M2794.010400
Fuel Cell Science & Technology

Course Introduction

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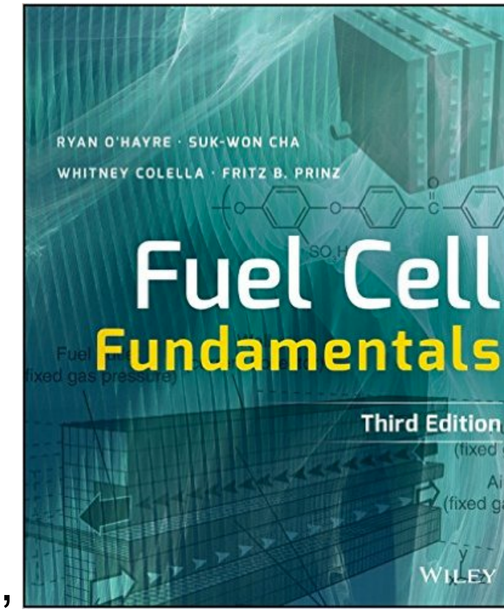
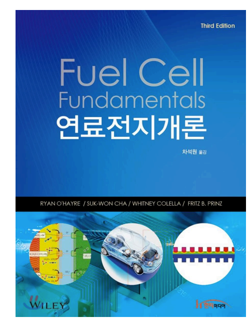
- **Text**:
  - 1. R. O'Hayre, S. W. Cha, W. Collela, F. B. Prinz, *Fuel Cell Fundamentals 3rd Ed*, Wiley, 2016
  - 2. *DOE Fuel Cell Handbook*, 7th Ed. 2004 (Available for free on the web but not updated anymore).





Course Introduction

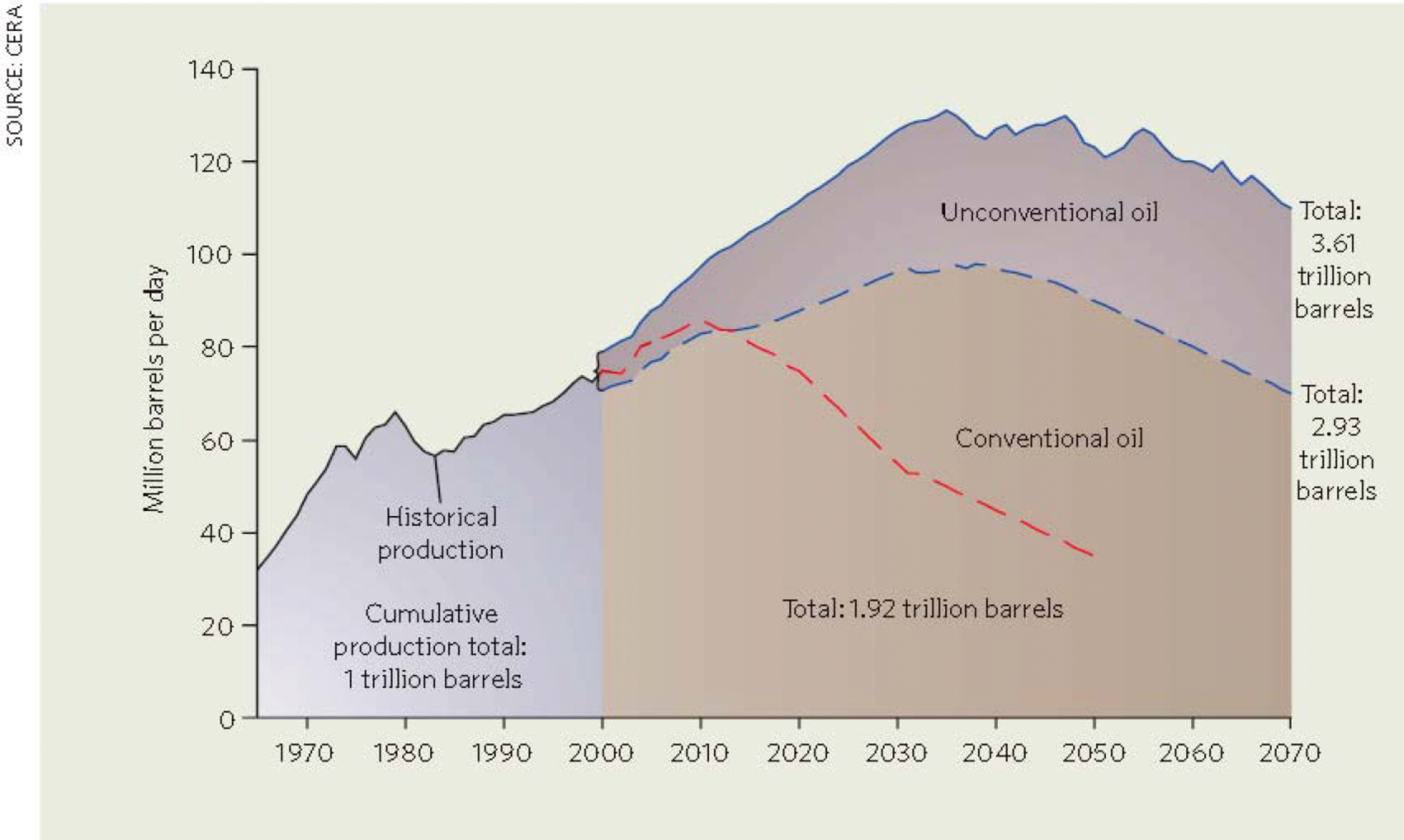
- **Prerequisites**: Engineering Mathematics, Basic Physics or Chemistry, Basic Thermodynamics, or equivalent.
- **Course Homepage:** http://etl.snu.ac.kr
- **Lecture schedule:** Every Mon, Wed 2:00PM-3:15PM, Bld 301, Rm 301
- **Grading:**
  - *Homework (25%)* Problem sets as homework for each lecture topic corresponding to each chapter of the main textbook. Due at the beginning of class. 10% penalty for each day late. No acceptance after solutions are posted -generally a couple of days after the assignment is due.
  - *Midterm (25%)* An 1 hour in-class exam. Open book policy.
  - *Final Exam (40%)* A comprehensive 3 hour in class final exam. Open book policy.
  - *Class Attendance (10%)*

Course Introduction

Weeks	Date	Contents
1	3/1,3	Introduction, Fuel Cell Thermodynamics
2	3/8,10	Fuel Cell Kinetics
3	3/15,17	Fuel Cell Charge Transport I
4	3/22,24	Fuel Cell Charge Transport II
5	3/29,31	Fuel Cell Mass Transport I
6	4/5,7	Fuel Cell Mass Transport II
7	4/12,14	Fuel Cell Modeling I
8	5/19,21	Fuel Cell Modeling II, Midterm Exam
9	5/26,28	Fuel Cell Characterization I
10	5/3,5	Fuel Cell Characterization II
11	5/10,12	Fuel Cell Types
12	5/17,19	Fuel Cell Materials
13	5/24,26	Fuel Cell Systems
14	5/31,6/2	Fuel Cell Design
15	6/7,9	Review, Final Exam

Introduction to Fuel Cells

Why Fuel Cell?



Twin peaks: peak-oil supporters think we have already reached or will soon reach a historical maximum of oil production (red line); others argue that oil production will not peak until at least 2030 (blue lines).

Why Fuel Cell?



High Efficiency

Clean Energy

Renewable Energy

What Is A Fuel Cell?

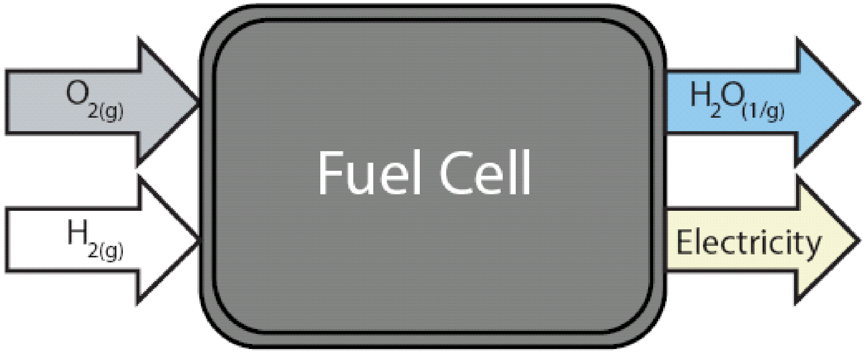
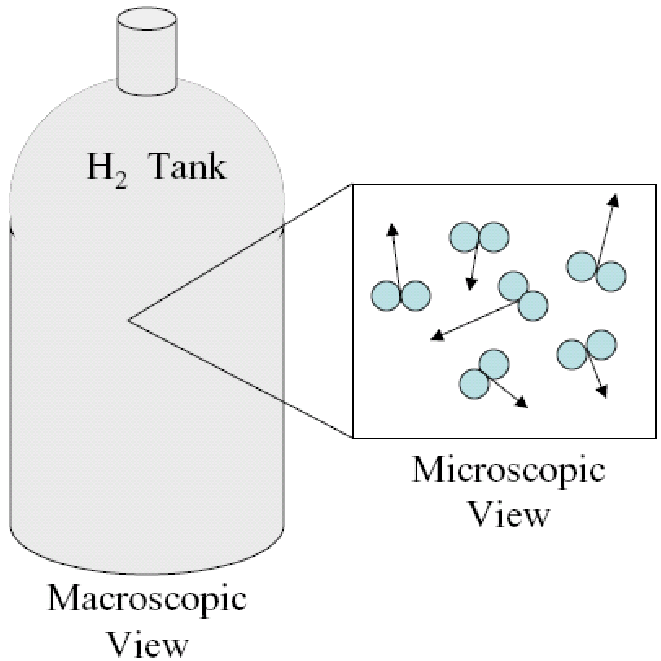
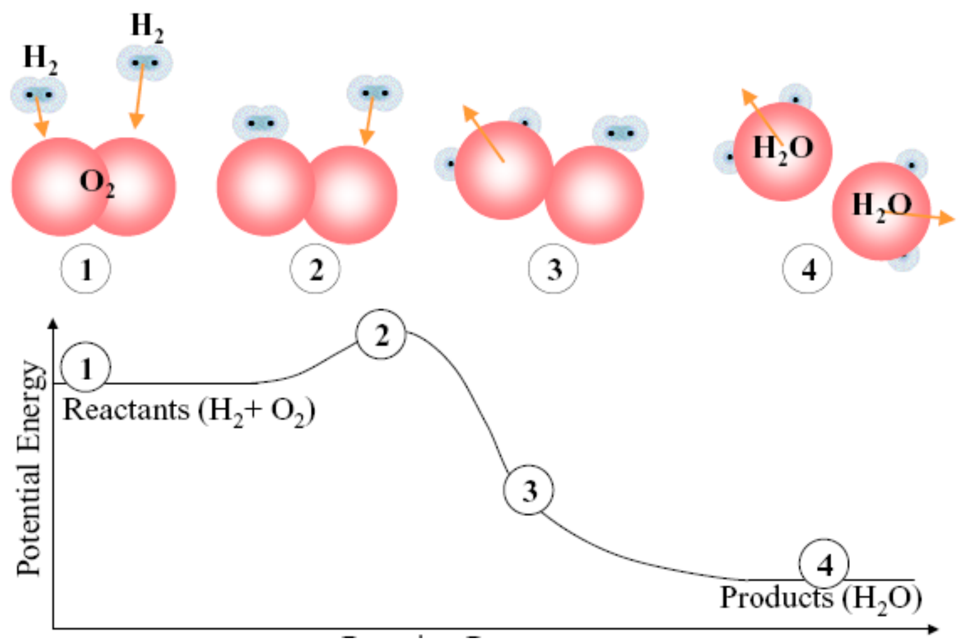


Figure 1.1: General concept of a hydrogen/oxygen (H_2/O_2) fuel cell.

- **Electrochemical** energy conversion device
  - **Directly** converts chemical energy to electrical energy
  - Heat engines: chemical -> thermal -> mechanical -> electrical
  - Losses are associated in any conversion step.

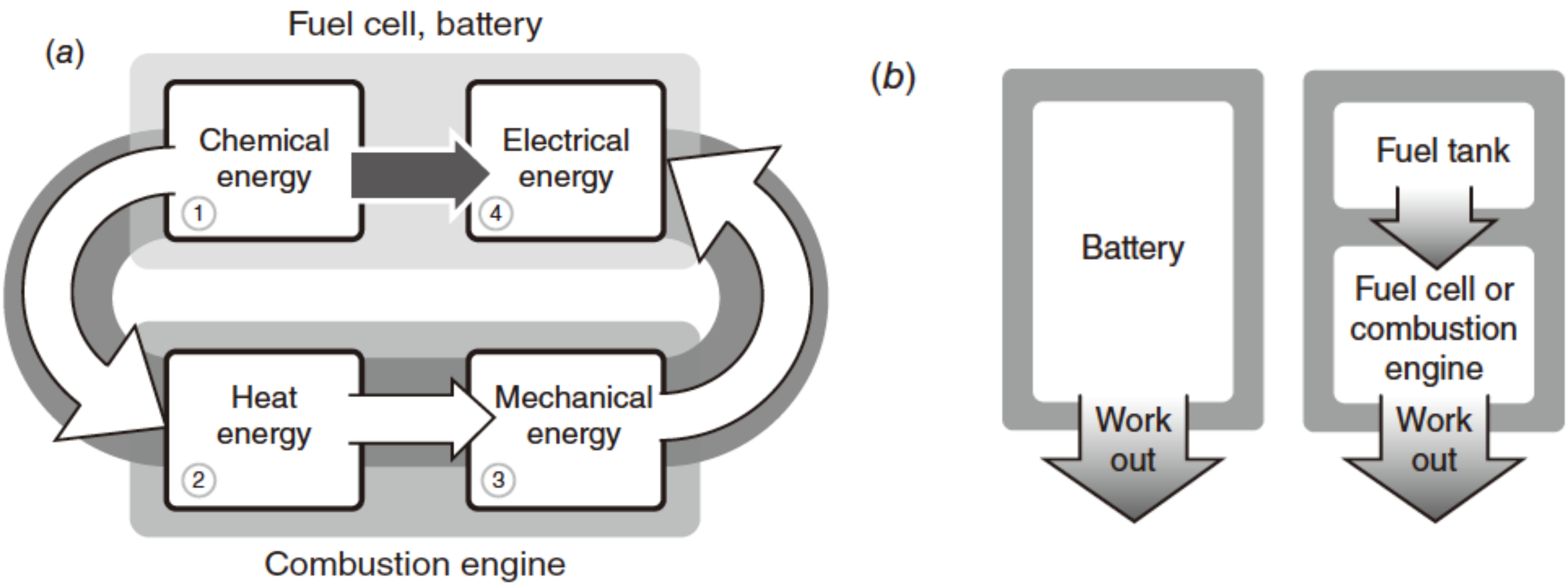
Driving Force



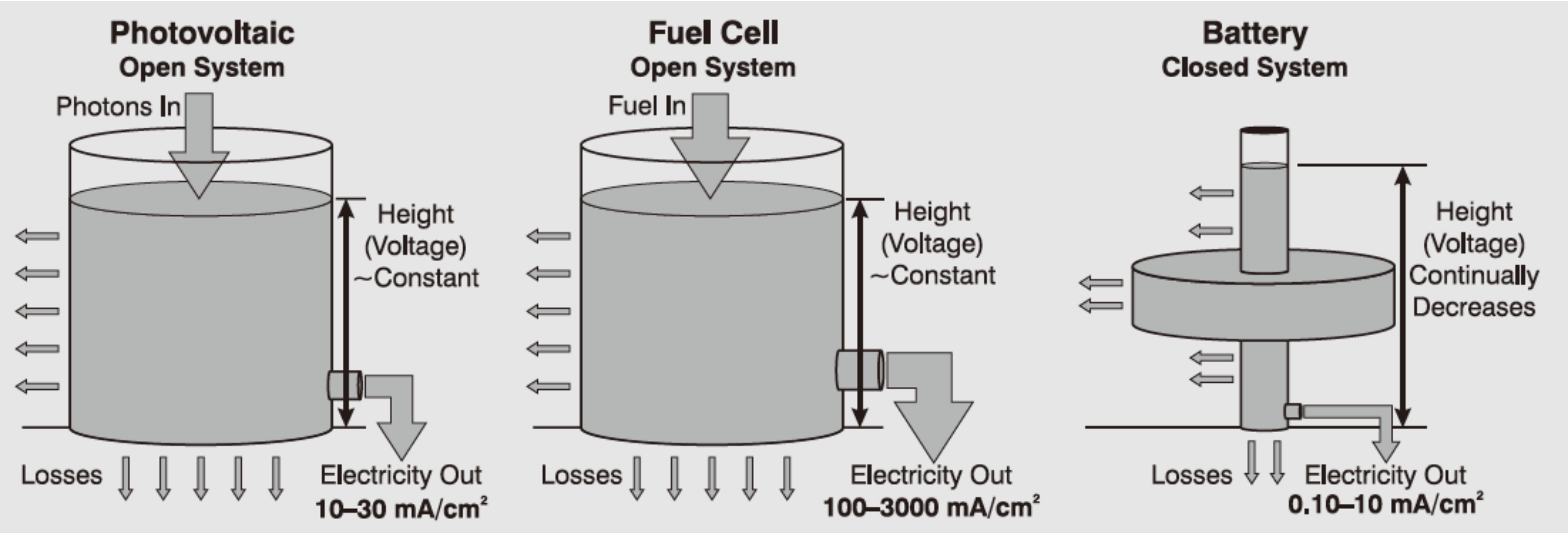


- Chemical reaction
  - Any substance favors more stable states.
  - **Energy** (usually heat) is released during the process

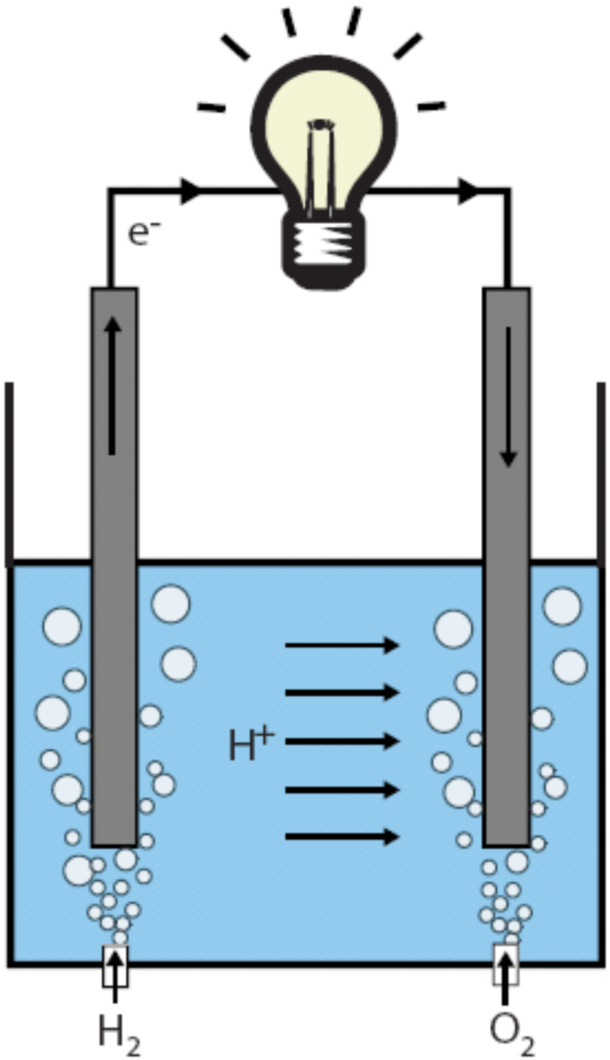
Fuel Cell vs. Battery vs. Combustion Engine



PV vs Fuel Cell vs Battery



A Simple Fuel Cell



Full cell reaction

$H_2 + 0.5\ O_2 \rightarrow H_2O$

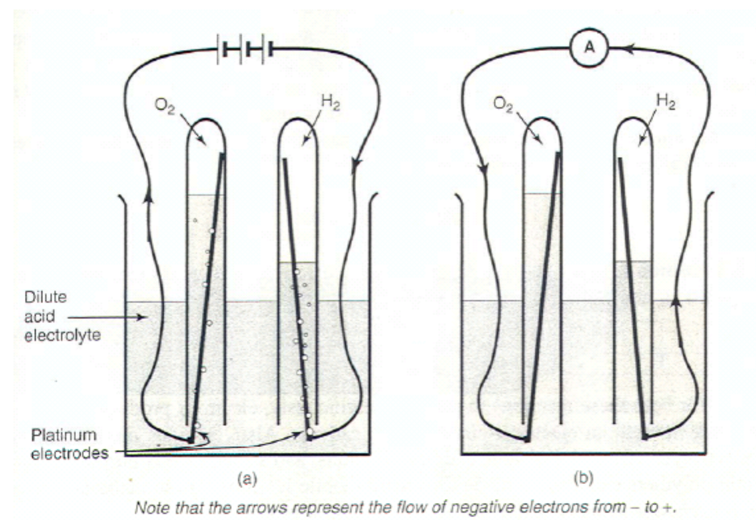
Half cell reaction

Anode: Oxidation (loss electrons)

$H_2 \rightarrow 2H^+ + 2e^-$

Cathode: Reduction (gain electrons)

$0.5\ O_2 + 2H^+ + 2e^- \rightarrow H_2O$



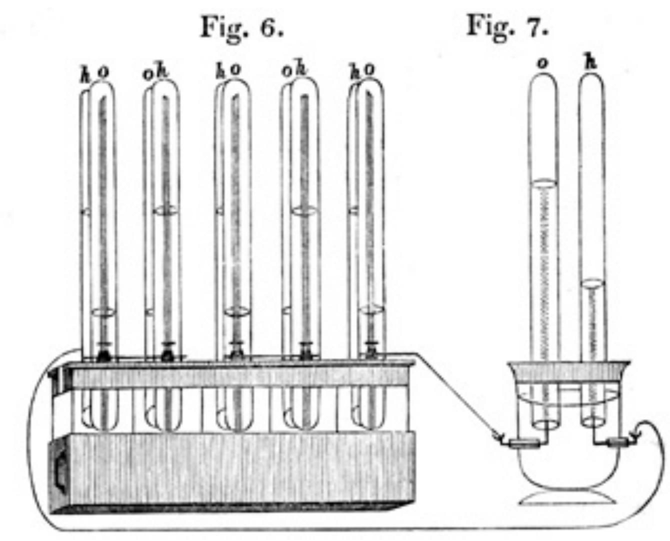
William Grove's drawing

A Brief History*

- **Electrolysis of water** by British scientists William Nicholson and Anthony Carlisle in 1800
- **Sir W. Grove** discovered **hydrogen-oxygen fuel cell** (gas battery what he called) in 1839 using sulfuric acid as electrolyte.

  (Otto invented 4 stroke IC engines in 1867)

William Robert Grove (1811 -1896)



William Grove's drawing of an experimental "gas battery" from an 1843 letter

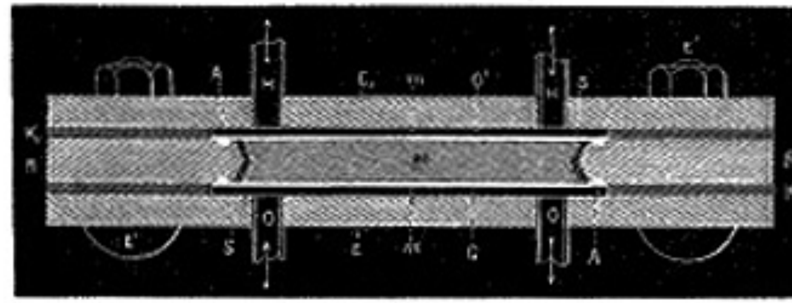
- **Friedrich Wilhelm Ostwald** (1853 - 1932), experimentally determined the interconnected roles of the various components of the fuel cell: **electrodes**, **electrolyte**, oxidizing and reducing agents, anions, and cations, in 1893.

* from Smithsonian Institution

A Brief History

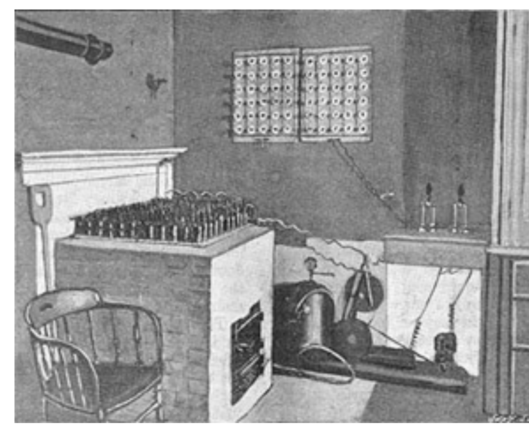
- **L. Mond** (1839 -1909) and **C. Langer** (d. 1935)'s fuel cell
  - Coal-derived "Mond-gas“ as fuel
  - 6 amps per square foot at .73 volts
  - Thin, perforated platinum electrodes
  - Electrolyte in a quasi-solid form; soaked up by a porous non-conducting material

FIG. 1.



Mond and Langer's fuel cell design from 1889

- Conclusion of **L. Cailleteton** (1832-1913) and **L. Colardeau** in 1894 - "only precious metals" would work for fuel cells to make it a impractical device.
- Carbon battery (for home) by **William W. Jacques** (1855 -1932)
  - injected air into an alkali electrolyte, react with a carbon electrode.
  - Actual reaction was thermoelectric of 8% efficiency instead of electrochemical reaction of 82% efficiency



Jacques' carbon battery apparatus, 1896

A Brief History

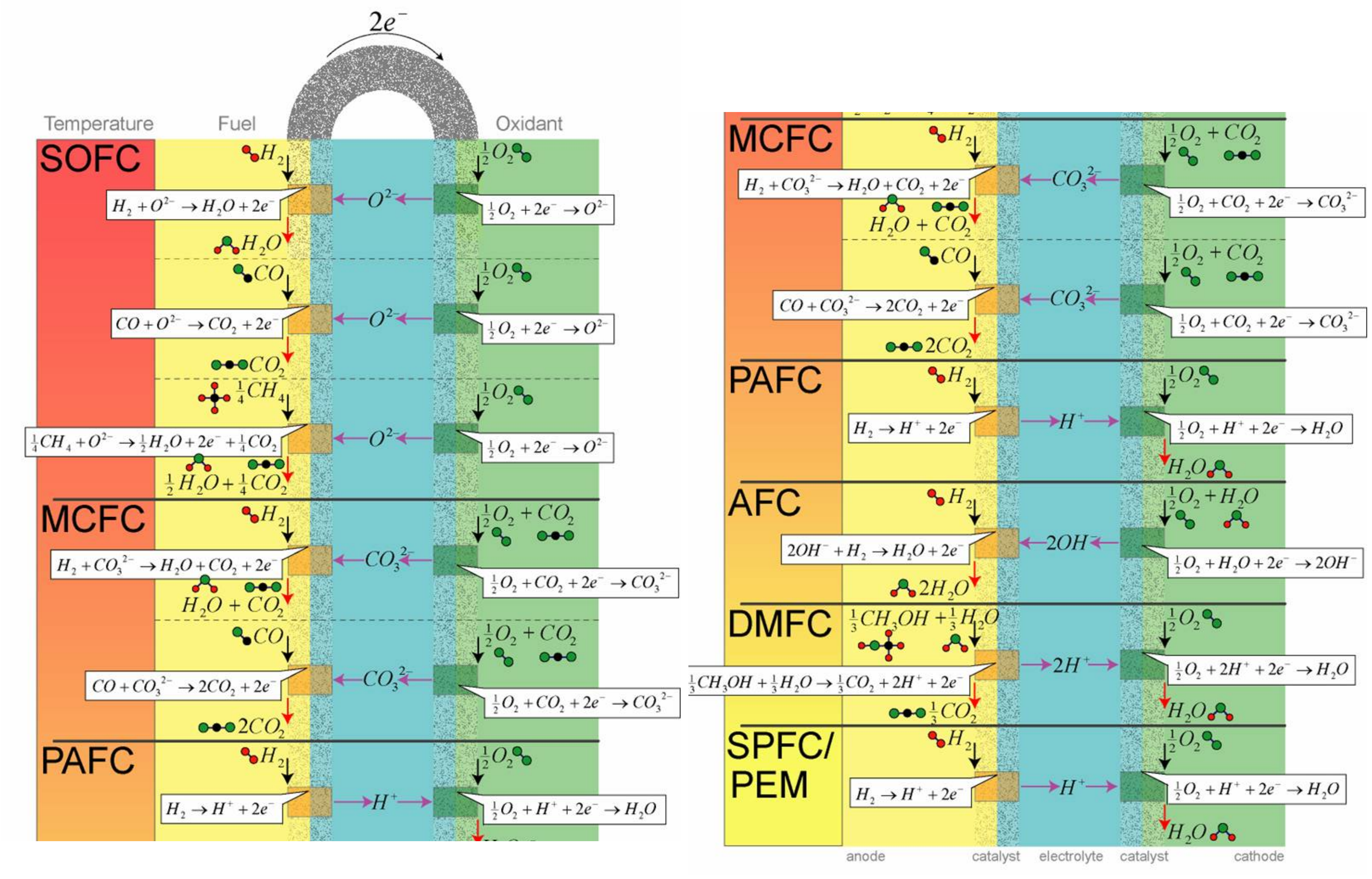
- In 1900, **Nernst** demonstrated SOFC using YSZ
- **E.Bauer** (1873 -1944), **O. K. Davtyan,** during the first half of the 20th century,
  - Established the fundamentals of high temperature fuel cells such as the *molten carbonate* and solid oxide fuel cell.
- **Francis Thomas Bacon** (1904 -1992)
  - In 1939, he built a cell that used nickel gauze electrodes and operated under pressure as high as 3000 psi.
  - In 1958, he demonstrated an **alkali cell** using a stack of 10-inch diameter electrodes for Britain's National Research Development Corporation. Bacon experimented with **potassium hydroxide (KOH)** instead of using the acid electrolytes. KOH performed as well as acid and was **not** as **corrosive** to the electrodes.
  - Though **expensive**, Pratt & Whitney licensed Bacon's **reliable** cell for the Apollo spacecraft fuel cells.
- **Various fuel cells types** began to follow divergent paths after 1960's, as some types were seen as more suitable for some applications than others.

Fuel Cell Types

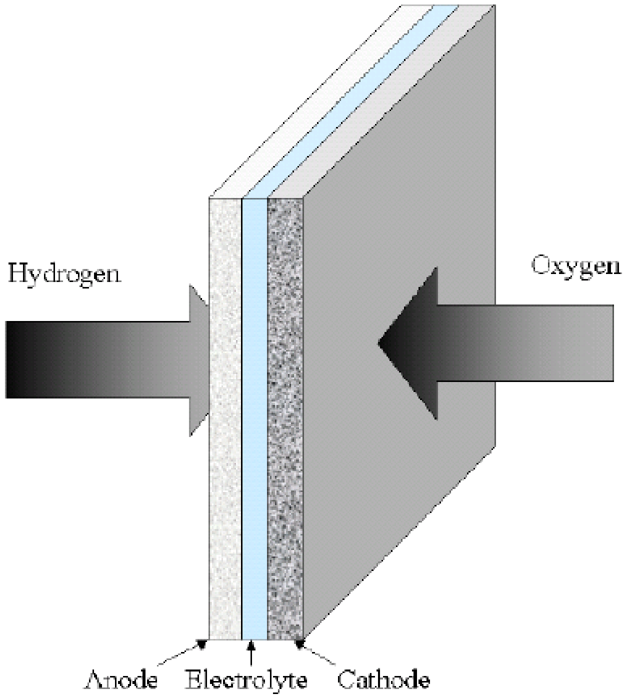
	PEMFC	PAFC	AFC	MCFC	SOFC
Electrolyte	Polymer Membrane	Liquid H_3PO_4 (Immobilized)	Liquid KOH (Immobilized)	Molten Carbonate	Ceramic
Charge Carrier	H^+	H^+	OH^-	$CO3^{2-}$	O^{2-}
Operating Temperature	80 °C	200 °C	60-220 °C	650 °C	600-1000 °C
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites (Ceramic)
Cell Components	Carbon-based	Carbon-based	Carbon-based	Stainless-based	Ceramic-based
Fuel Compatibility	H_2, Methanol	H_2	H_2	H_2, CH_4	H_2, CH_4, CO

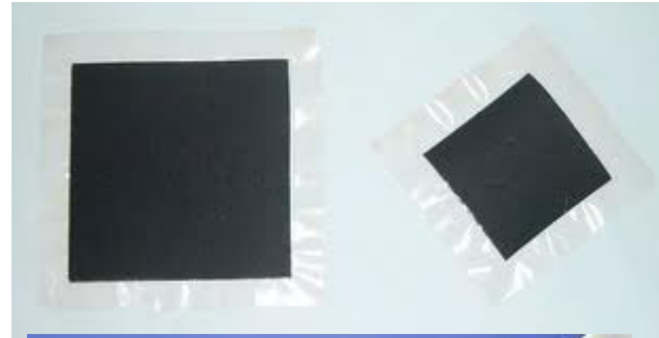
- Electrolyte determines the type of fuel cells and operating temperature.
  - Operation temperature significantly affects the use of other components such as catalyst.

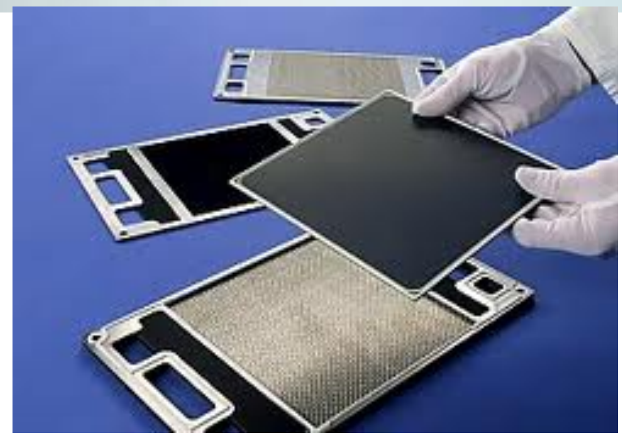
Fuel Cell Types



Compact Fuel Cells





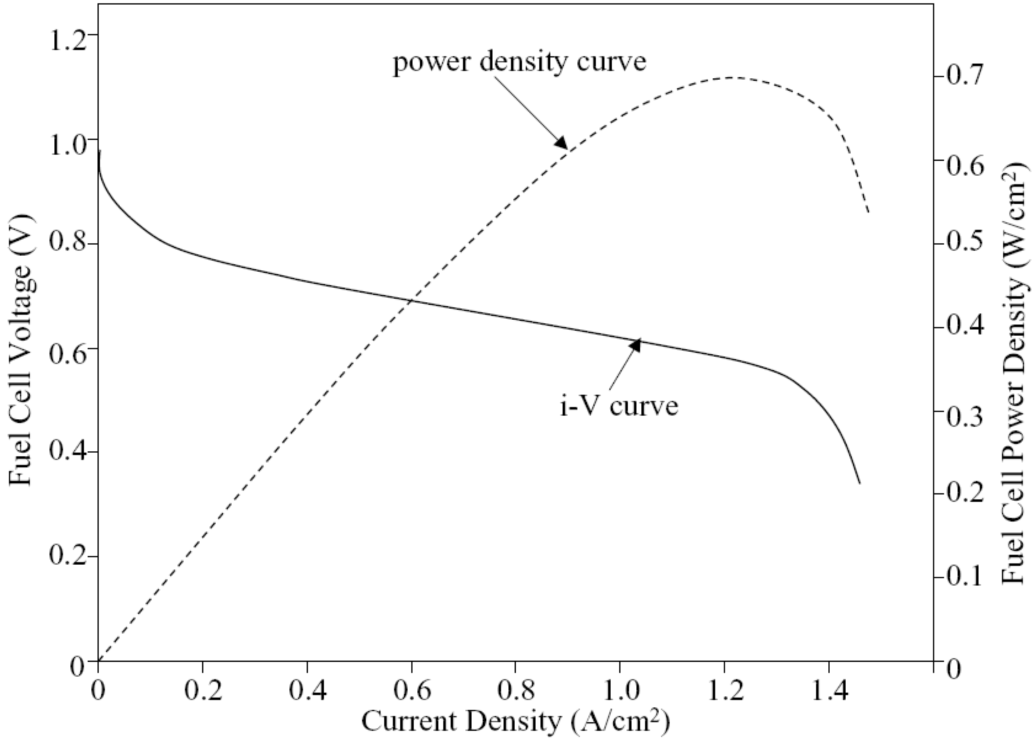


- Membrane-Electrode-Assembly (MEA)
  - Electrolyte: Immobilized liquid (MCFC, AFC, PAFC), Solid electrolyte (PEMFC (DMFC), SOFC)
  - Electrode: mixed conducting, porous solid containing catalyst materials
  - PEN (for SOFC) : Positive-electrolyte-negative assembly

Fuel Cell: Pros & Cons

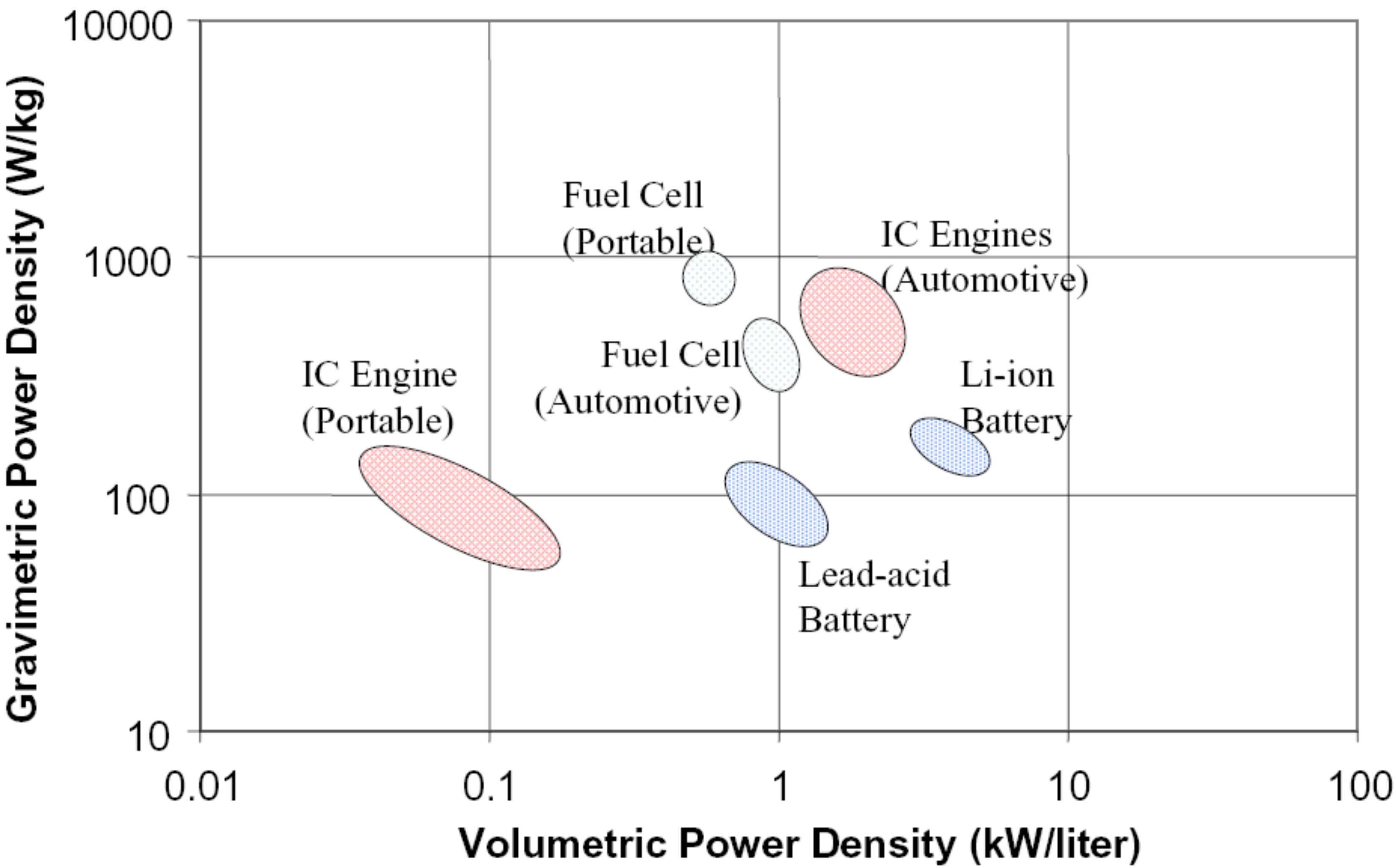
- Pros
  - Avoid carnot cycle limitations
  - High efficiency
  - No undesired reactions (NOx Sox), low particulate emissions
  - Silent mechanically robust
  - Scaleable, dispatchable
- Cons
  - Expensive
  - Fuel availability
  - Power/energy density (especially for portable appplications)
  - Operating temperature
  - Environmental posion
  - Durability during start/stop cycle

Fuel Cell Performance

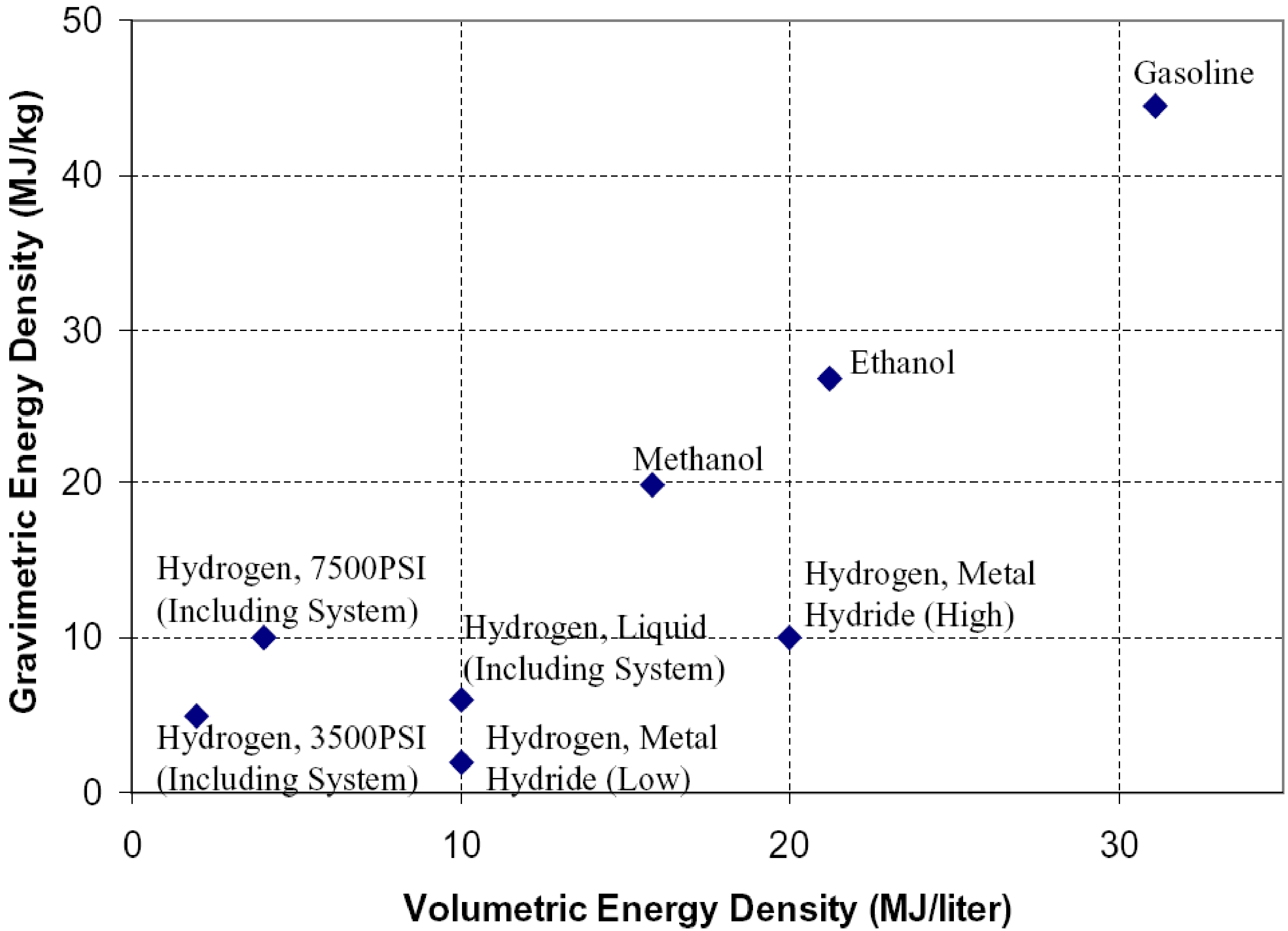


- Energy: U [J]
  - Work stored in a power system
  - Sets the operation time of a power system
- Power: P = U/time [J/s=W] = I [A] * V [V]
  - U [J] = P * time [Wh] (1 Wh = 3600 J)

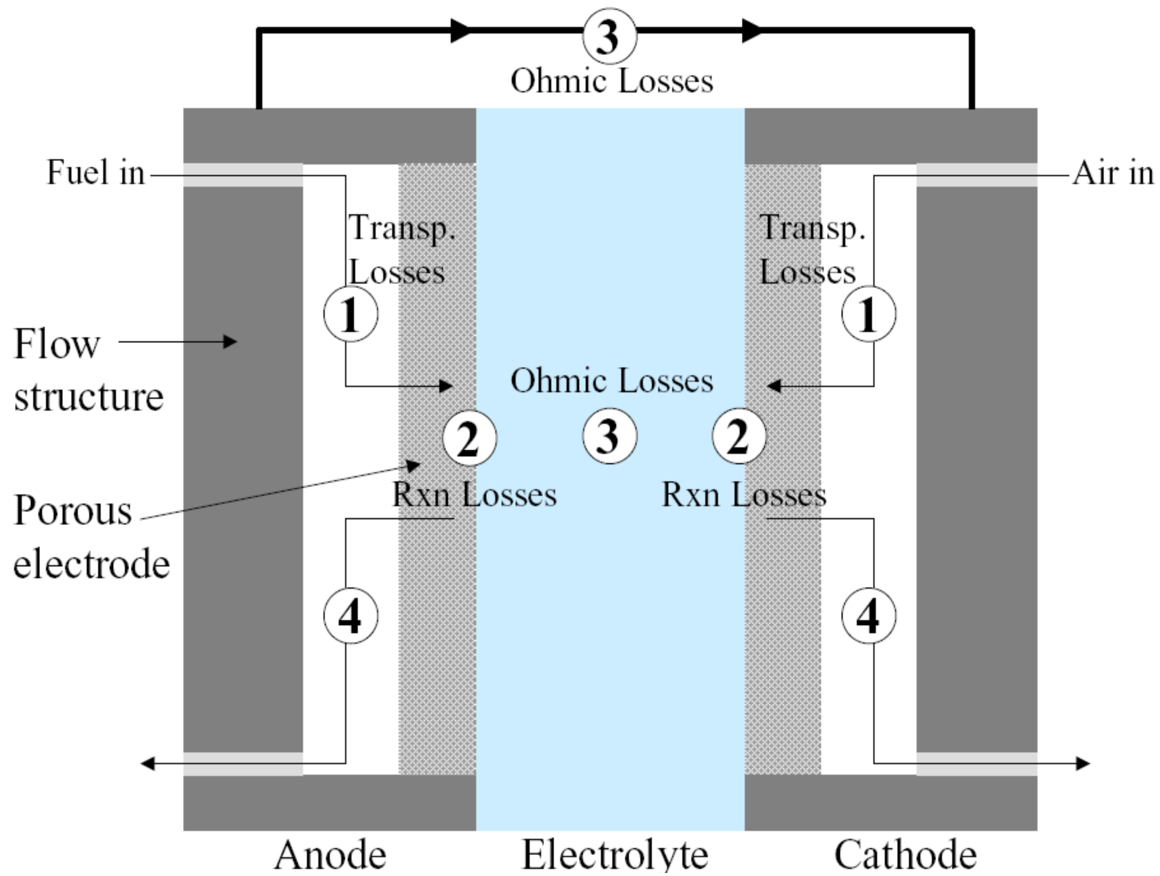
Power Density of Selected Technology



Energy Density of Selected Fuels

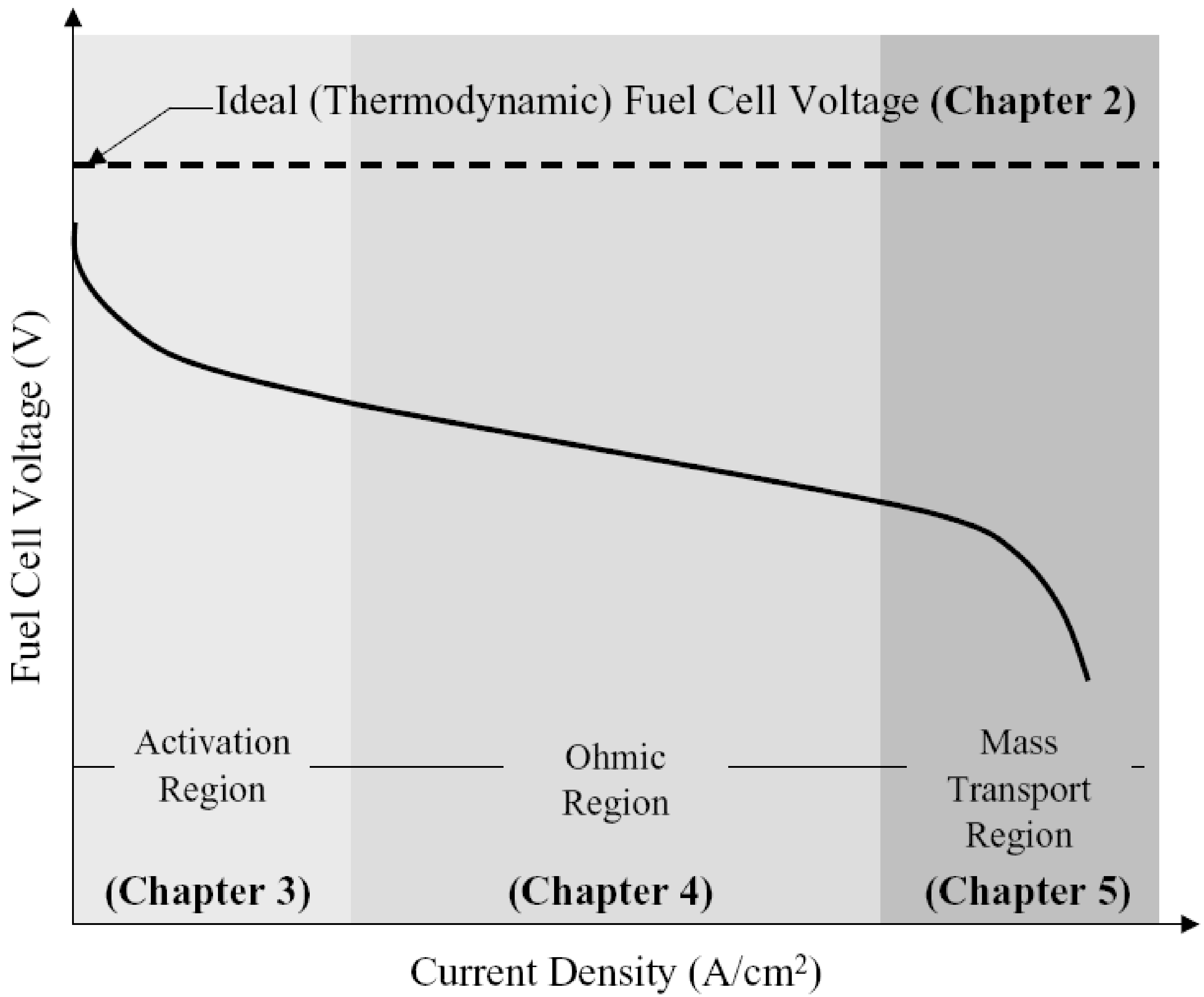


Transport, Losses & Components

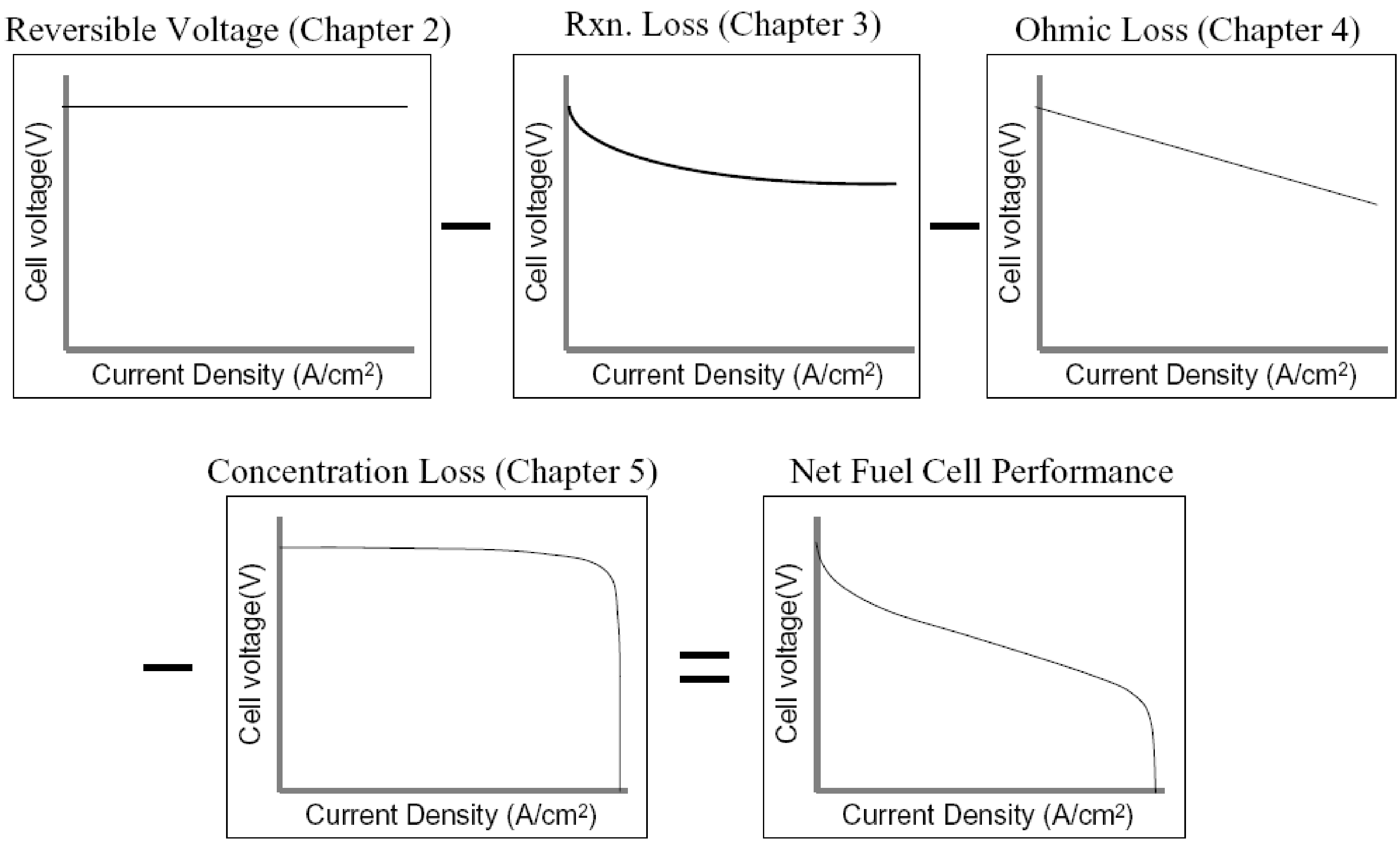


1. Reactant transport @ flow field & electrode: mass transport loss
2. Electrochemical reaction @ electrode (catalyst) : activation (reaction) loss
3. Ionic (electronic) conduction @ electrolyte : ohmic loss
4. Product removal @ flow field & electrode: mass transport loss

Losses in Fuel Cells



Losses in Fuel Cells

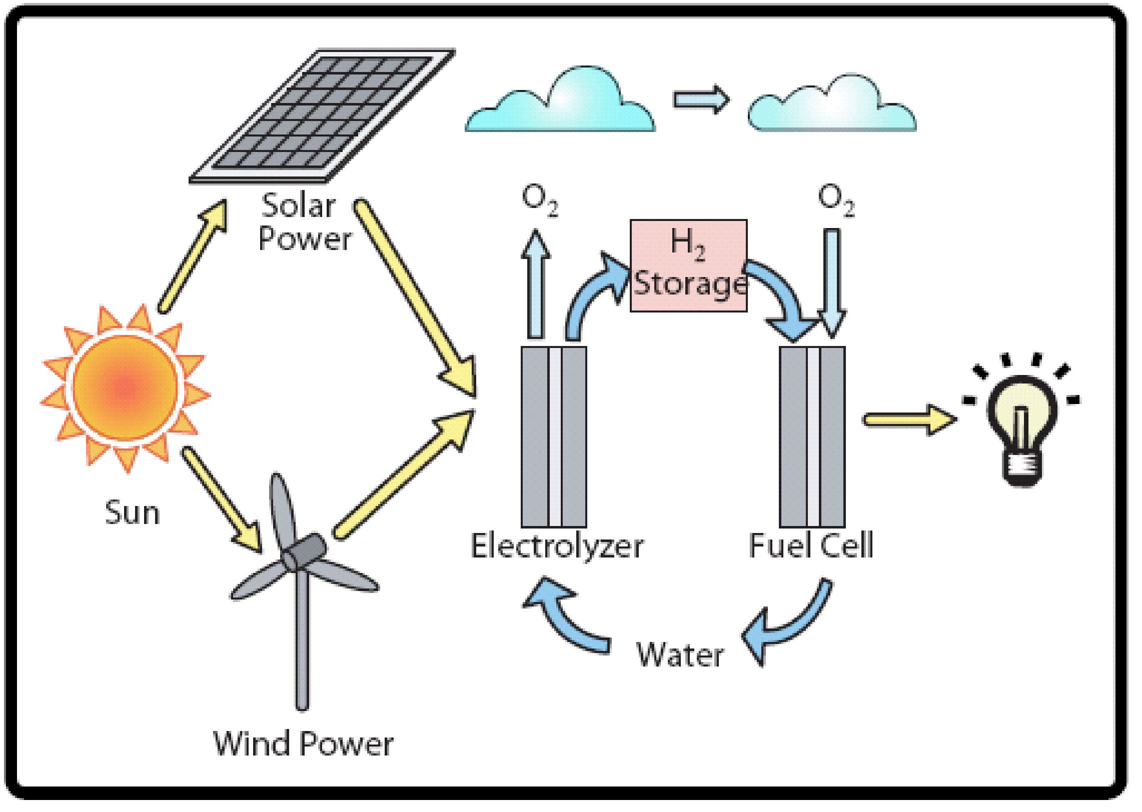


$$V = E_{thermo} - \eta_{act} - \eta_{ohmic} - \eta_{conc}$$

Fuel Cell Terms May Be Confusing

- Electrolyte or membrane
- Electrode or anode or cathode or catalyst layer or diffusion layer or current collection layer
- Flow structure or flow field or flow channels or bipolar plate or separator
- Current density (per area), energy density (per volume), power density (both!)
- I-V curve or polarization curve
- Voltage losses vs. overpotentials or overvoltages
- Ohmic loss or IR loss
- Reaction loss or activation loss or faradaic loss
- Mass transportation loss or concentration loss
- Voltage or potential
- This not the end of the list!!!

Hydrogen Economy



- How fuel cells fit to each energy sectors?
  - Residence: small distributed power systems
  - Industry: large distributed power systems
  - Transportation: portable power systems