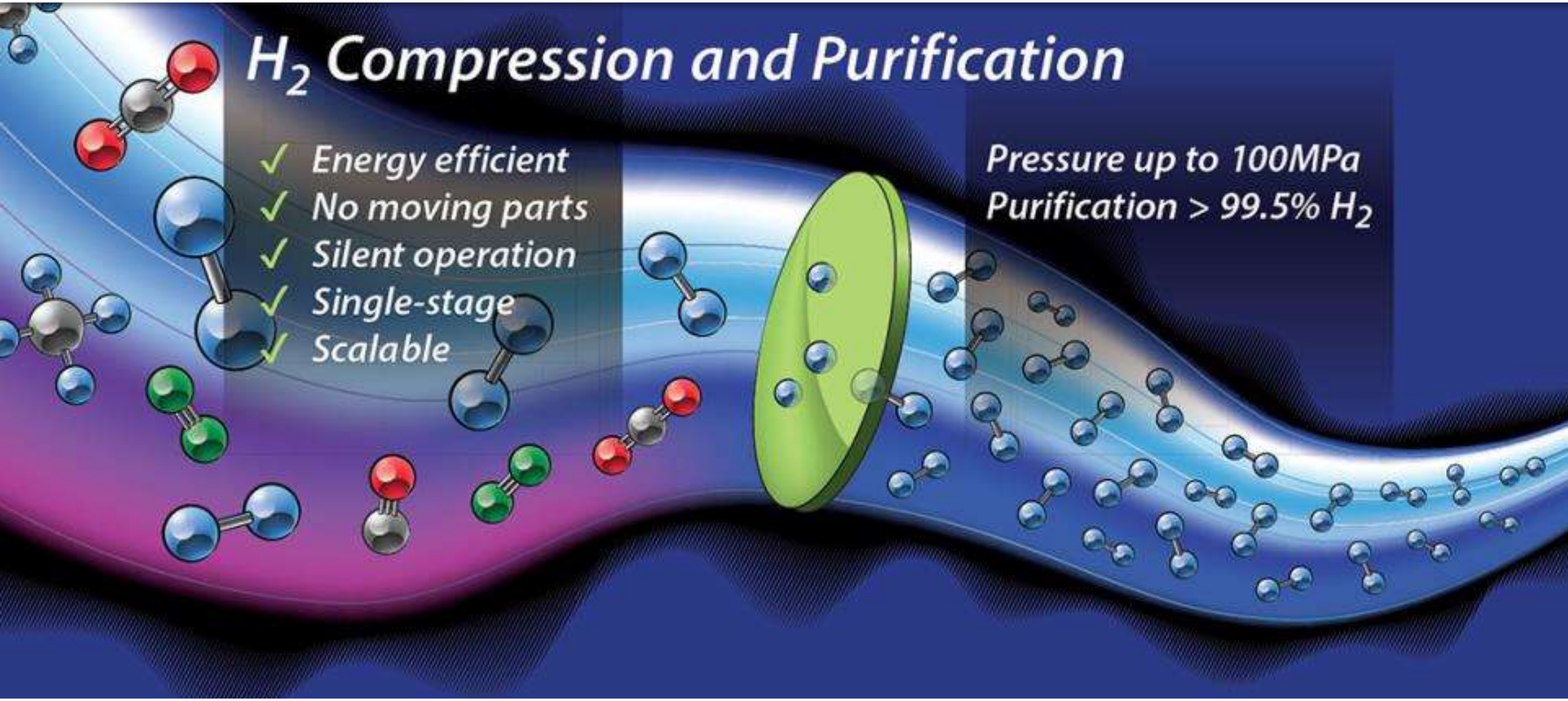
HyET

Hydrogen Efficiency Technologies



dr.ir. Peter Bouwman

Pure Pressure

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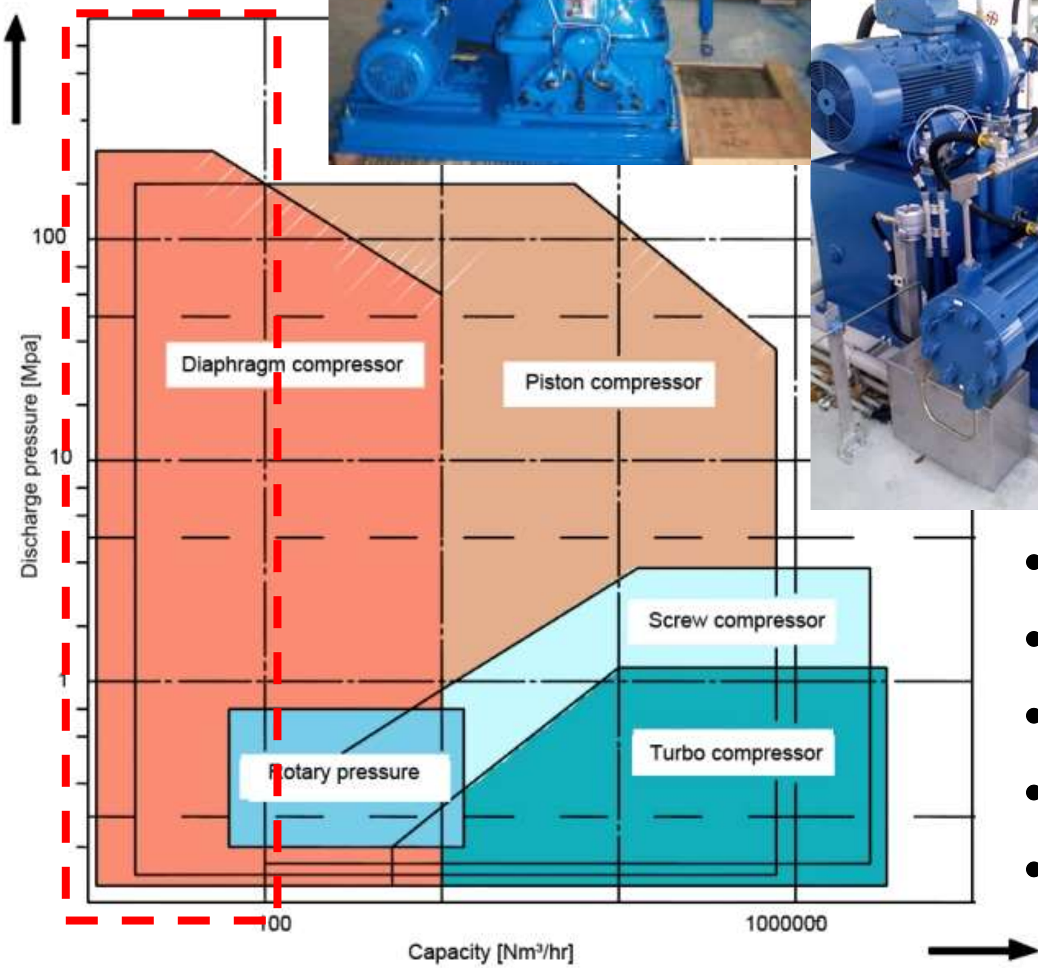
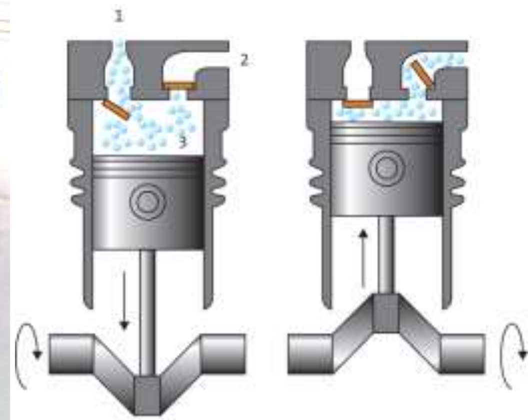
Mechanical Compression

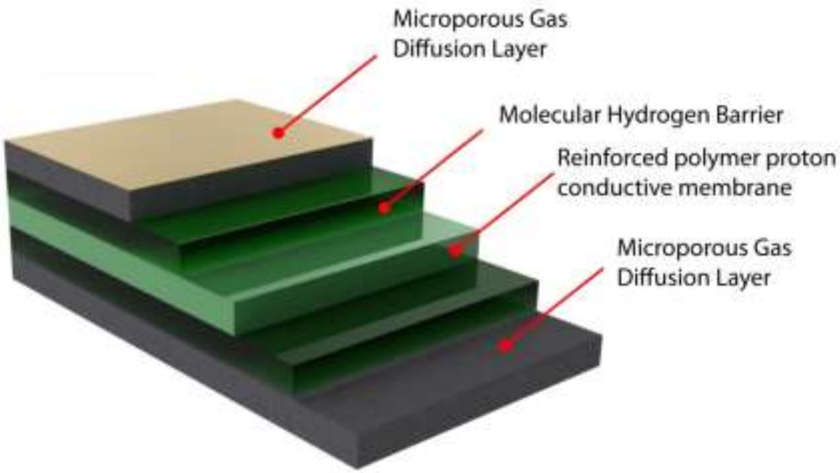




- Minimum feed pressure
- Multi-stage configuration
- Interstage cooling
- Regular maintenance
- Noisy

Mission & Competence

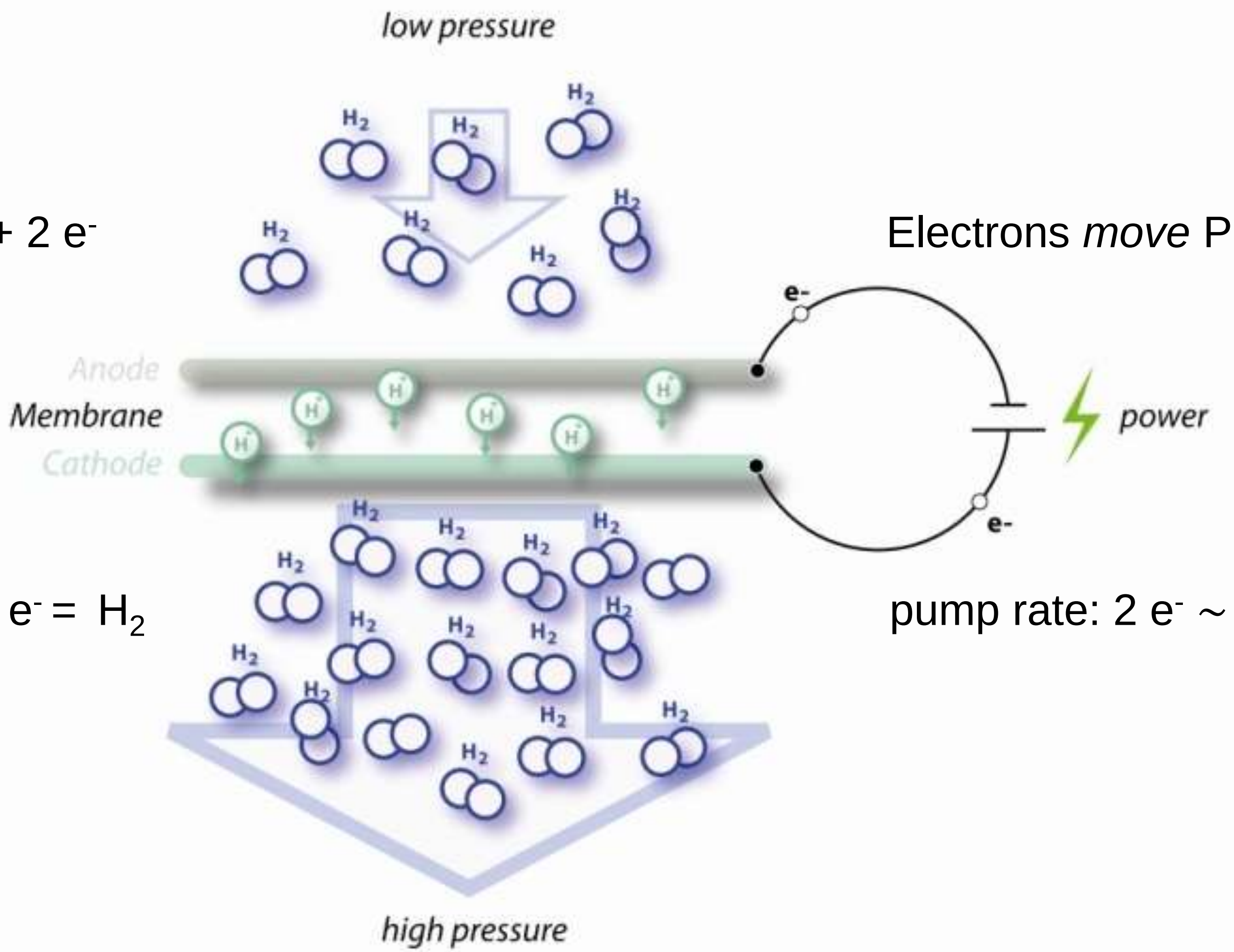
- **Mission:** Develop innovative *silent* technologies and make available products for **Purification** and **Compression** of hydrogen gas
- **Core competence:** deliver high pressure Membrane-Electrode-Assembly (MEA) in stack with BOP system.



Working Principle of EHC

Anode: $H_2 = 2\ H^+ + 2\ e^-$

Electrons *move* Protons

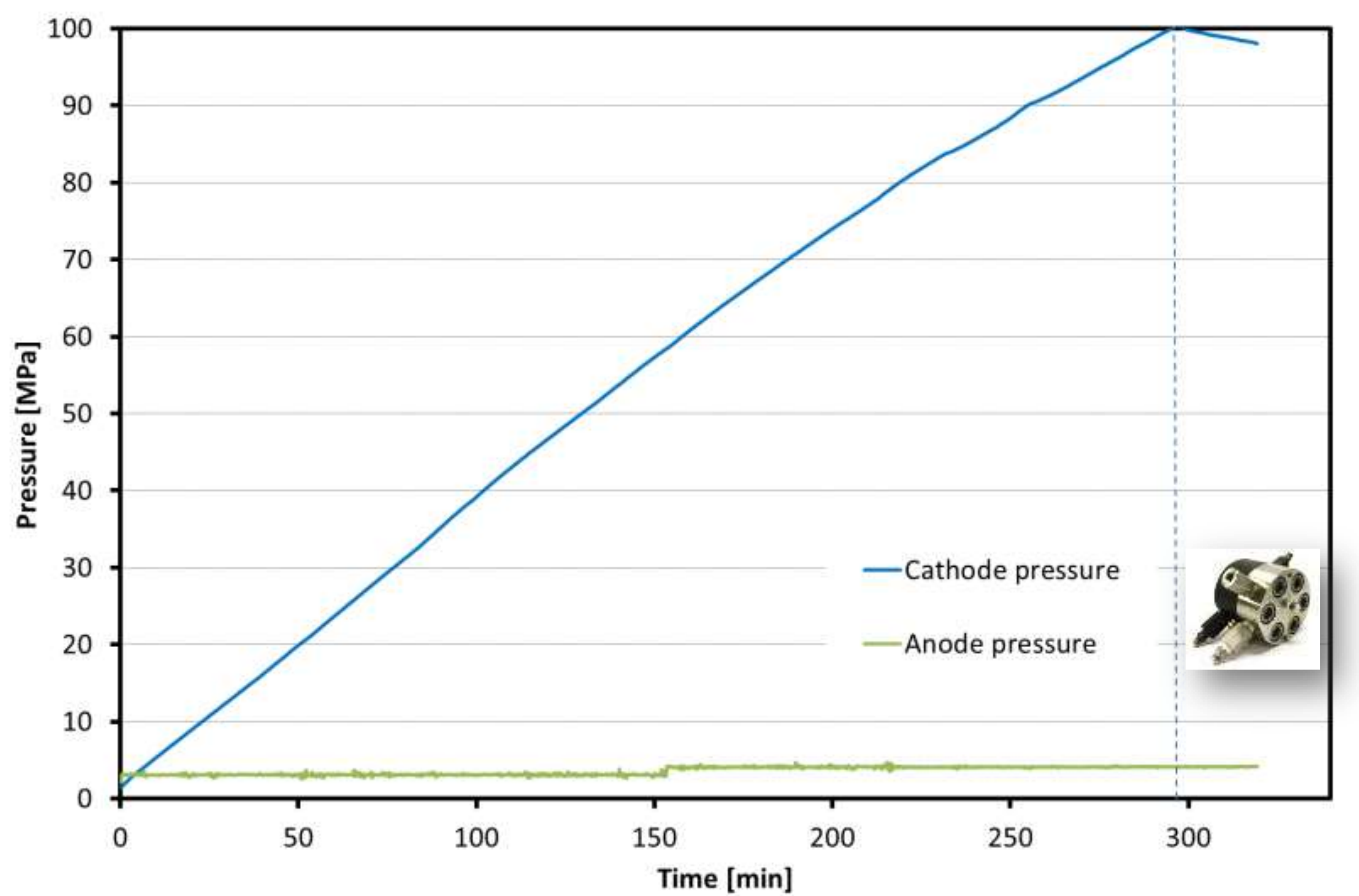


Cathode: $2\ H^+ + 2\ e^- = H_2$

pump rate: $2\ e^- \sim H_2$

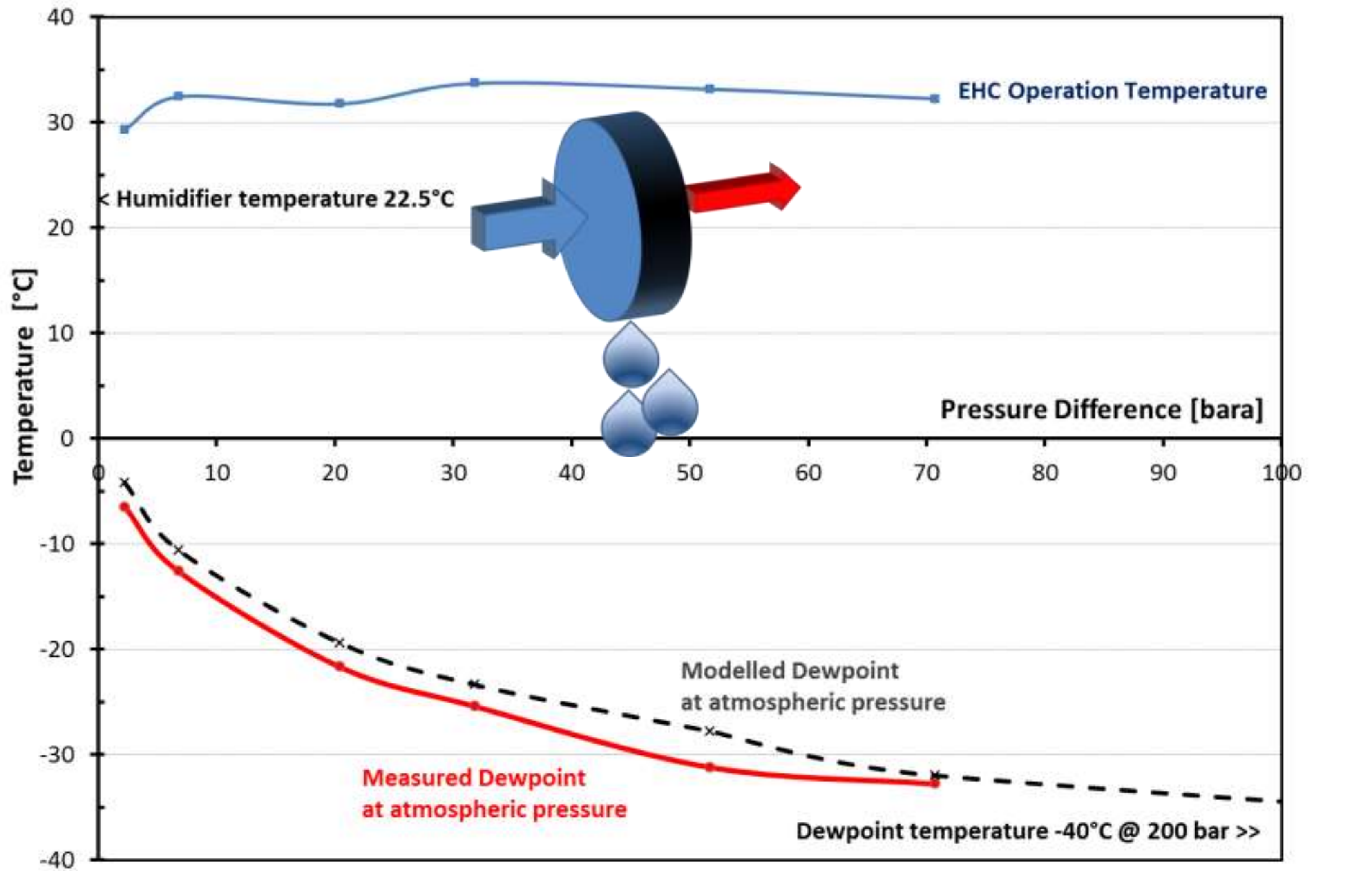
Special membranes block hydrogen gas, but allow fast proton conductivity. Catalysed interfaces enable the indicated redox reaction equilibrium. An external power source drives the electric current and the internal hydrogen mass transport direction, controlling hydrogen gas flow.

EHC Compression Record



HyET successfully demonstrated a pressure record of 100 MPa pressure, single stage, on a laboratory cell to prove the concept of Electrochemical Hydrogen Compression (EHC)

de-Humidification



Like with air-conditioning , isothermal compression effectively dried hydrogen supply.

Product-Market relationship

HyET provides a critical "Puzzlepiece" in the hydrogen infrastructure daisy chain

Source side

Demand side

Hydrogen Refueling Station

Project PHAEDRUS developed and validated a scalable HRS design using the latest technologies including Electrochemical Hydrogen Compression (EHC) and hydrogen production on-site .

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Hydrogen Refueling Station

HyET engages field testing using MoHyTO systems to assess customer applications and increase Technology Readiness Level above 5.

ITM
Electrolyser
(5 kg/day)

HyET
Electrochemical
Compressor
(here 2 kg/day)

PHAEDRUS

New Energy World JTI

Scalable Design

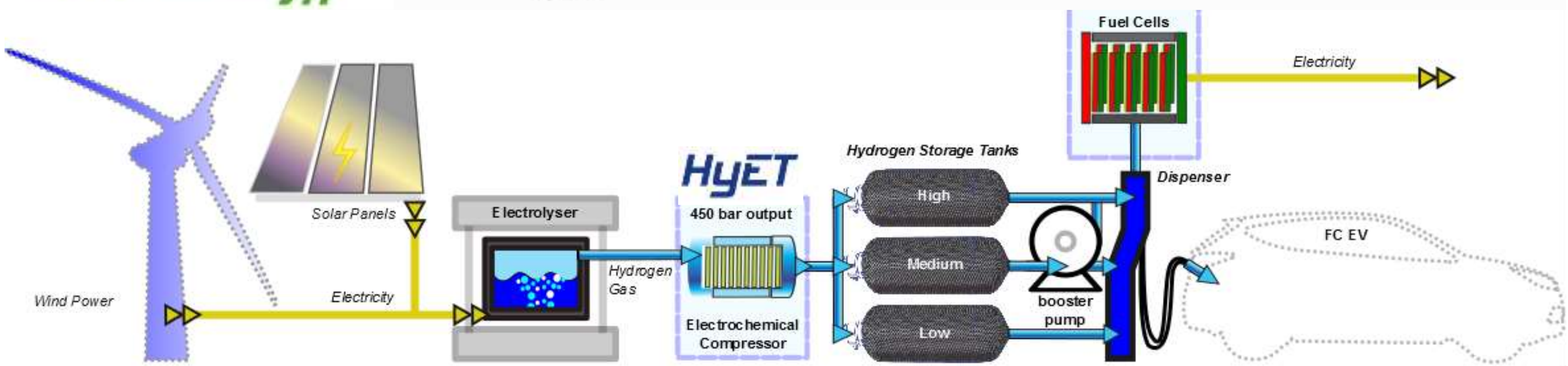
Successful integration of ITM electrolyser and HyET EHC validated in field test in summer 2015.

HyET
Hydrogen Efficiency Technologies

Hydrogen Refueling Station

DonQuichote
hydrogen out of wind turbine energy

New Energy World JTI



Project Don Quichote realises 60 kg/day hydrogen production, compression and storage at the Colruijt distribution centre in Belgium for refuelling forklift trucks and fuelcell power generation.

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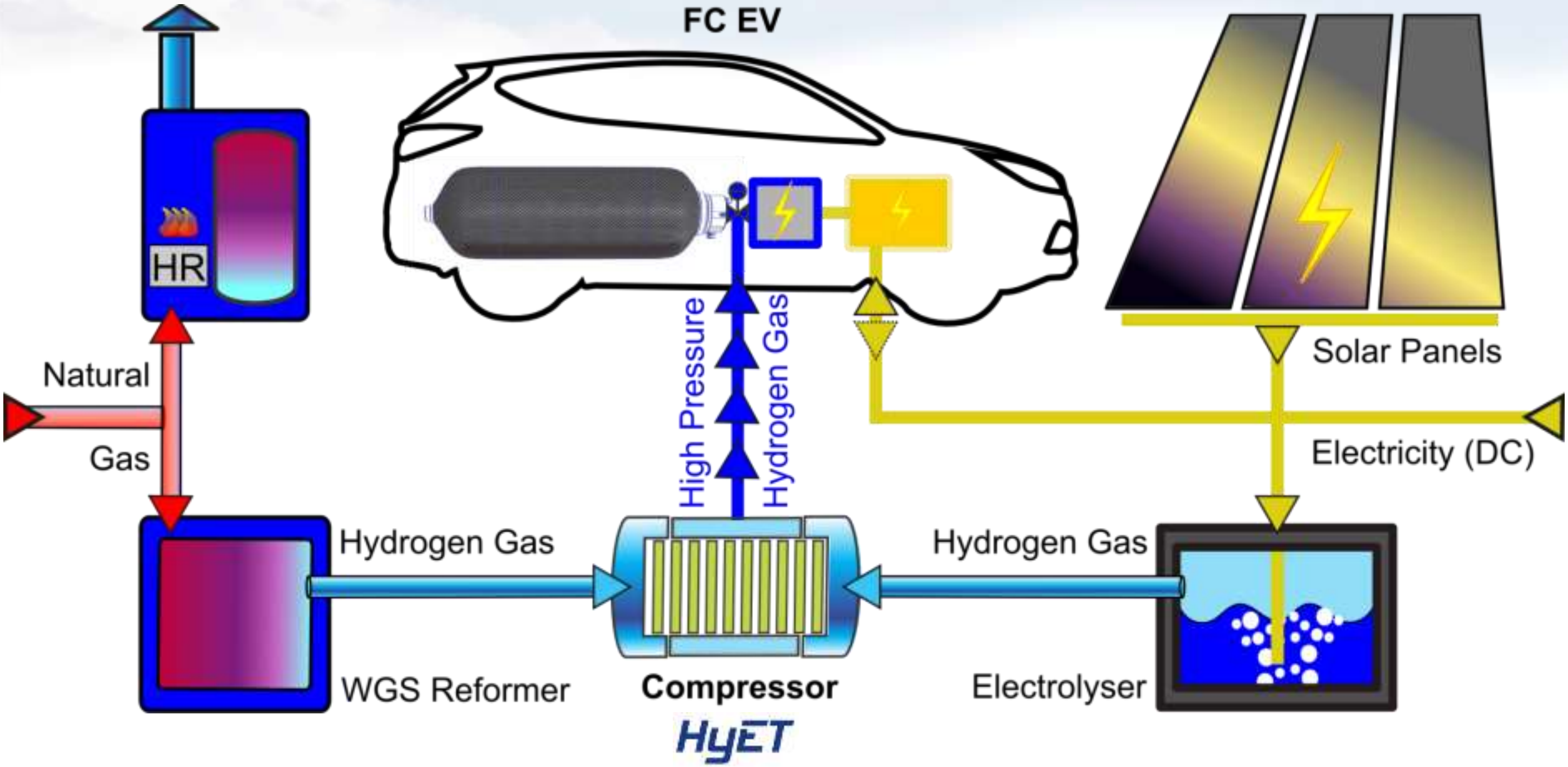
Scaled to demand

Base Oriented Compressor Iso-Thermal Organisation (BOCITO) in design phase

3x MoHyTO systems currently operational

The basic stack and subsystem form the basic element, enabling modular upscaling on demand

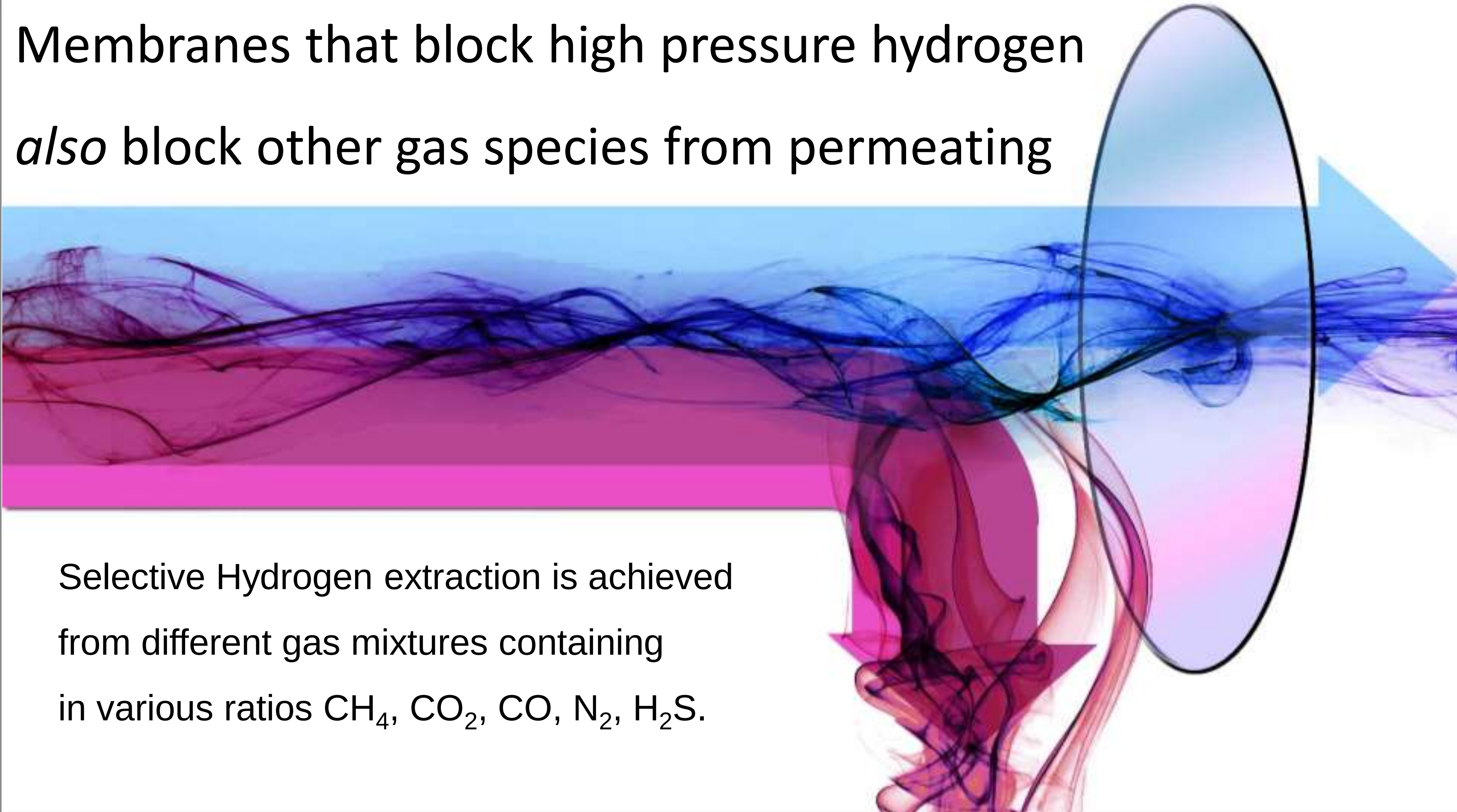
SMART Energy Integration



Ultimately, our silent EHC device could enable home refuelling : storing hydrogen in a tank, integrating renewable energy sources together with the security of gas and grid connections by combining electrolysis and/or reformer and/or heating systems under SMART GRID control.

Purification is Included

Membranes that block high pressure hydrogen *also* block other gas species from permeating



Selective Hydrogen extraction is achieved
from different gas mixtures containing
in various ratios CH_4, CO_2, CO, N_2, H_2S.

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Purification is Included

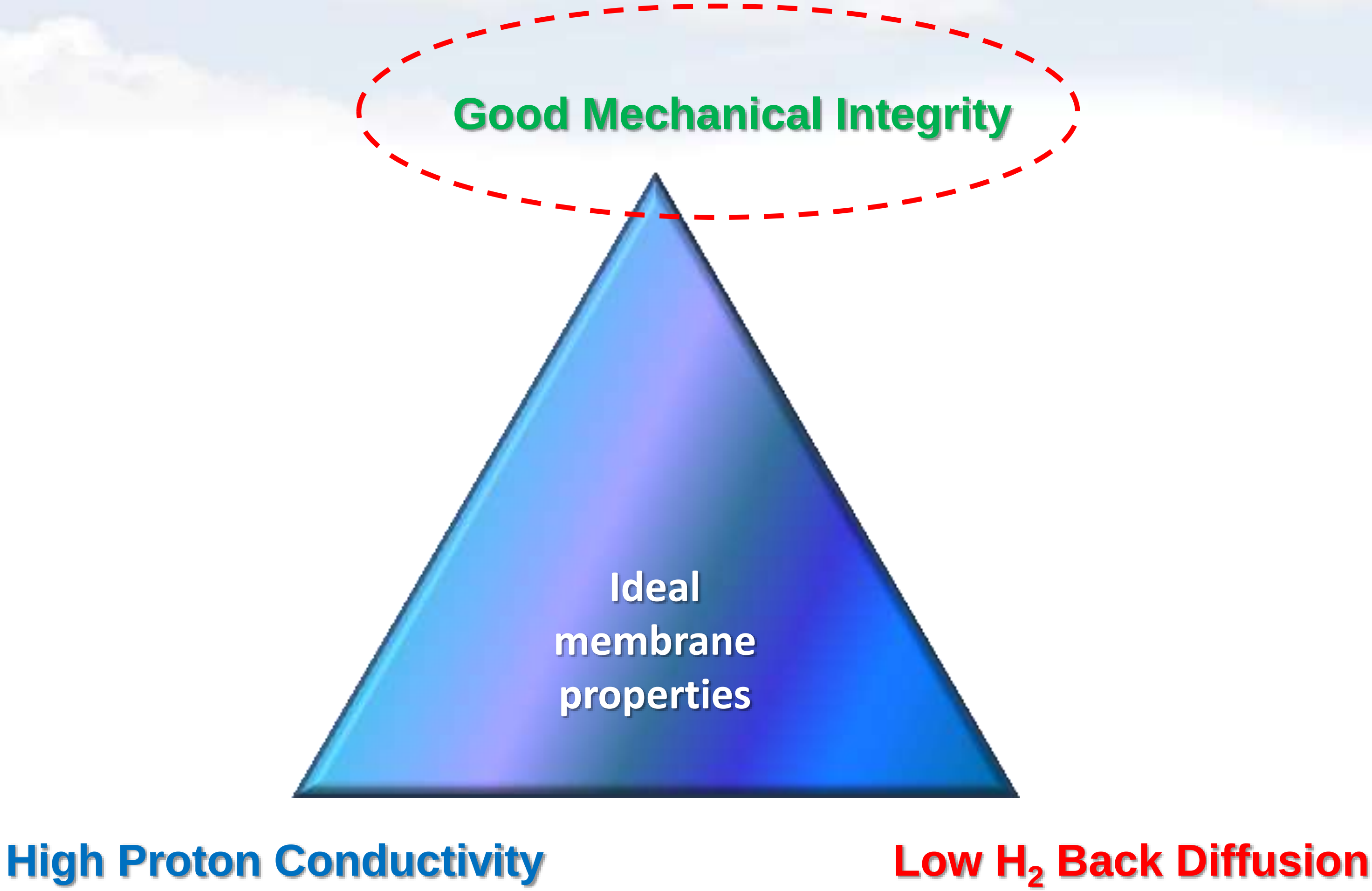
	Gasses >	H2 %	CO2 %	CO %	CH4 %	H2O %
supplied	**WGS gas mixture** *as-received from supplier*	**70.05**	**19.97**	**7.477**	**2.507**	**bubbler**
purified	**Permeating gas**	**99.551**	**0.024**	**0.002**		**0.423**

concentration of CO is reduced >**5000** fold,

CO_2 is reduced >**1000** fold

No CH_4 observed in the permeate gas

Membrane properties



Optimum balance between the key membrane properties depends on the application

External H_2 Pressure

Assuming:

35 cm ∅
70 MPa

The EHC classifies as pressure vessel

- Spherical form factor with wall thickness:

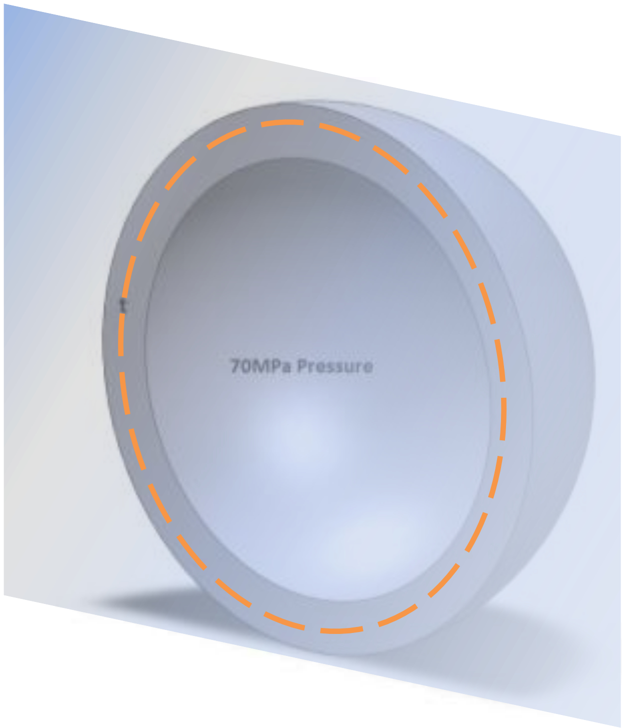
Material	Yield Strength [Mpa]	Wall Thickness [mm]	including Safety factor x2.35 [mm]
HDPE	26	236	554
Steel (average)	250	25	58
Steel (high strength)	690	9	21
Aluminium	15	408	960
Aluminium alloy	400	15	36
Titanium alloy	830	7	17
Lead	10	613	1439

Indicative values

Example to show how much material is required to keep such pressure in a sphere, depending on the materials used for its construction

Internal H_2 Pressure

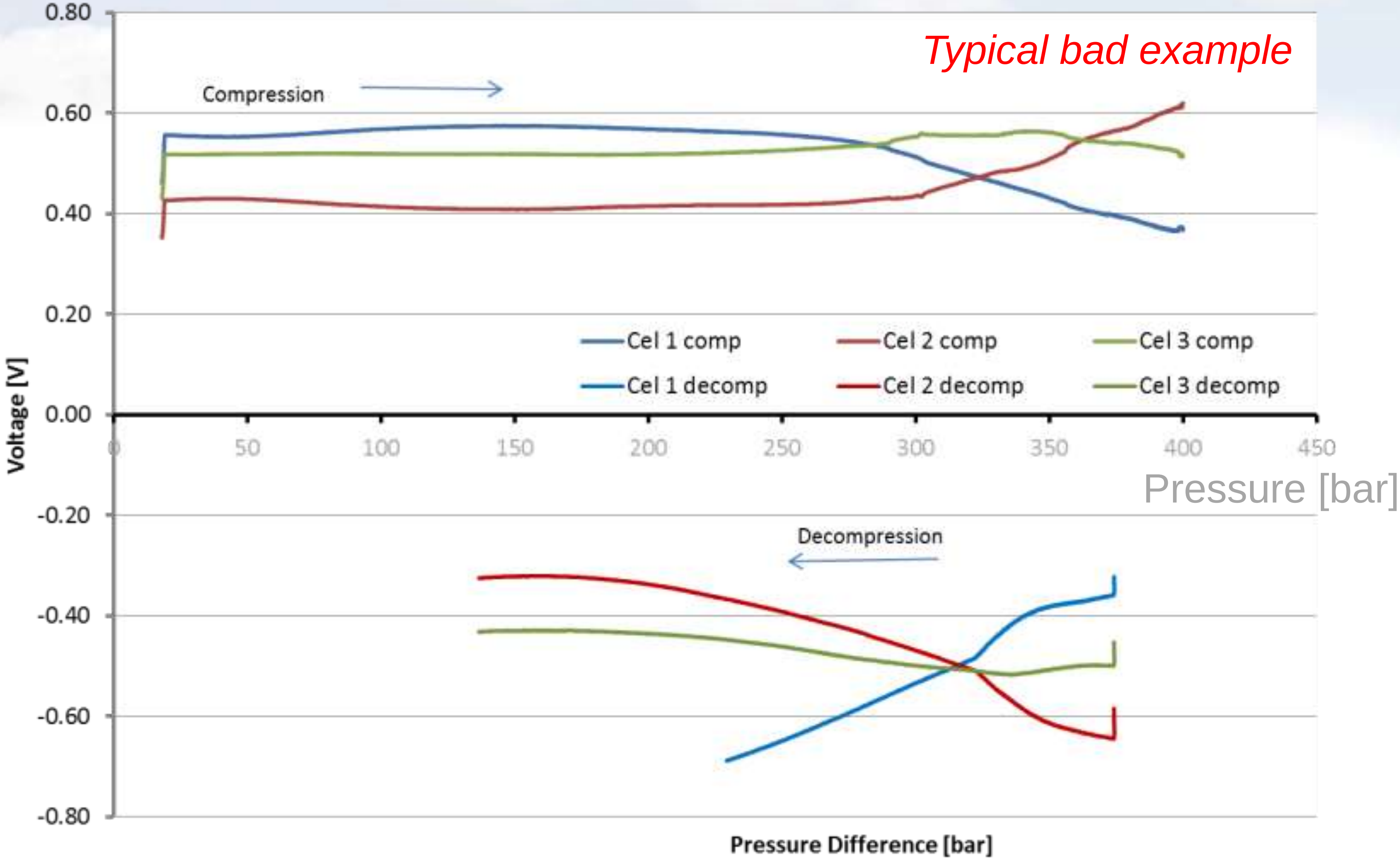
Hydrogen gas pressure also pushes against the membrane within EHC



- 70MPa Compressive force in z-direction
- Tension forces created in xy-plane
- Impact on water management
- Cell closing pressure subjected on MEA
- Tenting into gas flow-field channels
- Puncturing / pinhole propagation

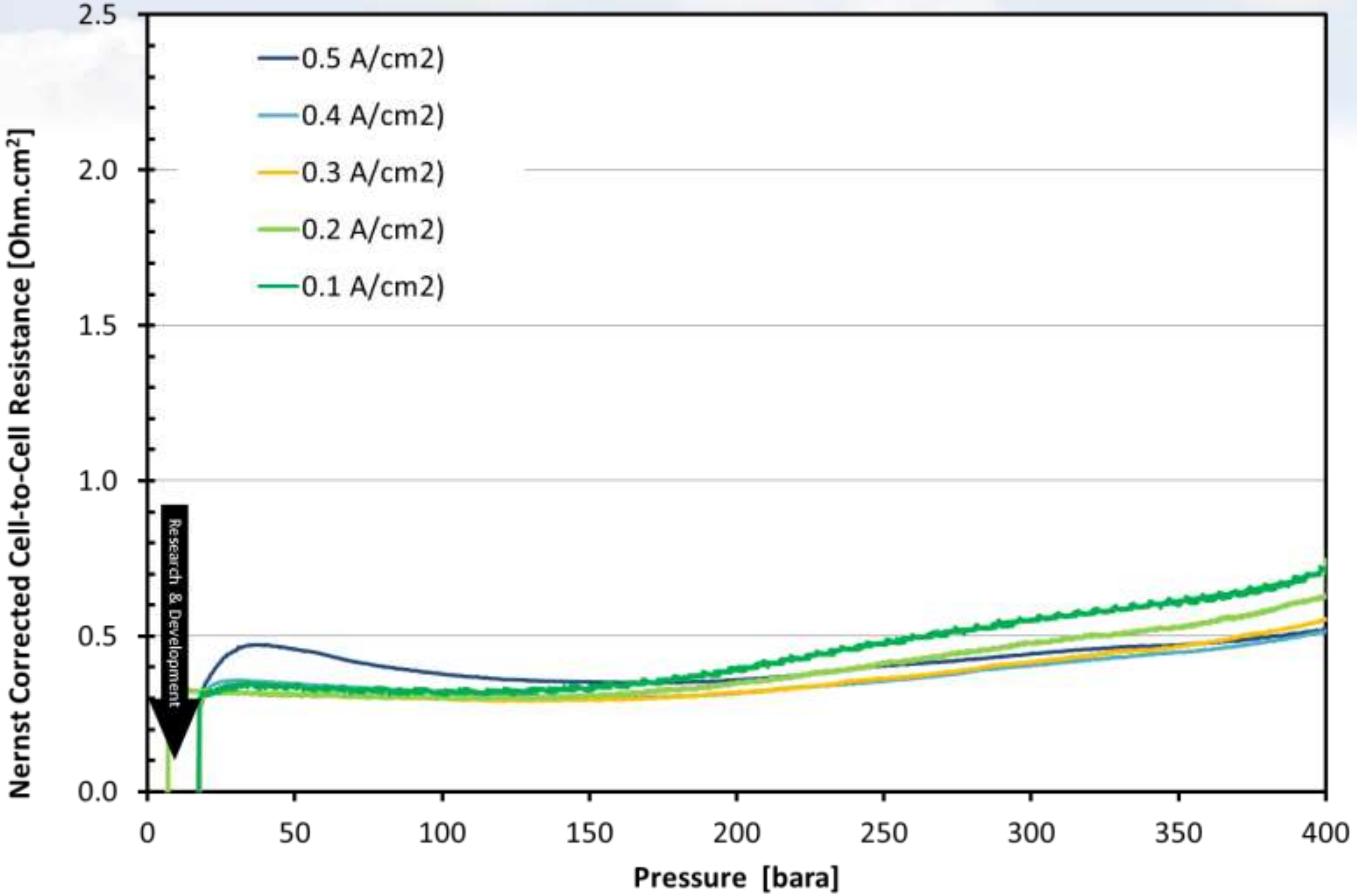
Technical solutions are called for when dealing with extreme pressures on soft matter

Variable cell-to-cell



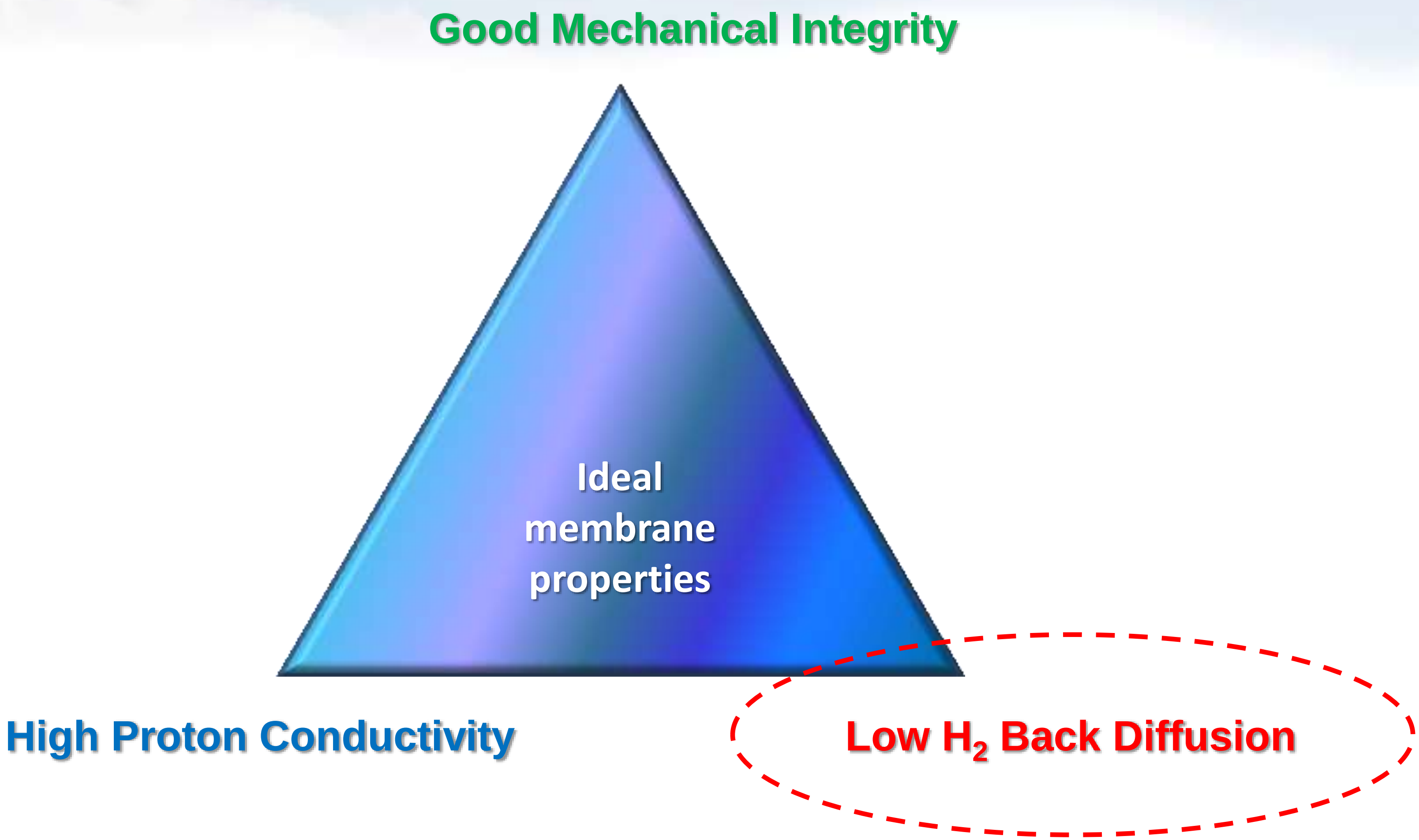
Forces during compression and decompression could cause cell-to-cell variations, if too much room is available for displacement and deformations between cells.

EHC Test Results



Pressure increase (bara) and current density have minor influence on resistance

Membrane properties



Optimum balance between the key membrane properties depends on the application

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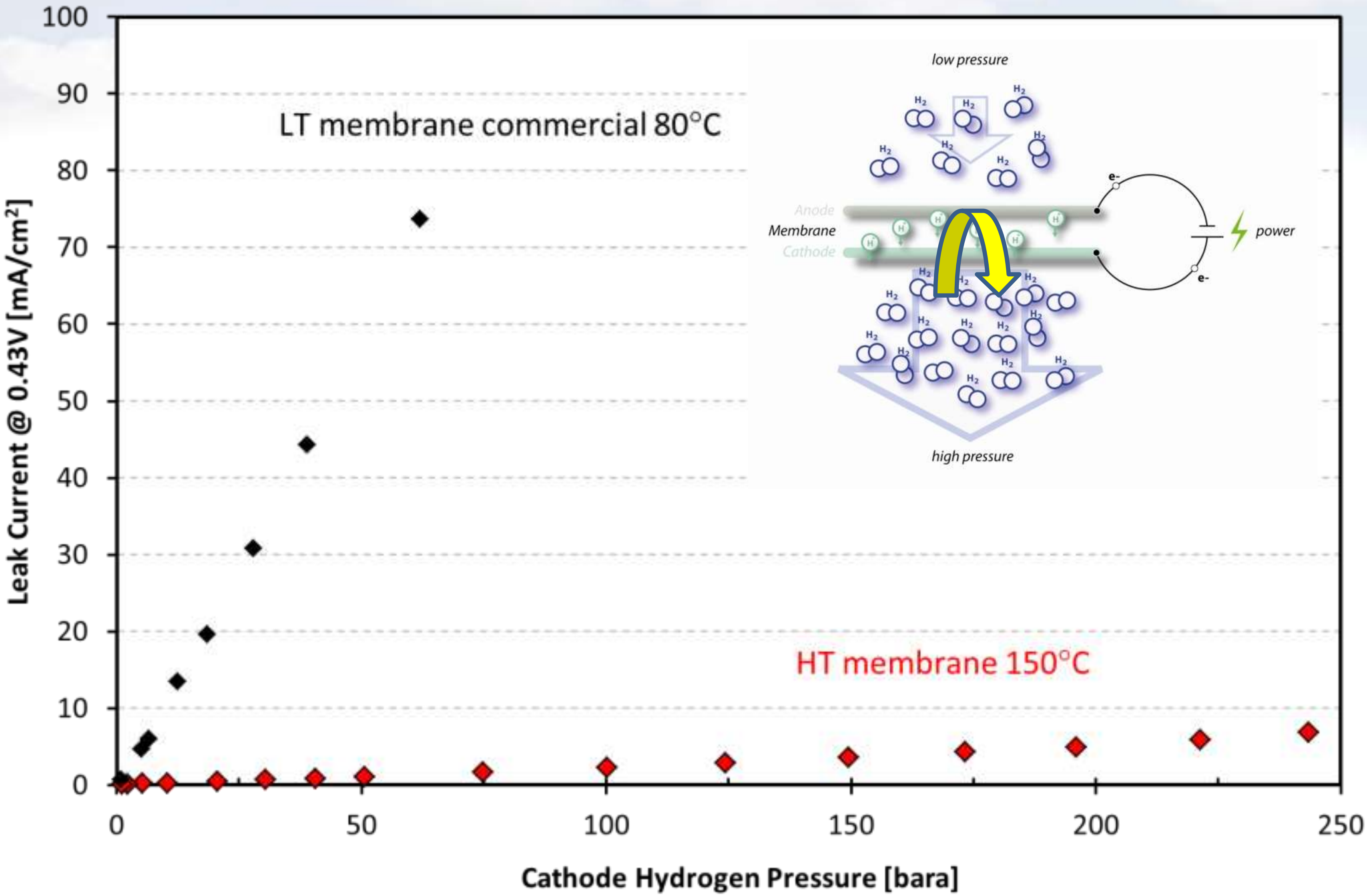
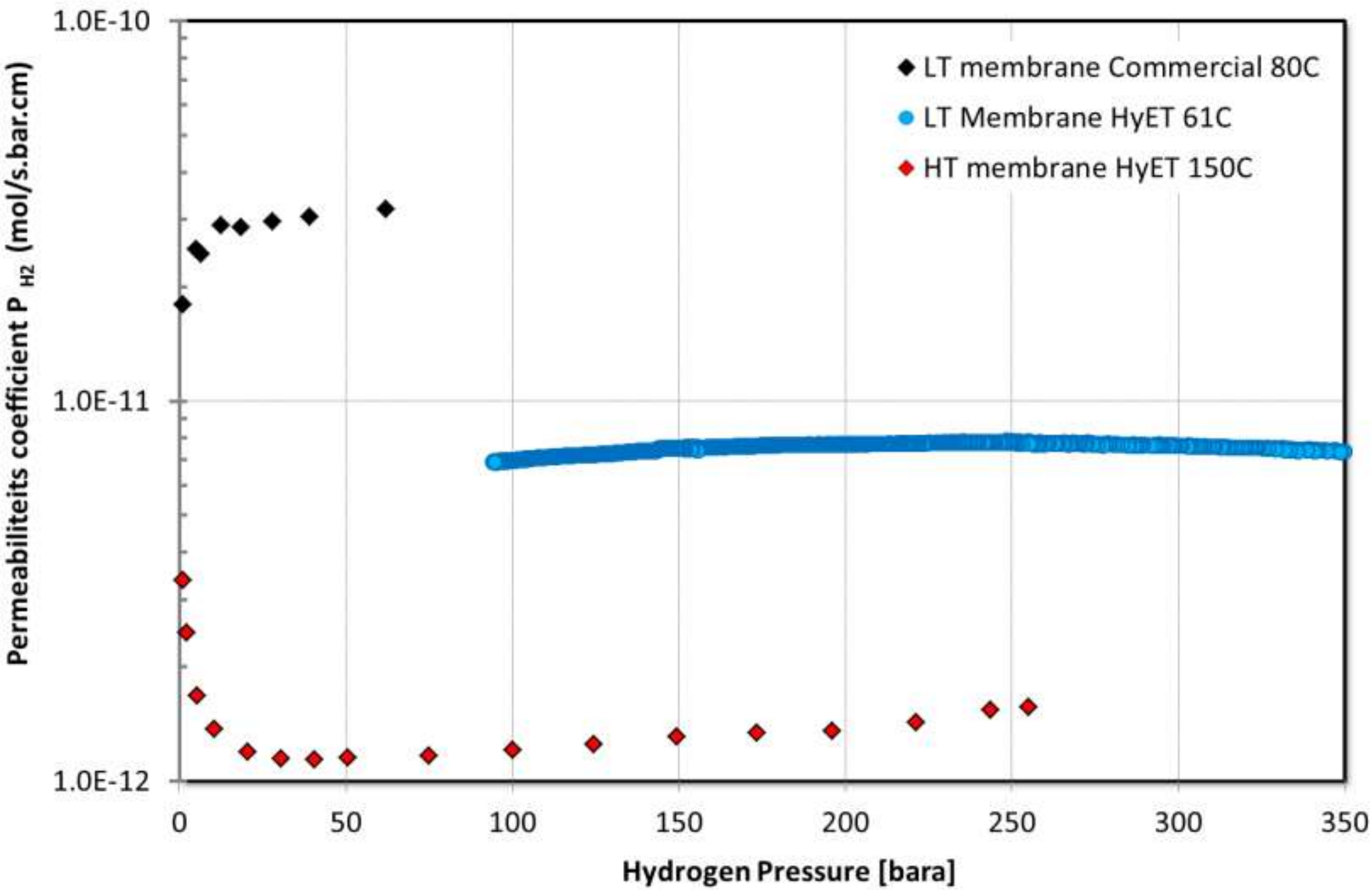
Impact of H_2 cross-over



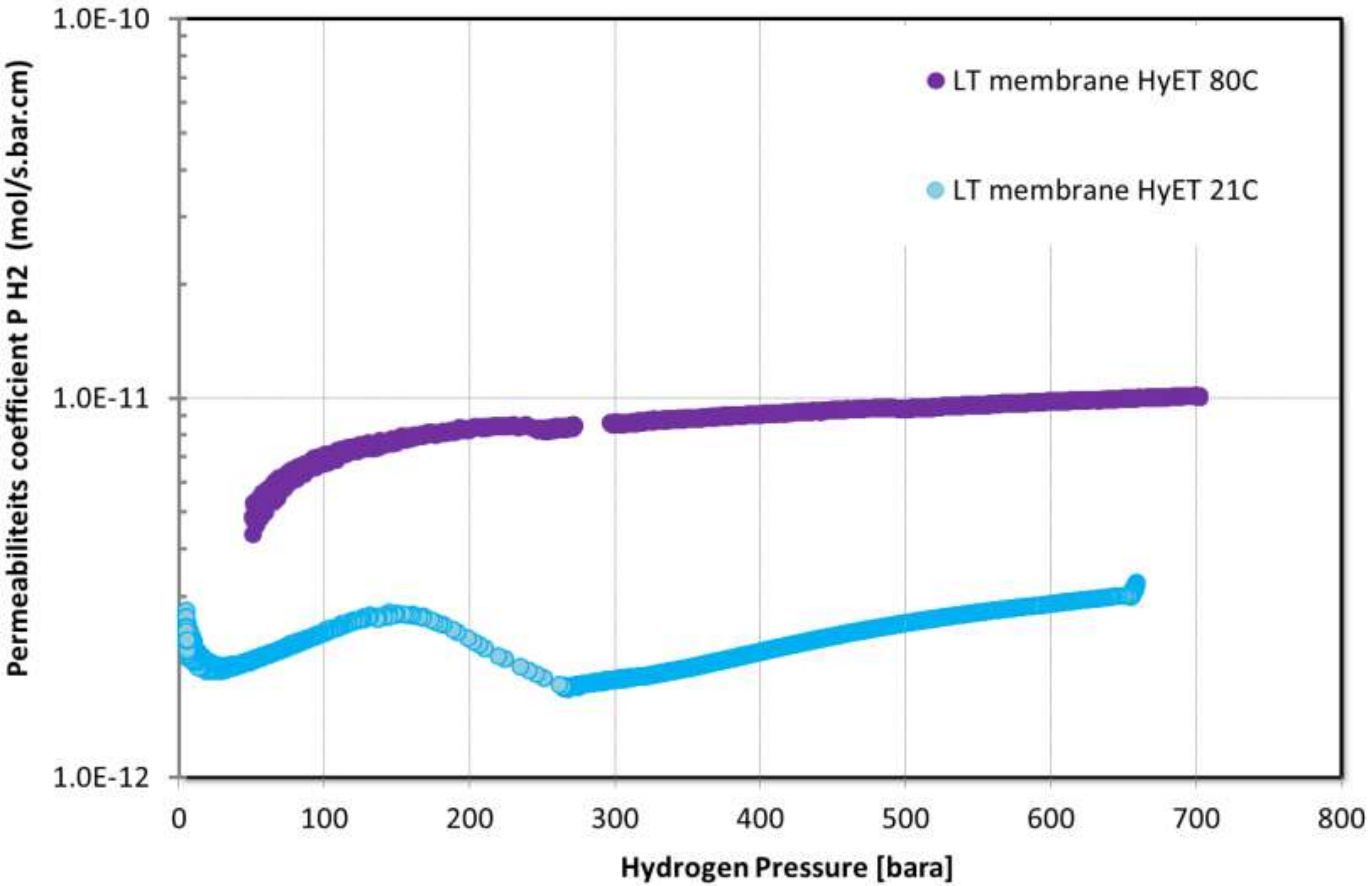
Cross over of hydrogen measured with 430mV polarisation and nitrogen on anode

Impact of H_2 cross-over



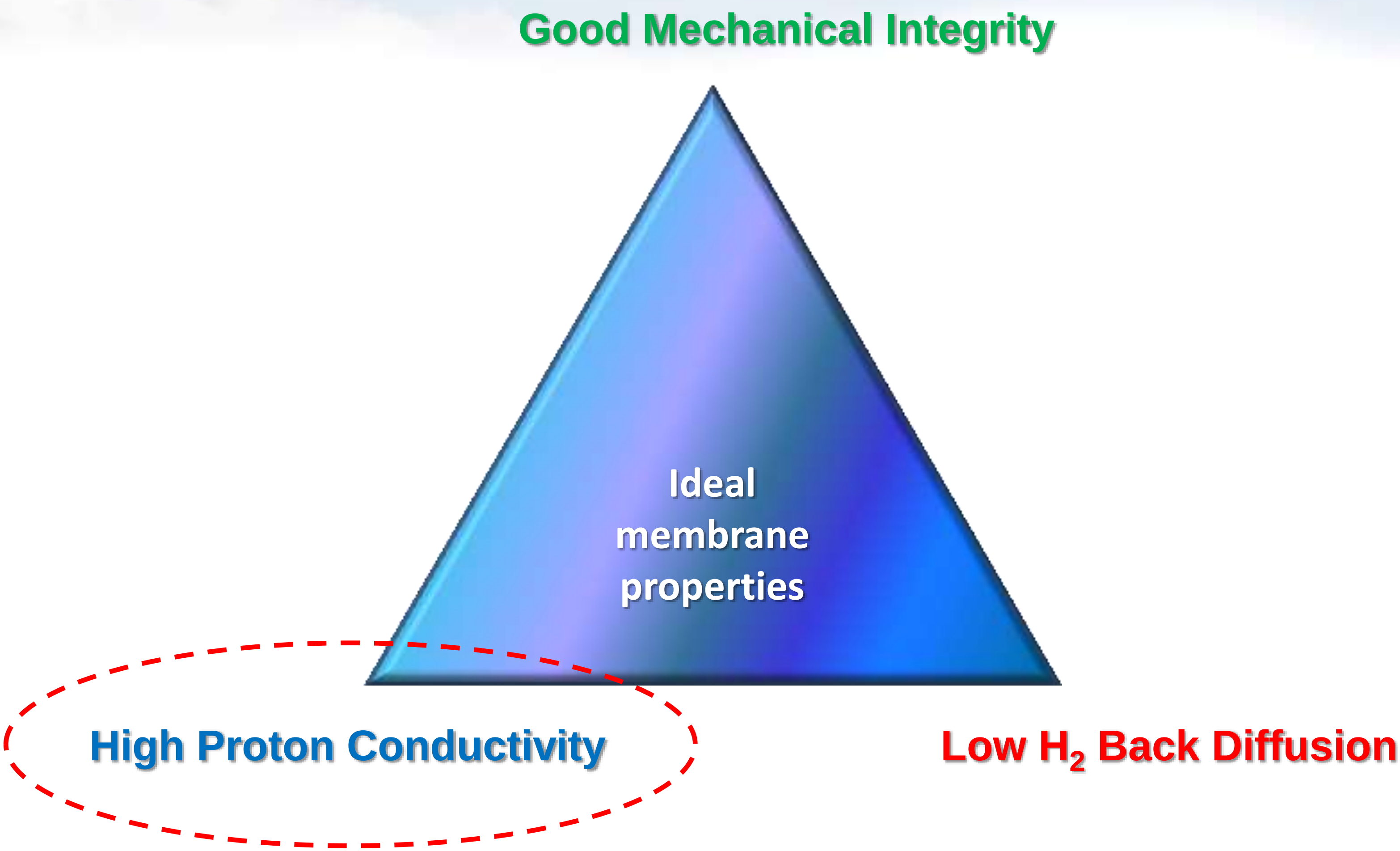
Membrane types are normalised for thickness, temperature indicated.

Impact of H_2 cross-over



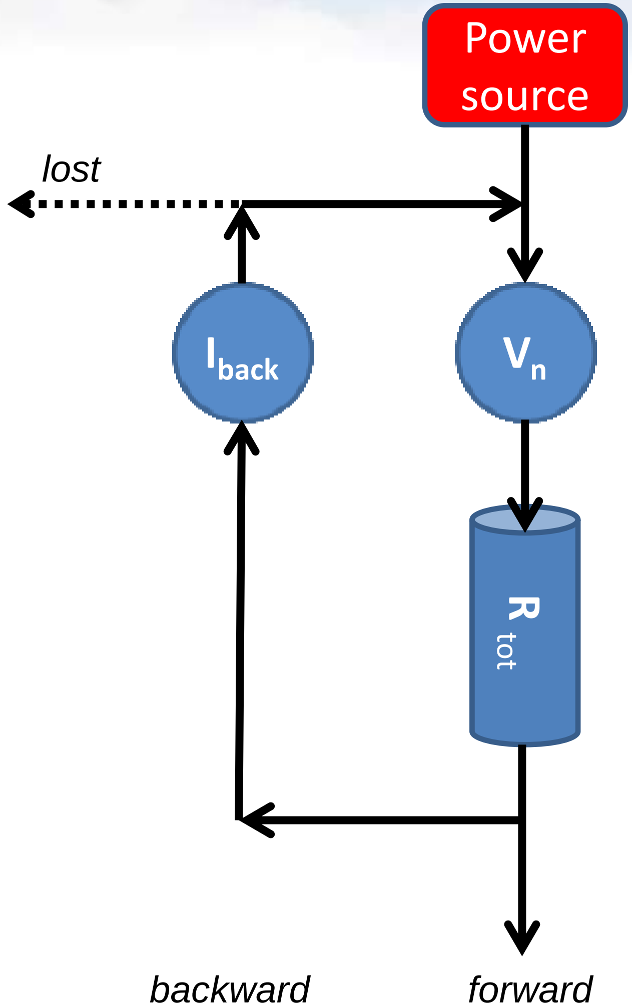
Temperature influences the hydrogen cross over through membrane significantly

Membrane properties



Optimum balance between the key membrane properties depends on the application

Schematic diagram



… Mapping all EHC resistances

Equivalent circuit model of the process in the EHC to pump hydrogen using DC current

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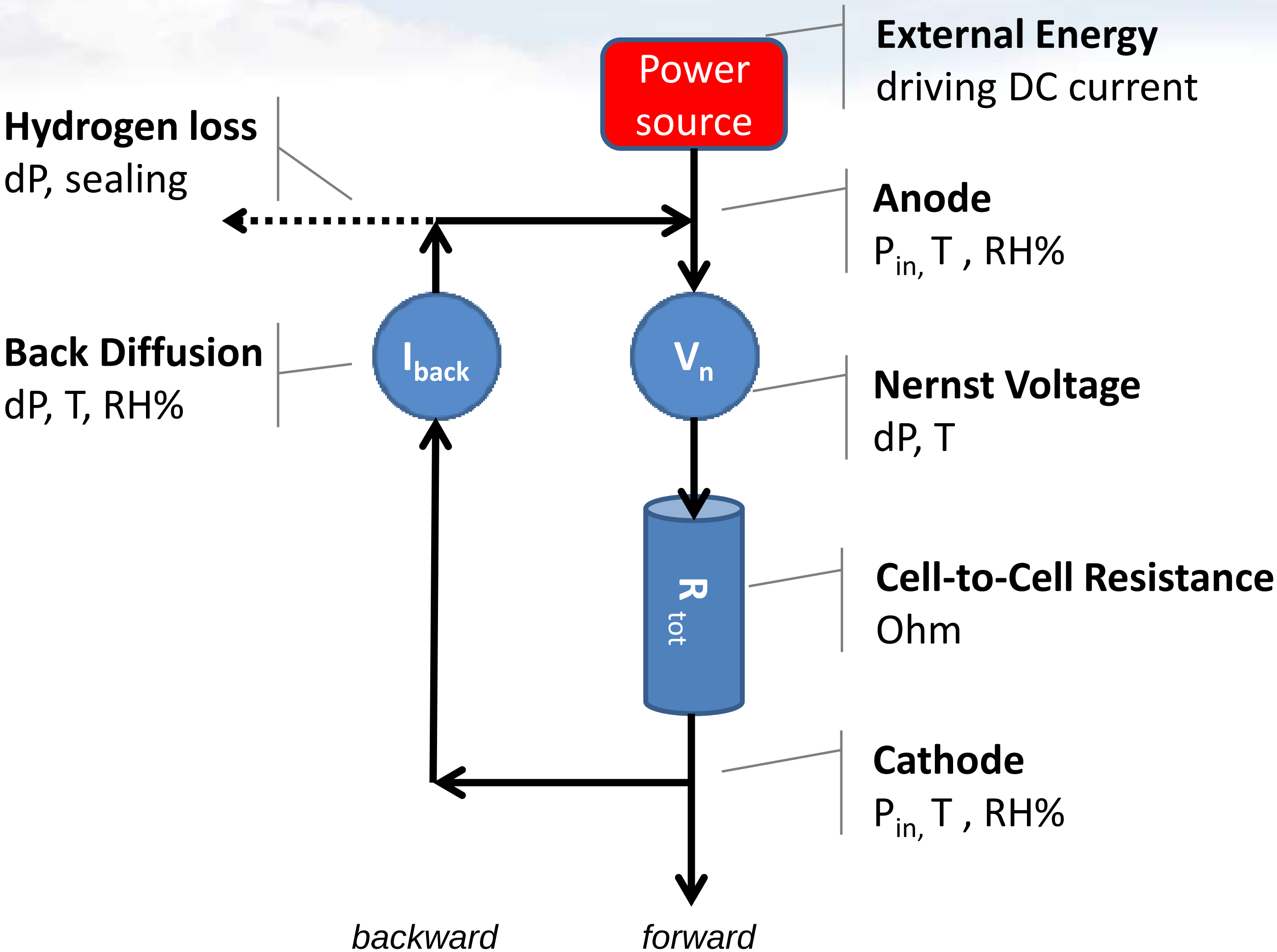
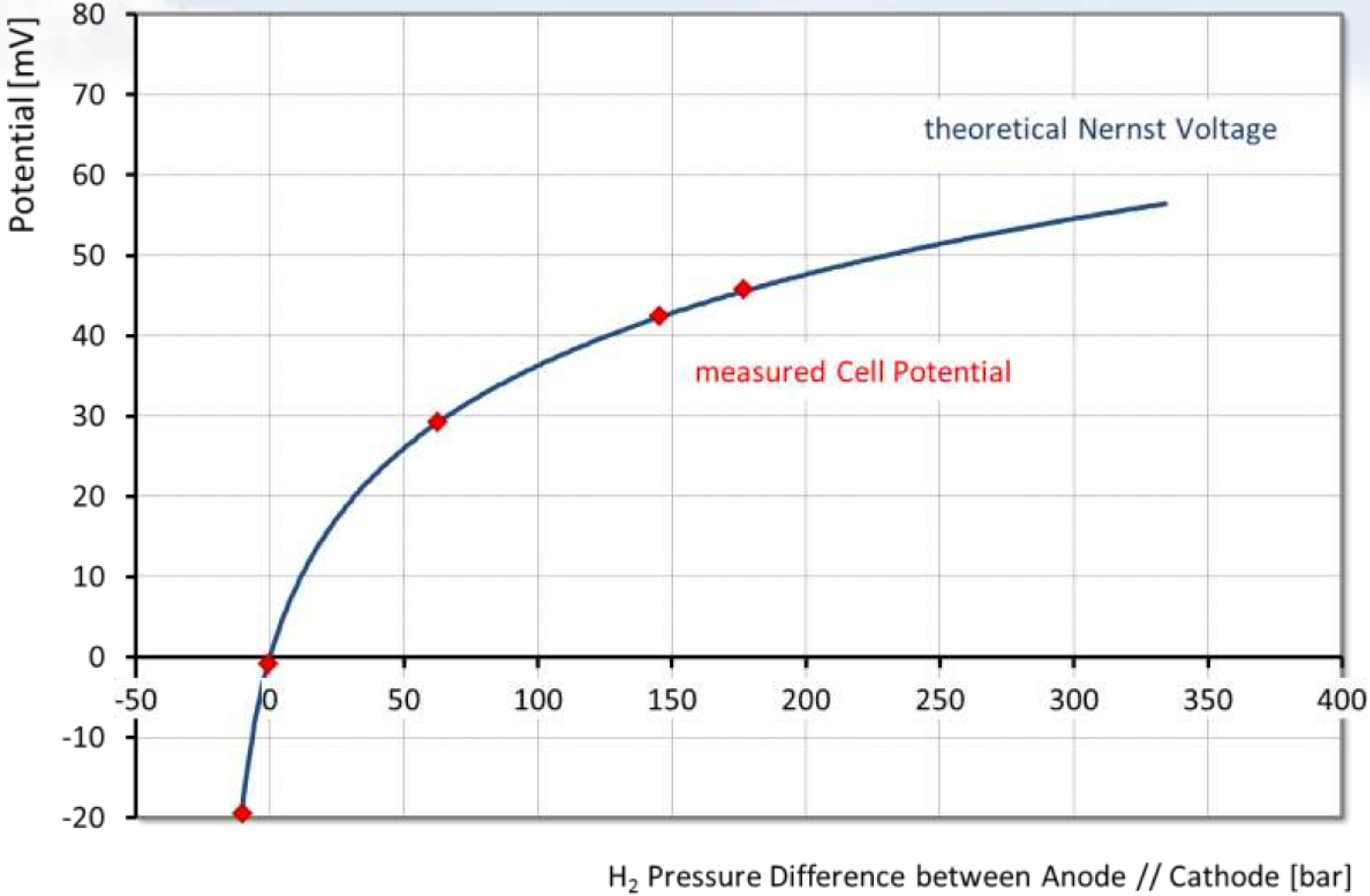
Schematic diagram



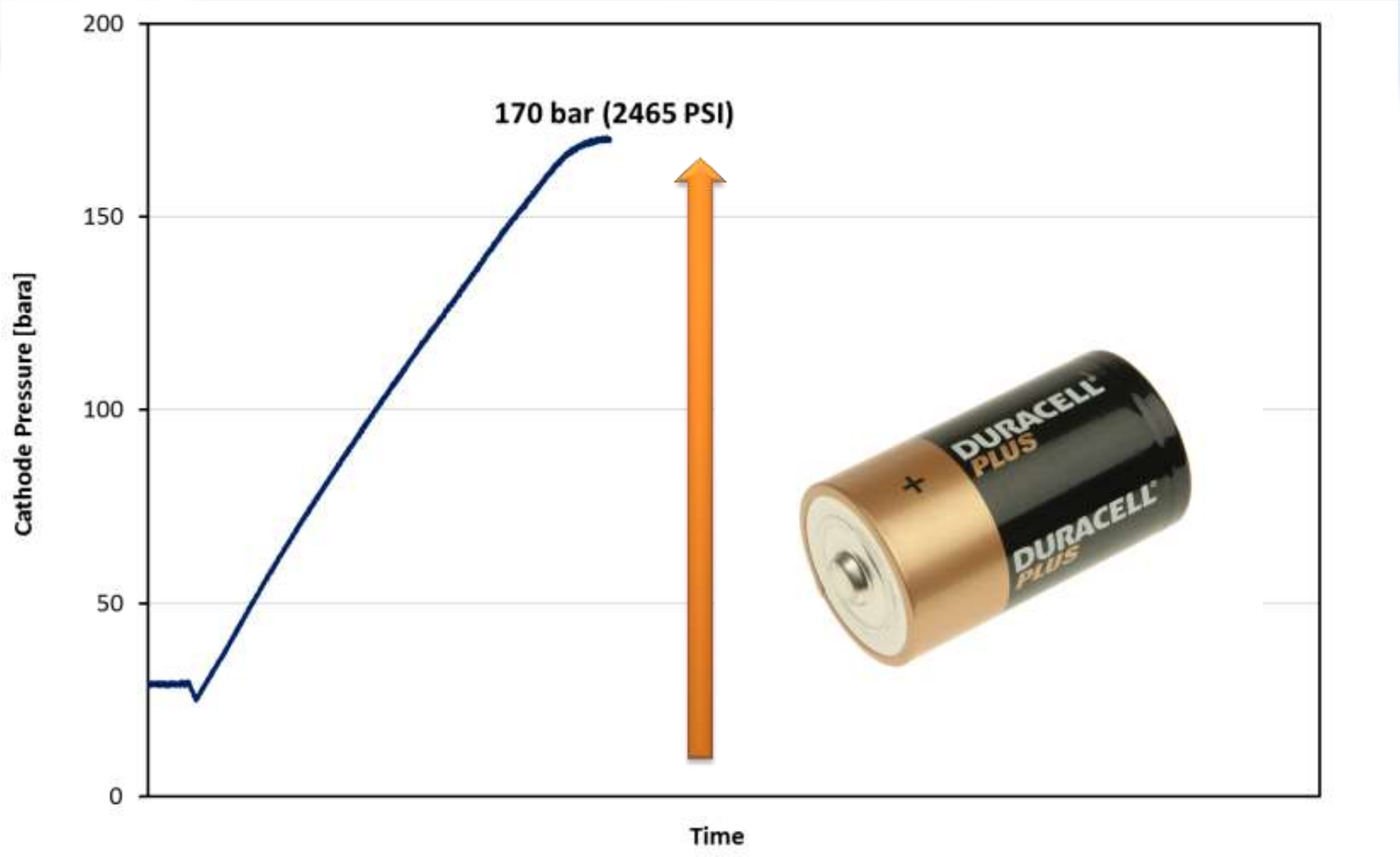
Equivalent circuit model of the process in the EHC to pump hydrogen using DC current

Compression Energy



Nernst energy equals compression energy, applying to over-pressure as well as vacuum

… low voltages suffice



Incredible compression was achieved with little energy from only one battery

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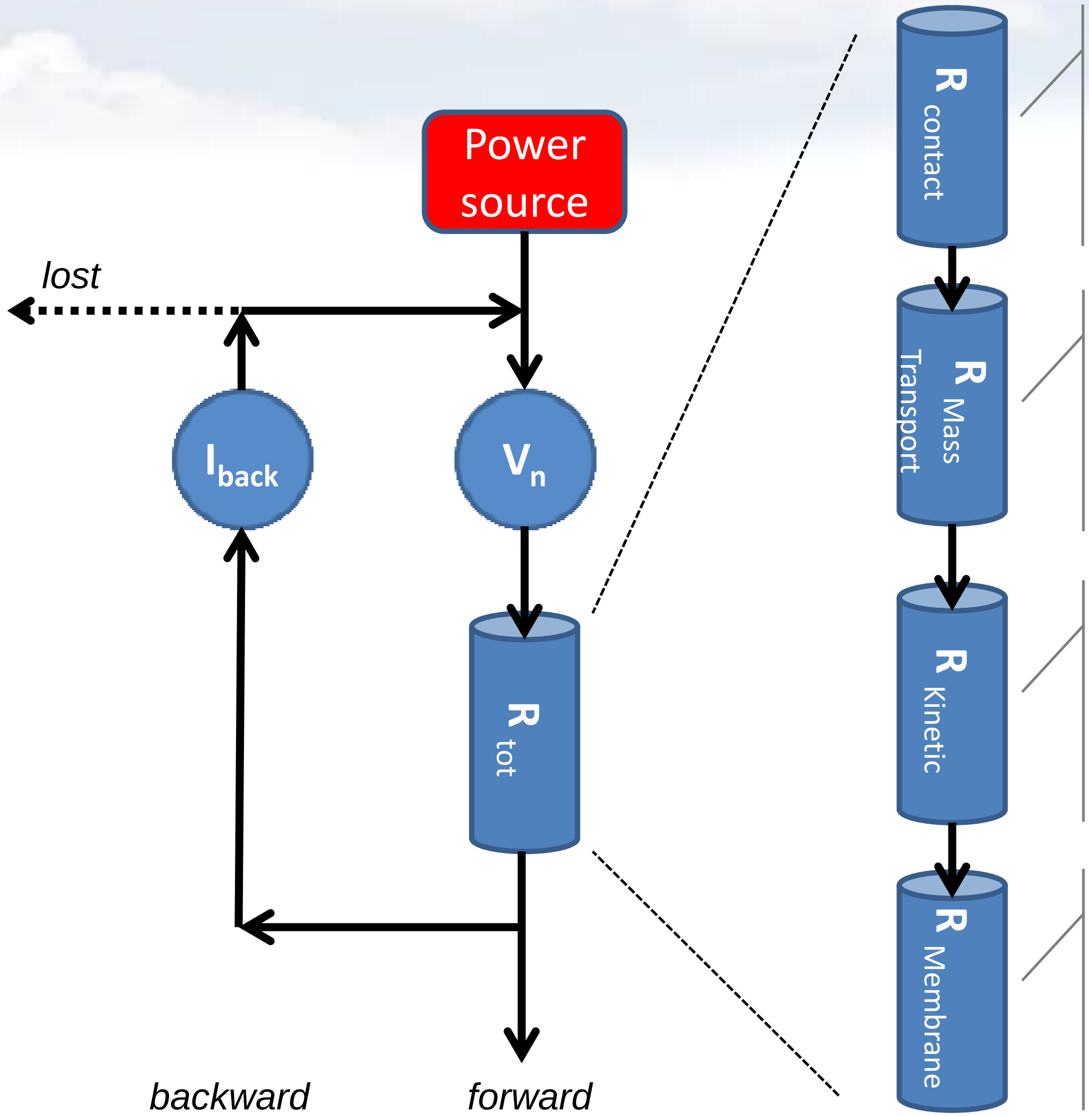
Schematic diagram



2x **Ohmic resistance**
wires, cellplate, flowfield, *including* interfaces

2x **H_2 gas transport**
supply flow anode, diffusion to/from catalyst, exit cathode

2x **Reaction $H_2 = H^+ + e^-$**
oxidation on anode, reduction on cathode

1x **Proton resistivity**
movement of H^+ through polymer electrolyte phase

Equivalent circuit model of the process in the EHC to pump hydrogen using DC current

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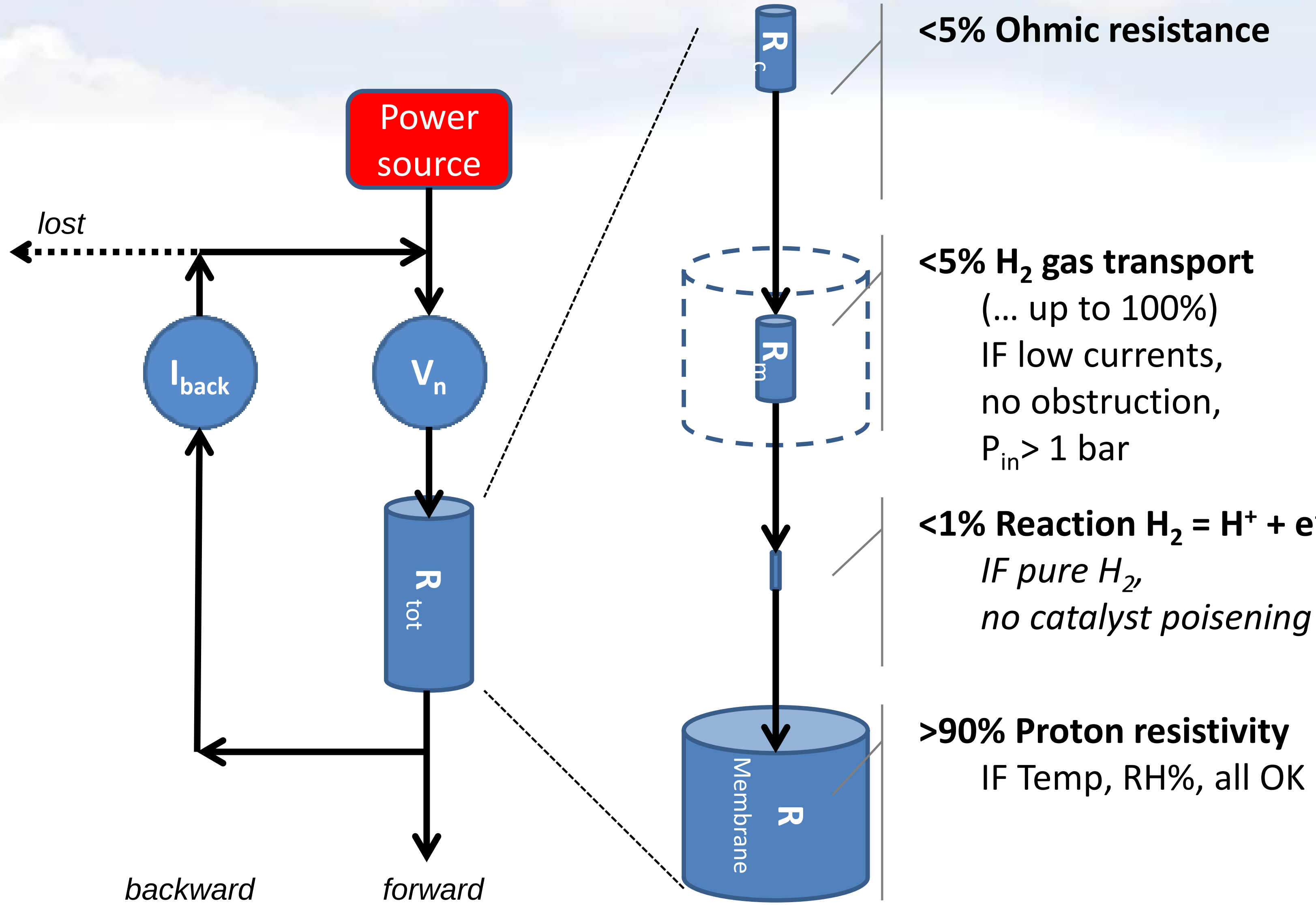
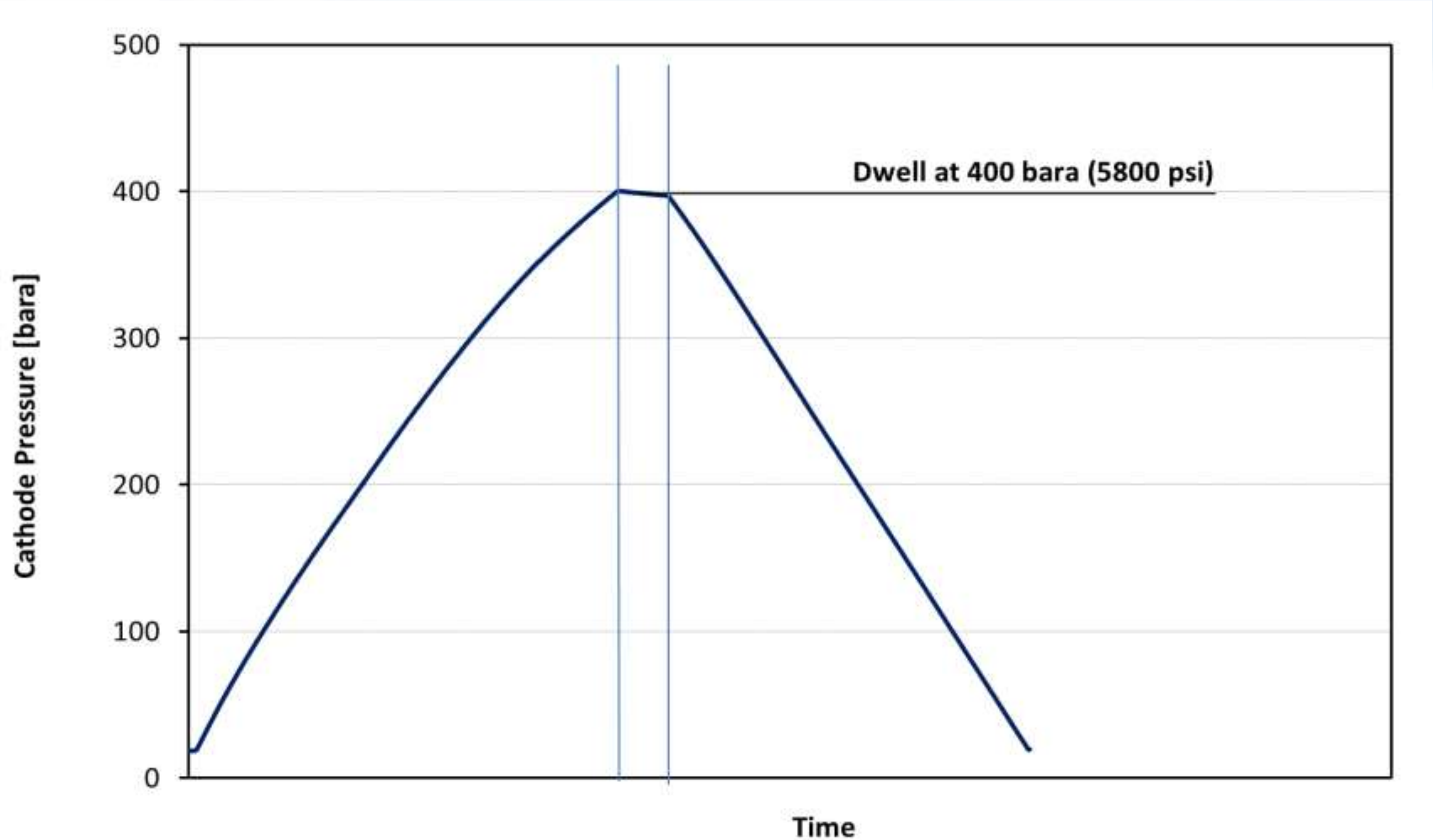
Schematic diagram



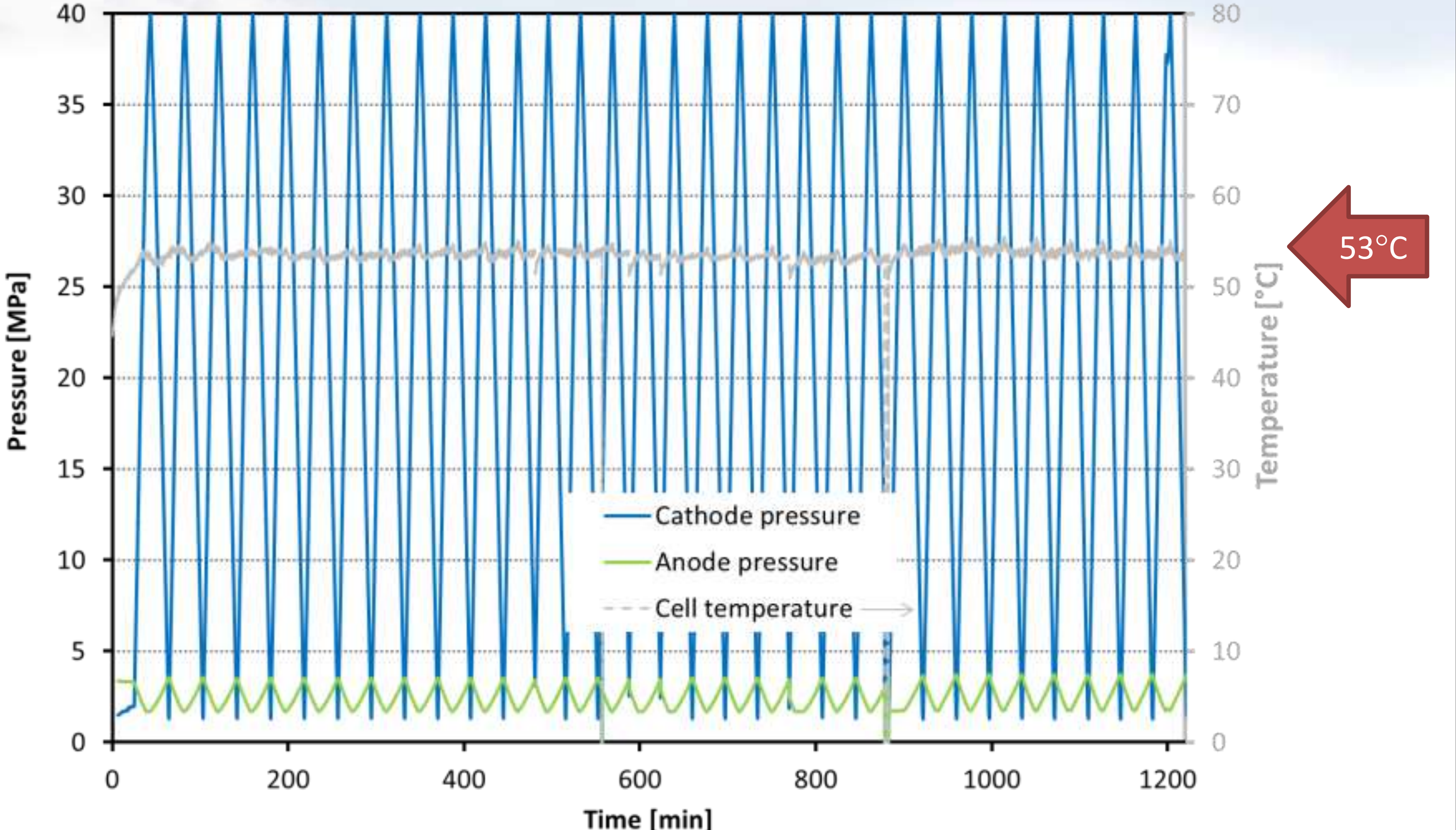
Equivalent circuit model of the process in the EHC to pump hydrogen using DC current

Compression Cycle



Potentiostatic hydrogen compression from 10 ↗ 400 bar and back from 400 ↘ 10 bar

Isothermal Compression



*Electrochemical pump need **one** single stage and have more isothermal compression*

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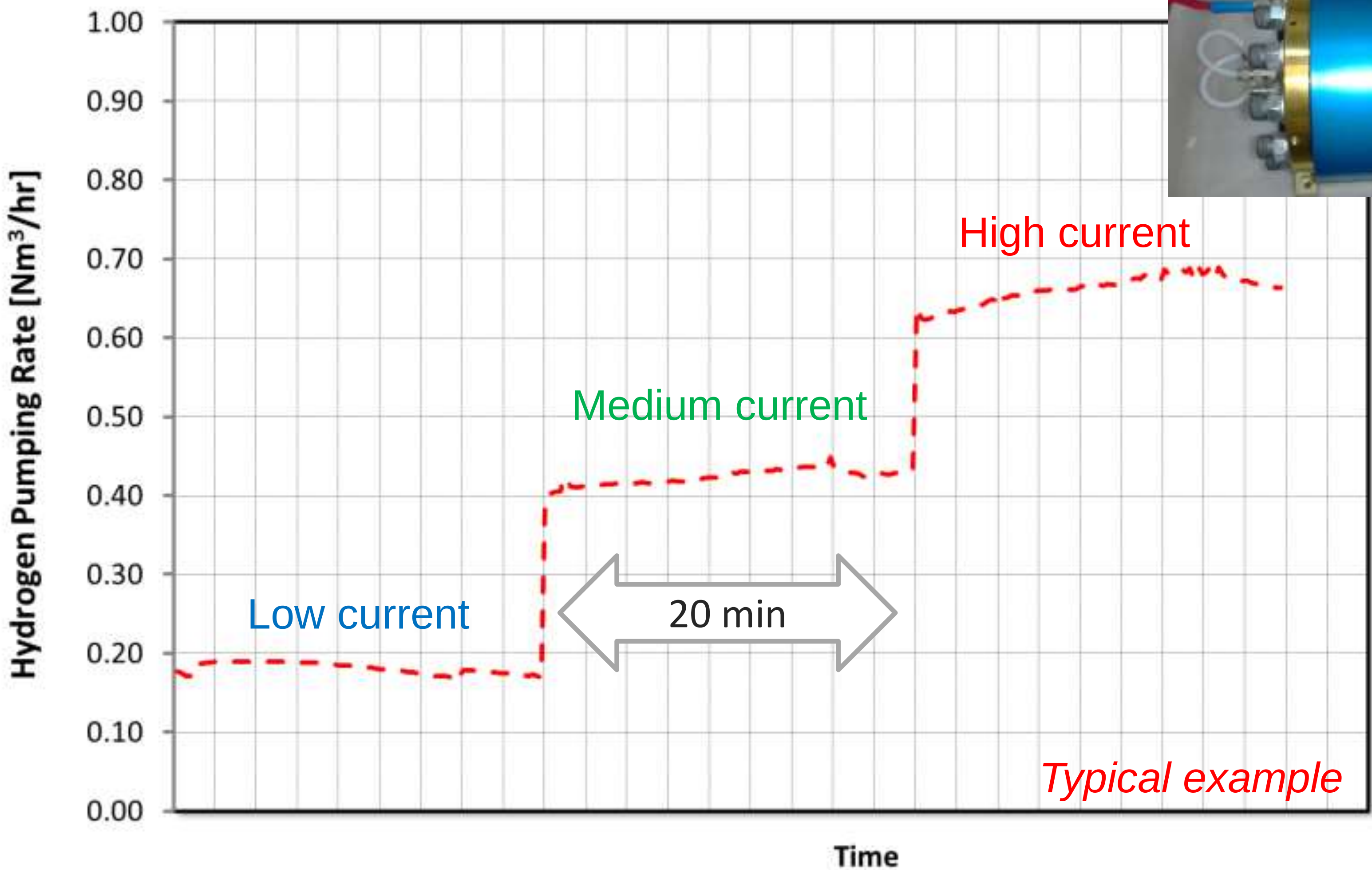
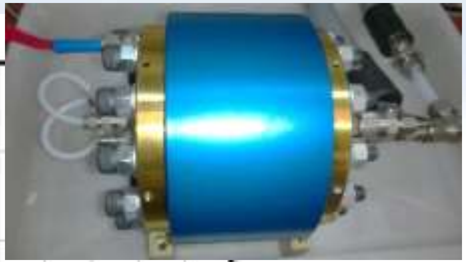
Pump rate flexibility





Variable hydrogen pumping rates feasible with one stack module

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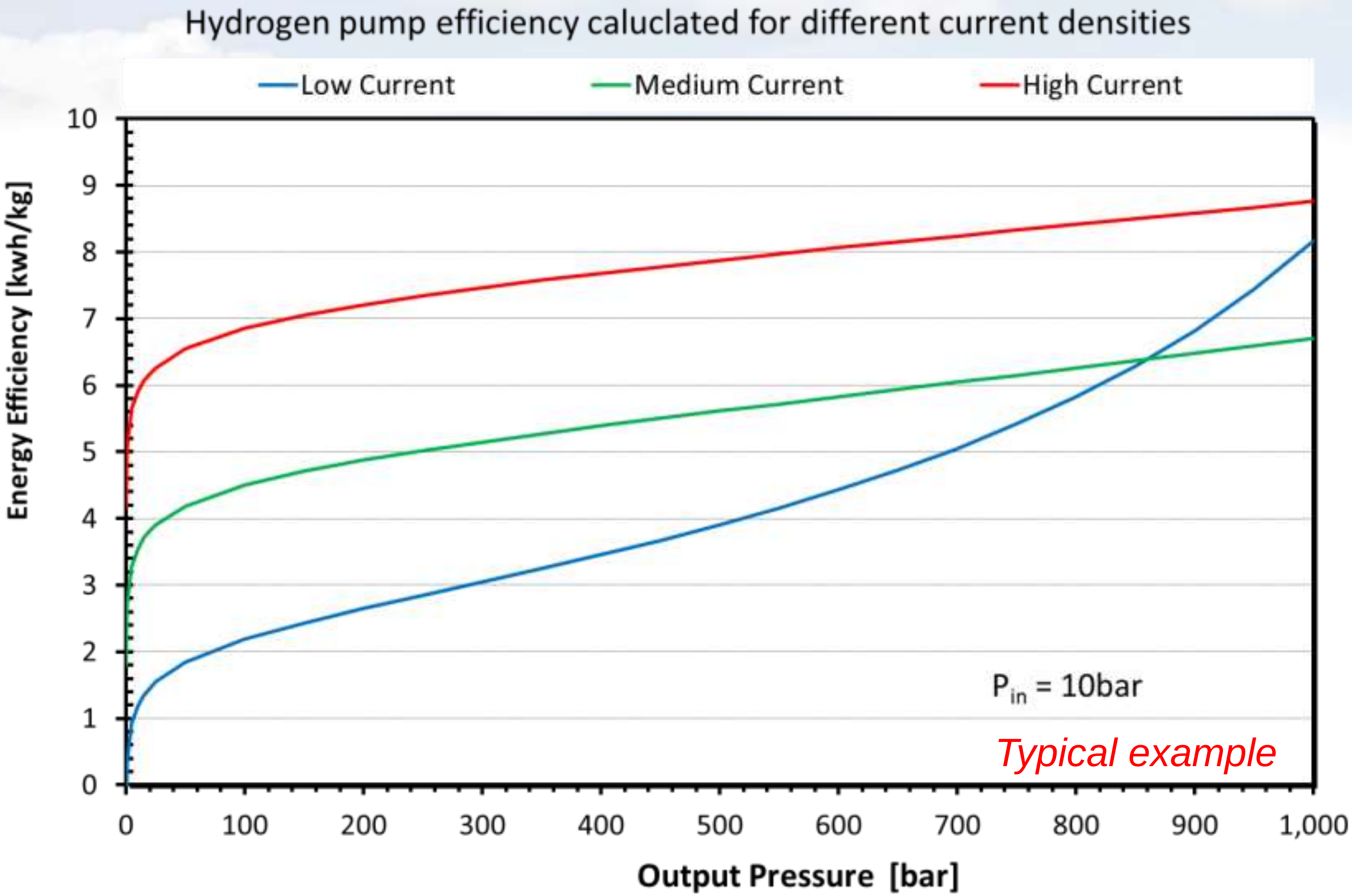
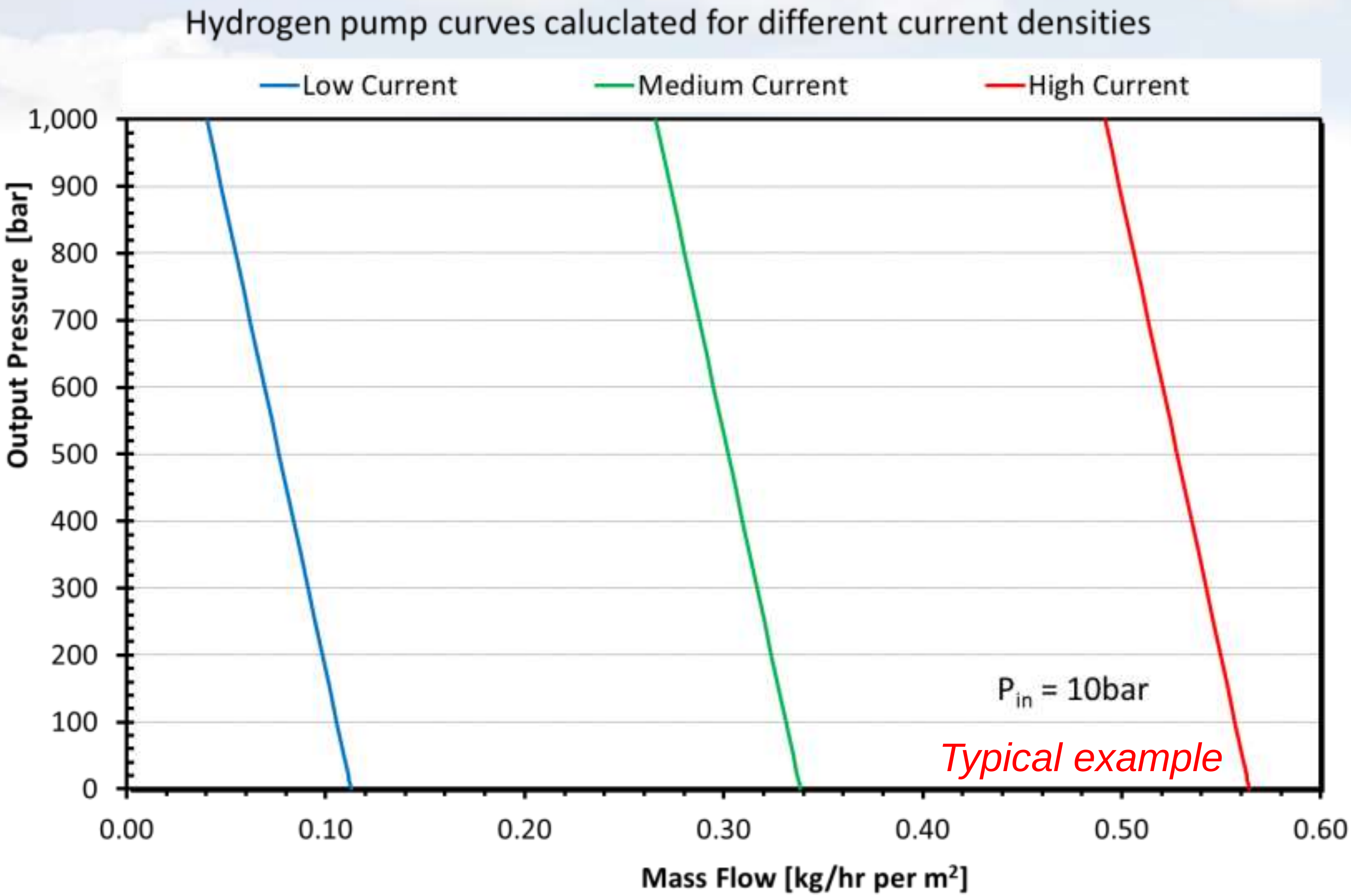
Pump energy [kWh/kg]



EHC energy requirement is a function of current density and pressure difference

EHC Pump Curves



Hydrogen pump curves plotted as a function of the current density (i.e. pump rate). Slow pumping is more energy efficient, and has little influence on pressure capability.

Total Energy Efficiency

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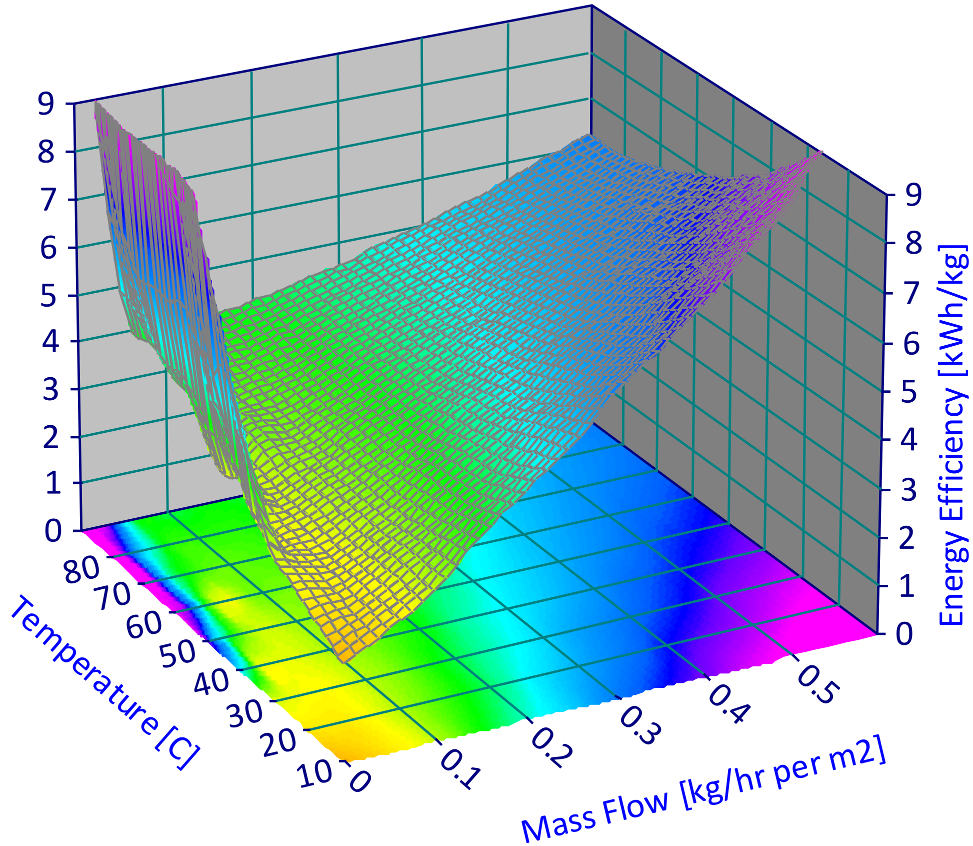
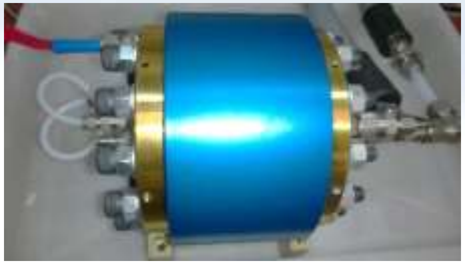
Compression Energy Efficiency 1 --> 45 MPa





IF active area = 1 m^2

10 bar anode
450 bar cathode

Energy efficiency with HyET membrane during compression from 10 → 45 MPa, plotted as a function of the Mass Flow rate (Current Density) and Cell Temperature.

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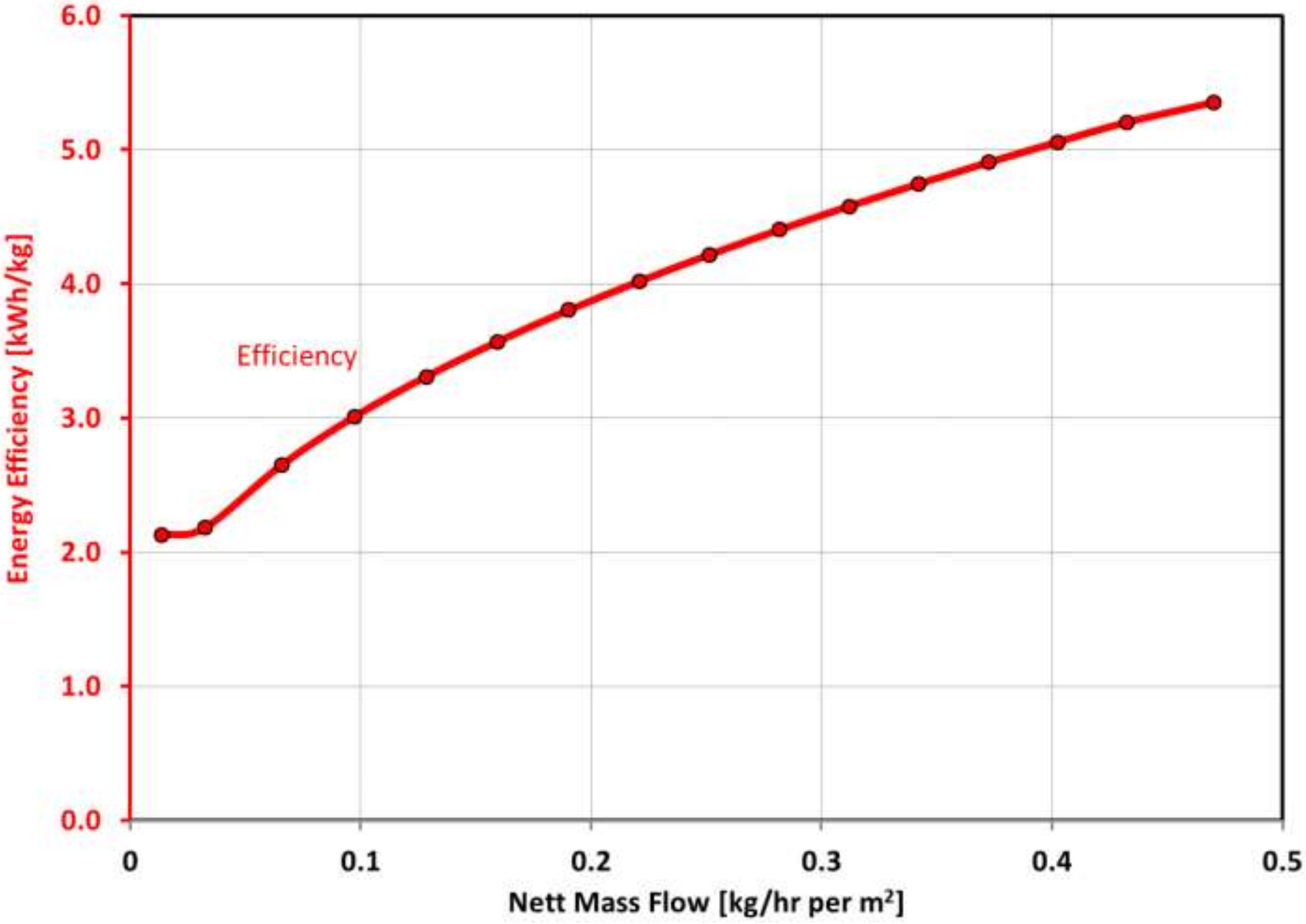
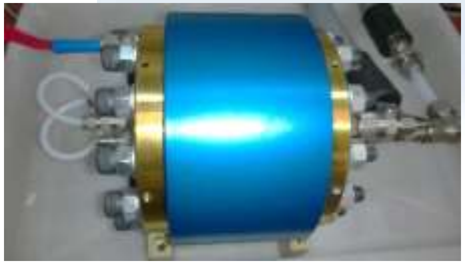
Total Energy Efficiency





IF active area = 1 m^2

10 bar anode
450 bar cathode

Energy efficiency with HyET membrane during compression from 1 → 45 MPa, plotted as a function of the Mass Flow rate (Current Density) under best conditions.

HyET Hydrogen Efficiency Technologies

Presentation Summary

HyET offers technology capable of simulteneous silent compression and selective purification of hydrogen gas

- **Purification** guarantees high quality hydrogen
- **Compression** up to 1000 bar output pressure feasible
- **Multiple sources** of hydrogen gas (mixtures) useable
- **Scalable units** enable growth with HRS market demand
- Compatible with “decentralised” Power and Smart Grid

Stand-alone 2 kg/day Electro-chemical Hydrogen Test unit **available now** for preliminary customer test trials (MoHyTO)

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The Netherlands

Pure Pressure

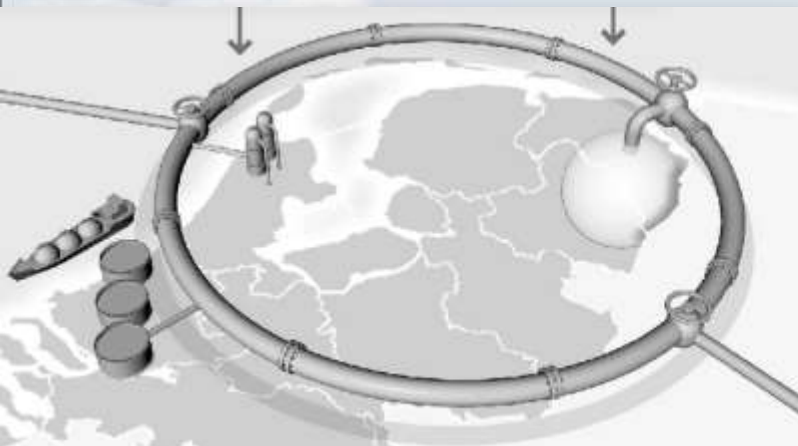
www.HyET.nl

EYA	ELA						LJA	ABO
EMU	SHR	CSO	NPO	CFA	GRO	LJO	DdG	LRA
GVI	JBL	RST	FGE	TMA	EMI	WBL	WVL	
GBI	RBU	BBA	MMU	WDA	KvE	EBI	JKO	DSE
DSW	PBO	JTO	LZW	JAK	MBO	JWI	DSI	
RSW	MJV	MKO	WKO	StH	MBE	AKO	EMI	FMU

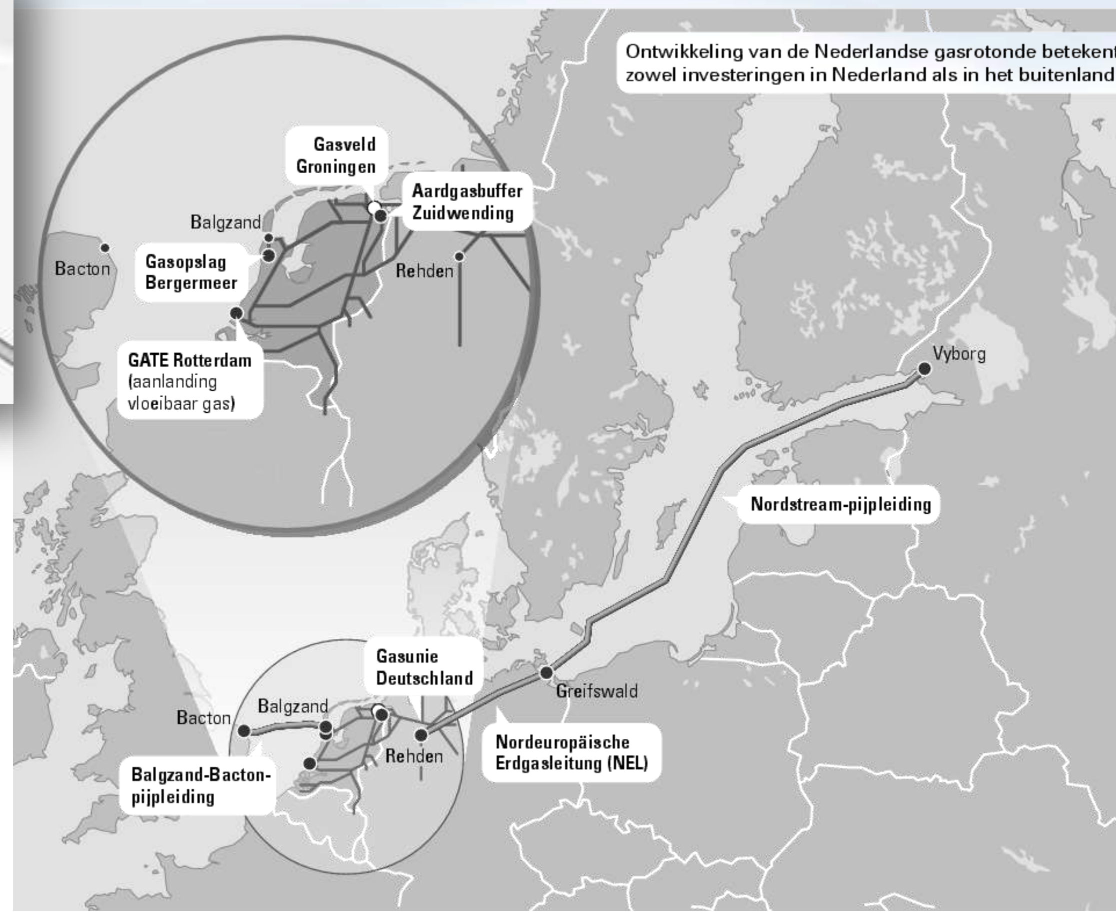
we thank everybody that contributed personally to building our foundation

Dutch Gas Roundabout

HyET Hydrogen Efficiency Technologies



Figuur 2 **Grote gasrotondeprojecten van Gasunie en EBN in binnen- en buitenland**



Source: http://www.rijksbegroting.nl/algemeen/gerefereerd/1/7/1/kst171191.html

Existing gas distribution networks serve as transportation pipelines as well as energy storage buffer

Hydrogen could play a role here…

“ Gas roundabout” infrastructure initiated to secure energy supply security