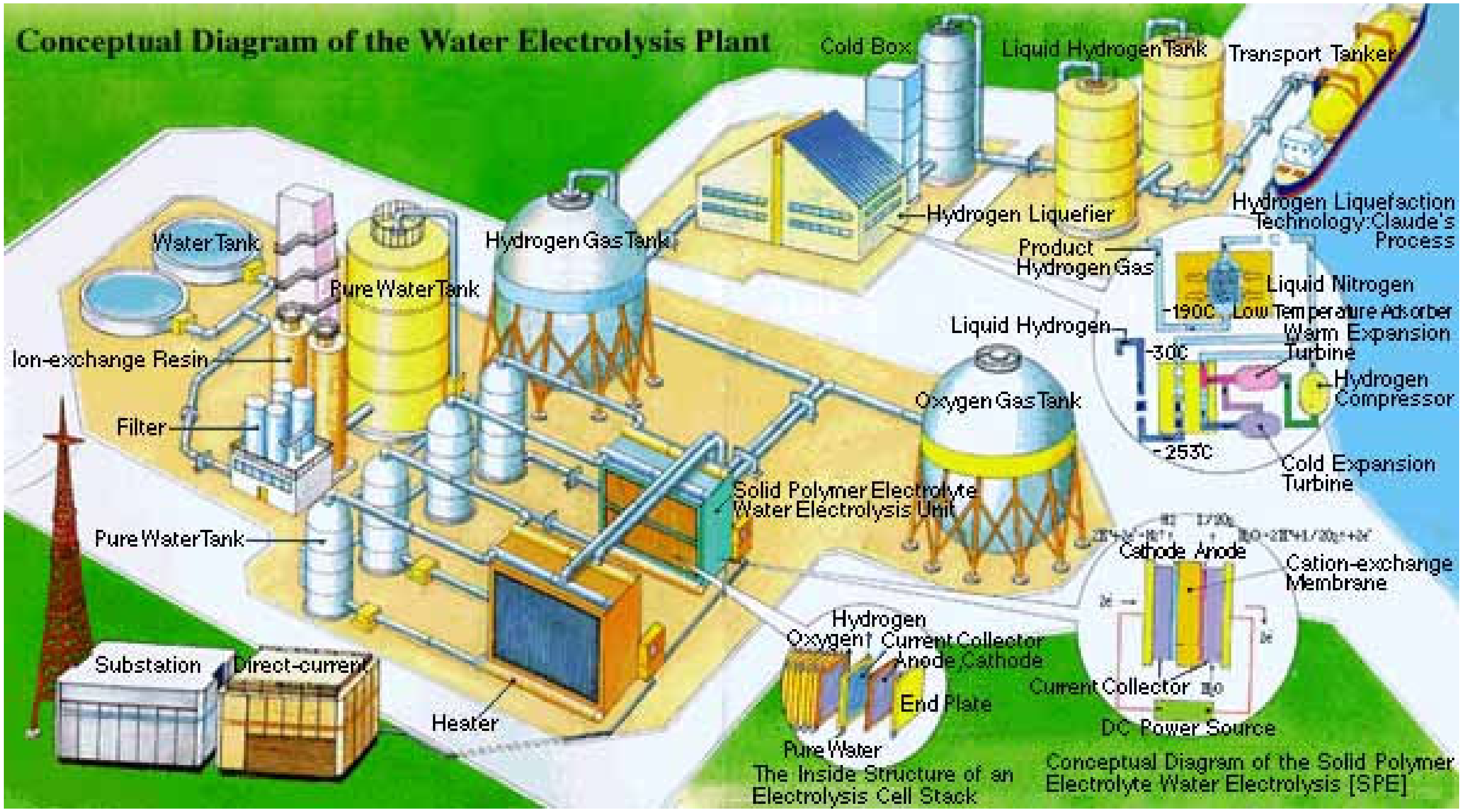
Water Electrolysis

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

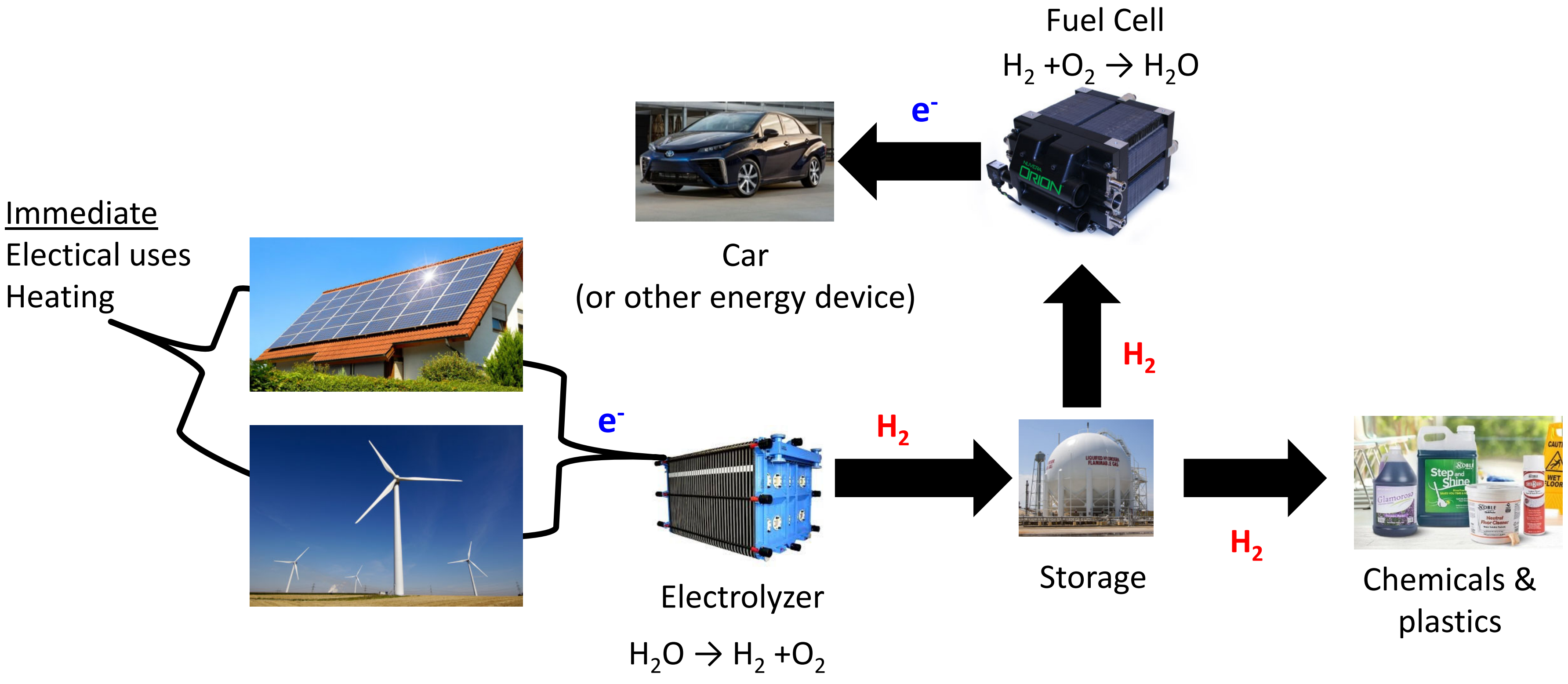


Learning Objectives

- From this lecture you should be able to understand:
  - The fundamental physics behind electrolyzers.
  - How to improve the efficiency/costs of electrolyzers.

The H_2 economy

- The issue with the hydrogen economy is how do we produce hydrogen?
  - – Currently we use fossil fuels.
- Electrochemistry can provide the solution.



Fuel Cell

$H_2 + O_2 \rightarrow H_2O$

Car

(or other energy device)

Immediate

Electical uses

Heating

Electrolyzer

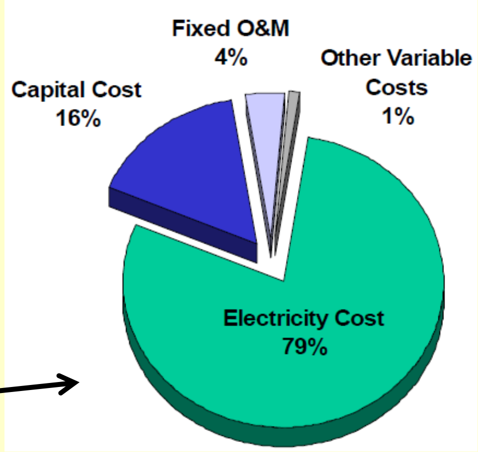
$H_2O \rightarrow H_2 + O_2$

Storage

Chemicals & plastics

Electrolyzers- economic limits

- The DOE did a sensitivity analysis with regards to electrolyzer cost.
- There are certain areas we can 'technology our way out of'.
- There are other areas we can't (directly).



NREL Electrolyzer report
(NREL/BK-6A1-46676)

- If we operate our electrolyzer only 50% of the time, what will be our effective capital costs roughly?

- Thermodynamically it takes 1.23 V to produce H_2. Thus at 0.1 €/KWh electricity, what is the minimum it would cost to produce 1 kg of H_2?

F =96485 C/mol

Remember: $\Delta E = \frac{-\Delta G}{nF}$

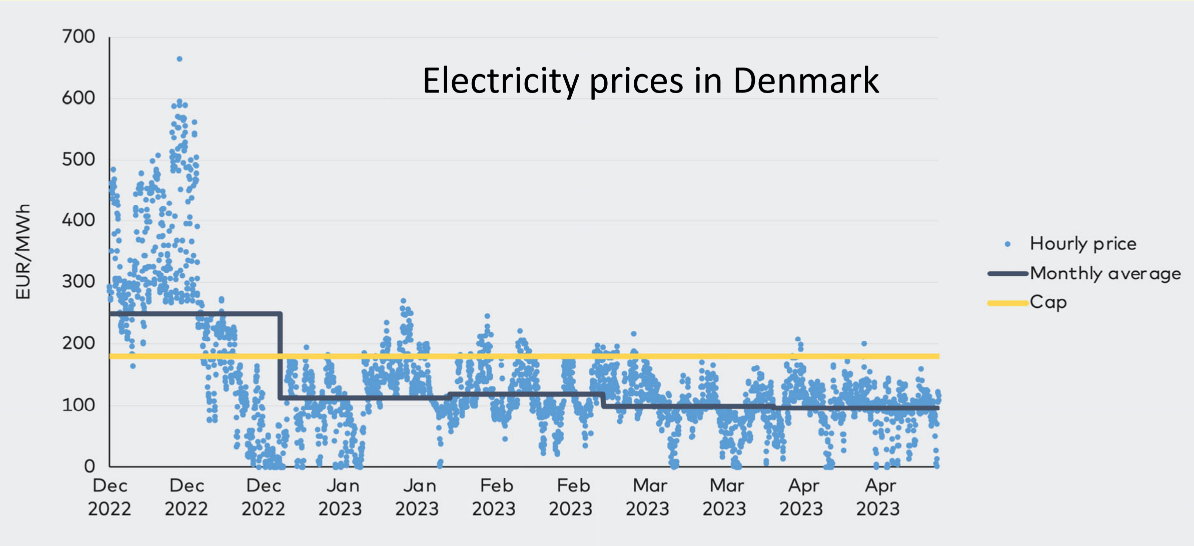
Costs of Hydrogen

- Thermodynamically it takes 1.23 V to produce H_2. Thus at 0.1 €/KWh electricity, what is the minimum it would cost to produce 1 kg of H_2.

$$\Delta G = EnF = 1.23 * 2 * 96485 = 237 \frac{kJ}{mol\ H_2} = 237 \frac{MJ}{kmol\ H_2}$$

$$237 \frac{MJ}{kmol\ H_2} * \frac{kmol\ H_2}{2kg} * \frac{0.28\ kWh}{MJ} = 33{,}2 \frac{kWh}{kg}$$

$$33{,}2 \frac{kWh}{kg} * 0{,}1 \frac{€}{kWh} = \mathbf{3{,}32} \frac{€}{kg}$$



https://pub.norden.org/nordicenergyresearch2023-04/

Electrolyzers

- Water electrolyzers only produce about 0.7% of the total H_2 with steam reformation of natural gas producing most of the rest. (IEA, as of end of 2022)
- All the H_2 the electrolyzers produce in 1 year corresponds to 79 TJ. This is enough energy storage to support the world for 4 seconds.
- Unlike fuel cells, you can keep adding voltage to get more H_2 and O_2.
  - Fuel cells run from 0.2-1.5 A/cm^2, electrolyzers run at 4-10 A/cm^2.
- There are 3 major types of electrolyzers.
  - Alkaline electrolyzers (done in a basic environment).
  - Cation Exchange Membrane (CEM) electrolyzers (done in an acidic environment).
  - Solid Oxide electrolyzers- can also work with organic/fossil fuels

Alkaline (basic) electrolyzers

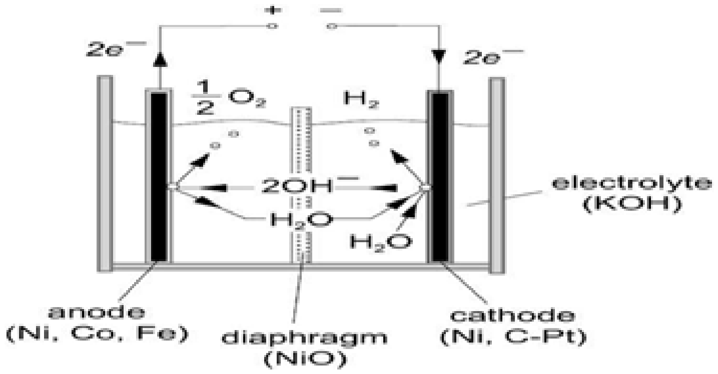
- Alkaline electrolyzers currently have the dominant market share.
- They are similar to an alkaline fuel cell, except done in reverse.

Cathode: $H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$

Overall: $H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad 1.23\ V$

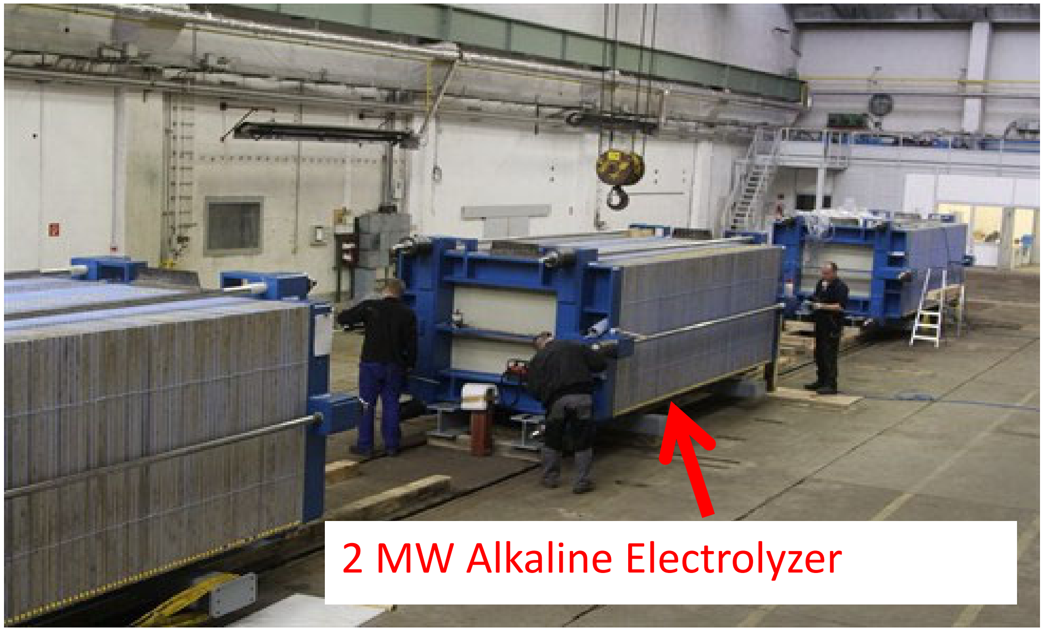
- They typically use a diaphragm rather than a membrane to keep the gases from mixing.



Alkaline electrolyzers

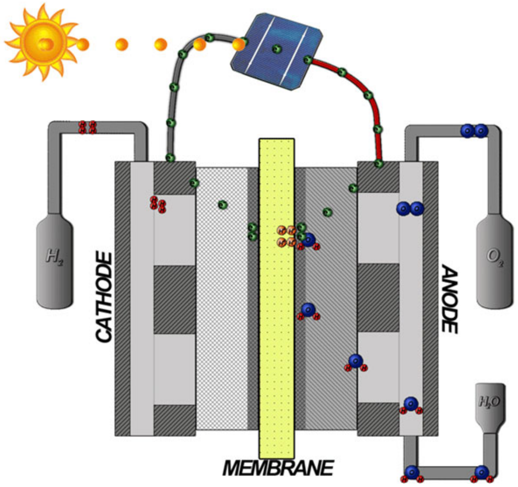
- The great thing about alkaline electrolyzers are they use cheap catalysts.
- Their major disadvantage is inefficient ionic conductivities / gas crossover.
- The alkaline electrolyte can easily cause corrosion as well.

- Electrolyzer cells are stacked just like fuel cells.
- Each device to the right produces roughly 33 kg/hr of H_2.



CEM electrolyzers

- The newer approach to electrolyzers is to basically run a cation exchange membrane fuel cell in reverse.
- The key advantage is that the efficiencies can be higher especially at high current densities.
- This is due to ionic conductivity advantages of a CEM
- The major issue with these is the best catalysts are noble metals.



Anode: $H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$

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

Overall: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$

Competing Technologies

🟩 Advantages 🟥 Disadvantages

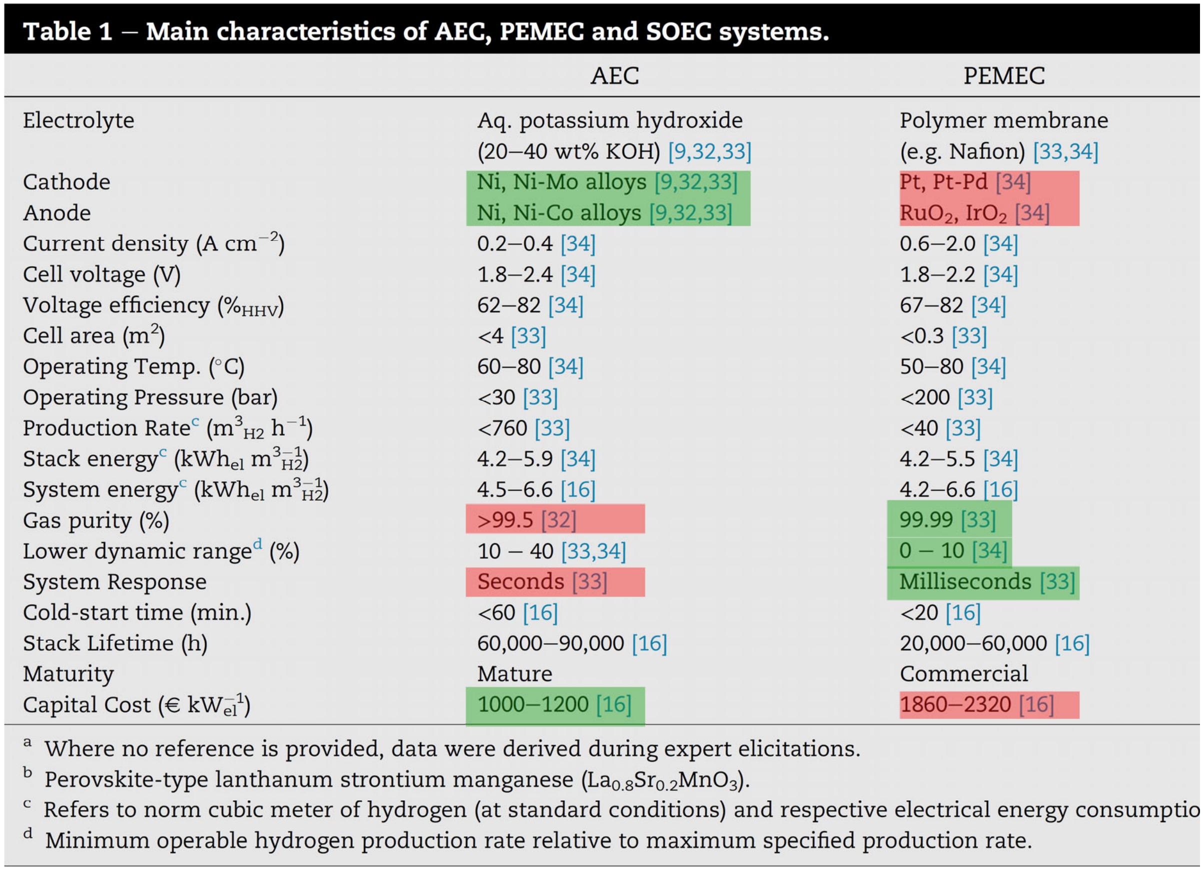


Table 1 — Main characteristics of AEC, PEMEC and SOEC systems.

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

[d] Minimum operable hydrogen production rate relative to maximum specified production rate.

Schmidt et al., 2017 Int, Jn. of Hyd. Energy, 42, 30470-30492

Why acidic or basic electrolyzers

- All electrolyzers (and fuel cell cells) need to minimize ionic conductivity losses.
- H^+ is the most conductive ion, and OH^- is the 2nd most conductive.
- If we try things at neutral pH, the ionic conductivity losses dominate.

$$V = i \times R_{Cond}$$

- Many researchers brag about electrolyzer catalysts that work at pH=7. *Who cares?*

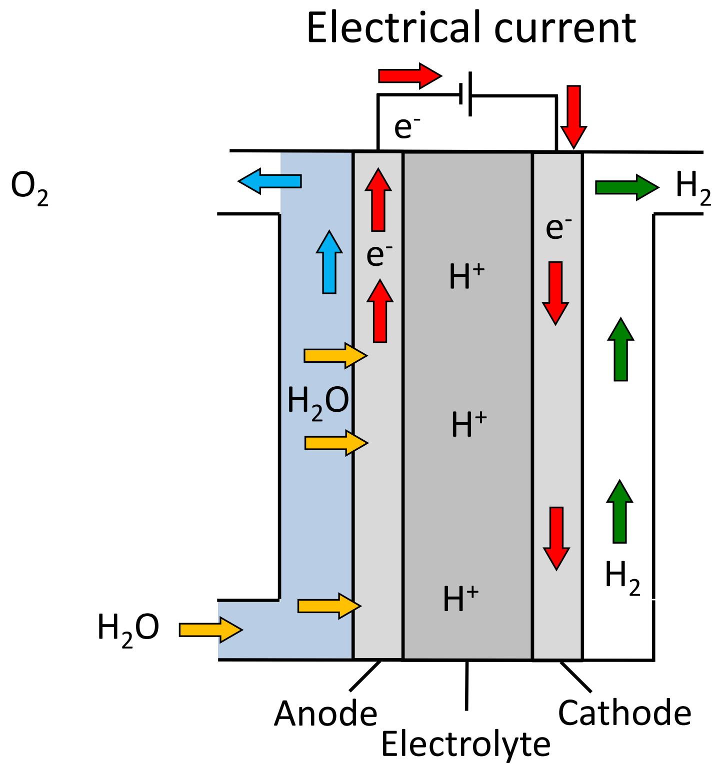
Cations	λ_+^0 mS m^{2}mol^{-1}	Anions	λ_-^0 mS m^{2}mol^{-1}
H^+	34.96	OH^-	19.91
Li^+	3.869	Cl^-	7.634
Na^+	5.011	Br^-	7.84
Mg^{2+}	10.612	SO_4^{2-}	15.96
Ca^{2+}	11.900	NO_3^-	7.14

Ionic conductivities (from wikipedia)

CEM Electrolyzer

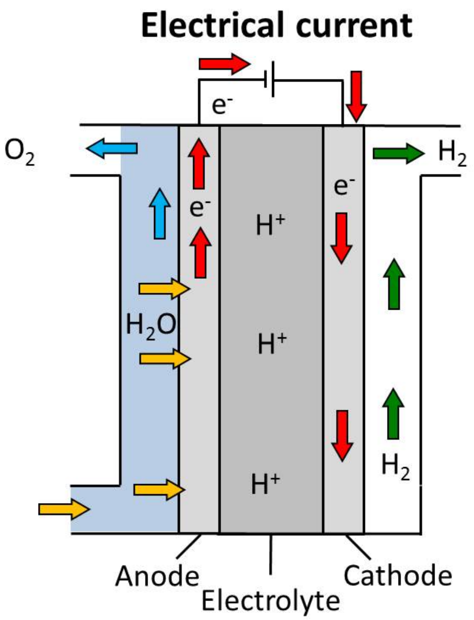
Places for potential energy loss

- Proton transfer
- Electron transfer
- Anode
- Cathode

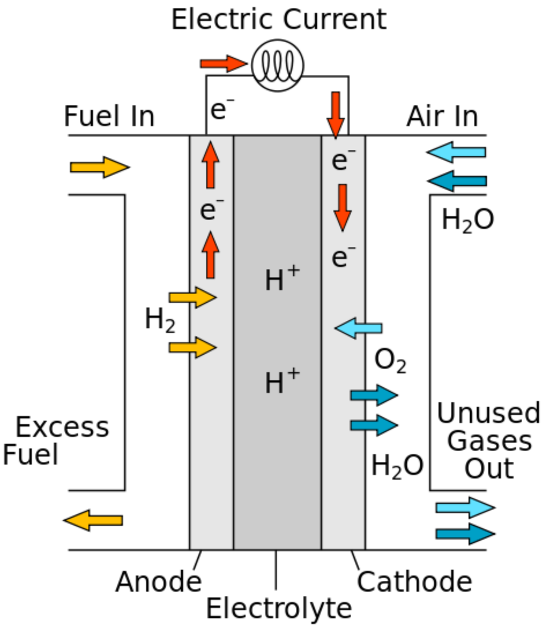


Proton transfer

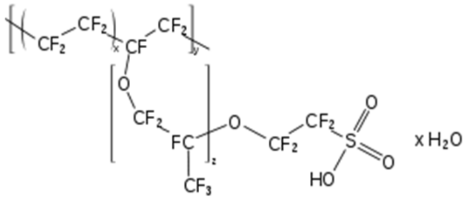
- This is just like fuel cells, but in reverse.
- In this field Nafion is also the best cation exchange membrane.

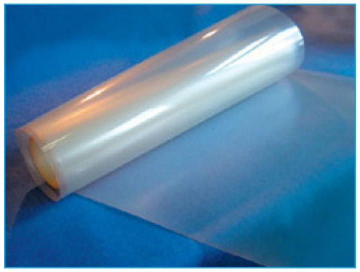


Electrolyzer



Fuel Cell

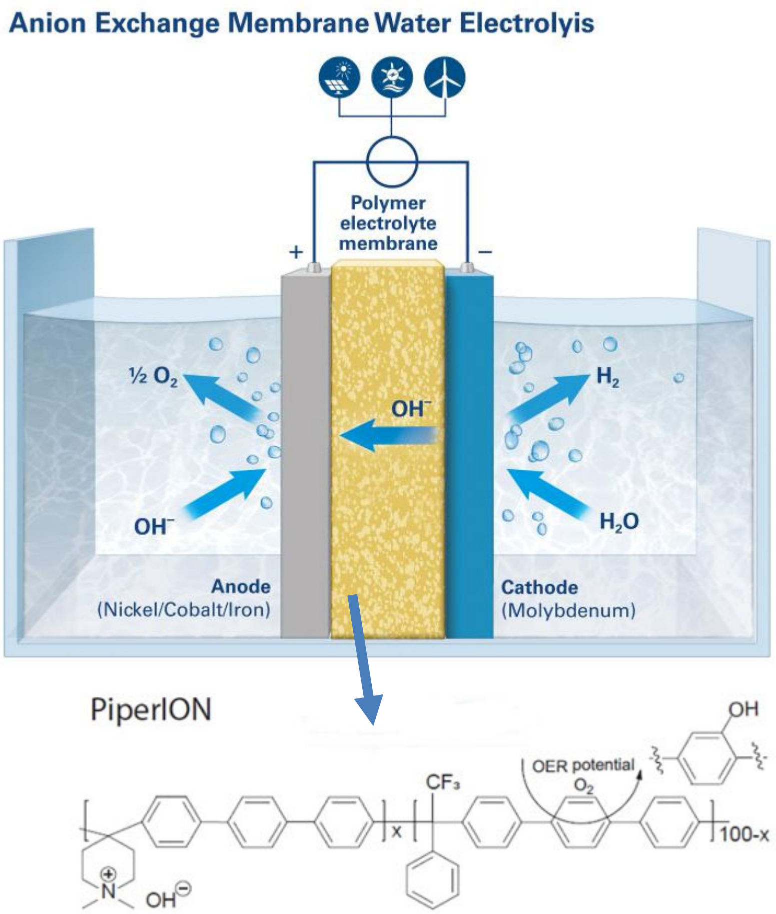




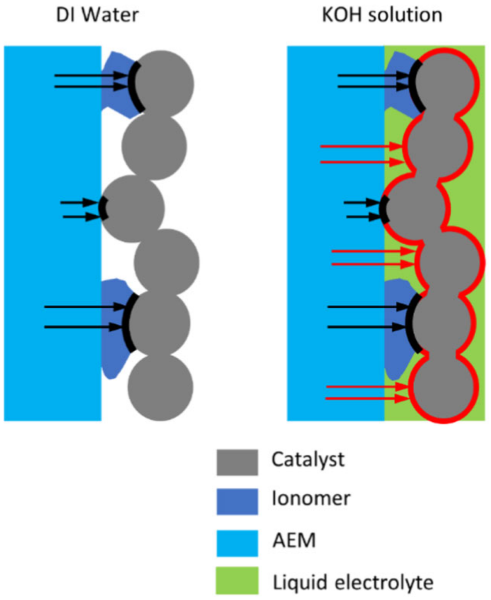
Nafion

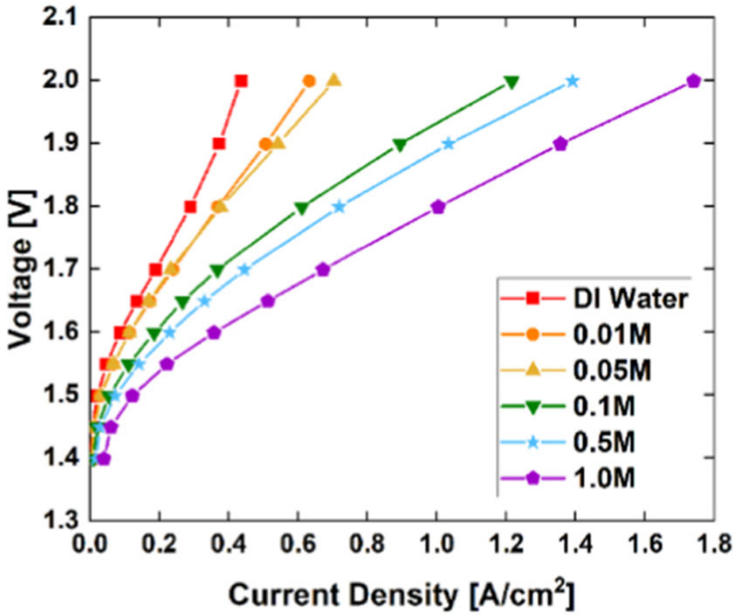
Anion exchange membrane electrolyzers

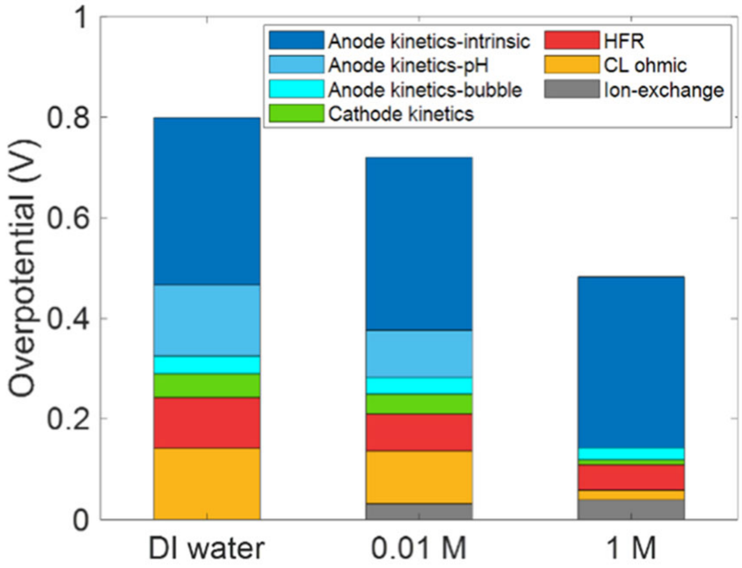
- It runs an anion exchange membrane, OH^- as transfer medium
- Advantage of CEM to apply at large current, high pure and pressure hydrogen;
- Advantage of AEM to use the low-cost catalysts;
- Disadvantage is durability.



Performance vs. electrolyte





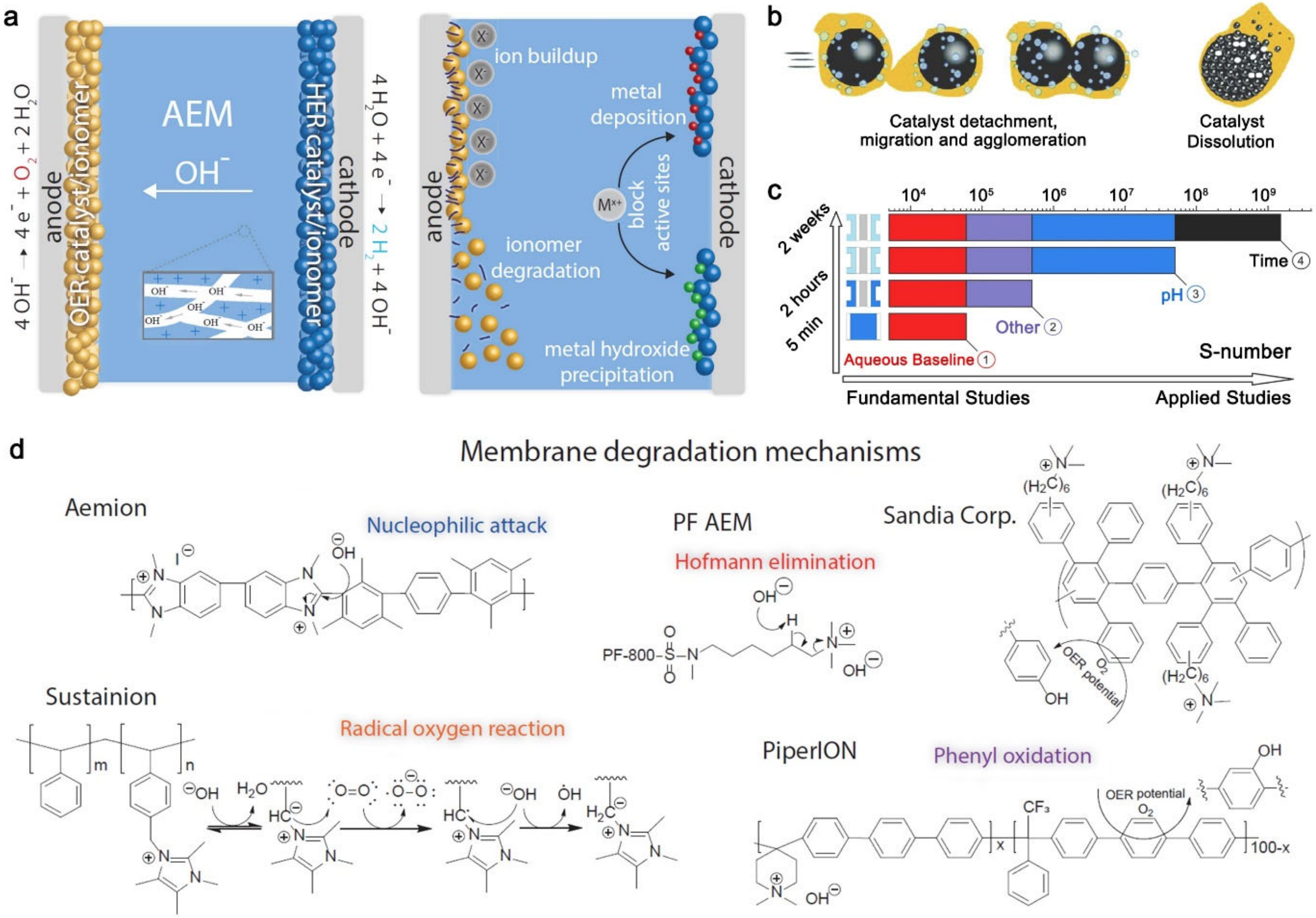


Very rough approximation

- Anode/cathode kinetics-pH and CL ohmic changes the most by the electrolyte.

2021 J. Electrochem. Soc. 168 054522

Degradation in AEM electrolyzer



EnergyChem 2022, 4, 100087.

Concept Check

Which of these ions can be transported through a cation exchange membrane

a) Na^+

b) CO_3^{2-}

c) $SO_4{}^{2-}$

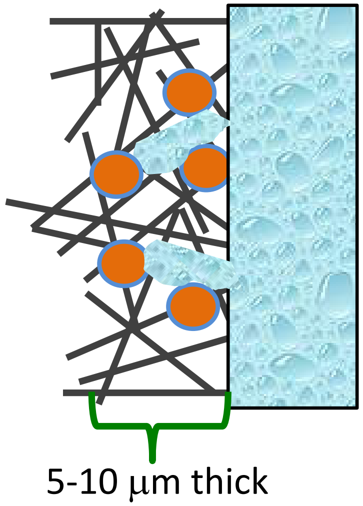
d) Fe^{2+}

Triple phase boundary

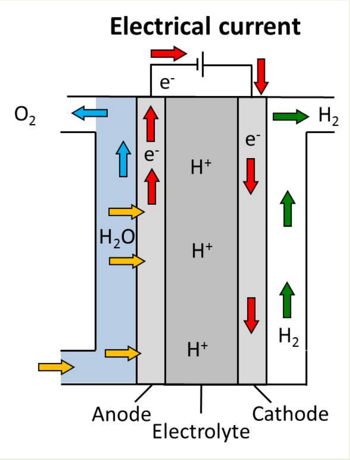
- In the fuel cell maximizing the triple phase boundary was extremely important.

- In electrolyzers the electrolyte the aqueous solutions works as a quasi-proton transfer medium.
- However these devices run in pure water rather than an acidic environment to prevent corrosion.

- It is still important to spread out the catalysts for minimizing gas transport issues due to bubble formation.

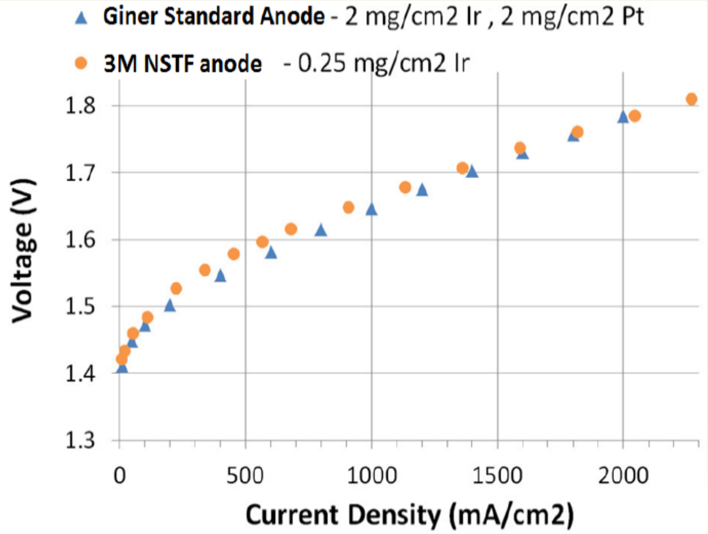


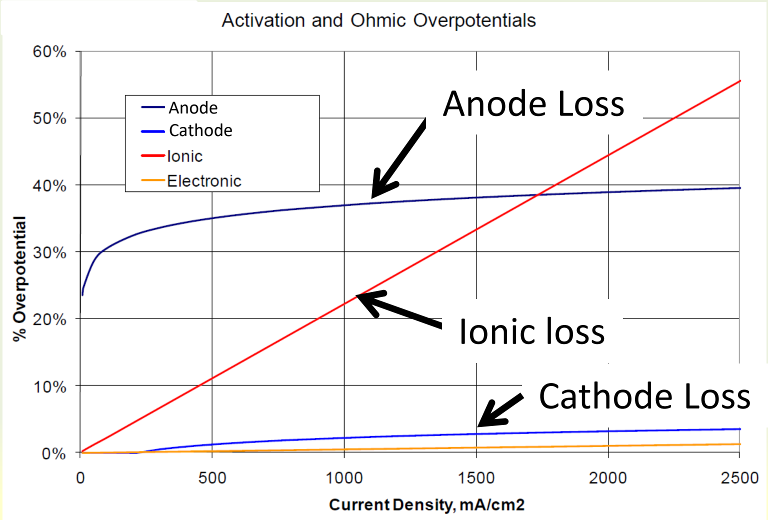
Efficiency



Places for potential energy loss

- Proton transfer
- Electron transfer
- Anode
- Cathode



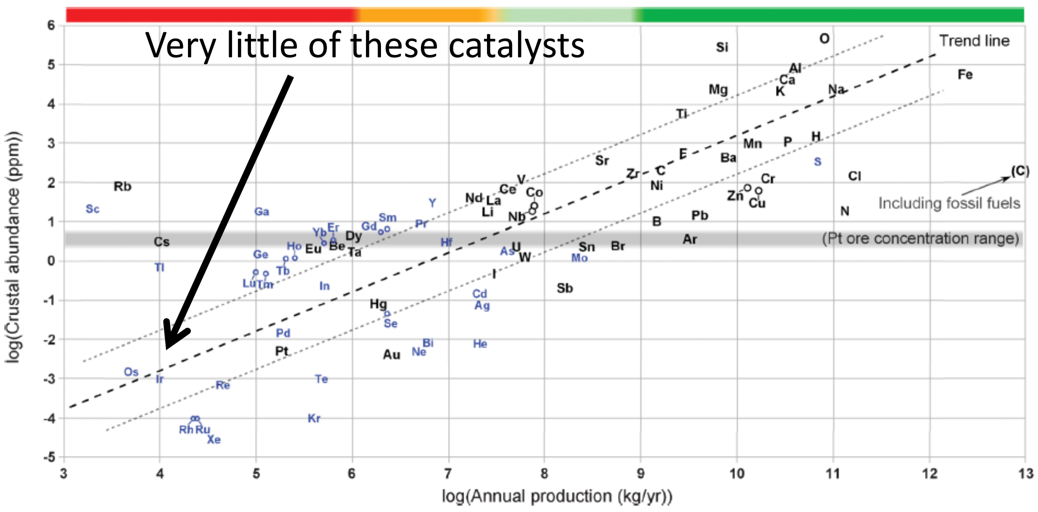


Proton On-site data

- Discuss why the anode and ionic losses look the way they do.

Scalable catalysts

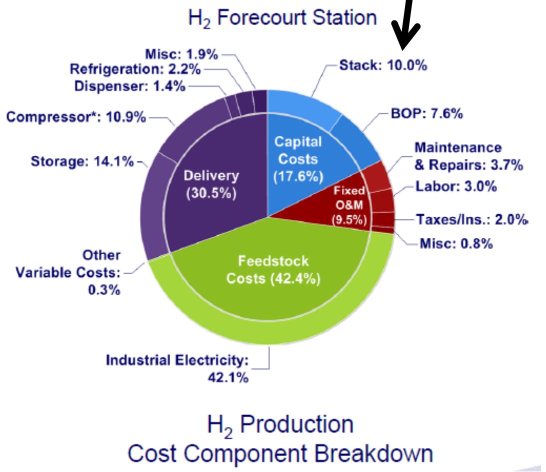
- As of 2020 electrolyzer’s small market share allow them to use large amount of noble metals. This is probably not scalable.
- Much of the issues are engineering issues.
- However the catalysis is still a fundamental science issue.



Very little of these catalysts

Vesborg and Jaramillo, RSC Advances, 2013

~10% of this is catalysis
(1% total as of 2014)



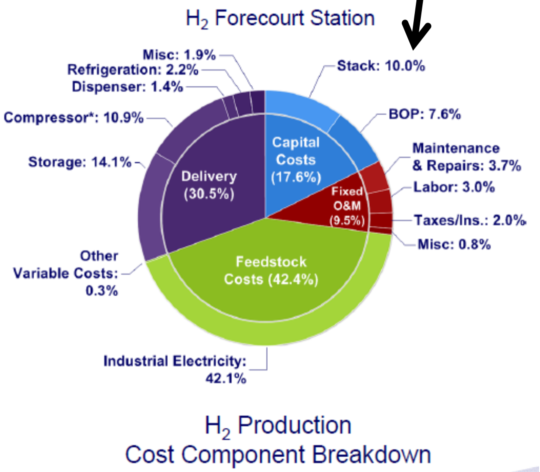
Giner: Presented at Hannover Messe **2014**, April 7-11

Scalable catalysts

- We are starting to see the issues with Ir though as PEM electrolyzers scale up

2014

~10% of this is catalysis
(1% total)



1% from Iridum is now 3-4%

As electricity and other capital cost decreases, Ir increases

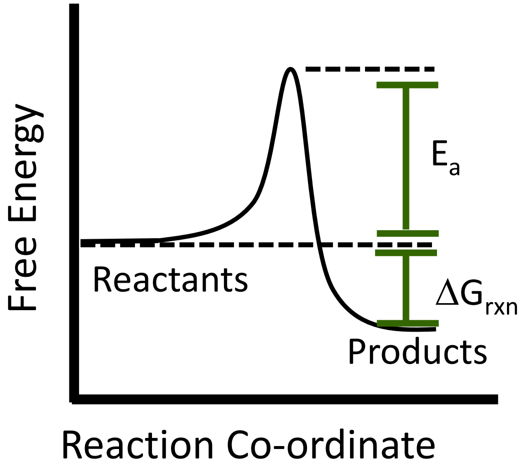
2024

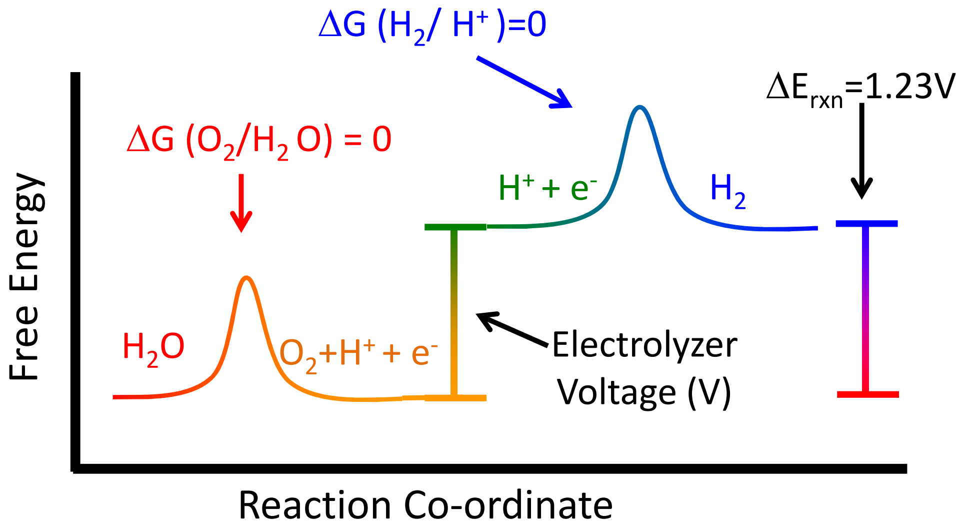
Anode and cathode

- We can use a similar approach as the fuel cells to understand the electrolyzer reactions.

Anode: $H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$

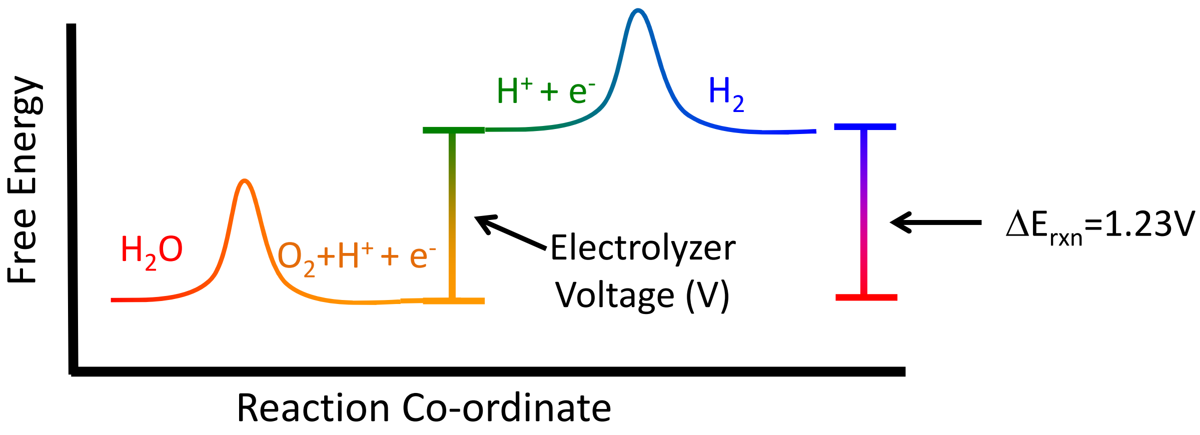
Cathode: $2H^+ + 2e^- \rightarrow H_2$

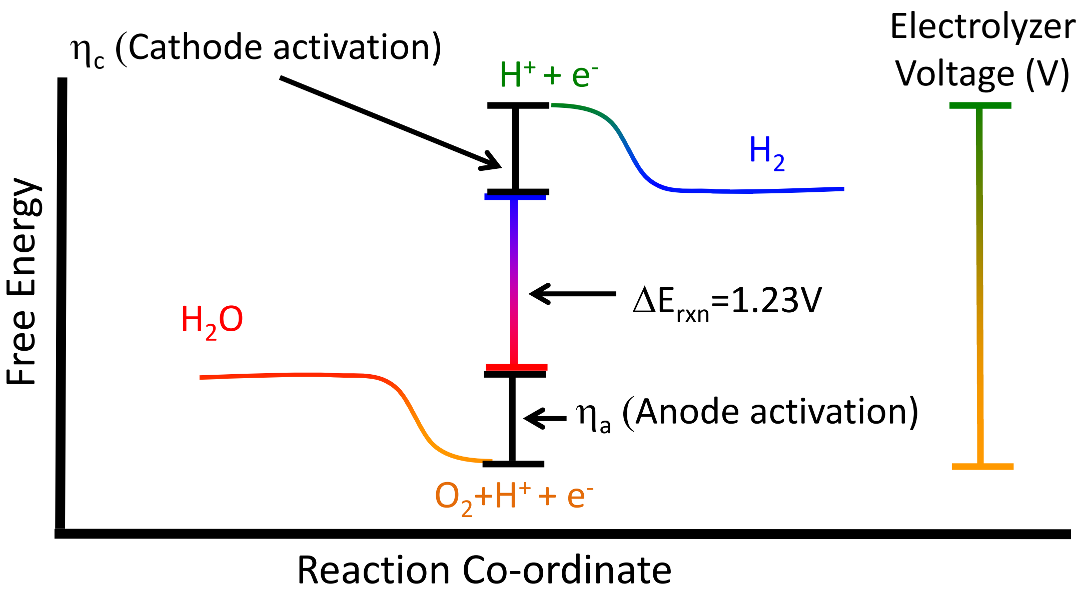




Heterogeneous Catalysis

Electrochemical Catalysis


Free Energy
H_2O
O_2+H^+ + e^-
H^+ + e^-
H_2
Electrolyzer Voltage (V)
ΔE_{rxn}=1.23V
Reaction Co-ordinate

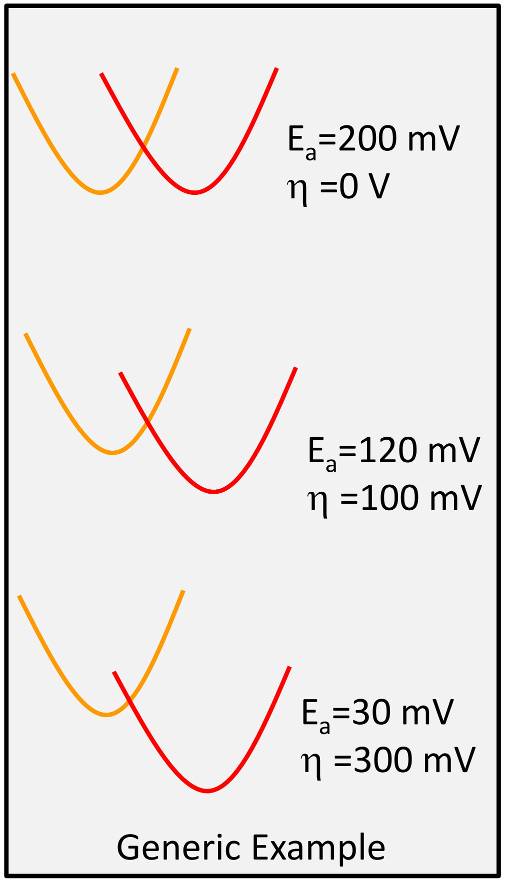

η_c (Cathode activation)
Electrolyzer Voltage (V)
H^+ + e^-
H_2
Free Energy
H_2O
ΔE_{rxn}=1.23V
η_a (Anode activation)
O_2+H^+ + e^-
Reaction Co-ordinate

Quantifying losses

- As you increase the voltage drop (η) you decrease the catalytic barrier.
- Again, the Tafel equation is used

$$i = i_0 exp^{\frac{\eta}{A}} \quad \text{or} \quad \eta = ALn\left(\frac{i}{i_0}\right)$$

i is the current (mA/cm^2)
i_0 is the current exchange density (mA/cm^2)
η is the overpotential (i.e. voltage drop) (V)
A is the Tafel slope



Generic Example

Catalysis

- Both the anode and cathode follow the same electrochemistry principles as the fuel cell.
- The hydrogen reaction is the easiest to understand, so we will start there first.

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2$$

- Platinum is good, but expensive.
- Can we find an alternative that is just as good, but much cheaper.
- Why is platinum a good catalyst?

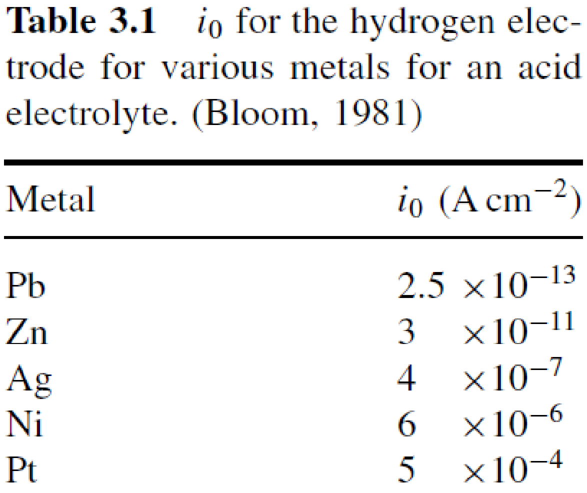


Table 3.1 i_0 for the hydrogen electrode for various metals for an acid electrolyte. (Bloom, 1981)

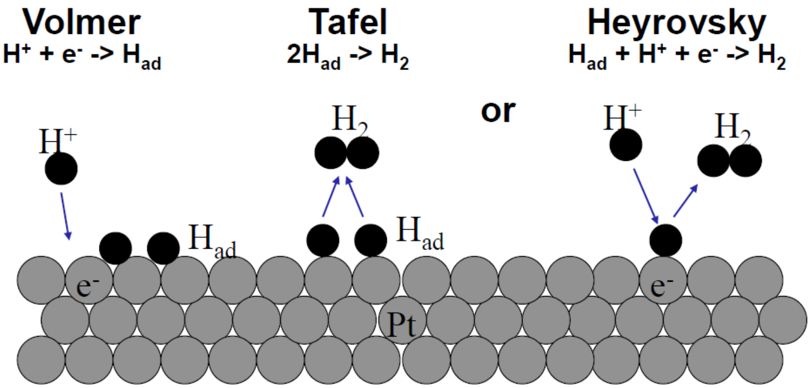
Metal	i_0 (A cm^{-2})
Pb	2.5×10^{-13}
Zn	3×10^{-11}
Ag	4×10^{-7}
Ni	6×10^{-6}
Pt	5×10^{-4}

Wrong, underestimated

Designing good catalysts

- Pt for H_2 evolution is almost the perfect catalyst, but why?
- First we need to understand the intermediates.

- Overall reaction: $2H^{+}+2e^{-} \rightarrow H_2$



- Either the Tafel or the Herovsky mechanism occurs depending on H surface coverage.
  - Lower surface coverage of H favors Tafel mechanism (i.e. H-H coupling)

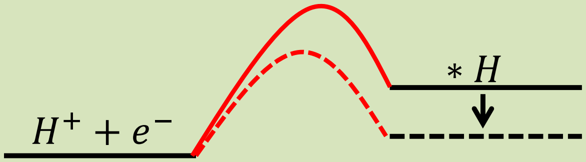
Volcano plot

- Volmer-Heyrovsky mechanism:

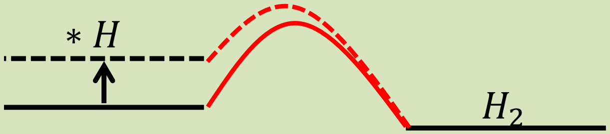
$$H^+ + e^- \rightarrow * H \qquad \text{(Volmer)}$$

$$* H + H^+ + e^- \rightarrow H_2 \qquad \text{(Heyrovsky)}$$

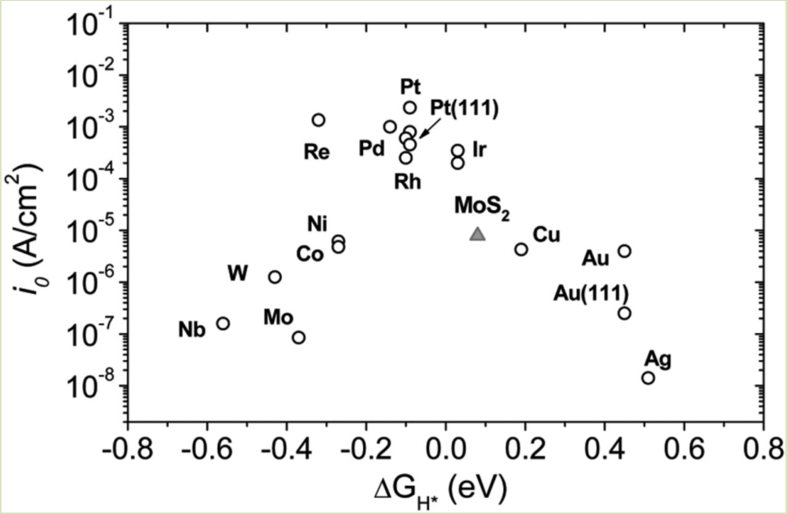
- If Volmer step is Rate-limiting step, a lower energy barrier requires a stronger H adsorption



- If Heyrovsky step is Rate-limiting step, a lower energy barrier requires a weaker H adsorption



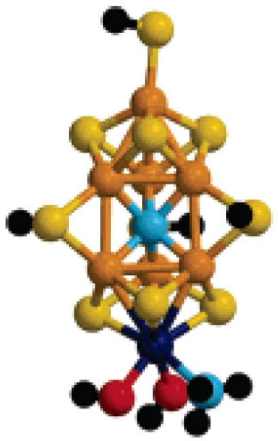
Sabatier's principle: the interaction between the reactant/intermediate should have a moderate binding, neither too strong nor too weak.



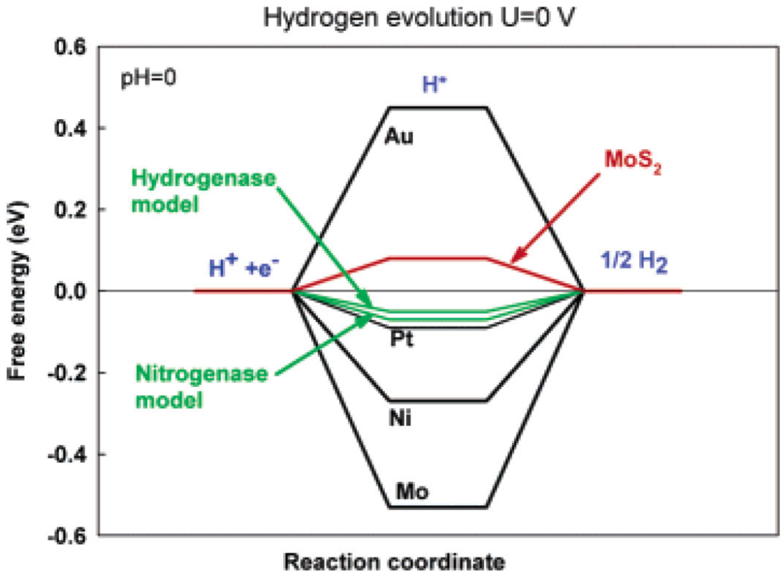
[Nørskov, J. K., et al. J. Electrochem. Soc. (2005)]

How nature resolves this issue

- The nitrogenase enzyme produces hydrogen and doesn’t use noble metals.
- Ib Chorkendorff, Jens Nørskov, and Tom Jaramillo realized that MoS_2 was pretty similar.

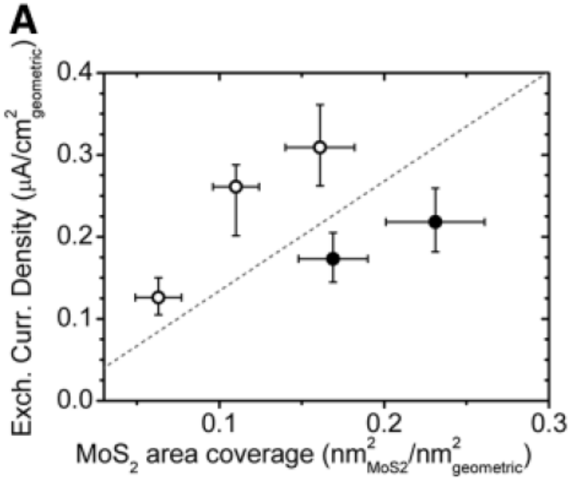


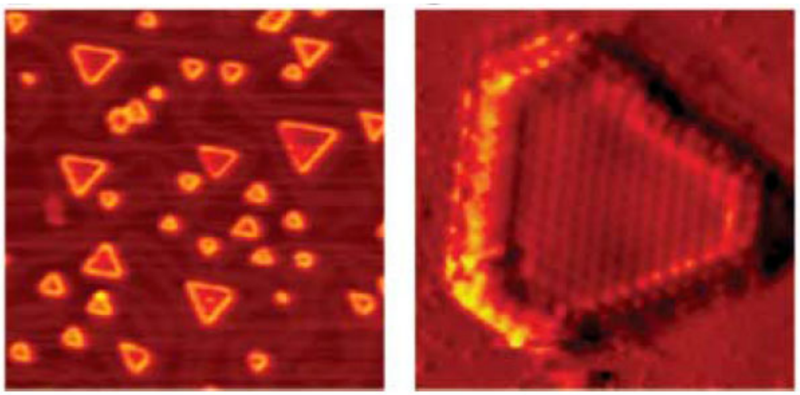
nitrogenase
active site



MoS_2

- The current exchange density was about the same as Ni (100x worse than Pt), but was stable in acid.
- Interestingly, it was only the edges that were active. The bulk was in-active.



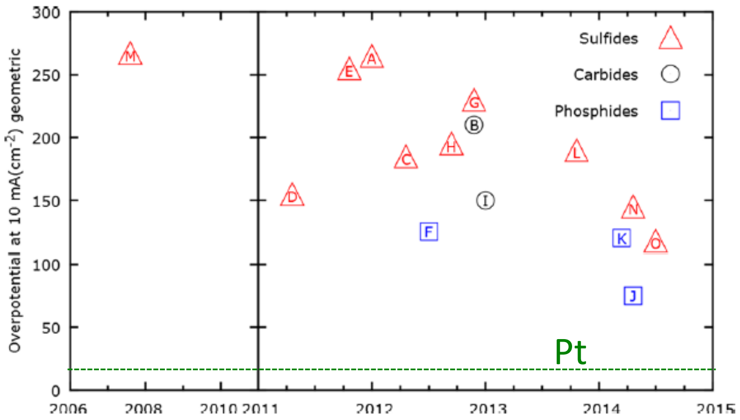


Microscopy images of MoS_2

Figures from Jaramillo, et al., Science, 2007

Progression over time

- The scientific community has slowly optimized this catalysis.
- Using a ‘follow nature’ approach phosphides such as MoS_2, CoP, NiP, and FeP all have been shown to be quite effective.
- Pt is so good though, we need such a small amount, it is actually scalable to the TW scale.



Vesborg, et al., JPC-L, 2015

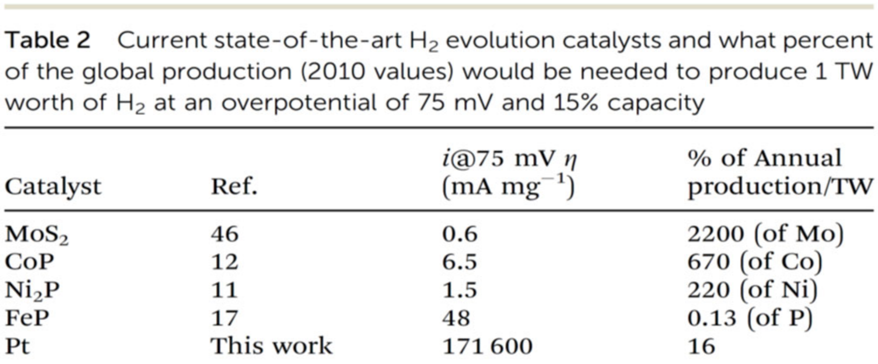


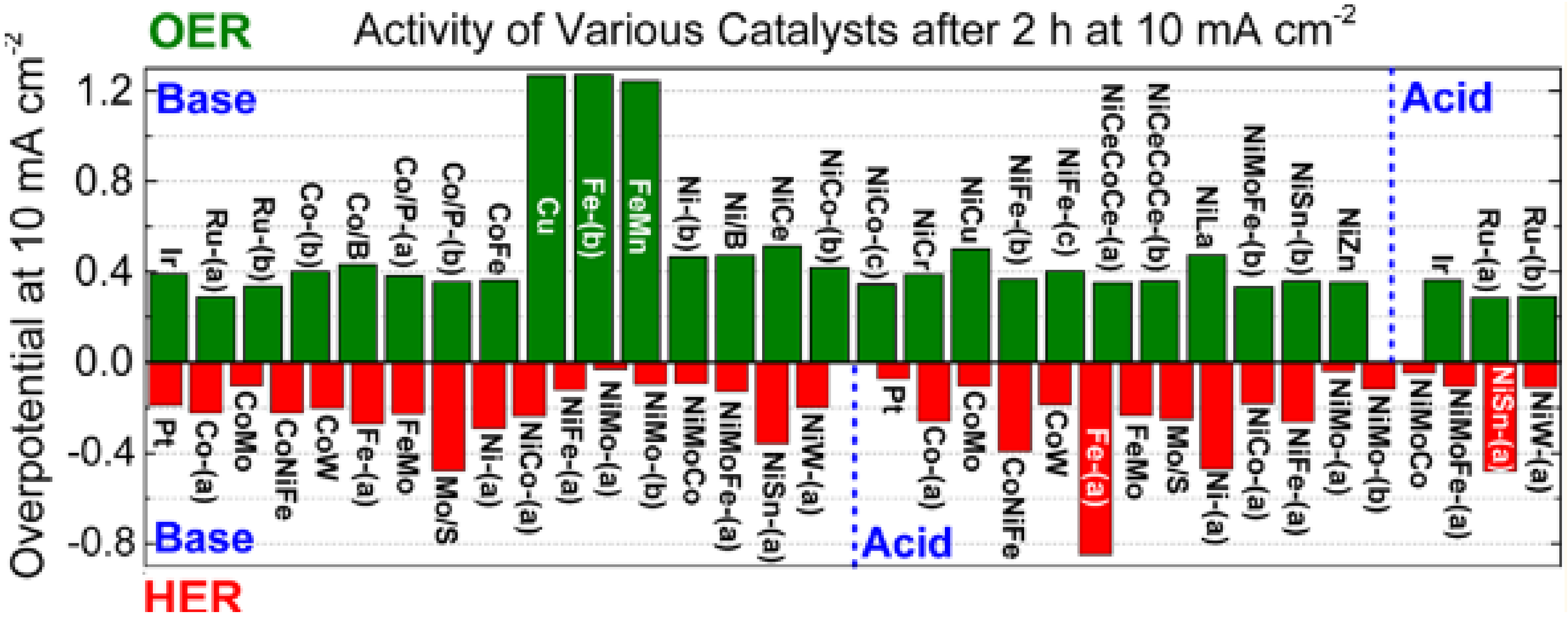
Table 2 Current state-of-the-art H_2 evolution catalysts and what percent of the global production (2010 values) would be needed to produce 1 TW worth of H_2 at an overpotential of 75 mV and 15% capacity

Catalyst	Ref.	i@75 mV η (mA mg^{-1})	% of Annual production/TW
MoS_2	46	0.6	2200 (of Mo)
CoP	12	6.5	670 (of Co)
Ni_2P	11	1.5	220 (of Ni)
FeP	17	48	0.13 (of P)
Pt	This work	171 600	16

Kemppainen, et al., E&ES, 2015

Hydrogen evolution catalysts acid vs alkaline

- Acid is better, but alkaline conditions have many cheap alternatives.
- Ionic resistance is worse in basic solutions.

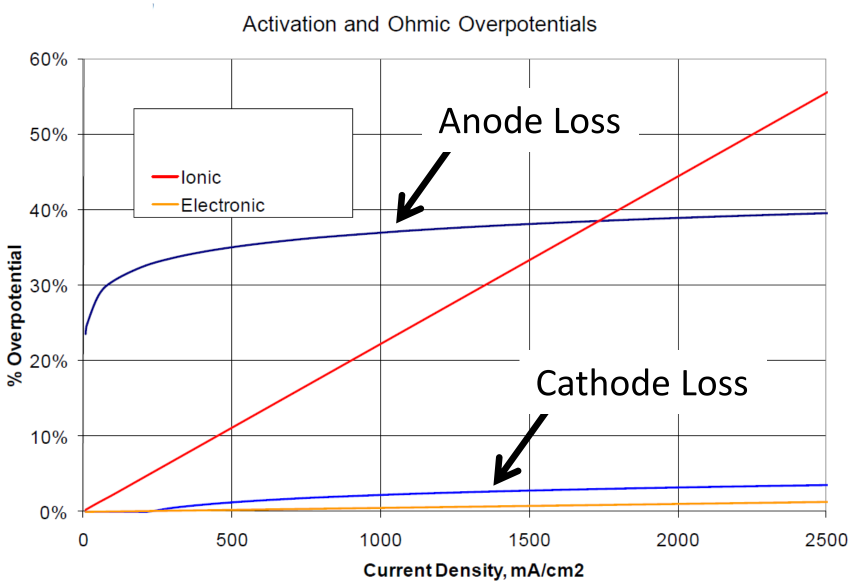


https://doi-org.proxy.findit.cvt.dk/10.1021/ja510442p

Oxygen evolution

Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

- The oxygen evolution reaction involves more electrons so it probably will be harder.
- Since this is the opposite of the fuel cell oxygen reduction reaction, it should be quite similar.
- If we take the same approach of looking at binding energies we should be able to minimize this loss.



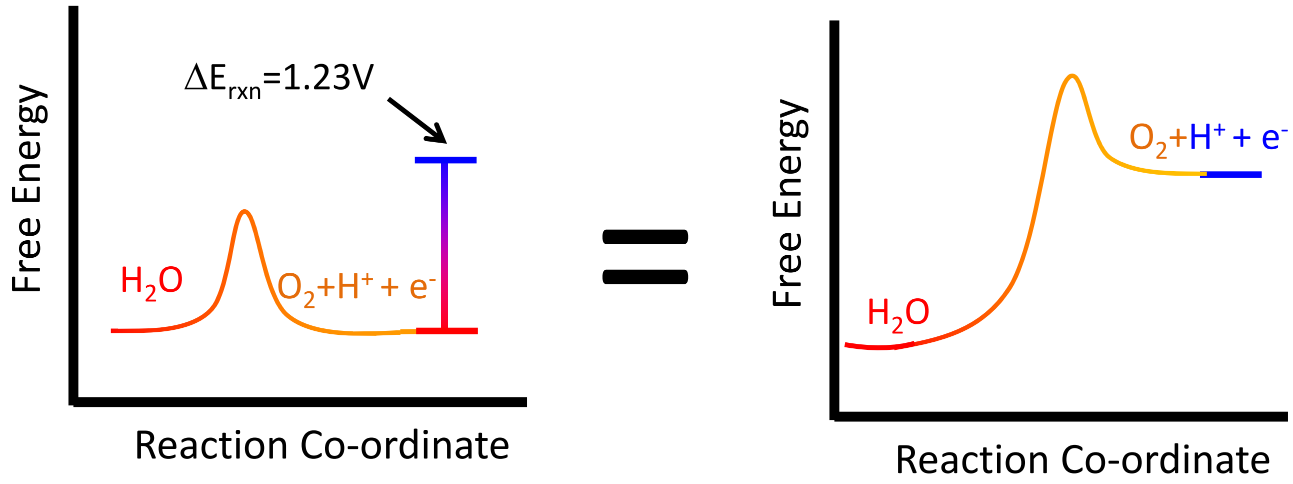
Anode Loss

Cathode Loss

Proton On-site data

Oxygen evolution mechanism

Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$



- We can equivalently state that when the H_2O oxidation progresses, the electrons need to move to a higher energy.
- This equivalent approach helps is explaining this mechanism.

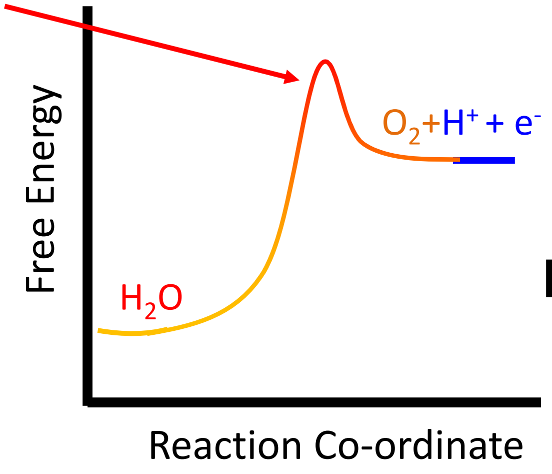
Oxygen evolution mechanism

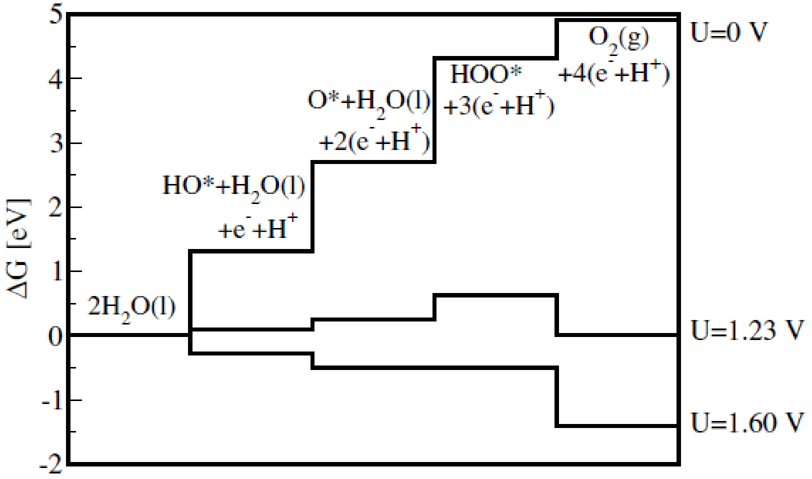
- The most commonly proposed mechanism is shown below:

$$\left.\begin{aligned} 2H_2O &\rightarrow H_2O + HO^* + H^+ + e^- \\ &\rightarrow H_2O + O^* + 2H^+ + 2e^- \\ &\rightarrow HOO^* + 3H^+ + 3e^- \\ &\rightarrow O_2 + 4H^+ + 4e^- \end{aligned}\right\} \text{Exact opposite of ORR for fuel cells}$$

*- Catalyst site

This barrier needs to be reduced to zero for all 4 e-





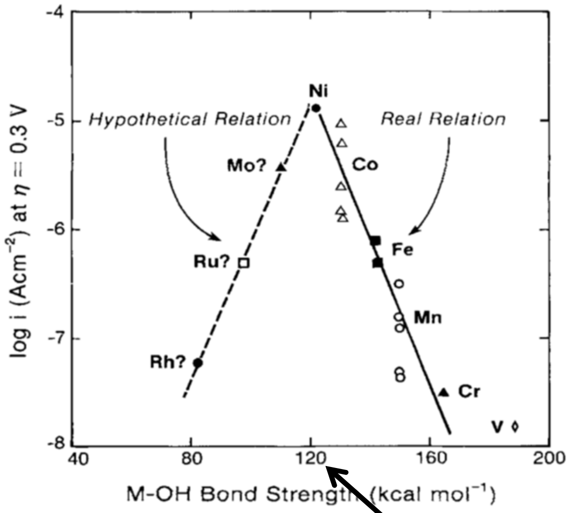
Rossmeisl, 2007, JEAC

Oxygen evolution mechanism

- The rate limiting step is catalyst dependent.
- It is not directly the binding of the HO*, O*, or HOO*.

Mechanism

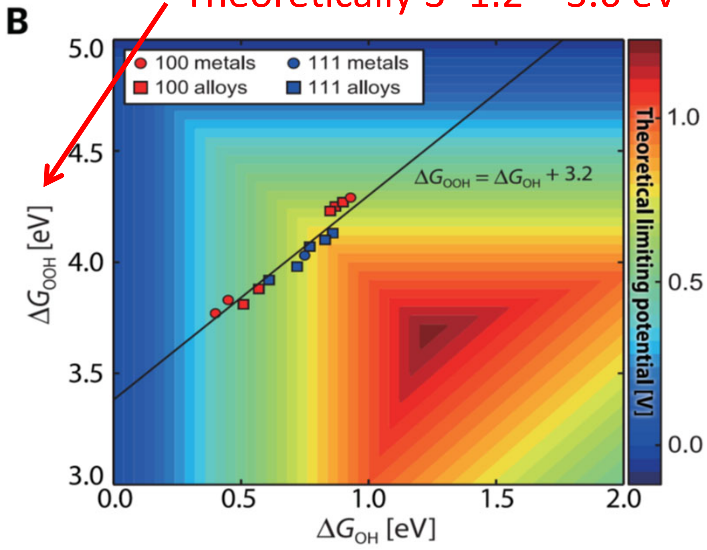
$$
\begin{aligned}
2H_2O &\rightarrow H_2O + HO^* + H^+ + e^- \\
&\rightarrow H_2O + O^* + 2H^+ + 2e^- \\
&\rightarrow HOO^* + 3H^+ + 3e^- \\
&\rightarrow O_2 + 4H^+ + 4e^-
\end{aligned}
$$



120 kcal/mol
=1.23 eV

Bockris et al., JES, 1984

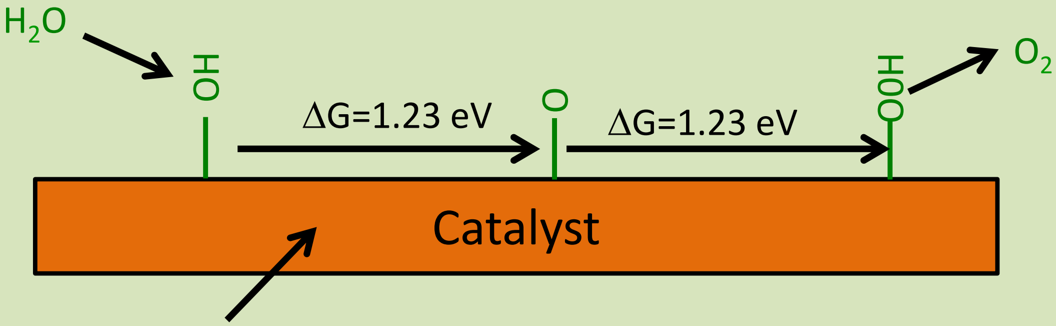
Theoretically 3*1.2 = 3.6 eV



Seh et al., Science, 355, 146 2017

Oxygen evolution mechanism

- **Why can't our volcano plot reach 0 V overpotential?**



H_2O

OH

ΔG=1.23 eV

O

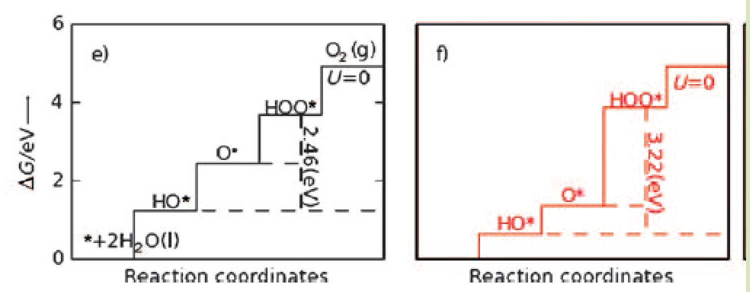
ΔG=1.23 eV

OOH

O_2

Catalyst

- All 3 intermediates have O bonded to the surface.
- We have 2 ΔG's we want to optimize, and only 1 parameter (bonding strength)
- The result is optimizing one ΔG, deoptimizes the other.
- **This is known as a scaling relationship**.



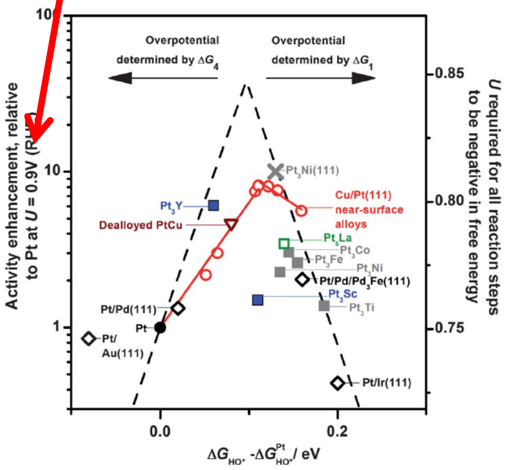
Man et al., ChemCat Chem, 2011

Oxygen evolution mechanism

- The scaling relationship forces the 2 electron process of HO*→O*→ HOO* to have a minimum ΔG=~3.2 eV, (1.6 eV/electron.)
- Thus we are forced to have ~400 mV of loss due to this process. In reality high surface area lets us minimize this to ~300 mV.
- This scaling relationship applies to the fuel cell ORR reaction as well.

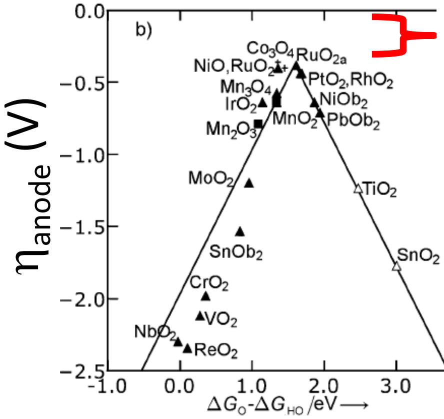
1.23V - 300 mV=

Fuel cell



[Stephens et al., EES, 2012]

Electrolyzer

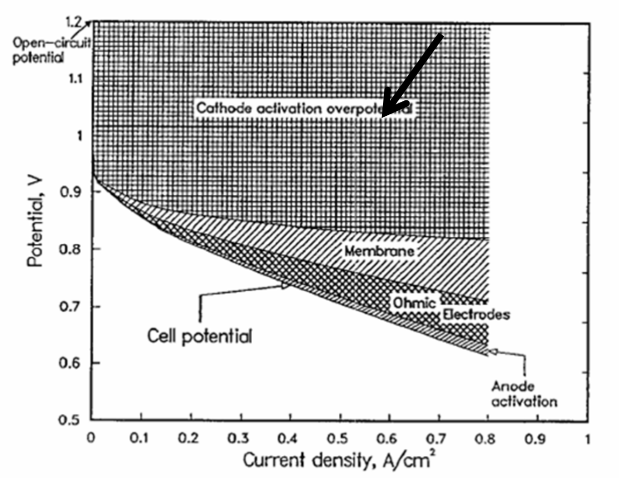


300 mV

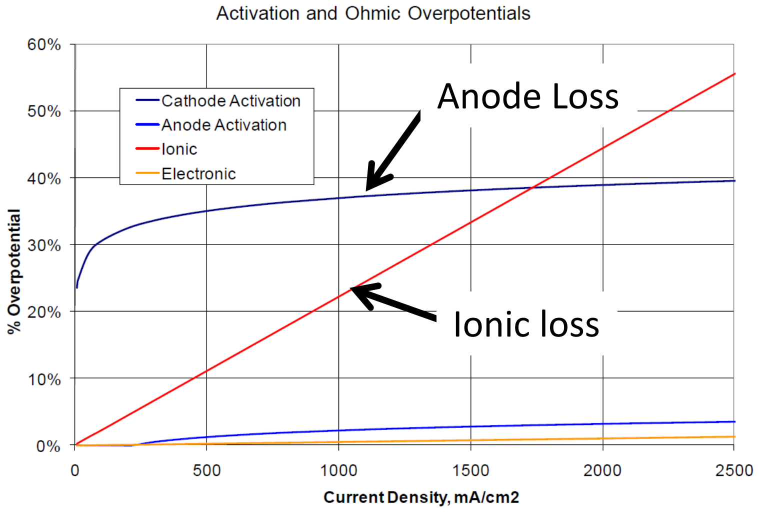
[Garcia-Moto et al., ChemCatChem, 2011]

Effect of scaling relationship

- The scaling relationship is the cause of the majority of losses in both fuel cells and electrolyzers.
- If it we didn’t have the scaling relationship issue, the losses on the oxygen side could be realistically as low as the losses on the hydrogen side.



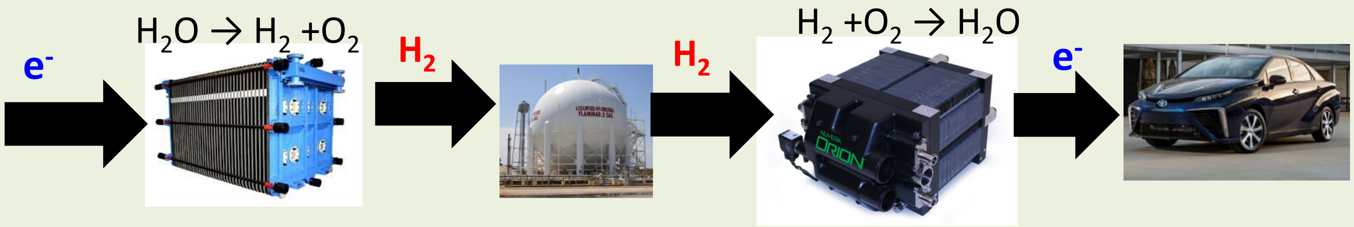
Bernardi and Verbrugge, JES, 1992



Proton On-site data

Efficiency Math

- How efficient is the hydrogen economy?



e^-

$H_2O \rightarrow H_2 + O_2$

H_2

H_2

$H_2 + O_2 \rightarrow H_2O$

e^-

Efficiency (using 1.23V as 100%)	Electrolyzer		Storage (Assumption)		Fuel Cell		Electric motor		Car (or other device)
Current Status	66%	X	~ 90%	X	57%	X	90%	=	30%
Without scaling issues	88%	X	~ 90%	X	81%	X	90%	=	58%
Gasoline / normal engine	Oil → gasoline 88%	X	~ 100%	X	Diesel engine 40%			=	39%
Battery	Charging 92%	X	~ 100%	X	Discharging 92% x 90%			=	76%

Breaking the scaling relationship

2010

Scaling relations bottlenecking
H_2 *economy*

→

2030

Scaling relations bottlenecking
H_2 *economy*

- Can we break the scaling relationship? It would probably give you a Nobel prize.

Discuss your ideas

Electrolyzer Thermodynamics

- Electrolyzers are the opposites of fuel cells in many ways

	CEM Fuel cells	CEM Electrolyzers
Overall reaction:	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$
Anode:	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2O \rightarrow 2e^- + 2H^+ + \frac{1}{2}O_2$
Cathode:	$2e^- + 2H^+ + \frac{1}{2}O_2 \rightarrow H_2O$	$2H^+ + 2e^- \rightarrow H_2$
Max Efficiency (η):	$\frac{\Delta G}{\Delta H}$	$\frac{\Delta H}{\Delta G}$
Operational Voltage:	$V_{op} < 1.23$ V	$V_{op} > 1.47$ V

Thermodynamic efficiency

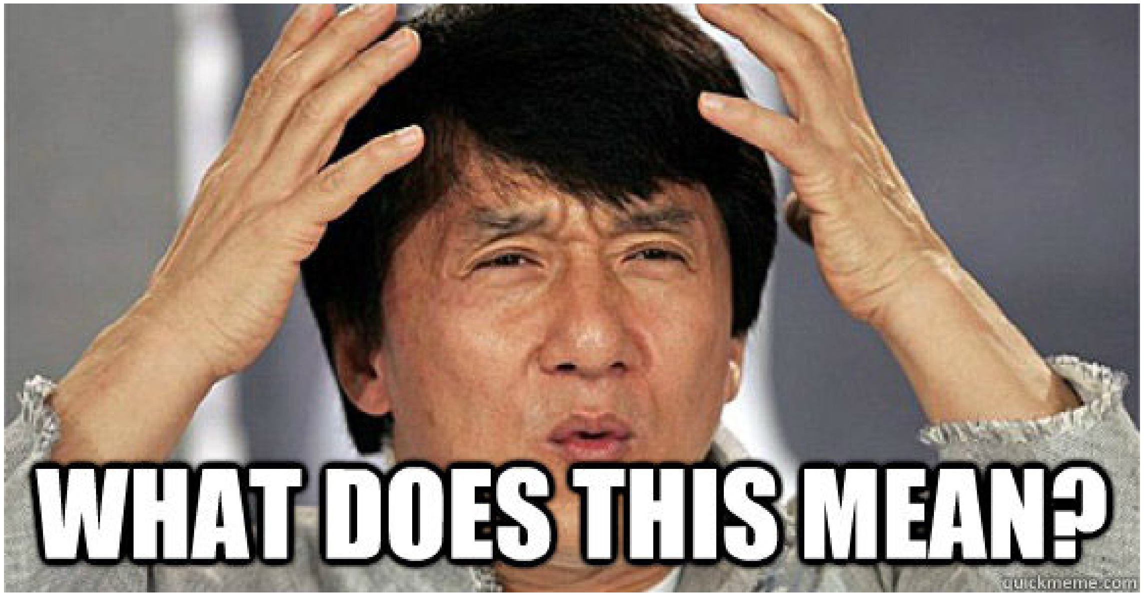
- Can we get over 100% thermodynamic efficiency in our electrolyzer?

$$\eta_{Fuel\ Cell} = \frac{\Delta G}{\Delta H} = \frac{1.23\ V}{1.47\ V} = 83\%$$

$$\eta_{Electrolyzer} = \frac{\Delta H}{\Delta G}$$

- G^f=-237 KJ/mol,
- H^f=-286 KJ/mol (HHV)

Yes!



- Can we get over 100% thermodynamic efficiency in our electrolyzer?
- You need to think of the entire system.

Thermodynamic efficiency

- The key is the entropy.
- If the electrolyzer is over 100% efficient, the entropic term will cool the reaction.

$$\eta_{Electrolyzer} = \frac{\Delta H}{\Delta G} = \frac{\Delta H}{\Delta H - T\Delta S} = \frac{1.48\,V}{1.23\,V} = 119\%$$

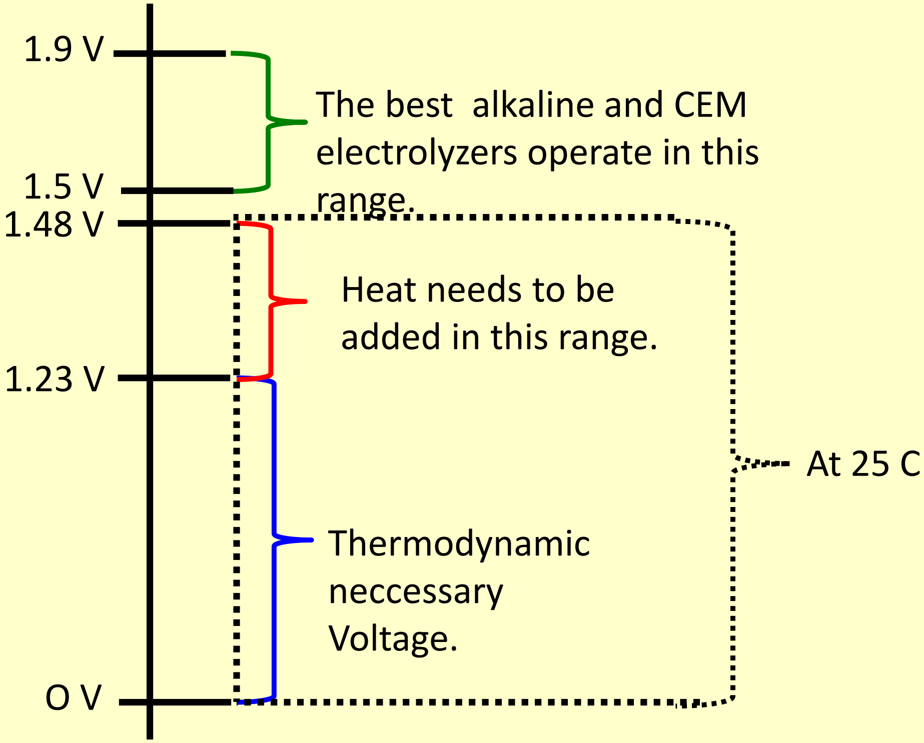
- In the case of >100% efficiency, heat would needed to be added to the cell to maintain the temperature.
- Thus the added heat would need to compensate from the entropic advantage the electrolyzer gets.
- In H_2 fuel cell/electrolyzer almost all the entropy is related to heat of vaporization of water.

Thermodynamic efficiency

- The 1.48 V is sometimes referred to as the thermo-neutral water splitting potential.

- Any device inefficiency (e.g. overpotential) will give us heat.

- Why go to higher voltages since it decreases efficiencies?



1.9 V

1.5 V

1.48 V

1.23 V

0 V

The best alkaline and CEM electrolyzers operate in this range.

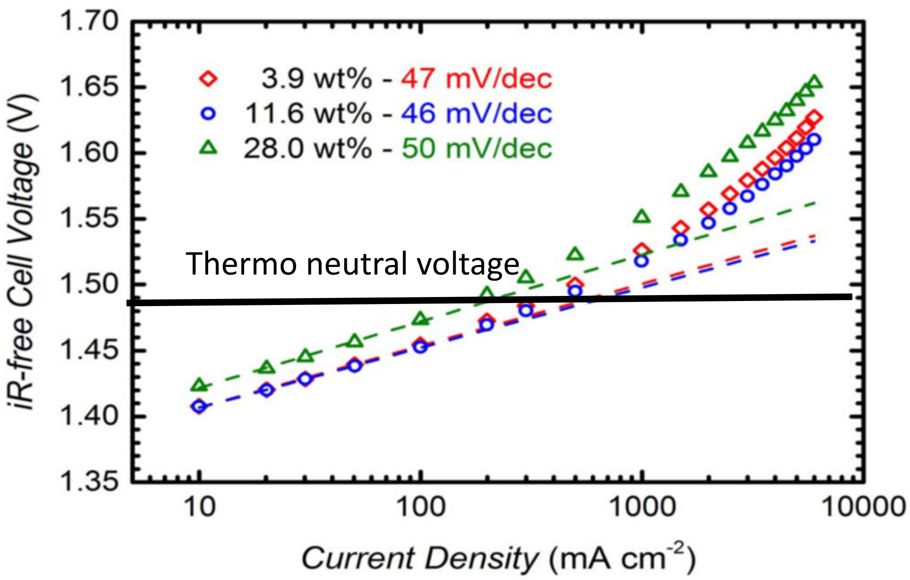
Heat needs to be added in this range.

Thermodynamic neccessary Voltage.

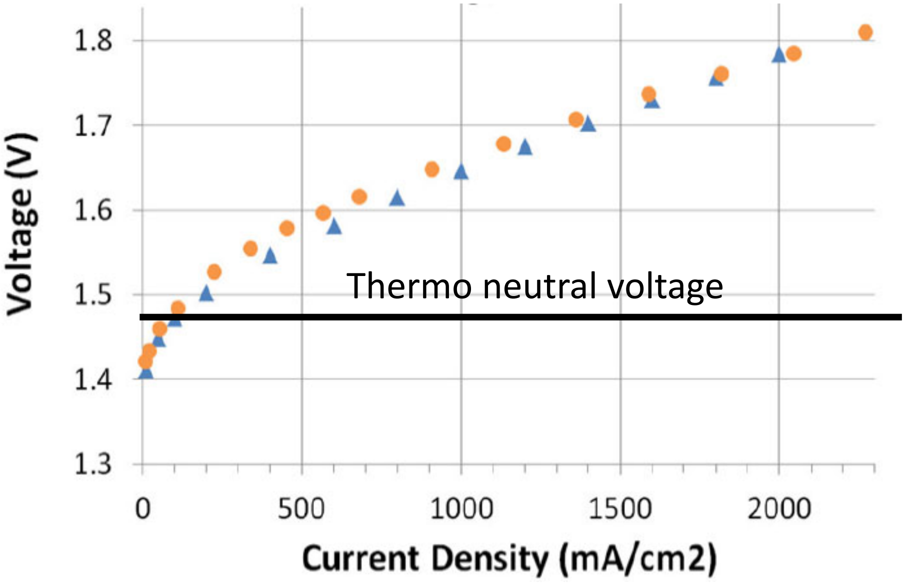
At 25 C

Efficiency

- Below are i-V curves of the best PEM electrolyzers.
- At low currents, it is possible to be below the thermoneutral voltage.
- Higher currents help out in minimizing capital costs.



[Bernt, et al., J.Elec. Soc., 163 (11) F3179-F3189 (2016)]



Data from Giner including ohmic losses

Thermodynamic efficiency

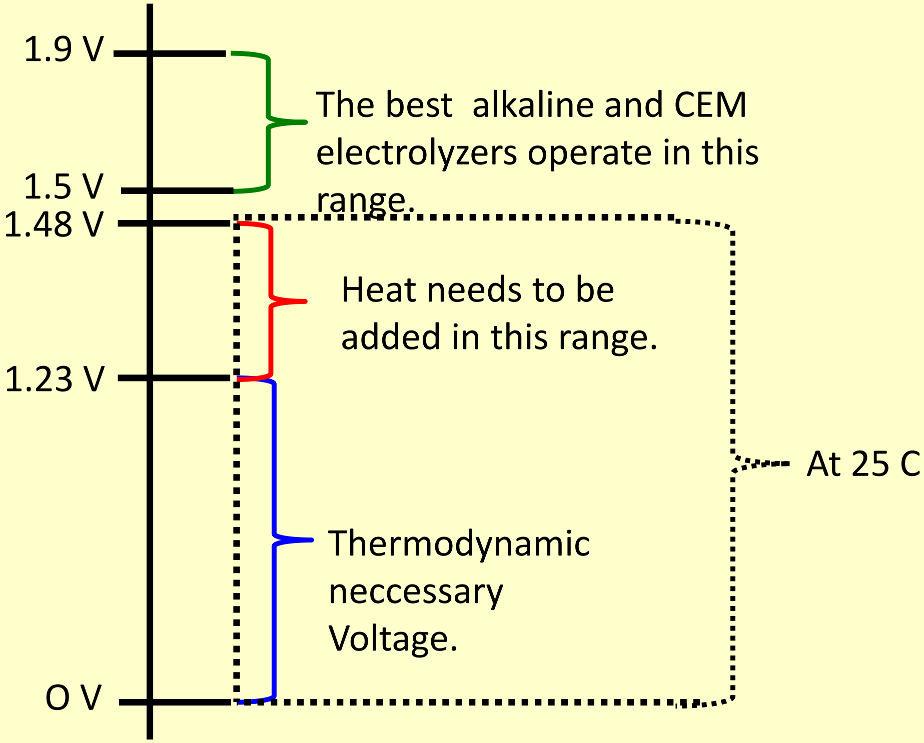
- The 1.48 V is sometimes referred to as the thermo-neutral water splitting potential.

- Any device inefficiency (e.g. overpotential) will give us heat.

- Why go to higher voltages since it decreases efficiencies?

- 1.48 V is the potential at T = 0K

$$E = \frac{\Delta G}{nFE} = \frac{\Delta H - T\Delta S}{nFE}$$

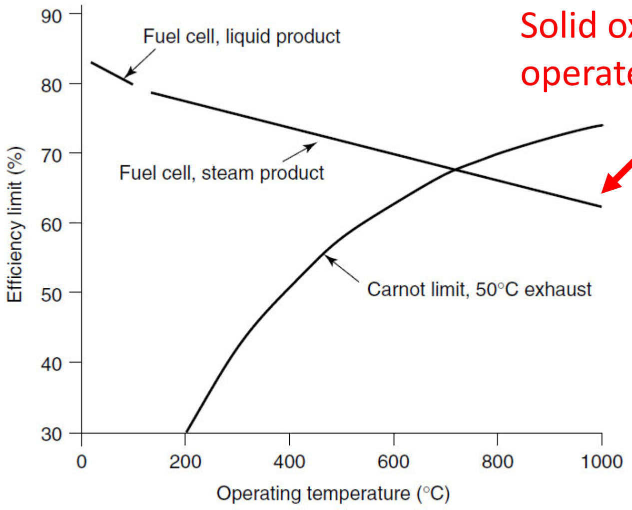


Solid oxide fuel cell/electrolyzer efficiency

- High temps are bad for electrical production (i.e. Solid oxide fuel cells)
- High temps are great for chemical production

$$\eta_{Fuel\ Cell} = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T\Delta S}{\Delta H}$$

$$\eta_{Electrolyzer} = \frac{\Delta H}{\Delta G} = \frac{\Delta H}{\Delta H - T\Delta S}$$



Solid oxide fuel cells operate at this temp

- Endothermic process
- Thus needs heat in addition to electricity

Concept Check

If I am operating a fuel cell at its thermodynamic limit I will

a) Consume heat, but less than an electrolyzer

b) Consume heat, but more than an electrolyzer

c) Give off heat with the heat increasing as I go to higher temperatures

d) Give off heat with the heat decreasing as I go to higher temperatures

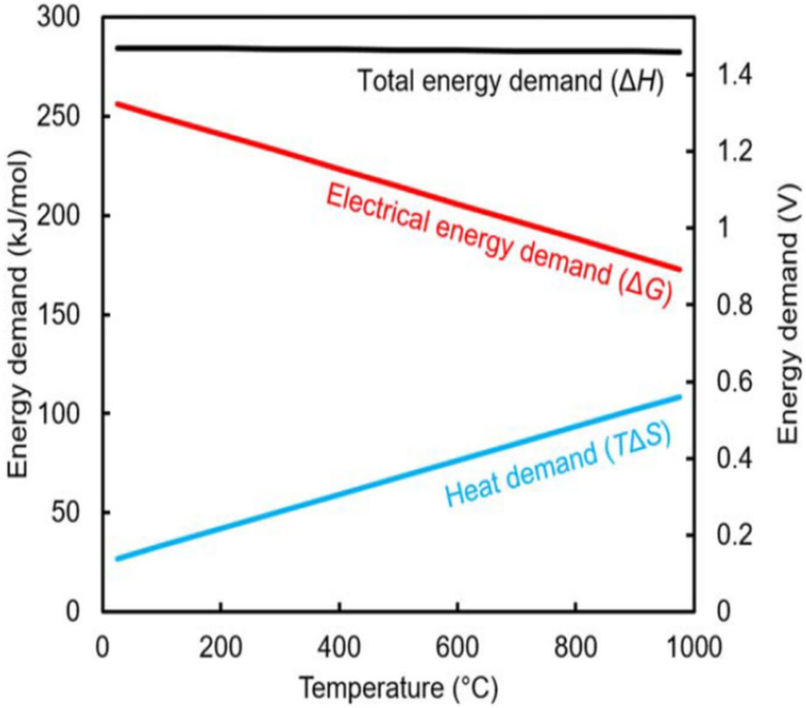
Solid oxide water electrolysis?

- From thermodyanmics higher temperature means greater efficiency (>100 %) for electrolytic processes. This assumes heat is for free.

- High temperature means faster catalysis, and lower overpotential

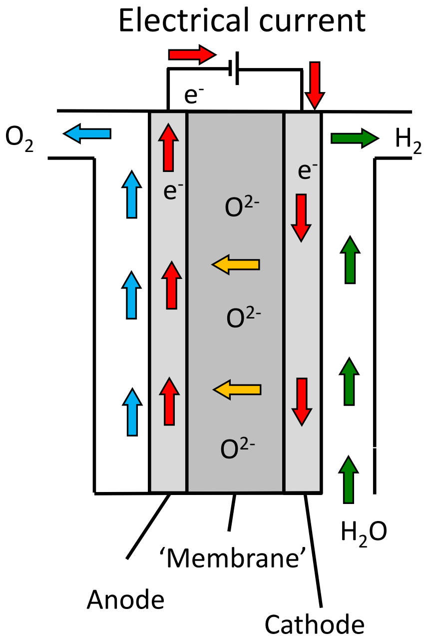
- Catalytic losses can not provide enough heat, so heat must be added

- By adding heat to make it thermo-neutral this decreases our efficiency to 100%.



Solid oxide water electrolysis

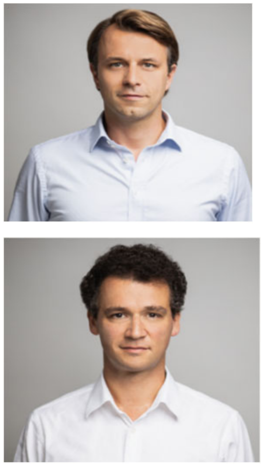
- O_2^- are unstable in water or air, but can occur in ceramics.
- To conduct current through ceramics, devices must operate at ultra high temperatures (600-800 °C)
- Disadvantages- high temp = **high capital cost & low durability**
- Advantages: Thermodynamics & minimal catalytst overpotential. No water/humidity mixed with gases



Who is doing this?

- Haldor Topsoe, who are located 1km from DTU
  - Originally focused on solid oxide fuel cells
  - Starting tommorow they will produce 500 MW/yr of electrolyzers (Official opening of plant is 30-11-2025)

- Sunfire is a German start-up (from 2010) that employs 250 people
  - Focus on H_2, CO, and syngas production
  - Highly developed, maybe a little behind Topsoe in commercialization
  - Parterning with a lot of other companies



Competing Technologies

🟩 Advantages 🟥 Disadvantages

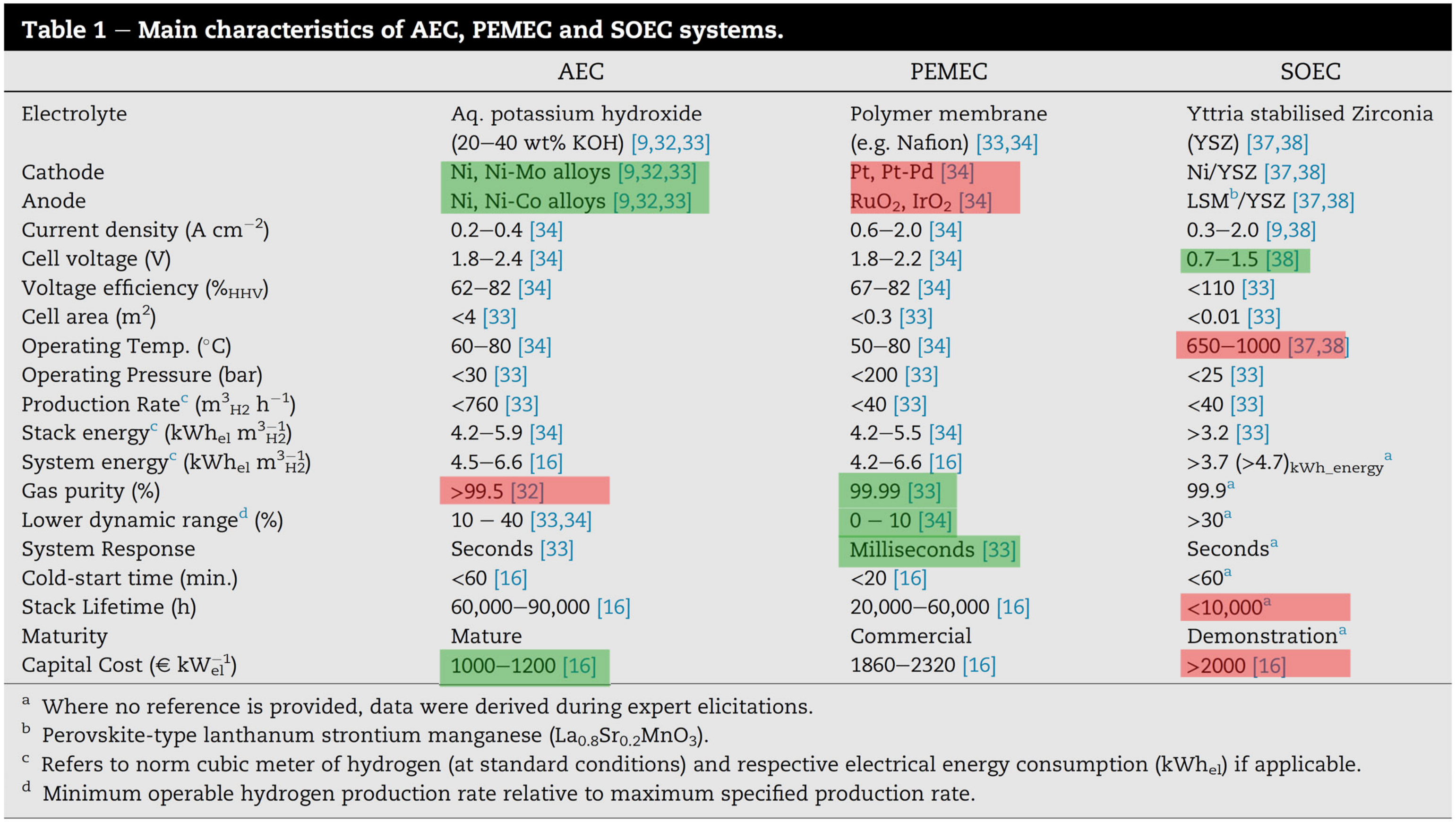


Table 1 – Main characteristics of AEC, PEMEC and SOEC systems.

	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^{-1}_{H2})	4.2–5.9 [34]	4.2–5.5 [34]	>3.2 [33]
System energy[c] (kWh_{el} m^{-1}_{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^{-1}_{el})	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.

Schmidt et al., 2017 Int, Jn. of Hyd. Energy, 42, 30470-30492

Learning Objectives

- From this lecture you should be able to understand:
  - The fundamental physics behind electrolyzers.
  - How to improve the efficiency/costs of electrolyzers.

Exercises

- If you are operating at 1 A/cm^2, what is the volumetric production rate of H_2 at 25C and 1bar pressure. Give the results in ml/cm^2 area.

- If we have 100 GW electrolyzers that operate 80% of the time at an energy efficiency of 90%, how much H_2 can be produced in 1 year. If most the world's energy consumption (11.8 TW) is from electricity produced by a fuel cell (operated at 0.8V), how long can the world run solely on our annual H_2 production.