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IEEE seminar 4.9.2024 – Hybrid Event at KTH Campus and on Zoom

Key Research Aspects of Green Hydrogen Production

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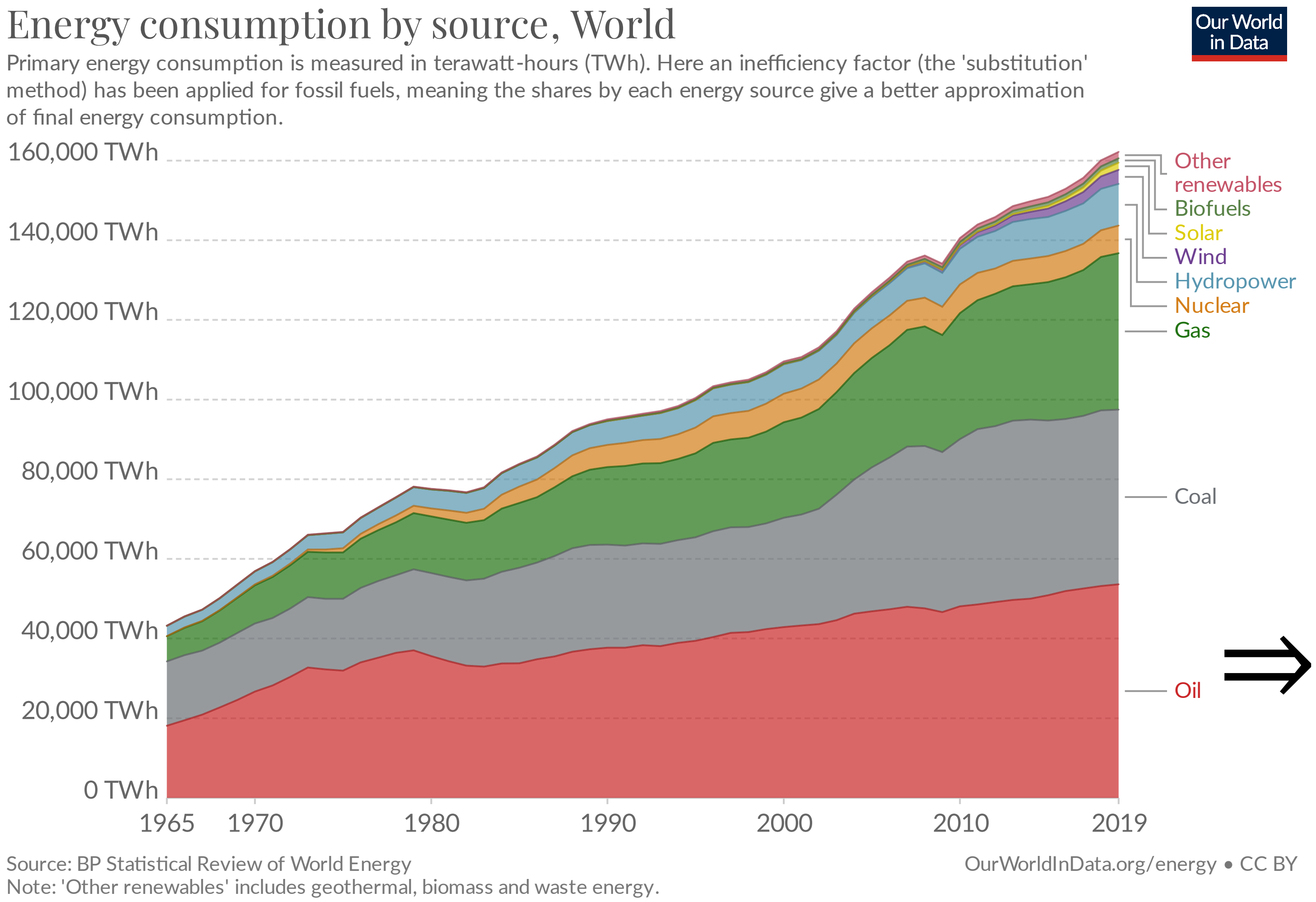
We already live in a hydrogen economy, what's the problem?

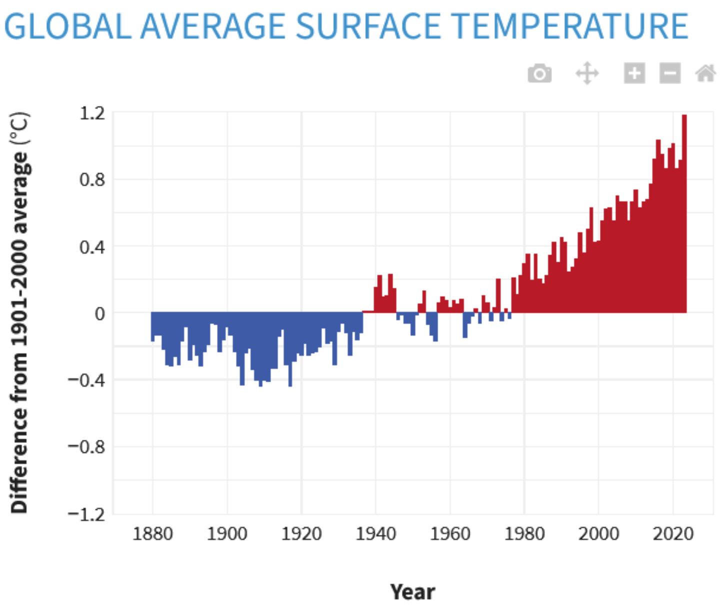


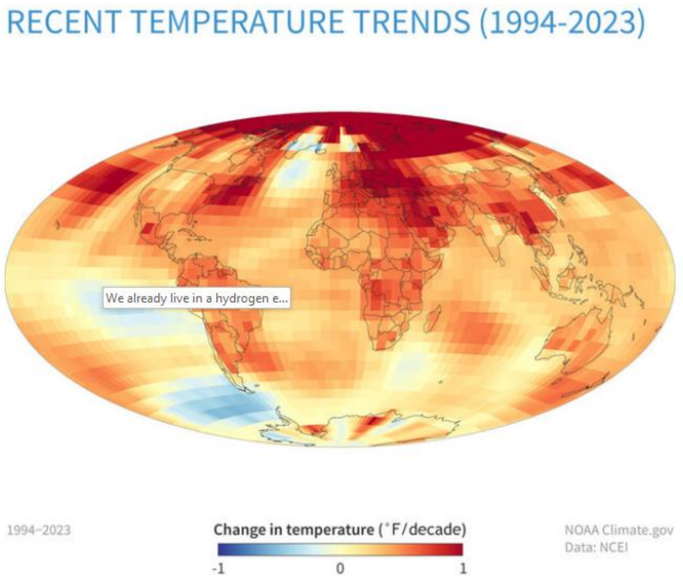
[What is a hydrogen economy?]

⇒

The problem is energy based on combustion, because in our energy sources, hydrogen is bound to carbon. Hydrogen is not available as such.

The goal is net zero emissions by 2050





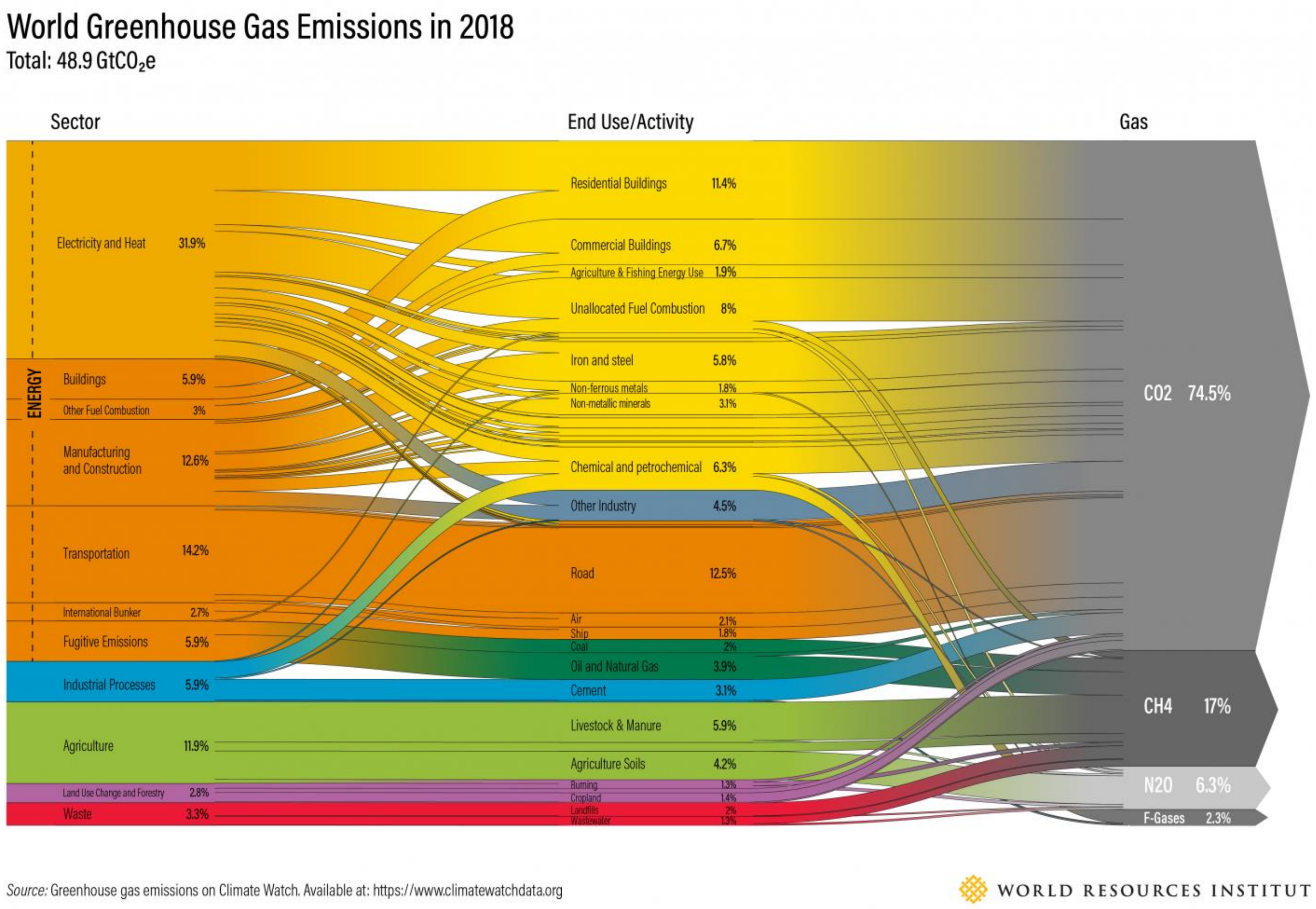
Electricity and heat (32%)

Industry (13%)

Transportation (14%)

Agriculture and land use change (15%)

ENERGY (73 %)



European energy system based on electricity

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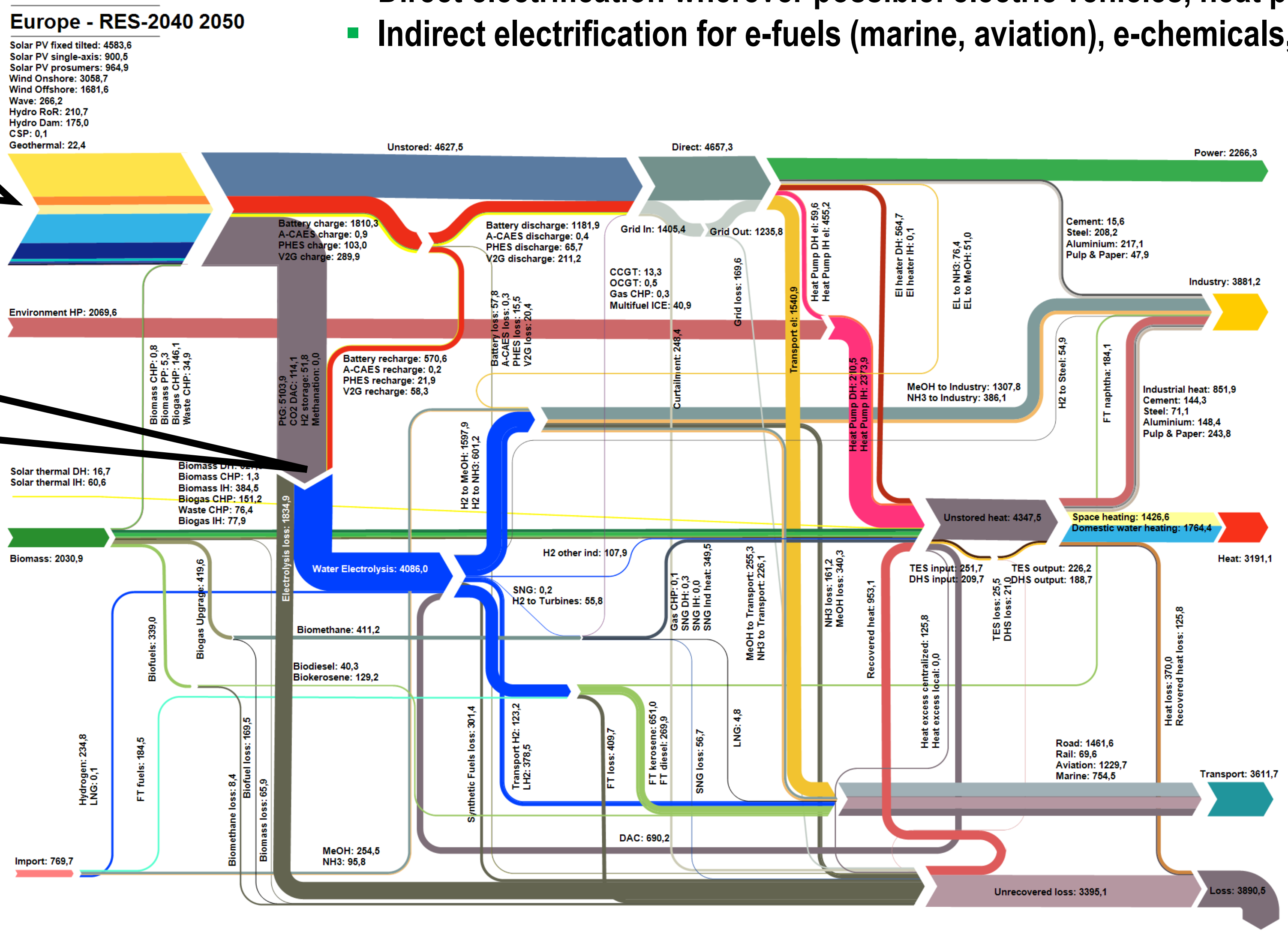
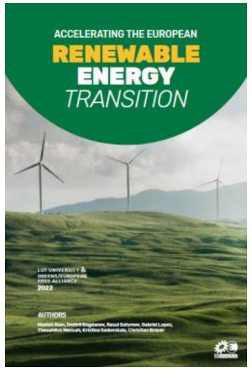
Electricity production 2,641 TWh (40 % RE) in 2022

- Zero CO_2 emission low-cost energy system is based on electricity (need about 12,000 TWh)
- Core characteristic of energy in future: Power-to-X Economy
  - Primary energy supply from renewable electricity: mainly solar and wind power
  - Direct electrification wherever possible: electric vehicles, heat pumps, desalination, etc.
  - Indirect electrification for e-fuels (marine, aviation), e-chemicals, e-steel; power-to-hydrogen-to-X

Electrical energy

Hydrogen economy is a subset of power-to-x - economy





Europe

Source:

Greens/EFA, 2022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POWER-TO-X

Industrial scaleup of green hydrogen – What might happen?

Main commercial water electrolyzer technologies

- Alkaline water electrolyzer (AWE)
  - Mature technology, but designed to operate at nominal point
  - Ready to scale up now → technology will be improved through the industry
- Proton exchange membrane water electrolyzer (PEMWE)
  - No liquid electrolyte, wide operation range
  - Industrial scale, but noble catalyst materials (iridium, platinum) restrict scaling up and decreasing the cost
- Solid oxide water electrolyzer (SOWE)
  - High operating temperature (700−1000°C) and efficiency at nominal point
  - Not industrial scale, problems to operate in partial loads and degradation of materials

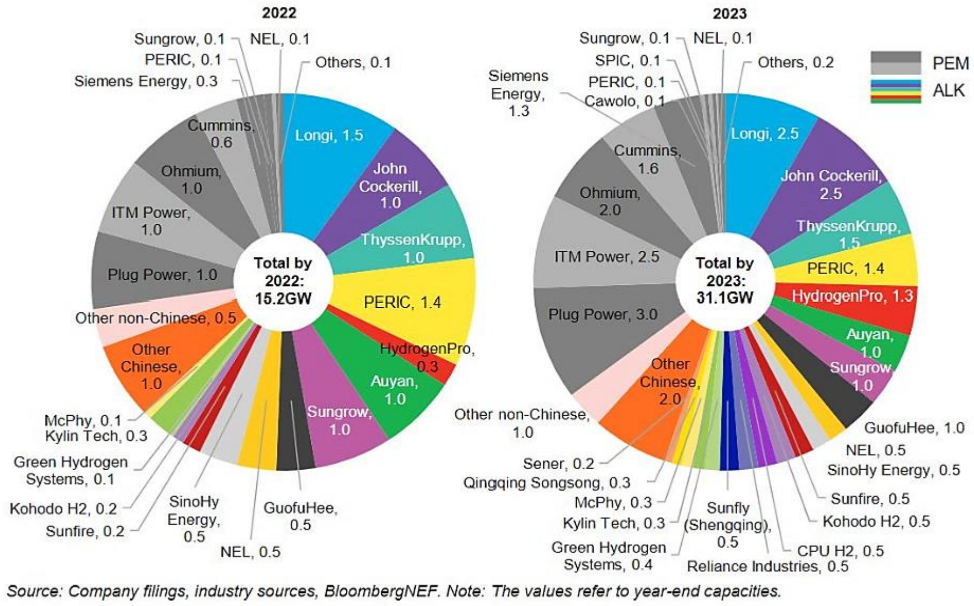

Fig. Annual electrolyzer manufacturing capacity. BloombergNEF

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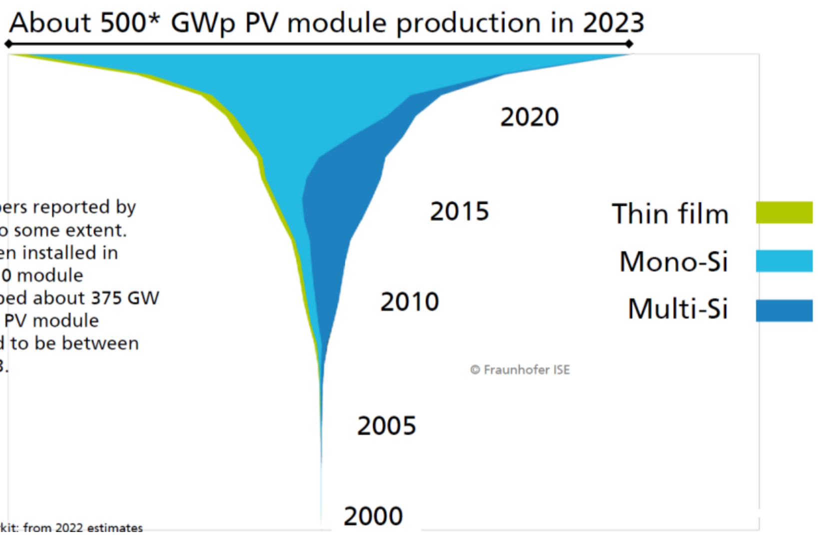
⇒ Most of the improvements are made elsewhere than in electrochemistry. Technology is scaling up now. Key technology in research!

⇒ How much to invest in research? High risk that these are not winning technologies in industry. To be used in special applications.

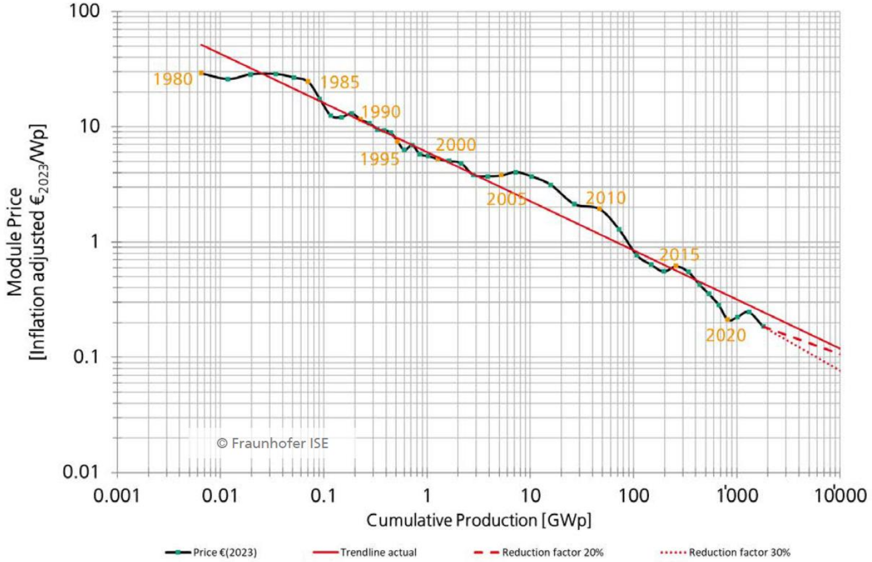
What have we learnt from solar power markets?

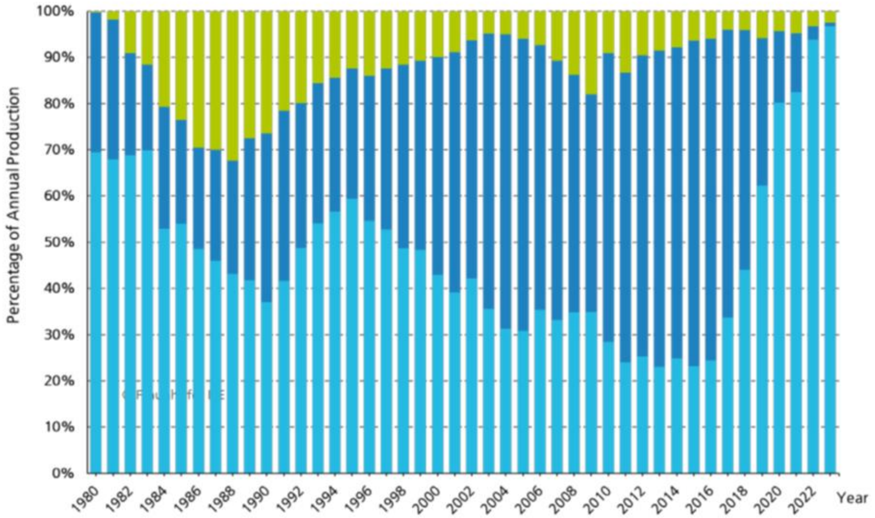


*2023 production numbers reported by different analysts vary to some extent. About 410 GW have been installed in 2023 globally. The TOP10 module producer together shipped about 375 GW PV panels in 2023. Total PV module shipments are estimated to be between 460 and 502 GW in 2023.

Navigant: from 2010 to 2021 IHS Markit: from 2022 estimates

1. **Scaling up**
2. **Technology**
3. **Cost**
4. **Efficiency**



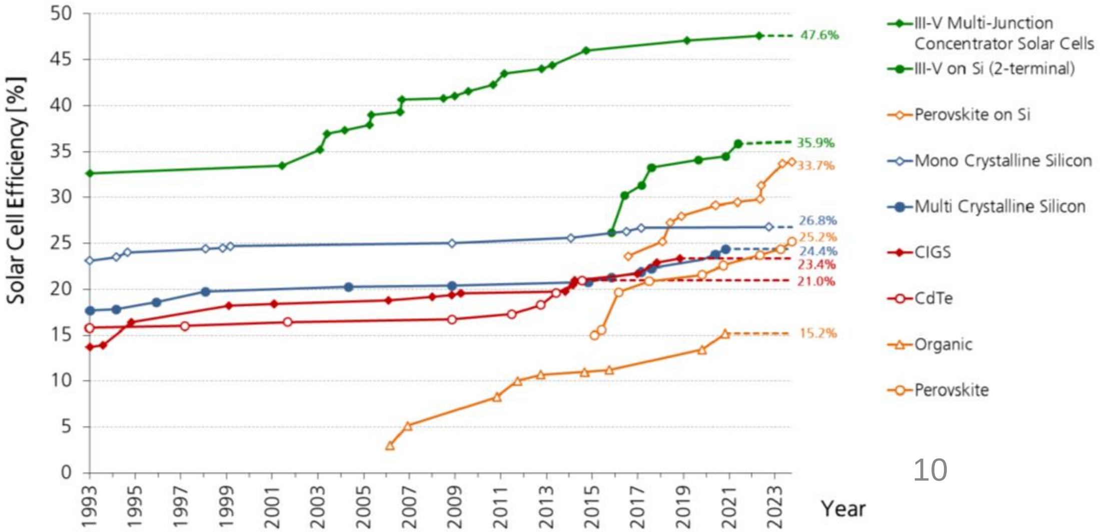


Production 2023* (GWp)

Thin film	13	
Multi-Si	4	
Mono-Si	485	
Total	502	(ITRPV)

*estimated numbers

Source: Photovoltaics report.



How to produce cheap green hydrogen?

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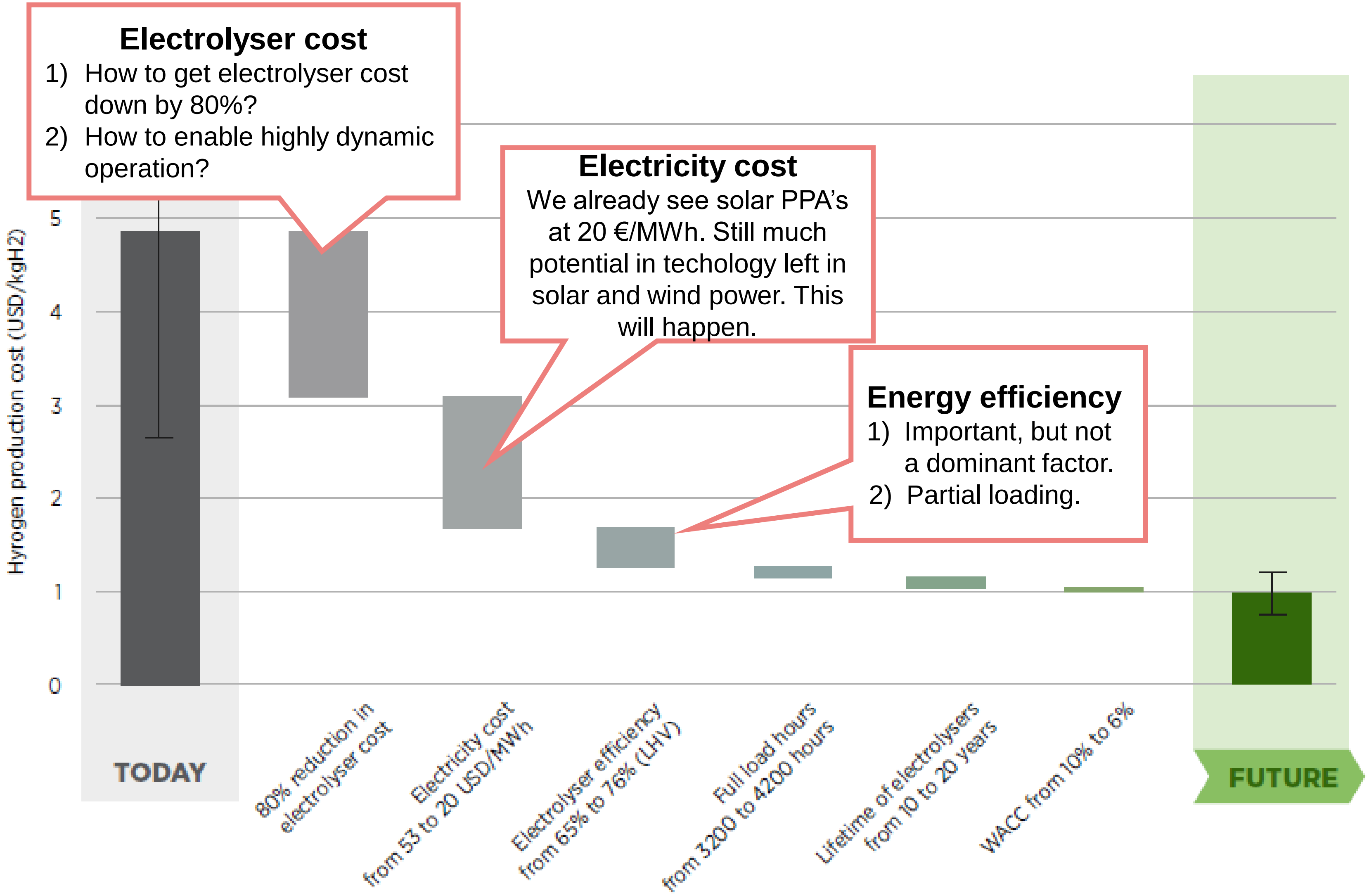

Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

IRENA (2020), [Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 °C climate goal](), International Renewable Energy Agency, Abu Dhabi.

Green hydrogen production based on wind and solar electricity

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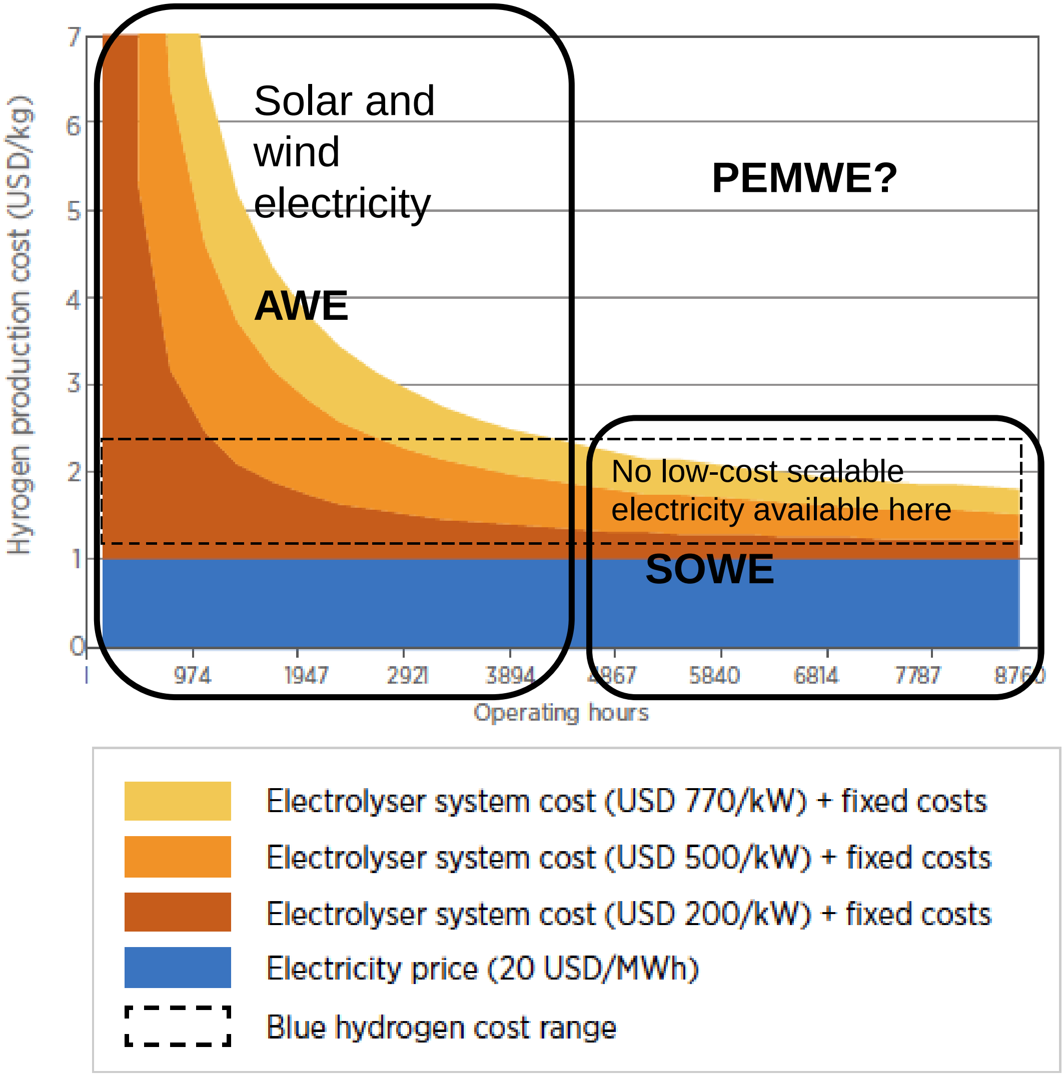
Effect of intermittency of electricity supply



Cost composition of alkaline water electrolysis

Electrolyzer plant size matters. 100 MW plant has significantly lower specific investment cost than 5 MW plant

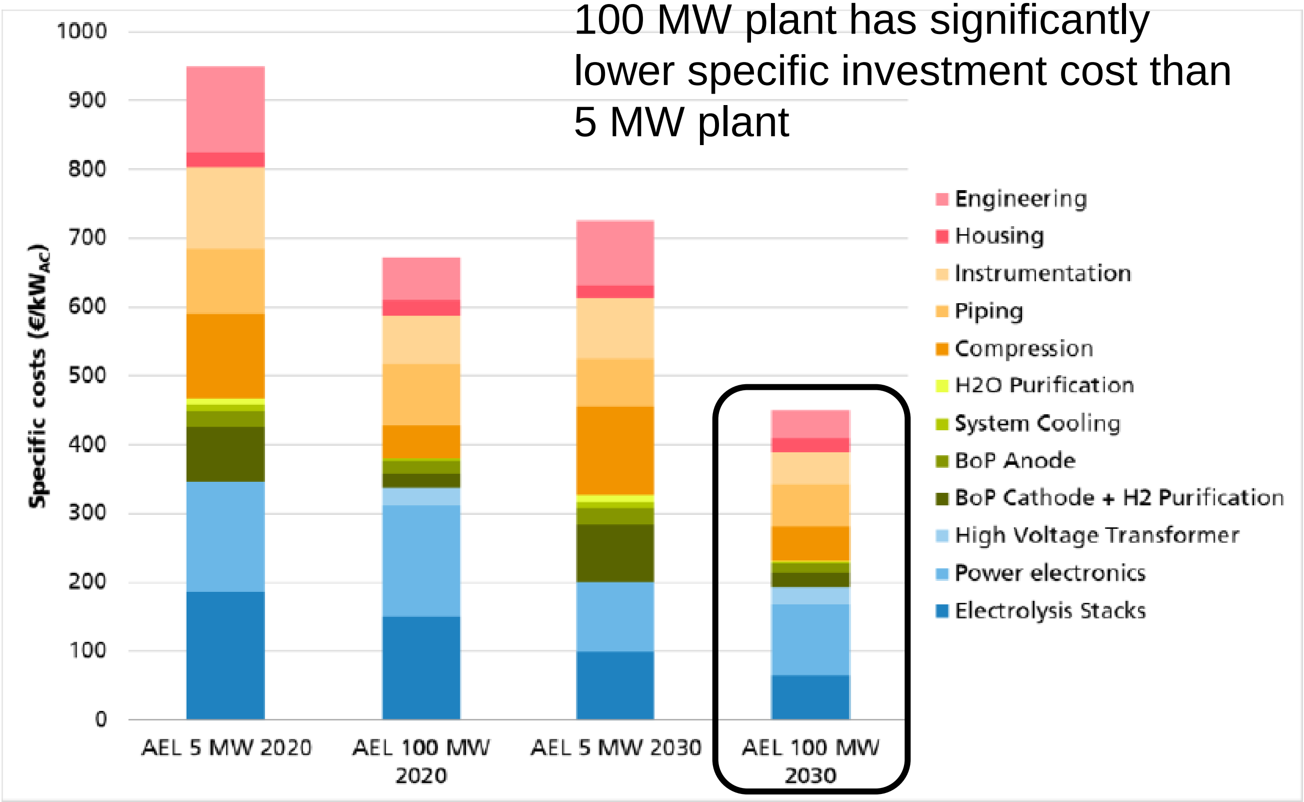


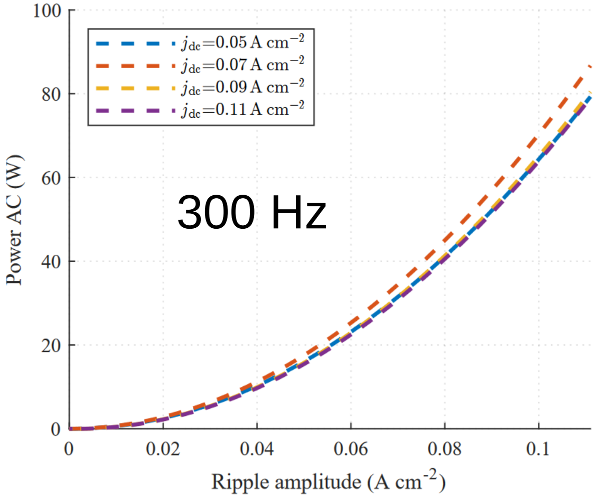
Figure 3-6: Specific costs of 5 MW and 100 MW next generation AEL systems (including mechanical compressors) for the design scenarios 2020 and 2030

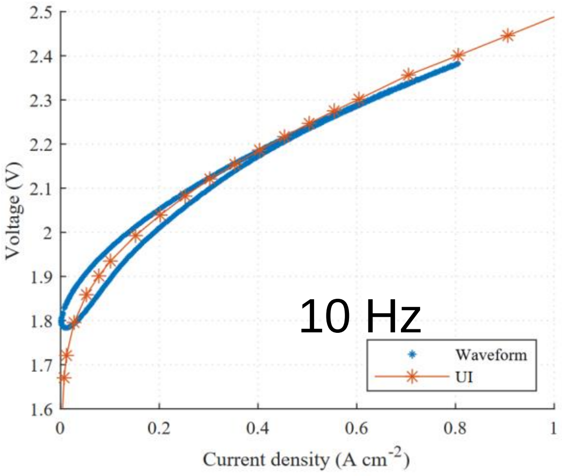
Source: M. Holst, S. Aschbrenner, T. Smolinka, C. Voglstätter, G. Grimm, Cost forecast for low-temperature electrolysis – Technology driven bottom-up prognosis for PEM and alkaline water electrolysis systems, Fraunhofer ISE, Oct. 2021.

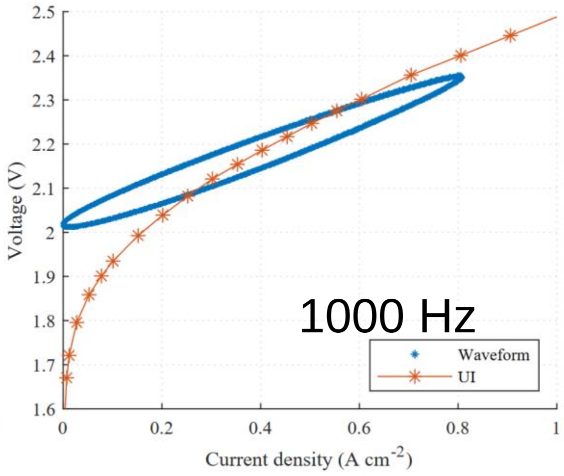
Role of power electronics?

Power quality effect on AWE performance (1/2)

- Järvinen et al: "Applicability of linear models in modeling dynamic behavior of alkaline water electrolyzer stack", Renewable Energy, 2024:
  - 3 kW AWE stack was used to conduct performance measurements under dynamic current supply
    - Ripple amplitude clearly increased the losses of the electrolyzer stack
    - At high frequencies (>300 Hz) the electrolyzer behaves as linear impedance load
  - Applicability of linear models was studied in the case of dynamic operation of the AWE
    - Tangent based linear approximation were found to give satisfactory results when the ripple frequency is high (>600 Hz)

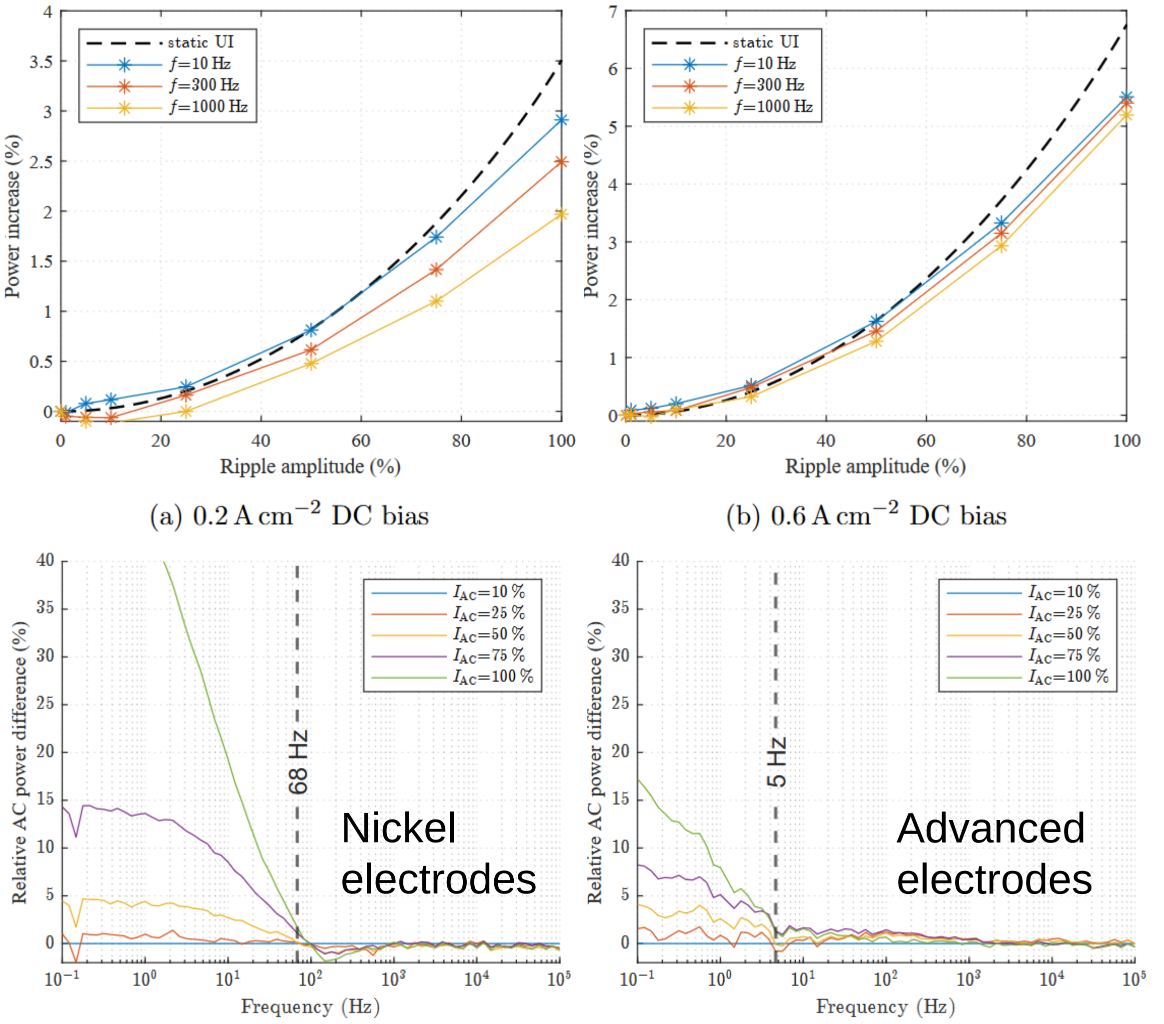






Power quality effect on AWE performance (2/2)

- Järvinen et al. "Experimental Study of Alkaline Water Electrolyzer Performance and Frequency Behavior Under High Frequency Dynamic Operation", International journal of hydrogen energy, 2024
  - Clear increase in power usage seen when ripple amplitude is increased
  - Ripple frequency counteracts the losses coming from ripple
    - Losses are reduced up to 32% when increasing frequency from 10 Hz to 1 kHz and 20% when moving from 300 Hz to 1 kHz (0.2 A cm^{-2} bias)
    - Frequency has high impact when operating at partial loads
  - Linearization frequency determined for two different electrode sets
    - Electrolyzer behaviour linearizes after 68 Hz when using nickel based electrodes
    - With more advanced electrode materials the linearization occurs after 5 Hz

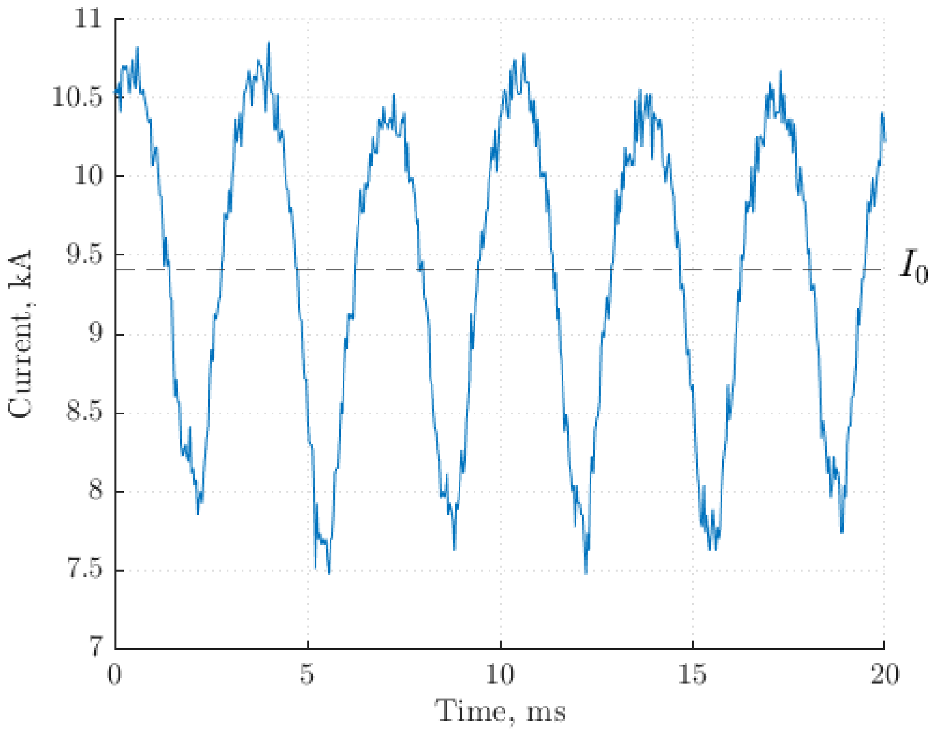


Industrial systems

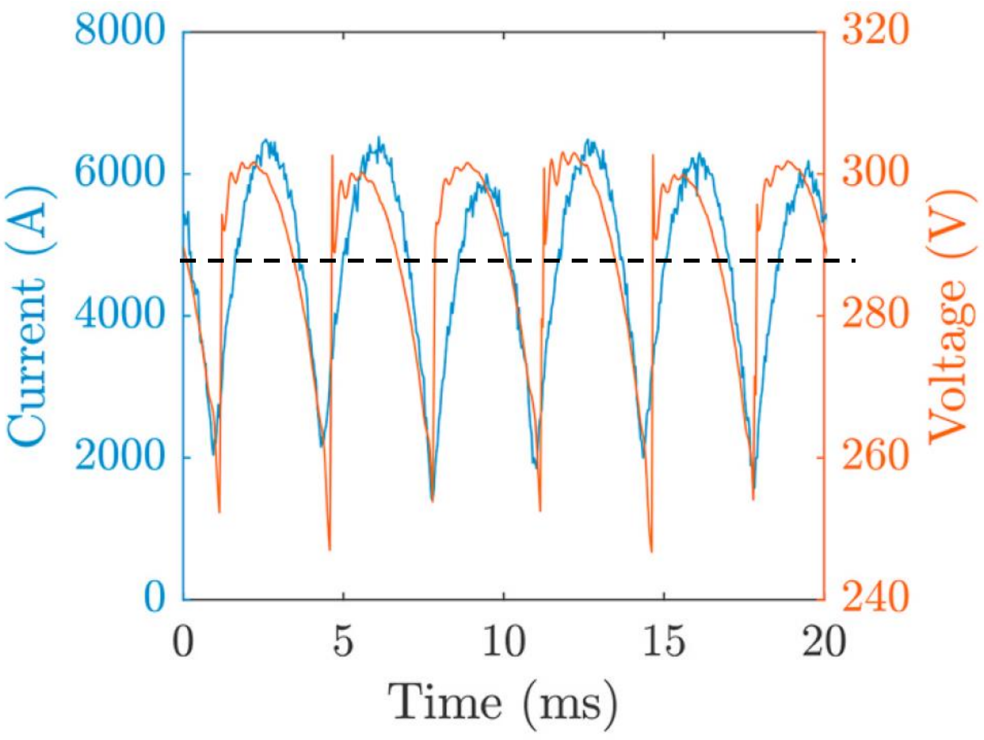
See: Comparison of different power supply technologies

- With an industrial electrolyzer the current always contains ripple from power electronics (source) → Voltage response also contains ripple
- Ripple is relatively highest in the partial loading

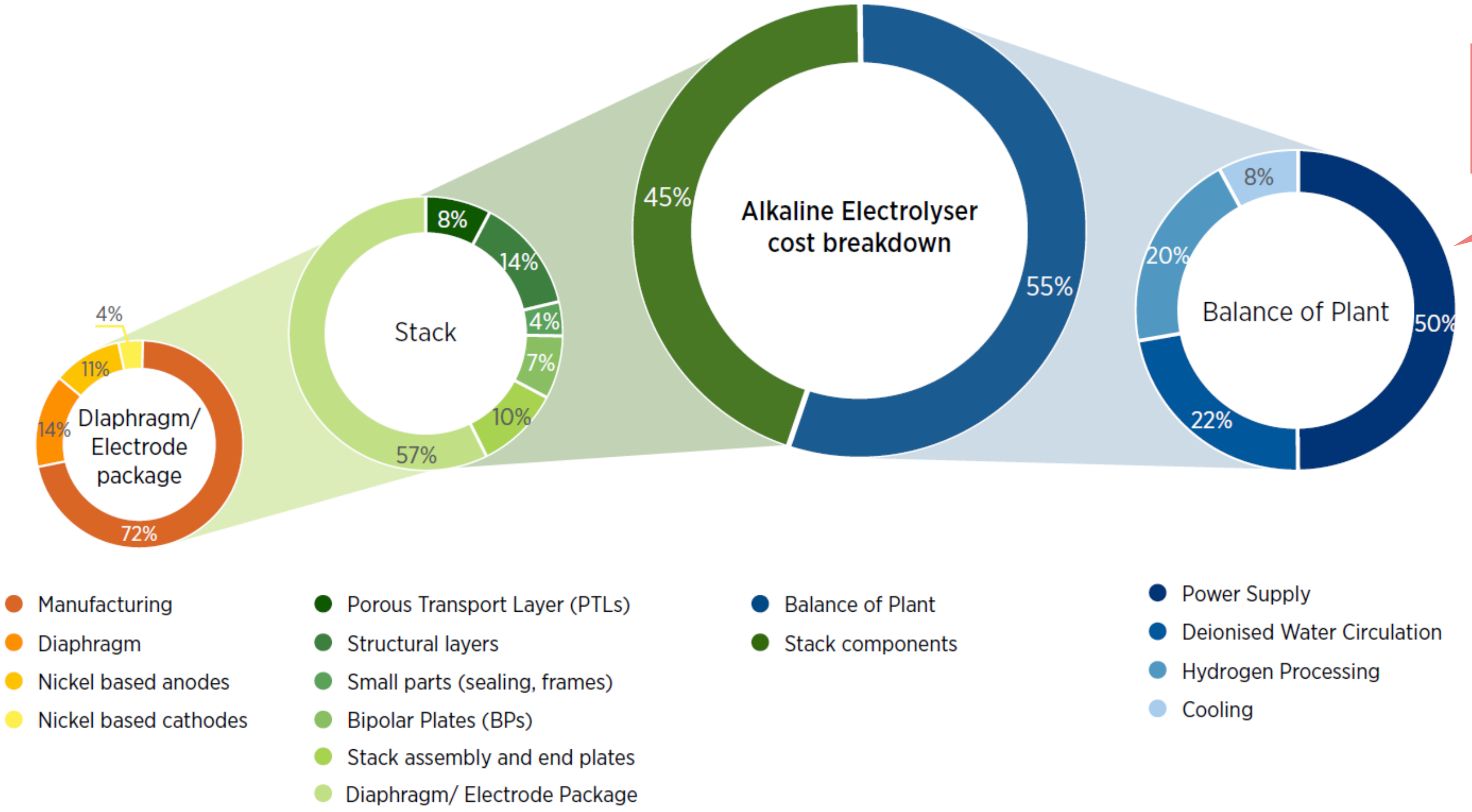
100% load, 6-pulse thyristor rectifier



50% load, 6-pulse thyristor rectifier



Cost structure of alkaline water electrolyzer



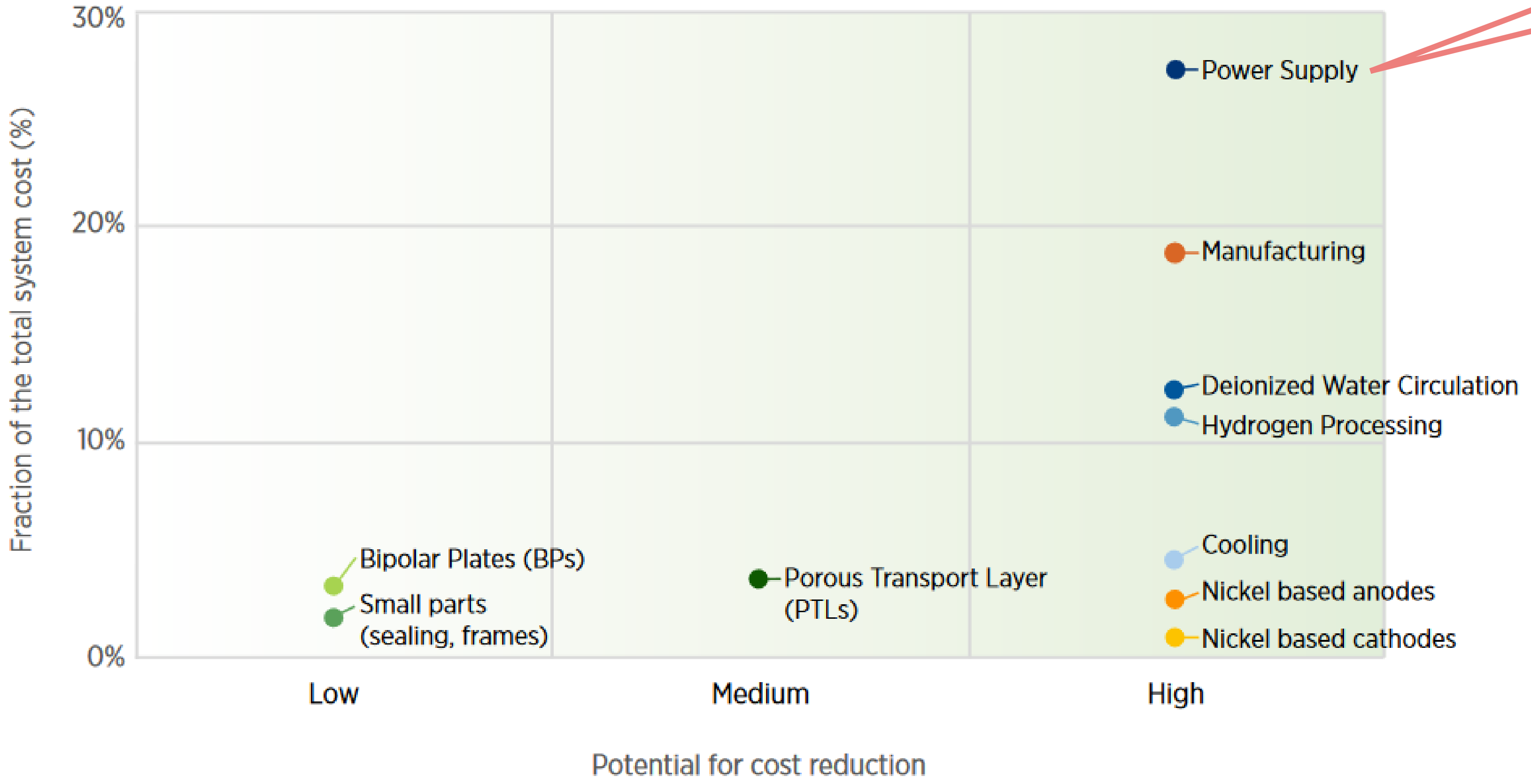
Power electronics
Electrical current defines the cost

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Potential cost savings in AWE

Voltage level elevation
Same power electronics can be used as in solar power.
Electrolysis stack voltage should be increased from 300 V to 1500 V!

Figure 21. System components for a 1-MW alkaline electrolyser classified based on contribution to total system cost and potential for cost reduction.



https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

AWE is mature technology – Nothing to study?

From electricity to chemical energy – Hydrogen production by alkaline water electrolyzer (AWE)

Fig. 3x3 MW alkaline water electrolyzer (AWE).

Summary:

- Located in Kokkola, Finland
- Power-to-Hydrogen: 1800 Nm^3/h (H_2)
- 3x3 MW pressurized alkaline water electrolyzers, 3x600 Nm^3/h, 16 bar (H_2)
- The main use of H_2 plant is at nearby Cobalt plant, hydrogen delivery by a pipeline
- The rest of H_2 compressed to 200–300 bar and stored in bottles for delivery with trucks

G. Sakas, A. Ibáñez-Rioja, V. Ruuskanen, A. Kosonen, J. Ahola, O. Bergmann, Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process, Int. J. Hydrogen Energy 47 (7) (2022) 4328–4345, https://doi.org/10.1016/j.ijhydene.2021.11.126

Alkaline water electrolyzer

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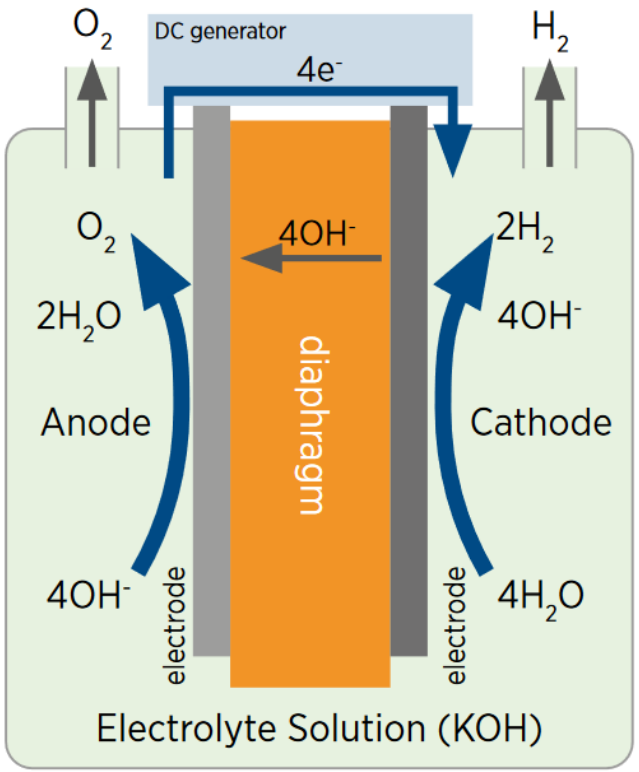
Cell level

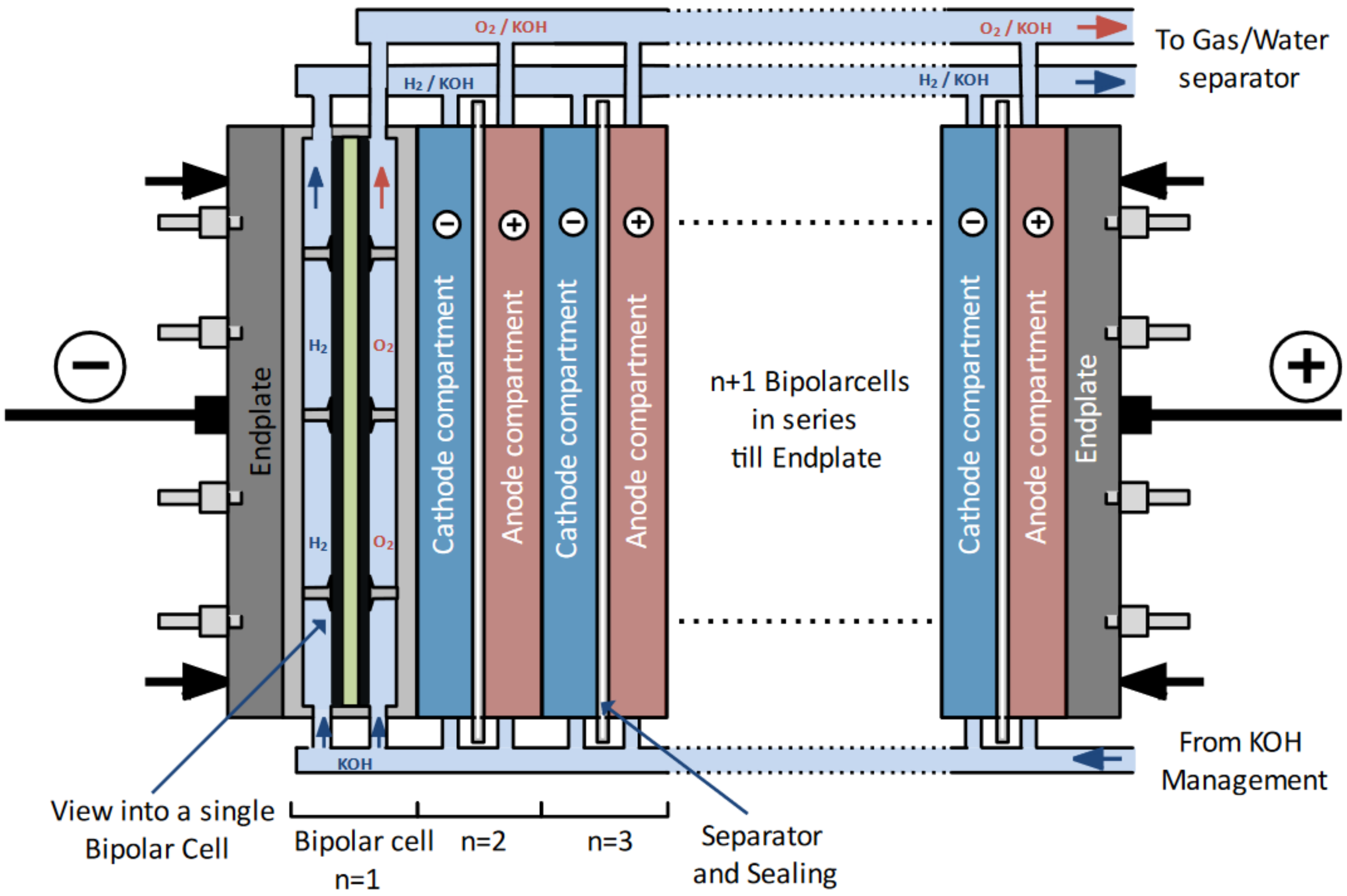


Anode: $4OH^- \leftrightarrow 2H_2O + O_2 + 4e^-$

Cathode: $4H_2O + 4e^- \leftrightarrow 2H_2 + 4OH^-$

[Source]

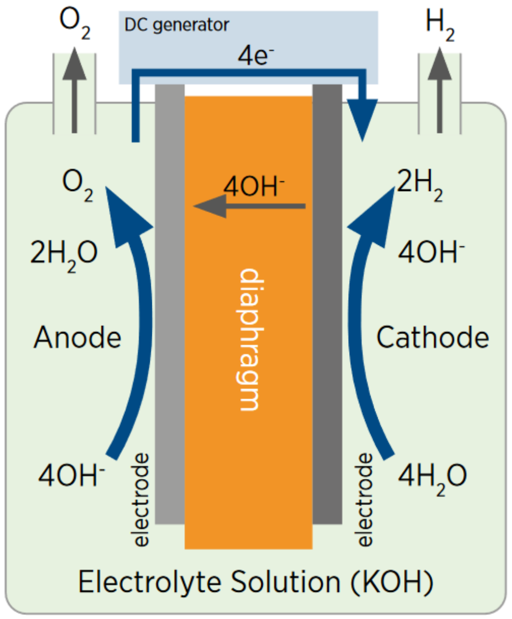
Stack level



[Source]

Shunt currents

- Fluid channels present a parallel path for current, bypassing the electrochemical reaction
  - Total supplied current = effective cell current + shunt current
- I s is (ions,



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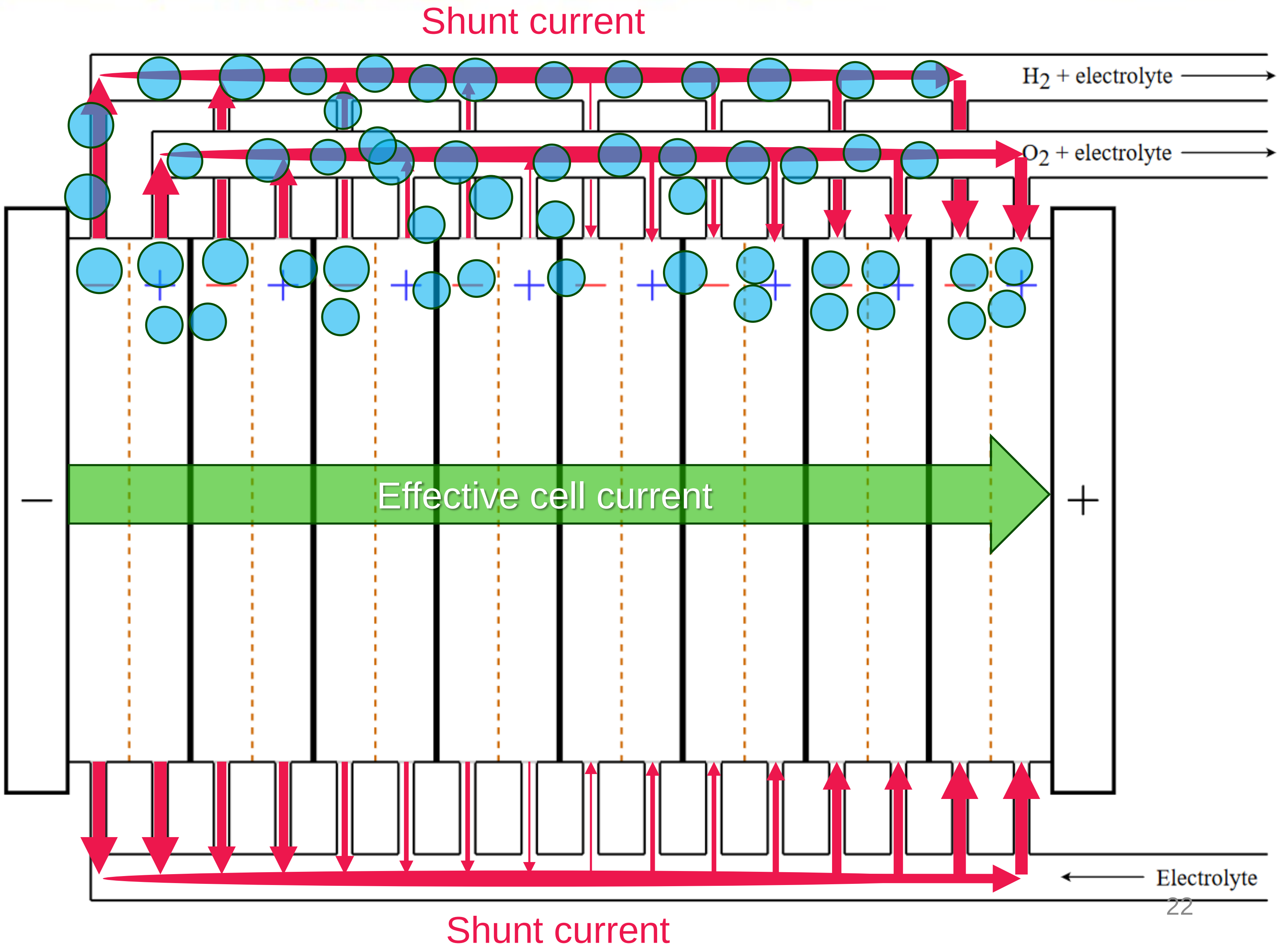
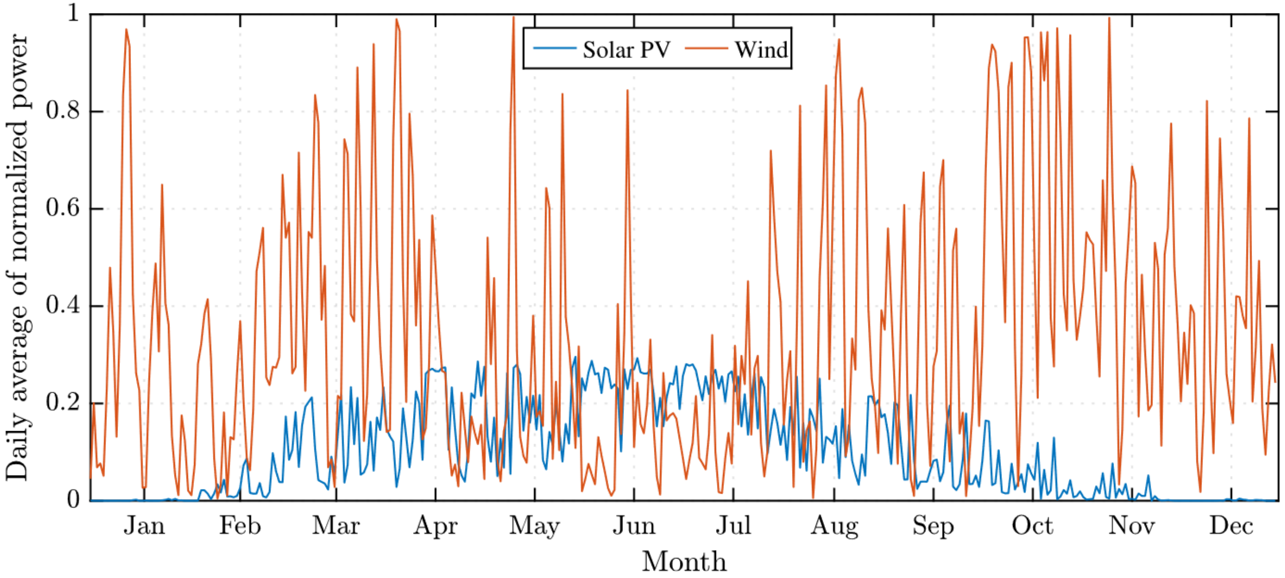
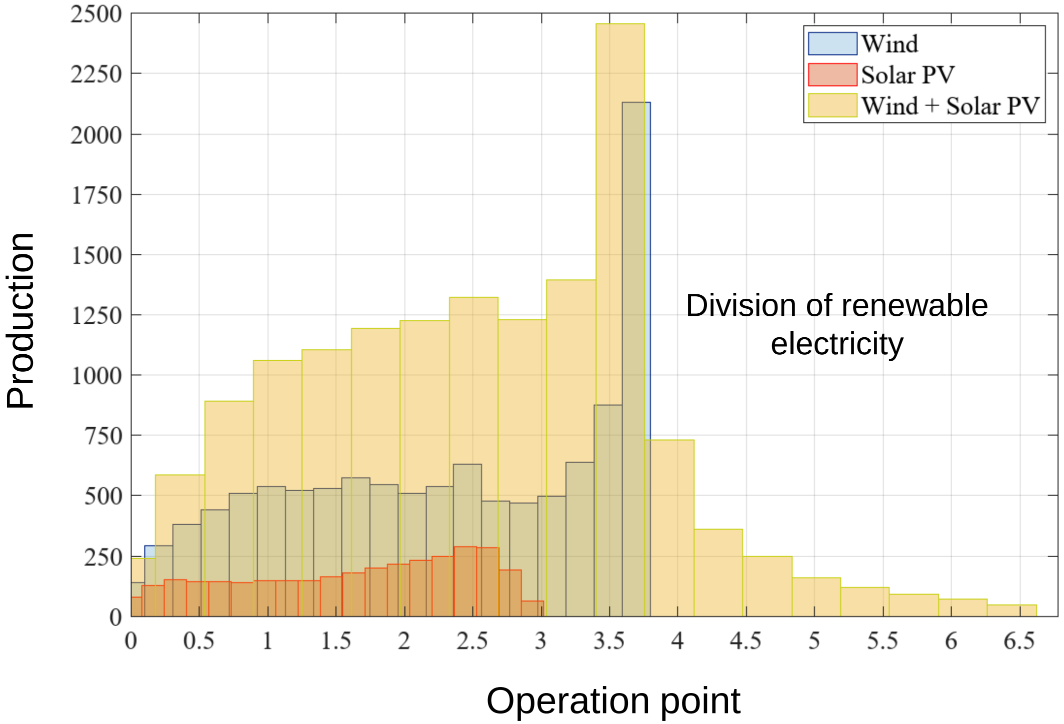


Renewable electricity

- Renewable electricity production has intermittent nature → Dynamics is required
- Most of the hydrogen will be produced under partial loads



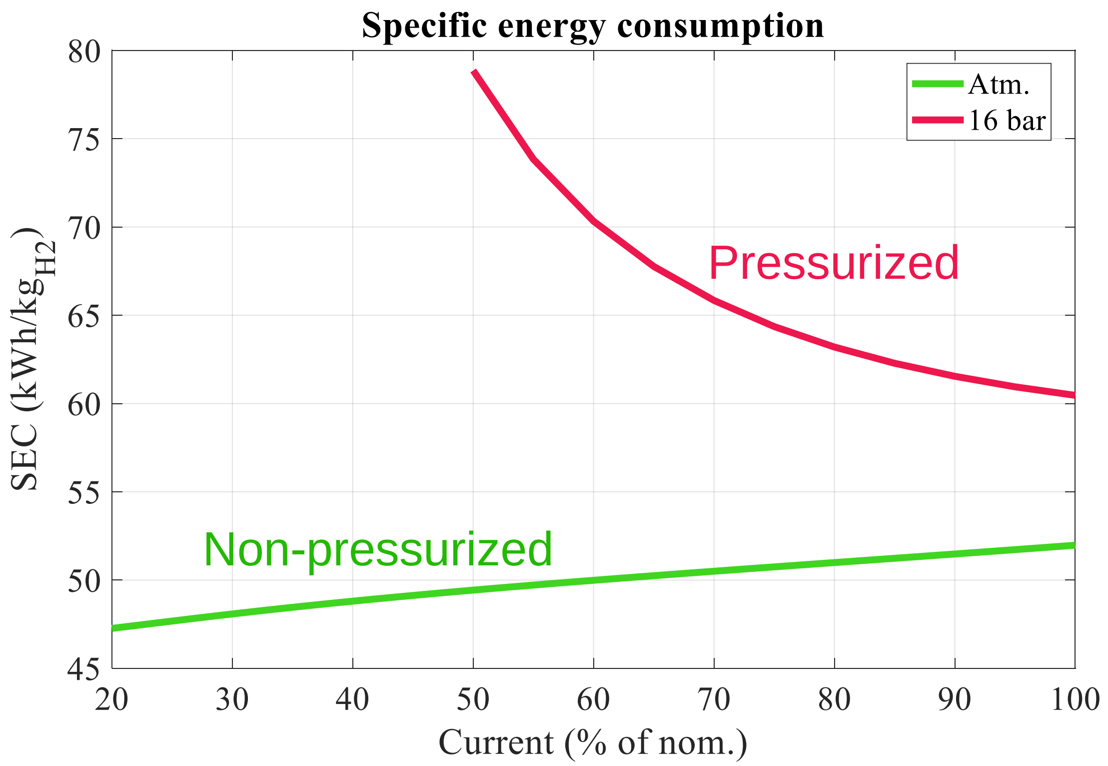


Pressurization

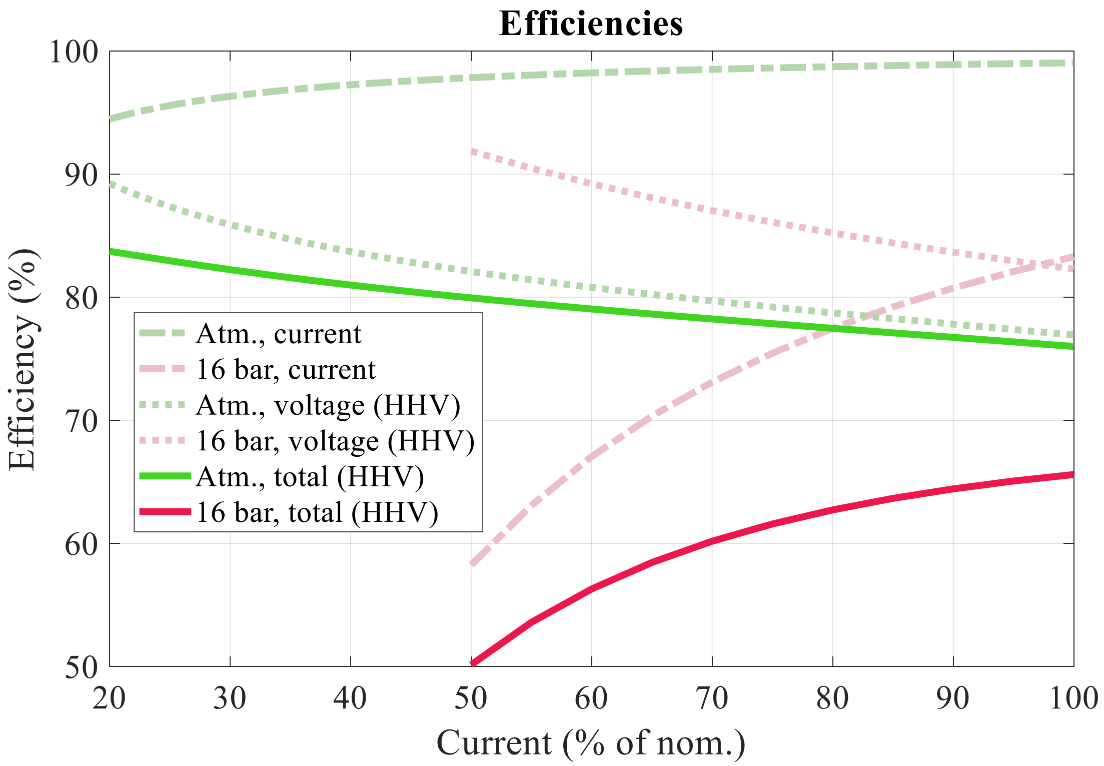
Control range because of impurities!

- There are differences in the designs and parameters (stack length, pressure, etc.)

Two commercial stacks



Efficiencies in detail



Elevated voltage and temperature levels

- Voltage level increase is related to the stack design
  - Cost decrease in power electronics
- Temperature level increase is mainly related to the separator diaphragm material
  - Higher voltage efficiency
  - Higher current densities possible → less cell area required to produce same amount of hydrogen
  - Higher value of waste heat

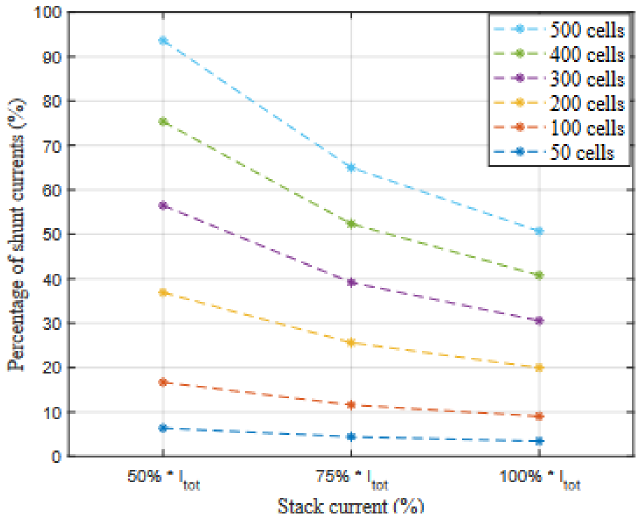


Fig. Shunt currents at partial-load operation for different stack lengths.

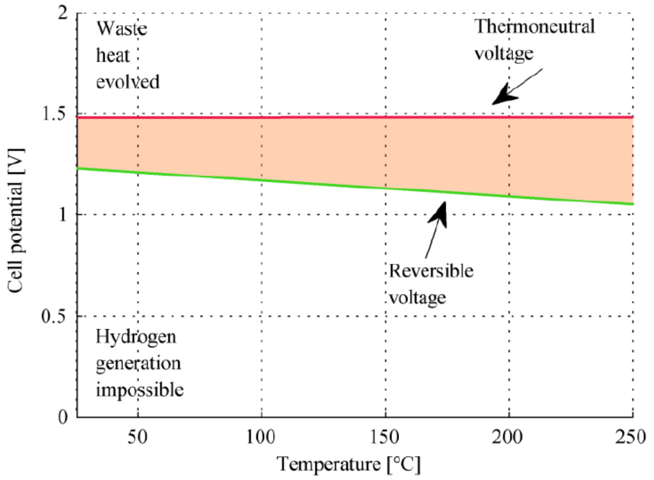


Fig. Example of cell potential as a function of temperature.

Dimensioning green H_2 production plants

GREEN HYDROGEN PRODUCTION PLANT LEVEL

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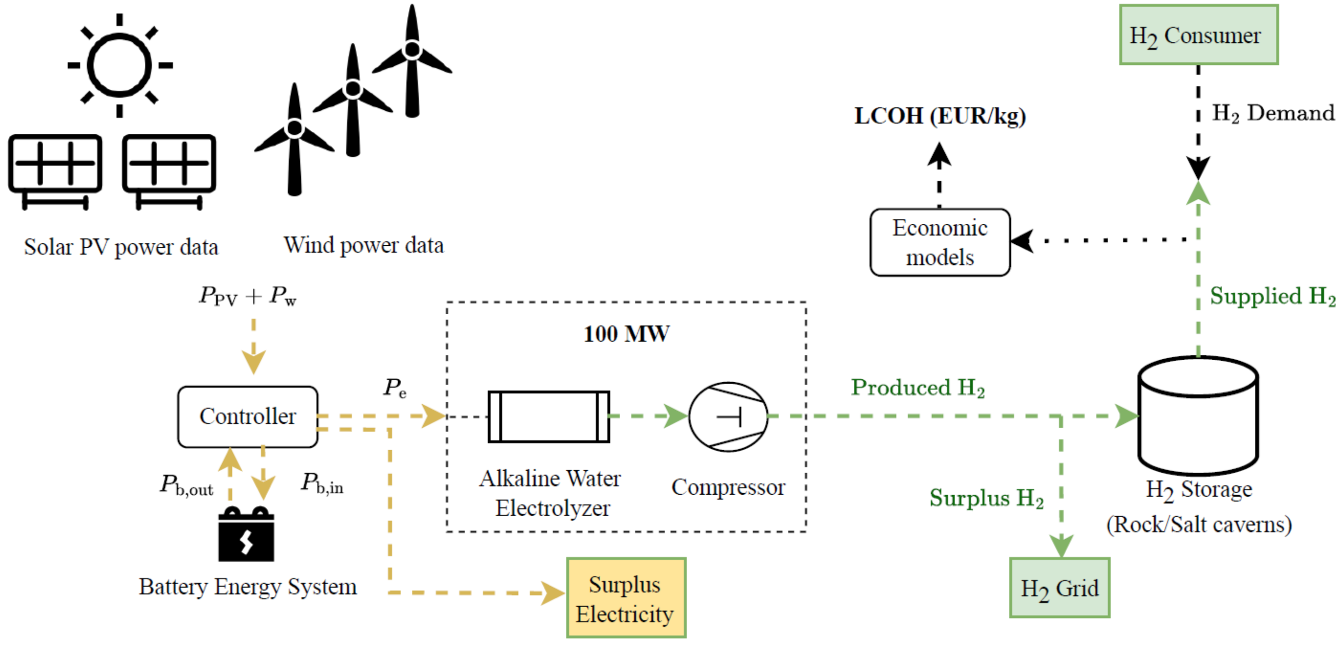
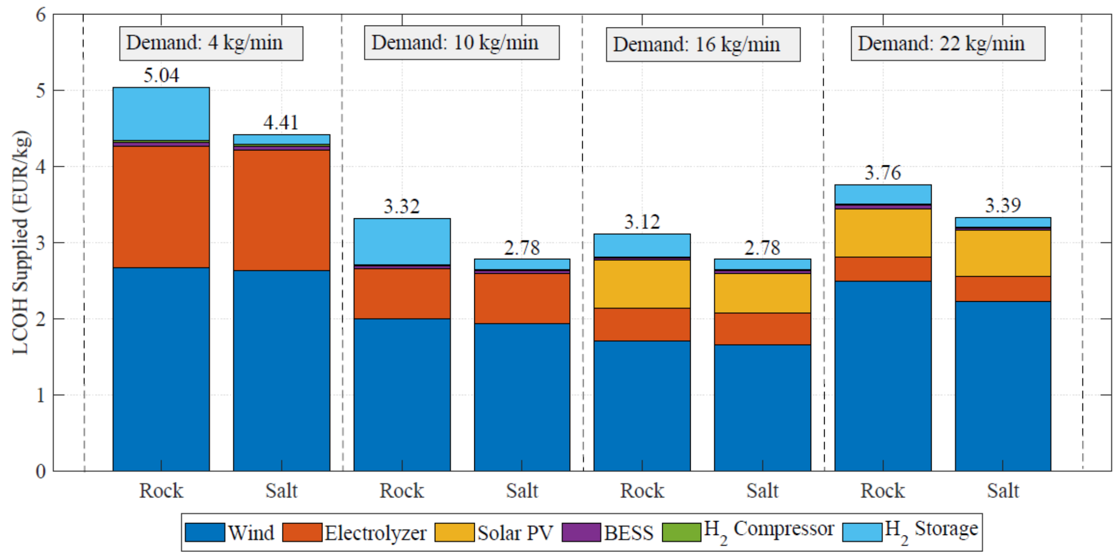
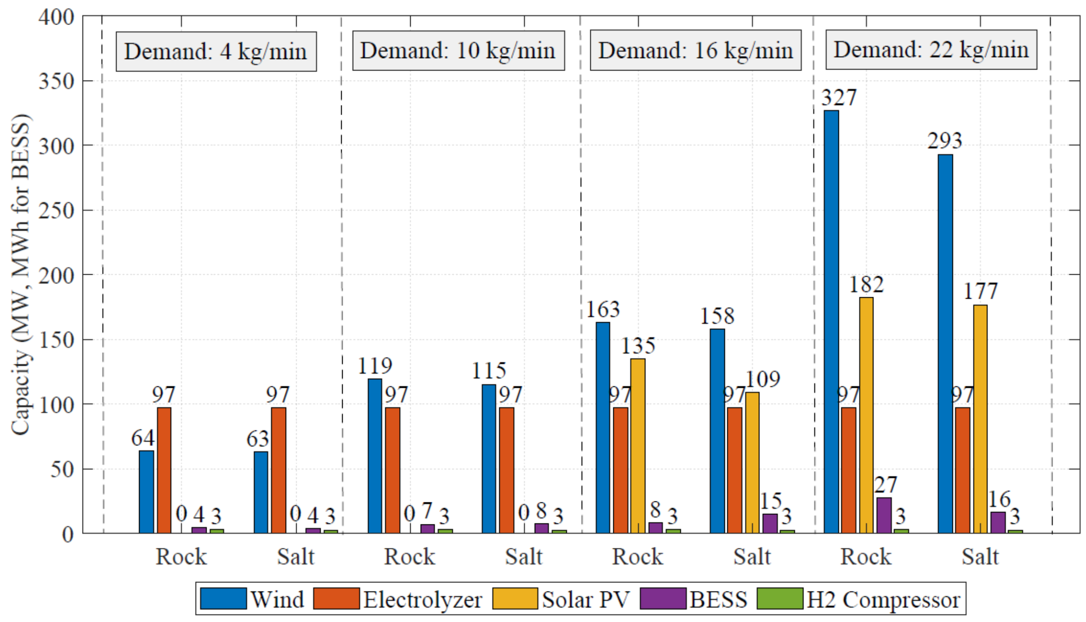
- Simulation and optimization of a complete green hydrogen production system
  - Minimizing LCOH with optimal dimensioning and control of electrolyzer, battery, wind and solar, storage, and compression, based on certain H2 demand







ELECTROLYZER WASTE HEAT RECOVERY

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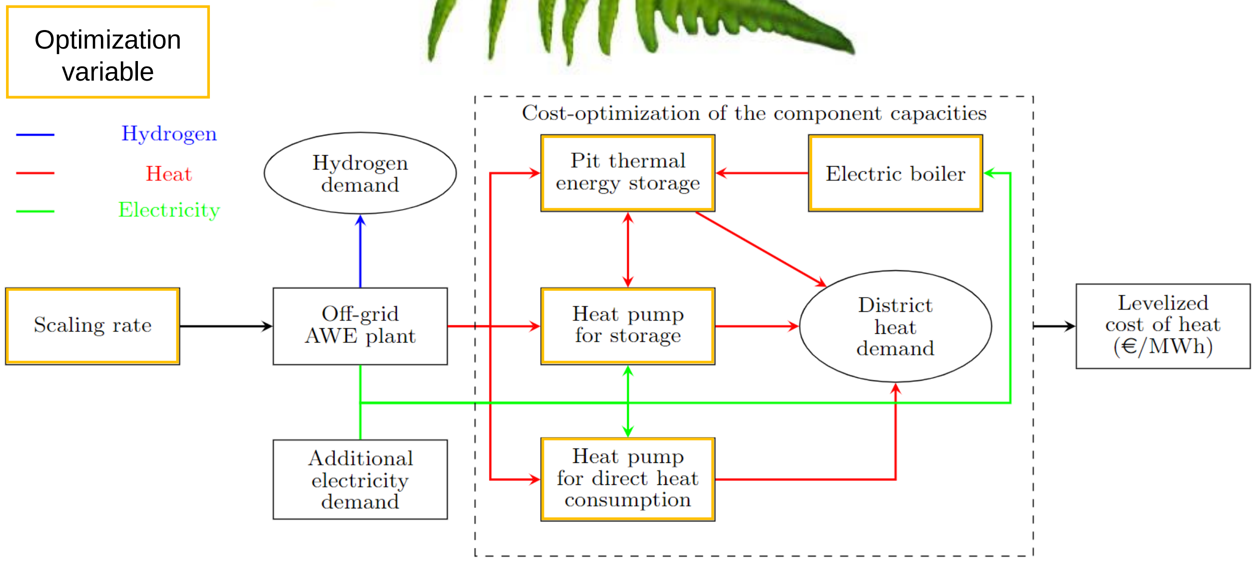
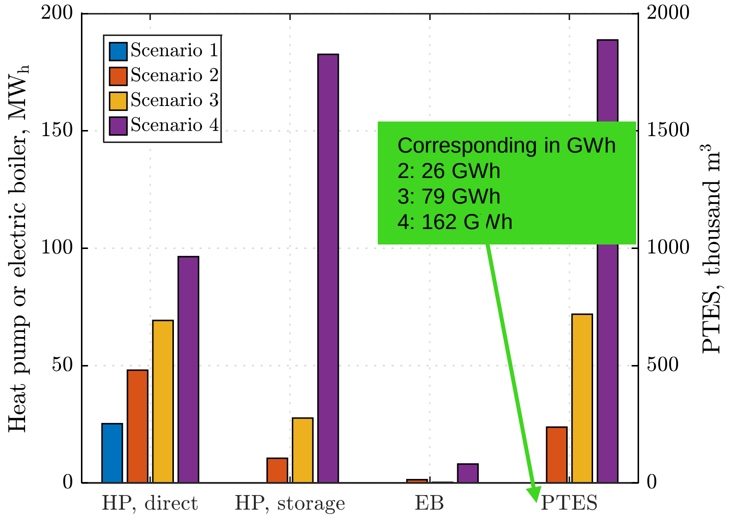
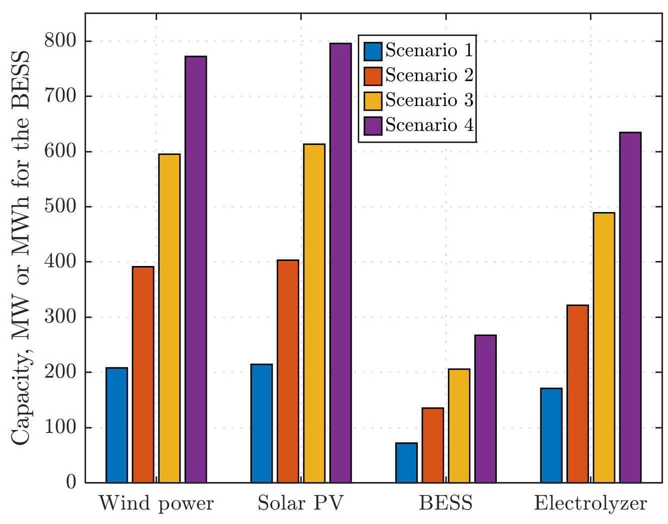
- Meriläinen et al: ”Techno-economic evaluation of waste heat recovery from an off-grid alkaline water electrolyzer plant and its application in a district heating network in Finland”, Energy, 2024:
  - Considerable amounts of electrolysis-based waste heat will be available in the future
  - Cost-optimization of component capacities is performed for different DH energy demand coverage rate requirements
    1. Maximization of the DH demand coverage rate without the PTES and the electric boiler
    2. 50–55% DH demand coverage
    3. 75–80% DH demand coverage
    4. 100% DH demand coverage
  - In all scenarios, at least 95% of the waste heat generated must be recovered
  - Measured district heat demand data from a medium-sized city in Finland was used





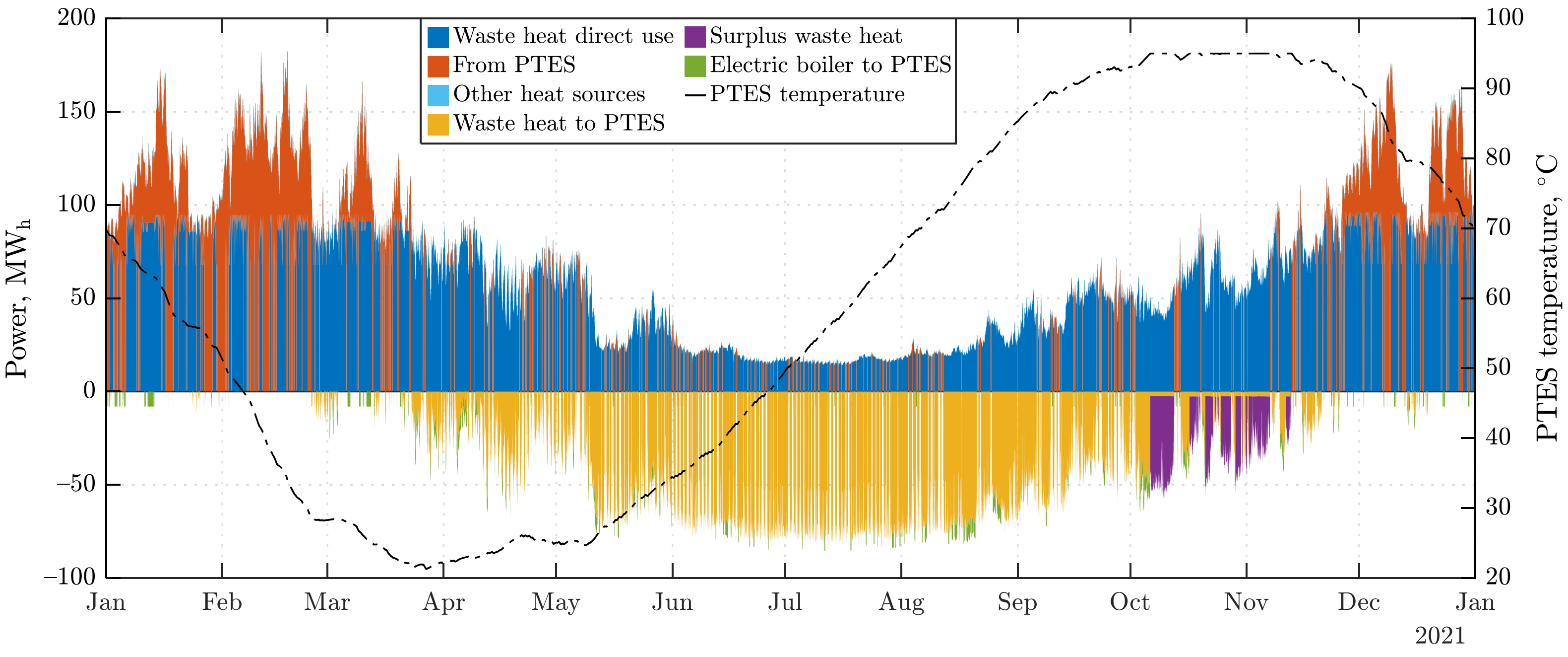
Dimensioning of the waste heat recovery system.



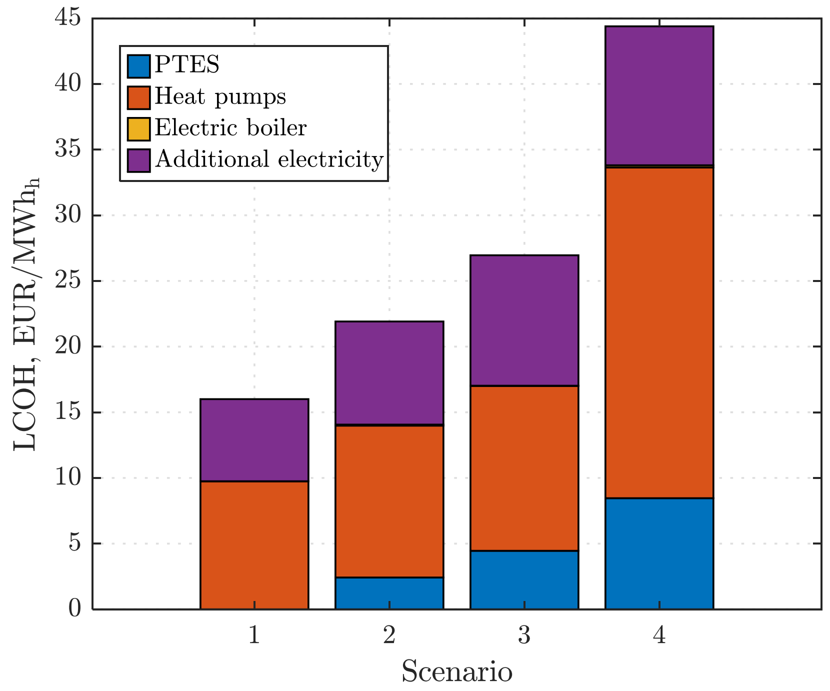
AWE plant dimensioning.

ELECTROLYZER WASTE HEAT RECOVERY

System operation in 5-min resolution



Levelized cost of heat

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