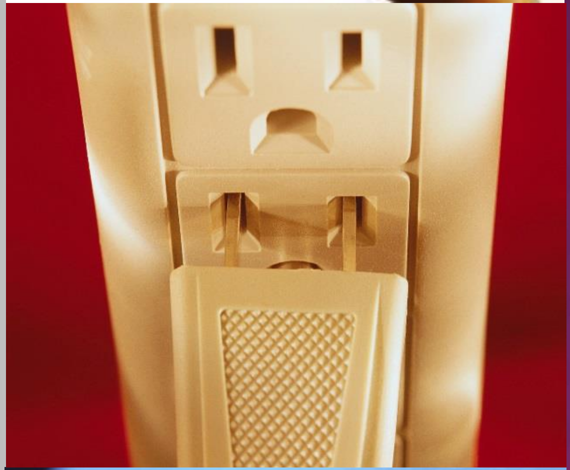


WEEK 1: Fuel Cell BASICS

MECH-526

FUEL CELL SCIENCE & ENGINEERING

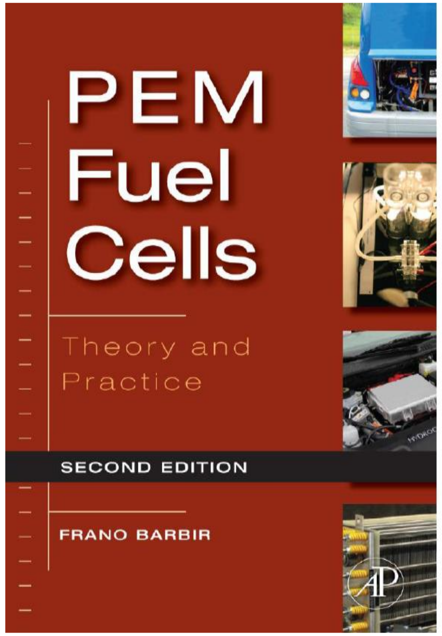
Center for FUEL CELL Systems & Powertrain Integration
Kettering University

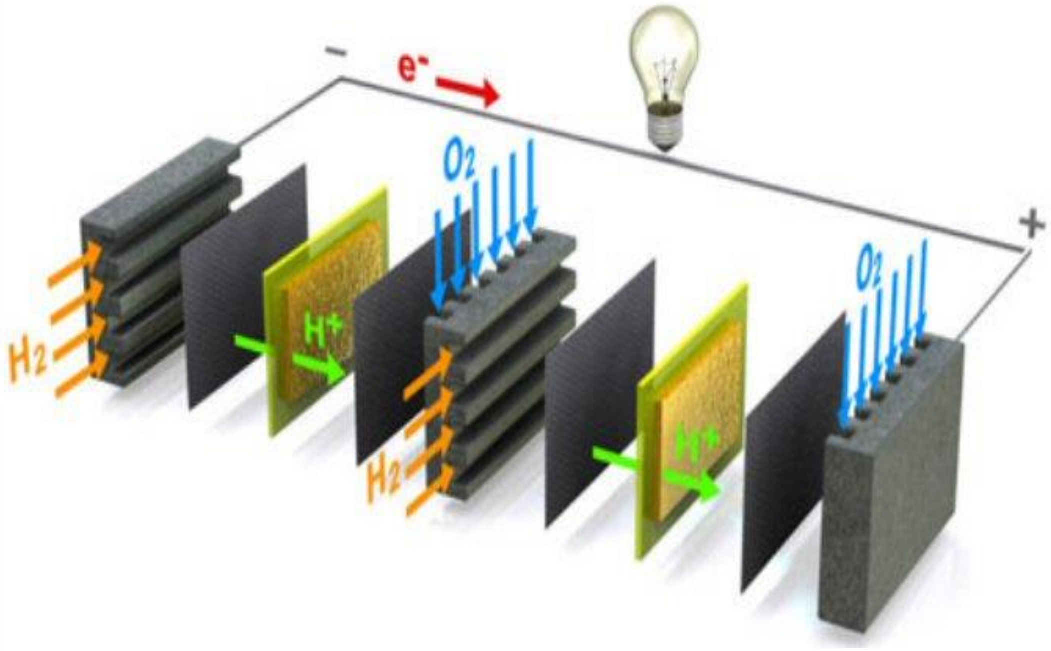
Dr. K. J. Berry. P.E.

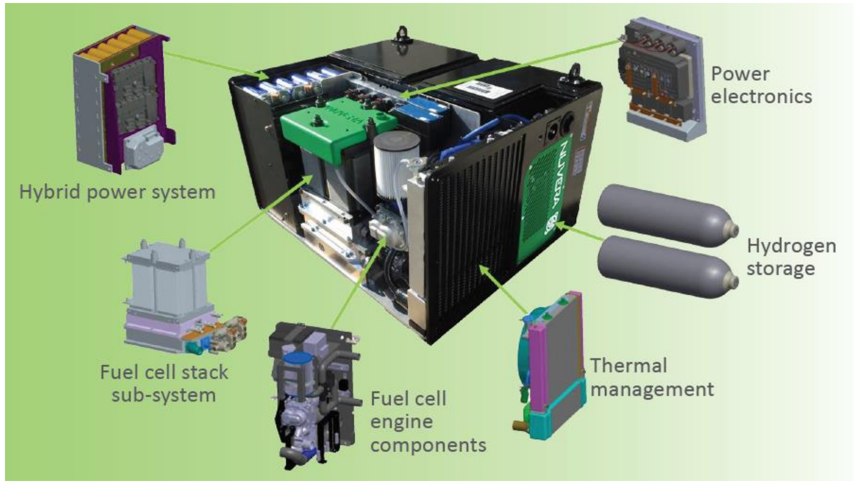
Mechanical Engineering
Kettering University
jberry@kettering.edu
www.DRKJBERRY.COM

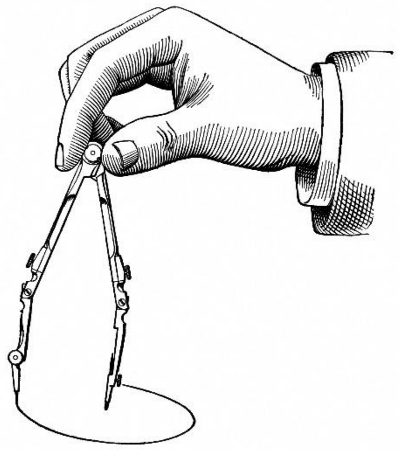
REFERENCES:

- PEM Fuel Cells: Frano Barbir, ELSEVIER.
- Fuel Cell Explained: Larmie & Dicks, WILEY.
- Fuel Cell Fundamentals: O’hayre, Cha, et al., WILEY.





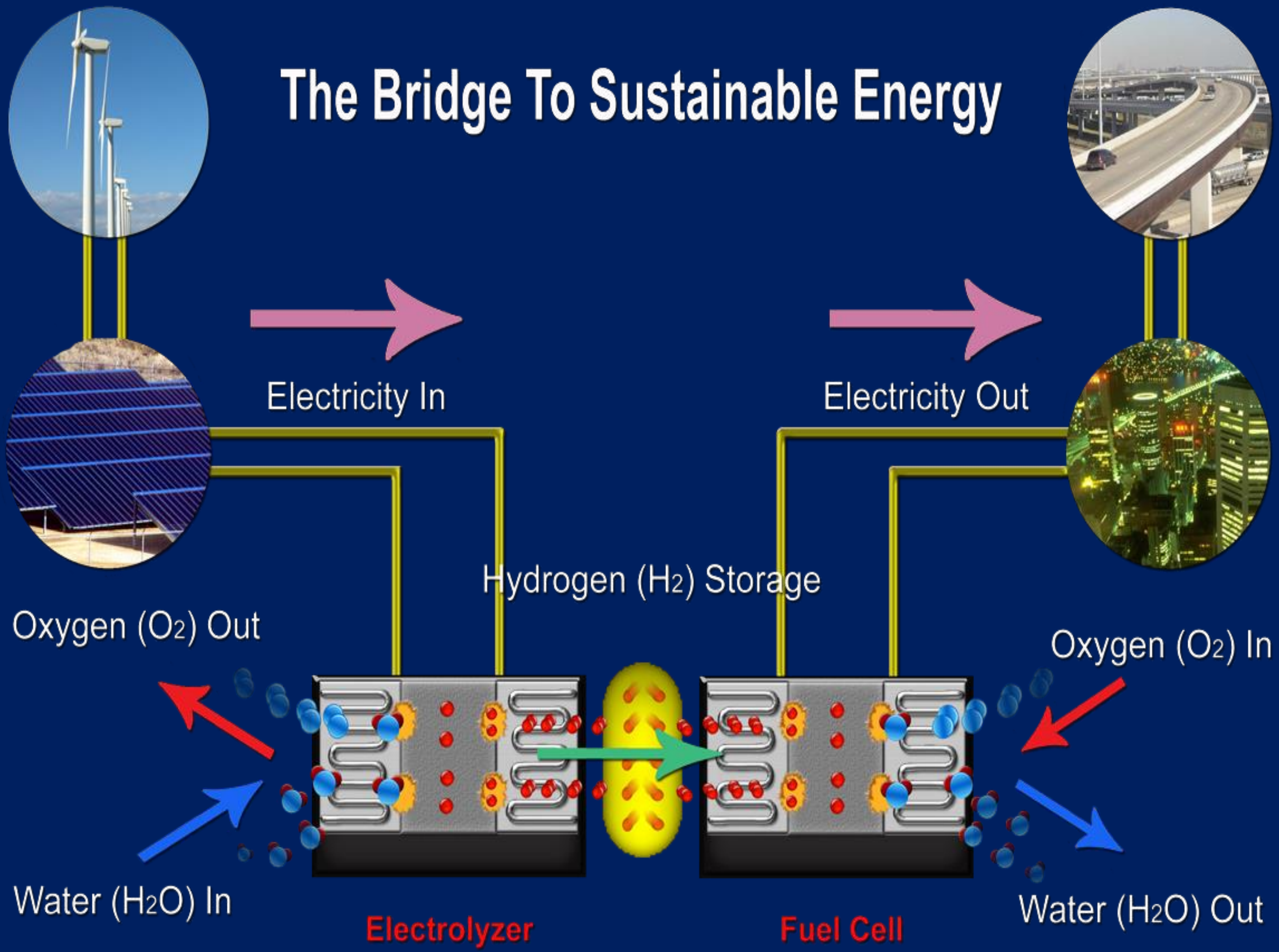




FUEL CELL BASICS& APPLICATIONS

CLIMATE CHANGE

Climate scientists are now concerned that these natural fluctuations are being overtaken by warm-side temperature changes induced by human activity, specifically the ***combustion of fossil fuels*** that release gasses and particles that have a warming effect on the atmosphere and producing extreme weather i.e. ***Hurricanes IAN LIVE 2022,Harvey, Irma, Dorian, Maria,and FIONA LIVE***.


The Bridge To Sustainable Energy
Electricity In
Electricity Out
Hydrogen (H_2) Storage
Oxygen (O_2) Out
Oxygen (O_2) In
Water (H_2O) In
Water (H_2O) Out
Electrolyzer
Fuel Cell

H_2

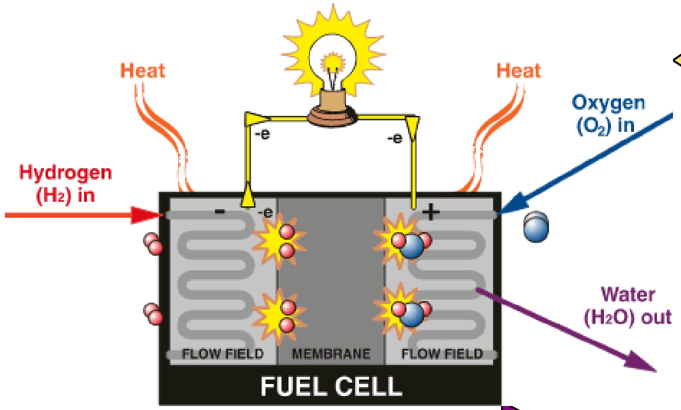
Fuel Cell Basics

H_2

H_2

Hydrogen

H_2

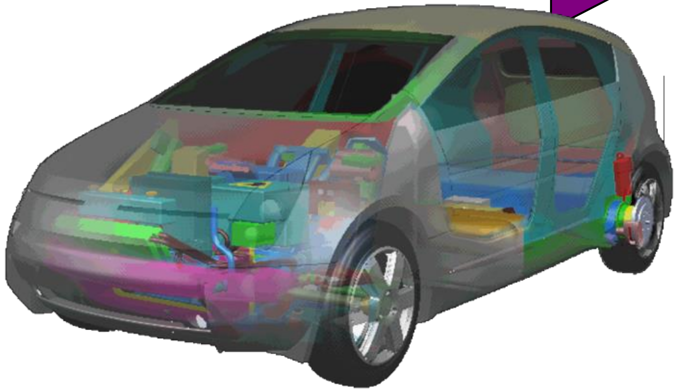


Oxygen

Water

Heat

CLEAN POWER

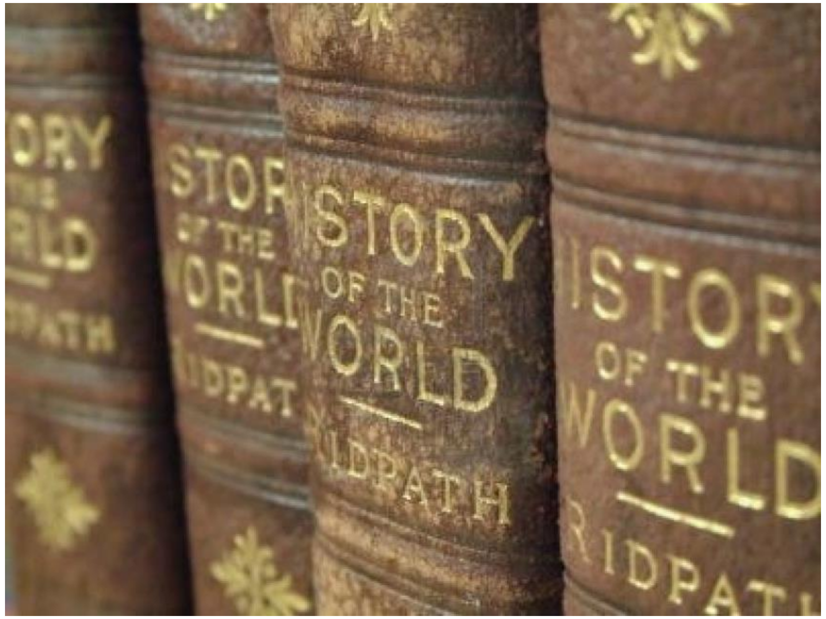


H_2

H_2

H_2

H_2

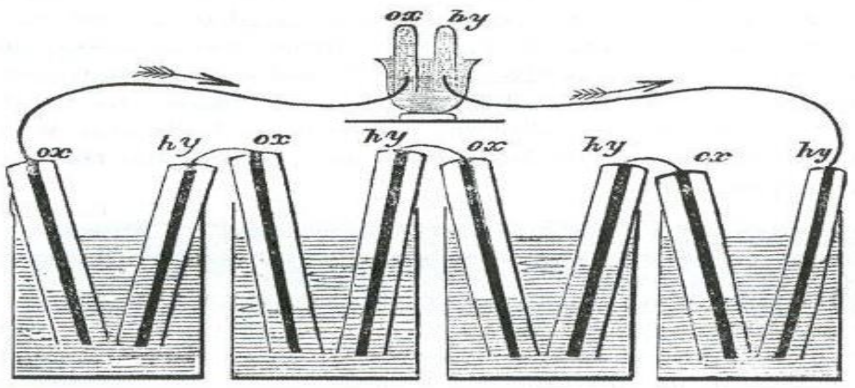


HISTORY

HISTORY

- Sir William R. Grove of Swansea, Wales invented the Gaseous Voltaic Battery, now referred to as the FUEL CELL, in 1839. He used TWO PLATINUM ELECTRODES, halfway submerged in a beaker of aqueous SULFURIC ACID as an electrolyte, with tubes inverted over each electrode one containing H_2 and the other O_2. When the tubes were lowered, the gases displaced the electrolyte, leaving only a thin layer of acid solution on the electrode. A galvanometer connecting the two electrodes deflected indicating current flow.

Reproduced from Fuel Cell Technology Handbook, G. Hoogers, Ed., CRC Press, 2003.



HISTORY

- Lord Rayleigh in ***1882*** developed a new form of gas battery to improve the efficiency of the platinum electrode by increasing the active surface area between solid electrode, the gas and the liquid. He used two pieces of platinum gauze with an area of about 20 in^2.
- Mond and Langer in ***1889*** built first prototype of the practical fuel cell (i.e., sustaining the fuel cell reaction) by solving the problem of electrode flooding [caused by a liquid electrolyte (H_2SO_4)] with the placement of the electrolyte in a matrix. They used a diaphragm to contain sulfuric acid electrolyte.
- In ***1894***, the conversion efficiency of chemical energy into mechanical energy in a steam engine was 10%. Oswald in 1894 perceived electrochemistry as the solution of inefficient energy conversion! His attempt to produce directly electricity from coal (direct coal fuel cell) resulted in the discovery of molten alkaline electrolytes.

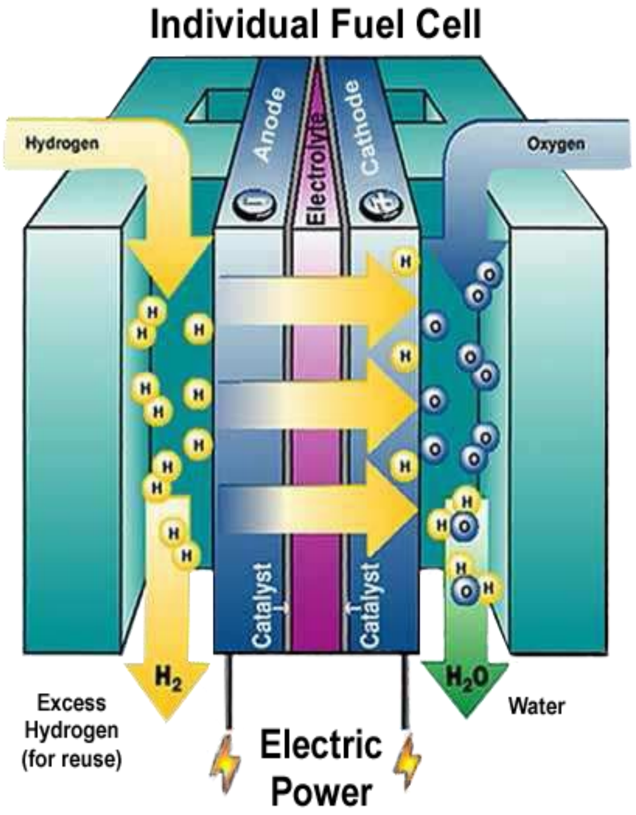
FUEL CELLS HISTORY VIDEO

CLICK

WHAT IS A FUEL CELL ?

- A Fuel Cell is an ***ELECTROCHEMICAL*** device that operates like a battery. However, unlike a battery, a fuel cell requires re-fueling, and not recharging. ***NO COMBUSTION***.
- A fuel cell uses fuel — usually hydrogen extracted from natural gas, propane, or other carbon based fuels, and oxygen extracted from air — to produce electricity.
- Fuel cells will continue to produce energy in the form of electricity and heat as long as there is a constant fuel source.
- "PURE" Hydrogen fuel cells work simply, have no moving parts, and operate silently with water and excess heat as the only by-products.
- Fuel cells are a highly efficient, combustion-less, and virtually pollution free energy source that provides electricity to power a wide array of applications including ***buildings***, ***automobiles***, emergency ***back-up*** systems, ***laptop computers***, and numerous other ***consumer devices***.

- Fuel Cells Require:
  - *Hydrogen & Oxygen*



Dr. Geoffrey Ballard: ***FATHER OF FUEL CELLS***
Vancouver, BC

- **1979**: **Ballard Research Inc**. is founded by Geoffrey Ballard, Keith Prater and Paul Howard to conduct research and development of high-energy lithium batteries.
- **1986**: Development of the first Ballard fuel cell stack operating on pressurized air.
- **1992**: Development of a 90 kW fuel cell engine for transit buses.
- **2009**: Deployment of 20 Ballard-powered fuel cell buses in Whistler, BC in conjunction with the 2010 Winter Olympics and Paralympic Games. The fleet surpassed one million kilometers in operation in 2011.
- **2016**: First 22 of 300 fuel cell buses planned for deployment in the cities of Foshan and Yunfu, China begin operation.

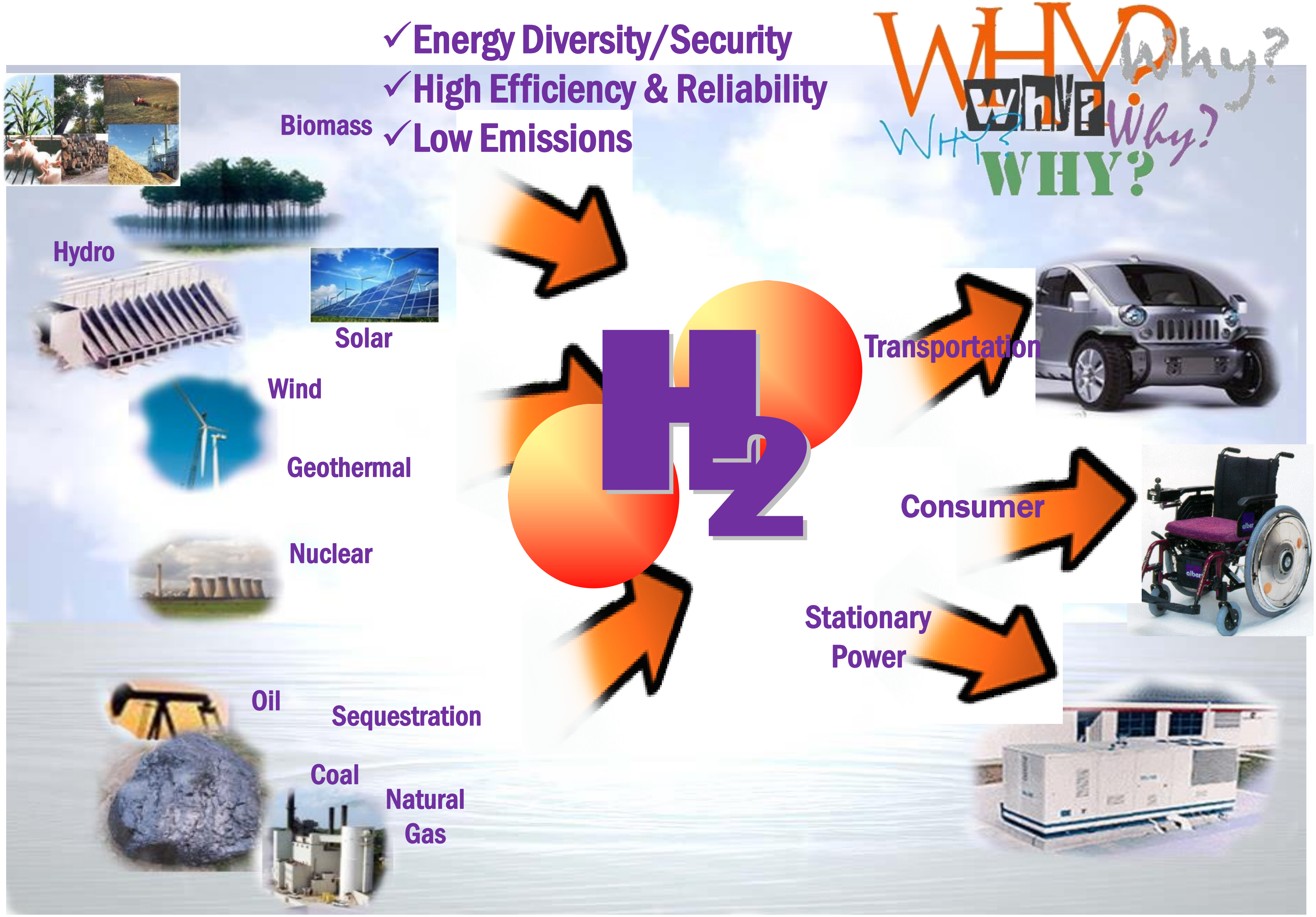
"It will take a combined effort of academia, government, and industry to bring about the change from a gasoline economy to a hydrogen economy. The forces are building and progress is being made. It is of major importance that a change of this magnitude not be forced on unwilling participants, but that all of us work together for an economically viable path to change."
— Geoffrey Ballard (1932-2008)

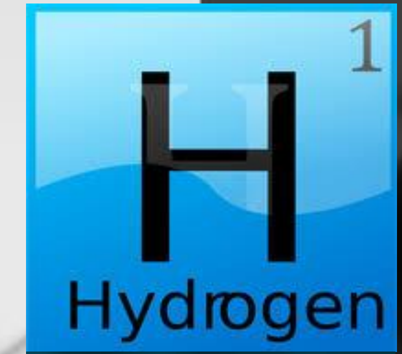
FUEL CELL APPLICATIONS: GENERAL

- First important applications were for manned space flights to provide the electricity and also water.
- High power output for space, microelectronics and other applications
- Automotive applications due significant decrease in emissions, improved fuel economy, less noise generation, etc.
- Fuel cell powered railway locomotives (can take care large variations in load)
- Fuel cell battery operated submarines (operating time increase of a submarine 20-30 times due to better space utilization, also no noise, pollution, etc.)
- For military applications, fuel cells are quiet, difficult to detect, reliable, more storage capacity than conventional batteries, and no need for recharging the batteries.

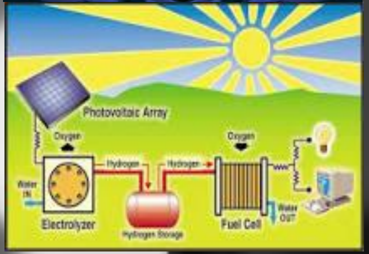
WHY HYDROGEN ?

✓Energy Diversity/Security
✓High Efficiency & Reliability
✓Low Emissions





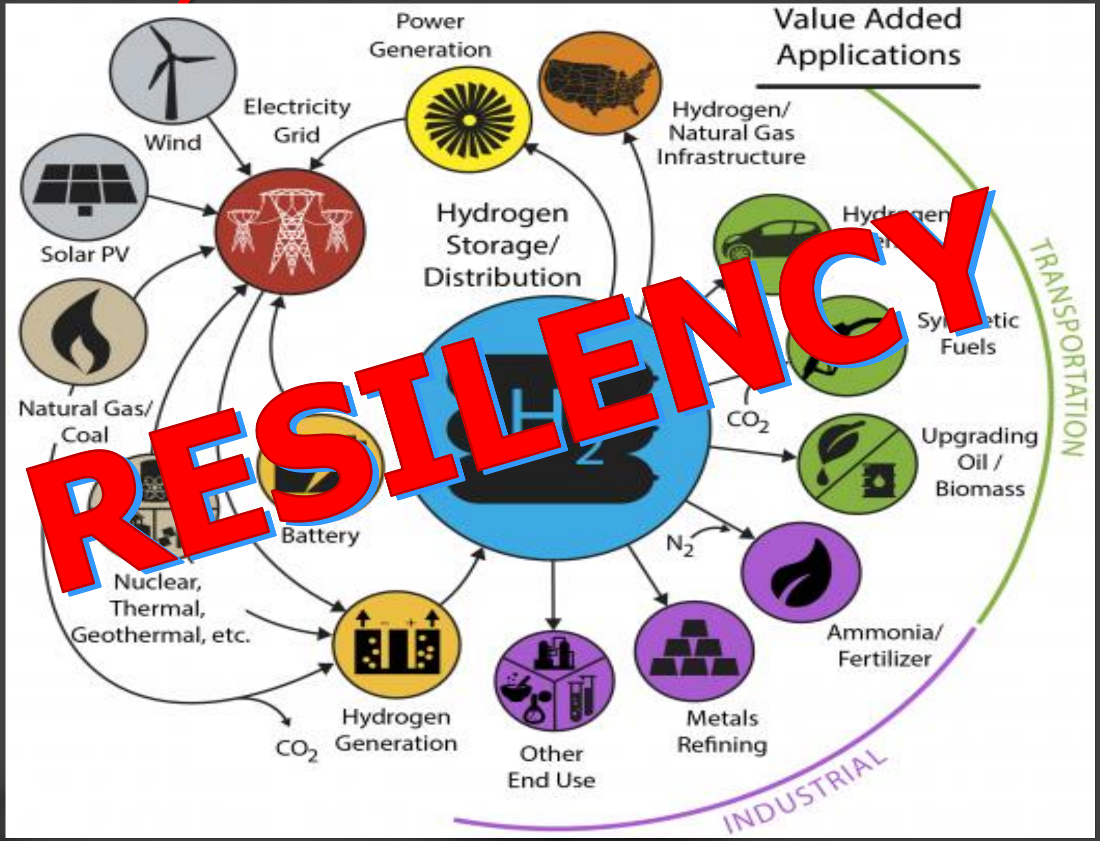




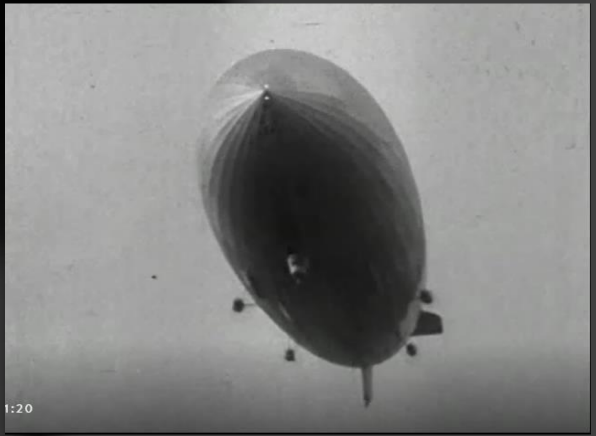
WHY HYDROGEN?

Storage/Power/Fuels

- Lightest of all elements and most abundant in the universe.
- Highest energy density of all fuels and burns cleanly with only heat and water by-products.
- Excellent storage medium or energy carrier for excess renewable energy sources.
- Obtained from multiple feed stock.



Hydrogen Safety Video?

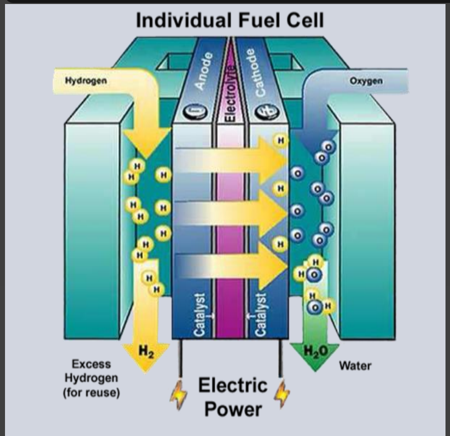


Famous:
HINDENBURGH
Hydrogen Air Ship

Hydrogen
Truth

Fuel Cell Fundamentals

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



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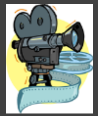
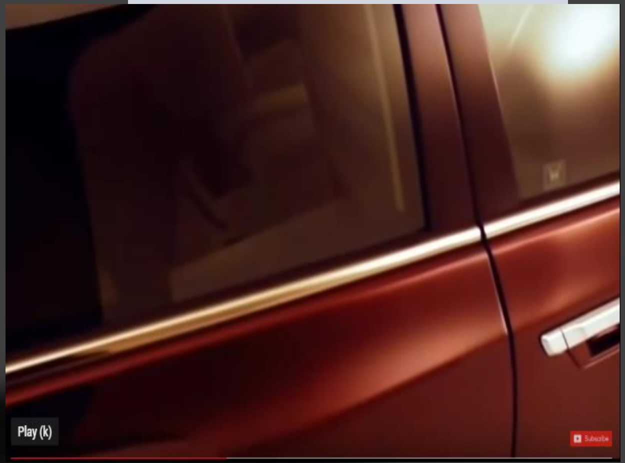
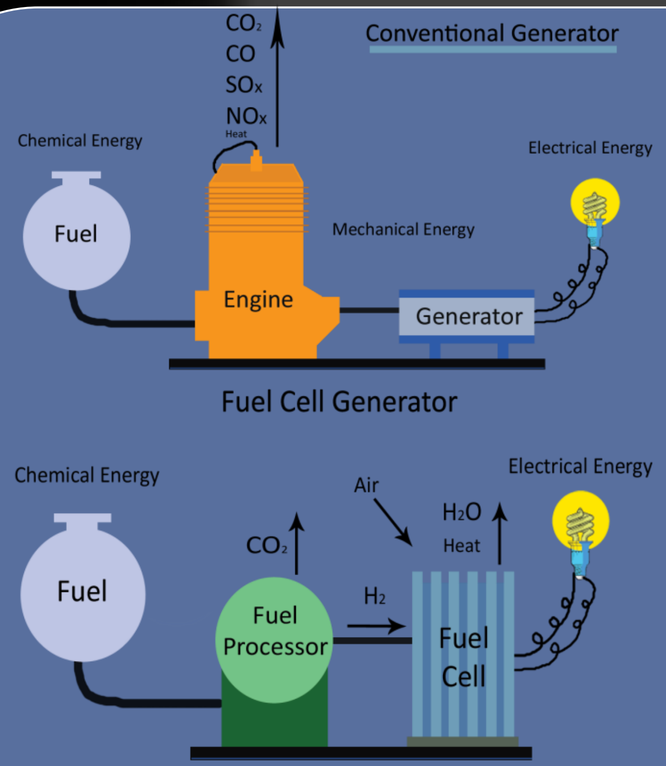




Chemical Combustion
vs.
ELECTROCHEMICAL REACTION



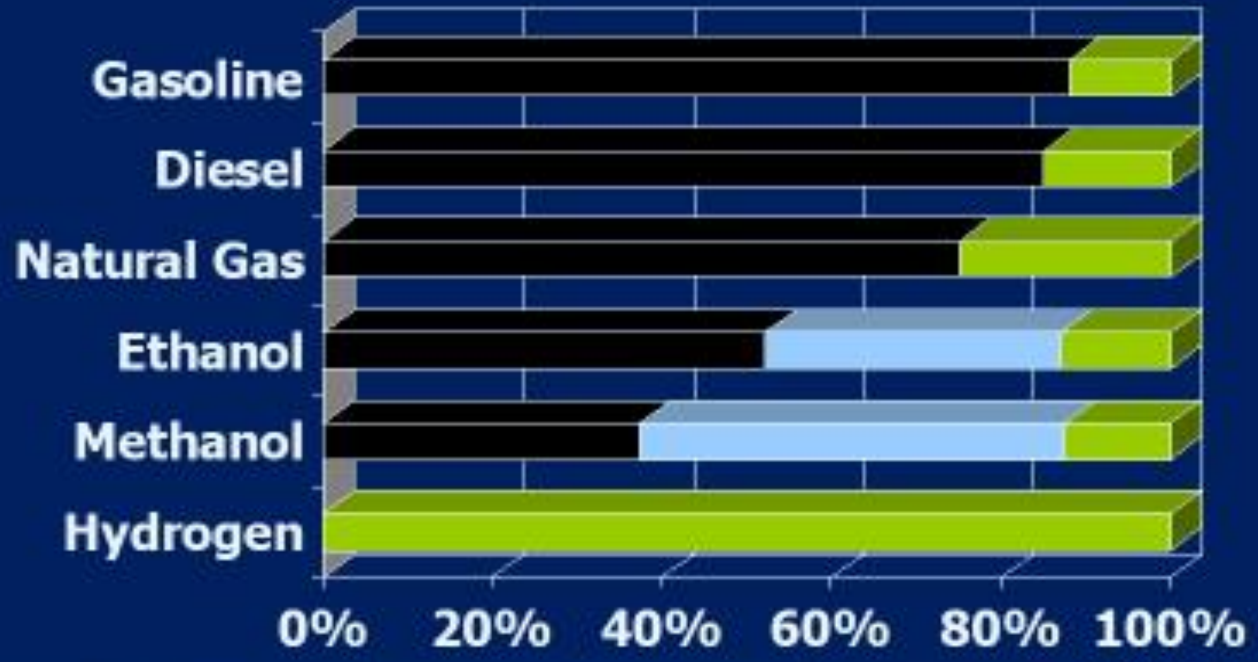
18% Efficiency

Chemical Combustion
½ Load, Full Load

46% Efficiency

Electrochemical Reaction
0-100% Load
90% Emission Reduction

MOVING AWAY FROM CARBON BASED FUELS TOWARDS CLEANER, RENEWABLE FUELS



CONSUMER FUEL CELLS

Smart FC A50 (DMFC)

Casio (RMFC)

Jadoo Power (Hydride)

Toshiba 100mW (DMFC)

MTI Micro Prototype (DMFC)

MOBILITY FUEL CELLS / STATIONARY

Peugeot Quad Quark

IdaTech FCS1200

Toyota Z-Capsule FC Hybrid

HDW U-212

GM Hy-wire

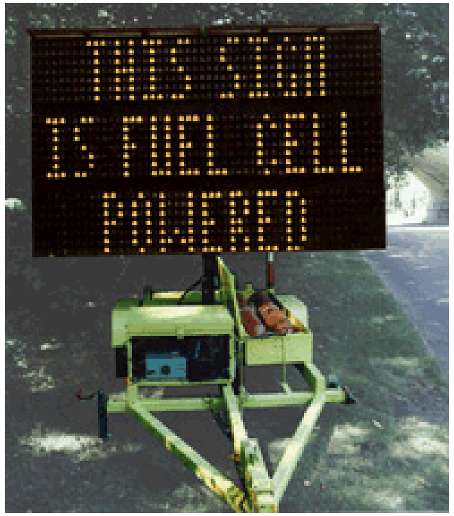
OTHER APPLICATIONS

6.5 times longer than with a conventional battery by weight

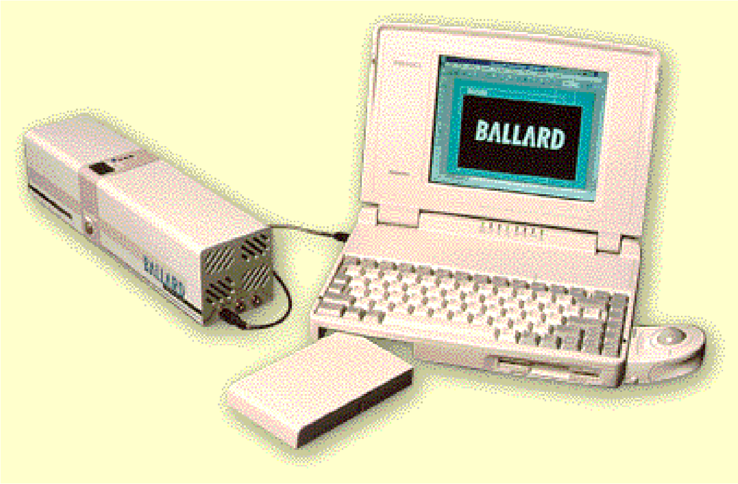
Source: H

OTHER APPLICATIONS

FC/Battery Hybrid
200hr/with
NiMH Storage
half the weight



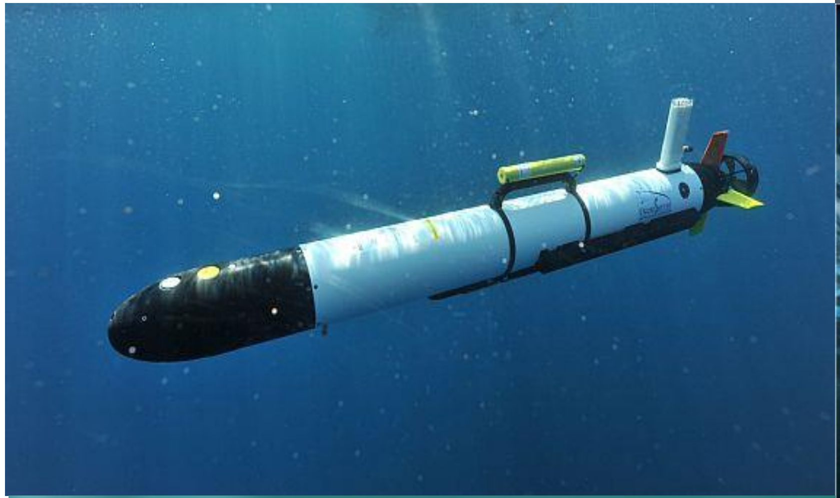
6 month uninterrupted service on single tank of Ammonia when used with solar panels

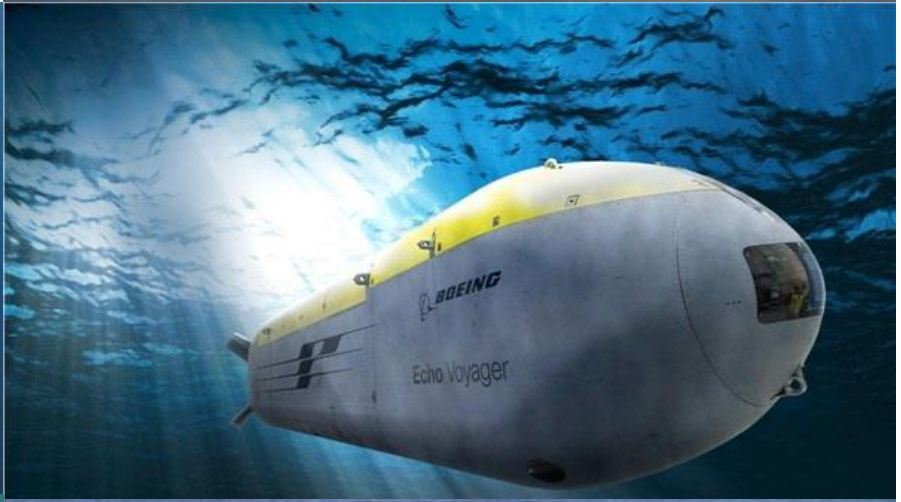


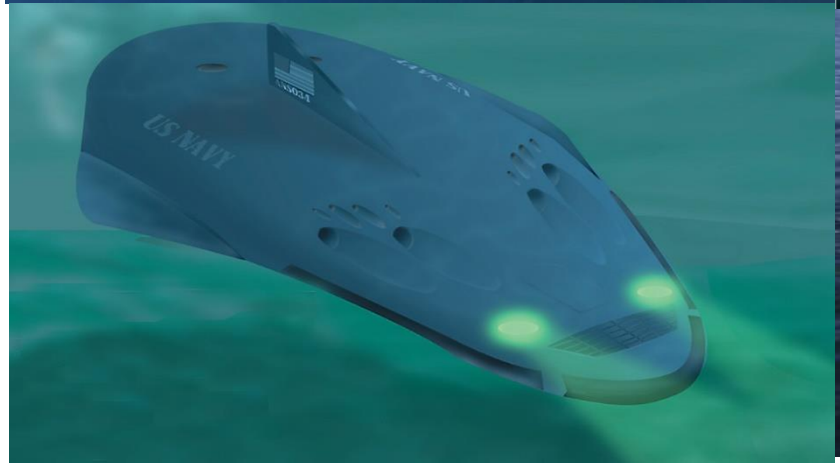
20 hour battery life on hydrogen charge

Source: H Power

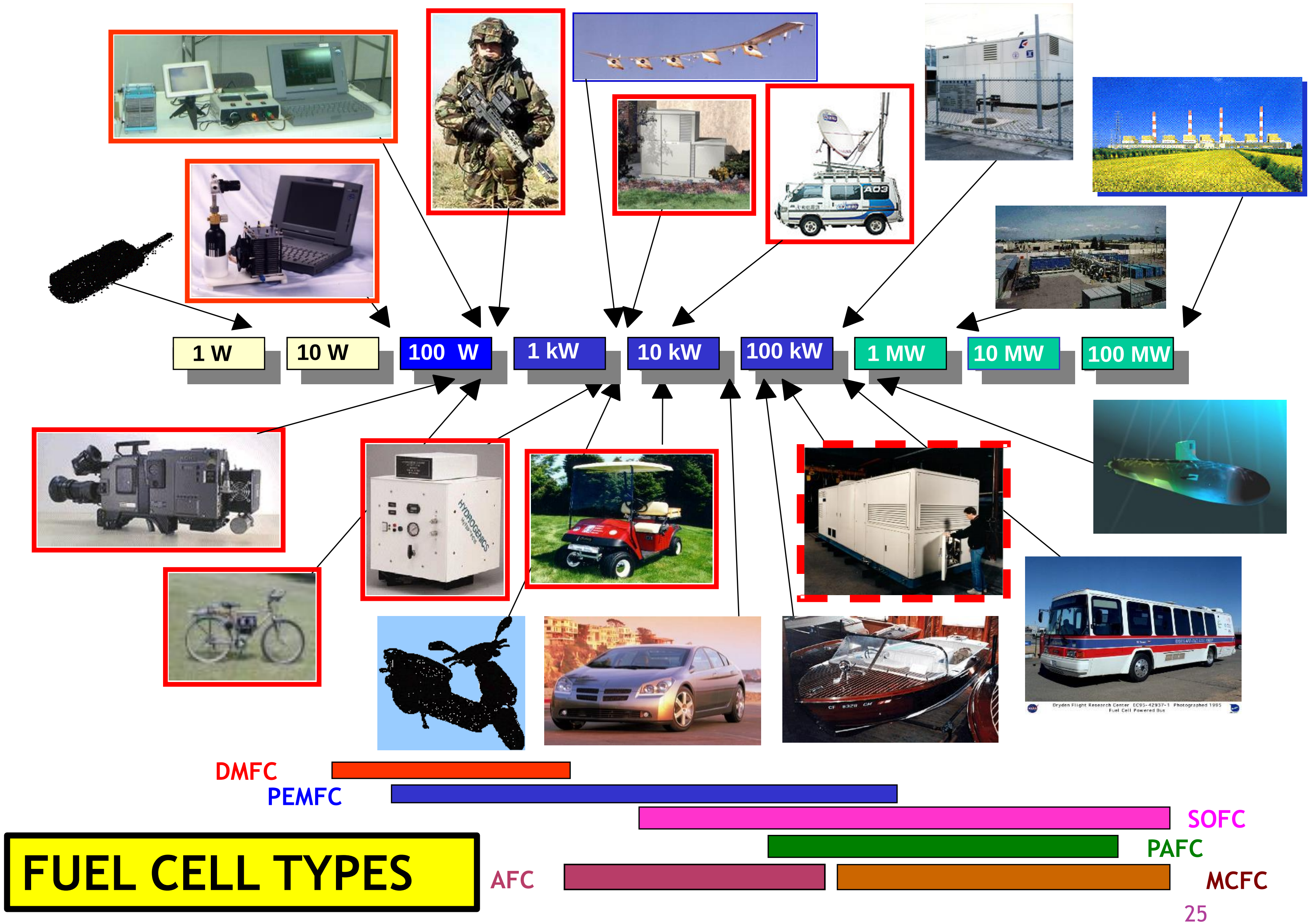
NAVY UUV'S
APPLICATIONS
DAYS -> MONTH
(BATTERY-> HYBRID:FC/BAT)



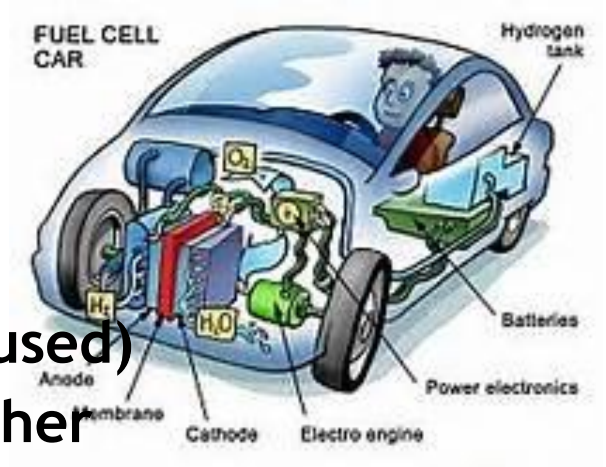




Fuel Cell Applications: 1 W to 100 MW Range

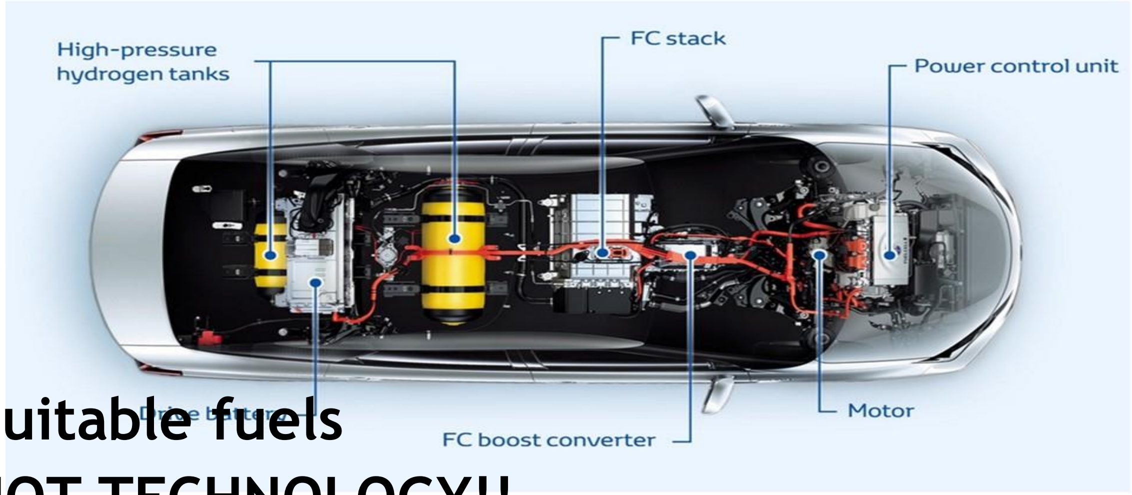


FUEL CELL APPLICATIONS: AUTOMOTIVE TRANSPORT



Advantages

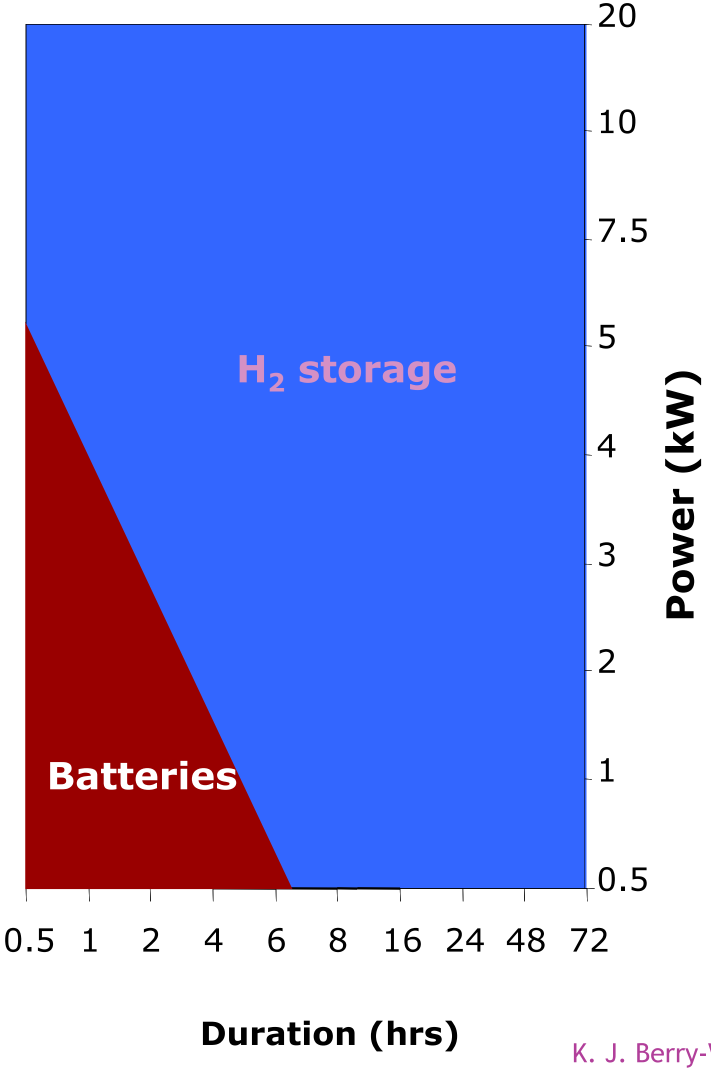
- Low or zero emission
- High efficiency
- Quiet (if bottoming cycle is not used)
- Gradual shift from gasoline to other fuels

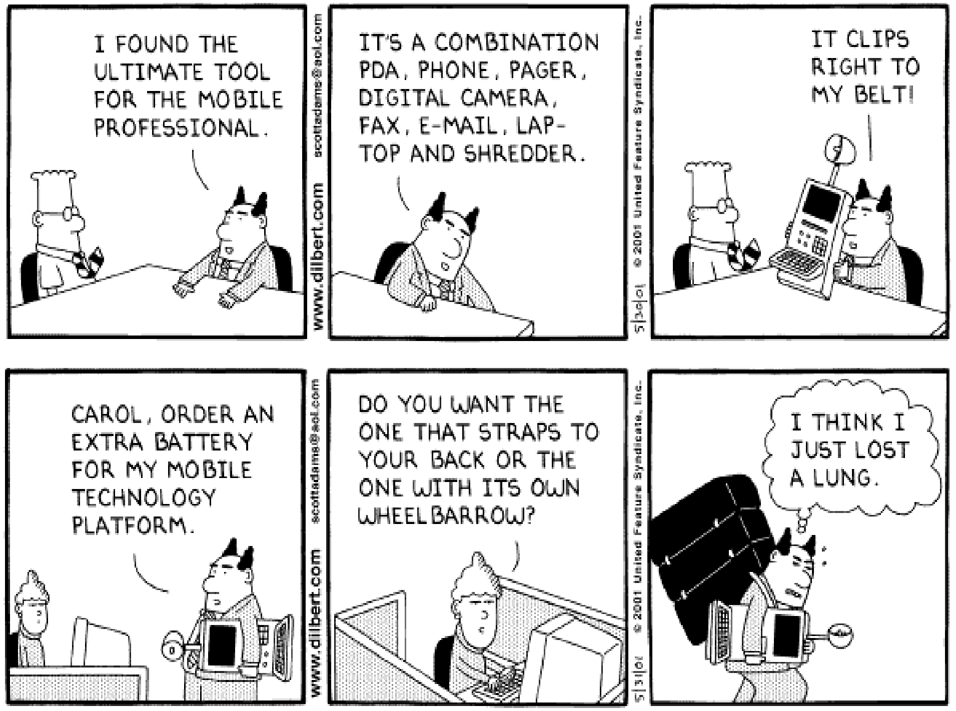


Challenges

- Cost
- Packaging
- Performance
- Availability of suitable fuels
- ENGINEERING;NOT TECHNOLOGY!!

OUR PORTABLE POWER DILEMMA



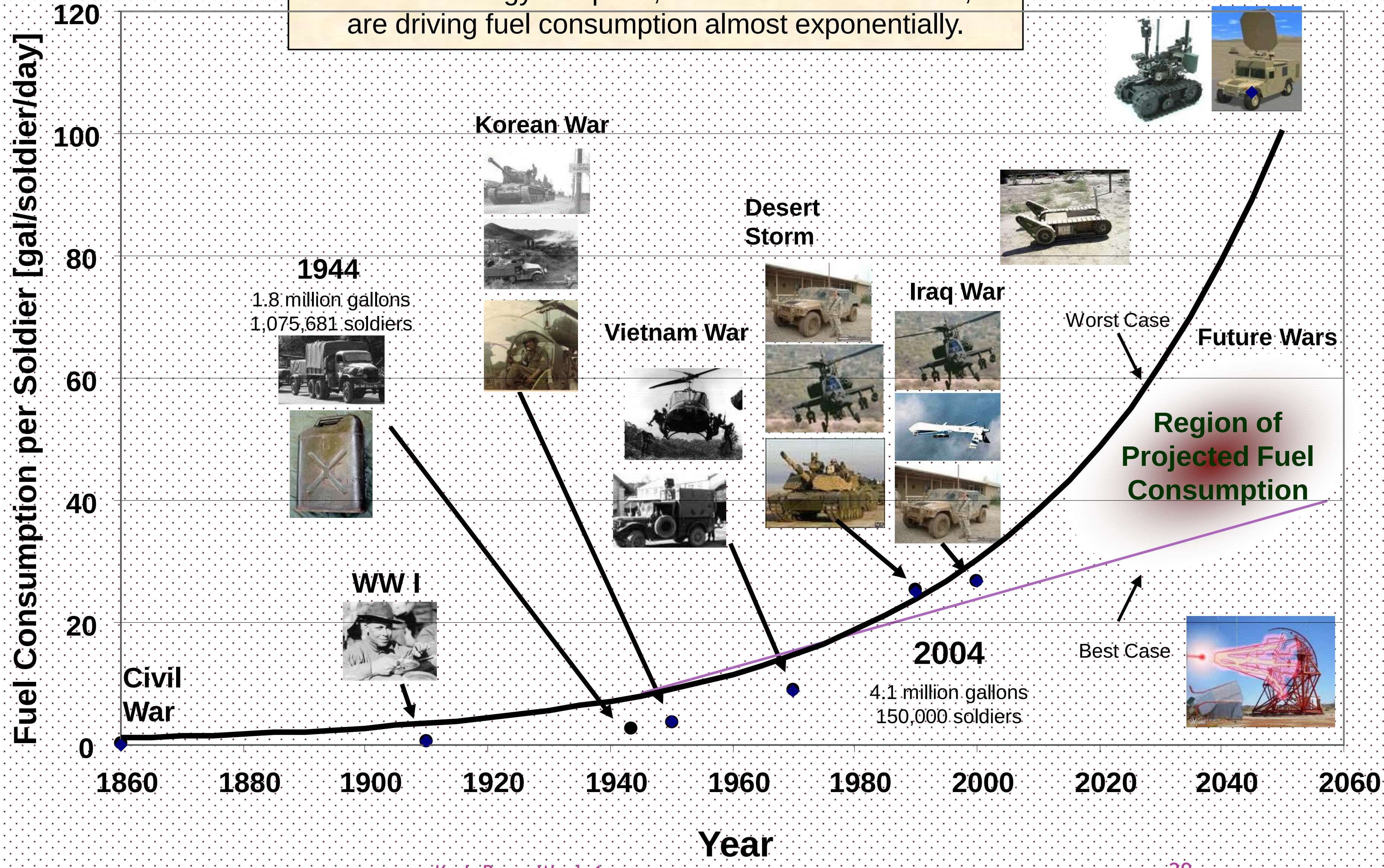


ADVANTAGES OF USING A FUEL CELL IN PORTABLE DEVICES

- Flexibility with respect to power and capacity achievable with different devices for energy conversion and energy storage.
- Long lifetime and long service life
- Good ecological balance
- Very low self-discharge
- A fuel cell running on methanol could provide power up to 10 times longer than Lithium-ion batteries in a comparable packaging size and weight.
- Fuel cells do not require lengthy charging, just provide fuel and air, and instant power.

Moving In The Wrong Direction

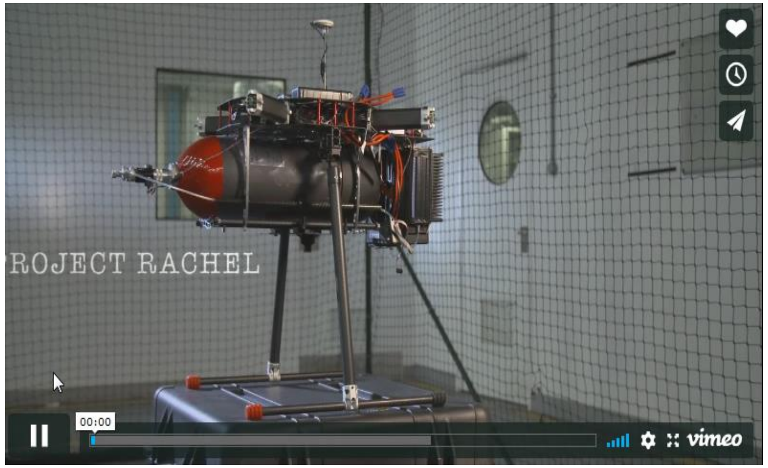
Technological advances, especially in C4ISR, future directed energy weapons, and unmanned vehicles, are driving fuel consumption almost exponentially.



THE FUTURE IS NOW!

- Laptop computers
- Cell phones, cordless phones
- Portable chargers for rechargeable cell phones
- Personal digital assistance (PDAs)
- Many military applications
- VCD/DVD players, MP3
- digital cameras
- Portable electronics
- Other portable consumer products
- MEMS devices and Sensors
- Emergency lighting
- Power tools
- DRONES

Fuel Cell Drone:
12 Minutes (Battery) to 70 Minutes Hydrogen

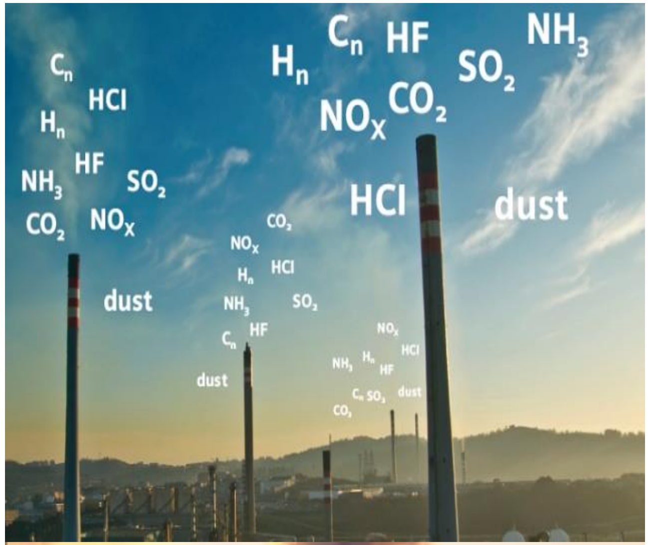


FUEL CELL AVOID EMISSIONS PRODUCED BY COMBUSTION

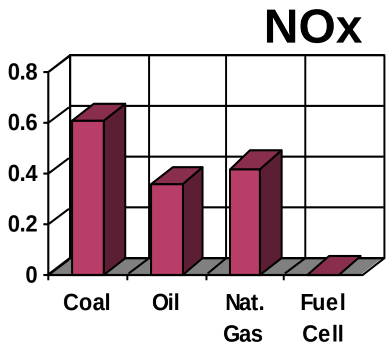
- Burning fossil fuels (coal, oil, natural gas) to produce electricity or space heating produces emissions of:
  - carbon dioxide (CO_2)
  - acid gases such as sulfur dioxide (SO_2) and nitrous oxides (NO_x)
- CO_2 is a greenhouse gas, which contributes to global warming, while SO_2 and NO_x emissions cause acid rain.

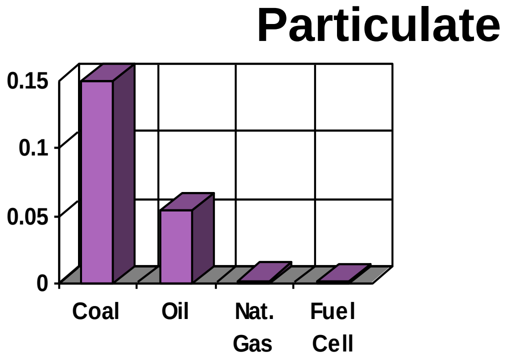
FUEL CELL EMISSIONS

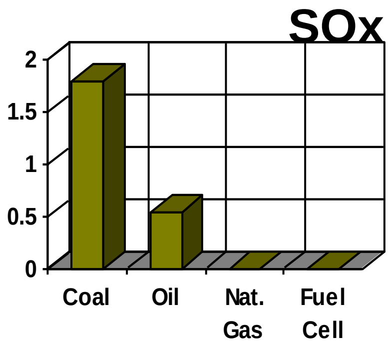
- Fuel cell power plants emissions are at least 10 times lower than the most stringent California standards.
- Fuel cells produce lower CO2 emissions than conventional power generating plants.
- Fuel cell power plants have water as a byproduct and have very low water usage. And water discharge is clean and does not require pretreatment.
- No ash or large volume waste are produced from fuel cell operations.

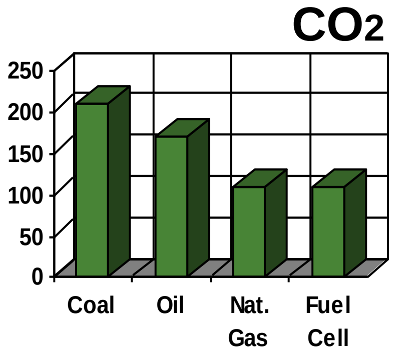


FUEL CELL EMISSIONS (FUEL REFORMING)









Source: NRDC Reports: Choosing Clean Power, March 1997

FUEL CELL NOISE EMISSIONS

- Since there is no combustion or moving parts, the fuel cell stack power generation process is very quiet.
- Normal conversation happens around 60 dBa, which is about the current noise measurements for all fuel cell applications.
- The only fuel cell noise source is from the fuel cell ***BOP*** (Balance of Plant), i.e. fans, compressor or turbines, pumps, condensers, valves, depending upon system)

https://www.noisehelp.com/noise-level-chart.html

PLANNING FLEXIBILITY

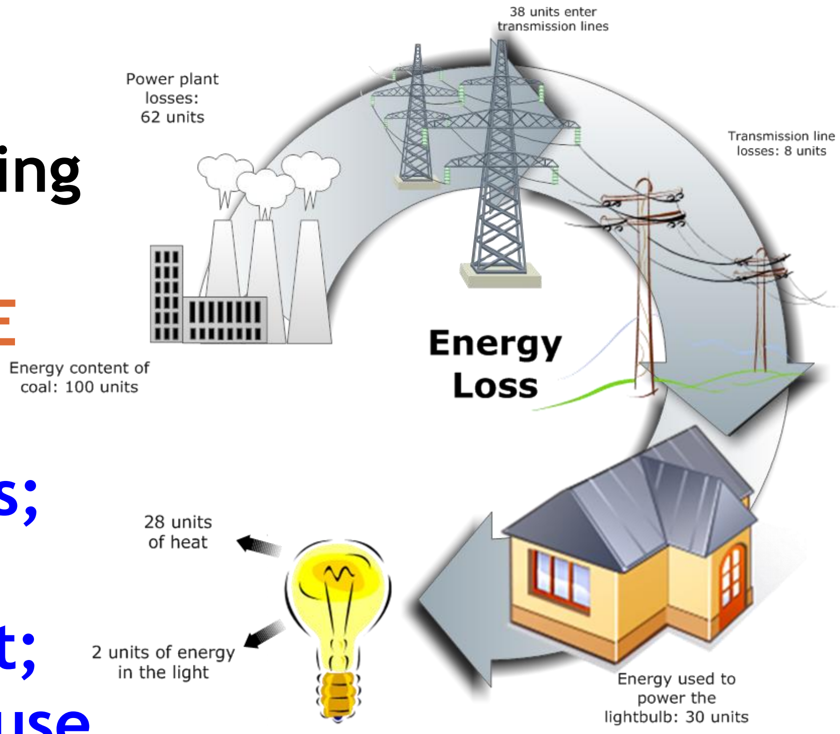
- Fuel cell performance is independent of power plant size. ***The efficiency does not deteriorate going from MW to kW to W size power plants***.
- *Fuel cells can scale up/scale down power output instantly, unlike fossil fuel generators, no need to size hybrid fuel cell generators for very short term intermediate current demands.*
- **Fuel cells respond instantaneously to the power demand request.**
- **Consumers capacity benefit in terms of cost, reliability, high efficiency, and load response.**

HIGH EFFICIENCY AND CHP

- Efficiency can be very high (up to 40-70%) for the fuel cells with COGENERATION compared to the system efficiency of current power generation about 30-40%.
- Fuel cells can co-generate since hot water or steam is a by-product. *COMBINED HEAT & POWER—90+ Efficient*.
- Can reduce costly transmission lines and transmission losses for a distributed system. Move closer to point-of-use.
- No moving parts in fuel cells and a very few moving parts in the fuel cell power system so that it has HIGHER RELIABILITY compared to an internal combustion or gas turbine power plant.

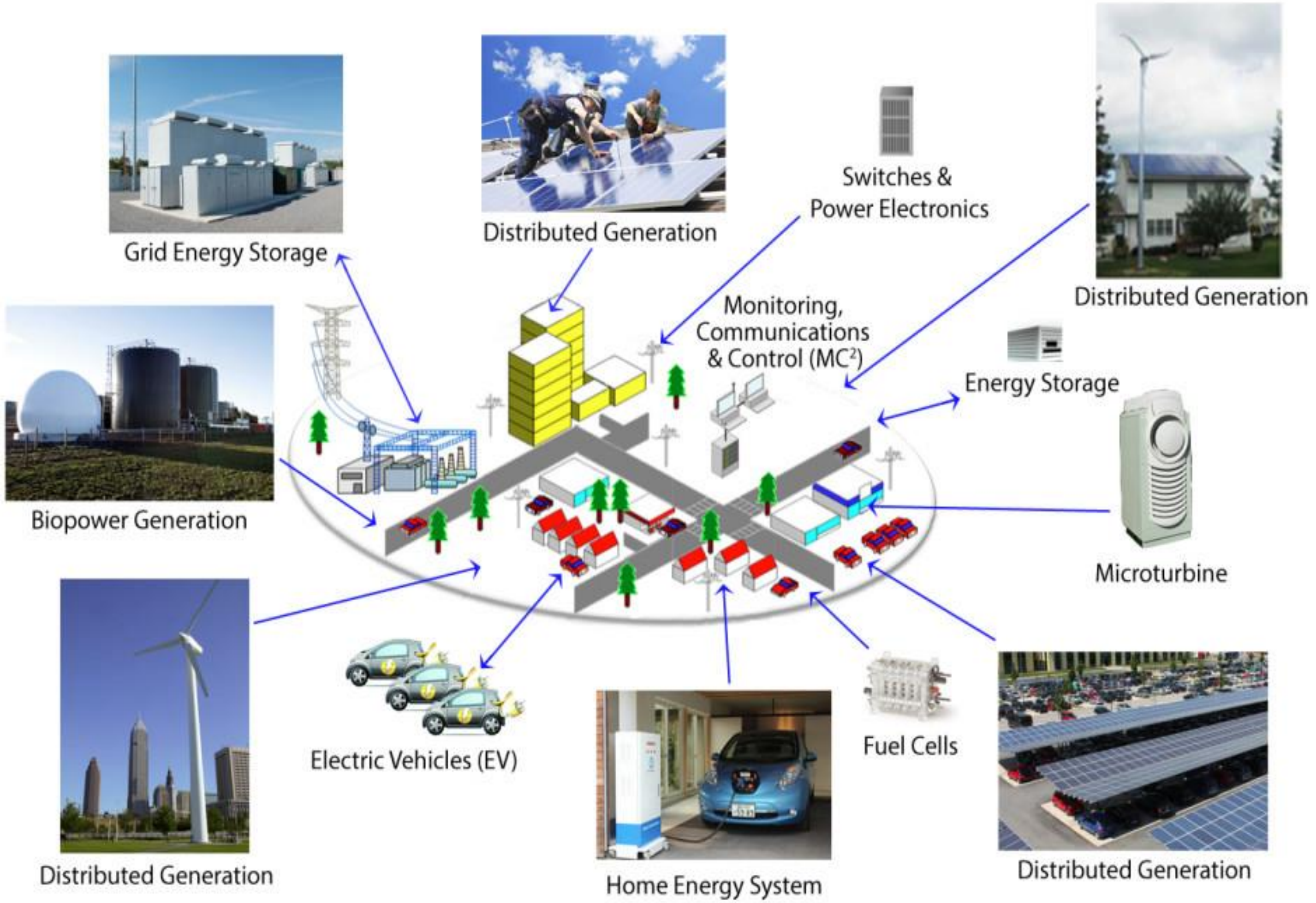
UNIQUE OPERATING CHARACTERISTICS: DISTRIBUTED GENERATION

- Fuel cells saves cost, quick response to central generating unit outages, VARIABLE DISTRIBUTION LINE VOLTAGE for multiple applications.
- Minimize transmission losses; Reduce requirement for auxiliary electric equipment; Ideal for "LOCAL" point-of-use *distributed power generation*.
- ***Fuel cells have an excellent part load heat rate and can respond to transmission loads.***



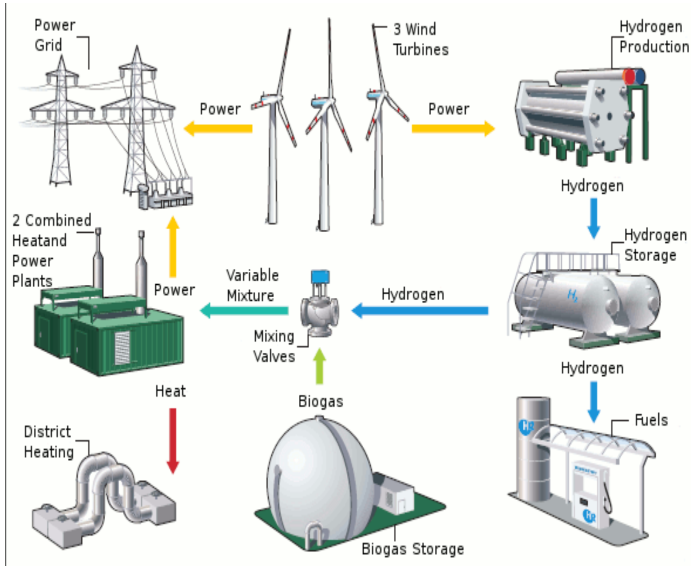
https://www.greentechmedia.com/articles/read/harveys-devastation-shows-the-need-for-distributed-energy-microgrids-during

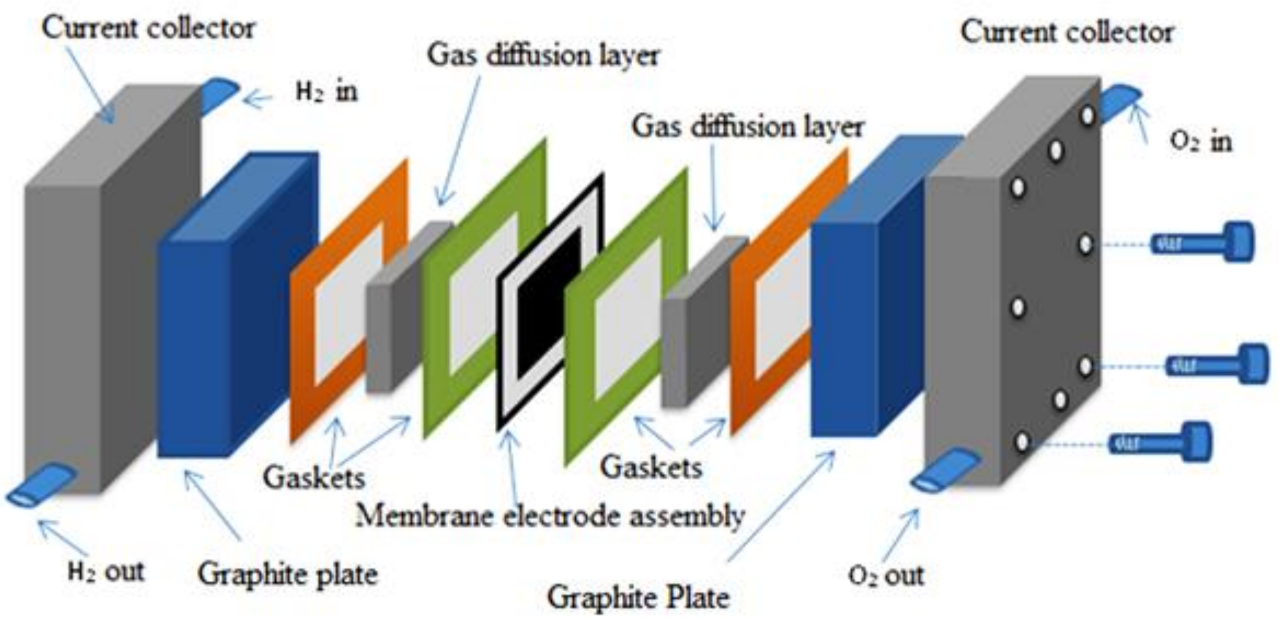
RURAL COMMUNITY MICRO GRIDS & SUSTAINABILITY CITIES



SUSTAINABLE CITIES MICRO-GRIDS

- Designed to operate detached from central grid and operates in ***"Island Mode", and reduces financial infrastructure stress for expanding central electrical grid.***
- Designed to connect to ***main central grid*** to obtain energy not economical to generate within micro-grid, and can ***store energy*** for future demands.
- Designed to connect to main central grid in demand response or ancillary services markets where regions receive ***monetary payments*** in exchange for distributed energy resources (***DER***) allocations.
- Community Micro-Grids are a key technology for ***Sustainable Cities*** and rely on ***DER's*** to achieve a more sustainable, secure, and cost effective energy system, while providing renewables-driven power backup for prioritized loads over indefinite durations.
- Community Micro-Grids leverages existing technology while integrating ***innovations*** in ***design, efficiency, and operations***.





TYPES OF FUEL CELLS

TYPES OF FUEL CELLS

- Proton exchange membrane fuel cells - PEMFC
  - PEM fuel cells are the most common type of fuel cell being developed for transportation use.
  - They operate at the one kW per liter of volumetric power level at a temperature under 90C.
  - PEM fuel cells react quickly to changes in electrical demand and will not leak or corrode.
  - PEM fuel cells use inexpensive manufacturing materials (plastic membrane—***perflorosulfonated*** acid polymer electrolyte).
- **Direct methanol fuel cells - DMFC**
  - Direct methanol fuel cells use methanol instead of hydrogen.
  - Operating temperatures of direct methanol fuel cells are in the same range as PEM fuel cells – 50 to 100°C (122 to 212°F).
  - Direct methanol fuel cells are being considered for use in the transportation industry.

TYPES OF FUEL CELLS

- Alkaline fuel cells - AFC
  - Alkaline fuel cells were first used in the Gemini-Apollo space program to produce drinking water and electrical energy.
  - Operate on compressed HYDROGEN AND OXYGEN.
  - Alkaline fuel cells generally use a solution of ***potassium hydroxide*** (chemically, KOH) in water as their electrolyte (50-200C).
  - Output of alkaline fuel cell ranges from 300 watts (W) to 5 kilowatts (kW).
- Phosphoric acid fuel cells - PAFC
  - Phosphoric acid fuel cells use ***phosphoric acid*** as the electrolyte to make electricity.
  - Efficiency ranges from 40 to 80 percent and operating temperature is 150 to 200° C (about 300 to 400°F).
  - Existing phosphoric acid cells have outputs up to 200 kW, and 11 MW units have been tested.

TYPES OF FUEL CELLS

- Molten carbonate fuel cells - MCFC
  - Molten carbonate fuel cells use a liquid solution of lithium, sodium, and/or potassium carbonates soaked in a ceramic matrix (LiALO2).
  - Units with output up to 2 megawatts (MW) have been constructed, and designs exist for units up to 100 MW.
  - The nickel electrode-catalysts of molten carbonate fuel cells are inexpensive compared to those used in other cells, but the high temperature (600-700C) also limits the materials and safe uses of MCFCs.

- Solid oxide fuel cells - SOFC
  - Solid oxide fuel cells use a solid, nonporous metal oxide as electrolyte (YSZ).
  - Output for solid oxide fuel cells is up to 100 kW.
  - Reformer is not required to extract hydrogen from the fuel due to high temperature (600-1000C).

Summary of Major Differences of Fuel Cell Types

	(a) PEMFC	(b) AFC	(c) PAFC	(d) MCFC	(e) SOFC
Transportation Application	Automotive power	Space vehicles, Apollo, Shuttle	Large vehicle power		Vehicle auxiliary power; Heavy vehicle propulsion
Other Applications	Portable power Small-scale stationary power		On-site cogeneration, Electrical power generation (200 kW)	On-site cogeneration, Electrical power generation, up to MW	On-site cogeneration, Electrical power generation, 2kW to multi MW
Electrolyte	Polymer (plastic) membrane (Nafion/Dow) Protons mobile, Electrolyte immobile	Solution of concentrated (30-50%) KOH in water	Liquid concentrated 100% phosphoric acid	Hot and Corrosive Liquid Molten Carbonate ($Li_2CO_3/Na_2CO_3/Na_2CO_3$) retained in a ceramic matrix of $LiAlO_2$	Solid Oxide Ceramic –Yttrium-stabilized Zirkondioxide (ZrO_2/Y_2O_3)
Operating Temperature Range	50-100°C	50-200°C	150-220°C	600-700°C	600-1000°C
Charge Carrier through Electrolyte	H^+	OH^-	H^+	$CO_3^=$	$O^=$
Prime Cell Components	Carbon-based	Carbon-based	Graphite-based	Stainless Steel	Ceramic
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites
Primary Fuel on the Anode Side	H_2	H_2	H_2	H_2, CO, CH_4	H_2, CO

Summary of Major Differences of Fuel Cell Types

Continued

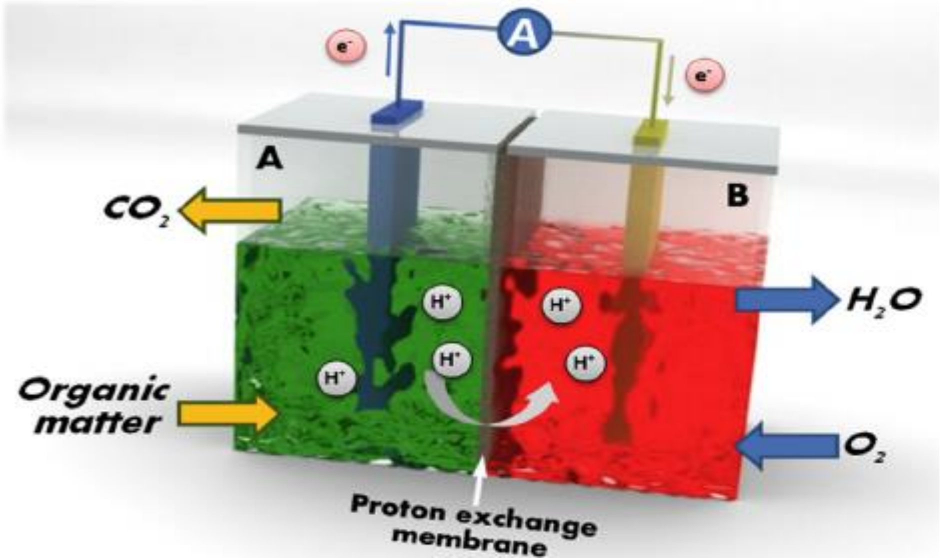
	(a) PEMFC	(b)AFC	(c) PAFC	(d) MCFC	(e) SOFC
Product Water Management	Evaporative	Evaporative	Evaporative	Gaseous Product	Gaseous Product
Product Heat Management	Process Gas + Independent Cooling Medium	Process Gas + Electrolyte Calculation	Process Gas + Independent Cooling Medium	Internal Reforming + Process Gas	Internal Reforming + Process Gas
Start-up Time	Second-minutes		Hours	Hours	Hours
Power Density [kW/m^2 of Active Cell Area]	3.8 – 6.5	~ 1	0.8 – 1.9	1.5 – 2.6	0.1 - 1.5
Fuel Cell Efficiency	50-60%	50-60%	55%	55-65%	60-65%
Reformer	External	External	External	Internal or External	Internal or External
Status of Development	Demonstration systems up to 50 kW 250 kW units expected in next few years	Due to CO_2 poisoning, there is very little develop-ment going on	Most commercial systems operating at 200 kW; An 11 MW model has been tested	Demonstration systems up to 100 kW	Demonstration systems up to 2 MW
Technical Challenges	<u>Lower Costs</u> Catalyst & Electrolyte <u>Improve Performance</u> High temperature CO tolerance High current density	<u>Lower Costs</u> CO_2 removal both from the H_2 and air streams	<u>Lower Costs</u> Catalyst & Bi-polar plate; Improve perform; High power density; Corrosion resistant materials	<u>Lower Costs</u> Bi-polar plate Production High cost elements	<u>Improve Performance</u> Electrolyte leakage Structural stability and composition Sulfur tolerance Bi-polar plate corrosion

ELECTROCHEMICAL REACTIONS

Fuel Cell	Anode Reaction	Cathode Reaction	Overall Reaction
Alkaline Fuel Cells	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$
Polymer Electro-lyte Fuel Cells	$H_2 \rightarrow 2 H^+ + 2e^-$	$\frac{1}{2} O_2 + 2 H^+ + 2e^- \rightarrow H_2O$	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$
Phosphoric Acid Fuel Cells	$H_2 \rightarrow 2 H^+ + 2e^-$	$\frac{1}{2} O_2 + 2 H^+ + 2e^- \rightarrow H_2O$	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$
Molten Carbonate Fuel Cells	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ $CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^-$	$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$
Solid Oxide Fuel Cells	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$ $CO + O^{2-} \rightarrow CO_2 + 2e^-$ $CH_4 + 4 O^{2-} \rightarrow 2 H_2O + CO_2 + 8e^-$	$\frac{1}{2} O_2 + 2e^- \rightarrow O^{2-}$	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

BIOLOGICAL FUEL CELLS

- Biological fuel cells use ENZYMES, instead of CHEMICAL CATALYSTS such as Pt, Ni, etc., to promote the electrode reactions.
- They replicate nature in the way that energy is derived from organic fuels.
- The power density of such fuel cell is quite low.
- A typical example is the alcohol fuel cell being developed by St. Louis University.
- These fuel cells are far away from any commercial applications.



FUEL CELL APPLICATIONS: STATIONARY POWER FUEL CELL SYSTEMS

- Stationary Power Applications
- High power for industrial applications
- Medium and low power for domestic applications
- Electricity for remote places to cut down the transmission cost of 60% (marine beacons, railway signals, remote telephone exchanges, isolated lighting, radio transmission, etc.)
  - *DISTRIBUTED GENERATION (Puerto Rico)*
- Large scale energy storage (electrolysis of water,…)
  - *NUCLEAR POWER/WIND/SOLAR*