



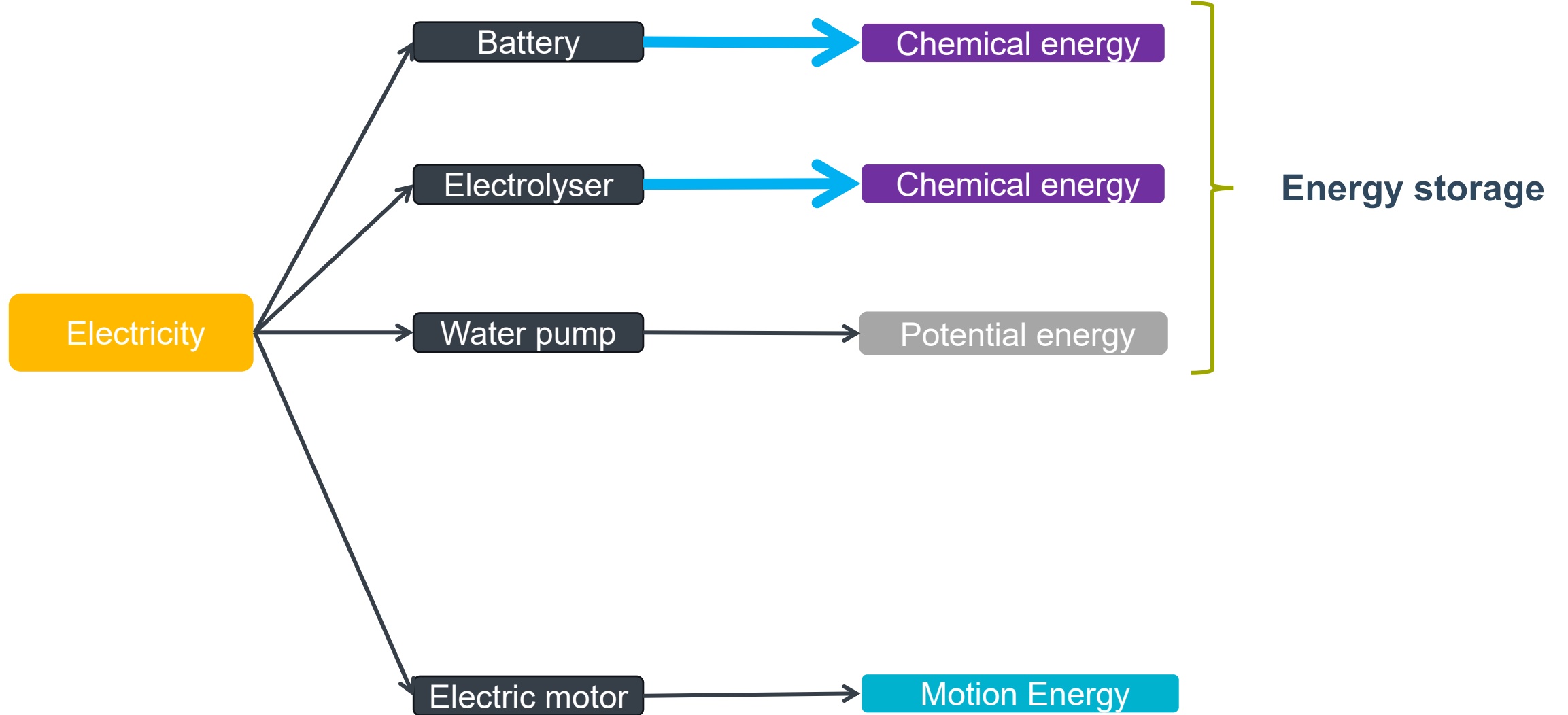
Chemical Energy

Renewable Energy Integration in the Energy System

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Research Group Energy in Transition

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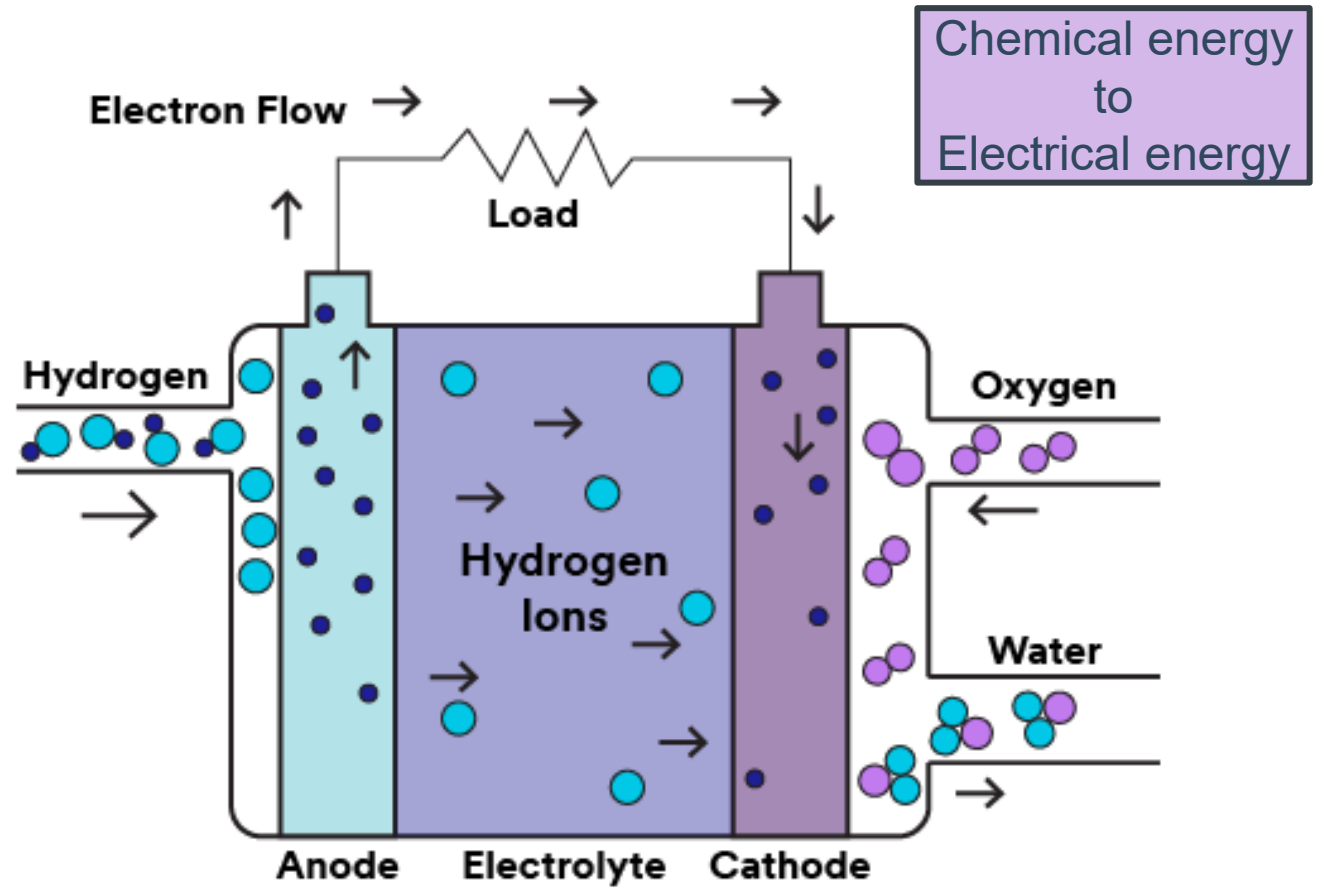
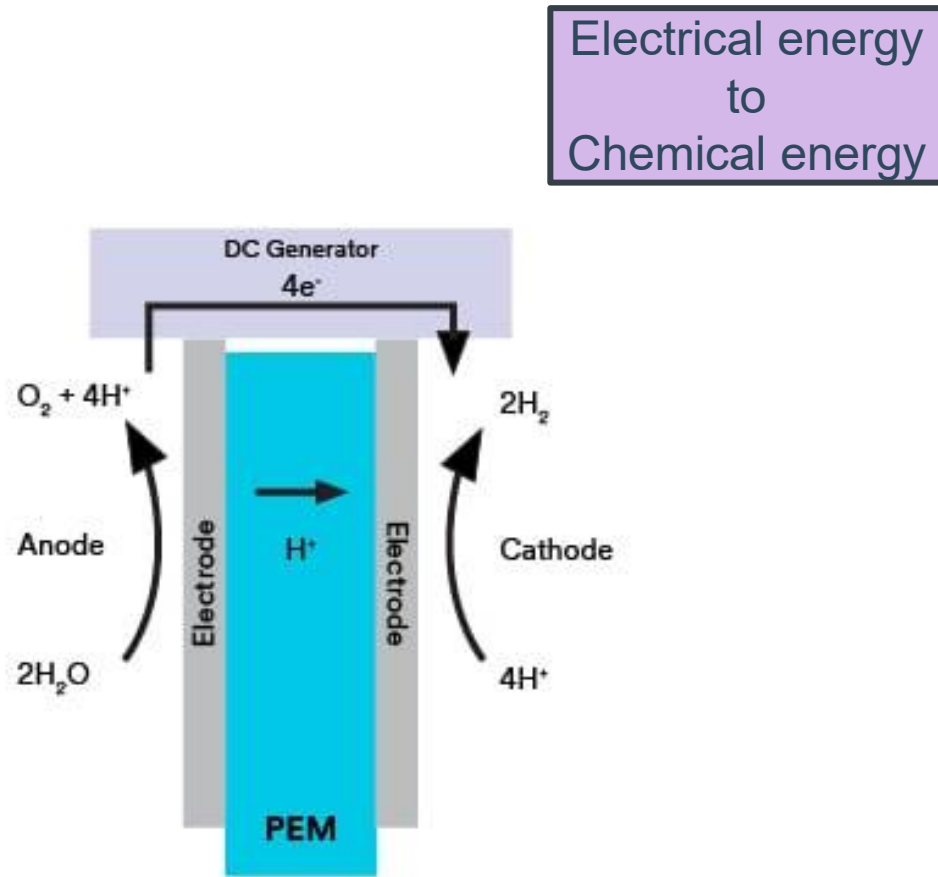


Energy transfer or conversion

FROM⇒ TO↓	RADIANT	CHEMICAL	NUCLEAR	THERMAL	MOTION	ELECTRICAL	GRAVITATIONAL
RADIANT							
CHEMICAL						Electrolyser Battery charging	
NUCLEAR							
THERMAL	Solar thermal collector	Combustion boiler	Fission reactor	Heat exchanger Phase change materials Heat pump		Electric boiler	
MOTION		Combustion engine Gas turbine		Steam Turbine	Water and wind turbine	Electric motor	Falling objects
ELECTRICAL	Photovoltaic panel	Electric battery Fuel cell			Electric generator	Transformer Converter	
GRAVITATIONAL					Rising objects		

The diagram illustrates energy conversion pathways between different forms of energy. A blue arrow points from Thermal to Electrical, and a red arrow points from Electrical to Gravitational.

Electrolyser / Fuel Cell



Electrolysis

Electrical energy
to
Chemical energy

Two electrodes (cathode, +, and anode, -) are immersed in a conducting liquid (melt / solution).

When a potential difference is applied, the electric current reacts.

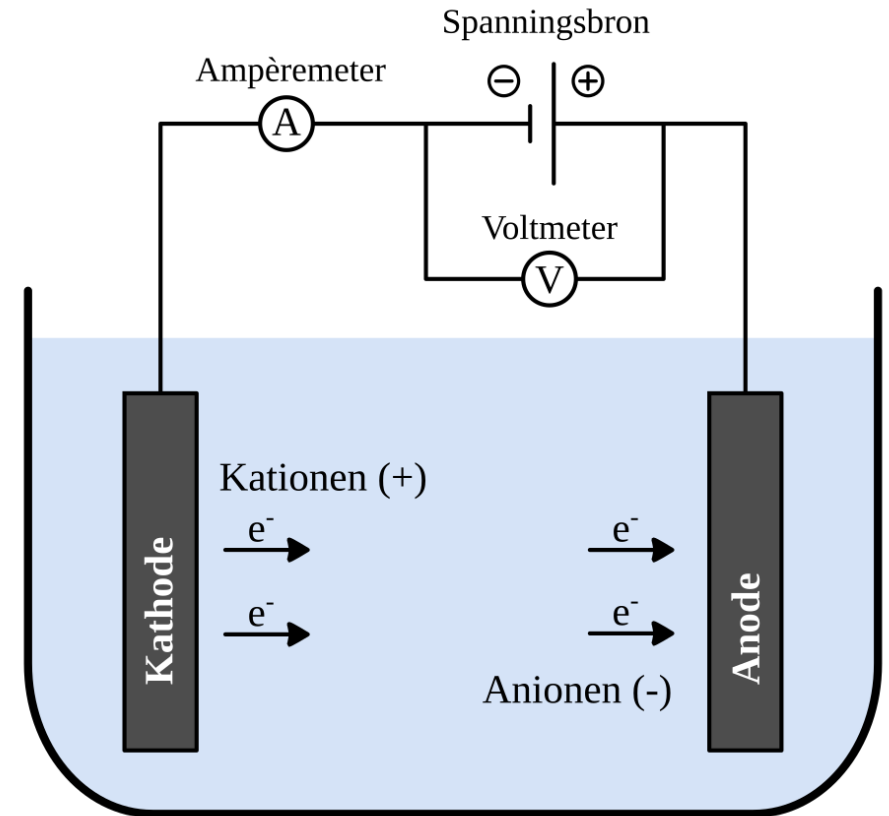
On the cathode a reduction takes place, generating electrons.

Those are transported to the anode, where an oxidation occurs.

Water dissociation:



Chloralkali process:



Water Electrolysis

Electrical energy
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Autoprotolysis:



Anode:



$$E^0(\text{an}) = 0.815 \text{ V}$$

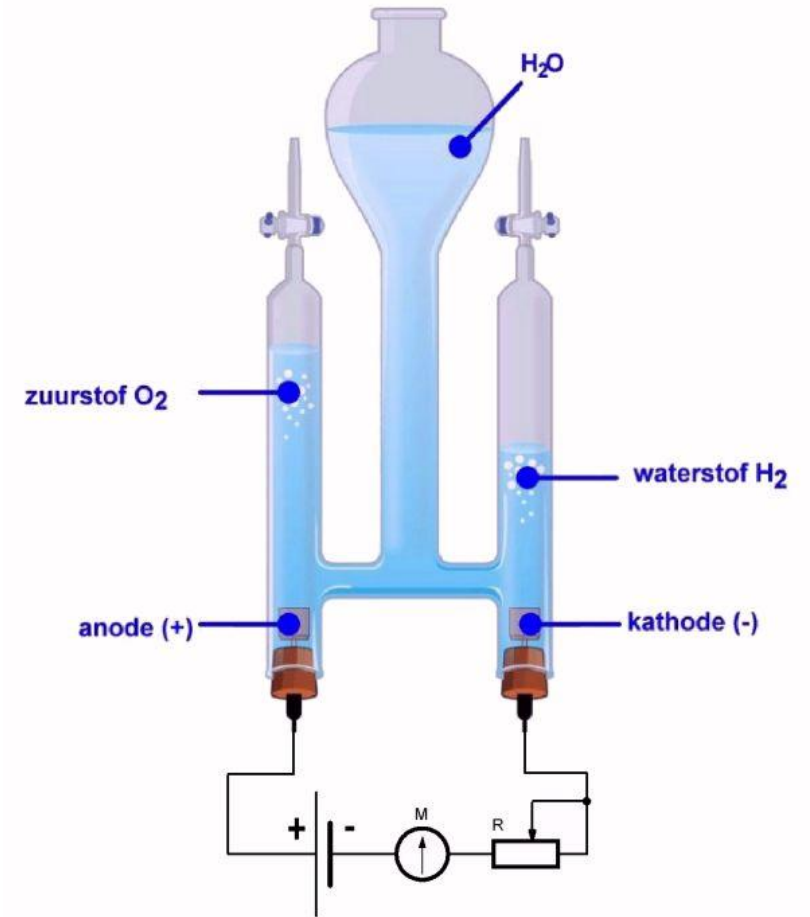
Cathode:



$$E^0(\text{cat}) = -0.414 \text{ V}$$

Required potential:

$$V \geq V_{\text{anode}} - V_{\text{cathode}} = 0.815 - (-0.414) = 1.229 \text{ V}$$

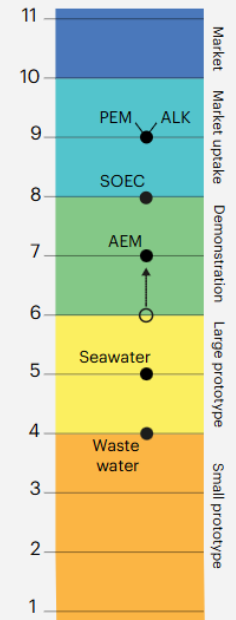


NB: when the pH changes, $E(\text{an})$ and $E(\text{cat})$ change as well, hence the required potential changes!

Electrolysers

Electrical energy
to
Chemical energy

Technology readiness levels of electrolyser technologies



	PEM-EL	AEM-EL	A-EL	HT-EL
	Polymer Electrolyte Membrane Electrolysis	Anion Exchange Membrane Electrolysis	Alkaline Electrolysis	High-Temperature Electrolysis
Electrolyte	acidic	alkaline	alkaline	O ²⁻ - conducting solid (ceramic)
	solid (Polymer)		liquid	
Operating temperature	50 – 80 °C	40 – 80 °C	60 – 95 °C	700 – 1000 °C

Alkaline Electrolysis

Alkaline (ALK) Electrolyser (AEL) / Alkaline Water Electrolyser (AWE)

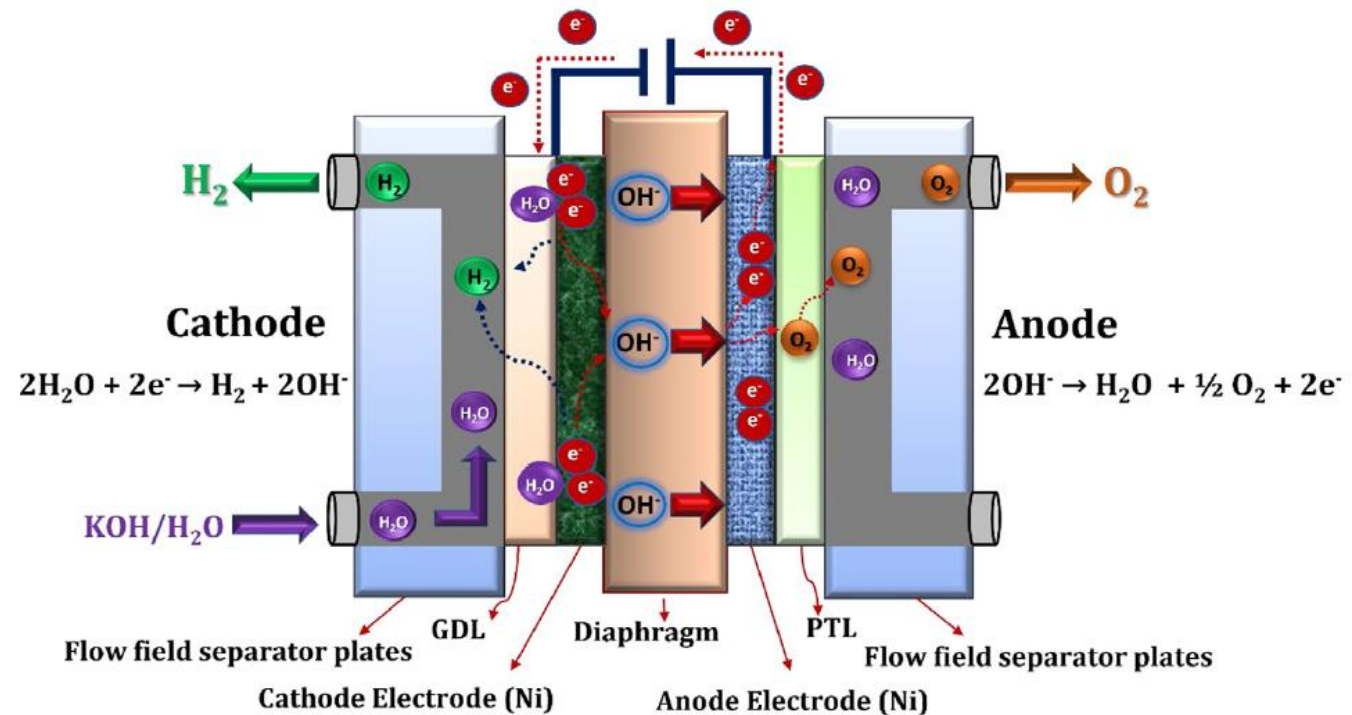
Electrical energy
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Alkaline electrolysis stack (most common) materials

- Diaphragm: historically asbestos, now Zirfon (ZrO_2 / polysulfone polymer)
- Electrolyte: potassium hydroxide (KOH)
- Electrode: nickel mesh
- Bipolar plates: nickel-coated stainless steel

Alkaline electrolyser system components

- Stack
- O_2 -liquid separator
- H_2 -liquid separator
- Electrolyte pumps



AEM Electrolysis

Anion Exchange Membrane (AEM) Electrolyser

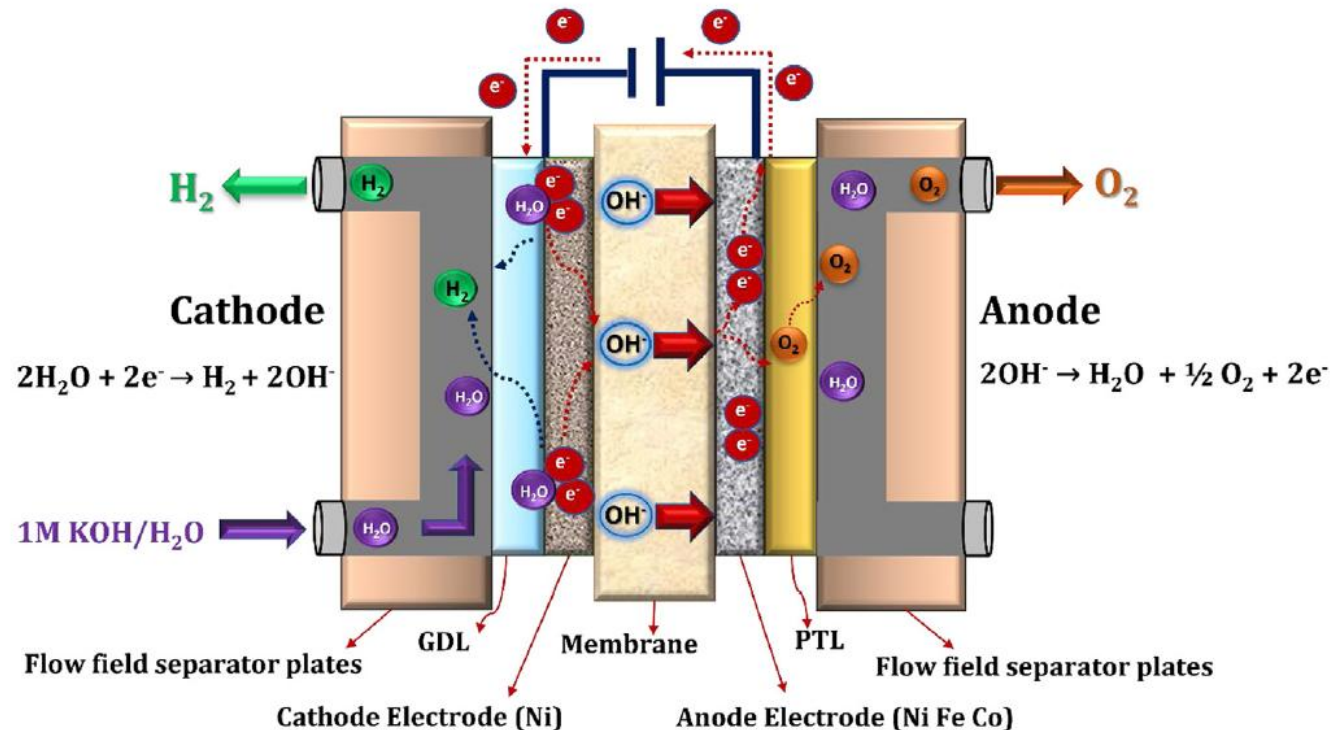
Electrical energy
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AEM electrolysis stack (most common) materials

- Diaphragm: solid polymer
- Electrolyte: potassium hydroxide (KOH) or pure water
- Electrode: nickel mesh
- Bipolar plates: nickel-coated stainless steel

AEM electrolyser system components

- Stack
- O₂-liquid separator
- H₂-liquid separator
- Electrolyte pumps



PEM Electrolysis

Proton Exchange Membrane (PEM) Electrolyser

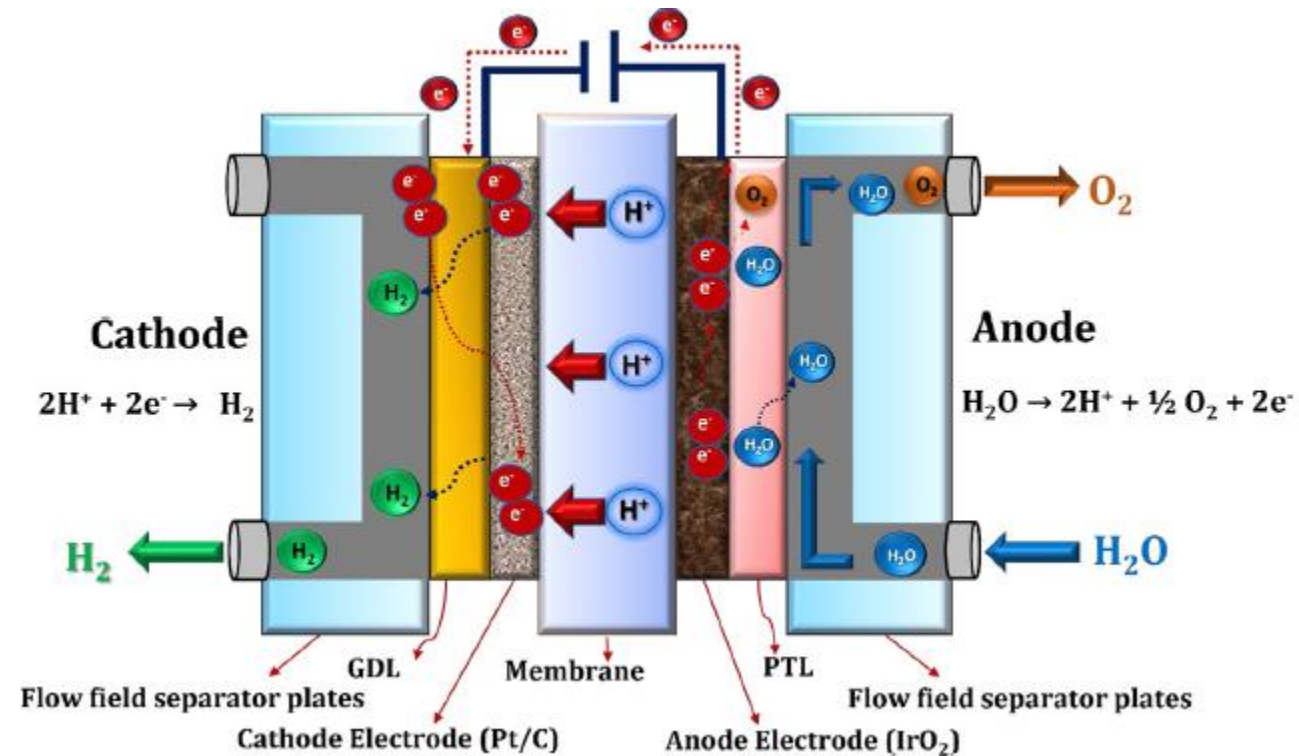
Electrical energy
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PEM electrolysis stack (most common) materials

- Proton exchange membrane: Nafion®
- Electrode: iridium oxide (IrO_2 , an) / platinum (Pt, cat)
- PTL (porous transportation layers): titanium (Ti, an), carbon paper / titanium (cat)
- Bipolar plates: titanium Pt-coated, an / Au-coated, cat

PEM electrolyser system components

- Stack
- O_2 -liquid separator
- H_2 -liquid separator
- Water pumps



Solid Oxide Electrolysis

Solid Oxide Electrolyte Cell (SOEC) / High Temperature (HT) Electrolyser

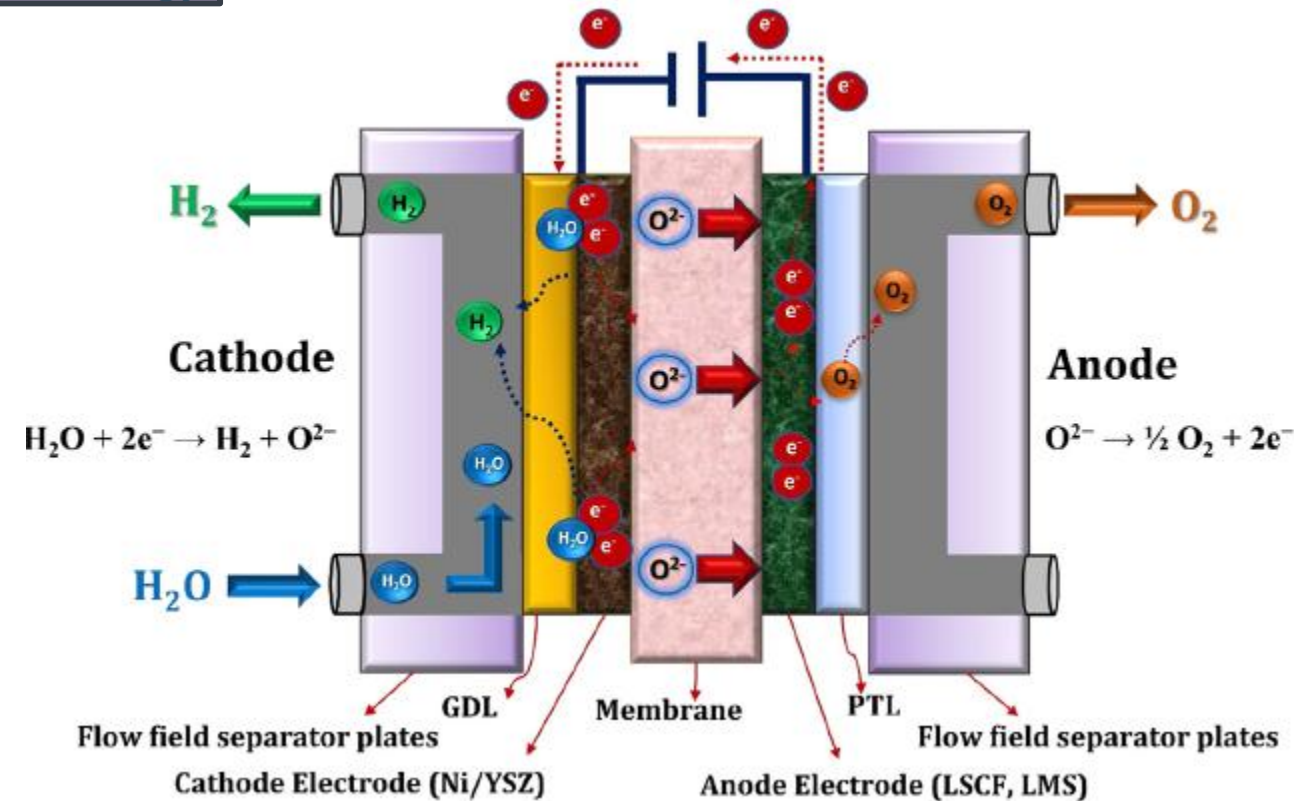
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SOEC electrolysis stack (most common) materials

- Oxygen exchange membrane: YSZ
- Electrode: LSC / LSM / LSCF (an), Ni + YSZ (cat)
- Bipolar plates: stainless steels (high temperature) with protective coating
- Seals: glass, glass-ceramic, mica

SOEC electrolyser system components

- Stack
- Steam generator
- High temperature insulation materials



Electrolyzers

Electrolyser BoP (Balance of Plant) :

- Power electronics (power source, converter AC-DC, rectifier) + automation system
- Water purification
- Heat exchangers
- Pipes and mechanical structures
- Gas analysis equipment (gas chromatography, GC) to monitor quality and safety of the product gas.
- Oxygen removal unit and hydrogen dryer
- Compressor (often needed to reach desired pressure)

Electrical energy
to
Chemical energy

	ALK / AWE	AEM	PEM	SOEC
Pros	Mature technology	High current density	High purity hydrogen	High electrical efficiency
	Low cost catalyst	Low/No alkalinity needed	Wide power range	Compact
	Simple construction	Low cost catalysts	Fast ramp rates	
	High stability		Compact (pressurized)	
Cons	Low current density	Not yet commercial	Noble metal catalysts	Lifetime
	Atmospheric, hence bulky	Short lifetime	Acid resistant materials	Cost of production
	Alkaline resistant materials	Temperature sensitie (< 60 °C)	Gas cross-over	Sensitive to temperature fluctuations
		Gas cross-over	Fluorinated membrane	

Hydrogen Storage

<https://www.youtube.com/watch?v=yWWYiDTVbRY&t=8s>



Hydrogen Storage

Advantages

- High storage capacity
- Low weight, compared to batteries

Disadvantages

- Expensive system
- Round-trip efficiency (electricity to hydrogen to electricity) is low
- Technology only reaching maturity

Fuel Cell

Chemical energy
to
Electrical energy

Steam reforming of methane (natural gas)



Basic principle is the reverse reactions of an electrolyser.

Not only hydrogen can be used as a fuel, but other molecules as well; most notably CO (formed by reformation of a hydrocarbon, e.g. methane).

Two types dominate the market: PEM and SOFC (rSOC).

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer electrolyte membrane (PEM)	Perfluorosulfonic acid	<120°C	<1 kW–100 kW	60% direct H ₂ ; 40% reformed fuel	Backup power Portable power Distributed generation Transportation Specialty vehicles	Solid electrolyte reduces corrosion and electrolyte management problems Low temperature Quick start-up and load following	Expensive catalysts Sensitive to fuel impurities
Solid oxide (SOFC)	Yttria stabilized zirconia	500°–1,000°C	1 kW–2 MW	60%	Auxiliary power Electric utility Distributed generation	High efficiency Fuel flexibility Solid electrolyte Suitable for CHP Hybrid/gas turbine cycle	High temperature corrosion and breakdown of cell components Long start-up time Limited number of shutdowns

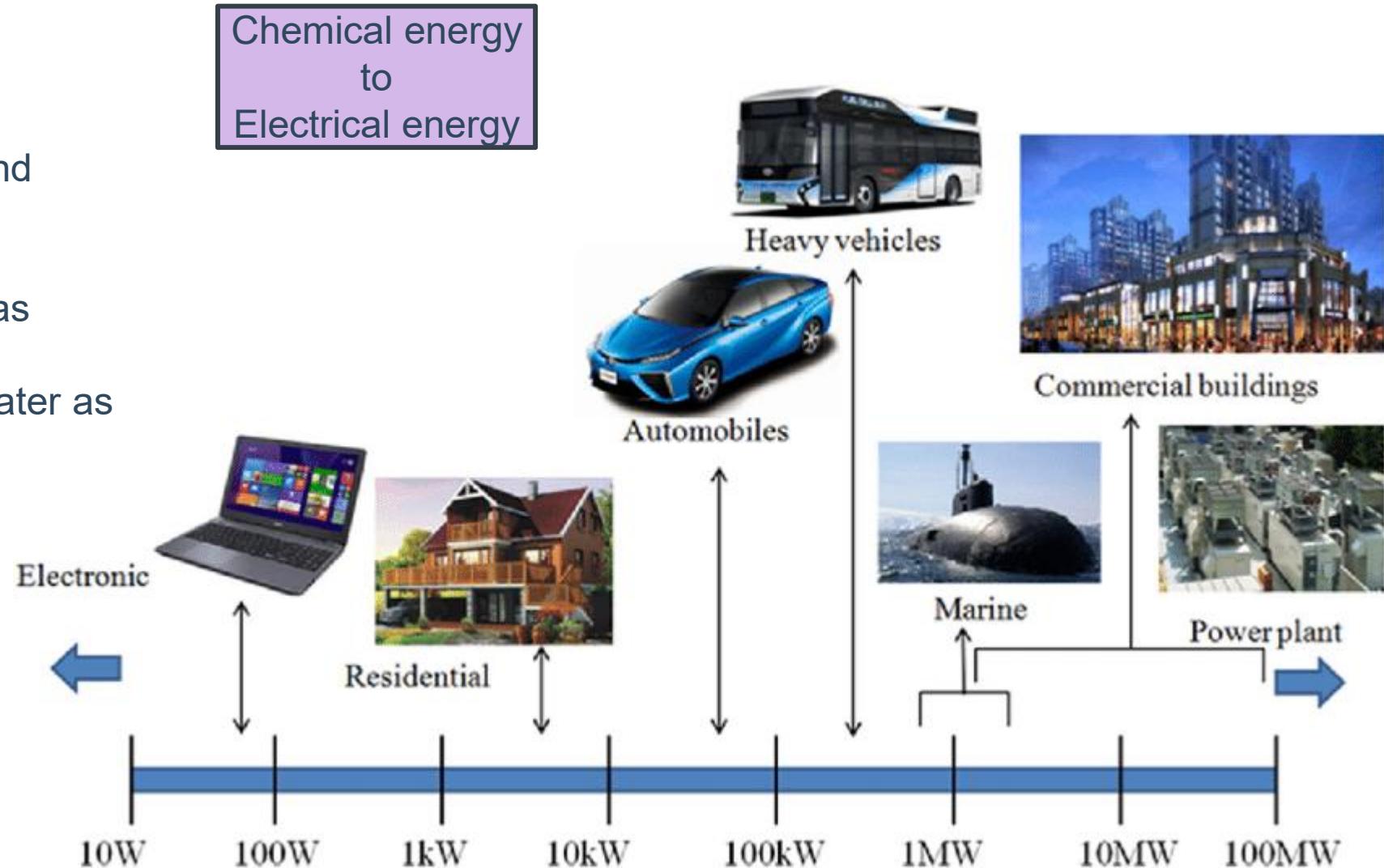
Fuel Cell

Wide range of applications

Potential for co-generation: heat and electricity

With hydrogen as fuel, only water as product

Hydrocarbons produce CO_2 and water as emission



Fuel Cell



Hydrogen Fuel Cell at festivals, construction sites, rail works

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Green Public Transport

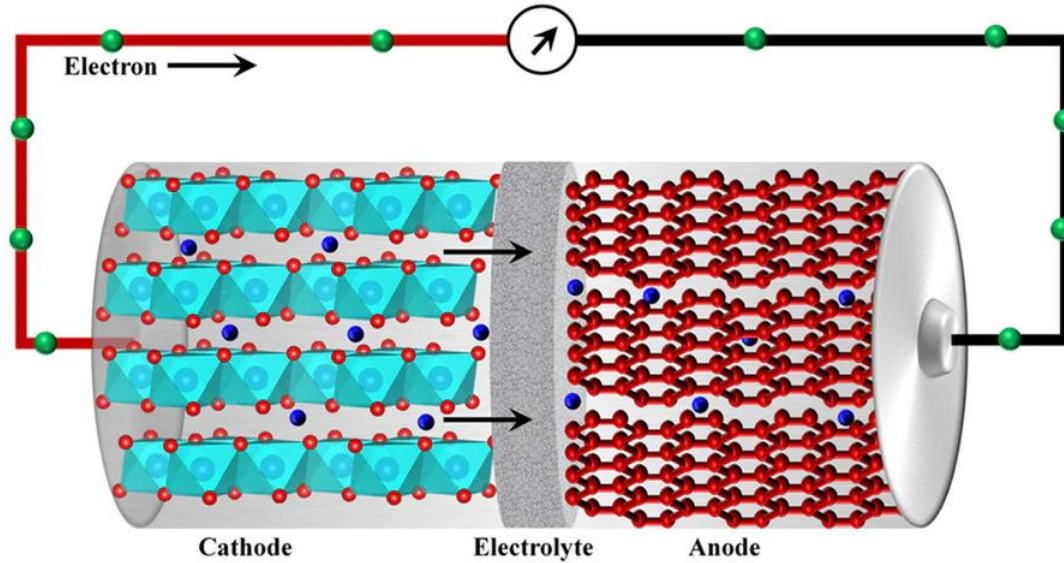


Hydrogen car: Toyota Mirai



[Hydrogen Truck](#)

Electric Battery



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In case it is
rechargeable also

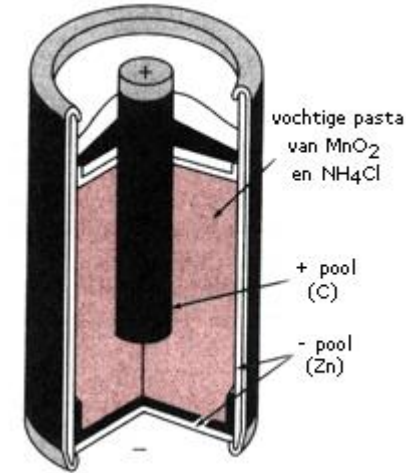
Electrical energy
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Two electrodes or poles (cathode, +, and anode, -) are placed next to an electrolyte (ion conductor).

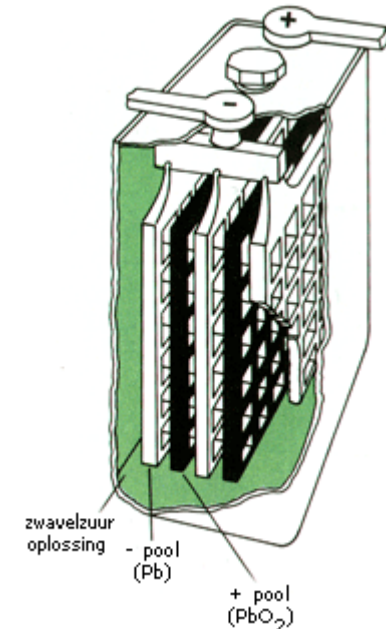
When the poles are connected, chemical reactions produce/consume electrons at the poles.

Electric Battery

Battery Type	Cathode (+)		Electrolyte	Anode (-)	
Disposable (only discharge)	Materials	Reaction		Materials	Reaction
Dry Cell	Carbon with black manganese	$2 \text{MnO}_2 + \text{H}_2\text{O} + 2 e^- \rightarrow \text{Mn}_2\text{O}_3 + 2\text{OH}^-$	Paste of ZnCl_2 or NH_4Cl	Zinc	$\text{Zn} \rightarrow \text{Zn}^{2+} + 2 e^-$
Alkaline	Carbon with black manganese	$2 \text{MnO}_2 + \text{H}_2\text{O} + 2 e^- \rightarrow \text{Mn}_2\text{O}_3 + 2\text{OH}^-$	Paste of KOH	Zinc	$\text{Zn} \rightarrow \text{Zn}^{2+} + 2 e^-$
Lithium-manganese	Carbon with black manganese	$2 \text{MnO}_2 + \text{H}_2\text{O} + 2 e^- \rightarrow \text{Mn}_2\text{O}_3 + 2\text{OH}^-$	Paste of KOH	Lithium	$\text{Li} \rightarrow \text{Li}^+ + e^-$



Battery Type	Cathode (+)		Electrolyte	Anode (-)	
Rechargeable	Materials	Reaction		Materials	Reaction
Lead acid	Lead oxide	$\text{Pb}(s) + \text{SO}_4^{2-}(aq) + 4 \text{H}^+ \rightleftharpoons \text{PbSO}_4(s) + 2 \text{H}_2\text{O}(l)$	Sulfuric acid solution	Lead	$\text{PbO}_2(s) + \text{SO}_4^{2-}(aq) \rightleftharpoons \text{PbSO}_4(s) + 2 e^-$
Nickel-cadmium (NiCd)	Nickeloxyhydroxide	$\text{NiO}(\text{OH}) + \text{H}_2\text{O} + e^- \rightleftharpoons \text{Ni}(\text{OH})_2 + \text{OH}^-$	Paste of KOH	Cadmium	$\text{Cd} + 2 \text{OH}^- \rightleftharpoons \text{Cd}(\text{OH})_2 + 2 e^-$
Nickel-metalhydride (NiMH)	Nickeloxyhydroxide	$\text{NiO}(\text{OH}) + \text{H}_2\text{O} + e^- \rightleftharpoons \text{Ni}(\text{OH})_2 + \text{OH}^-$	Paste of KOH	Metalhydride (e.g. Fe, Ni, Cr, Co, V, Ti)	$\text{MH} + \text{OH}^- \rightleftharpoons \text{M} + \text{H}_2\text{O} + e^-$
Lithium ion	Lithium-metaloxides (e.g. LiCoO_2 , LiNiO_2 , LiFePO_4)	$\text{Li}^+ + \text{MO}_x + e^- \rightleftharpoons \text{LiMO}_x$	Lithiumsalt in solution	Lithiated graphite	$\text{LiC} \rightarrow \text{C} + \text{Li}^+ + e^-$
Solid state*	Lithium-metaloxides (e.g. LiCoO_2 , LiNiO_2 , LiFePO_4)	$\text{Li}^+ + \text{MO}_x + e^- \rightleftharpoons \text{LiMO}_x$	Solid electrolyte	Lithium or silicium	



Rechargeable Battery

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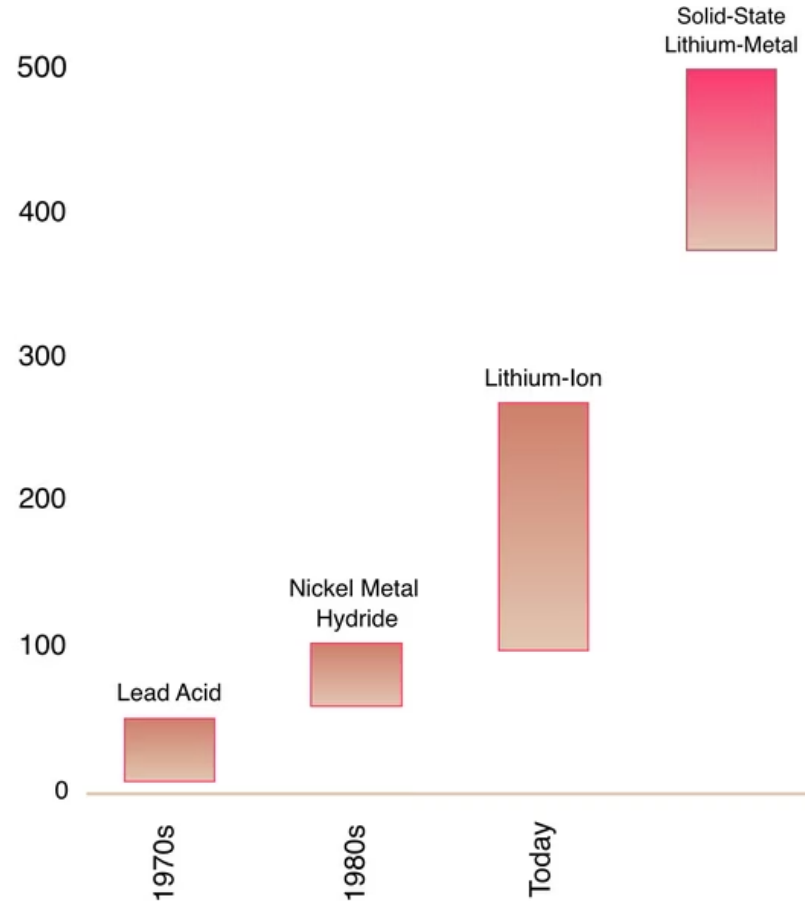


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Energy Density

Cell Mass-specific Energy (Wh/kg)



Home Battery

Advantages

- Store energy generated by solar panels.
- Using an EMS (Energy Management System) you could trade at the energy market.
- To be used for peak shaving.

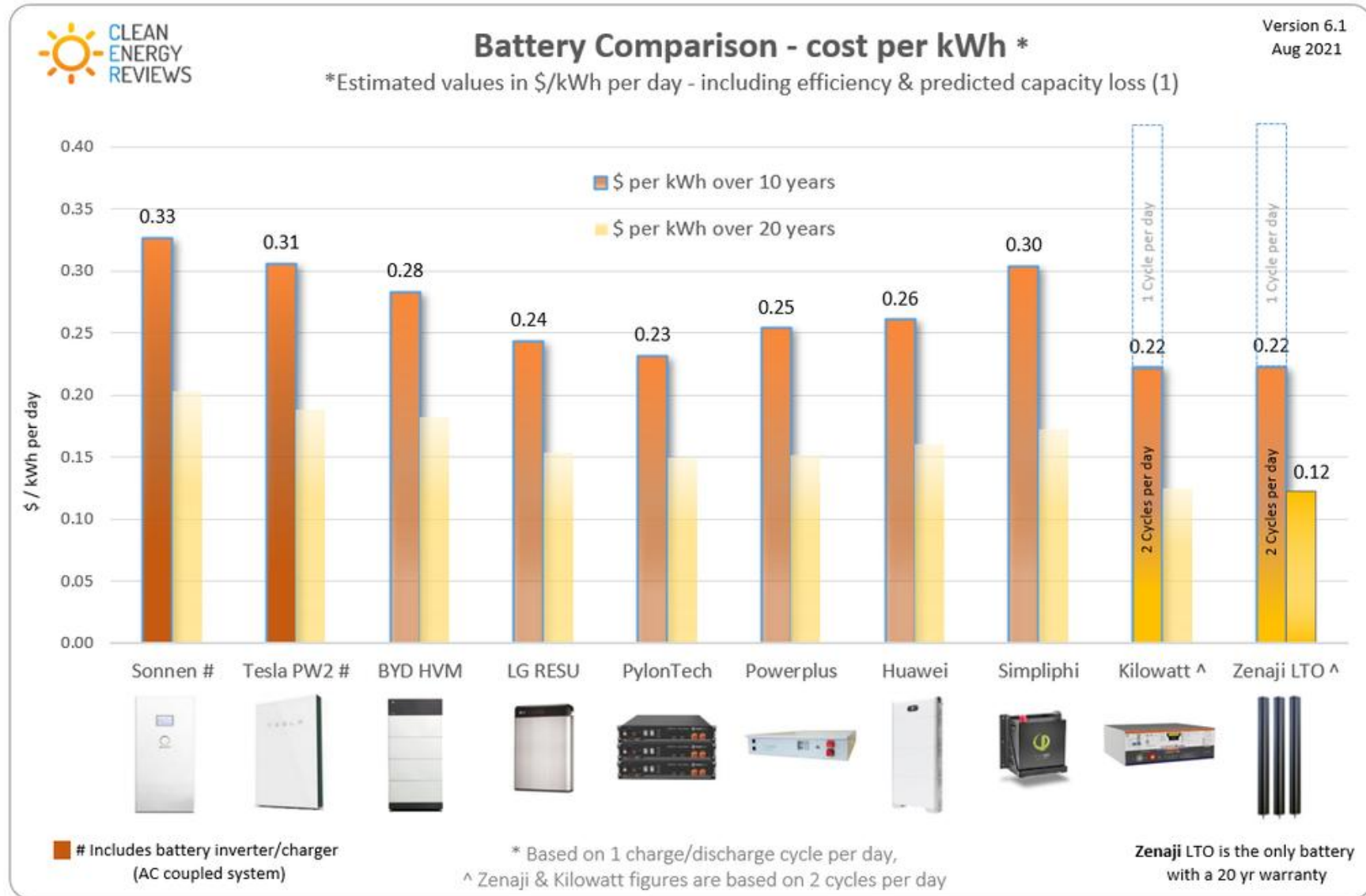


Disadvantages

- Expensive system.
- Difficult to predict payback time (uncertainties).



Home Battery



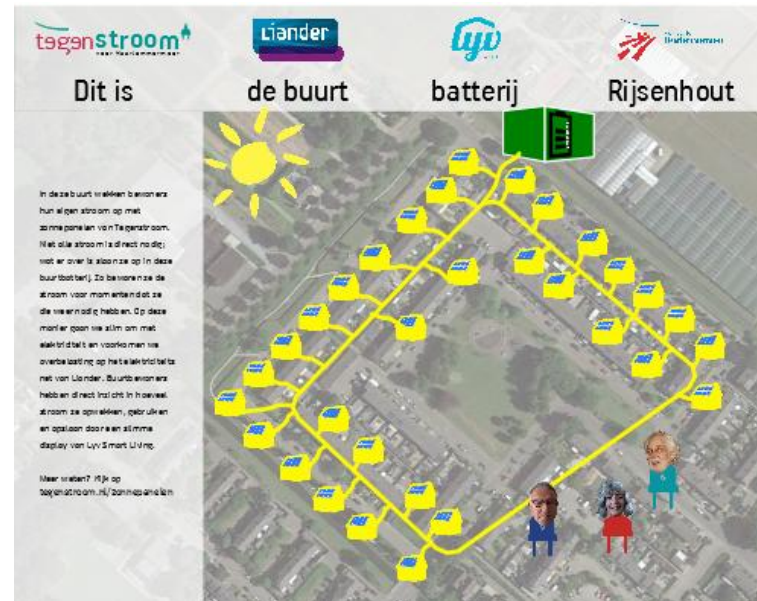
Neighbourhood Battery

Advantages

- Share energy with neighbours (averaging demand).
- Used for peak shaving.
- Preventing additional (expensive) expansion of local grid.

Disadvantages

- Expensive system.



Content references

[What is energy?](#) BBC bitsize

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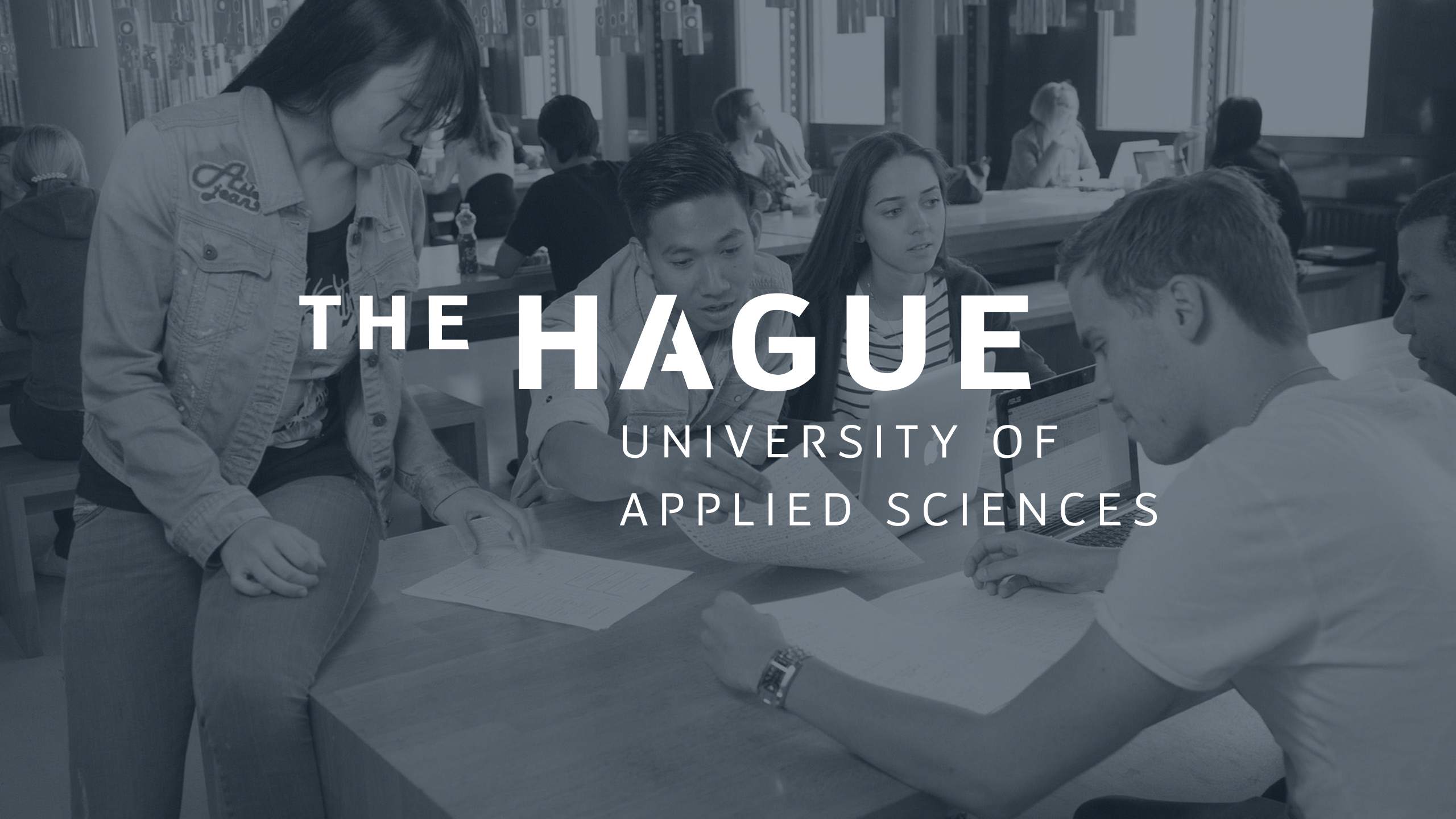
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A grayscale photograph of a modern classroom or study hall. In the foreground, a group of four students are gathered around a table. A young woman on the left, wearing a denim jacket with a 'Live Years' patch, is leaning over and pointing at a document. A young man next to her is also looking at the document. Behind them, another young woman is looking on. To the right, a young man is sitting at the table, looking at a laptop. In the background, other students are seated at long tables, and the room has large windows and decorative elements hanging from the ceiling.

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