UiO Department of Chemistry
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STEAM ELECTROLYSIS USING PROTON CERAMIC CELLS AND MODULES – DESIGN AND PERFORMANCE MODELLING

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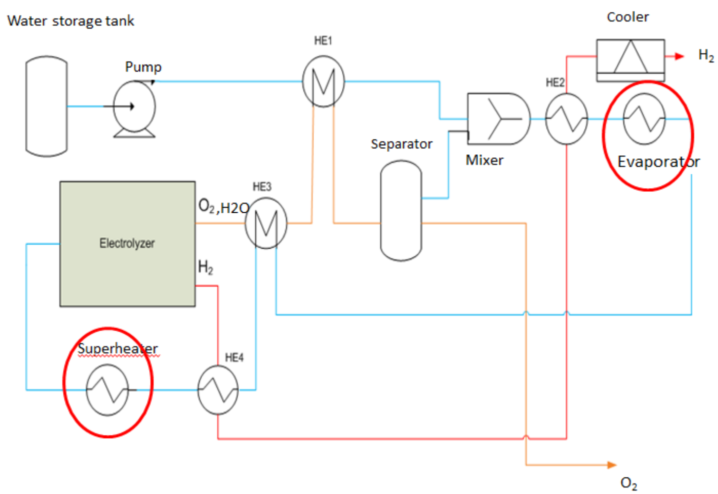
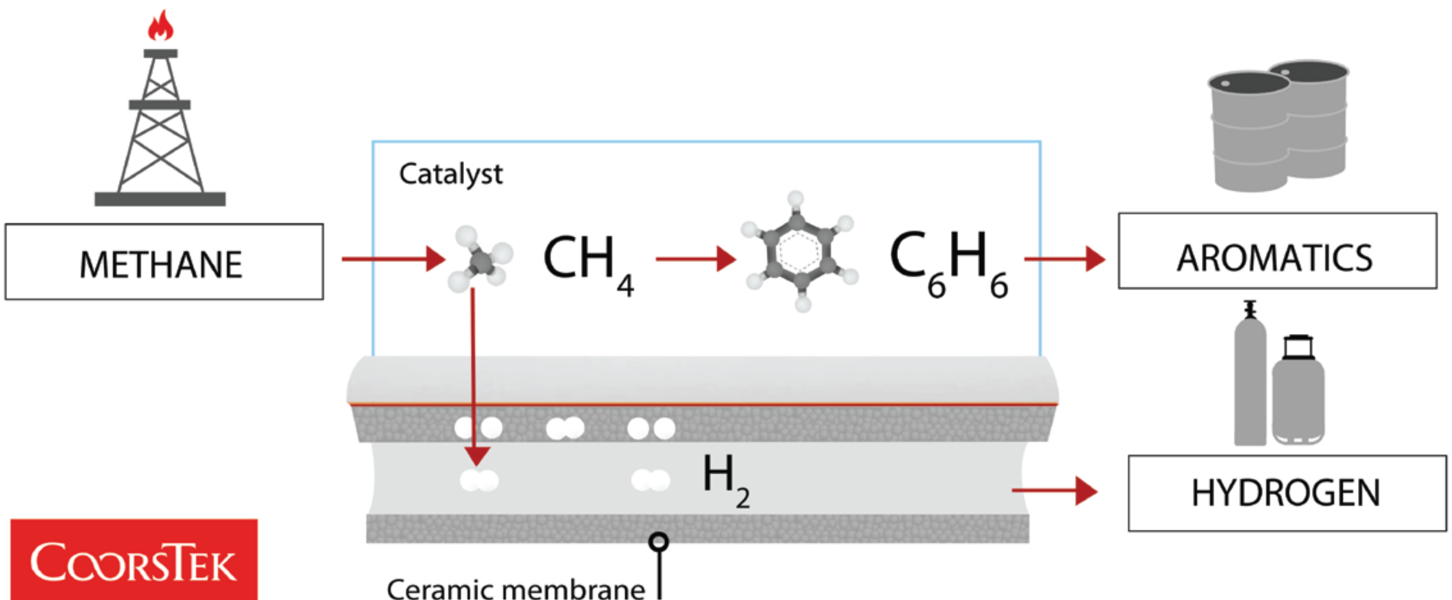
FCH FUEL CELLS AND HYDROGEN JOINT UNDERTAKING



- PCE fundamentals
- REN integration
- Design modelling
- Cost evaluation
- ~~Co-electrolysis~~

H from H_2O+renewables (-O-H) or fossil (-C-H)?

- Proton ceramics can extract H from H_2O (steam)
- But also from hydrocarbons
  - Dehydrogenation; Produces H_2 + higher hydrocarbons (liquids)
  - Much lower energy (electricity) cost

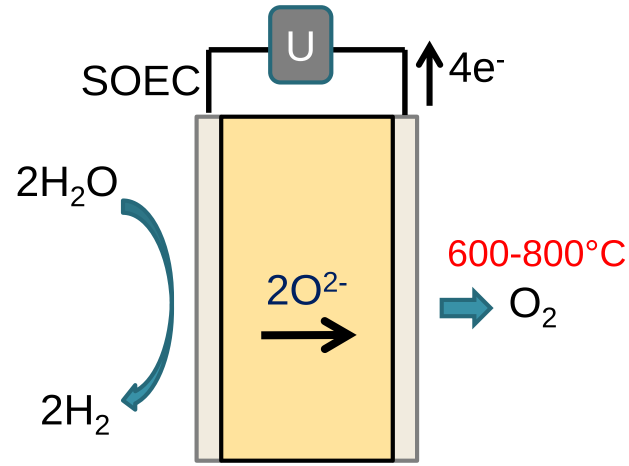


CoorsTek
MEMBRANE SCIENCES

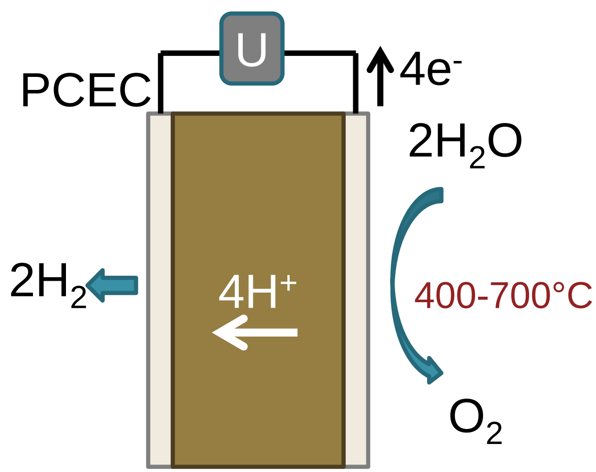
S.H. Morejudo, R. Zanón, S. Escolástico, I. Yuste-Tirados, H. Malerød-Fjeld, P.K. Vestre, W.G. Coors, A. Martínez, T. Norby, J.M. Serra, C. Kjølseth, **"Direct conversion of methane to aromatics in a catalytic co-ionic membrane reactor"**, *Science*, **353** [6299] (2016) 563-566.

Key differences between SOEs and PCEs
- advantages and challenges

- Solid Oxide Electrolysers (SOEs)
  - Well proven technology
    - Scalable production
    - High current densities at thermo-neutral voltage
  - Long term stability challenges
    - Delamination of O_2-electrode
    - Oxidation and degradation of Ni-electrode with high steam contents and/or low currents
  - High temperatures



- Proton Ceramic Electrolysers (PCEs)
  - Less mature technology
    - Fabrication and processing challenges
  - Produces dry H_2 directly
  - Potentially intermediate temperatures
    - Slow O_2-electrode kinetics



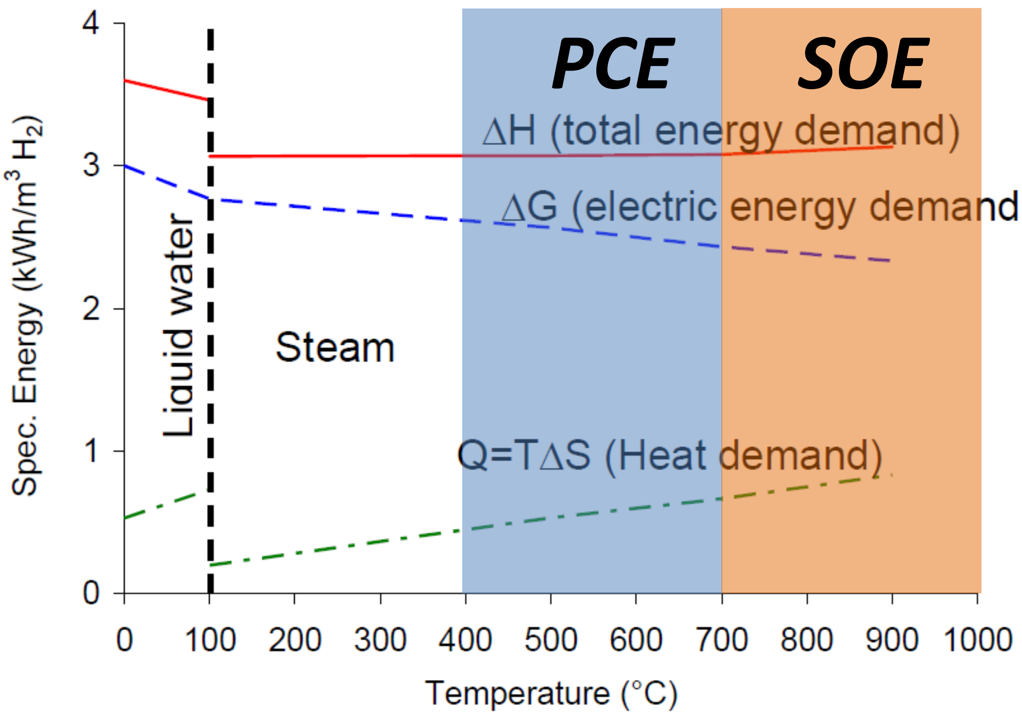
High temperature steam electrolysis

- Heat reactant steam to operating *T*
  - Product gas heat exchange
  - Electrical heater
  - Waste/geo/solar heat?

- Provide energy Δ*H* to split H_2O at *T*
- In electrolysis supplied as $w_{el}=\Delta G$
- Balance heat $Q=T\Delta S$
- Supply by overpotentials
  - Endothermic
  - Thermoneutral
  - Exothermic

- Heat value of product gases
  - Heat exchange with input steam

$$2H_2O \xrightarrow{\Delta H=\Delta G+T\Delta S} 2H_2 + O_2$$

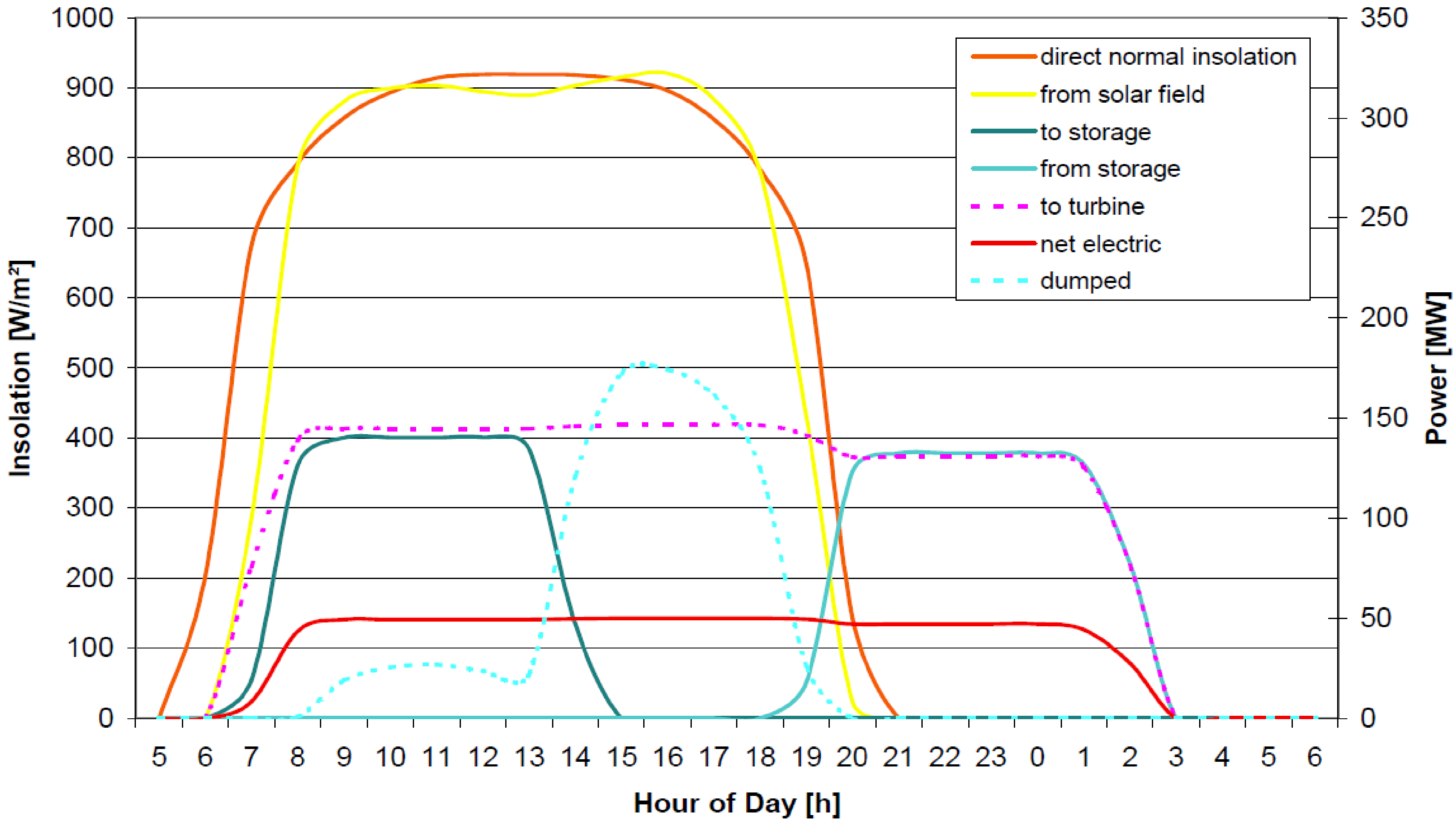


W. Doenitz et al., "Hydrogen production by high temperature electrolysis of water vapour," *Int. J. Hydrogen Energy,* p. 55, 1980.

Integration with renewable energy sources

Source	Regularity	Electricity + Heat	Steam
Grid	Constant	El	-
Hydro	Constant	El	-
Wind	Variable	El	-
Wave	Variable	El	-
Tidal	Variable	El	-
PV	Variable	El (+ low T heat)	-
Thermosolar	Variable	El + heat (high+low T)	-
Geothermal	Constant	El + low T heat	Steam

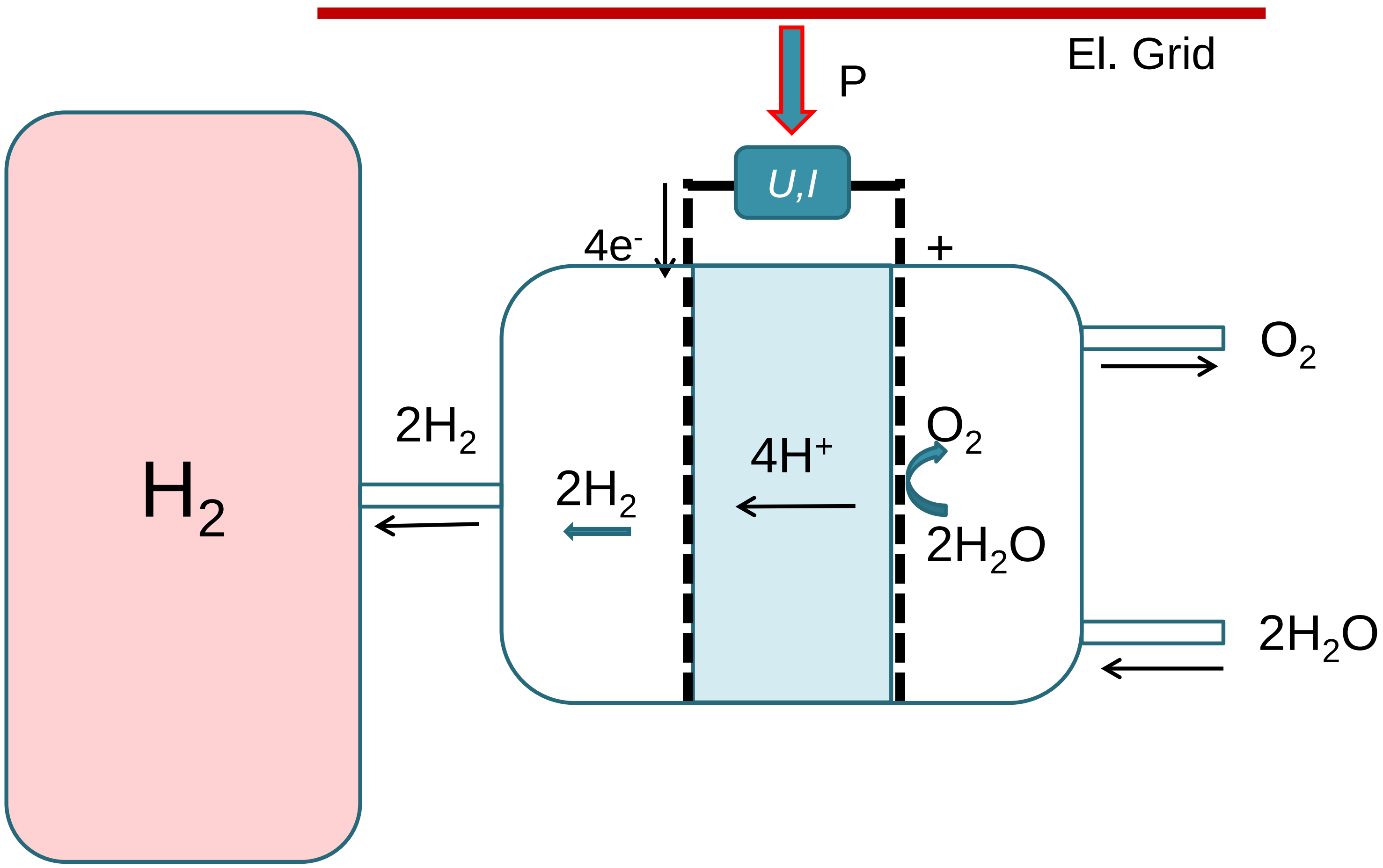
Thermosolar with molten salt storage



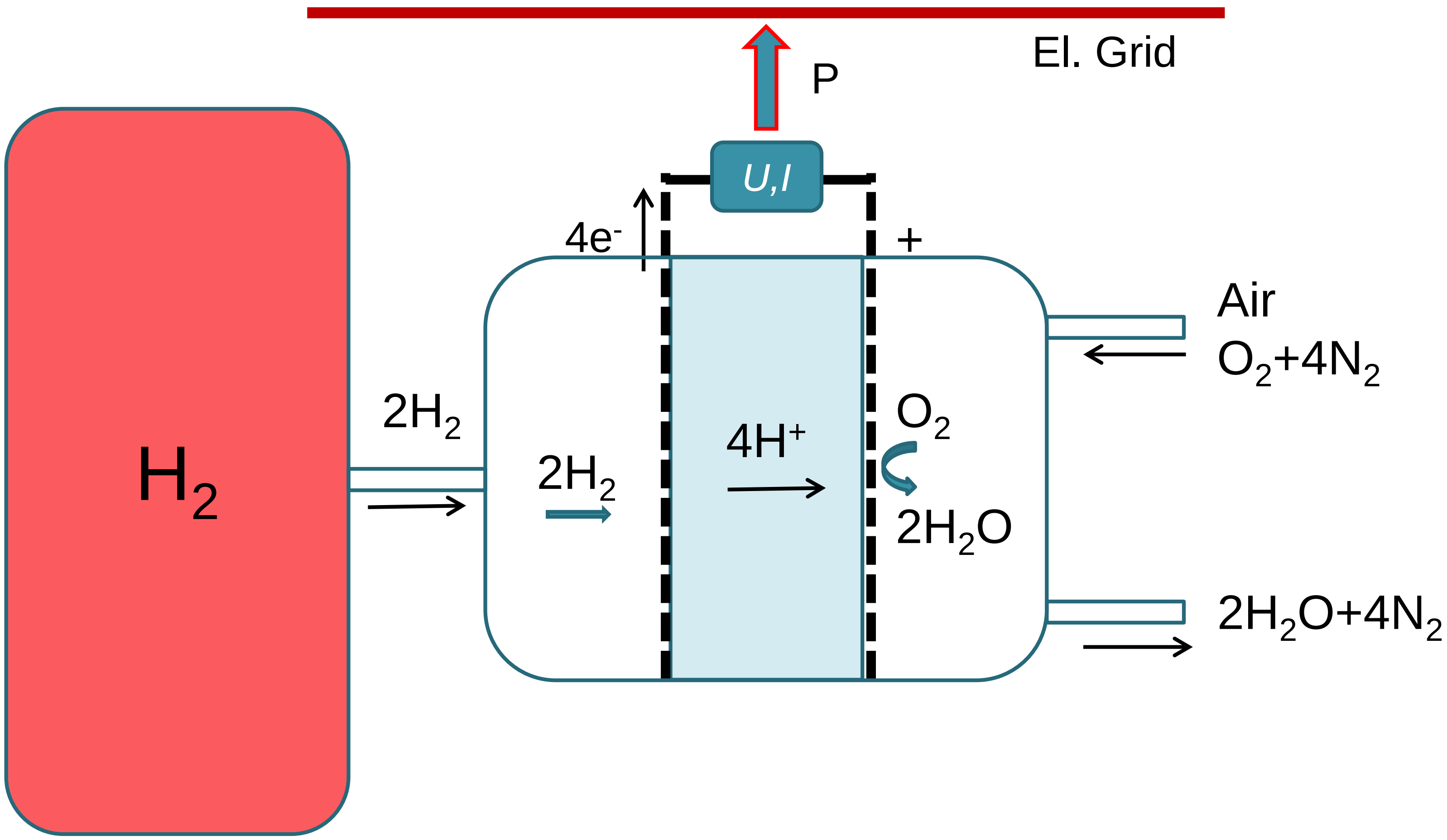
Operational modes of electrolyzers

- Electrolyzers – especially solid-state – don’t like intermittent operation
- Three options:
- Constant sources (Grid, hydro, geothermal (+wind, vawe, tidal, PV))
- Operation with intermittent storage (thermosolar)
- Reversible operation?

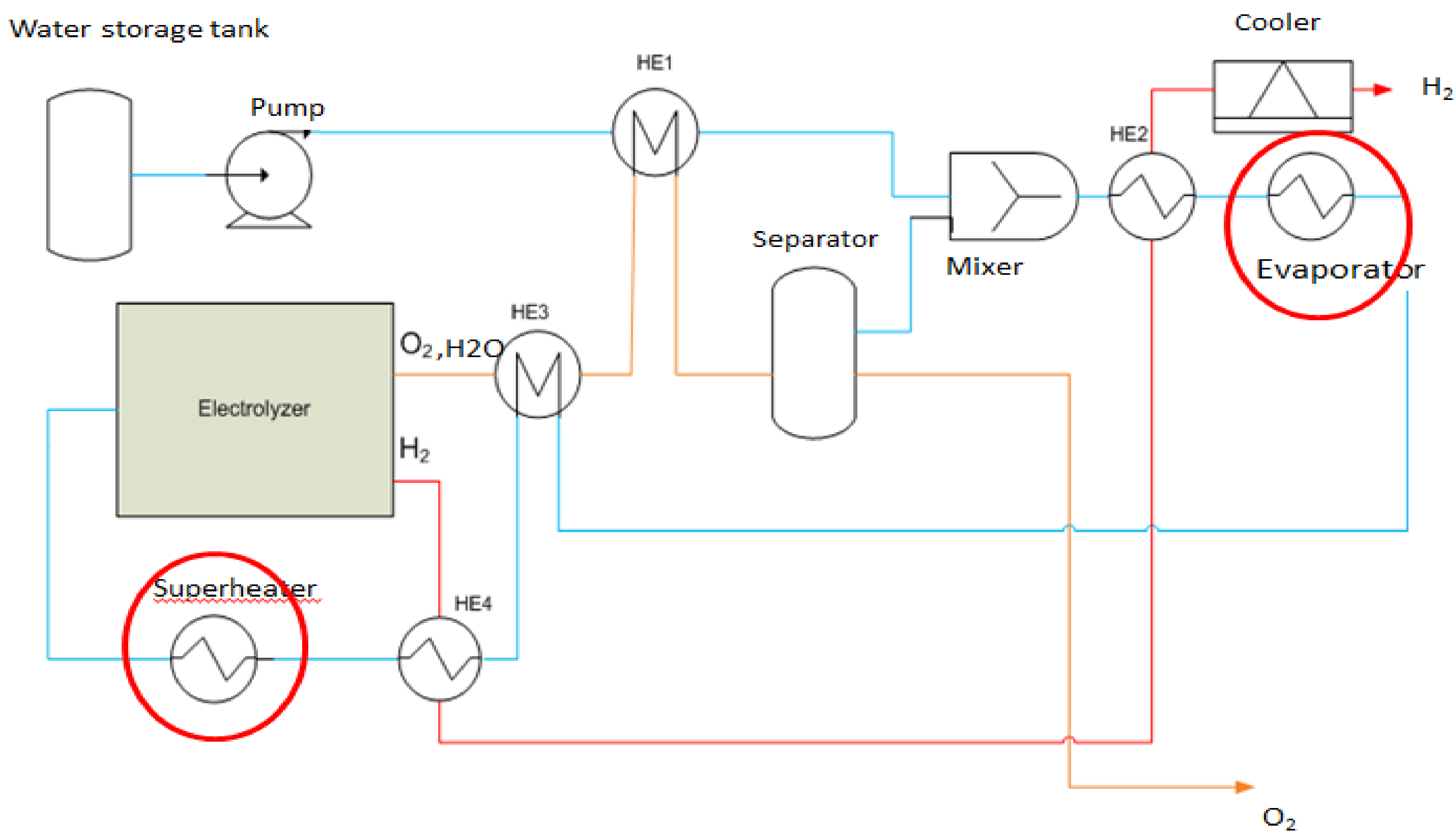
Electrolyser



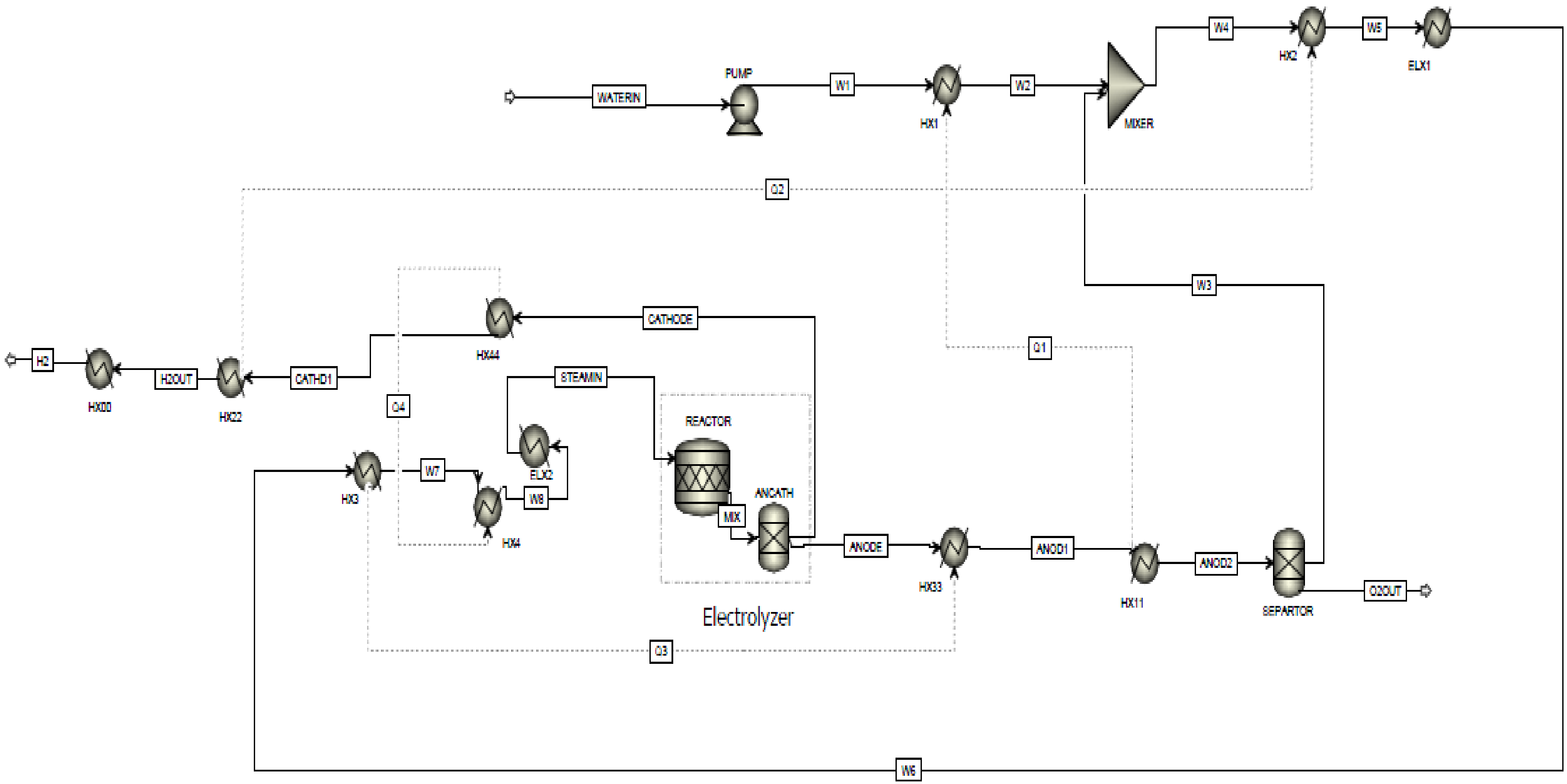
Fuel cell



Flow diagram of PCE



Aspen diagram of PCE



Aspen model of electrolyser plant where ELX1, ELX2 and the Electrolyser require electricity for vaporization, superheating and electrolysis respectively.

Electrolyser process design and efficiency

Specifications	
Sweep	No sweep gas
Air at the anode inlet	No air
Operating pressure	20 bar
Steam utilization	60%
Operating mode	Thermoneutral
Temperature at anode Inlet and outlet	700ºC
Temperature at cathode Inlet and outlet	700ºC

Stream	Mass flow	Units
Steam in	0.1635	kg/s
H_2	0.0110	kg/s
Power to electrolyzer	1.35	MW
Pump	253	W
Electric heater	0.04	MW
Heat of vaporization	0.31	MW
Electrolyzer electric efficiency	3.07	kWh_e/Nm^3
Plant electric efficiency	3.86	kWh_e/Nm^3
Faradayic efficiency	83.60	%

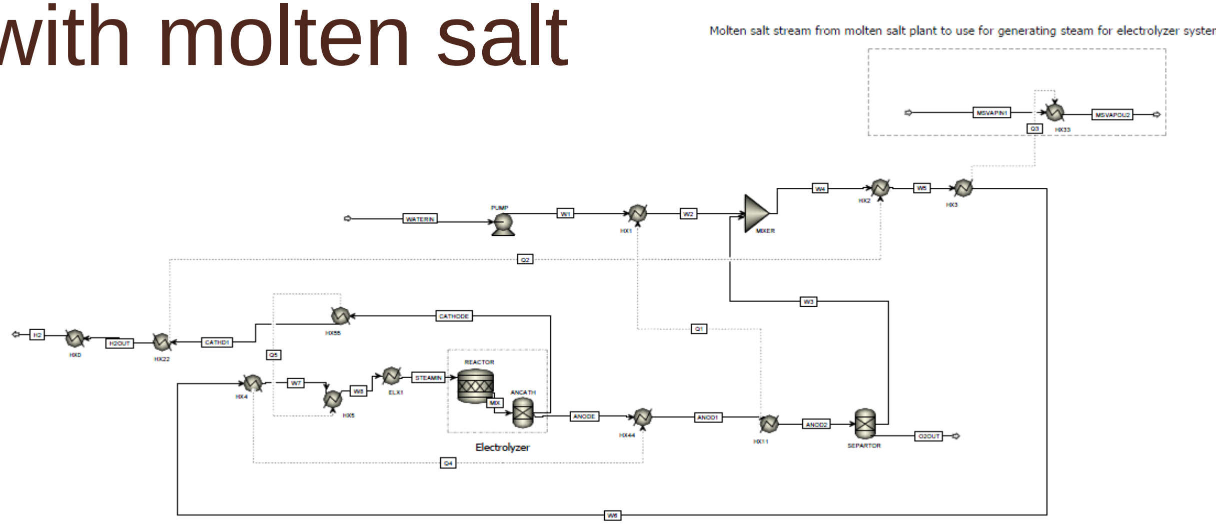
$$\eta_F = \frac{\Delta G \times H_2\ flow}{P_{electrolyser}}$$

Integration with geothermal power plant

- Steam from turbine at 180-240°C
  - used to preheat water for electrolyser
- Thus one more heat exchanger
- Otherwise same scheme

Heating Consumption (MW)	0.35
Electrolyser Consumption (MW)	1.35
Total Electric Consumption (MW)	1.64
Total consumption (MW)	1.70
Cooling Water (m^3/hr)	15.2
Geothermal Steam (MT/hr)	0.23
Electrolyser Efficiency (kWh/Nm^3)	2.86
Plant electric efficiency (kWh/Nm^3)	3.47

Thermosolar with molten salt



Stream	Mass flow	Units
Steam in	11.76	kg/s
H_2	0.79	kg/s
Power to electrolyzer	97.26	MW
Pump	0.02	MW
Superheating the inlet steam	2.87	MW
Heat of vaporization	22.16	MW
Cooling	1.38	MW
Electrolyzer Efficiency	3.07	kWh_e/Nm^3
Plant electric efficiency	3.17	kWh_e/Nm^3
Faraday efficiency	83.65	%

Techno-economic evaluation – capital cost

- 1.35 MW case

	Grid/PV/Wind	Geothermal
Electrolyser	534,200 €	534,200 €
Heat Exchanger	30,000 €	36,000 €
Electrical heaters	12,000 €	12,000 €
Other Components	20,000 €	20,000 €
Process Control/HSE/HVAC	215,000 €	215,000 €
ISBL	811,200 €	817,200 €
OSBL	324,480 €	326,880 €
E&D	405,600 €	408,600 €
Contingency	81,120 €	81,720 €
Total Fixed Capital Cost	1,622,400 €	1,634,400 €

Operating costs

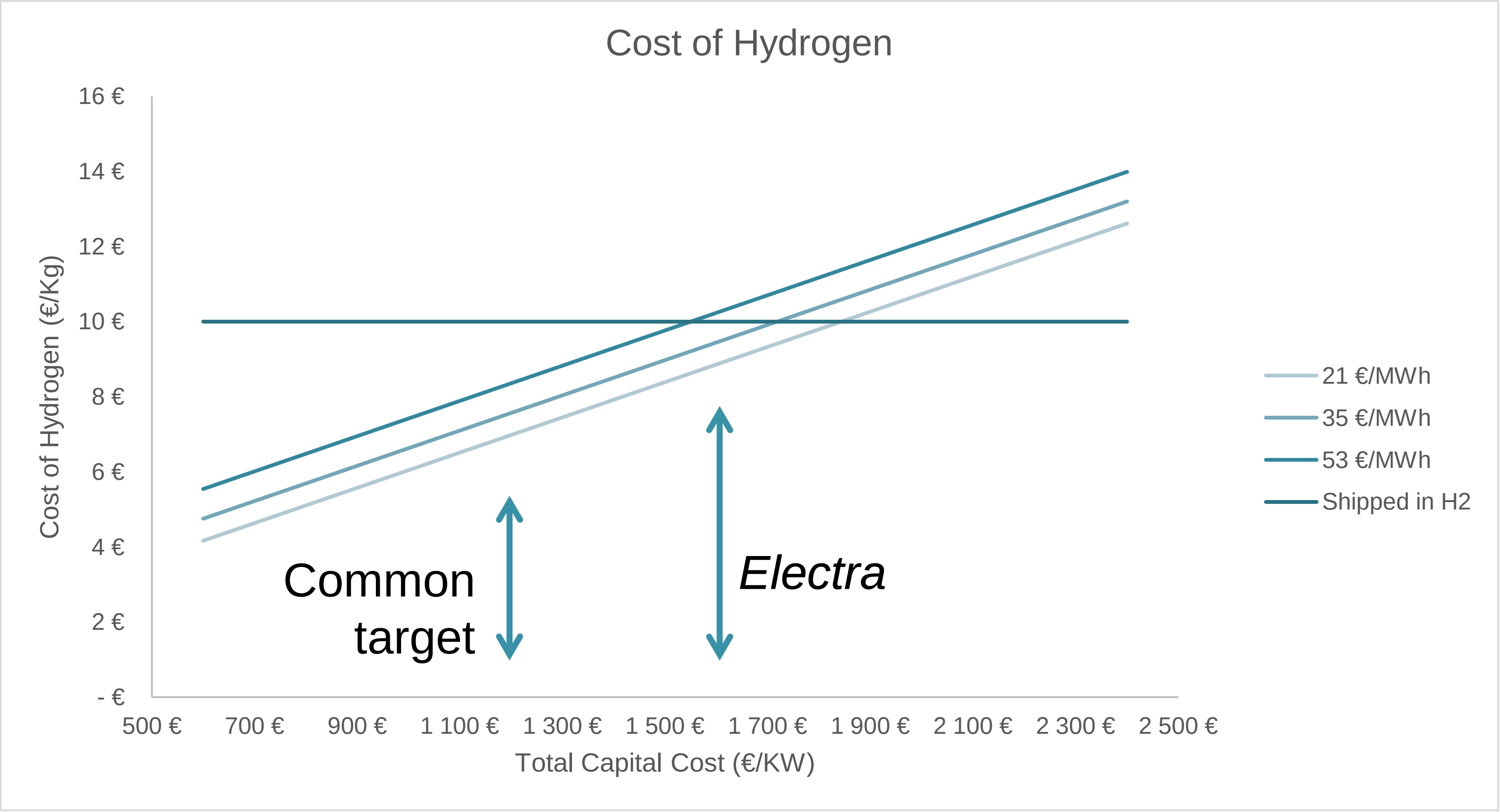
- 1.35 MW case

H_2 Production 1.35 MW	Grid / PV / Wind	Geothermal	Method of approximation
Maintenance	24,336 €	24,336 €	3% of ISBL Investment
General Plant Overhead	15,818 €	15,818 €	65% of Maintenance
Fixed Operating Costs	40,154 €	40,154 €	

Prices		Units
Steam	15	€/MT
CW	0.05	€/m3
Deionised water	1.15	€/m3
Interest rate	10	%
Time	10	Years
Hours of operation per year	8000	Hours

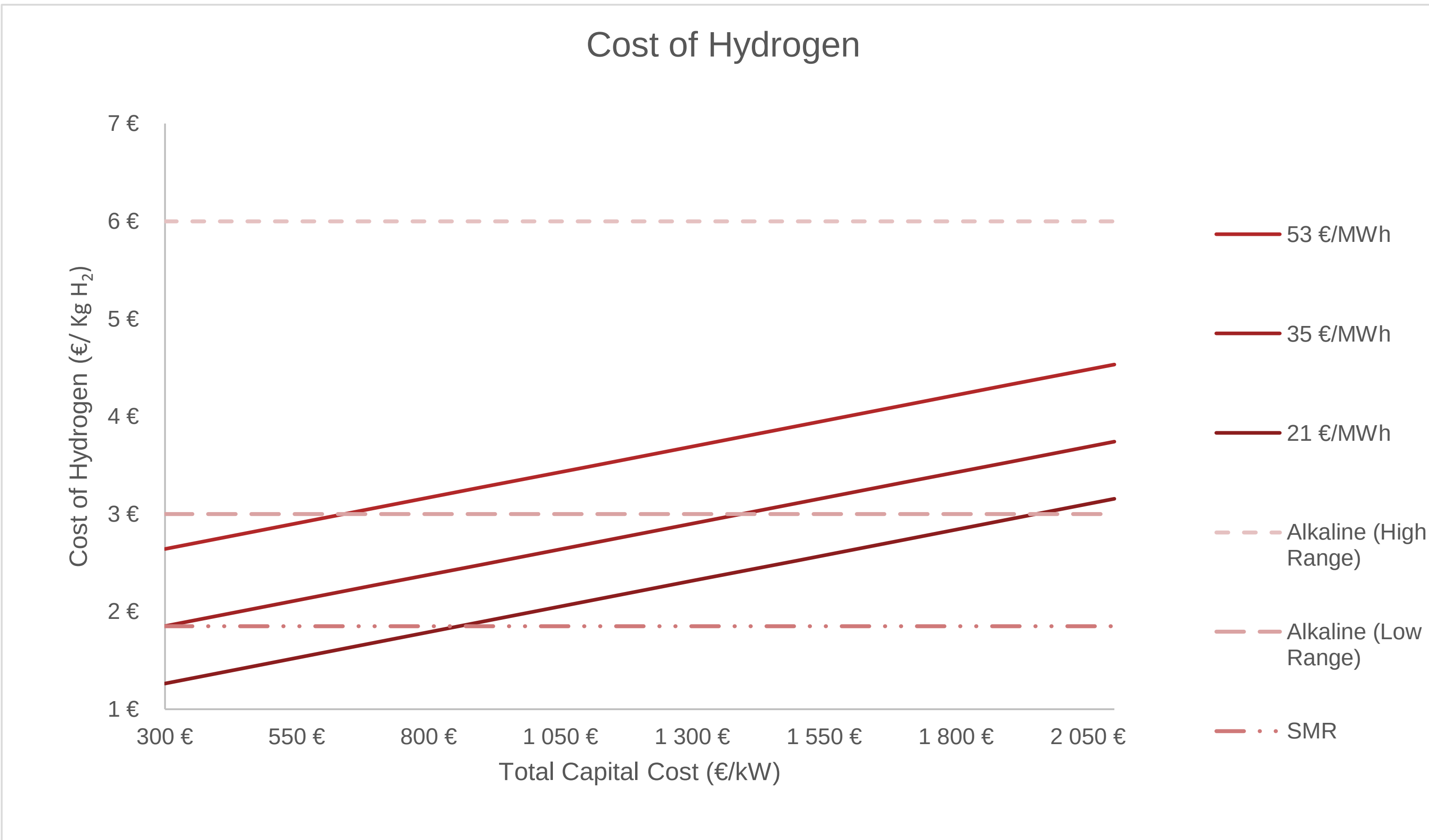
Techno-economic evaluation

- 1.35 MW case



Tehno-economic evaluation

- 100 MW case



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Conclusions

- Proton ceramic electrolyser (PCE) fundamentals
  - 3.86 MWh/Nm^3 H_2
- Increased efficiency by integration with geothermal and thermosolar energy (el+heat)
  - 3.47 MWh/Nm^3 H_2 and 3.17 MWh/Nm^3 H_2, respectively
- Minor differences in process design and efficiency to SOEs
  - Potentially lower operating temperature
- Capital cost analyses uncertain at this stage

Acknowledgements

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