Fuel cell system fundamentals

VINCENZO LISO
VLI@ET.AAU.DK
DEPT OF ENERGY TECHNOLOGY

AALBORG UNIVERSITY
DENMARK

Agenda

- Basic introduction to different fuel cell technologies
- Describe main components of a Galvani and Electrolytic cell
- Basic fuel cell thermodynamics and performance
- Describe main voltage losses affecting the fuel cell

Good references:
- Fuel cell handbook https://www.netl.doe.gov/sites/default/files/netl-file/FCHandbook7.pdf
- Fuel cell fundamentals by Ryan O'Hayre, Suk-Won Cha, Whitney Colella, and Fritz B. Prinz

AALBORG UNIVERSITY
DENMARK

Chemical reaction vs electrochemical reaction

- A chemical reaction is a process in which reactants rearrange in the products
- Electrochemical reaction is characterized by a transfer of electrons, in other words, some substances will gain electrons and some will lose them. This class of reactions it is also called redox.
  - **Oxidation**

    It is called Oxidation because the reactant looses electrons
    $$Reductanct \rightarrow Product + e^-$$

  - **Reduction**

    In a reduction process the reactants acquire an electron
    $$Oxidant + e^- \rightarrow Product$$

AALBORG UNIVERSITY
DENMARK

Galvanic Cells: A simple fuel cell

- A **galvanic cell** (or voltaic cell) transforms the energy in the reactants generating an electrical current or *electromotive force*

- The **electrolytic cell** convert the electrical current into chemical energy (i.e. gasses)

- In both cases there is a redox reaction involved, however it operates in the opposite direction.

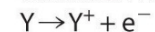- A cell consists of:

2 electrodes: they collect the electrons

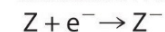Electrolyte: it transport charges (protons; anions)
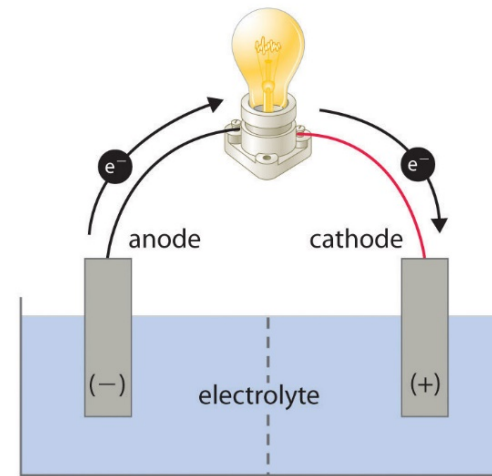
GALVANIC CELL

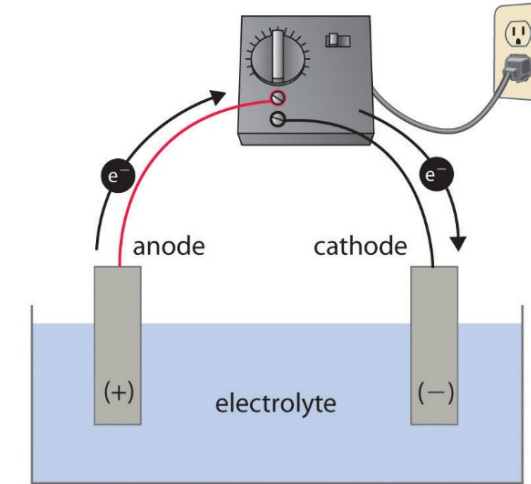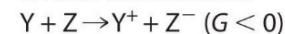Energy released by spontaneous redox reaction is converted to electrical energy.
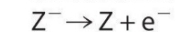
Oxidation half-reaction:
$Y \rightarrow Y^+ + e^-$

Reduction half-reaction:
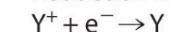$Z + e^- \rightarrow Z^-$

Overall cell reaction:
$Y + Z \rightarrow Y^+ + Z^-$ $(G < 0)$

ELECTROLYTIC CELL

Electrical energy is used to drive nonspontaneous redox reaction.

Oxidation half-reaction:
$Z^- \rightarrow Z + e^-$

Reduction half-reaction:
$Y^+ + e^- \rightarrow Y$

Overall cell reaction:
$Y^+ + Z^- \rightarrow Y + Z$ $(G > 0)$
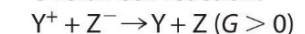
https://chem.libretexts.org/Core/Analytical_Chemistry/Electrochemistry/Electrolytic_Cells

AALBORG UNIVERSITY
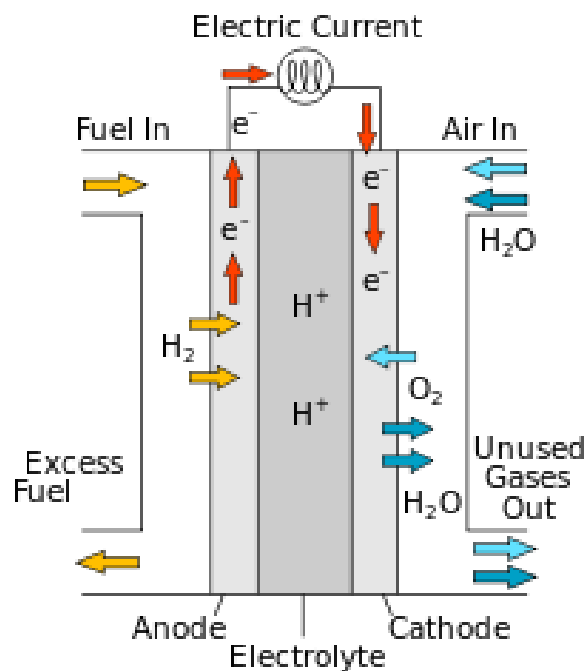DENMARK

Electric double layer

- A phenomena that happen at the **electrode/electrolyte interface**
- Transition region between 2 phases in which there is an **imbalance of charges which strongly interact.**
- It is the area of the electrode where electrochemical reaction occurs like for instance a metal immersed in a solution. It will be a thin layer between the metal and the solution.
- We should remind that in nature a **bulk is characterized by neutral charged unless electrically perturbed**
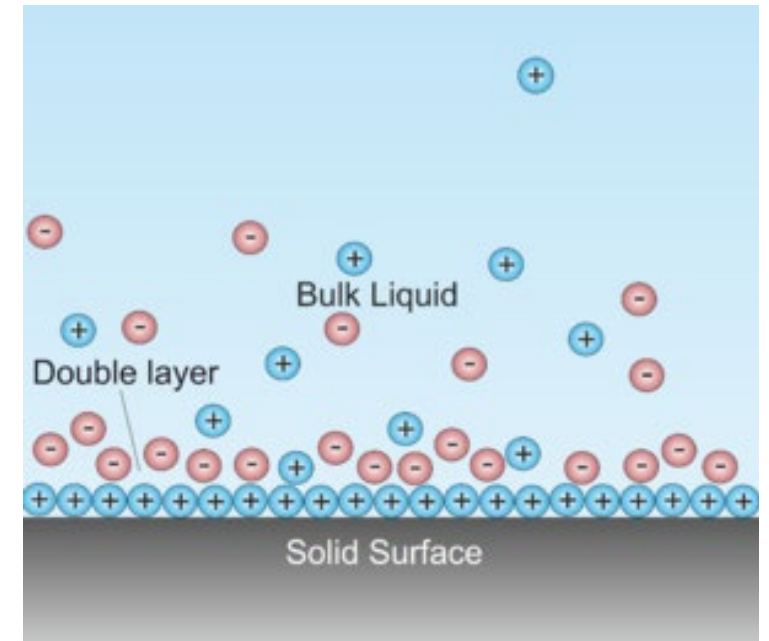
SOURCE: Wikipedia Larryisgood

Fuel cell basic configuration

Electric Current

Fuel In — e^- | Air In

e^-

H_2O

e^- | e^-

H^+

H_2

H^+ | O_2

Excess Fuel | Unused Gases Out

H_2O

Anode | Cathode
Electrolyte

What will be the overall cell potential?

From
http://ncert.nic.in/ncerts/l/lech103.pdf

AALBORG UNIVERSITY
DENMARK

Fuel cell types

Fuel cell are divided according to electrolyte material
Note the different ions crossing the electrolyte, different temperature of operations and material.
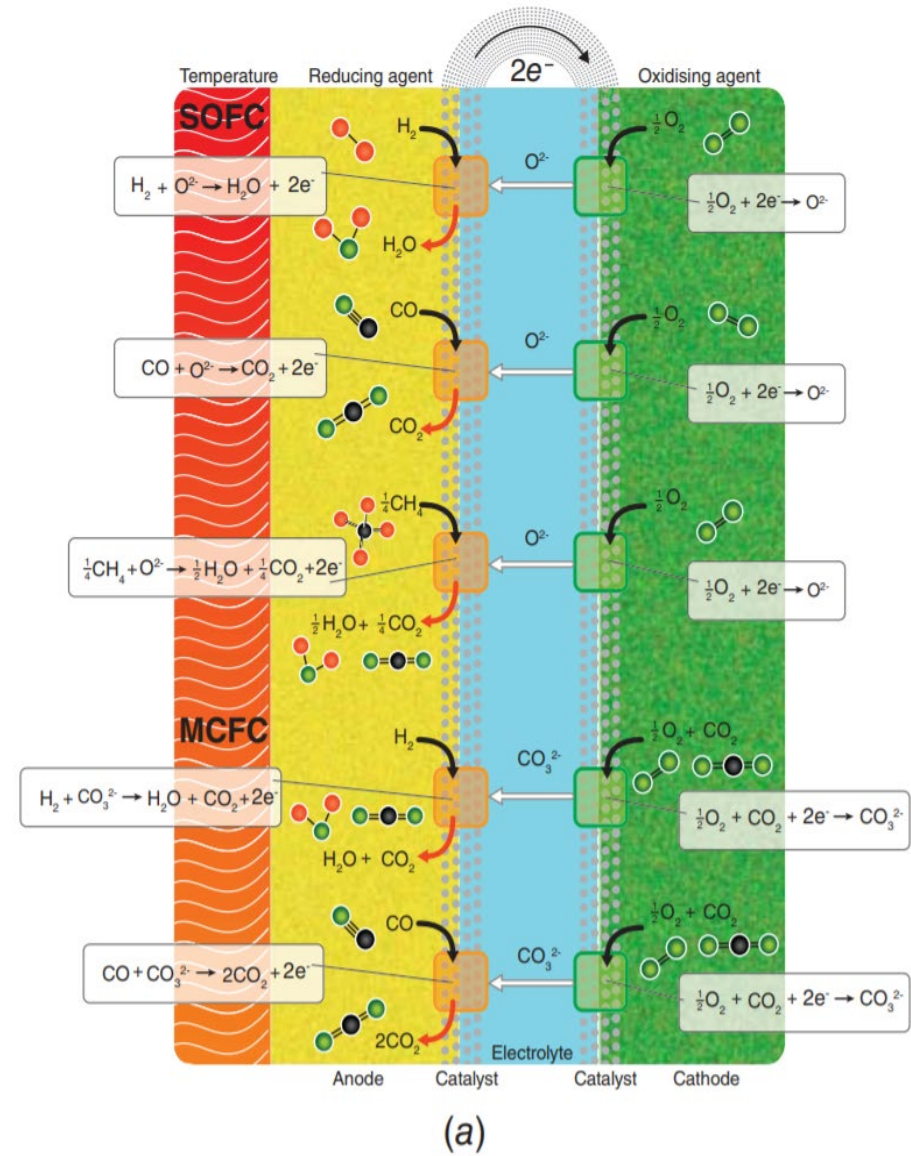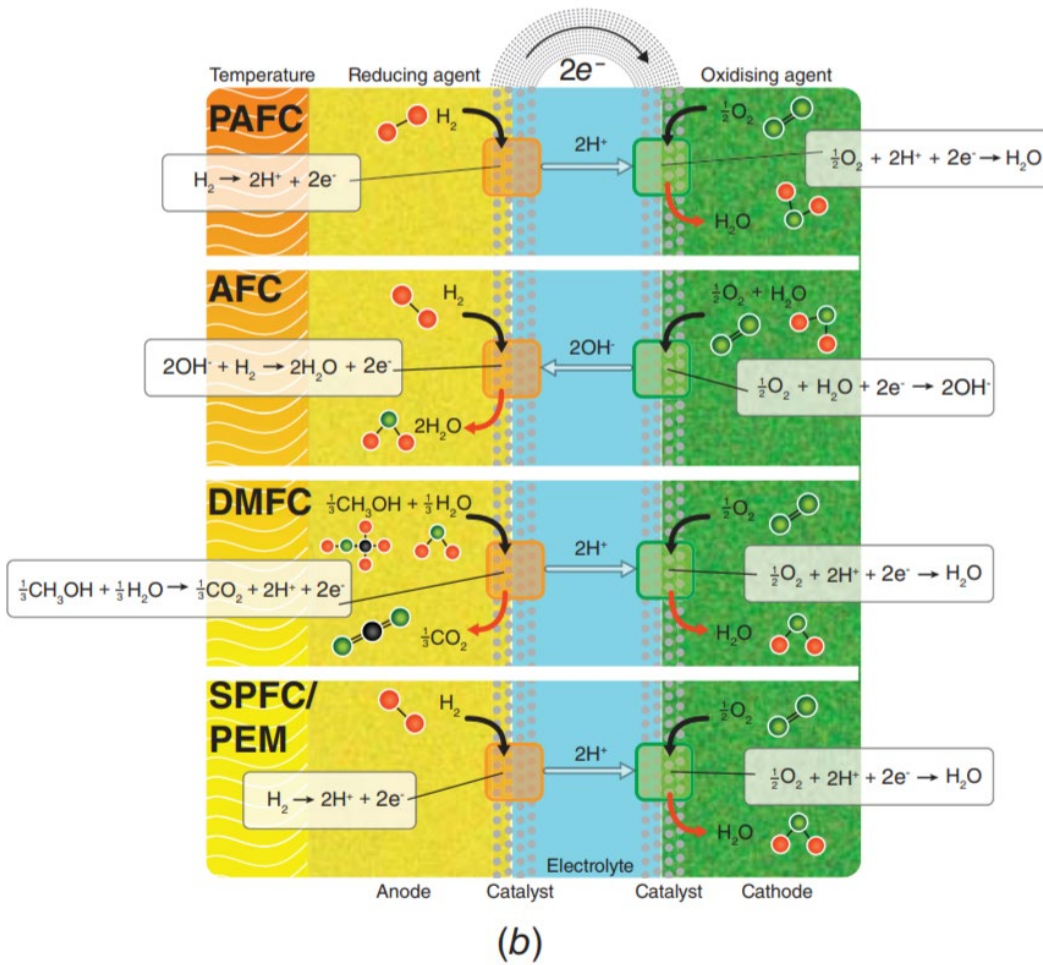
There are 5 main fuel cell types.
1. Phosphoric acid fuel cell (PAFC)
2. Polymer electrolyte membrane fuel cell (PEMFC)
3. Alkaline fuel cell (AFC)
4. Molten carbonate fuel cell (MCFC)
5. Solid-oxide fuel cell (SOFC)

PS the classification of FC is provided in Chapter 8 of Fuel cell fundamentals

Classification of Fuel cells

Summary of electrochemical reaction if different type of Fuel cell

- The table from the US department of Energy provide a comparison between different type of fuel cells

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FUEL CELL TECHNOLOGIES PROGRAM

Comparison of Fuel Cell Technologies

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

For More Information

More information on the Fuel Cell Technologies Program is available at *http://www.hydrogenandfuelcells.energy.gov*.

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

EERE Information Center
1-877-EERE-INFO (1-877-337-3463)
www.eere.energy.gov/informationcenter

February 2011
Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post consumer waste.

AALBORG UNIVERSITY
DENMARK

From
https://web.archive.org/web/20130301120203/http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf

Stationary Fuel Cell Power Systems

**Fuel Cell Energy
2 MW MCFC**

**Plug Power 7kW
Residential PEFC**

**Siemens-Westinghouse
100kW SOFC**

**UTC Fuel Cells
200kW PAFC**

**Ballard 250kW
PEFC**

**Plug Power 10 kW
Residential unit**

AALBORG UNIVERSITY
DENMARK

Breakthrough Technologies Institute: www.fuelcells.org

Fuel cell system
In the car

AALBORG UNIVERSITY
DENMARK
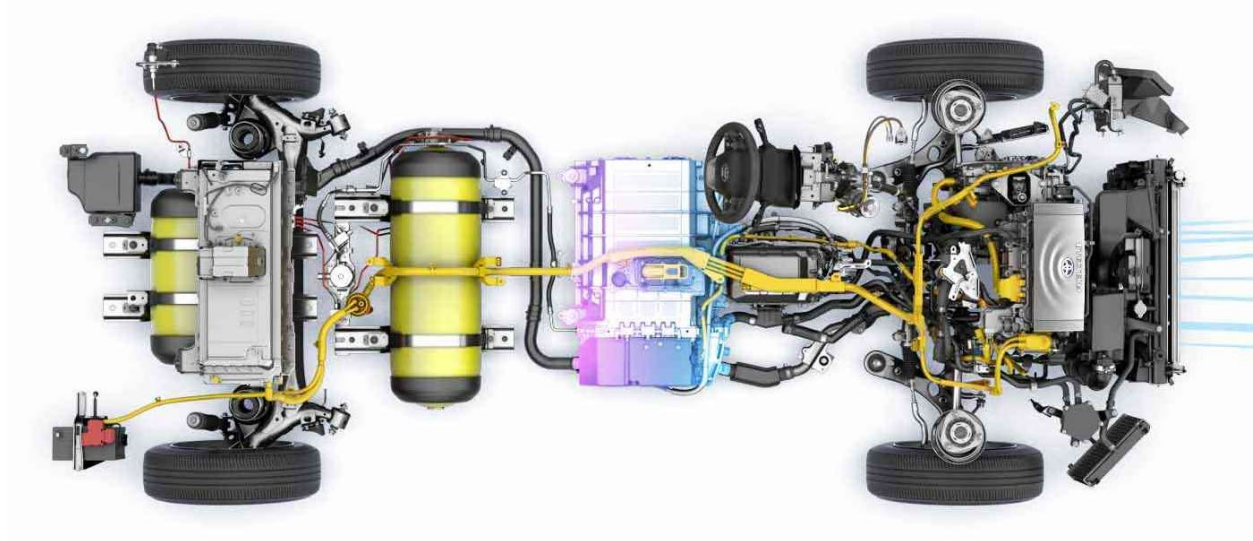
Fuel cell system
In the car
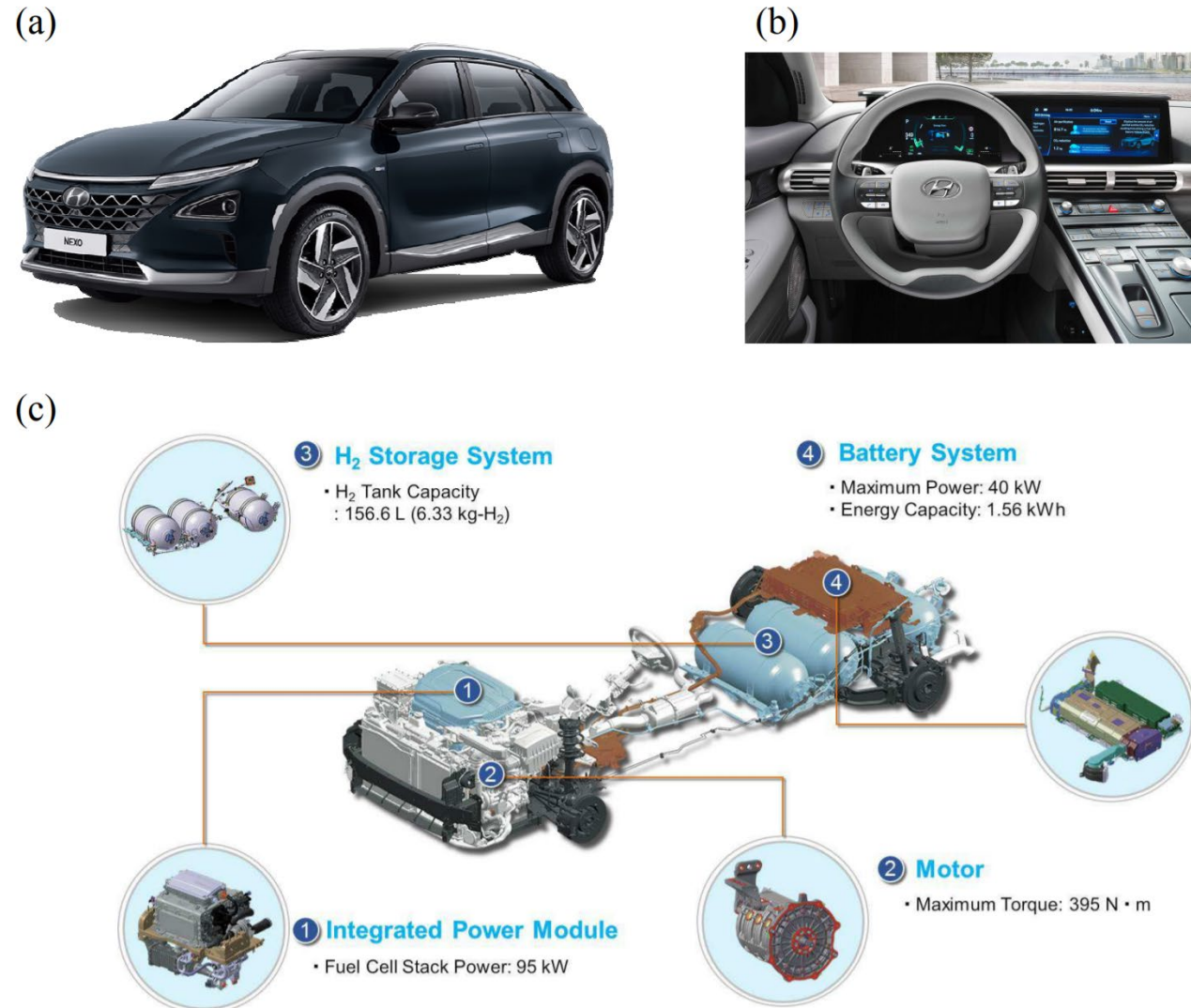
Figure 3. An overview of the Nexo FCEV: (a) exterior; (b) interior; (c) vehicle layout.

AALBORG UNIVERSITY
DENMARK

Gibbs free energy and voltage

The FC reactions are:

$$\text{Anode:} \qquad H_2 \rightarrow 2H^+ + 2e^-$$
$$\text{Cathode:} \qquad \tfrac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$$
$$\text{Overall:} \qquad H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O$$
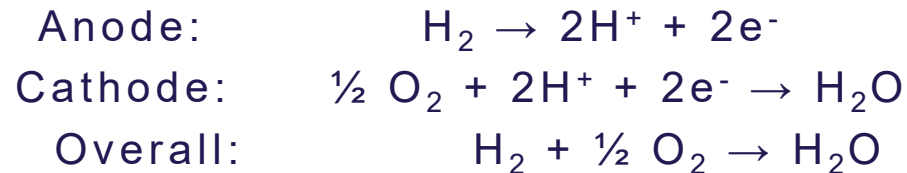
The standard free energy of an electrochemical reaction

$$\Delta \boldsymbol{G} = -\boldsymbol{nFE} = 2 \text{ mol } e^-/\text{mol reactant} *96485 \text{ C/mol} * 1.23 \text{ V} = -237000 \text{ J/mol}$$

E: Reversible potential at equilibrium or ideal potential 1.23V

F: Faraday constant(i.e. magnitude of the electric charge for moles of electrons)

n: nr of electrons exchanged in the electrochemical reaction $H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O$

Relationship between Gibbs Free energy and equilibrium

- For a general reaction $aA + bB \rightarrow cC + dD$ the equilibrium constant is defined:

$$K = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

- Where A;B;C;D are the concentrations and a;b;c;d are the stoichiometric coefficient of the reaction
- The relationship between the eq constant and the Gibbs free energy of reaction is given below:

$$\Delta G = -RT \, ln(K)$$

Nernst Equation

- The relationship accounts for the effect of pressure and temperature when calculating the cell electrical potential E

- $E°$ represents the ideal standard potential at standard condition

- If pressure and temperature of the reactants H2 and O2 is increased the equilibrium potential E will also increases.

- For a cell reaction $H_2 + O_2 \rightarrow H_2O$ the Nernst eq is:

$$E = E° + \frac{RT}{nF} \ln \left(\frac{P_{H_2} \cdot P_{O_2}^{1/2}}{P_{H_2O}} \right)$$

Fuel cell performance

We can assume the fuel cell curve as the algebraic sum of the reversible cell voltage
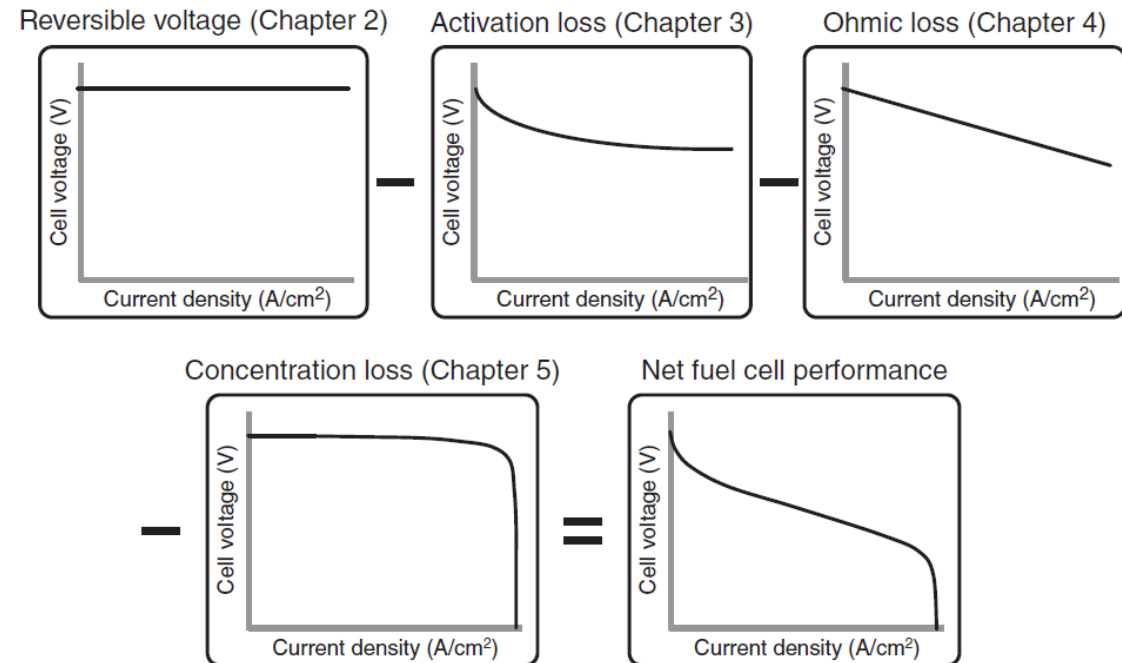
Fuel cell Fundamentals

Activation overvoltage
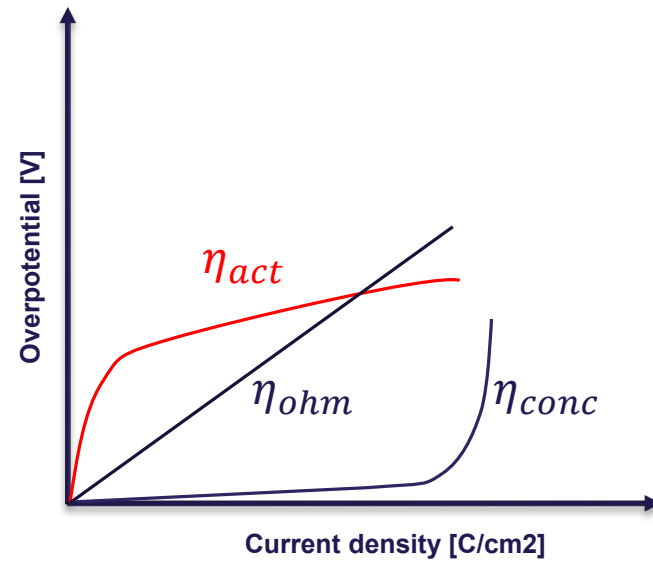
Can you come with an example of Activation energy?

Rate of the electrochemical reaction

- Reactions happen spontaneously when the reactants free energy is larger than products free energy
- The activation energy is represented by the energy "barrier" that the reaction has to overcome to convert reactants into products.
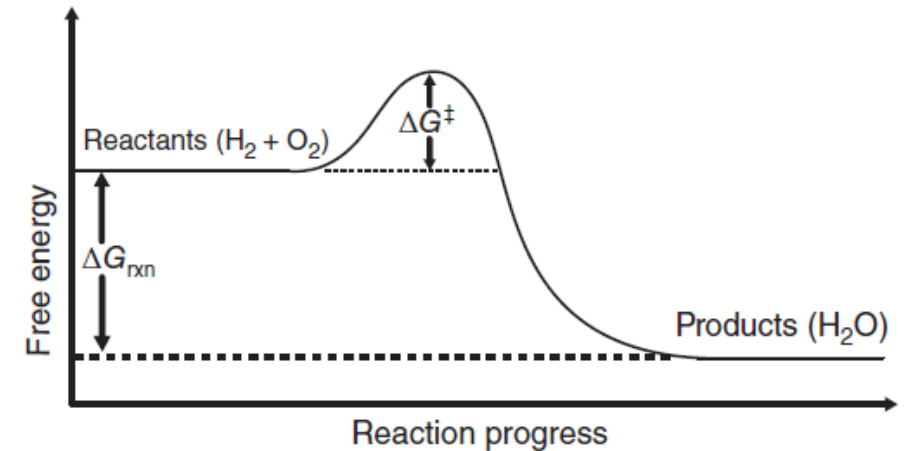- The activation energy limits the rate of reaction

AALBORG UNIVERSITY
DENMARK

Net rate of reaction

- In the **forward reaction**, hydrogen releases one electron the metal catalyst (i.e. platinum)
- In the **backward reaction**, the hydrogen ion gain an electron from the metal.
- At equilibrium both this reactions must balance; although both reactions are taking place the net rate is 0

$$J = C_R^* f_1 e^{-\Delta G_1/RT} - C_P^* f_2 e^{-\Delta G_2/RT}$$

Forward reaction   **Backward reaction**

J: net reaction rate
C_R/P: reactant/product surface concentration
f_1/2: decay rate to product/reactant (i.e. likelihood that the reaction will convert to product/reactant)
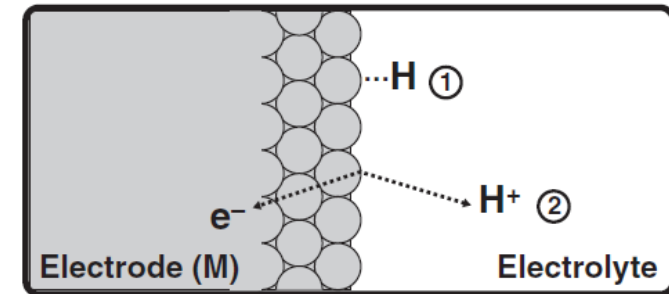
Figure 3.4. Schematic of chemisorbed hydrogen charge transfer reaction. The reactant state, a chemisorbed hydrogen atom (M⋯H), is shown at 1. Completion of the charge transfer reaction, as shown at 2, liberates a free electron into the metal and a free proton into the electrolyte ((M + e⁻) + H⁺).

$$Forward\ reaction: M \cdots H \rightarrow (M + e^-) + H^+$$
$$Reverse\ reaction: \ (M + e^-) + H^+ \rightarrow M \cdots H$$

Chemisorbed Hydrogen

Source: Fuel cell fundamentals Chapter 3

Net rate of reaction

- We can restate the rate of reaction as a function of ΔG of reaction

$$J = C_R^* f_1 e^{-\Delta G_1/RT} - C_P^* f_2 e^{-\Delta G_2/RT}$$

Forward reaction   Backward reaction

Figure 3.4. Schematic of chemisorbed hydrogen charge transfer reaction. The reactant state, a chemisorbed hydrogen atom (M⋯H), is shown at 1. Completion of the charge transfer reaction, as shown at 2, liberates a free electron into the metal and a free proton into the electrolyte ((M + e⁻) + H⁺).

- The activation barrier for the overall reaction can be calculated as the difference between the activation barrier for forward an backward reaction.
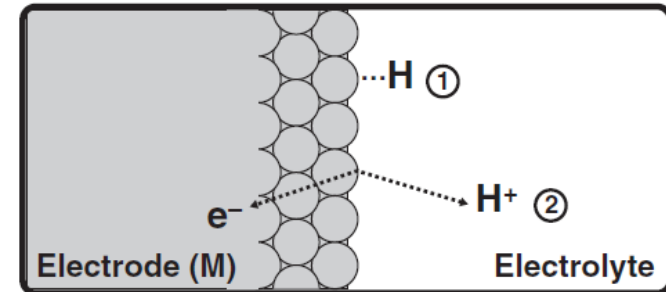
$$\Delta G_{react} = \Delta G_1 - \Delta G_2$$

- Therefore ΔG_2 can be expressed as a function of ΔG_{react} and ΔG_1

$$J = C_R^* f_1 e^{-\Delta G_1/RT} - C_P^* f_2 e^{-(\Delta G_{react} - \Delta G_1)/RT}$$

$$Forward\ reaction: M \cdots H \to (M + e^-) + H^+$$
$$Reverse\ reaction:\ (M + e^-) + H^+ \to M \cdots H$$

Chemisorbed Hydrogen

Source: Fuel cell fundamentals Chapter 3

- At equilibrium the reaction rate of reaction is 0

$$J = 0$$

AALBORG UNIVERSITY
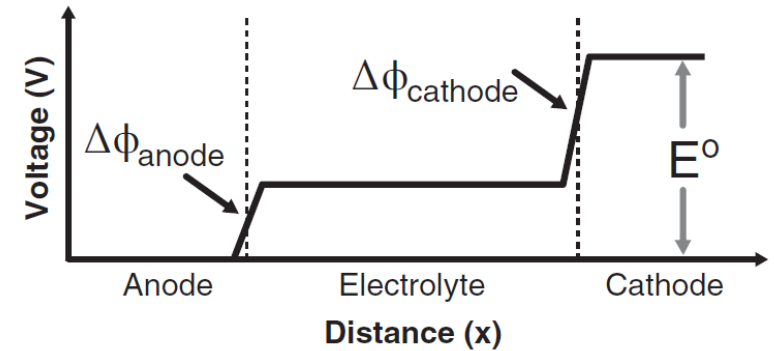DENMARK

Potential of reaction at equilibrium in a fuel cell

- In a fuel cell we have 2 electrodes, electrochemical reactions occurs both at anode and cathode, hence generating 2 electrical potentials.
- The overall cell voltage, E^0, will be the sum of the 2 electrode potentials.

$$E^0 = \Delta\phi_{Anode} + \Delta\phi_{Cathode}$$

AALBORG UNIVERSITY
DENMARK

Butler Volmer equation

- Current density and reaction rate are related by the relationship:

$$j = nFJ$$

Lower case   Capital case

- The current density is defined as (Butler Volmer eq.):

$$j = j_0 \left(\frac{C_R^*}{C_R^{0*}} e^{\alpha nF\eta/(RT)} - \frac{C_P^*}{C_P^{0*}} e^{-(1-\alpha)nF\eta/(RT)} \right)$$

- η: activation voltage loss
- n: number of electron transferred by the electrochemical reaction
- α: charge transfer coefficient (proportional to the energy "barrier")
- C_R^*, C_P^*: actual reactant and product concentration
- C_P^{0*}, C_P^{0*} : reference reactant and product concentration
- j_0 : reference current density

- Current density increases exponentially with activation overvoltage

Source: Fuel cell fundamentals Chapter 3

AALBORG UNIVERSITY
DENMARK
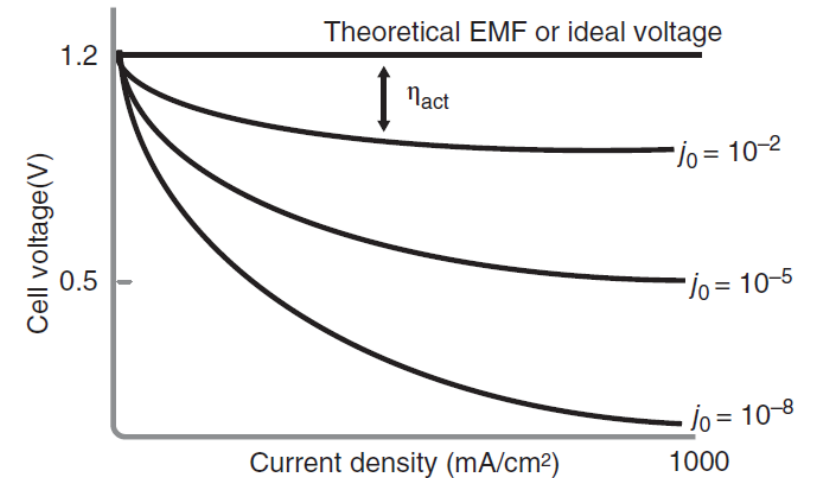
Butler Volmer equation

- Based on this equation we can say that there are different ways increase cell performance.
  - Increase reactant concentration (e.g. increase reactant flow rate and pressure)
  - Reduce the activation barrier (e.g. better catalyst material)
  - Increase temperature (i.e. higher temperature will cause a larger moments in the gas and a higher probability to engage in reactions)
  - Increase the reaction sites (i.e. more sites available for electrochemical reactions)

$$j = j_0 \left(\frac{C_R^*}{C_R^{0*}} e^{\alpha n F \eta / (RT)} - \frac{C_P^*}{C_P^{0*}} e^{-(1-\alpha) n F \eta / (RT)} \right)$$

AALBORG UNIVERSITY
DENMARK

Tafel equation

- If voltage is larger than 50-mV the forward reactions in the Bulter Volmer equation dominate, so that the rate of reverse reaction is negligible

$$\cong 1 \qquad\qquad = 0$$

$$j = j_0\left(\frac{C_R^*}{C_R^{0*}}e^{\alpha nF\eta/(RT)} - \frac{C_P^*}{C_P^{0*}}e^{-(1-\alpha)nF\eta/(RT)}\right)$$
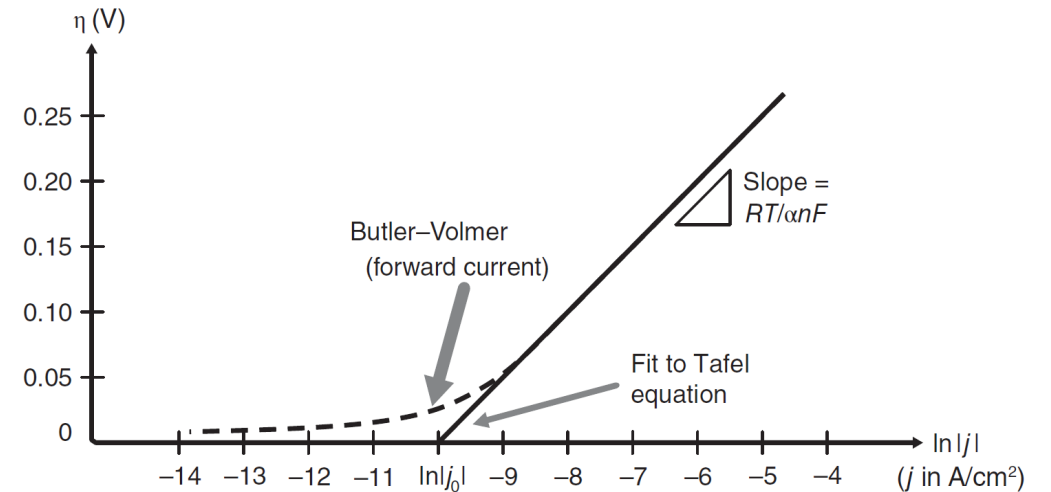
- We can rewrite the current density as:

$$j = j_0 e^{\alpha nF\eta/(RT)}$$

- We can rewrite the equation solving for the activation voltage loss (TAFEL EQUATION)

$$\eta_{Act} = -\frac{RT}{\alpha nF}\ln j_0 + \frac{RT}{\alpha nF}\ln j$$

Const $\qquad$ Tafel slope

η (V)

0.25

0.20 — Butler–Volmer (forward current), Slope = RT/αnF

0.15

0.10

0.05 — Fit to Tafel equation

0

−14 −13 −12 −11 ln|j₀| −9 −8 −7 −6 −5 −4   (j in A/cm²)
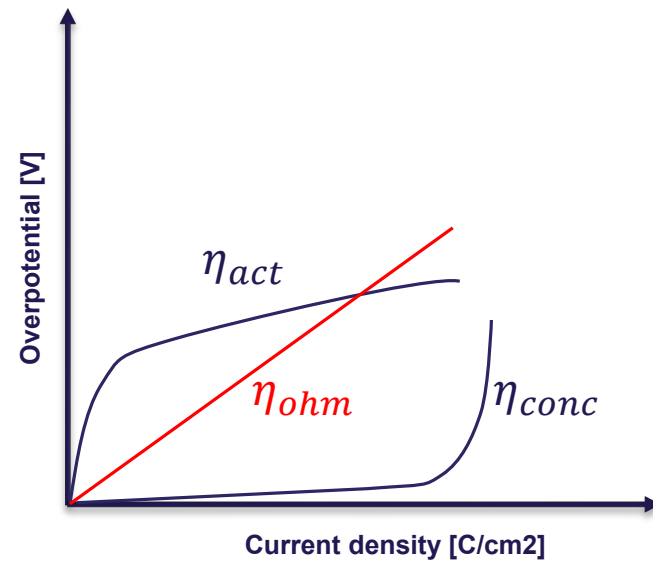
ln|j|

Source: Fuel cell fundamentals Chapter 3

AALBORG UNIVERSITY
DENMARK

Ohmic overvoltage

Examples?

Fuel cell charge transport

- The current density can be related to charge transport via a relationship with voltage and conductivity, σ
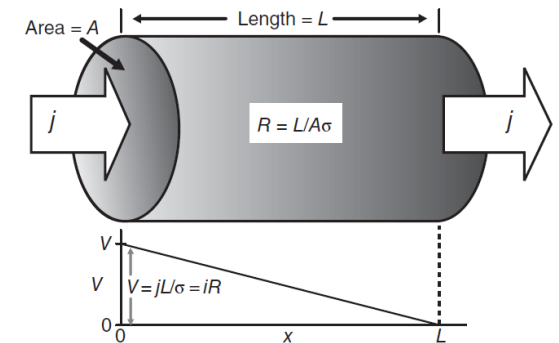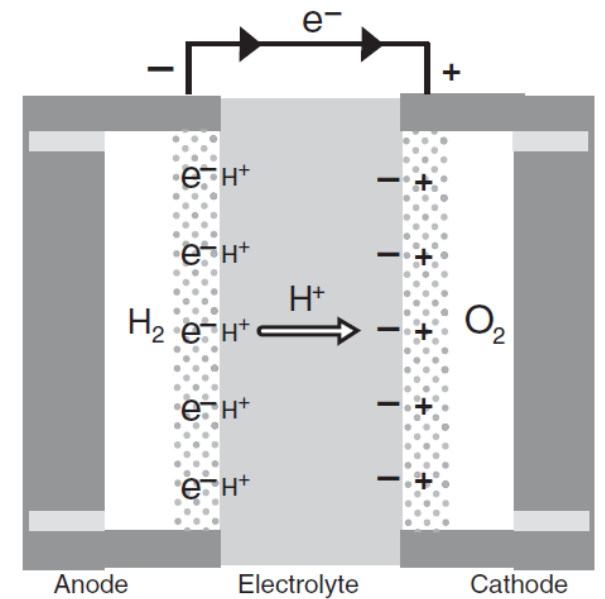
$$j = \sigma \frac{dV}{dx}$$

- We can deduce the voltage as a function of current and resistance:

$$j = \sigma \frac{V}{L} \qquad V = j\frac{L}{\sigma} = i\left(\frac{L}{A\sigma}\right) = iR$$

$$i = jA \qquad R: resistance$$

Anode   Electrolyte   Cathode

Area = A   Length = L

j $R = L/A\sigma$ j

$V = jL/\sigma = iR$

Source: Fuel cell fundamentals Chapter 4

AALBORG UNIVERSITY
DENMARK

Charge transport

- Charge transport is linear and is evident in the electrolyte where there is a reduction of voltage from anode to cathode due to resistance of the electrolyte to the hydrogen ion
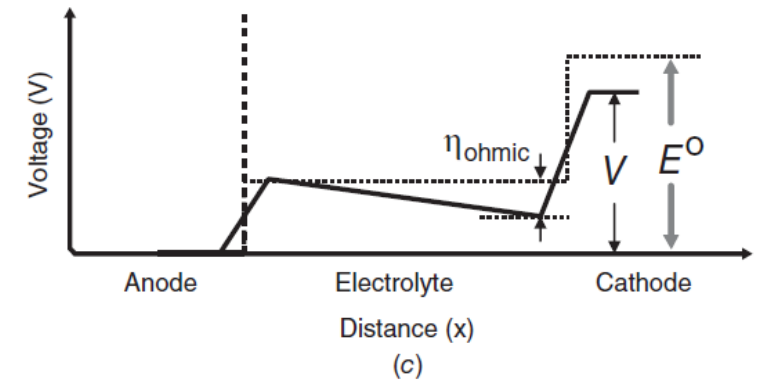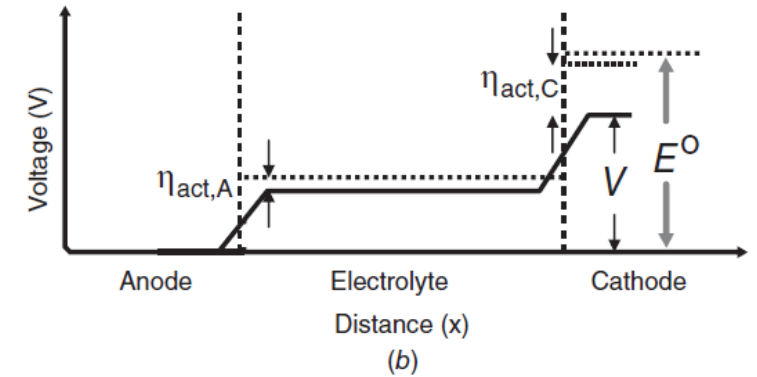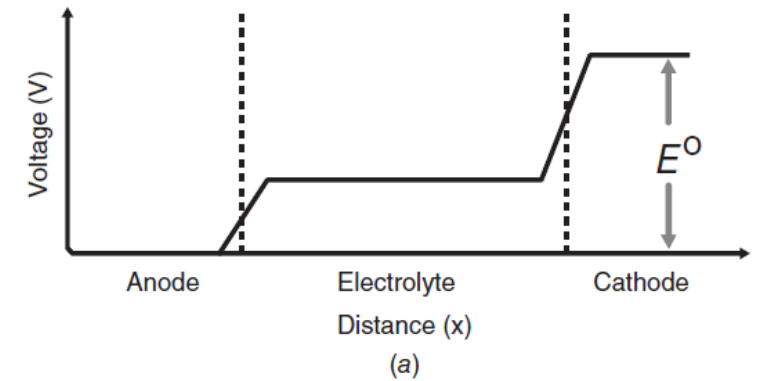
$$\eta_{Ohm} = i \cdot R_{Ohm} = i(R_{Elec} + R_{Ionic})$$

$$R_{Ionic} \gg R_{Elec}$$

$$\eta_{Ohm} = j \cdot ASR$$

ASR: Area specific resistance $[\Omega \cdot cm^2]$

$$ASR = A_{FC}R_{Ohmic} = \frac{L}{\sigma}$$

Source: Fuel cell fundamentals Chapter 3

AALBORG UNIVERSITY
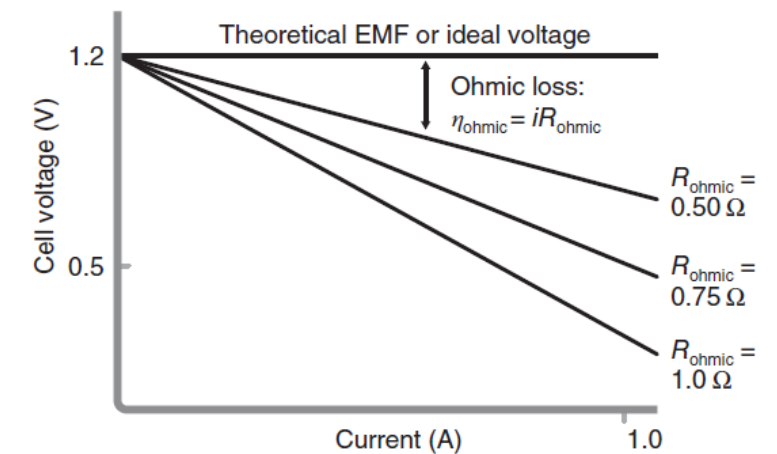DENMARK

Charge transfer

- Resistances in different stacked components can be summed
- The electrolyte accounts for most of the resistance
- Charge transfer reduces cell voltage
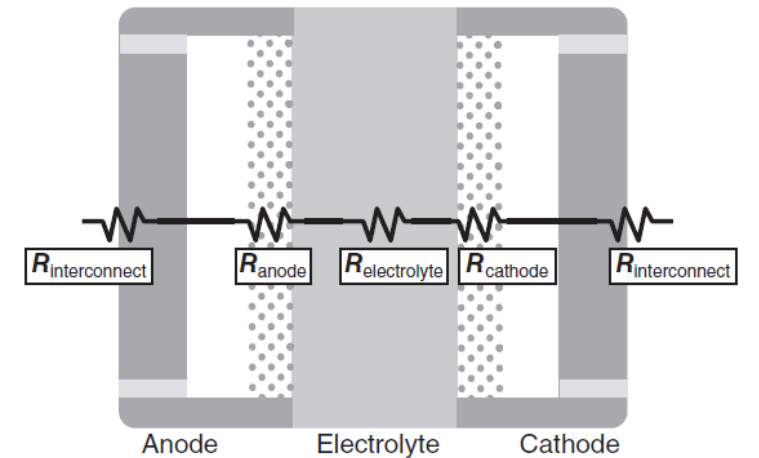
Source: Fuel cell fundamentals Chapter 4

Concentration overvoltage
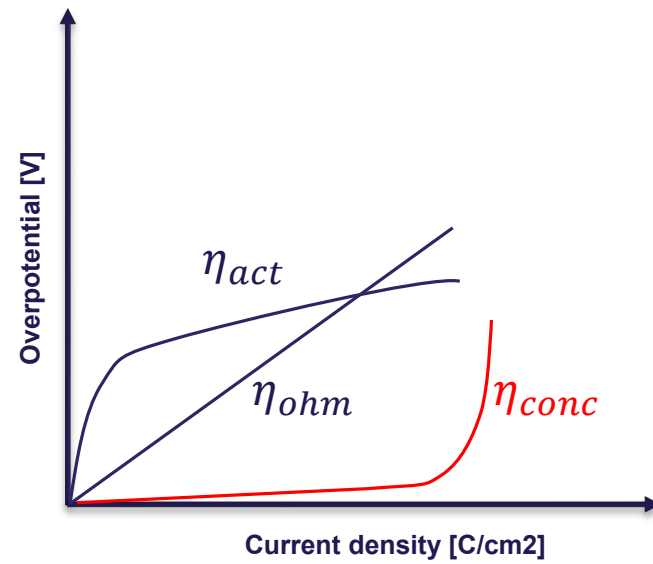
Examples?

Mass transport in FC

Combination of:

(1) Nerstian losses: Due to depletion of reactants (and their activity) in the channel

$$E = E^0 - \frac{RT}{2F} \ln \frac{a_{H2O}}{a_{H2}a_{O2}^{1/2}}$$

(2) Reaction losses: Activation losses increases due depletion of reactants (J_R reduces along the gas diffusion layer)

Source: Fuel cell fundamentals

Gas depletion along the channel

- Reactants are consumed along the channel

- In the right figure we consider mass transport by diffusion along the GDL and convection along the channel
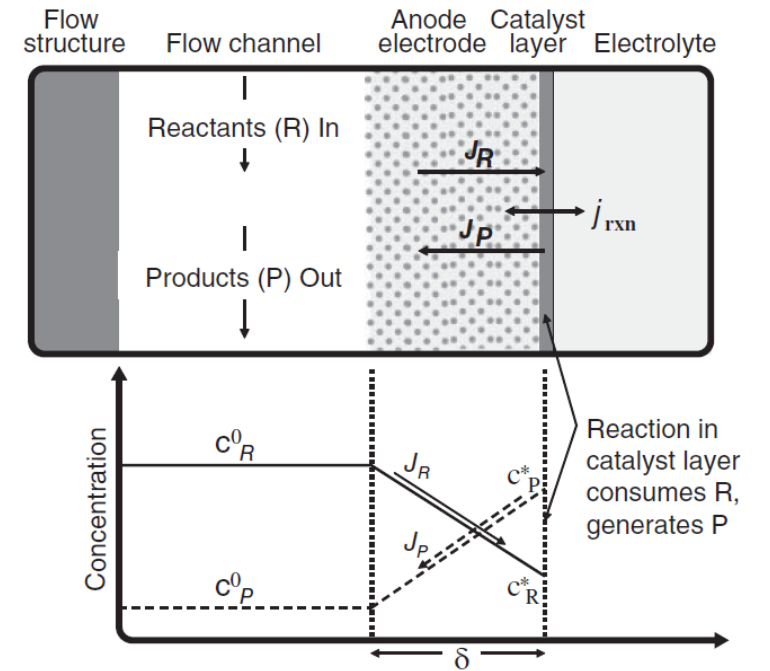
- The oxygen mass flux is depending on current density produced at the fuel cell electrolyte (Faraday Law):

$$\frac{1}{2}H_2 \Leftrightarrow H^+ + e^-$$

$$J_{O2}^{RXN} = M_{O2}\frac{j(x)}{4F}$$

$$H^+ + e^- + \frac{1}{4}O_2 \Leftrightarrow H_2O$$
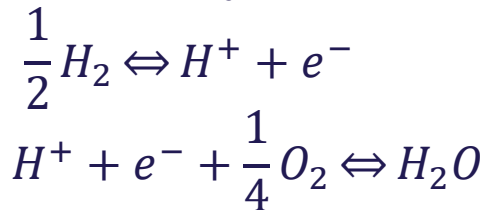
- Oxygen gas consumed by the electrochemical reaction has to be provided by diffusion across the gdl (Fick law):

$$J_{O2}^{Diff} = -D_{O2}^{Eff}\frac{\rho_{O2}^C - \rho_{O2}^E}{H_E}$$

- Convective mass transport across the channel

$$J_{O2}^{Conv} = -h_m(\rho_{O2}^E - \hat{\rho}_{O2}^{Channel})$$

Steady state $\quad J_{O2}^{RXN} = J_{O2}^{DIFF} = J_{O2}^{CONV}$

Source: Fuel cell fundamentals

AALBORG UNIVERSITY
DENMARK
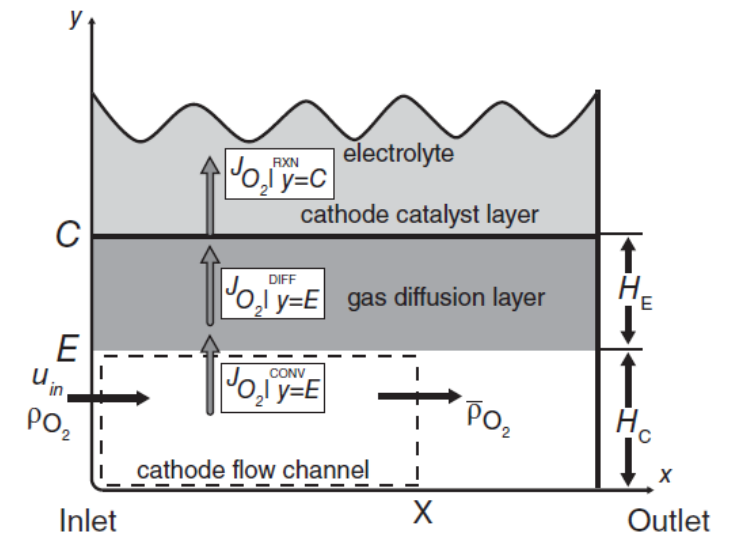
Limiting current density

- When reactants concentration drops to is very low, current cannot produced.
  We call this instance "Limit current density":

$$j_L = nFD^{eff} \frac{C_R^0}{\delta}$$ ← Gas diffusion layer thickness

- In a fuel cell where hydrogen and oxygen are the reactants

  The conversion rate is 0

Source: Fuel cell fundamentals

Fuel cell power

Power = I*V

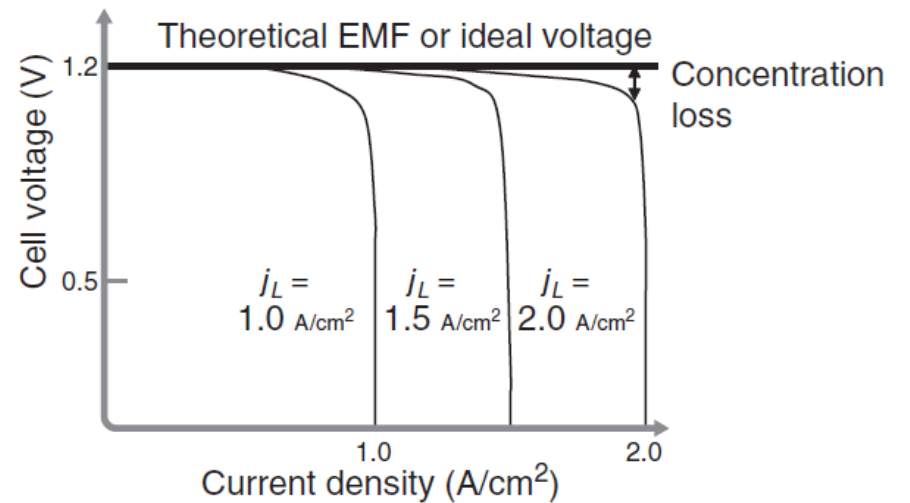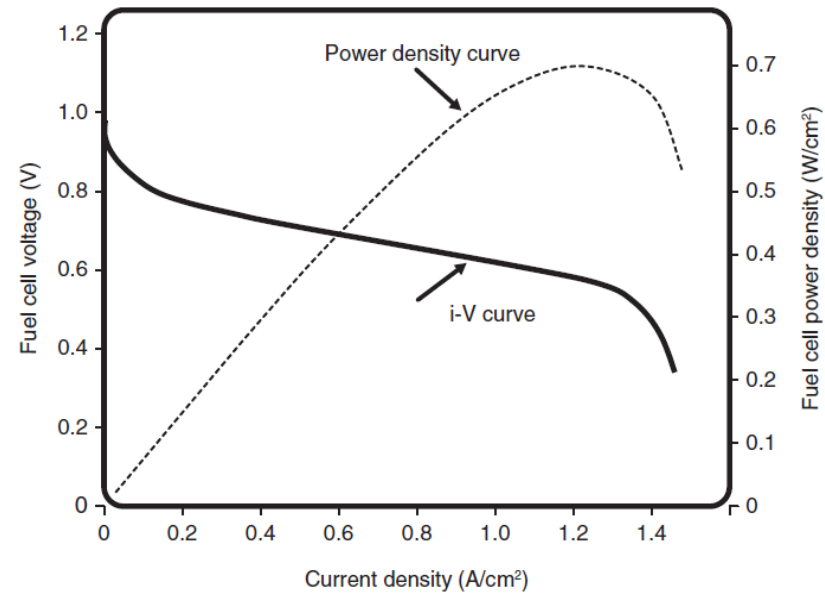From: Fuel cell fundamentals, Chapt.1

Cell performance

Under load a decrease of cell voltage is exirience

$$V = E - \eta_{act} - \eta_{ohm} - \eta_{conc}$$

η_{act}:**Activation overvoltage** due to kinetics of reaction. It occur at all current densities but are dominant at low current density and are associated with sluggish electrode reaction kinetics

η_{ohm}:**Ohmic resistance** due to Ohmic resistance. resistances to charge conduction through the various cell components demonstrate a linear dependence with current.

η_{conc}: due to mass transport. The cell is essentially "starved" of reactants as they cannot be supplied at the rate at which the electrode reactions demand.

From: Fuel cell fundamentals, Chapt.1
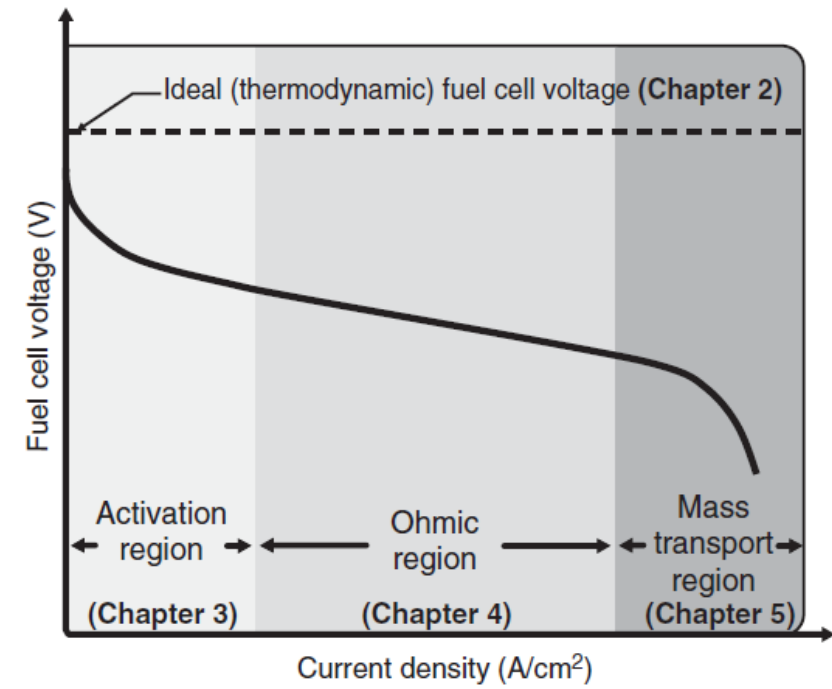
AALBORG UNIVERSITY
DENMARK
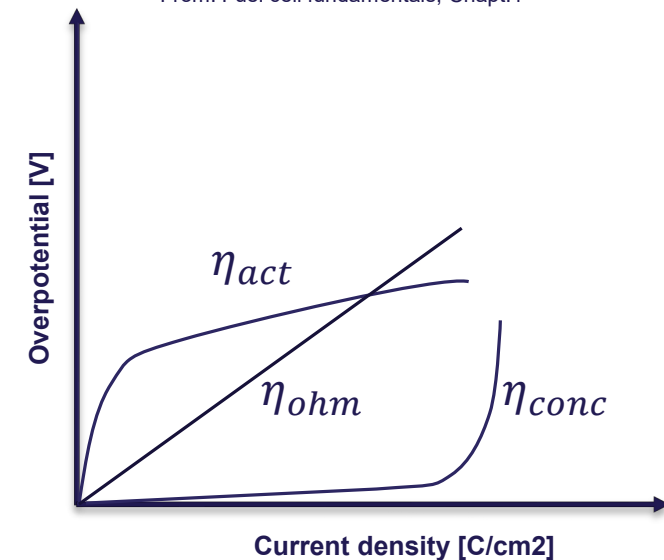
Thanks for your attention

Simple mathematical model of a Fuel Cell in Matlab

Cell voltage can be expressed a difference between open circuit voltage and voltage losses:

$$V_{Cell} = V_{OCV} - V_{loss}$$

The open circuit voltage can be expressed using the Nenrst Equation:

$$V_{OCV} = V_{Rev} = \frac{-\Delta G°}{n_e F} + \frac{RT_{FC}}{n_e F} \ln \left(\frac{P_{H2} \sqrt{P_{O2}}}{P_{H2O}^{Sat}} \right)$$

The activation losses can be expressed using the Tafel equation:

$$\eta_{act} = \frac{RT}{\alpha n_e F} \cdot \ln \left(\frac{i}{i_o} \right) = - \underbrace{\frac{RT}{\alpha n_e F} \cdot \ln i_o}_{Const} + \underbrace{\frac{RT}{\alpha n_e F} \cdot \ln i}_{Tafel\ Slope}$$

α: Simmetry factor (It measure the direction of the reaction)

i_o: exchance current density (Material parameter which depend the ability of the cell to exchange current)

AALBORG UNIVERSITY
DENMARK

Simple mathematical model of a Fuel Cell in Matlab

The Ohmic losses are depending on Ohmic resistance R_{ohm}

$$\eta_{ohm} = i \cdot R_{ohm}$$

The Ohmic losses are function of the Limiting current density which is the max current a fuel cell can exchange

$$\eta_{conc} = \frac{RT}{\alpha n_e F} \ln \frac{j_L}{j_L - j}$$

AALBORG UNIVERSITY
DENMARK

MatIab model (1)

```matlab
clc;
close all;
clear all;

%Fuel cell reaction H2 + 0.5*O2 => H2O Gibbs Free energy [Source FC Explained fig2.4]

%Liquid H2O
T_tab_liq = [25 80];
T_ql = 25:5:80;
DeltaG_tabl = [-247.2 -228.2]; %kJ/mol
DeltaGl = interp1(T_tab_liq,DeltaG_tabl,T_ql); %kJ/mol
%Gas H2O
T_tabg = [100 200 400 600 800 1000];
T_qg = 100:10:1000;
DeltaG_tabg = [-225.2 -220.4 -210.3 -199.6 -188.6 -177.4]; %kJ/mol
DeltaGg = interp1(T_tabg,DeltaG_tabg,T_qg); %kJ/mol

DeltaG0 = interp1(T_tab_liq,DeltaG_tabl,70)*1000; %[J/mol of H2] standard Gibbs free energy of reaction with liquid water as bioproduct at
70C
Tcell = 70+273.15; %[k] Cell temperature
n = 2; %[-] Number of electrons involved in the electrochemical reaction
F = 96485; %[C] Charge of 1 mole of electrones
R = 8.314; %[J/mol] Universal gas constant

P_an = 101325; %[Pa] Anode pressure
P_cat = 101325; %[Pa] Cathode press

P_sat = exp(23.1963-3816.44./(Tcell-46.13)); % [Pa] Saturation pressure of water vapor
p_H2 = (P_an-P_sat)/P_an; %[-] H2 partial pressure with RH100%
p_O2 = (P_cat-P_sat)*0.21/P_cat; %[-] O2 partial pressure
p_H2O = 1; %Water partial pressure assuming liquid water
```

MatIab model (2)

```matlab
j_cell = 0.01:0.01:1;   %[A/cm^2] Cell current density
%Reversible voltage [V]
E = -DeltaG0/(n*F);
%Open circuit voltage (OCV)
p_RATIO = (p_H2*p_O2^0.5)/p_H2O;
Vocv = E + (R*Tcell)/(n*F)*log(p_RATIO);   %[V] open circuit voltage
%Activation overvoltage
alpha = 0.2;   %[-] Simmetry factor
j_0 = 0.01;       %[-]
S_Tafel = (R*Tcell)/(alpha*n*F);%Tafel slope
Vact = S_Tafel*log((j_cell)/j_0);%[V]
%Ohmic overvoltage
ASR = 0.1; %[Ohm*cm^2]
Vohm = j_cell*ASR;%[V]
%Concentration overvoltage
c = 0.032;
j_cell_L = 1;%[A/cm^2]
Vcon = c*log(j_cell_L./(j_cell_L-j_cell));%[V]
%Cell voltage
V = Vocv-Vact-Vohm-Vcon;%[V]
A_cell = 10*10;%cm2
ncell = 50;
P_cellcm2 = j_cell.*V;
I_cell = j_cell*A_cell;
V_stack = A_cell*ncell*V;
P_cell = A_cell*j_cell.*V;
P_stack = P_cell*ncell;

%Plotting results
figure(1)
plot(j_cell,V,j_cell,Vact,j_cell,Vohm,j_cell,Vcon,j_cell,P_cellcm2),legend('Vcell','Vact','Vohm','Vcon','P_cell')
xlabel('Current Density [A/cm2]')
ylabel('Voltage [volt]  // Power [watt]')
figure(2)
plot(T_ql,DeltaGl,T_qg,DeltaGg),legend('DeltaG(g)','DeltaG(l)')
xlabel('Temperature [degreeC]')
ylabel('DeltaG')
figure(3)
plot(I_cell,V_stack,I_cell,P_stack),legend('V_{stack}','P_{stack}')
xlabel('Current [A]')
ylabel('Voltage [volt] (Blue) // Power [watt] (red)')
```

AALBORG UNIVERSITY
DENMARK