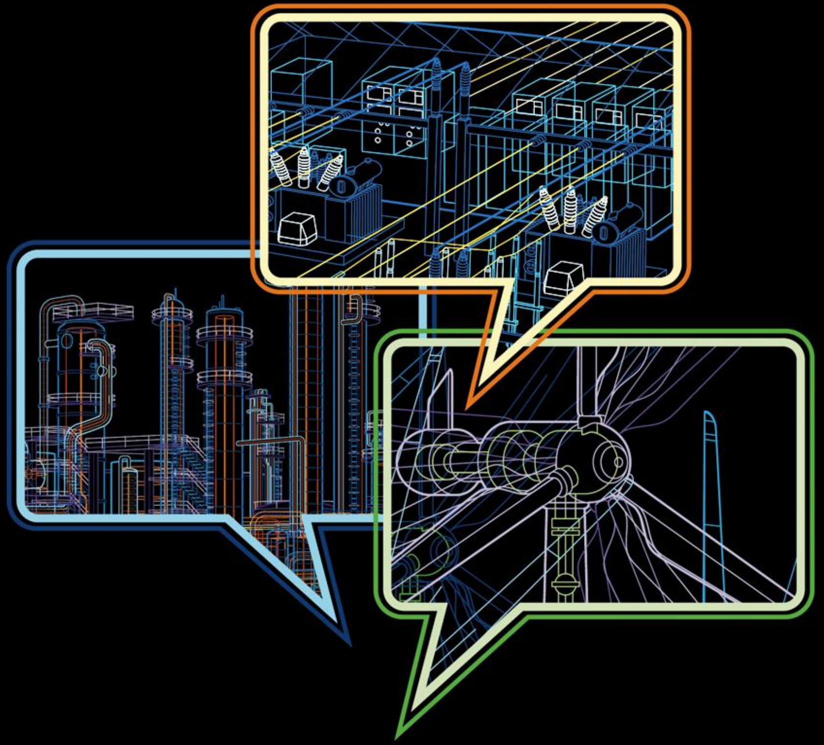


ABB Automation & Power World: April 18-21, 2011

WRE-113-1

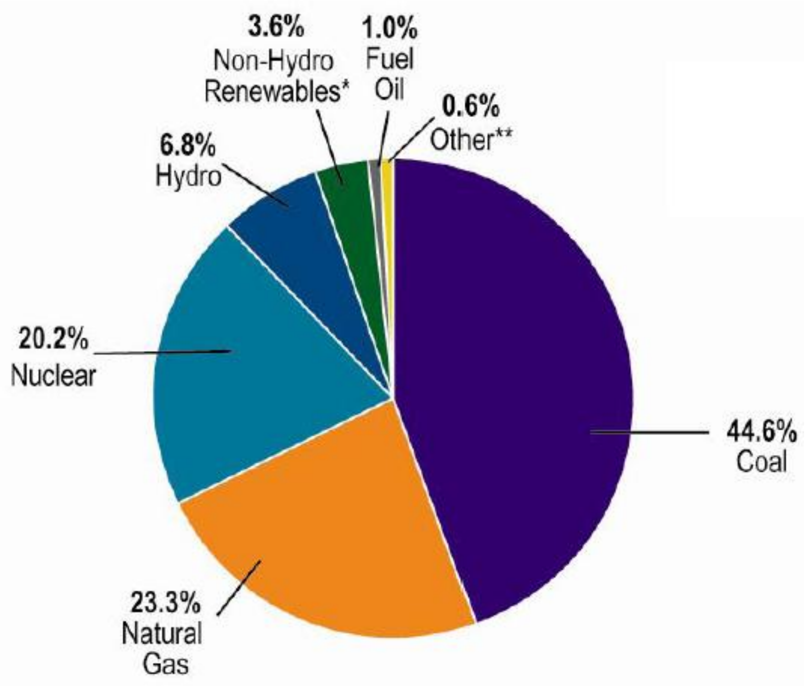
Power Electronics for Hydrokinetics and Fuel Cells

Content

- **Power generation & the grid**
- **Introduction to Hydrokinetics**
- **Fuel Cells**
  - What is a fuel cell?
  - Fuel cell history
  - Fuel cell types / comparison
  - Fuel cell applications
  - Power Conversion Systems
  - Future and Challenges
  - Fuel Cell for Distributed Generation
  - Fuel cell Cars

Power Generation

- Power Generating Sources
  - *Traditional* (Coal, Gas, Nuclear, Hydro)
  - *Renewable* (Solar, Wind, Geothermal, Small Hydro, Hydrokinetics, Fuel Cells)

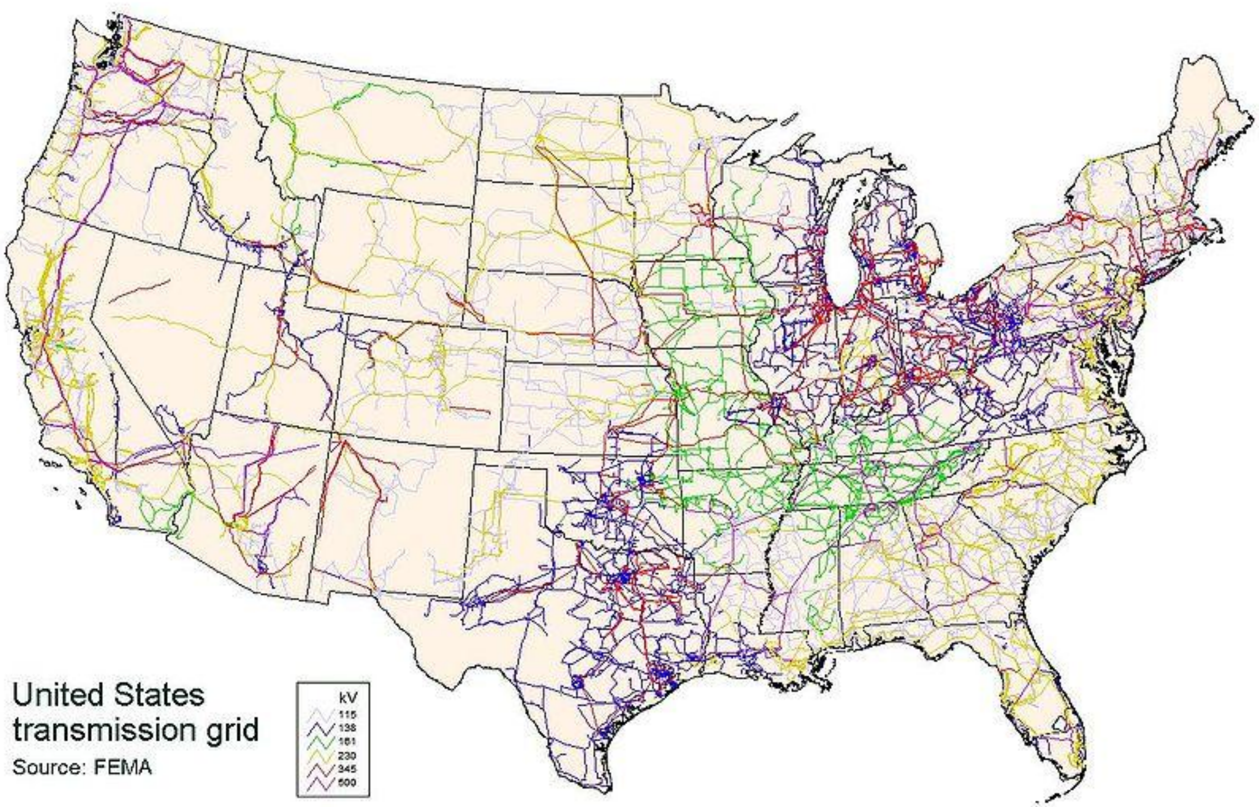


Source: US Department of Energy, Power Plant Operations report (EIA-923), 2009

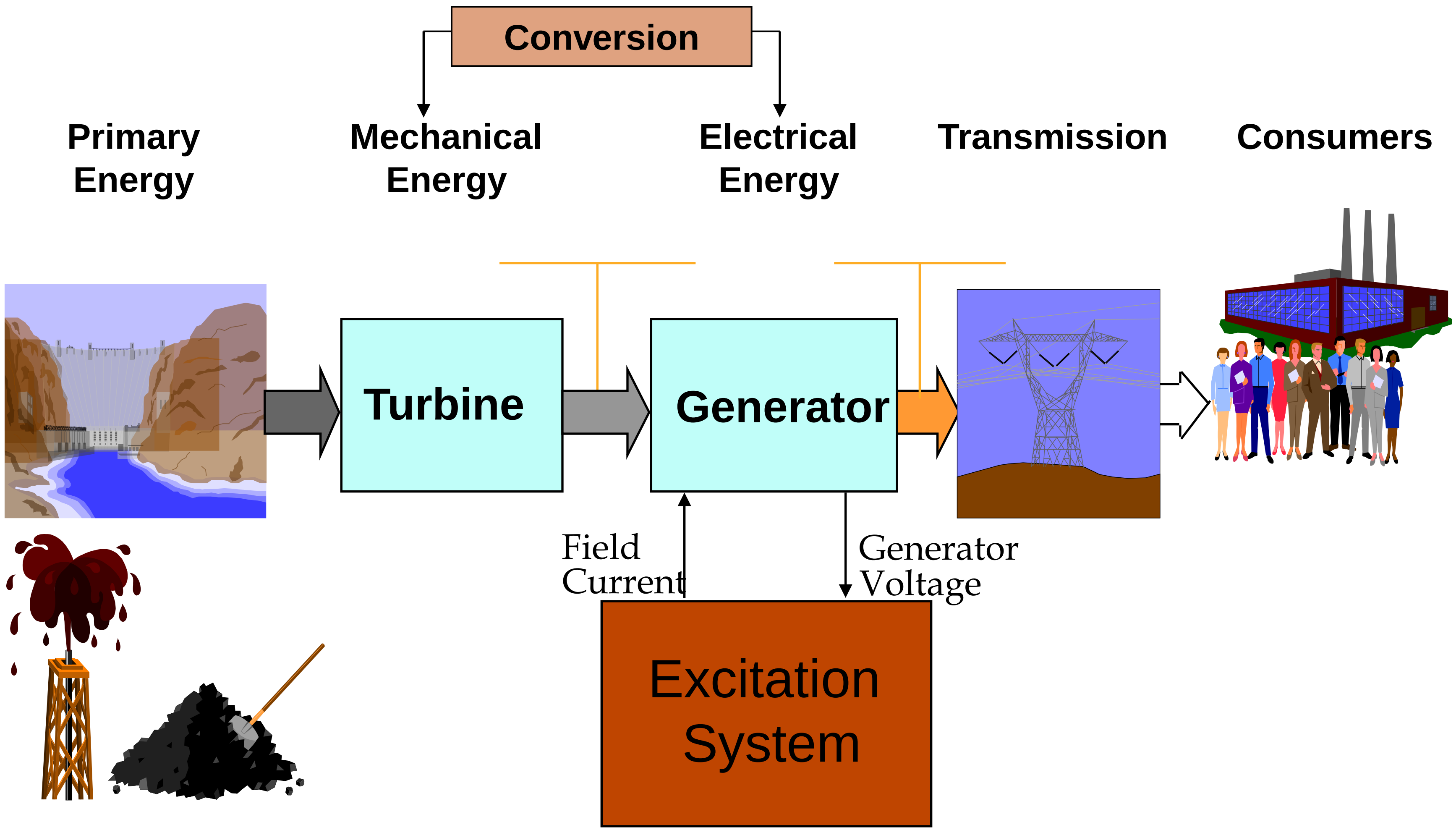
US National Electric Grid

- Very Complex System with over 300,000 km of transmission lines
- Over 5,000 power generating stations supplying electricity to the grid
- Millions of loads utilizing the power at different rates and at different times

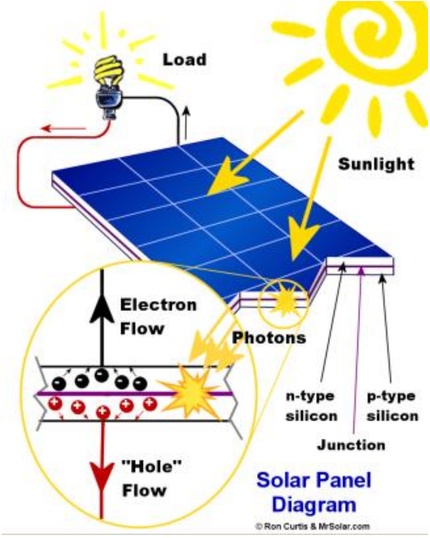
The grid must be Available, Stable and Safe.



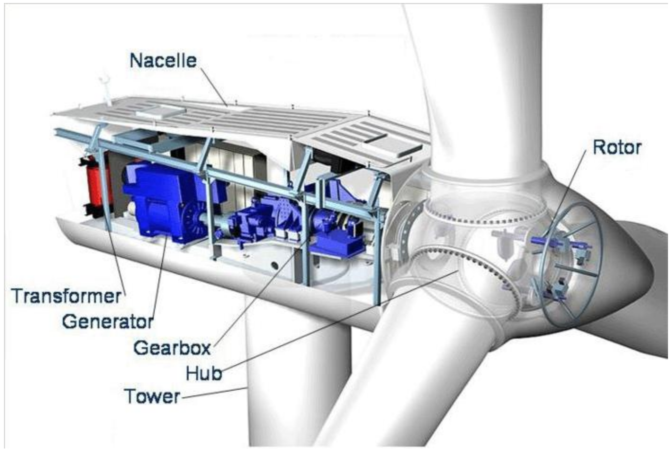
Traditional (Coal, Gas, Nuclear, Hydro)



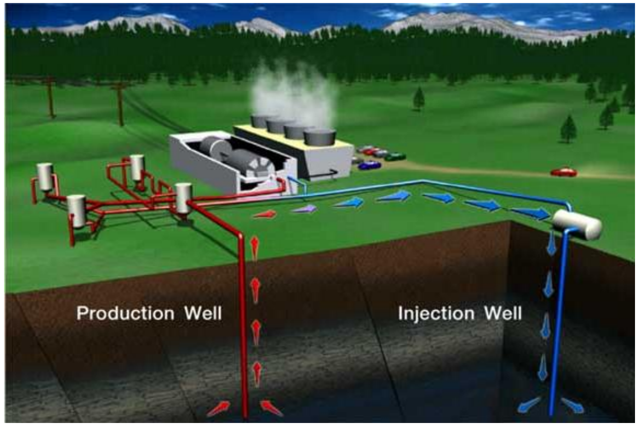
Renewable (Solar, Wind, Geothermal, Small Hydro, HK, FC)



Courtesy of www.solarpanels.com



Courtesy of www.wistatutor.com



Courtesy of www.cleanenergyclassrooms.com

Hydrokinetics

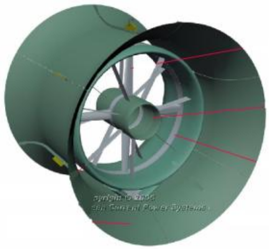
- Hydro Kinetic applications utilize the energy from Oceans and Rivers unlike traditional hydro which uses large hydroelectric dams.

Run-of-the-River

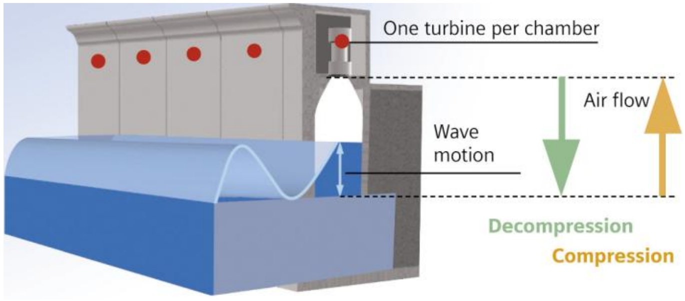
- Various VLH Turbines and or completely submerged TG technologies
- US has over 250,000 rivers, (3,500,000 miles)
- Missouri River is the longest and the Mississippi is the largest in terms of water volume
- Canada has more lakes and inland waters than any other country in the world.

Tidal

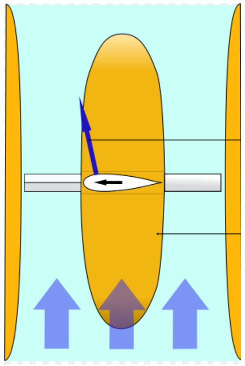
- The moon's revolution around the earth produces tides that can be used for energy generation.
- Technology is similar to Wind Turbines Submerged, or specially designed underwater TG
- Largest Tides in the World (Bay of Fundy, NS; Ungava Bay, QC; Bristol Channel, UK; Severn Estuary, UK)
- Pentland Firth, Scotland described as the Saudi Arabia of Tidal Power (10GW Potential)



Wave



- Harnesses the Wave motion, or the waves crashing on the coastline or barrage.
- The most developed technologies utilize the Wells Turbine (Voith Siemens Hydro).



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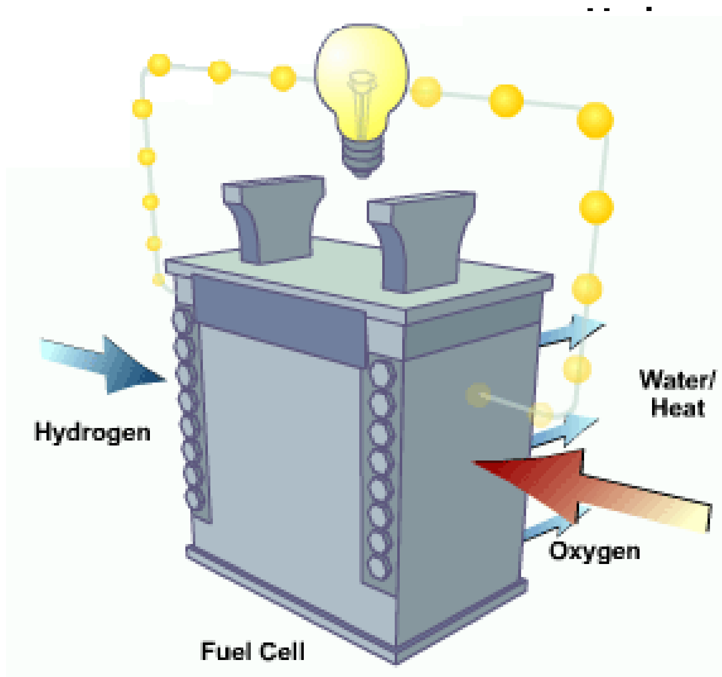
Fuel Cells

Fuel Cell Inverters

- **A Fuel Cell produces DC Power**
- **The Inverter is the Power Conversion System (DC to AC)**
- **Fuel cell applications:**
  - Transportation (Automotive, Buses, Lifts)
  - Backup Power (ex: Telecommunication)
  - Residential and Commercial Buildings (Electricity and Heating)



n is the most abundant
on the planet (75% of
lemental mass)

n is Colorless, Odorless
eless – Not Harmful

ct is Water and Heat only -

Cell produces power as
ıydrogen is fed to it

utput is constant

mpact and Lighter then
onal Batteries

- **Virtually Silent**

Hydrokinetic Experience and Expertise

- **ABB leading the business since 2007**
- **Solutions installed and commissioned ranging from 25kW to 3 MW**
- **Over 20 units installed and commissioned**
- **ABB Scope of Supply:**
  - AC-AC Power Converters
  - Generators
  - Switchgear
  - Transformers
  - Containerized Solution

Fuel Cell Experience and Expertise

UTC Power
A United Technologies Company

BALLARD®

FuelCell Energy

- **ABB leading the business since 2004**
- **Proven solutions from 300kW to 1.3MW**
- **Over 30 units installed and commissioned globally**
- **Over 100 units in production**
- **ABB Scope of Supply:**
  - DC-AC Power Converters
  - Switchgear
  - Transformers
  - Containerized Solution

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Fuel Cells

- What is a fuel cell?
- Fuel cell history
- Fuel cell types / comparison
- Fuel cell applications
- Power Conversion Systems
- Future and Challenges
- Fuel Cell for Distributed Generation
- Fuel cell Cars

Fuel Cell 101

- Electrolysis
  - A process that separates bonded elements and components into their components by passing an electric current through them.

- Water is a common compound that is separated into Hydrogen and Oxygen by electrolysis.

$$2H_2O \rightarrow 2H_2 + O_2$$

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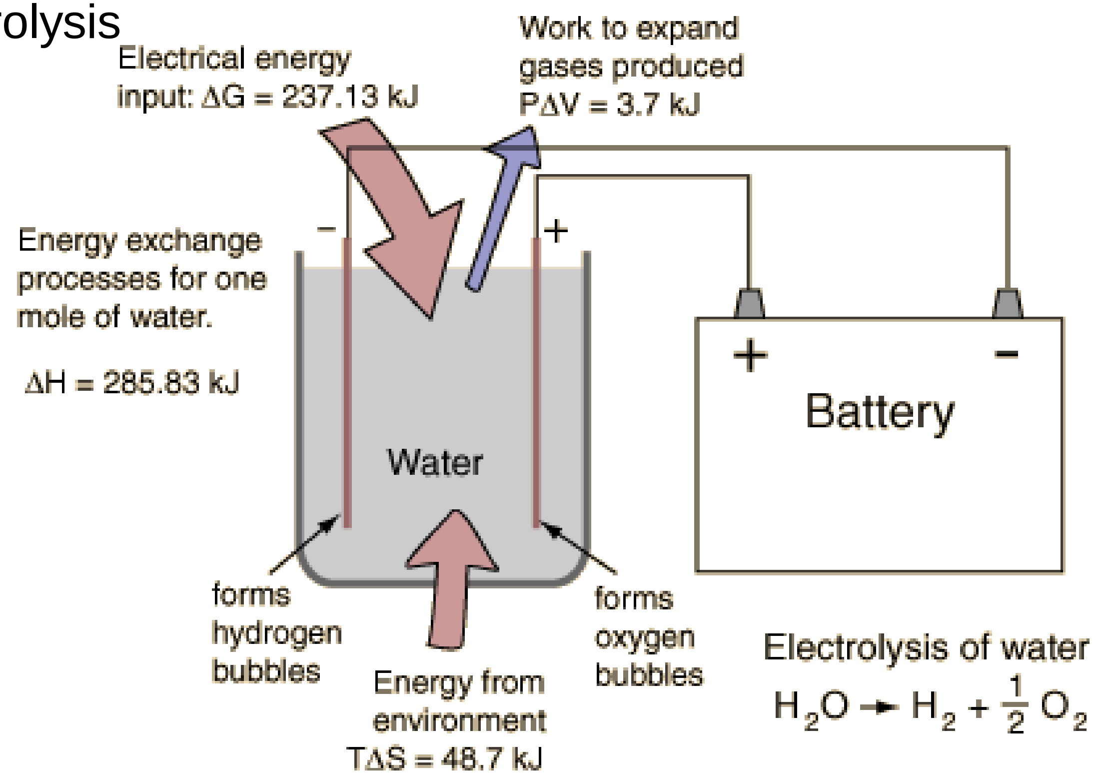
Fuel Cell 101

Electrolysis



Source: Hyperphysics.phy-astr.gsu.edu

Fuel Cell 101

What is a fuel Cell?

- A device that generates electricity through a chemical reaction known as ***reverse electrolysis.***
- Similar to a battery, but the fuel is continually supplied
- All fuel cells have two electrodes (anode + and cathode -)
- All fuel cells have an electrolyte and a catalyst to speed up the chemical process

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Fuel Cell 101

What is a fuel Cell?

- Hydrogen is the main fuel of the fuel cell
  - Can be derived from substances containing hydrogen (ie fossil fuels)
- Hydrogen and Oxygen combine to form water and electricity.

$$2H_2 + O_2 \rightarrow 2H_2O$$

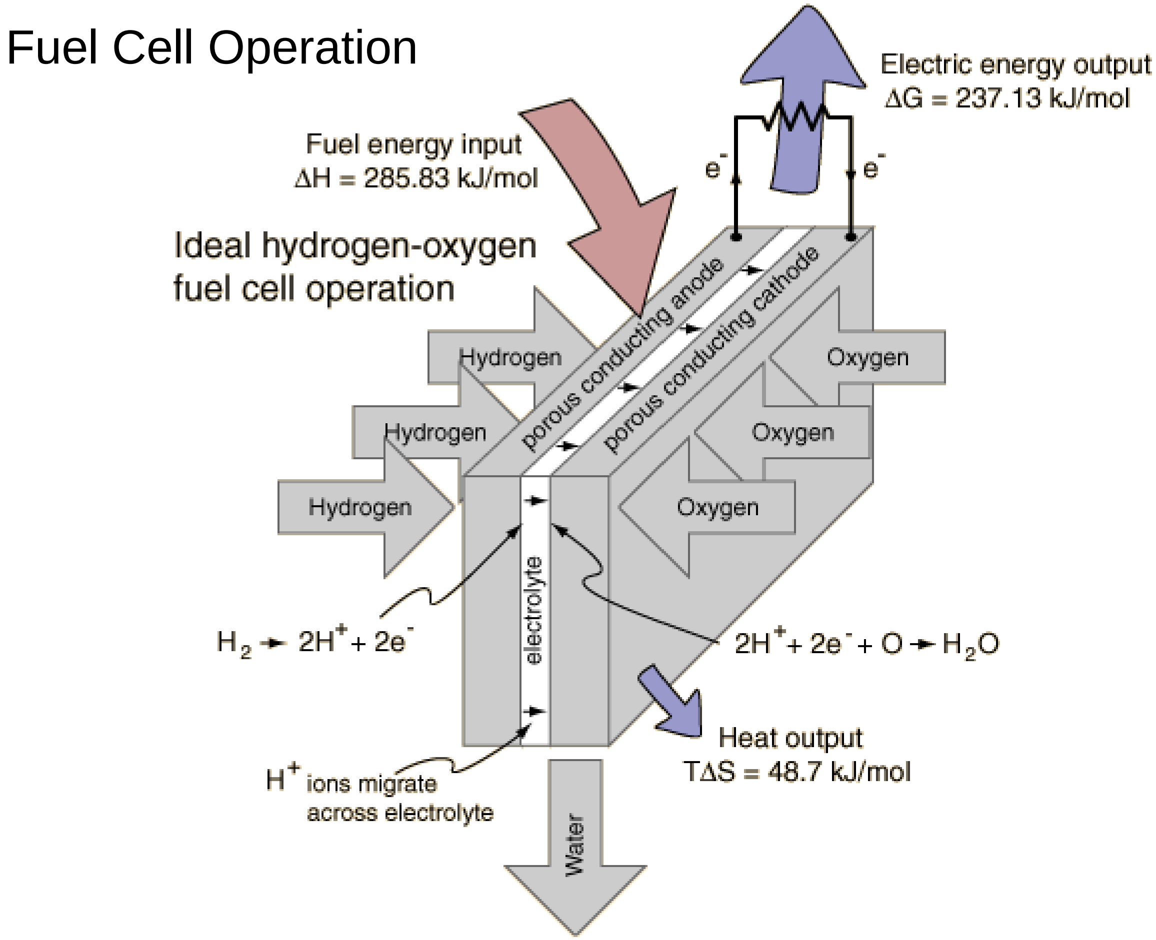
- During the above process, 4 electrons are released (from the hydrogen atoms)

Fuel Cell 101

So, What does this mean?

- Fuel cells convert chemical energy directly into electrical energy without combustion
  - As a result, much higher efficiency is realized
  - Also fewer emissions result (eg CO_2, NOx, SOx)

Fuel Cell 101



Source: Hyperphysics.phy-astr.gsu.edu

Fuel Cell History

- WOW! That’s neat! Are fuel cells a new technology?
  - No. They have been around for more than 150 years!

Fuel Cell History

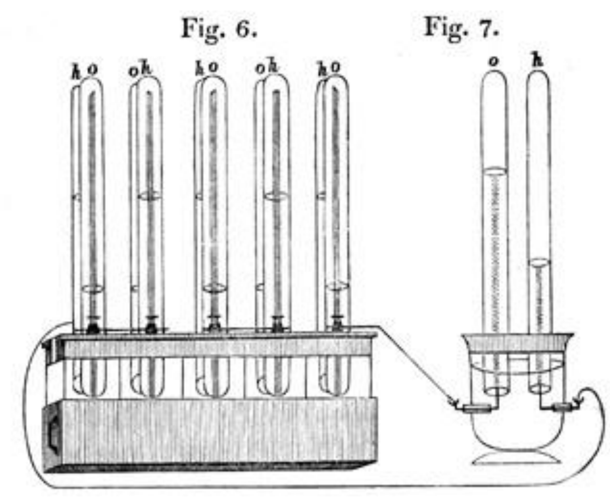
- In 1800 two scientists, William Nicholson and Anthony Carlisle “discovered” the process of ***electrolysis.***

- 1832 Michael Faraday began his work on electrolysis and eventually developed the first law of electrolysis in 1834.

  - The mass of a substance produced at an electrode during electrolysis is proportional to the quantity of electricity (moles of electrons) transferred at that electrode.

Fuel Cell History

- Welsh scientist Sir William Robert Grove theorized that ***if electrolysis is possible, then the process of reverse electrolysis was also possible.***
- In 1839 he developed the first fuel cell – the "gas battery"
  - Made by immersing platinum electrodes into sulfuric acid



Drawing of experimental Gas battery for 1843

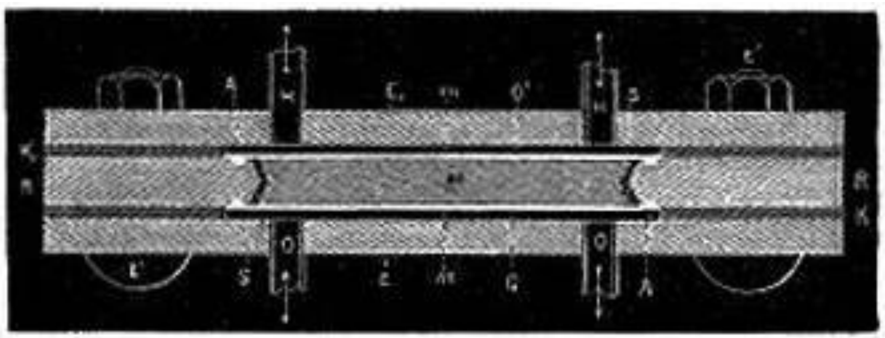
Source: americanhistory.si.edu

Fuel Cell History

- While Grove laid the foundation for the fuel cell, ***not much was known about chemistry and electricity at the time,*** so fuel cells were not embraced by the scientific community.
- Grove himself had many questions about exactly how his “gas battery” worked.
  - Still, his experiments exhibited strong evidence that hydrogen and oxygen could produce an electric current.
  - He did not know the reason for the heat developed during the reaction, or other liquids and gasses formed during his process.

Fuel Cell History

- By the late 1800’s, fuel cell designs were popping up, but the basic understanding of the device was still unknown.
  - The laws of thermodynamics were not fully understood
  - The electron had not yet been discovered
  - Relationships between energy and matter were not completely understood



1889 Fuel Cell by Ludwig Mond and Carl Langer

Source: americanhistory.si.edu

Fuel Cell History

- More fuel cell designs emerged as the scientific community began to understand the physics behind them.
- By the early 1900's fuel cells were understood well enough, but viewed as an expensive and complicated way to produce electricity.
  - Batteries were simple and Hydro-electric and steam plants produced relatively low cost power.
  - Fossil fuels were widely available and cheap too
- Hence, fuel cells took the back burner to these other methods and were considered novel devices.

Fuel Cell History

- Military needs during WWII kept the development of fuel cells moving forward
- **In 1939**, Francis Bacon developed the alkaline fuel cell using nickel electrodes. (patented in 1946)
  - It worked under pressures as high as 3000psi.
  - The first use of alkaline (KOH) electrolytes rather than acid.

This was the first practical fuel cell!

Source: wikipedia.org

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Fuel Cell History

- A 6kW 40cell stack was publicly demonstrated in 1959 by Baron with support of Marshall of Cambridge Ltd.
- In October,1959, Allis-Chalmers fitted a farm tractor with a 1008 cell stack.

- This produced 15kW which was enough for the tractor to pull a 3000lb load.
- It plowed an alfalfa field in West Allis, WI in a demonstration
- ***Allis-Chalmers continued working with the fuel cells making a golf cart, and a fork lift among other things.***

Source: wikipedia.org and americanhistory.si.edu

Fuel Cell History

- In 1960 Pratt & Whitney licensed Bacon's fuel cell for use on the Apollo space missions.
  - Attractive to space missions because batteries were too heavy, solar too bulky, and nuclear was too dangerous and impractical at such small sizes.

Source: wikipedia.org

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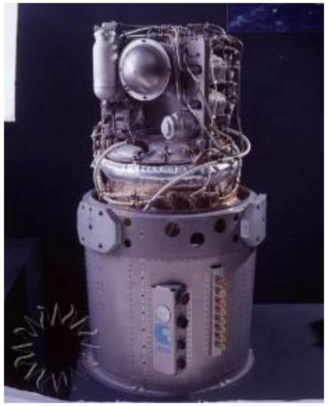
Fuel Cell History

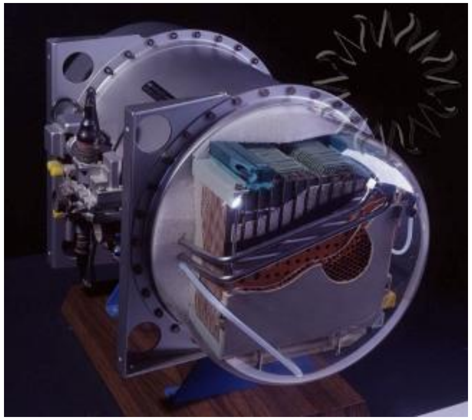
- The Apollo fuel cells also provided drinking water for the astronauts!



- Later, the Gemini space program also used fuel cells.

These were

manufactured by GE.



Source: www.nasm.edu

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Fuel Cell History

Other early uses of fuel cells

1967 Union Carbide Motorcycle

1960’s Allis Chalmers golf cart

1965 Portable power for the US Army

Source: americanhistory.si.edu

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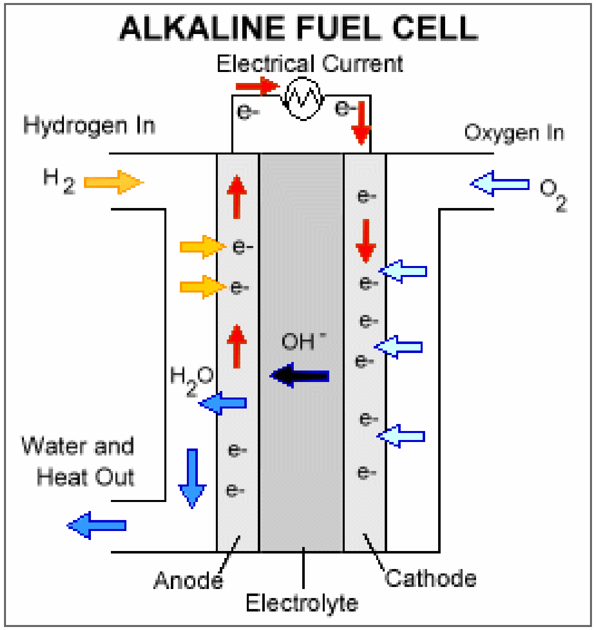
Fuel Cell Types

Today, there are six basic types of fuel cells:

1) Alkali (AFC)
2) Phosphoric Acid (PAFC)
3) Proton Exchange Membrane (PEM) – sometimes called Polymer Electrolyte Membrane
4) Molten Carbonate (MCFC)
5) Solid Oxide (SOFC)
6) Direct Methanol (DMFC) – sometimes called Direct Alcohol (DAFC)

Alkali Fuel Cell (1/6)

- Developed in late 1950's by Francis Thomas Bacon



- Uses Potassium Hydroxide as electrolyte
- Can use a variety of metals for catalyst (nickel, silver, platinum)
- Operate at temperatures of 200 to 400 degrees F
- Efficiencies of 60% - 70%.
- 85% efficiency possible with co-gen

Anode:	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$
Cathode:	$½\ O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$
Cell:	$H_2 + ½\ O_2 \rightarrow H_2O$

Source: eere.energy.gov and Visionengineer.com

Alkali Fuel Cell (1/6)

- Advantages
  - Low temperature operation
  - Quick start-up and long durability
  - High electrical efficiency and performance

- Disadvantages
  - Platinum catalyst is expensive
  - Extremely sensitive to CO_2 poisoning – forms a solid carbonate compound that interferes with the chemical reactions. Pure hydrogen is a must.

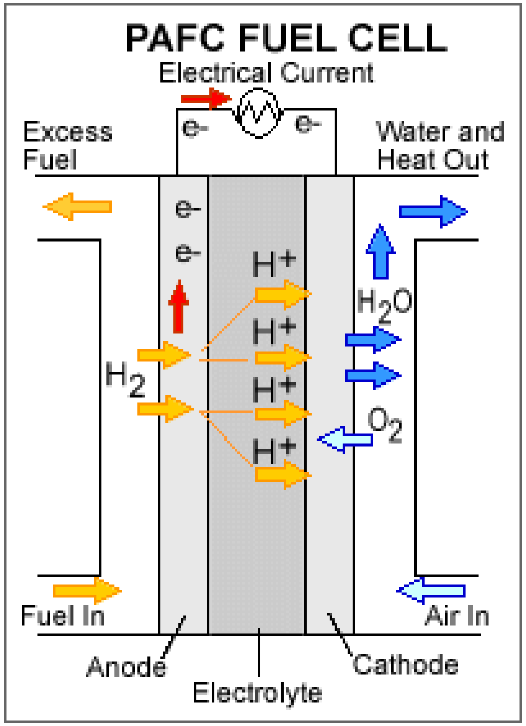
Source: eere.energy.gov

Phosphoric Acid Fuel Cell (2/6)

- Acid fuel cells were the first types developed.
- Phosphoric acid fuel cell development began in the 1960's. Less corrosive than sulfuric acid.

  - Uses Phosphoric Acid as electrolyte
  - Platinum catalyst
  - Operate at temperatures of 200 to 400 degrees F
  - Efficiencies of 37% - 45%.
  - 80% efficiency possible with co-gen

Anode: $H_2 \rightarrow 2H^+ + 2e^-$
Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$



Source: eere.energy.gov and Visionengineer.com

Phosphoric Acid Fuel Cell (2/6)

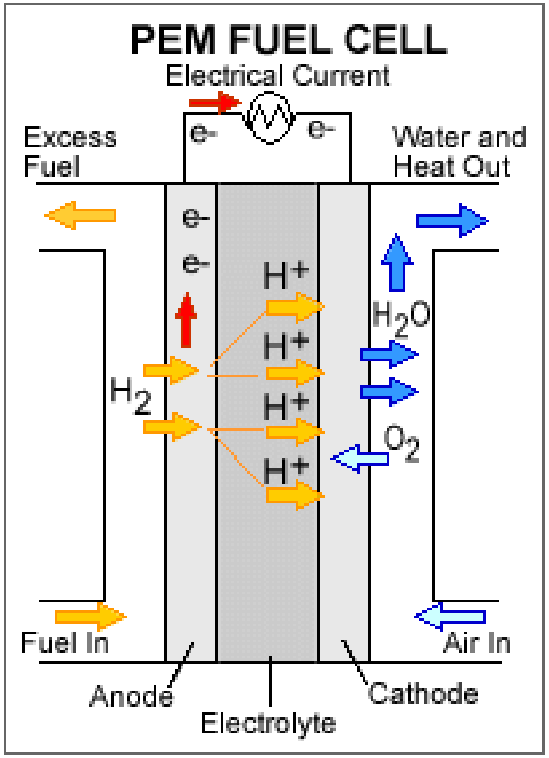
- Advantages
  - Low temperature operation
  - Quick start-up
  - Not as sensitive to impure hydrogen as other types. Can tolerate 1.5% CO concentration.

- Disadvantages
  - Platinum catalyst is expensive
  - Low current and power ; high size/weight ratio

Source: eere.energy.gov

Proton Exchange Membrane (3/6)

- Developed in early 1960's by Thomas Grubb and Leonard Niedrach of GE



- Uses a solid polymer as the electrolyte
- Porous carbon electrodes with platinum catalyst
- Operate at temperatures of 150 to 190 degrees F
- Efficiencies of 40% - 48%.
- 80% efficiency possible with co-gen

Anode:	$H_2 \rightarrow 2H^+ + 2e^-$
Cathode:	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Cell:	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

Source: eere.energy.gov and Visionengineer.com

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Proton Exchange Membrane (3/6)

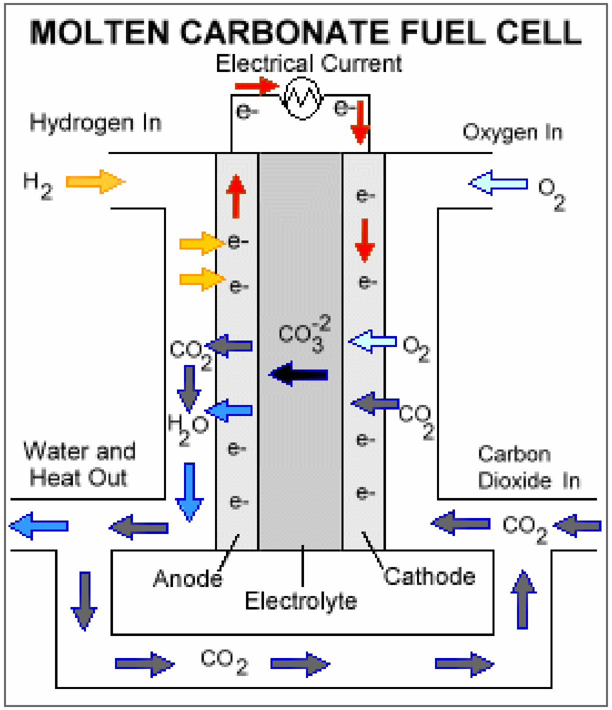
- Advantages
  - Low temperature operation
  - Quick start-up and long durability
  - Water is the only liquid present – minimal corrosion problems
  - High power density and low weight

- Disadvantages
  - Platinum catalyst is expensive
  - Needs more platinum than PAFC
  - Platinum extremely sensitive to CO poisoning. Pure hydrogen is a must.
  - Temperature regulation important to keep membrane moist.

Source: eere.energy.gov

Molten Carbonate (4/6)

- Early research began in 1930's with successful example by 1960



- Uses carbonate salts as the electrolyte suspended in $LiAlO_2$
- Non precious metals as catalyst
- Operate at temperatures of about 1200 degrees F
- Efficiencies of 50 - 55%.
- 60 – 70% efficiency with gas turbine
- 85% efficiency possible with co-gen

Anode:	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$
Cathode:	$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
Cell:	$H_2 + \frac{1}{2} O_2 + CO_2 \rightarrow H_2O + CO_2$

Source: eere.energy.gov and Visionengineer.com

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Molten Carbonate (4/6)

- Advantages
  - High efficiency
  - Fuel flexibility with either internal or external reformer
  - Can use inexpensive catalysts such as nickel
  - Not as sensitive to fuel impurities

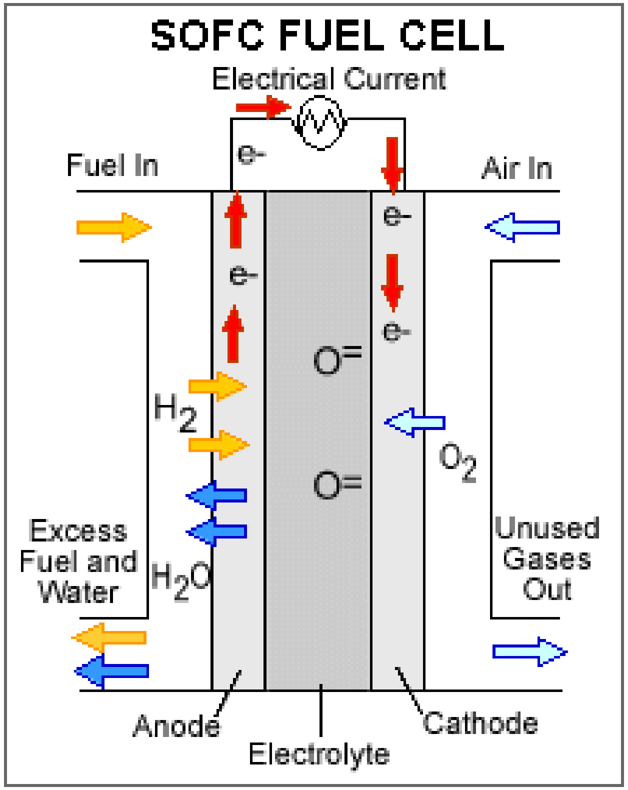
- Disadvantages
  - High temperature
  - Long start-up time
  - Liquid electrolyte not as attractive as solid (like in SOFC)

Source: eere.energy.gov

Solid Oxide (5/6)

- Early development followed along with MCFC.
- Westinghouse researchers made a working example in 1962.

- Uses hard ceramic compounds as the electrolyte
- specialized metals as catalyst
- Operate at temperatures of about 1800 degrees F
- Efficiencies of 55%.
- 85% efficiency possible with co-gen



Anode:	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$
Cathode:	$\frac{1}{2} O_2 + 2e^- \rightarrow O^{2-}$
Cell:	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

Source: eere.energy.gov and Visionengineer.com

Solid Oxide (5/6)

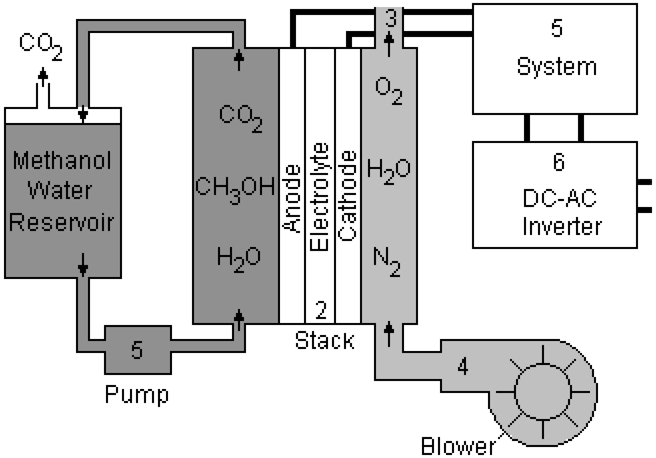
- Advantages
  - High efficiency
  - Fuel flexibility with either internal or external reformer
  - Can use inexpensive catalysts such as nickel
  - Not sensitive to fuel impurities
  - Solid electrolyte reduces corrosion problems

- Disadvantages
  - High temperature
  - Long start-up time

Source: eere.energy.gov

Direct Methanol (6/6)

- Newer Technology that takes methanol directly in as the fuel without reforming. Like a PEM fuel cell.



- Electrolyte is polymer or liquid alkaline
- Platinum as catalyst
- Operate at temperatures of 120-150 degrees F
- Efficiencies of 25 - 40%.

Anode: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$

Cathode: $3/2\ O_2 + 6H^+ + 6e^- \rightarrow 3\ H_2O$

Cell: $CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2\ H_2O$

Source: eere.energy.gov , Rogerlovejoy.co.uk and Visionengineer.com

Direct Methanol (6/6)

- Advantages
  - Low temperature
  - Ideal for small portable power supplies

- Disadvantages
  - Low efficiency
  - Technology new -- 3 to 4 years behind PEM
  - Fuel crossover problem (leaking across the electrolyte)

Source: eere.energy.gov

Fuel Cell Applications

1) Space vehicles
2) Cars, busses, other transportation
3) Military applications – portable power supplies, submarines
4) Supplemental power generation to the grid
5) Small power supplies such as cell phones, laptop computers, highway road signs, area lighting, etc.
6) Medical equipment
7) Emergency power
8) Off grid power generation

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Fuel Cell Power Conversion

How do we obtain the power from the fuel cell?

Fuel Cell Conversion

- Fuel Cells make DC power
  - Need to convert to AC in almost all fuel cell applications
  - Also the fuel cell voltage varies under load, so there is a need to regulate the output in many cases
- Here is where Power Electronics comes in!
  - Regulators such as DC/DC conversion (choppers)
  - Inverters to convert DC to AC

Fuel Cell Example Single Line Diagram

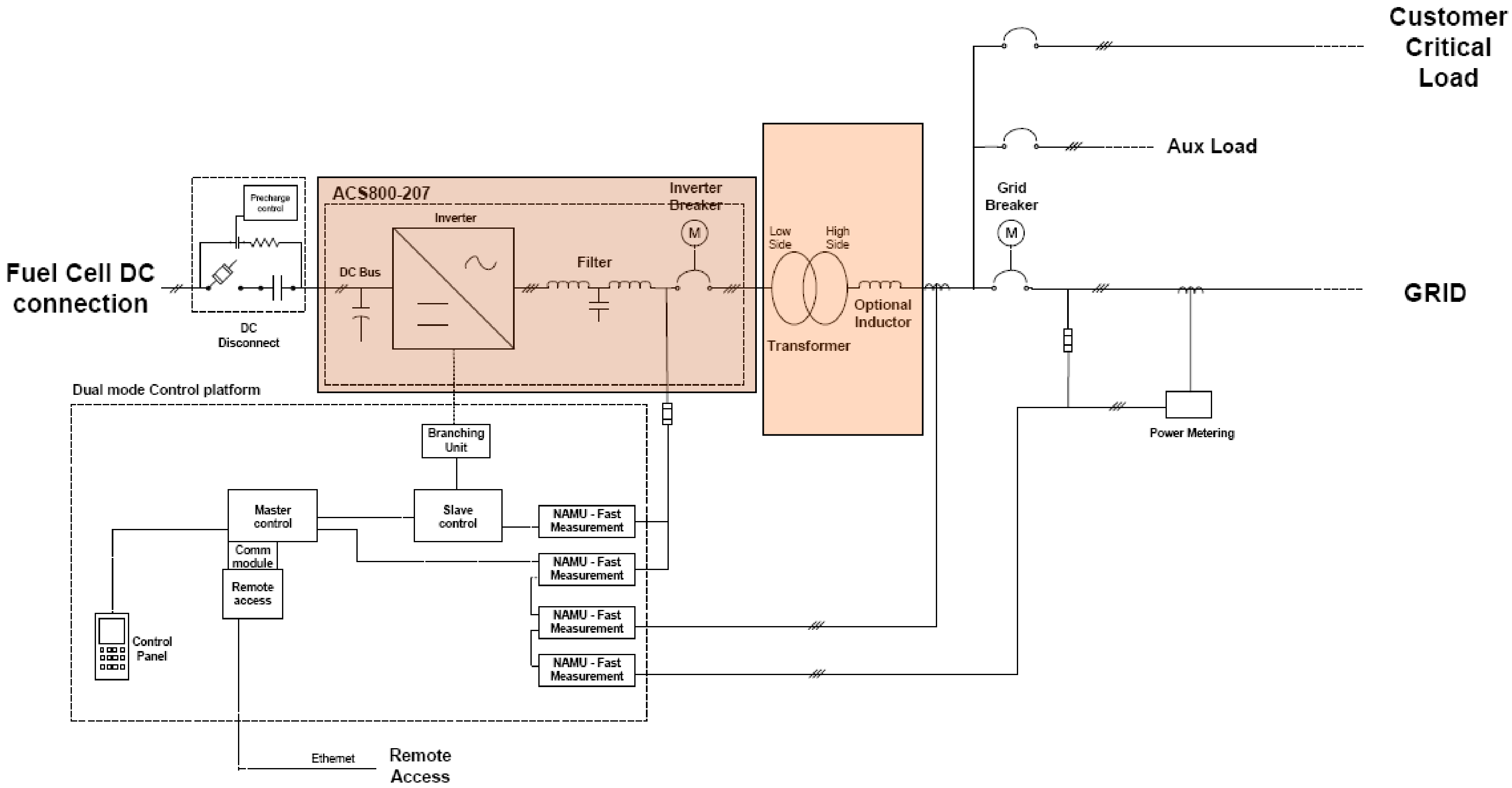
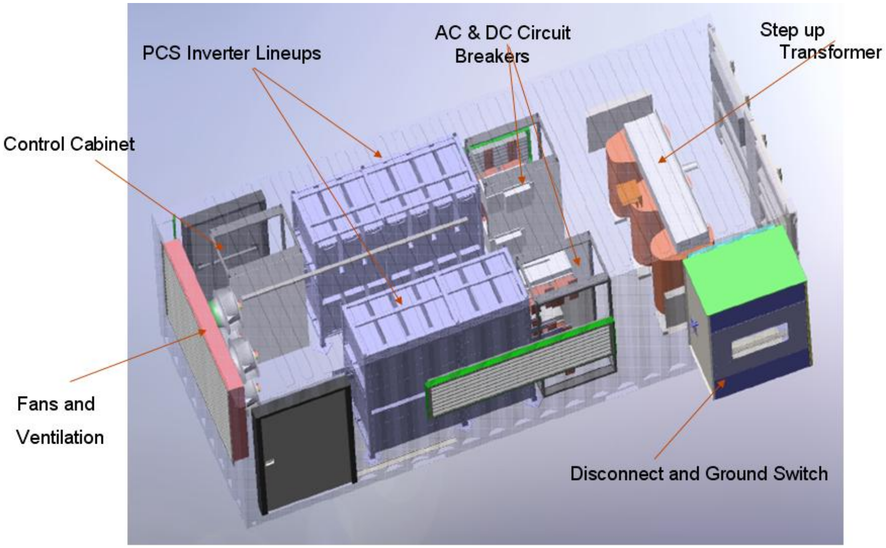


ABB PCS Solution

- Fully Enclosed Solution and prewired
- Electrical Balance of Plant (Ebop) supplied
- FAT Tested prior to shipment
- Cost effective shipping
- Faster installation time
- ***Includes:***
  - Converters
  - Transformers
  - Switchgear
  - Other as needed

1-2 MW Containerized Solution



Fuel Cell Future

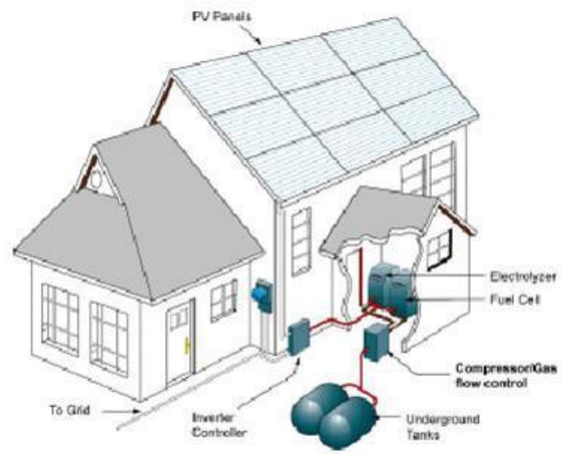
- Fuel cells are a viable power option, but…

Key obstacles need to be overcome…

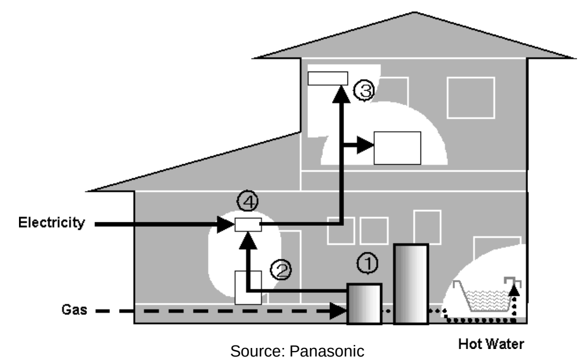
Distributed Generation – Residential and Commercial

Co-generation:

- Combined use of the electricity and heat produced by the fuel cell.
    - Heat can either drive a turbine for additional power generation, or
    - Heat can heat water needed in the process or for building heating
- Dramatically improves the overall efficiency of the fuel cell system
- High temperature fuel cells (MCFC or SOFC) work best
- Ballard Video



Source: US Dept of Energy



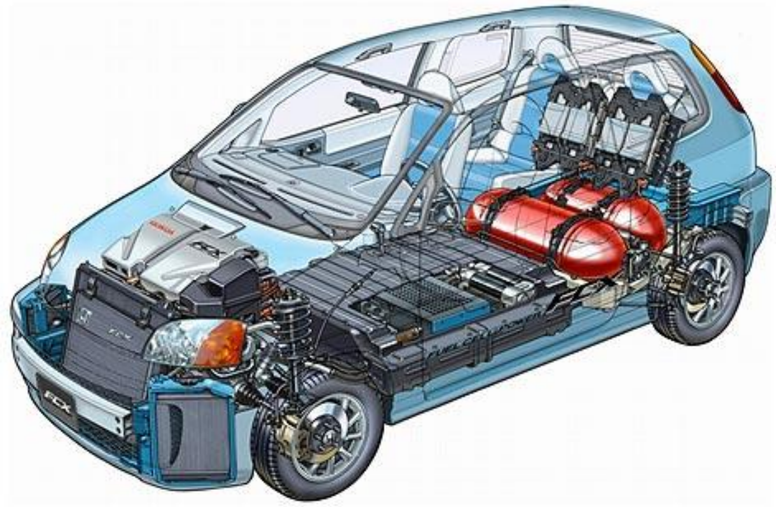
Source: Panasonic

(1) Fuel cell cogeneration system
(2) Commercial power supply splitter system (for connection to system-linked inverter)
(3) Electrical appliances such as air conditioners
(4) Electrical distribution board for home use

Fuel Cell Cars

- Honda to have FCX available to the consumer in just 3-4 years.

- 4 passenger
- 93 mph top speed
- 190 mile range
- EPA city/hwy of 62/51 mpkg



- 107 HP/ 201 lb-ft torque
- Runs on hydrogen in on-board 5000psi tanks
- 3.75 kg capacity
- Honda PEM fuel cell
- Zero emissions (water vapor only)

Source: Honda

Fuel Cell Cars

Mercedes Benz A Class

Targeted for production by 2012

Source: Daimler Chrysler

Fuel Cell Cars

Ford Focus FCV

- 4 passenger
- 80 mph top speed
- 100 mile range
- Zero Emissions

- 90 HP/ 140 lb-ft torque
- Runs on hydrogen in on-board 2600psi tanks
- Ballard PEM fuel cell

Source: Ford Motor Company

ABB

Fuel Cell Cars

General Motors

HydroGen3

Sequel

Hy-wire

Silverado 1500

Autonomy

Source: General Motors

Fuel Cell Cars

General Motors Sequel – by 2010

- 5 passenger
- 0-60 in under 10 seconds
- 300 mile range
- 90 mph top speed

- Skateboard design
- 73 kW (98 HP)
- 10,000psi Hydrogen
- 8 kg storage capacity
- Zero Emissions
- GM PEM fuel cell

Source: General Motors

Fuel Cell Cars

Toyota

Hydrogen-Powered Fuel Cell Vehicle

Fuel Cell Engine (top) and Hybrid Engine (bottom)

- Target production model by 2015 – will be $50,000
- Also working on Fuel cell hybrid (FCHV) vehicles

Hydrogen Fuel Pump
– Photo by Dreamscapephotoart

Source: Toyota Motors

Fuel Cell Cars

Other Auto manufacturers working on fuel cell technology

- Hyundai Tucson FCEV

- Kia Sportage FCEV

- Nissan XTrail FCV

- VW HyMotion

- Audi FCV

Note : The Nissan runs on a DMFC.

Source: MSN Auto

Reminders
Automation & Power World 2011

- Please be sure to complete the workshop evaluation
- Professional Development Hours (PDHs) and Continuing Education Credits (CEUs):
  - You will receive a link via e-mail to print certificates for all the workshops you have attended during Automation & Power World 2011.
  - BE SURE YOU HAVE YOUR BADGE SCANNED for each workshop you attend. If you do not have your badge scanned you will not be able to obtain PDHs or CEUs.

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