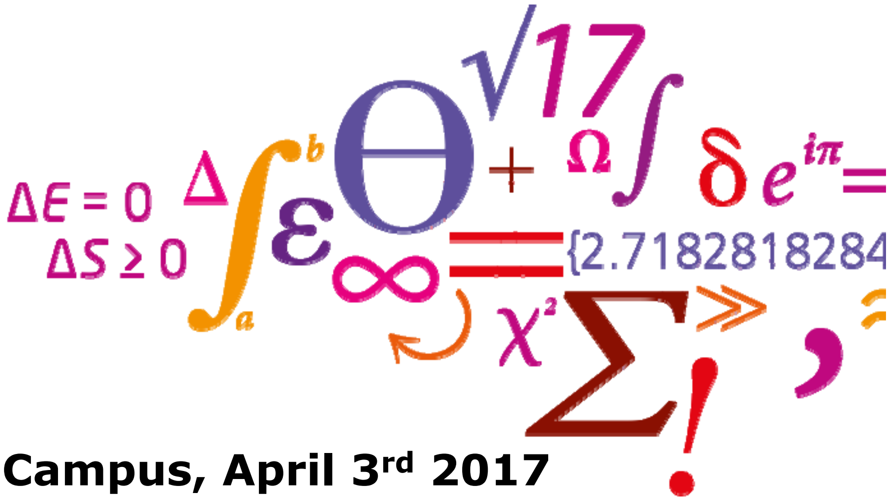
Electrolysis for energy storage

Mogens B. Mogensen and Christodoulos Chatzichristodoulou
Department of Energy Conversion and Storage
Technical University of Denmark

Acknowledgements to colleagues at DTU Energy Conversion



Joint Gas Workshop
Building 424, Room 025, DTU Lyngby Campus, April 3rd 2017

Introduction

- **At DTU Energy we have been doing R&D on all the three main types of electrolyzer cells for some years**
  - **Solid Oxide Electrolysis Cell (SOEC) since 2002**
  - **Alkaline Electrolysis Cell (AEC) since 2009**
  - **Polymer Electrolyte Membrane Electrolysis Cell (PEMEC) since 2015**

- **We spend more than 50 man-years per year on electrolysis R&D because we think that a world based on renewable energy needs electrolysis**

We need electrolysis because:

- **Many technical principles suitable for energy conversion + storage:**
  - **pumping of water to high altitudes**
  - **batteries**
  - **superconductor coil**
  - **flywheels**
  - **Thermo-chemical looping**
  - **Solar Thermal Electrochemical**
  - **Photo-electrochemical HER and CO_2 reduction**

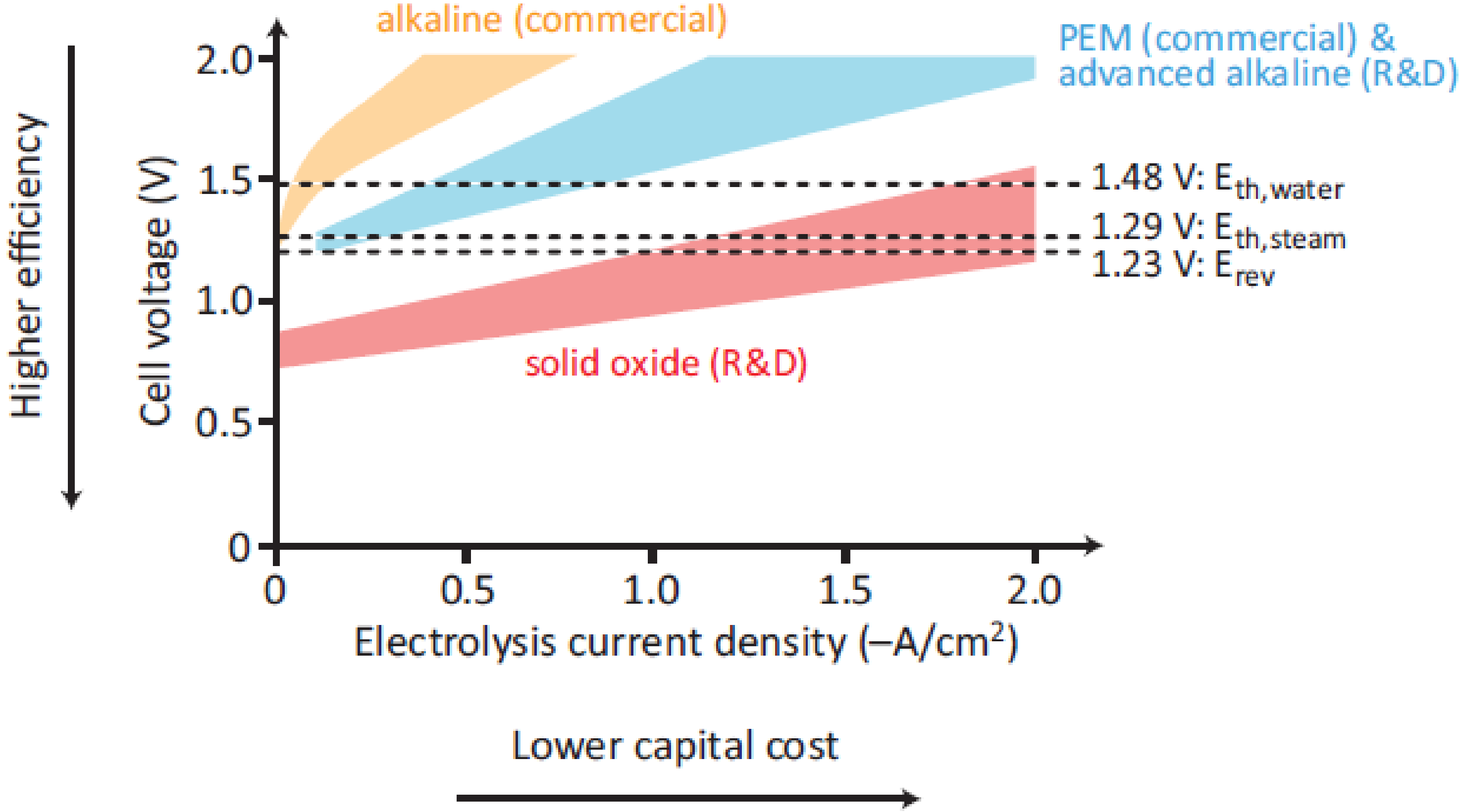
- **All are very important! But: first 4 are not for long distance (> 500 km) transport like cars, trucks, ships, airplanes. 3 last are early stage research - may prove efficient in the far future.**

- **Therefore, within a "foreseeable" future (10 years): Electrolysis is necessary in order to get enough renewable fuels!**

Electrolyser status I

- **Two types commercialized Alkaline (AEC) and polymer electrolyte (PEMEC), i.e. you can buy them. Both have operation temperature around 60 - 120 °C.**
- **None of them are commercial from an energy conversion and storage point of view in today's energy markets**
- **If significant amounts of green fuel to be produced via electrolysis in near future (the next few years) - only AEC is available multi MW scale**
- **Compact and expensive PEMEC <u>popular for demo-projects</u> – noble metals**
- **Several other types are under development**
- **SOEC is in demo phase – e.g. Sunfire (DE), Haldor Topsøe A/S (DK)**

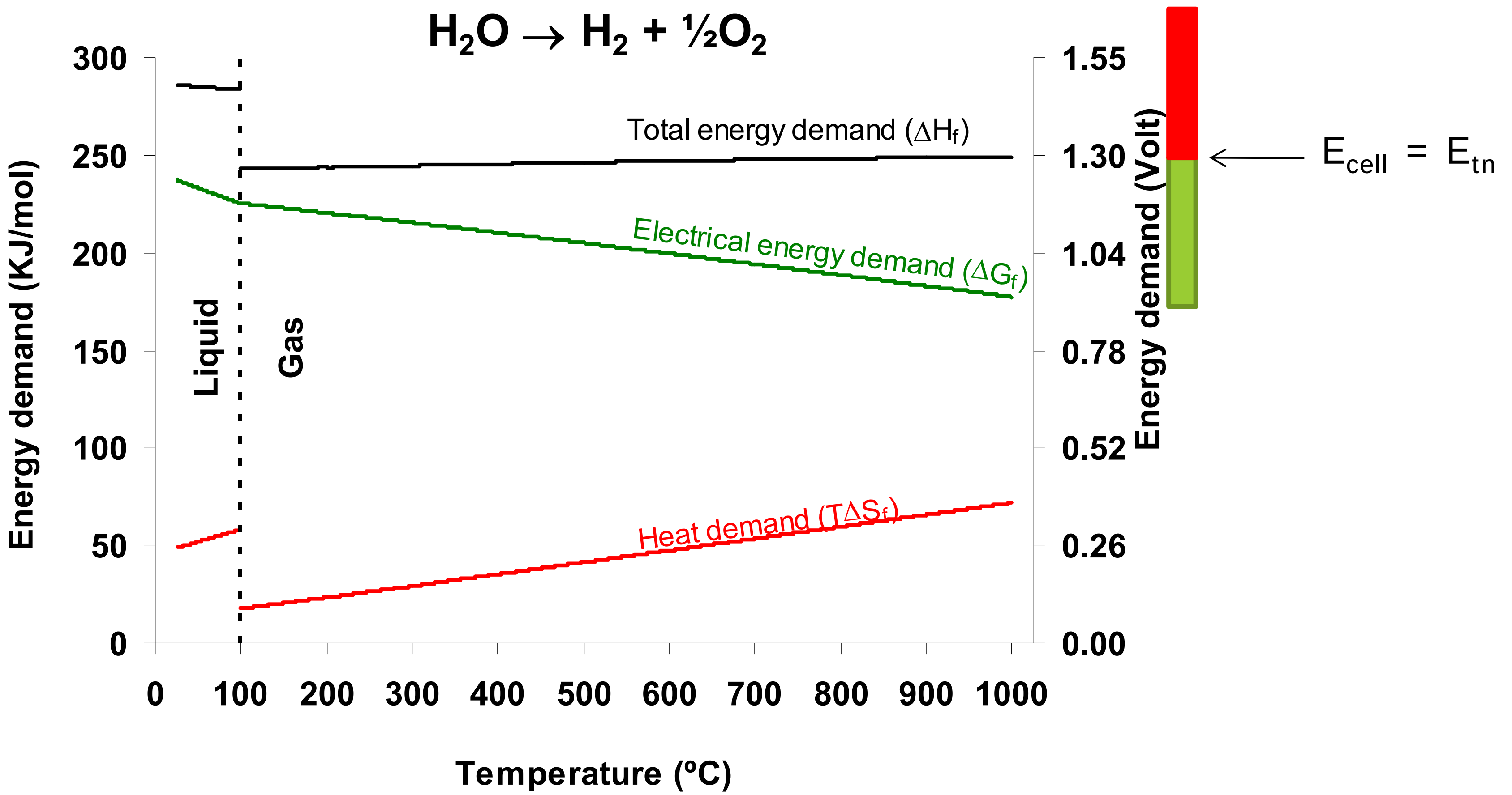
Electrolyser status II



Typical ranges polarization ranges for state-of-the-art water electrolysis cells. $E_{th,water}$ and $E_{th,steam}$ are the thermoneutral voltages. E_{rev} is the reversible voltage at standard state.

C. Graves, S. D. Ebbesen, M. Mogensen, K. S. Lackner, *Renew. Sustain. Energy Rev.*, 15 (2011) 1–23

Thermodynamics



Energy ("volt") = Energy (kJ/mol)/2F

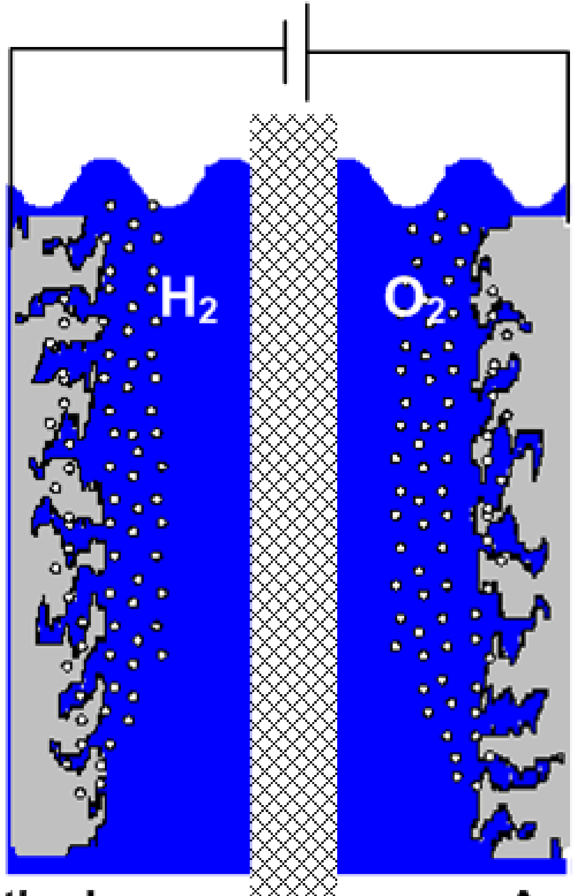
$i \propto E_{cell} - \Delta G/2F$

$E_{tn} = \Delta H/2F$

Price $\propto$ 1/i [A/cm²] ,

$\Delta H/\Delta G > 1$, $\eta = 100\%$ at $E = E_{tn}$ (no heat loss)

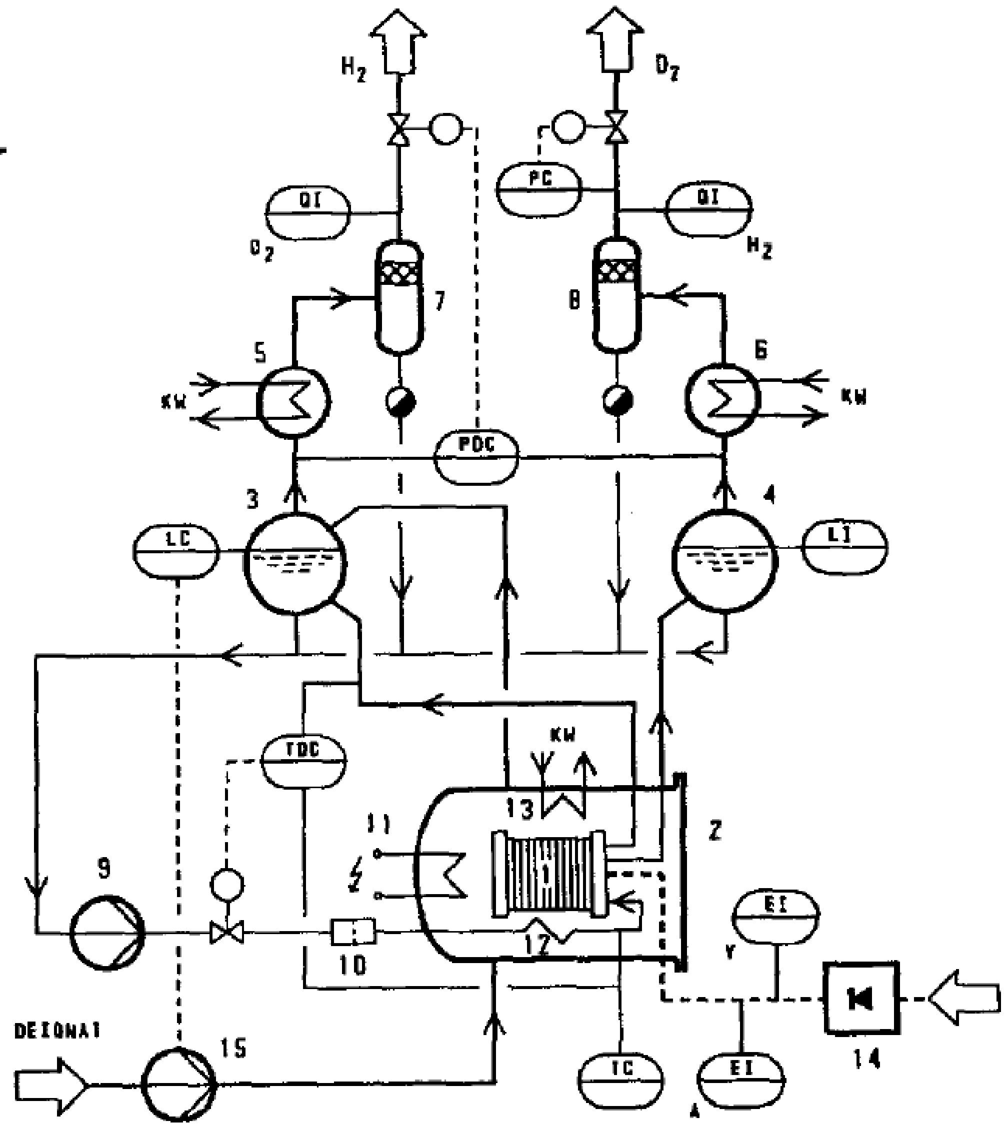
Classical Alkaline Electrolysis



- **Anode (+): $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$**
- **Cathode (-): $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$**
- **Very simple reaction, which may be carried out in practice at a temperature as low as 60 °C**
- **Even so, it shows up that systems are not that simple**

Process flow diagram of a modern electrolyzer

1 Electrolytic cells
2 Electrolyzer pressure vessel
3 Hydrogen-electrolyte separator
4 Oxygen-electrolyte separator
5 Hydrogen cooler
6 Oxygen cooler
7 / 8 Condensate separators
9 Electrolyte circulating pump
10 Electrolyte filter
11 Electric heater
12 Electrolyte heater/cooler
13 Water cooler
14 Rectifier unit
15 Electrolyte feed pump



Hydrogenics Alkaline system

From Hydrogenics' homepage:

HySTAT® 10 – 10

10 Nm^3H_2 h^{-1}, 5.4 kWh/Nm^3 H_2

High temperature high pressure alkaline electrolysis cell (HTP-AEC) at DTU Energy

Advantages of operating at T ~ 150-300 °C, P ~ 20-100 atm:

1. **Increased electrolyte conductivity.**

   (Reduced ohmic losses. Lower operating cost)

2. **Improved electrode performance.**

   (Reduction of capital and operating cost)

3. **Use of aq. KOH electrolyte with gas diffusion electrodes.**

   (Improved mass transport. No need for electrolyte degasing. Reversible operation)

4. **System simplification and increased efficiency arising from improved performance.**

   (No need for cooling and electrolyte circulation)

5. **Production of pressurized H_2 (and O_2). No/reduced compression need.**

   (Reduction of capital and operating cost)

6. **Decreased footprint arising from improved performance.**

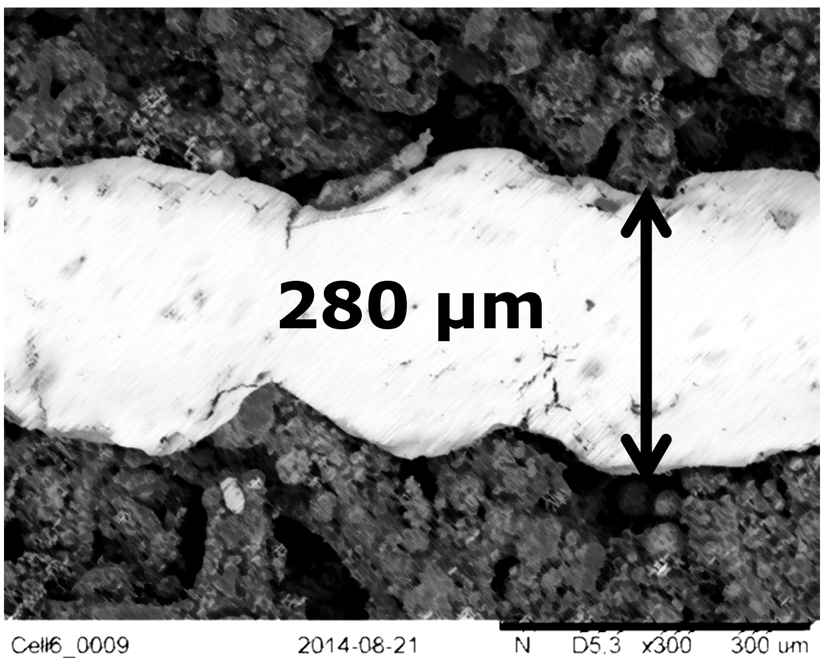
   (Reduction of capital cost)

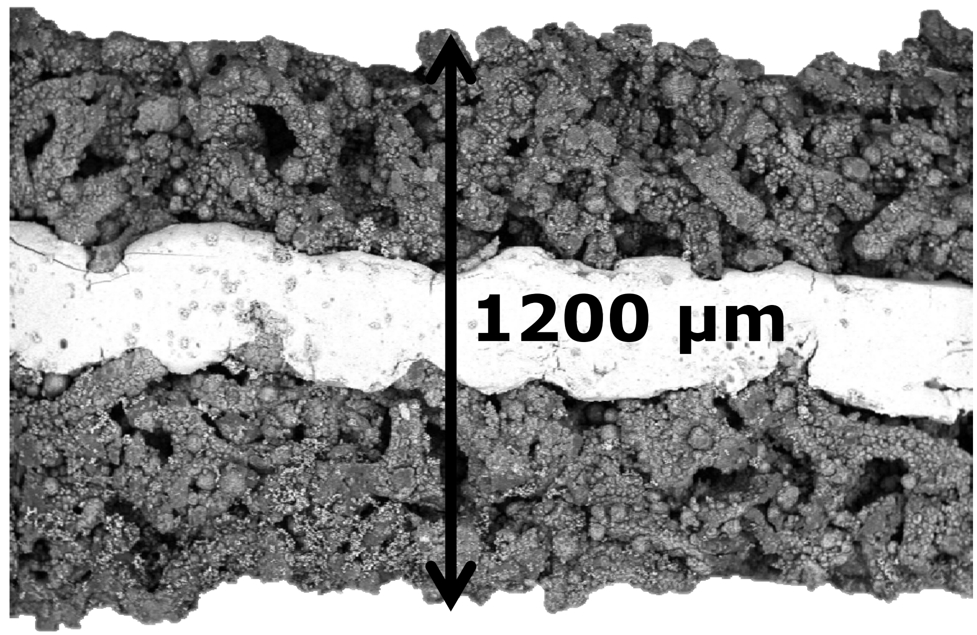
7. **Reduced electricity demand. Possibility to use “waste” heat.**

   (Reduction of operating cost)

High temperature alkaline electrolysis
Design and upscaling

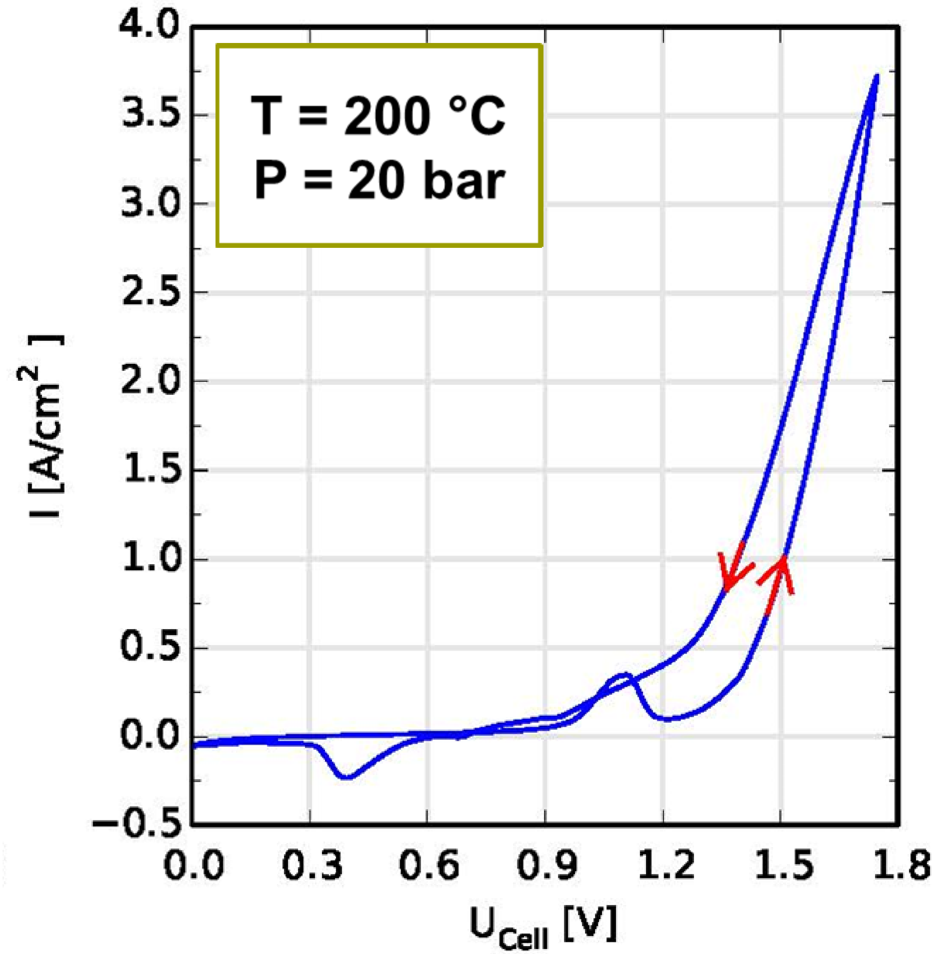
- **NiFeCrAl foam (oxygen electrode)**
- **Tape cast porous YSZ as electrolyte (soaked with concentrated KOH aq.)**
- **Inconel foam (fuel electrode)**
- **Cell size: ø 4.8 cm (circular); 5 x 5 cm² (rectangular)**

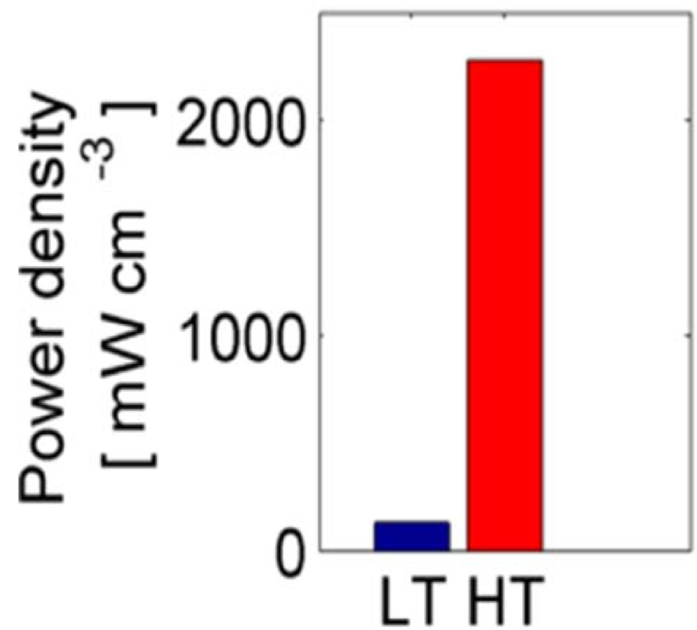




C. Chatzichristodoulou, F. Allebrod, and M. B. Mogensen, High Temperature Alkaline Electrolysis Cells with Metal Foam Based Gas Diffusion Electrodes, *J. Electrochem. Soc.,* 163(11): F3036-F3040, 2016.

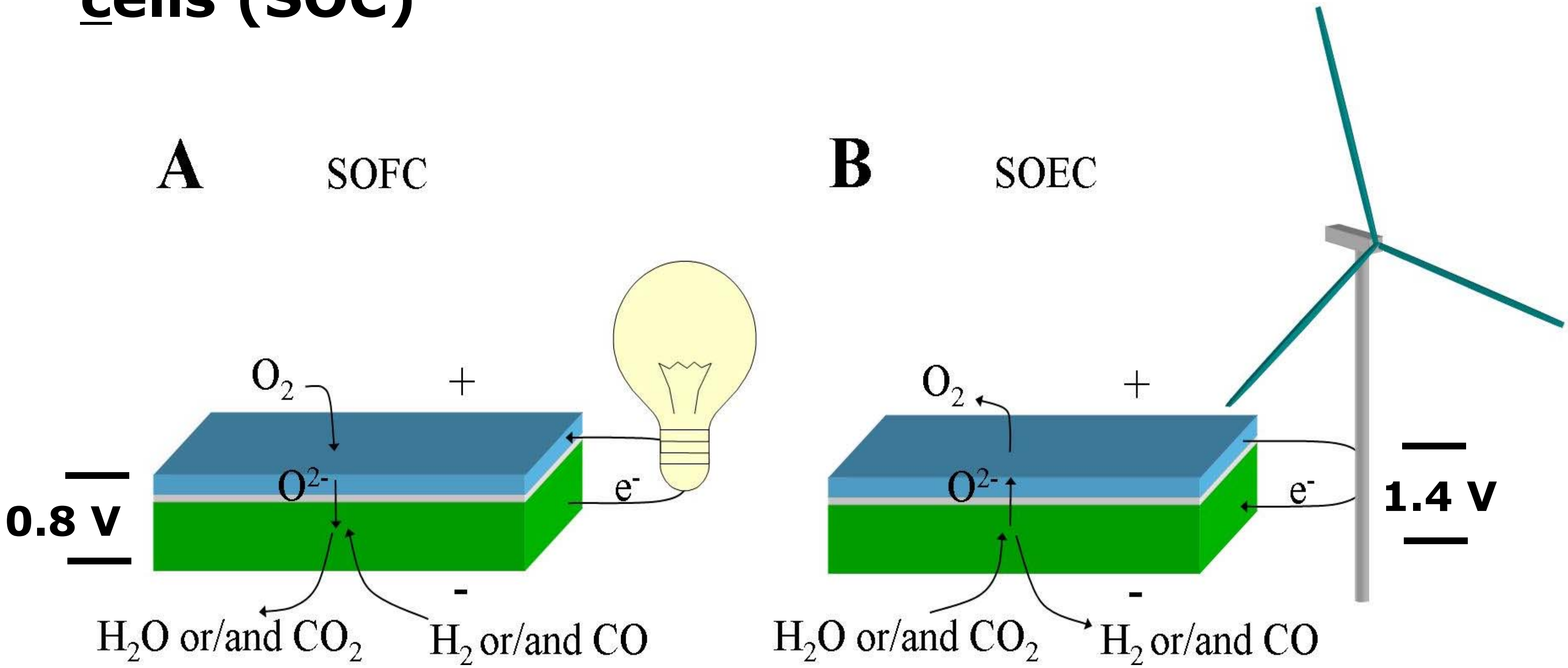
HTP-AEC performance and comparison with Low Temperature AEC





C. Chatzichristodoulou, F. Allebrod, and M. B. Mogensen, *J. Electrochem. Soc.*, 2016, 163, F3036

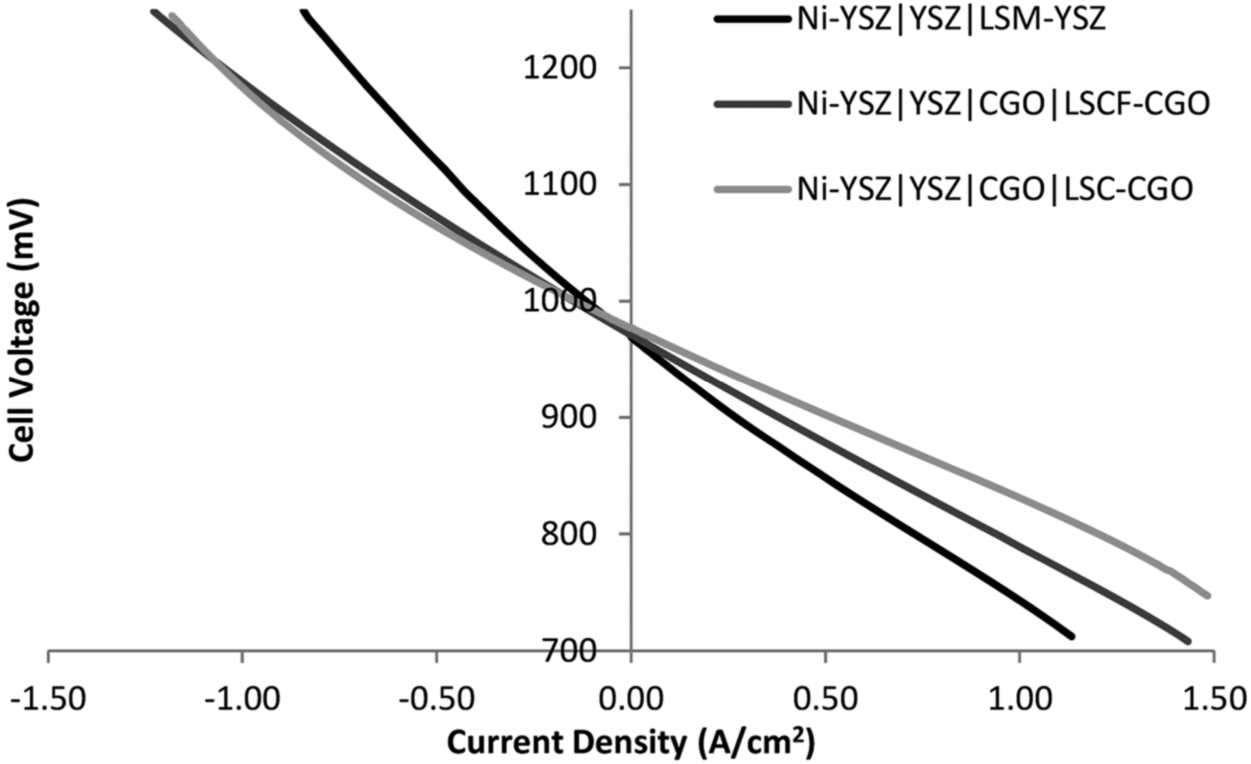
Principle of solid oxide electrolysis and fuel cells (SOC)



750 °C EMF ca. 1.1 V

Working principle of a reversible Solid Oxide Cell (SOC). The cell can be operated as a SOFC (A) and as a SOEC (B).

DTU Energy - Reversible SOC performance

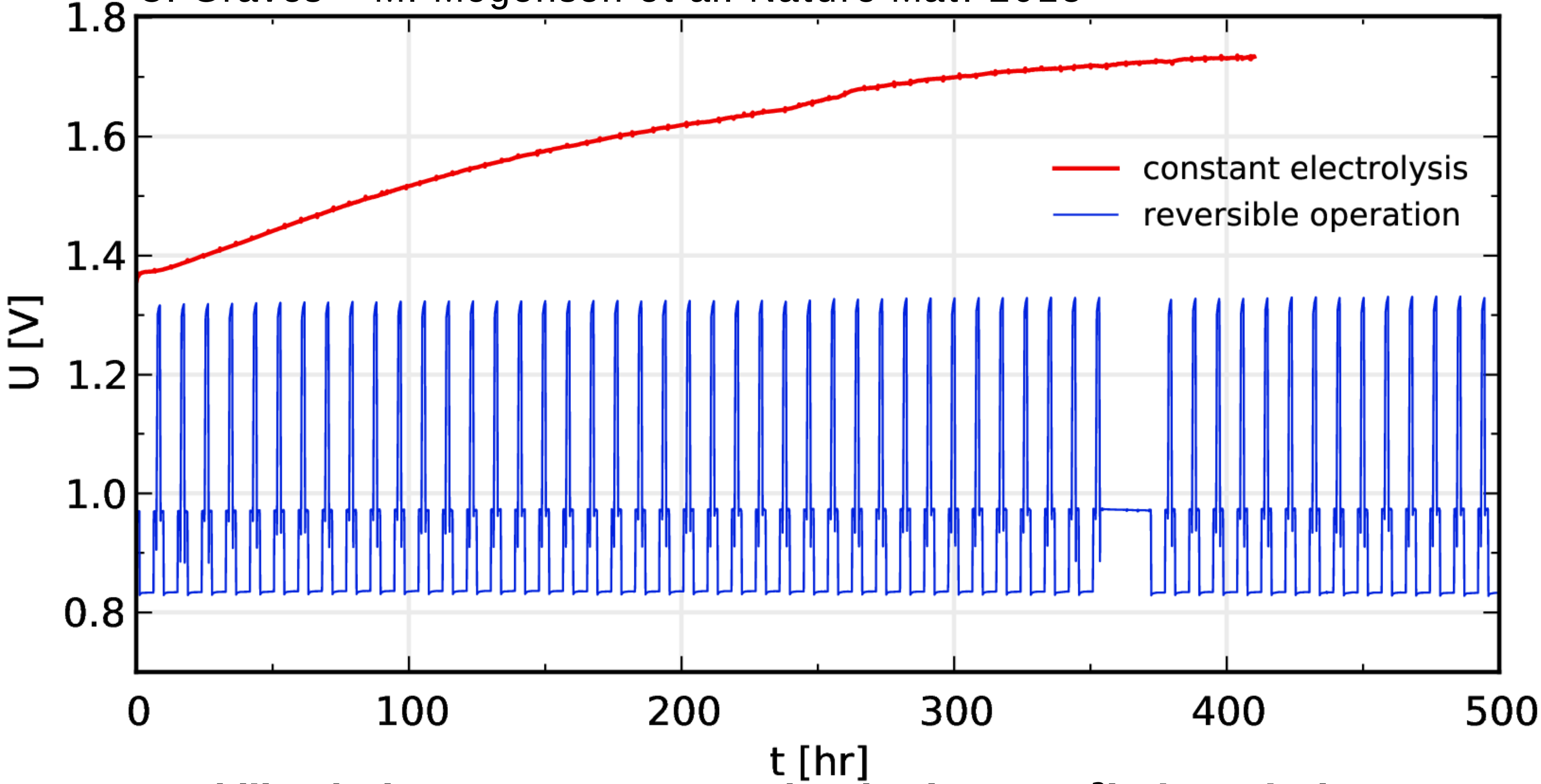


Polarization characterization for the planar Ni-YSZ based cells: Ni-YSZ|YSZ|LSM-YSZ, Ni-YSZ|YSZ|CGObarrier|LSCF-CGO, and Ni-YSZ|YSZ|CGObarrier|LSC-CGO. Conditions: 800 °C, 50% H_2O−50% H_2, pure O_2 at O_2-electrode

S. D. Ebbesen, S. H. Jensen, A. Hauch, M. B. Mogensen, *Chemical Reviews*, 114 (2014) 10697

Reversible operation

C. Graves – M. Mogensen et al. Nature Mat. 2015



SOC stability during constant current density (-1 A cm^{-2}) electrolysis test compared to reversible cycling test of 1 h EC (-1 A cm^{-2}) + 5 h FC (+0.5 A cm^{-2}). During open-circuit and FC mode, ~25 L/h of $pH_2/pH_2O \approx 50/50$ and EC mode ~13 L/h of $pH_2/pH_2O \approx 10/90$ gas was supplied. Pure O_2 at the O_2-electrode.

Summary

- PEMEC: very high power densities at high cell voltage – high costs of materials - relative low energy efficiency- commercial available
- LT- AEC: low cost - low power density – commercial available
- HTP-AEC: potential low cost, very high power density, high efficiency – not commercial available, early stage
- SOEC: potential low cost, very high power density, high efficiency – demo can be ordered
- Lifetime seems promising for all three types
- Still huge potentials for improvements by R&D