
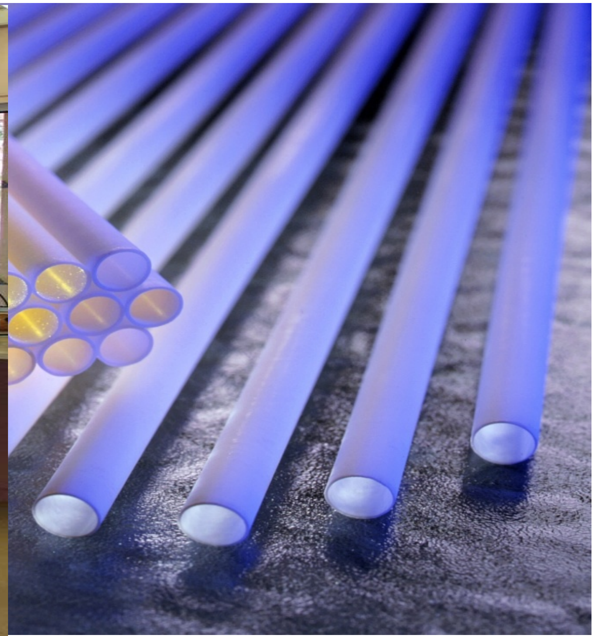

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The Direct Carbon Fuel Cell - a Super Clean Coal Combustion Technology

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CSIRO Energy Technology

All Energy 2009

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Fuel Sources and Lifetime

(Based on current and forecast consumption rates)

Energy Source	Reserves	Life Expectancy*
Coal	1000 billion tons	>200Year
NG	173 trillion m^3	~ 50 Years
Oil	1.0 trillion barrels + (~1 trillion unproven)	~ 30-40 Years
Nuclear	Once through fuel cycle Fast breeder reactor / fuel recycling	85 years 5000-6000 Years
Renewable Energy	More than 10 times the current energy consumption	Unlimited

Global Primary Energy Consumption / Y = 135.4 Trillion (10^{12}) KWh **(27% Coal)**.

Global Electricity Consumption / Y = 17Trillion kWh in 2005 (40% from Coal).

Global Electricity Production Capacity: 2000GW in 2008, forecast to grow to 3800GW in 2030. RE accounts for 19% (85% of this is Hydro)

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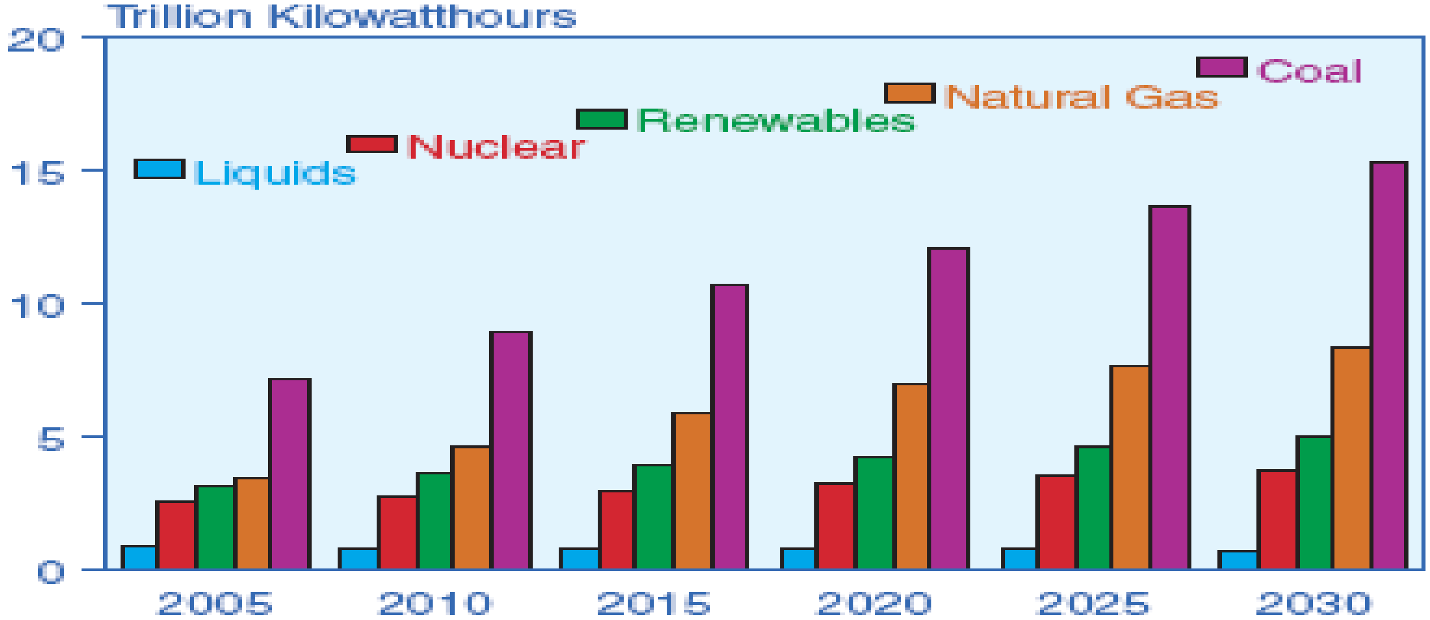
World Electricity Generation by Fuel
(2005 to 2030) - EIA, USA

85% of global energy consumption is provided by fossil fuels



Coal represents 70% of Global fossil fuel resources.

Coal is a major source for electricity production and is forecast to remain so in the future energy mix

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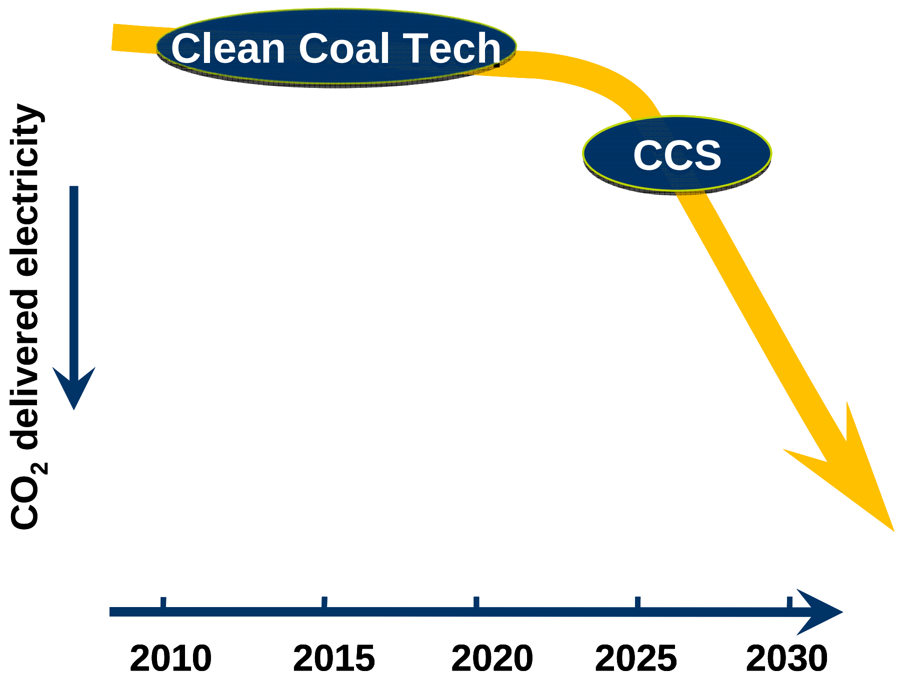
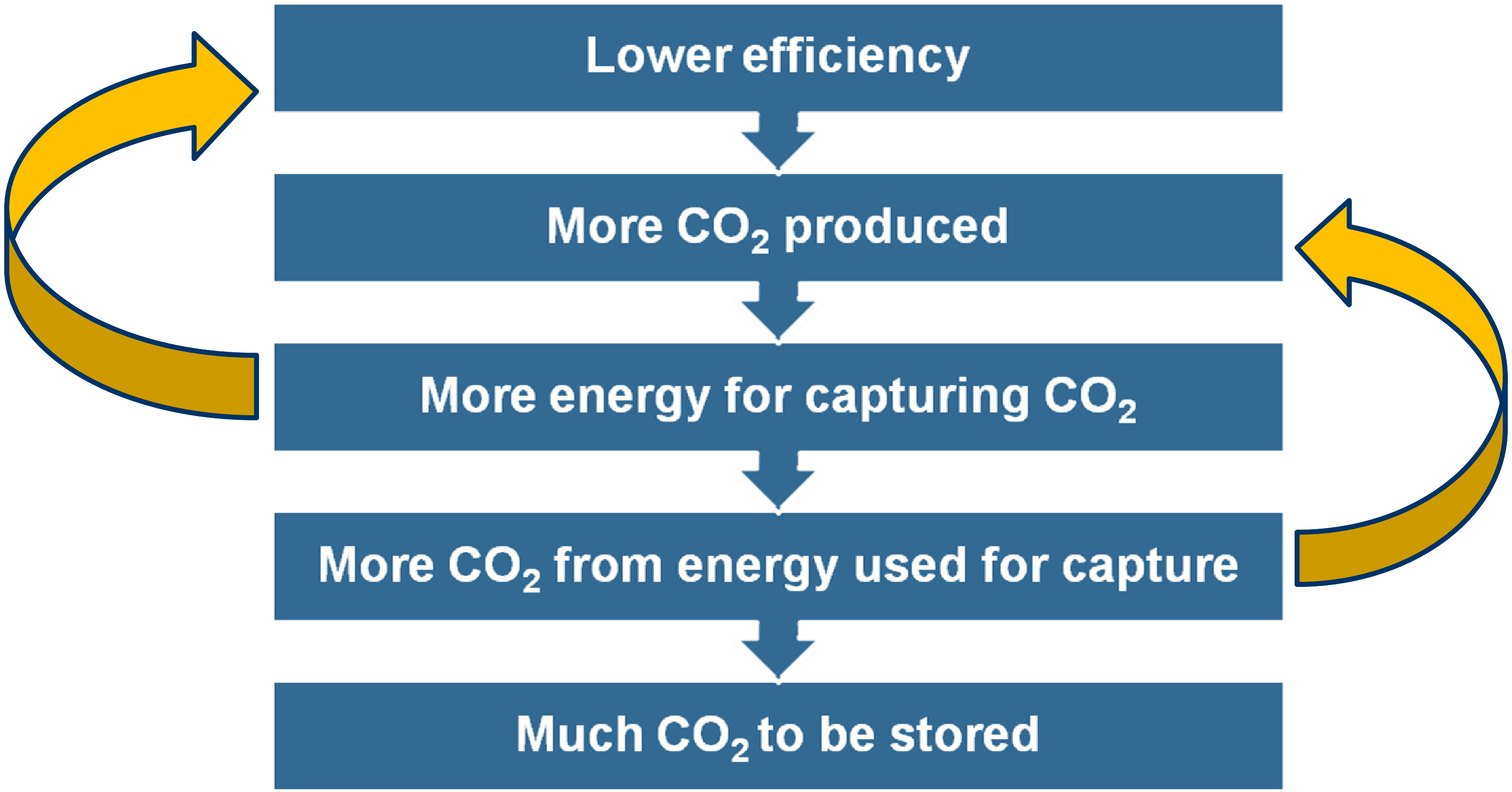
Current approach to reduce CO_2 emissions

- Limited reduction in CO_2 through efficiency … so the focus is on reducing the cost of new plants with CO_2 capture and storage
- Technologies are (38-45% efficiency):
- PC/USC
- PC/Oxy/USC
- IGCC



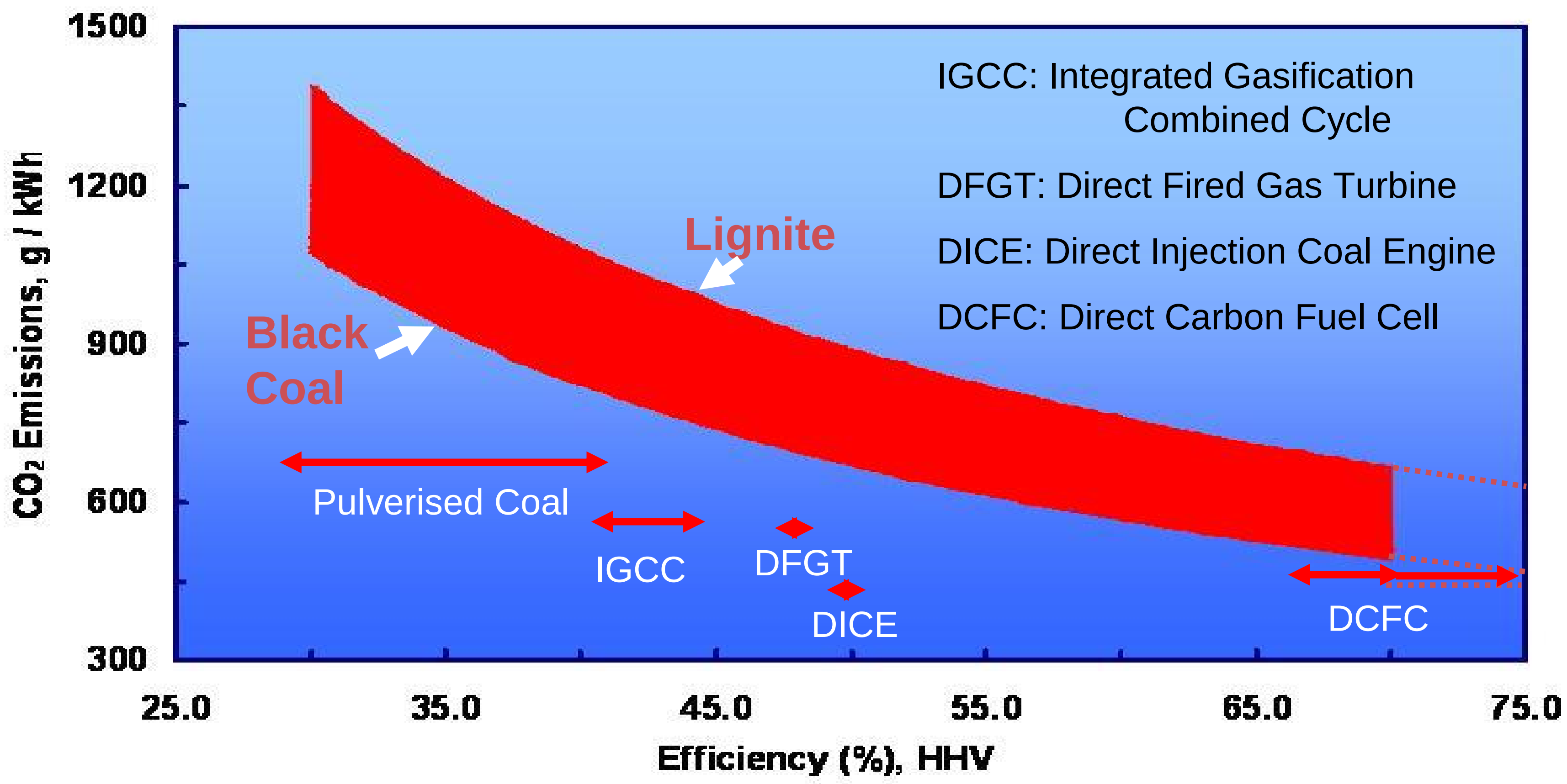
What happens if large scale CO_2 capture and storage is not so successful ??

Efficiency with capture – a vicious circle



Can we do better with coal?

Low Emission Electricity from Coal



DCFC – Holy Grail of Carbon Combustion

- Most efficient conversion of fuel energy to electricity is via fuel cells.
- Coal could achieve a step increase in electric efficiency to over 70% using Direct carbon fuel cell (DCFC).
- No other technology can offer such a high efficiency for power generation from coal.

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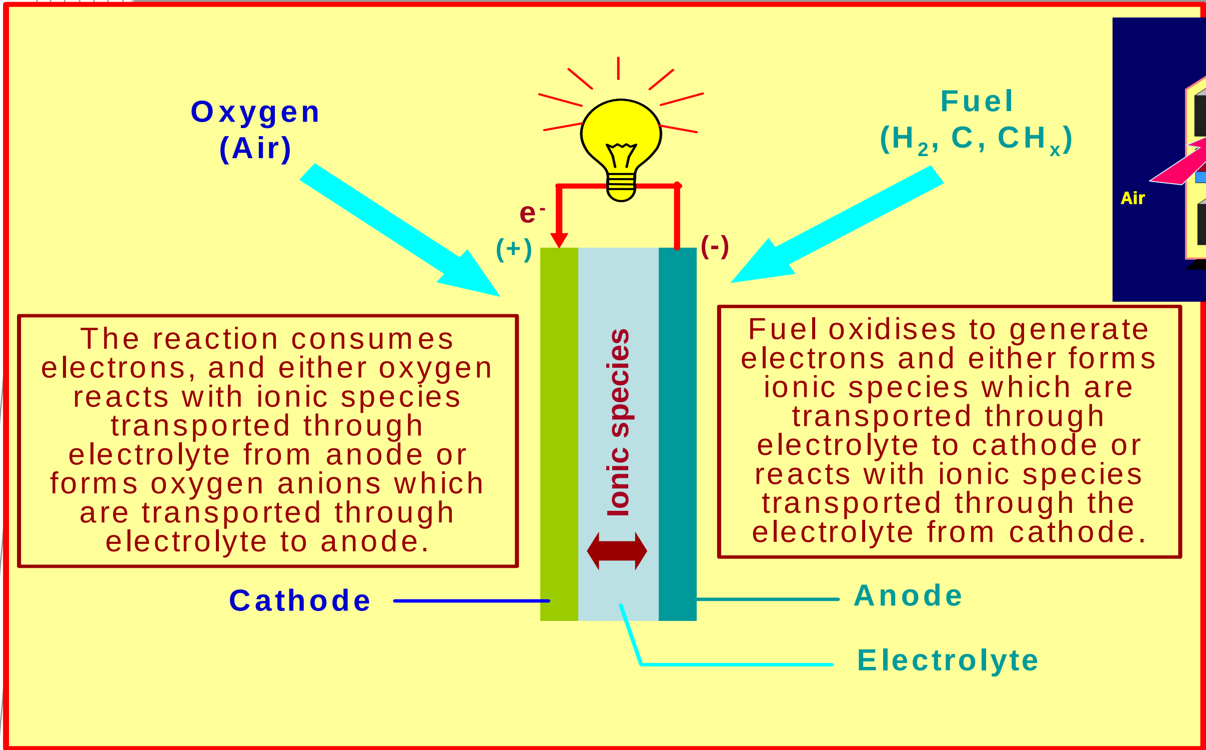
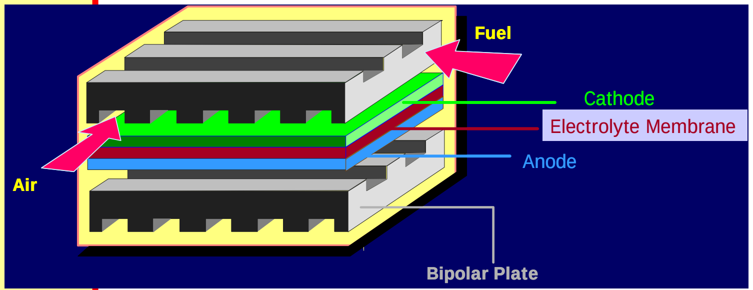
How a Fuel Cell Operate?





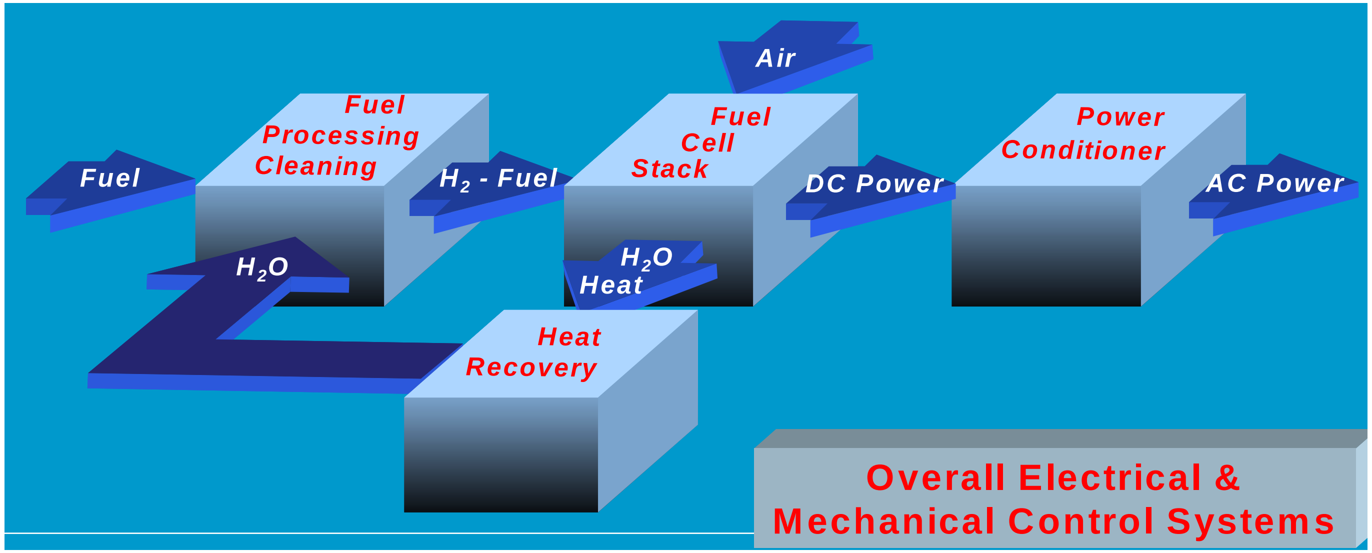
By product:

Water or Water / CO_2

Fuel cell is an electrochemical device like a battery which generates electricity continuously by harnessing the energy content of the fuel through its electrochemical oxidation. No direct combustion is involved.

Advantages of Fuel Cell Technology

- Combined heat and power (CHP) generation at demand centres thus minimising transmission/distribution costs & losses.
- High efficiency.
- Low greenhouse gas, pollutant and particulate emissions.
- High quality premium power free of spikes & simple balance of plant (BOP).



Fuel Cell Applications

- **Distributed Energy:** Co-gen. of heat & electricity in office buildings, hospitals, apartment complexes, etc.
- **Large scale power generation**
- **Residential Power**
- **Transport**
- **Others: Portable, Premium and Back-up Power**

Different Types of Fuel Cells

Low Temperature (Ambient to 220ºC)

- Alkaline Fuel Cell (AFC)
- Direct Methanol Fuel Cell (DMFC)
- Polymer Electrolyte Membrane Fuel Cell (PEMFC)
- Regenerative – can be reversed to produce H_2 + O_2 from water
- Phosphoric Acid Fuel Cell (PAFC)

High Temperature (600 – 1000ºC)

- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)
- Direct Carbon Fuel Cell (DCFC)

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Fuels for Most Fuel Cells

- Most fuel cells use gaseous fuels (H_2 / CO) with some exceptions (methanol or ethanol for portable power generation).
- Other fuels such as NG, LPG, Kerosene, Naphtha, etc. can be used with up-front fuel processing to generate hydrogen and CO.
- Hydrogen generated with renewable / nuclear / fossil energy sources.
- For central or large scale power plants, coal or biomass gasification to produce H_2 or H_2 + CO is also an option.

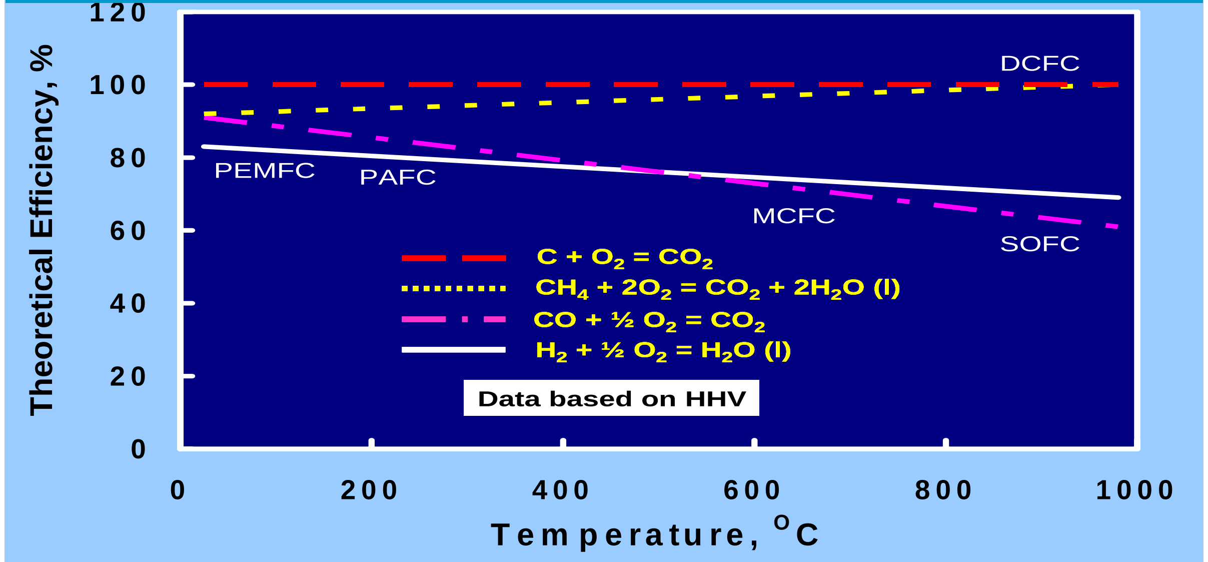
Direct Carbon Fuel Cells (DCFC)

- A DCFC converts the chemical energy in **solid carbon** into electricity through its direct electrochemical oxidation (600-900ºC).
- Fuel utilisation (F_u) almost 100% (fuel feed and product gas CO_2 are distinct phases – fuel can be separated & recycled) – 80-85% for most other fuel cells.
- 100% theoretical efficiency ($\Delta G = \Delta H$). it varies with operating Temp for other fuel cells.

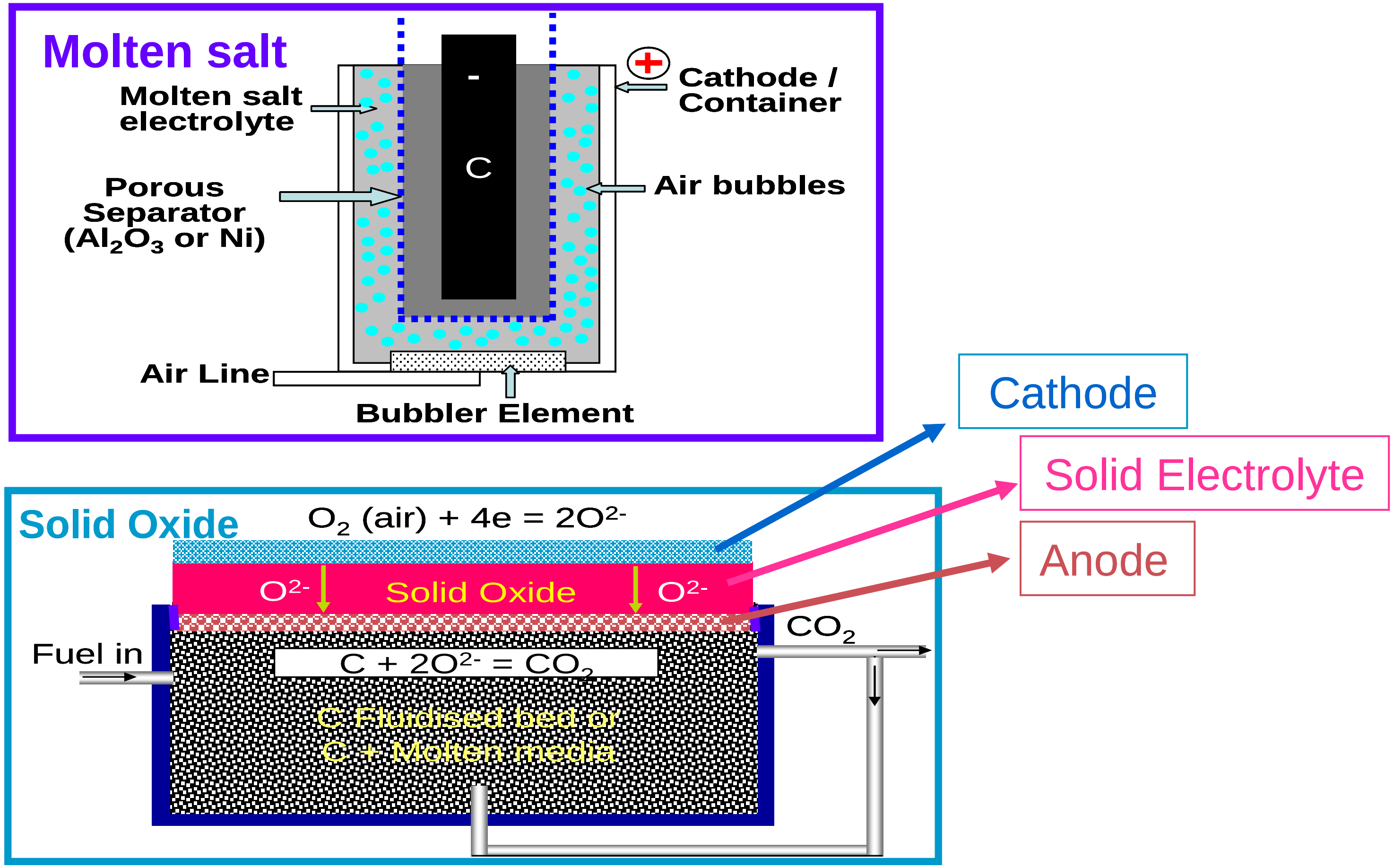
Electric Efficiency = Th_{eff} x F_u x V_{eff}

It is projected to be >70% for DCFC.

The effi. of fuel cells & fuel reactions as a function of operating temperature



How a DCFC Operate

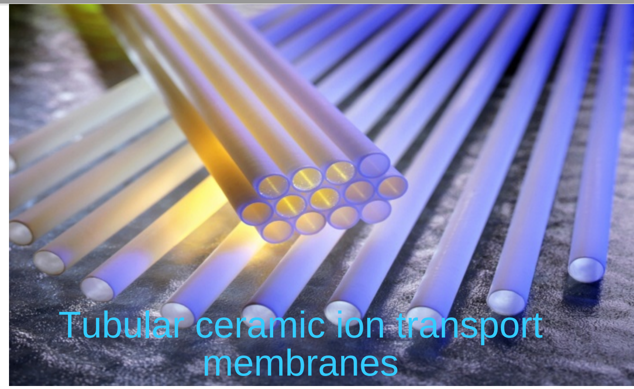


Other Benefits of Direct Carbon Fuel Cells

- With electric efficiency double that of a typical coal fired plant – the amount of CO_2 for storage/ sequestration would be halved.
- By-product is pure CO_2, no gas separation is required (cost & energy savings).
- In coal fired power plants CO_2 capture can result in ~20-25% energy penalty further increasing the amount of CO_2 to be captured & stored per unit net electricity delivered.
- A variety of low cost fuels (coal, coke, tar, biomass and organic waste) can be used.
- Expected low fuel processing costs compared with other fuel cell types.

CSIRO's Program

- CSIRO has started a R & D Program on DCFC recently, based on its significant expertise and capability in fuel cells, high temperature electrochemistry, ceramic fabrication, carbon chemistry and ultra clean coal processing.
- State-of-the-art test facilities for development of individual components and cells with multiple levels of safety redundancy.
- Evaluation of fuel cells to understand coal processing requirements and carbon reaction mechanism is in progress.
- Development of new processes for the production of micronised refined coal resulting in 1-2% ash from any coal at >90% combustibles recovery.


Tubular ceramic ion transport membranes

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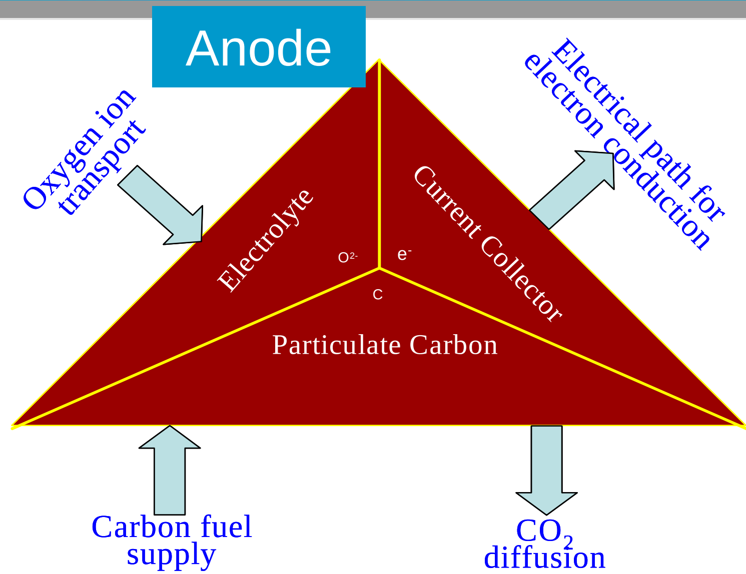
Direct Carbon Fuel Cells (DCFC)
Broad Technology Challenges

- How to deliver solid fuel to the cell for continuous operation.
- Understanding the reaction mechanisms for carbon oxidation, enhance fuel utilisation, optimise efficiency and fuel cell performance.

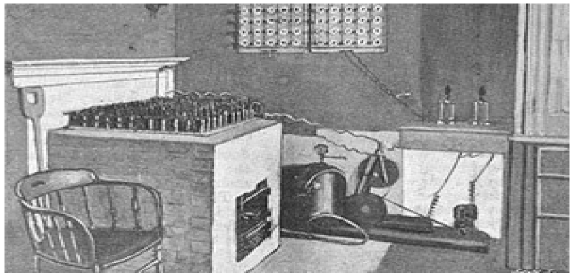


- Development of high temp corrosion resistant cell / stack materials
- Optimisation of operational parameters, life time, degradation
- Optimisation of system components, power densities, stack & system design
- Technology up-scaling
- Solid fuel processing ready for use in DCFC (C structure, purity, etc.).

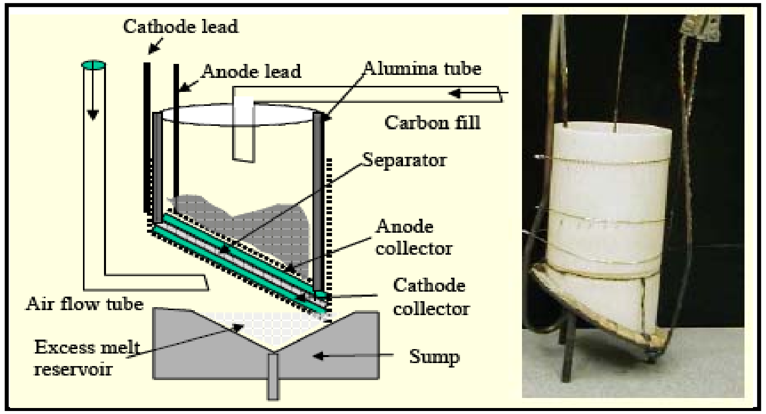
Conclusions & Technology Status

- The technology is at an early stage of development, globally 4-5 spin-off companies.
- Most groups are testing small cells and stacks.
- Substantial materials development & engineering effort is required.
- Considerable benefits in terms of highest efficiency, less CO_2 for sequestration, minimal CO_2 capture costs, and low fuel & processing costs.
- Given the substantial advantages the technology offers, the R & D effort must increase.

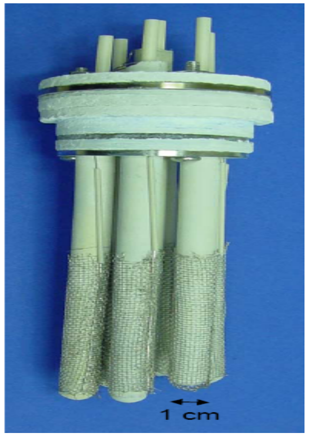
DCFC stack built by William Jacques in 1896, consisting of 100 cells in series, 16A, 90V.

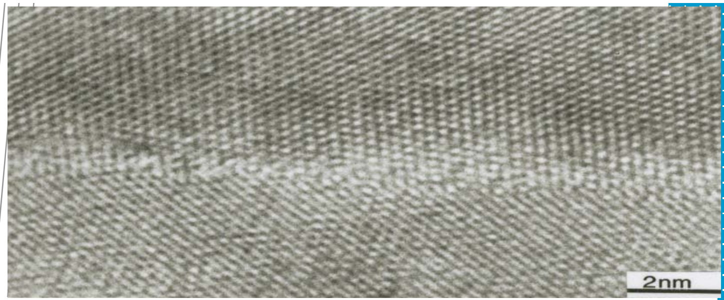


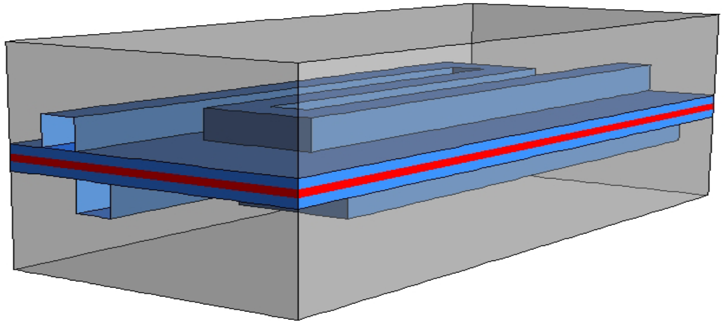
LLNL Molten Carbonate DCFC



SRI multi-cell DCFC unit







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Thank you