Aalto University
School of Electrical
Engineering

Electrical Modeling of Alkaline and Proton Exchange Membrane Electrolyzers

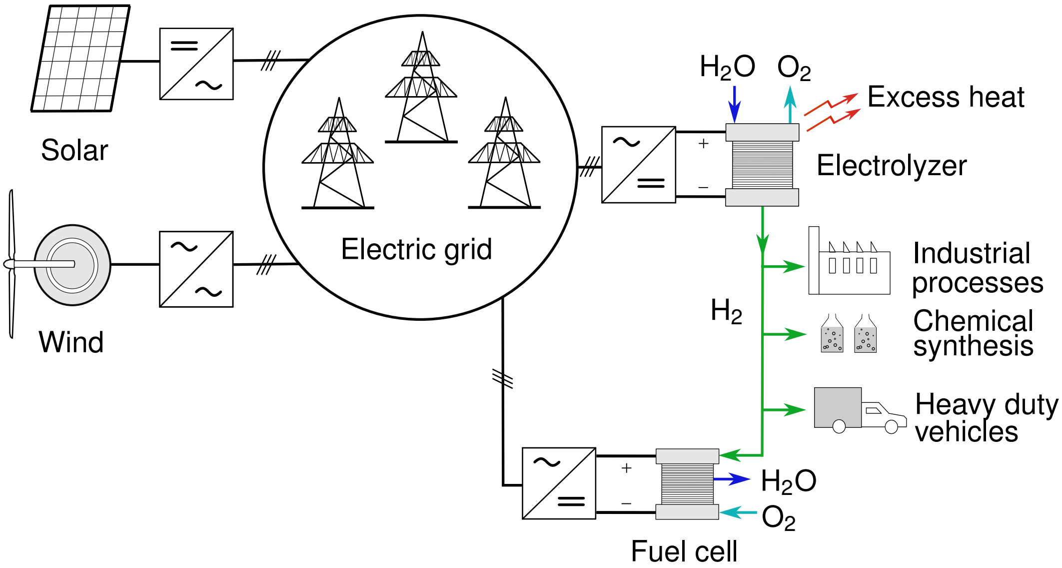
Ushnish Chowdhury

October 4, 2024

Contents

- Overview of green hydrogen technology
- Basic principle of electrolysis and electrolyzers
- Electrical model of electrolyzers to represent static and dynamic behaviors
- Showcasing simulation results (in PLECS)

Green Hydrogen Technology



Hydrogen Production in Europe[1]

- Current statistics
  - 11.5 Mt produced in 2022, with 96% based on natural gas reforming
  - Only 0.3% based on water electrolysis
  - Prime contributors: Germany, the Netherlands and Poland
- Targets for 2030
  - Scale up production up to 10 Mt/year
  - Directly connecting 80-120 GW of renewable energy production capacity to electrolyzers
- Targets for 2050
  - Increase renewable electrolyzer capacity to at least 500 GW

[1] European Commission. Directorate General for Energy., Guidehouse., and Tractebel Impact., *Hydrogen generation in Europe: overview of costs and key benefits.* eng. LU: Publications Office, 2020. Accessed: Sep. 9, 2024. [Online]. Available: https://data.europa.eu/doi/10.2833/122757.

Hydrogen Production in Finland [2]

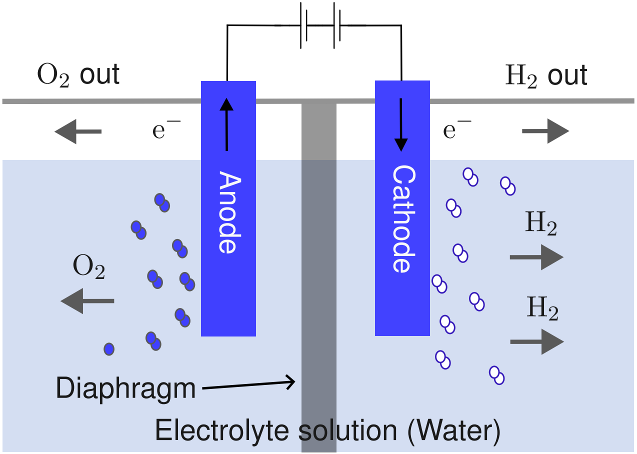
- Current statistics
  - 0.2 Mt/year, with 99% based on natural gases
- Targets for 2030
  - Produce at least 10% of EU's green hydrogen
  - 1 Mt production with a forecasted consumption of 12-98 TWh clean electricity
- Advantages for Finland
  - Abundance of renewable energy source, wind energy in particular
  - Availability of resource reserves
  - Expertise in designing cost-effective electrolyzers

[2] Source: Hydrogen cluster Finland - h2cluster.fi

Basic Principle of Water Electrolysis

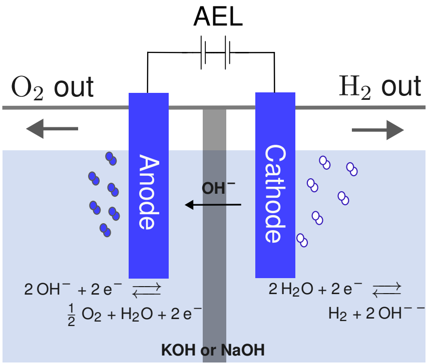
- Process of passing electric current through a substance to induce a chemical change (oxidation and reduction)
- Electrolyzer is a device which uses electrolysis to split water molecules into hydrogen and oxygen [a]

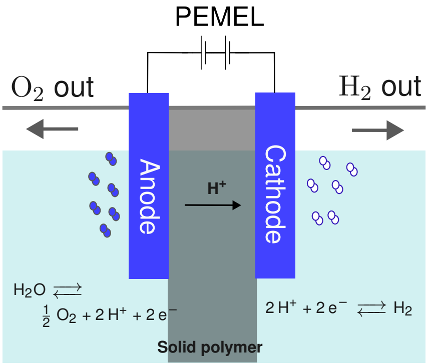
$$H_2O\ (l) = H_2\ (g) + \frac{1}{2} O_2\ (g)$$



[a] Water needs to be pre-processed;
1 kg H_2 production requires $\approx$ 9 L processed water

Alkaline and PEM Electrolyzers [3]



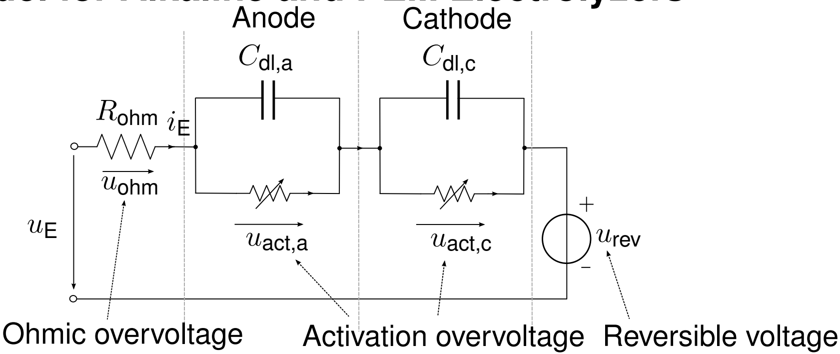


- Matured and widely commercialized
- Minimal capital expenditure
- Less flexible; low current density

- High current density; compact
- Output hydrogen purity >98 %
- Expensive; use of rare metals

[3] EU ban on perfluorosulfonic acid can be a potential setback for PEM electrolyzer technology

Dynamic Model for Alkaline and PEM Electrolyzers

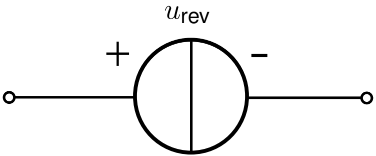


$$u_{\text{E}} = u_{\text{rev}} + u_{\text{ohm}} + u_{\text{act}}$$

- Helps acquiring relevant data regarding energy consumption under various operating conditions

Reversible Voltage

- Minimum electrolysis initiation voltage, derived from thermodynamics of electrochemical reactions
- Calculated by combining anodic and cathodic half reactions potentials
- 1.229 V at standard operating conditions (25 ℃, 1 bar)[4]



$$u_{\text{rev}} = u^0_{\text{rev}} + \frac{\bar{R}T}{n_{\text{e}}F} \ln \frac{p}{p^0}$$

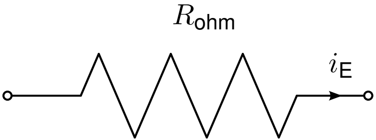
where u^0_{rev} is the standard reversible voltage

[4] L. Järvinen *et al.*, "Automized parametrization of pem and alkaline water electrolyzer polarisation curves," *International Journal of Hydrogen Energy*, vol. 47, no. 75, pp. 31 985–32 003, 2022.

Ohmic Overvoltage

- Resistance to electron and ion flow in the system
- Increases linearly following Ohm's law
- Area specific resistance is expressed as a function of temperature

$$r = r_1 + r_2 T + \frac{r_3}{T} + \frac{r_4}{T^2}$$



$$u_{\mathsf{ohm}} = i_{\mathsf{E}} R_{\mathsf{ohm}} = i_{\mathsf{E}} \frac{r}{A}$$

where A is the electrolyzer cell area

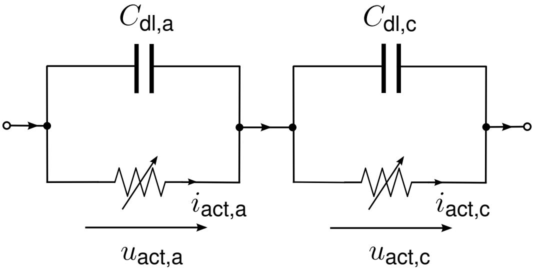
Activation Overvoltage

- Formed at the electrode-electrolyte interface, voltage required to overcome reaction energy barriers[5]
- Causes double-layer effect, modeled by the capacitors $C_{\mathsf{dl,a}}$ and $C_{\mathsf{dl,c}}$

$$u_{\mathsf{act,x}} = s_{\mathsf{x}} \ln\left(\frac{1}{t_{\mathsf{x}}} i_{\mathsf{E}} + 1\right)$$

or $$i_{\mathsf{act,x}} = t_{\mathsf{x}}\left[\exp\left(\frac{u_{\mathsf{act,x}}}{s_{\mathsf{x}}}\right) - 1\right]$$

$$C_{\mathsf{dl,x}} \frac{du_{\mathsf{act,x}}(t)}{dt} = i_{\mathsf{E}} - i_{\mathsf{act,x}}$$



[5] A. Ursúa and P. Sanchis, “Static–dynamic modelling of the electrical behaviour of a commercial advanced alkaline water electrolyser,” *International Journal of Hydrogen Energy*, vol. 37, no. 24, pp. 18 598–18 614, 2012.

State-space Representation

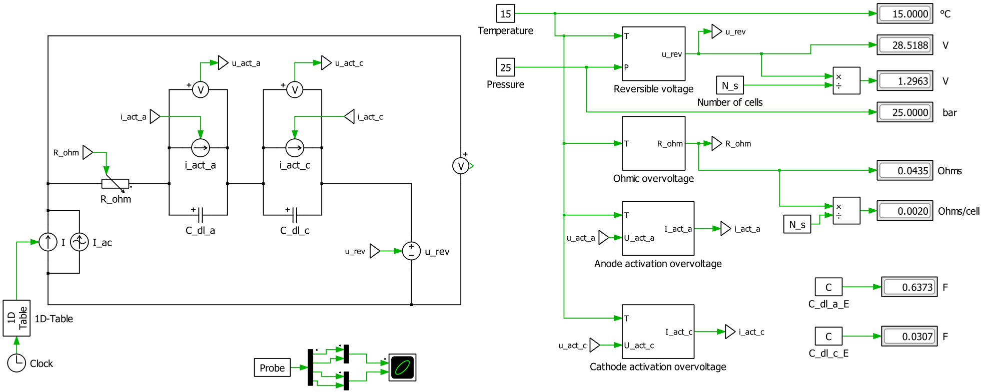
$$C_{\text{dl,a}}\frac{du_{\text{act,a}}}{dt} = i_{\text{E}} - i_{\text{act,a}}(u_{\text{act,a}})$$

$$C_{\text{dl,c}}\frac{du_{\text{act,c}}}{dt} = i_{\text{E}} - i_{\text{act,c}}(u_{\text{act,c}})$$

$$u_{\text{E}} = R_{\text{ohm}} i_{\text{E}} + u_{\text{act,a}} + u_{\text{act,c}} + u_{\text{rev}}$$

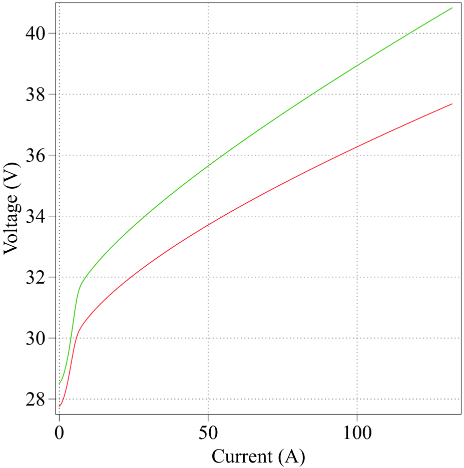
where the current i_E is the input and the voltage u_E is the output

Model in PLECS

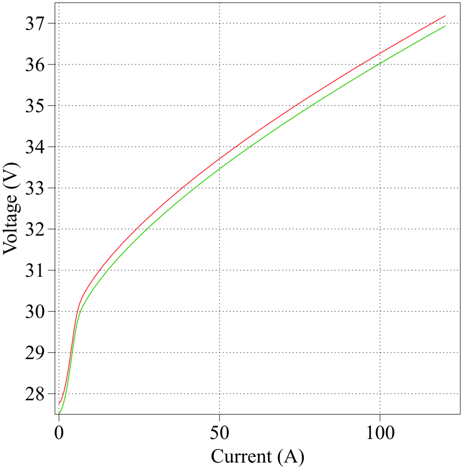


Simulation Results

Constant pressure = 25 bar
Temperatures = 15 ℃, 65 ℃



Constant temperature = 65 ℃
Temperatures = 5 bar, 25 bar



1. Green Hydrogen Technology

2. Basic Principle of Water Electrolysis

3. Electrical Modeling of Electrolyzers

4. Simulation Results

5. Summary

Summary

- Brief overview of green hydrogen technology
- Discussed on basics of electrolysis and different types of electrolyzer technology currently available
- Demonstrated an electrical equivalent circuit to portray the nonlinear and dynamic behaviors of electrolyzers
- Briefly explained various components of the electrical model