TSFS17 - Föreläsning 11
Fuel Cells and their Performance

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Outline

Fuel cell principles and take home messages

To understand fuel-cell performance we need to understand three properties

- Current density and cross-section area – Builds current.
- Number of cells in series a stack – Building voltage.
- Connection between Voltage and Current Density – The Polarization Curve.

Current and voltage gives power and the polarization curve is cell efficiency.

Fuel Cell System

- To make a fuel cell work a support system with pumps and fans needs to be added and they consume power.
- When everything is connected and operational this results in a fuel cell system efficiency.

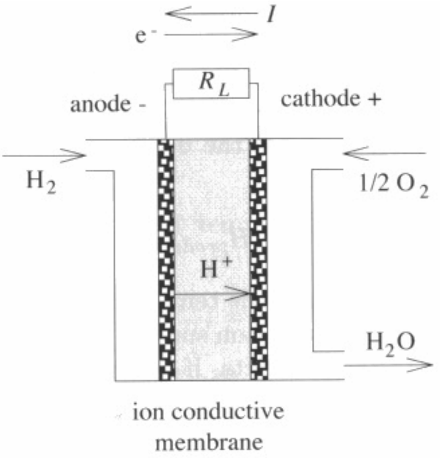
Fuel Cell Basic Principles

Basic principles

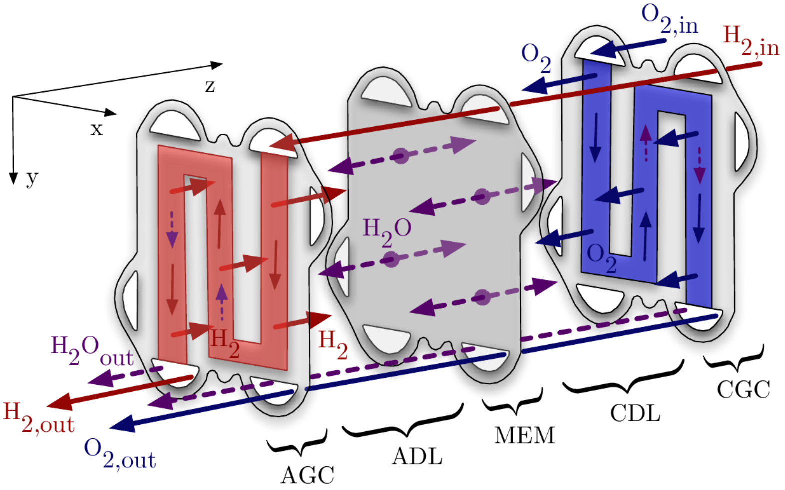
- Convert chemical energy directly to electric
- Let an ion pass from an anode to a cathode
- Take out electrical work from the electrons
- To generate current we need many reactions
- Cross section area is proportional to current

For a fuel cell we specify the performance with the current density in [A/cm^2].

Square cm is often used as it is a convenient size for material and performance experiments.



Cross-Section of One Cell



AGC Anode Gas Channel

ADL Anode Diffusion Layer

MEM Membrande

CDL Cathode Diffusion Layer

CGC Cathode Gas Channel

More area gives more current – Obvious!?

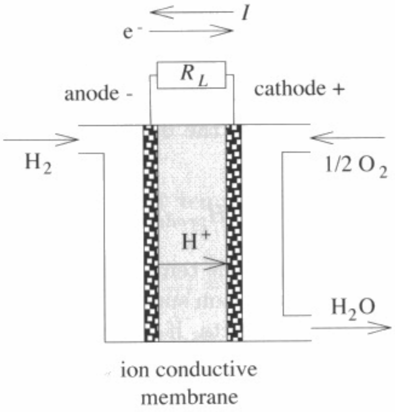
Fuel Cell Basic Principles

Basic Principles – Again

- Convert chemical energy directly to electric
- Let an ion pass from an anode to a cathode
- Take out electrical work from the electrons

The operatinag fundamentals are chemical reactions, similar to those in batteries

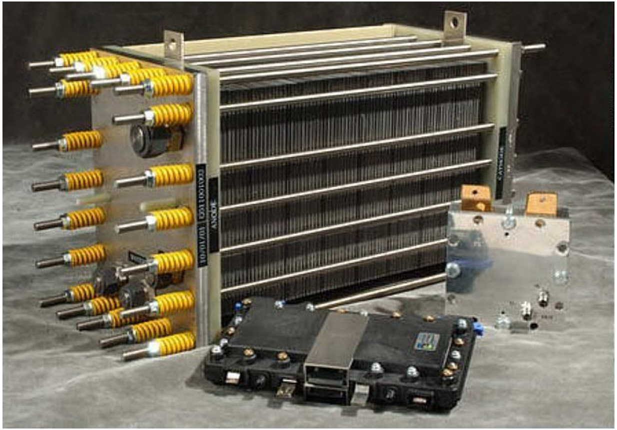
- The result is low voltages ≤ 1 V
- We want power $P = U\,I$
- High power would require a high current
- High current in any device is high losses

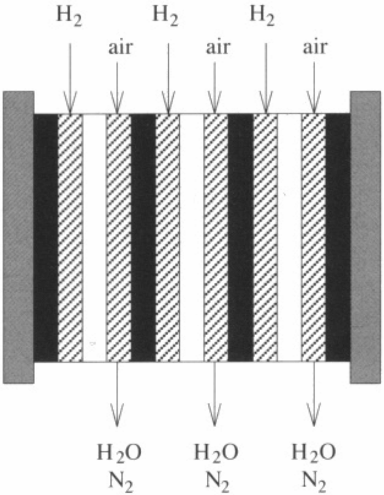


Need to build voltage in a practical system – Series connections = stack.

Fuel Cell Stack

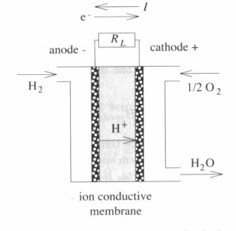
- The voltage out from one cell is just below 1 V.
- Fuel cells are stacked, N_{cell} series connected.

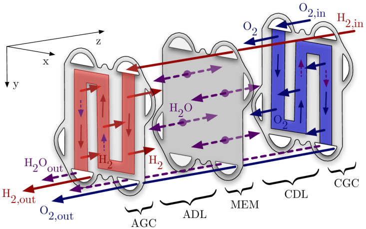


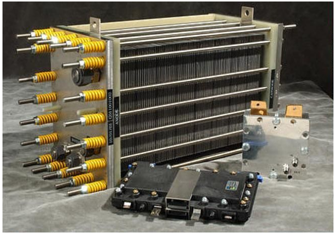


To summarize

- Fuel cell power is Voltage times Current, $P = U I$
- Current is the cross-section area of a cell
- Voltage is number of cells connected in series (length)
- Power is proportional to area times length, same as volume.

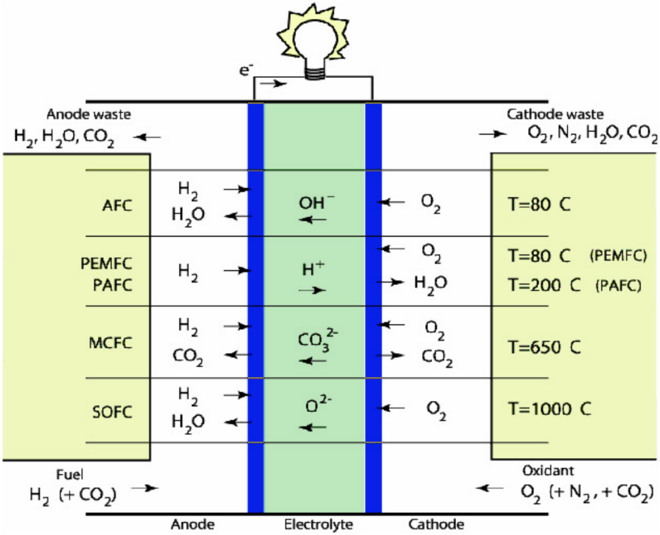






Outline

Overview of Different Fuel Cell Technologies



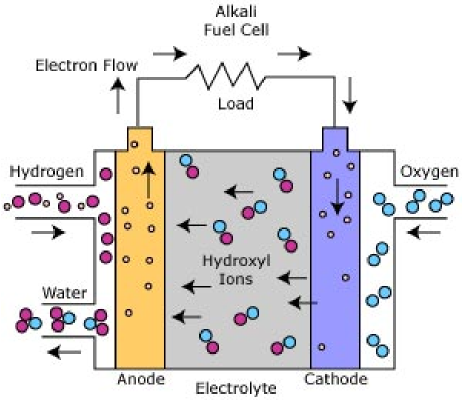
Several options

- Different electrolytes
- Let different ions pass through the membrane

Results

- Varying operating characteristics
- Especially temperature

AFC – Alkaline Fuel cell

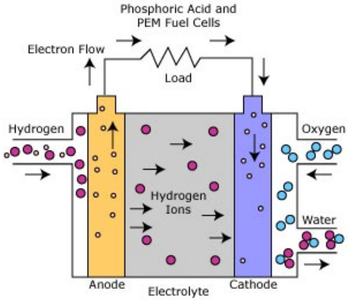


- Among the most efficient fuel cells 70%
- Low temperature 65-220°C
  - Quick start, fast dynamics
  - No co-generation
- Sensitive to poisoning

PEMFC – Proton Exchange Membrane Fuel Cell

Advantages:

- Relatively high power-density characteristic
- Operating temperature, less than 100°C
  –Allows rapid start-up
- Good transient response, i.e. change power
  –Top candidate for automotive applications
- Other advantages relate to the electrolyte being a solid material, compared to a liquid

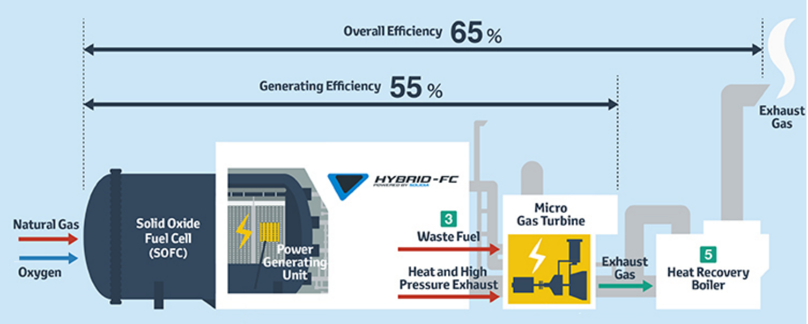


Disadvantages:

- Require expensive catalyst material (Platinum)
- For some applications operating temperature is low
- The electrolyte is required to be saturated with water to operate optimally.
  –Careful control of the moisture of the anode and cathode streams is important

The Other Types of H_2 Fuel Cells

- Other fuel cell types are
  - PAFC – Phosphoric Acid Fuel Cell 175°C
  - MCFC – Molten Carbonate Fuel Cell 650°C
  - SOFC – Solid Oxide Fuel Cells 1000°C
- Hotter cells, slower, more difficult to control
- Biggest benefit – Power generation through co-generation (high system efficiency)



Hydrogen Fuel Storage

- Hydrogen storage is challenging
  - Small molecule – Can creep out through material
  - Low weight per molecule – Low density as gas
  - Liquefies at low temperatures.
- Some examples of options.
  - Compressed Hydrogen storage 700 bar
  - Liquid phase – Cryogenic storage, -253°C
  - Metal hydride
  - Sodium borohydride $NaBH_4$

Comparison of H_2 Fuel Cells – US DOE

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

Early Fuel Cell Applications in USA – US DOE

Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts.

~75,000 *fuel cells have been shipped worldwide.*

>15,000 *fuel cells shipped in 2009*

Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts.

Production & Delivery of Hydrogen

In the U.S., there are currently:

- ***~9 million metric tons*** *of H_2 produced annually*
- ***> 1200 miles*** *of H_2 pipelines*

Source: US DOE 09/2010

Fuel Cells for Transportation

In the U.S., there are currently:

- *> 200 fuel cell vehicles*
- *~ 20 active fuel cell buses*
- *~ 60 fueling stations*

Sept. 2009: Auto manufacturers from around the world signed a letter of understanding supporting fuel cell vehicles in anticipation of widespread commercialization, beginning in 2015.

Outline

Modeling of a Fuel Cell

Key concepts in the coming slides; polarization curve and supporting system.

- Keys for understanding a cell:
  - Cell voltage.
  - Cell current density.
  - The polarization curve (PC) connects cell voltage and current density [A/m^2].
- Understanding a stack.
  - Scale current density with active cell area A to get current in [A].
  - Multiply the cell voltage with the number of cells in series to get the stack voltage.
  - Stack power is (stack voltage)$\times$(stack current).
- Understanding a system.
  - Power from the PC and stack dimensions.
  - Operation – The Supporting System

Fuel Cell Thermodynamics

- Starting point reaction equation

$$H_2 + \frac{1}{2}O_2 \Rightarrow H_20$$

- Open system energy – Enthalpy H

$$H = U + pV$$

- Available (reversible) energy – Gibbs free energy G

$$G = H - TS$$

- Open circuit cell voltages

$$U_{rev} = -\frac{\Delta G}{n_e F}, \qquad U_{id} = -\frac{\Delta H}{n_e F}, \qquad U_{rev} = \eta_{id} U_{id}$$

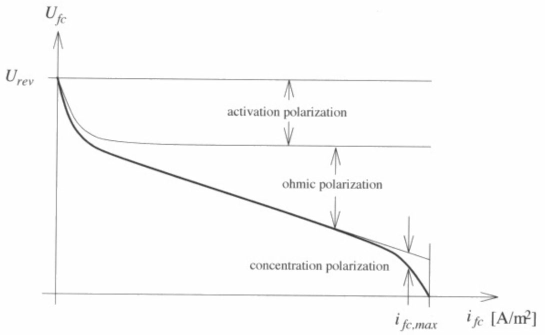
F – Faradays constant ($F = q N_0$)

- Heat losses under load $P_l = I_{fc}(t)\,(U_{id} - U_{fc}(t))$ $\Rightarrow$ Cooling system

Fuel Cell Performance – Polarization curve

Previous slide gives the theoretical limit U_{rev}. Every reaction could theoretically give this voltage. The top of the polarization curve.

- When current flows through the cell the voltage drops. This is called the Polarization curve of a fuel cell
- It connects the current density $i_{fc}(t) = I_{fc}(t)/A_{fc}$, and cell voltage $U_{fc}(t)$
- The efficiency, η_{cell}, is proportional to the Voltage
- A cell has excellent part load efficiency



Single Cell Modeling – Describing the Polarization Curve

Coming slide

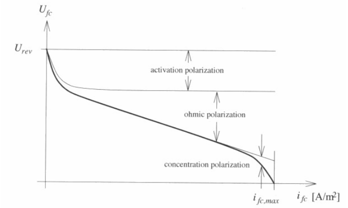
The processes behind the voltage drops depend on physical processes and can be described with different equations.

The principles are interesting to know about but the details of the equations are not important to memorize.

Single Cell Modeling – Describing the Polarization Curve

Fuel cell voltage

$$U_{fc}(t) = U_{rev}(t) - U_{act}(t) - U_{ohm}(t) - U_{conc}(t)$$



- Activation energy – Get the reactions going
  Semi-empirical Tafel equation

$$U_{act}(t) = c_0 + c_1 \ln(i_{fc}(t)), \text{ or } U_{act}(t) = \ldots$$

- Ohmic – Resistance to flow of ions in the cell

$$U_{ohm}(t) = i_{fc}(t)\,\tilde{R}_{fc}$$

- Concentration, change in concentration of the reactants at the electrodes

$$U_{conc}(t) = c_2 \cdot i_{fc}(t)^{c_3}, \text{ or } U_{conc}(t) = \ldots$$

Outline

Fuel Cell System Needs for Power

A fuel cell system needs power to operate.

- Air and hydrogen need to be supplied.
- Some other properties need to be monitored and controlled.

There are some major power consumers and some other non-negligible consumers.

Fuel cell system – Power consumers

Components with major needs for power

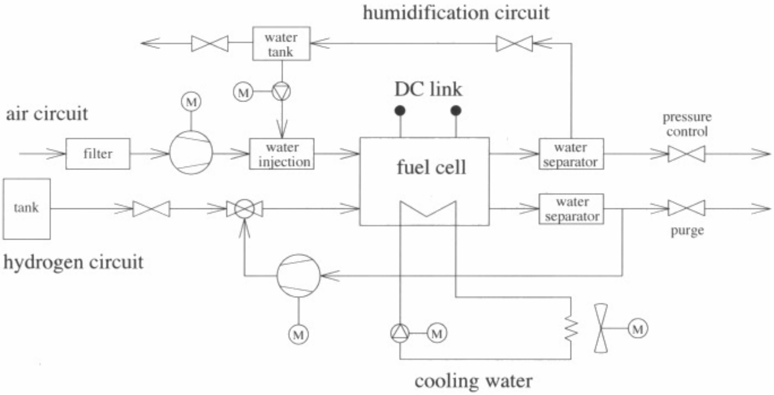
A fuel cell needs oxygen and hydrogen to operate

- Hydrogen is fed to the system from a high pressure source (using pressure reduction control valves)
- Oxygen comes from air and needs to be fed using a fan or a compressor (this needs power)
- The cell losses are released as heat and need to be transported away, using a cooling system with pumps and fans (these need power)

Additional needs for power

- Need to recirculate water to humidify the membrane (a pump)
- Some hydrogen slips past and it needs to be recirculated (a pump)

- A complete fuel cell system



- Power at the stack with N cells

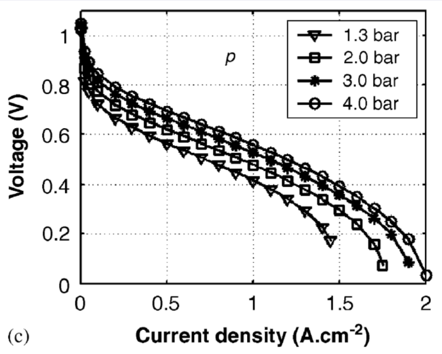
$$P_{st}(t) = I_{fc}(t)\, U_{fc}(t)\, N$$

Performance enhancement and tuning

Beside just keeping the cell alive the major power consumer, the air compressor, can give additional performance to the fuel cell. These are shown on the next slide.

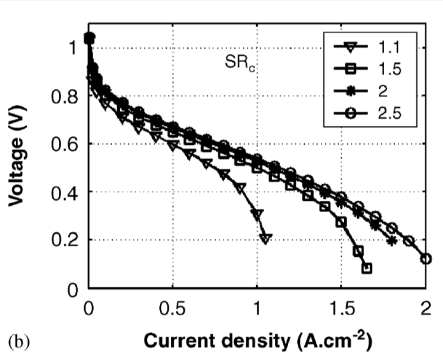
Important effects for the cell and system

Cell Pressure



Boosting the performance

Cell excess air λ



$$2H_2 + \lambda O_2 \rightarrow 2\,H_2O + (\lambda - 1)O_2, \lambda \geq 1$$

Performance enhancement and tuning

Effects from previous slide

- Left: A higher internal cell pressure increases the efficiency (higher polarization curves).
- Right: A higher air flow, gives more air than what is necessary for the hydrogen to water reaction, this also increases the efficiency (higher polarization curves at high currents).

Both these effects increase the efficiency of the cell but it comes at the expense of an increased power consumption of the compressor and the auxiliary system.

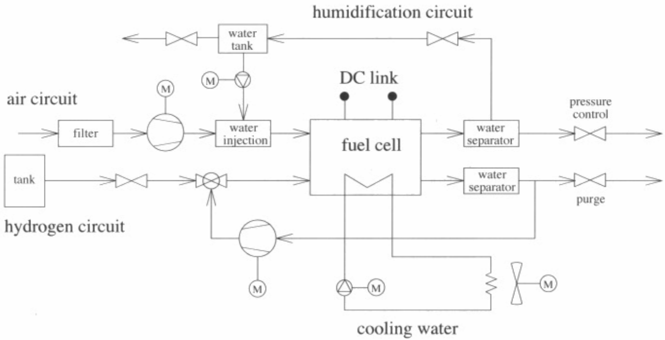
Fuel Cell System Modeling

- Describe all subsystems with models

$$P_{out}(t) = P_{st}(t) - P_{aux}(t)$$

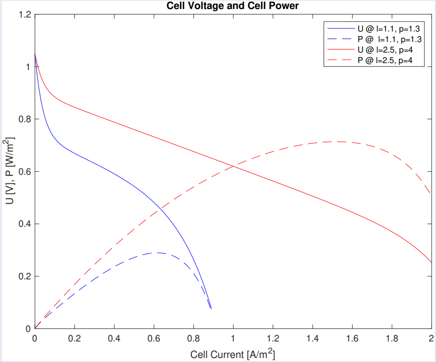
$$P_{aux} = P_0 + P_{em}(t) + P_{ahp}(t) + p_{hp}(t) + P_{cl}(t) + p_{cf}(t)$$

em–air compressor electric motor, ahp – humidifier pump, hp – hydrogen recirculation pump, cl – coolant pump, cf – cooling fan.

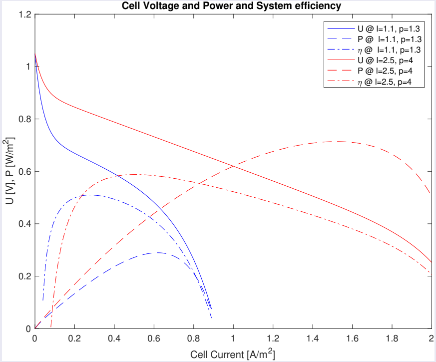


Fuel Cell System Performance at Low and High P_c

Individual Cell



Fuel Cell System



–Efficiency is highest at part loads towards low load.
–The system needs a minimum current from the cell to keep the cell operating.

Computations in the previous slide

The air system is run in two modes blue=(low pressure and low flow) and red=(high pressure and high flow). These two modes give two polarization curves (solid lines) and the auxiliary system consumes low power in the first and and high power in the second.

- Input power is $P_{in} = U_{id} \, I_{fc}$
- Solid lines (Polarization curve) represent the cell voltage.
- Dashed lines – Cell power is calculated from cell current and voltage $P_{cell} = U_{cell} \, I_{fc}$. Looking at the shapes of the power curves we can note that both endpoints $U_{cell} = 0$ and $I_{fc} = 0$ give $P_{cell} = 0$, so there is a power maximum in between. The maximum power is not attained at maximum current since $U_{cell} = 0$ there.
- With I_{fc} being stack current the stack power is now $P_{st} = N_{cell} \, P_{cell}$
- With the auxiliary powers we get the output power $P_{out} = P_{cell} - P_{aux}$ and can compute the efficiency $\eta = \frac{P_{out}}{P_{in}}$, these system efficiencies are plotted as dashdotted lines in the left figure.

Summary of the results from the computations

- Cell efficiency is the same as the polarization curve, since $\eta_{cell} = \frac{P_{cell}}{P_{in}} = \frac{U_{cell} I}{U_{id} I}$, and since U_{id} is constant.
- System efficiency is reduced at low loads, since auxiliary power is necessary to keep the cell operational.
- Zero cell current requires some other system to provide power to the supporting system. A side effect is that a battery or another energy source is needed to start the system.
- Maximum efficiency is attained for low loads.
- Maximum power is attained for currents below the maximum current.
- Going beyond the maximum power reduces the efficiency, which is equivalent to increasing the losses. Increasing losses increases the heat generation, which is bad for the cell.

You can now return to slide 3 to see if it makes sense.