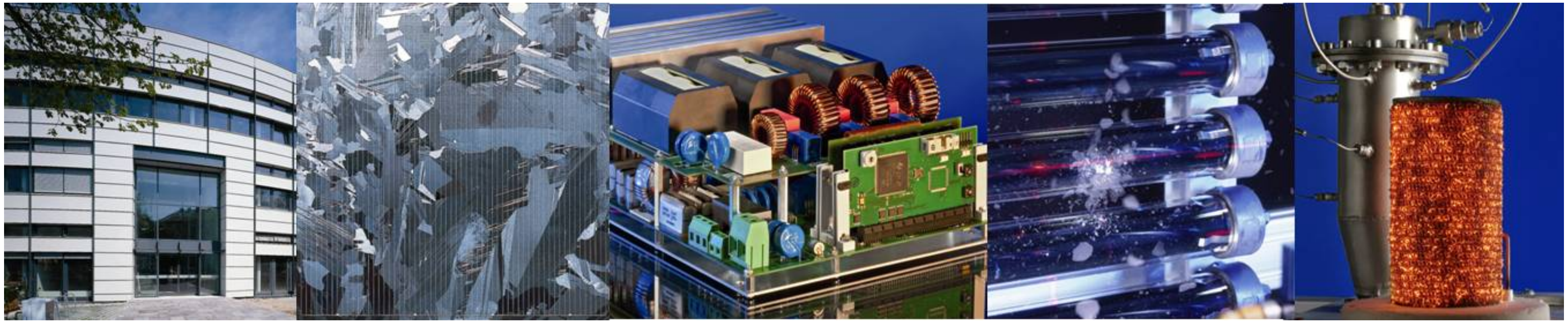
- PEMEL
  - Increasing life time of materials/ stack
  - Proof of scale up concepts for stack
  - Decreasing costs by substitution or reduction of expensive materials
  - (Decreasing production costs through economies of scale)

- HTEL
  - Development of adapted electrodes/ electrolyte for SOEL
  - Cell and stack design
  - Proof of life time
  - Pressure tightness
  - Cycling stability

Summary

- The principle of water electrolysis is known for more than 200 years
- Importance of water electrolysis gets larger with growing integration of renewable energy sources
- New market opportunities (PtG concept, hydrogen FCEV) entail new requirements for water electrolysis systems
- Alkaline electrolysers are a mature technology in the MW range for industrial use but needs to be adapted to new markets requirements
- PEM electrolysis is available in the small scale as proven technology with several advantages but has to enter the MW class
- HT electrolysis is still in the lab scale but has made considerable progress, substantial R&D is required before systems are on the market

Thanks a lot for your kind attention!



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