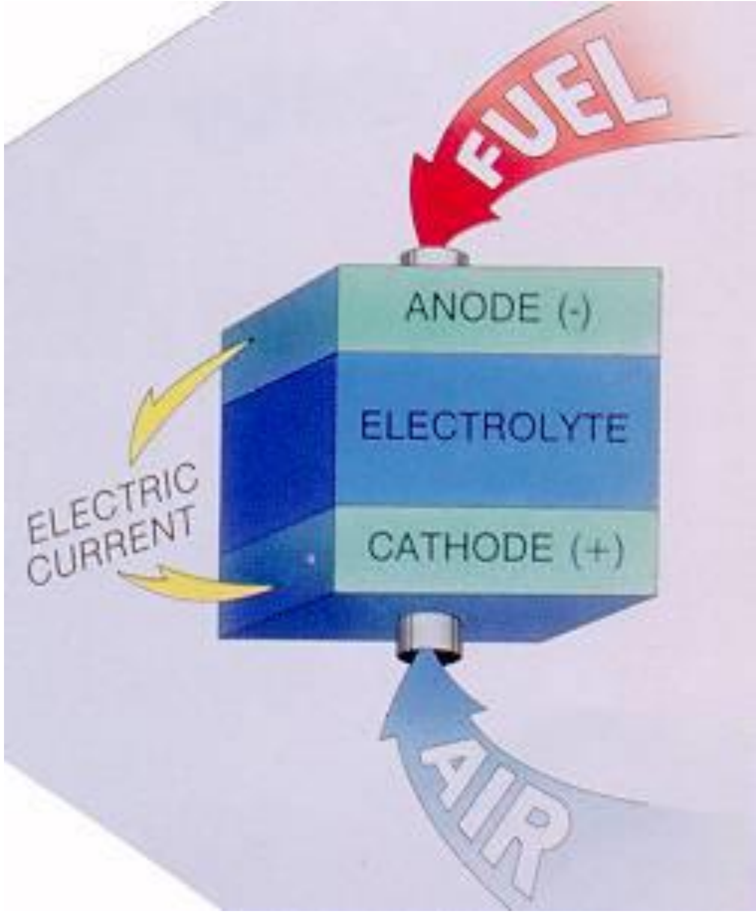
FUEL CELLS



Fuel Cell: an electrochemical device, closely related to the battery, that can generate electricity from hydrogen, which in turn can be extracted from natural gas or other hydrocarbon gases through a chemical process called reforming.

Topics – Fuel Cells

- Fuel Cells, Its Uses and History
- Fuel Cell Principle, Characteristics, Operating Conditions
- Fuel Cell Concept for Power, Heat & Water
- Balance of Plant Equipment
- Fuel Cell Process Diagram, Hydrogen Gas Reformation
- Types of Fuel Cells (AFC, PAFC, PEM, MCFC, SOFC)
- Advanced Fuel Cell Technologies (CHP, Hybrid FC-GT-IGCC)
- Cost of Fuel Cells
- Fuel Cell Applications, Advantages
- Environmental Impact & Risks

History of Fuel Cell

- **Hydrolysis –** if an electrical voltage is applied to water by placing two electrodes into the liquid and attaching a battery to them, the voltage induces a chemical reaction: hydrogen is produced at one electrode and oxygen at the other
- **1839 – Sir William Grove** observed that the process known as “hydrolysis” can also go backwards – hydrogen will react at one electrode and oxygen at the other producing water and an electrical voltage between the electrodes. It was only a century later that **Francis Bacon** began to develop practical fuel cells.
- **1950s –** Pratt and Whitney (now United Technologies) licensed Bacon’s technology and developed it for the US space program. The Gemini, Apollo and space shuttle program all used fuel cells to generate electricity and produce drinking water on-board by just bringing hydrogen fuel and oxygen with them.

Fuel Cell Principle

- If an electrical voltage is applied on water, by placing two electrodes into the liquid and attaching a DC battery to them, the voltage induces a chemical reaction; hydrogen and oxygen is produced at each electrode:

  H_2O + DC voltage ➔ H_2 + O_2

- In 1839, Sir William Grove observed this process, known as **hydrolysis**, can also go backwards – reversible. Hydrogen will react at one electrode and oxygen at the other, producing water and DC electrical voltage between the electrodes.
- During **reverse hydrolysis**, hydrogen would act at one electrode and oxygen at the other, producing water, heat and electrical voltage (DC) between the electrodes.
- **Fuel (H_2) + O_2 + platinum catalyst ➔ H_20 + DC voltage**

Fuel Cell Characteristics

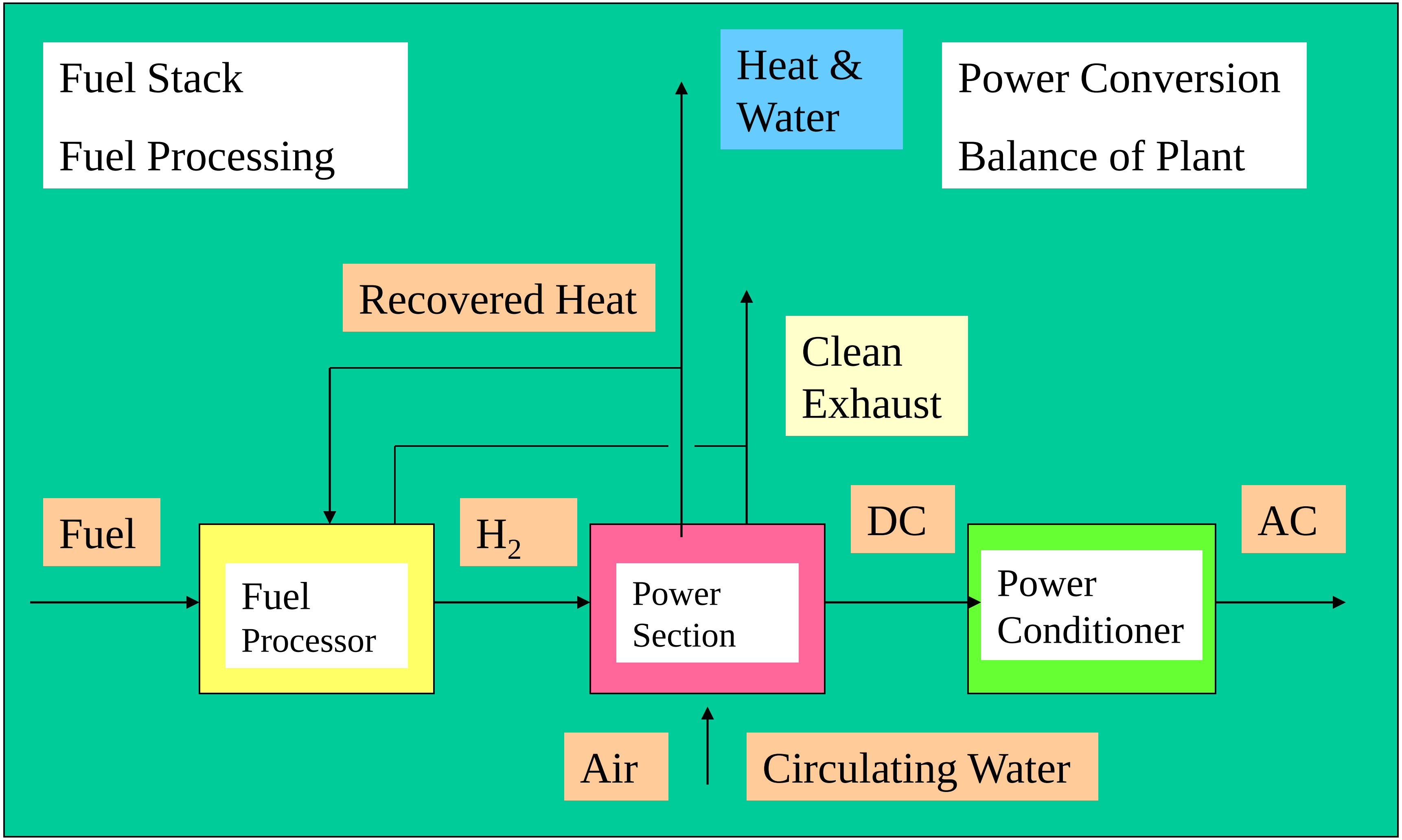
- **Operates as a continuous battery – continuous fueling**
- **Never needs recharging**
- **Based on reverse hydrolysis – converts hydrogen and oxygen into water and electricity**
- **Current depends on electrode area**
- **Voltage depends on materials of construction, typically less than 1 volt.**

Fuel Cell Operating Conditions

Type of Fuel Cell	Electrolyte	Operating Temp., C	Fuel	Overall Efficiency, %	Power Range Applications
Alkaline (AFC)	KOH	50-100	Pure H_2	40-60	Aerospace
Proton PEM	Solid polymer (Nafion)	50-100	Pure H_2 tolerates CO_2	35 (45)	Automotive, CHP (5-250 kW) portable
Acid (PAFC)	Phosphoric Acid	~ 220	Pure H_2 tol. CO_2, 1% CO	< 45	CHP (200 kW)
Molten Carbonate	Lithium & Potassium	~ 650	H_2, CO, CH_4, etc. tol. CO_2	47 (60)	200 kW-2 MW CHP, stand alone
Solid Oxide	Stabilized Zirconia	~ 1000	H_2, CO, CH_4, etc. tol. CO_2	47 (65)	2-1000 kW, CHP stand alone

Renewable Energy World, "Renewable Fuel Cell Power from Biogas", Nov-Dec 2001

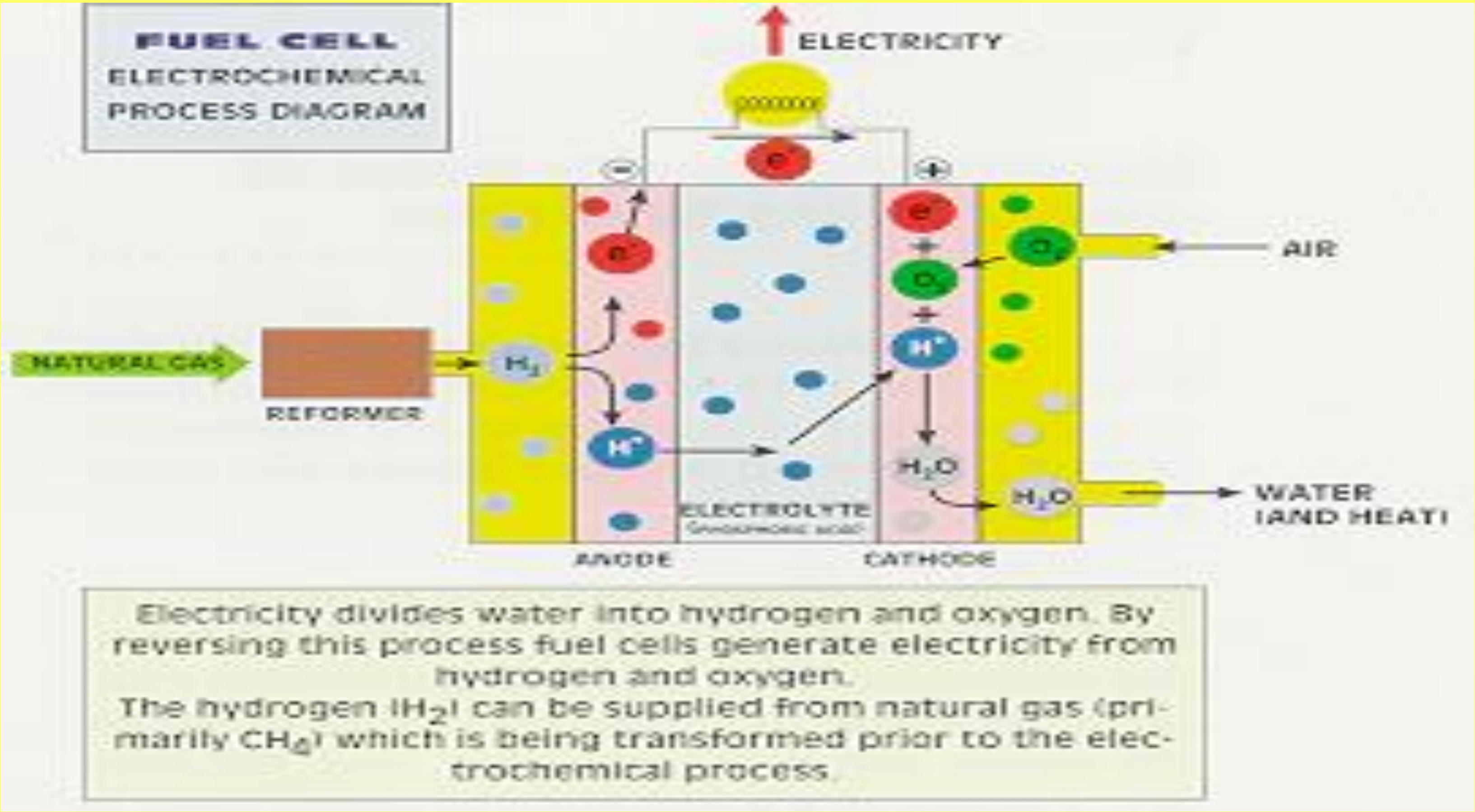
Fuel Cell Concept for Power, Heat & Drinking Water



Balance of Plant Equipment

- Power-conditioning equipment needed are expensive
- Fuel processing comprises a large part of cost and project development.
- The front-end processing and fuel cell technology is affected by the fuel and application:
  - Hydrogen
  - Natural gas
  - Methanol
  - Gasoline
  - Biomass
  - Coal

Fuel Cell Process Diagram



Hydrocarbon Gas Reformation

- Simplest fuel cell "burns" hydrogen and oxygen in order to generate power, but hydrogen is not readily available. Through the **reforming process**, however, hydrocarbon gases such as natural gas or producer gas from biomass can be converted into a mixture of hydrogen [H_2] and carbon dioxide [CO_2].
- At low temperature, gas reforming is carried out only using expensive rare metal **catalyst**. At high temperatures, however, the reaction can proceed without this catalyst.
- The reforming process produces some **carbon monoxide** [CO] which can **poison the electrodes** in low temperature cells. At higher temperatures, the electrodes become more tolerant of CO impurity, and some high temperature fuel cells utilize CO as fuel.
- Fuel cells **produce the same amount of CO_2** as it extracts H_2 from the hydrocarbon fuel, though at a **lower rate because of its higher thermal efficiency** for each kWh of power generated.

Types of Fuel Cells

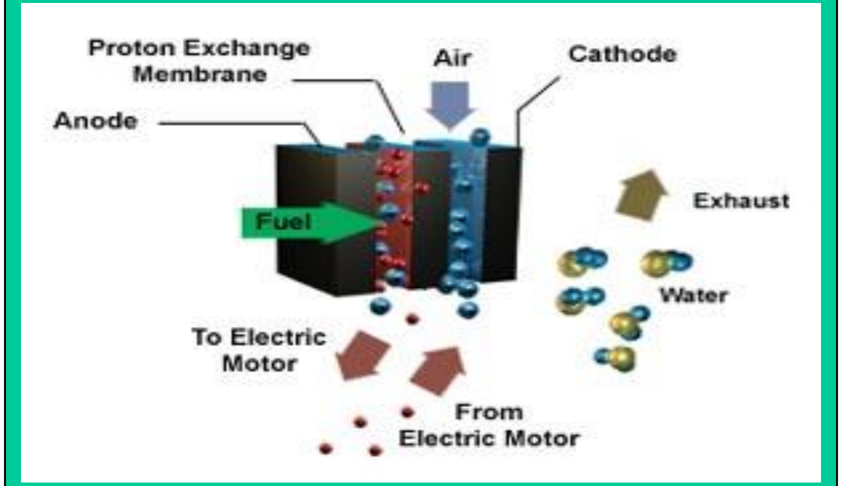
- **Low temperature cells –** The most advanced is the **phosphoric acid** fuel cell and are already in commercial operation. The other one is **proton exchange membrane (PEM)** fuel cell (also **polymer** fuel cell).
- **High temperature cells –** The **molten carbonate** fuel cell operates at around 650 C, imposes severe demands on materials, not yet in commercial use, but a large pilot scale project has been operated in California. The **solid oxide** fuel cell requires the highest temperature of all at 1000 C, contains no liquids, offers the greatest potential for future power generation.
- Some literature mention **direct methanol (DMFC)** fuel cell. It is a type of PEM cell.

Phosphoric Acid Fuel Cell (PAFC)

PAFC uses an electrolyte of concentrated phosphoric acid (H_3PO_4) operating at 150-200 C and could tolerate up to 1.5% CO. It uses natural gas or propane as source of H_2.

PAFC was the first fuel cell to achieve commercial status where 40-kW units were field tested late 1980s and early 1990s. A 200- kW unit costing $850,000 with an electrical efficiency of 36% was later developed by ONSI Corporation, a JV between Toshiba and United Technologies. Used in buses (no emission, low noise) with a fleet reliability of 96%. Needs replacement every 5 years. Costs $1,500-3,000/kW.

Proton Exchange Membrane (PEM)



PEM fuel cell uses a polymer membrane as its electrolyte, contains water, operates up to 100 C, low tolerance to CO. Can be started quickly, good for peak and emergency power, slightly lower efficiency than PAFCs.

Developed by General Electric, the early PEM fuel cells were used in the Gemini space programme, had limited life. Ballard Power Systems of Canada is the commercial leader in PEM, has high energy density, attractive to automotive industry (Daimler Benz). Ballard Generating Systems developed a 250-kW power generating prototype in 1997 with efficiency of 40%. Costs less than $1,000/kW.

Molten Carbonate Fuel Cell (MCFC)

MCFC fuel cell has an electrolyte composed of carbonates that are solid at room temperature, but become liquid at 650 C, making reaction between H2 and O_2 efficient, tolerant and "burns" CO.

An EPRI demonstration project has operated a 2-MW plant for over 4,000 hours in Santa Clara, California. It is more efficient than PAFC (> 36%) and likely best suited in the 1-20 MW range. Costs may be lowered to around $1,500/kW, still too high compared with conventional power generation, but might be attractive in niche markets requiring low noise and low emissions.

Solid Oxide Fuel Cells (SOFC)

SOFC is a true solid fuel cell and contains no liquid components. Electrolyte used is a ceramic material called zirconium oxide, stabilized with yttrium oxide. To have good conductivity, it is heated to 1000 C and has efficiency of 50%. Temp could be lowered to 800 C.

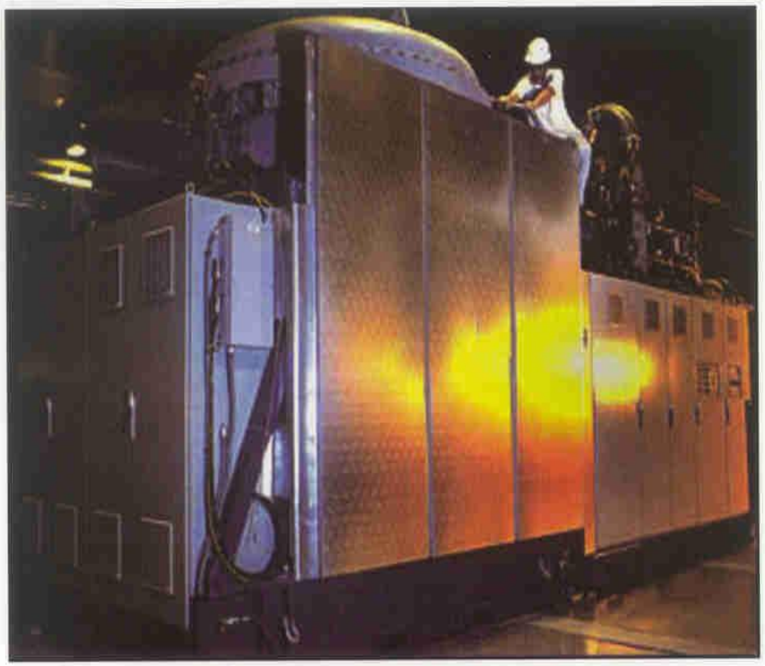
Waste heat can be used in a cogeneration system or in a GT, known as SOFC-GT, to raise efficiency from 60-70%. SOFC can be operated under pressure of 15 atmospheres to improve performance and integrate with a GT, permitting the highest possible energy to electricity conversion efficiencies. Westinghouse built a 100-kW pilot plant in the Netherlands. A more cost-effective 250-MW SOFC-GT combined cycle plant is being planned. Costs from $1,000-1,500/kW for plants in 1-5 MW.

Advanced Fuel Cell Technologies

- **Fuels cells as CHP units –** when H_2 and O_2 combines to produce electricity and the CO is likewise burned to keep the proper operating temperature, a great deal of heat is wasted that could be recovered from this electrochemical cycle. Nominal capacity range are: PEM 5 - 250 kW, PAFC 200 kW, MCFC 200 kW – 2 MW and SOFC 2 - 1,000 kW.

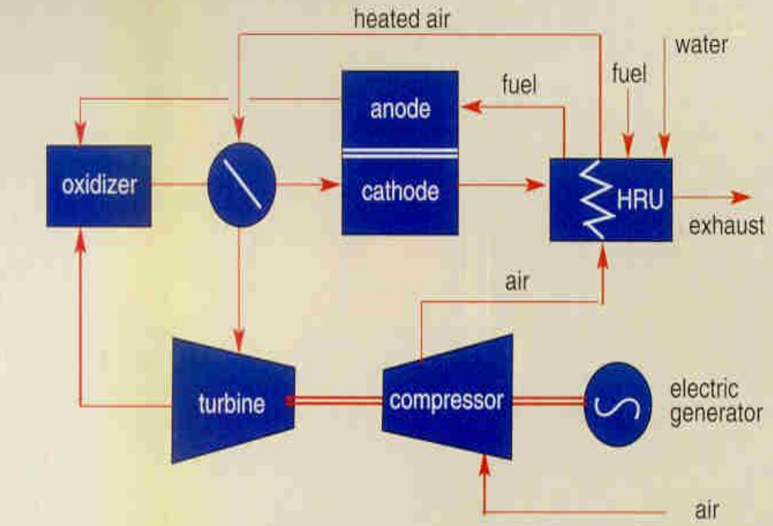
- **Fuel cell-gas turbine and IGCC hybrids –** achieves 50-58% or even 60% net efficiencies (LHV) by combining the fuel cell to electro-chemically generate power from H_2 and O_2 and using the exhaust to drive turbine. Fuel derived from gasification of coal or biomass is used by the fuel cell.

Fuel Cell-IGCC Hybrid



Tubular solid oxide hybrid. This 225-kW hybrid system on test at the University of California is designed around Siemens Westinghouse fuel cells and Ingersoll Rand microturbine which runs off the 850 C exhaust temperature of the fuel cell module.

Hybrid direct fuel cell system. Compressed air is heated by the waste heat recovery unit (HRU), expanded through the gas turbine power section, and then used as the fuel cell oxidant. Cathode exhaust is used for fuel preheat and water vaporization; anode exhaust is used for cathode air preheat.



Coal or biomass is gasified to H_2 and CO and fed to HRU. Compressed air is heated by HRU, expanded thru gas turbine, and then used as fuel cell oxidant. Cathode exhaust is used to fuel preheat and water vaporization. Anode exhaust is used for cathode air preheat.

Fuel Cell Costs

Fuels cells are only just entering the commercial market place and its costs are at best tentative: O&M costs for fuel cell power plants should be comparable or lower than conventional gas-fired power plants. But generating costs will depend on the plant lifetime, and that remains unknown as yet.

(1996 $)	Capital $/kW	Fixed $/kW/yr	Variable $/kWh	LEC c/kWh
PAFC 200kW-1MW	3,000			8.4-9.9
PEM 5-250kW	500-1,000			
MCFC	1,440	0.144	0.200	9.9-15.2
MCFC 1-20MW	1,500-3,000			
SOFC 1-5MW	1,000-1,500			

Fuel Cell Applications

Type of Fuel Cell	Electrolyte	Operating Temp., C	Overall Efficiency, %	Uses
PEM	Polymer	50	50-60	Vehicles
Direct Methanol	Polymer	100		Vehicles
Alkaline	Potassium Hydroxide	80	Low	Space Program
Acid	Phosphoric Acid	200	80	Back-Up Power
Molten Carbonate	Alkali Carbonates	650	75-80	Power Plants
Solid Oxide	Stabilized Zirconia	1000	75-80	Power Plants
SOURCE: Richard Rocheleau, Hawaii Natural Energy Institute				

Advantages of Fuel Cells

- Suitable in urban areas and small efficient units can be placed adjacent to buildings where waste heat generated by the plant can be used for heating and hot water (**cogeneration**).
- The water from the fuel cell is pure enough to drink.
- Utilities can utilize fuel cells to boost power at both ends of the transmission lines (**distributed generation**)

Environmental Impact of Fuel Cells

- Fuel cells are probably the **most benign** of all power generation technologies that use fossil fuels.

- The levels of both CO_2, SO_2, NO_X and particulate **emissions are extremely low**, aside from low noise compared to conventional methods for generating power.

- Thermal efficiencies are higher, so that emissions of CO_2, SO_2, NO_X and particulates are **lower per kWh** of power produced.

Risks Associated with Fuel Cells

- In small sizes, phosphoric acid fuel cells are compact, off-the-shelf power and combined heat & power (CHP) units. Very *long-term performance has still to be demonstrated*, but over the medium term (< 5 years), these units look both efficient and reliable. Based on environmental grounds, the risk attached to the investment in such generating units would appear to be *low*.
- The less well-developed technologies have yet to prove themselves in commercial environments and cannot yet be considered for practical applications; *high risk*
- In the near future, the PEMs and SOFCs look likely to offer attractive commercial investments, especially once proven in their commercial operations; *medium risk*