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SOLID OXIDE FUEL CELLS – What is a Bloom Box ?

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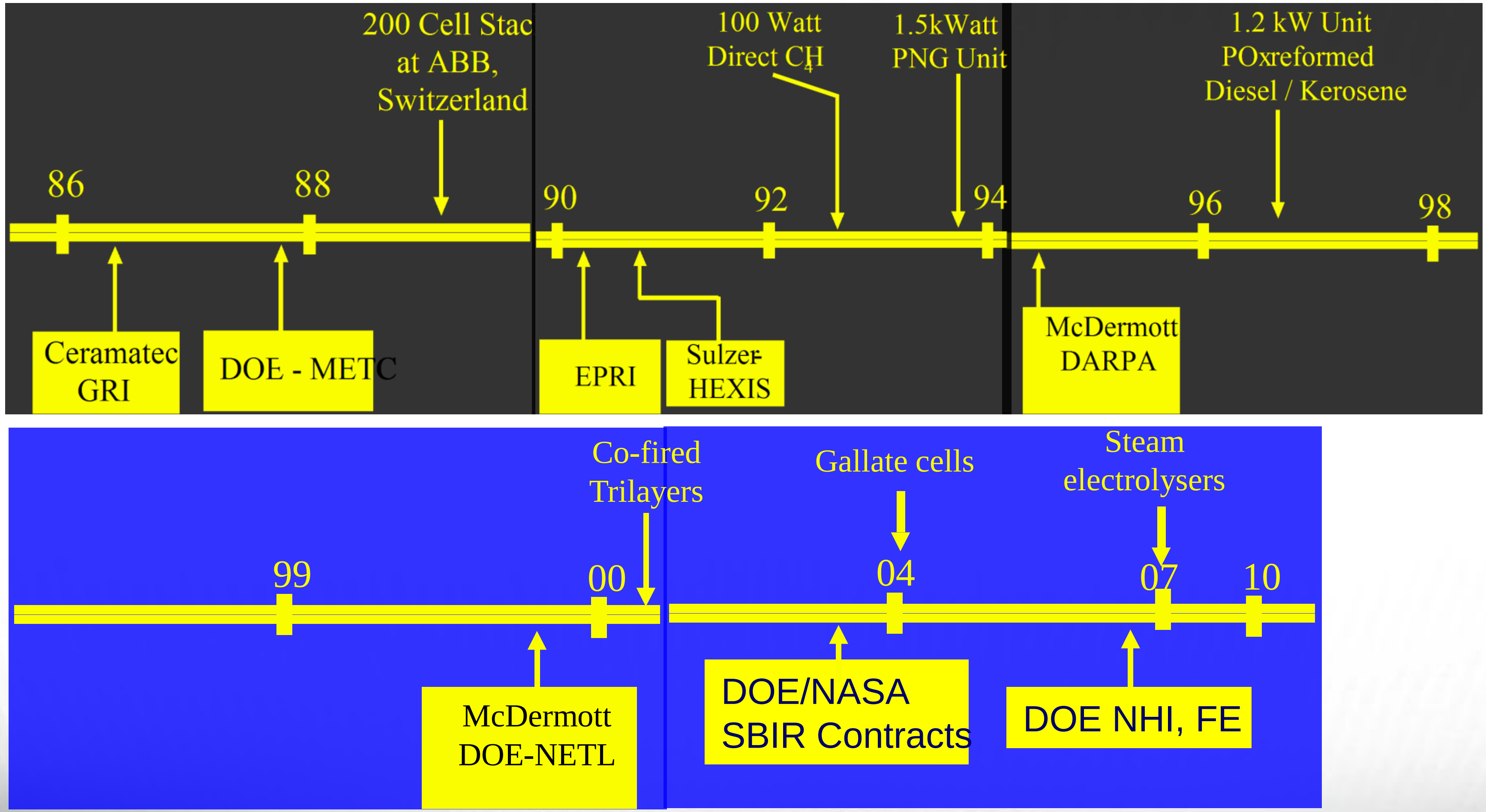
Outline

- **What is a solid oxide fuel cell.**
- **How a solid oxide fuel cell works.**
- **What can a solid oxide fuel cell do.**
- **Similarities/dissimilarities with other fuel cells.**
- **Status of the technology.**

Ceramatec SOFC History

>20 years of SOFC R&D



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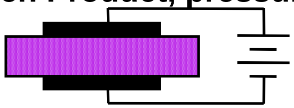
Company Overview

- **Privately Owned, Coors Family**
- **Subsidiary Company of CoorsTek**
- **165 Employees (3x growth in 7 years)**
  - Large Fraction - Engineers and Scientists
- **140,000 ft^2 Mfg and R&D Facility**
- **Concept to commercialization**
  - **R&D --> prototype --> pilot scale fabrication -->**
  - **Large scale manufacturing with CoorsTek**
- **Core competencies: electrochemistry, ionic conducting ceramics, & advanced materials**

Ion Transport Membranes (ITM)

ITM SEOS- point of use generation of high purity oxygen

Oxygen Product, pressurized



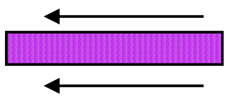
Ambient Pressure Air

3 liter/min Ceramic Stack

Superior purity and excellent benefits with respect to cylinder oxygen.

ITM Oxygen- Tonnage Oxygen Supply With 30+% Cost Reduction

O_2 Product



High Pressure Air

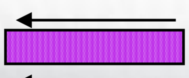
Multi-Wafer Ceramic Stacks

Pilot Plant

Focused on a range of applications requiring tons-per-day of oxygen. Integrates well with high temperature processes.

ITM Syngas- Tonnage Syngas, H2 Supply With 25+% Capital Reduction

Product of Reaction



Low Pressure Air

1 MMSCFD Throughput

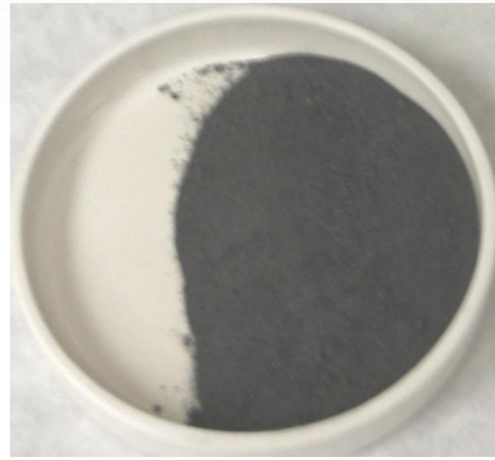
24 KSCFD Throughput

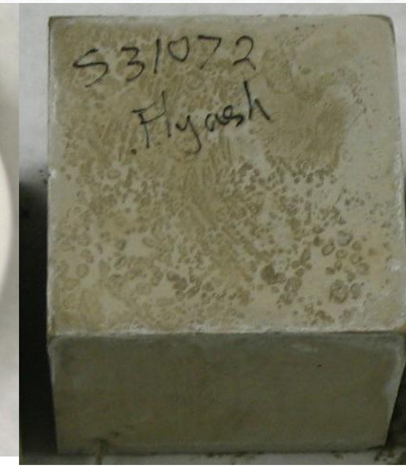
Focused on large applications such as gas-to-liquid fuels, H2, and gasification.

Treated Fly Ash for Concrete

Technology Description:

- Beneficiation of high carbon-containing fly ash for use in concrete applications
- Proprietary treatment process reduces interference effects of carbon on concrete
- Only process employing chemical treatment of fly ash for concrete
- Increases coal-power plants ability to sell fly ash to the concrete industry





Results to Date:

- 85% reduction in “foam index score”
- Increased compressive and flexural strength of concrete
- Have demonstrated “treatment” of kg-size batch processing; need to demonstrate process on slipstream capacity

Potential Applications:

- Direct sales of treated fly ash to ready-mix concrete industry
- Technology lease to coal-fired power plants
- Internal use of treated fly ash for fabrication of “green” building products, i.e. precast concrete

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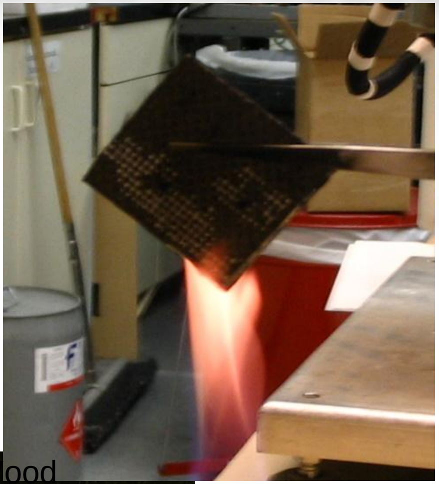
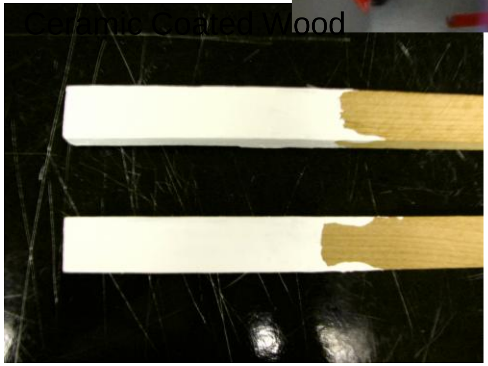
Fire Resistant Ceramic Coatings



BENEFITS

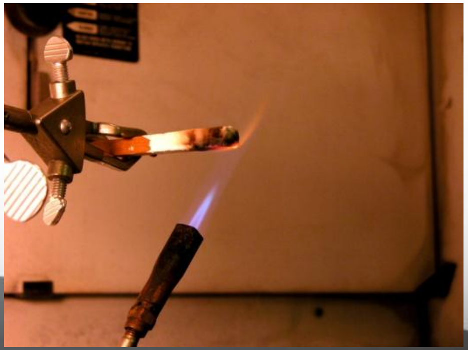
- Ability to easily coat metals, ceramics, wood & plastic
- Prevents smoking of organic materials
- Can be cured at room temperature – $<100^{o}C$
- Low cost, User friendly, and Non-toxic



Ceramic Coated Wood

Project Status

- Looking for partners for second phase testing and large scale demonstrations



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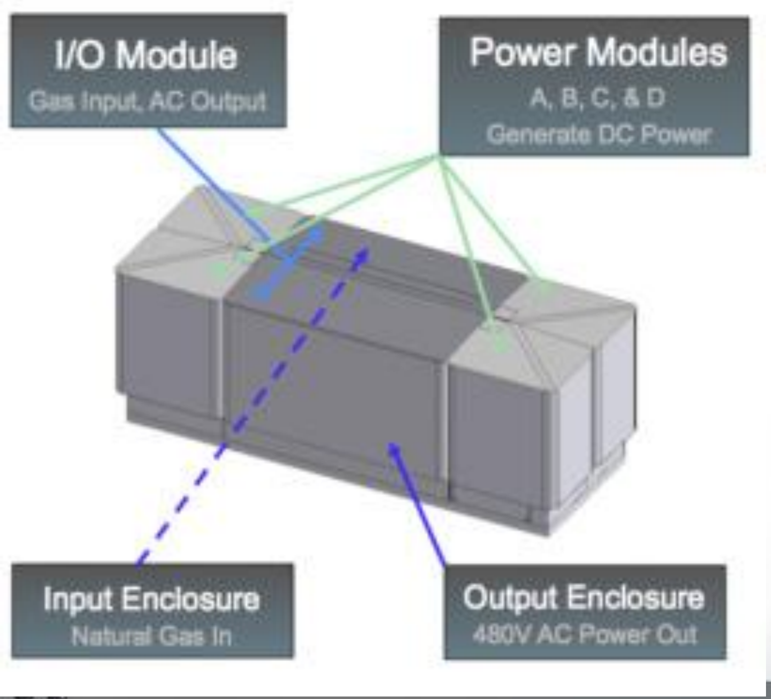
What is a Bloom Box ?

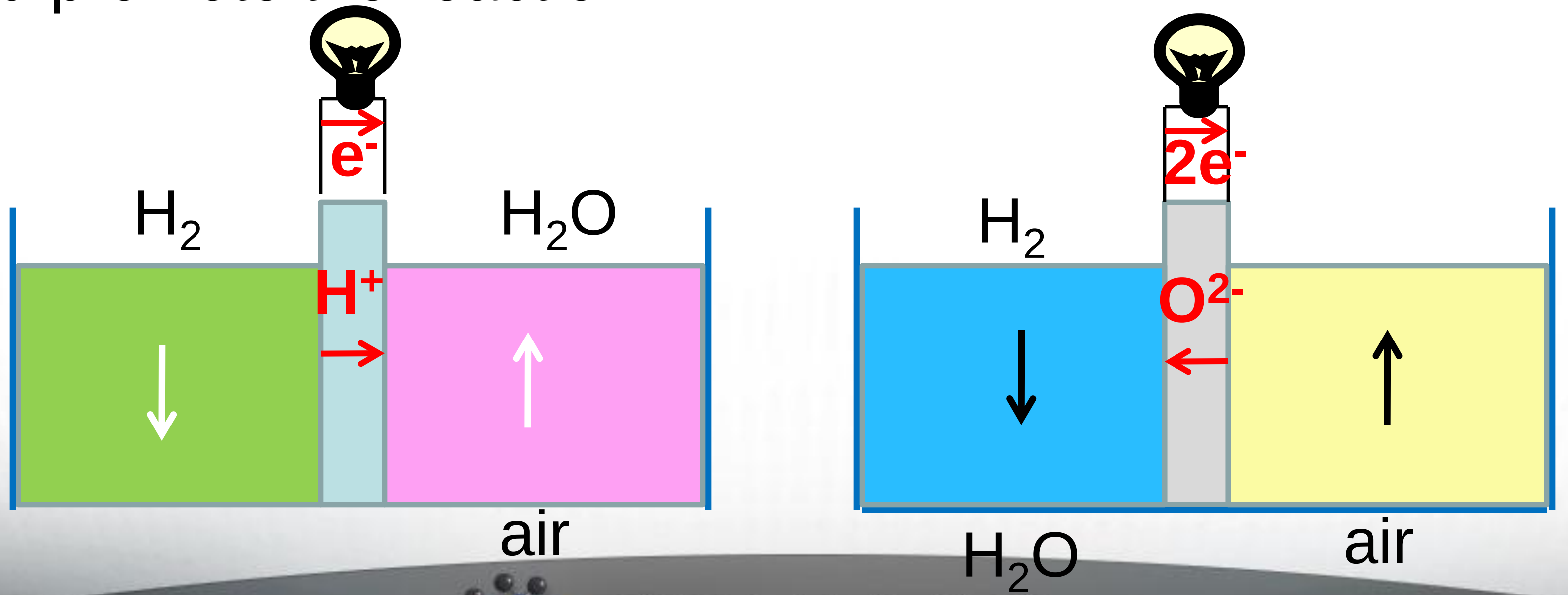
“Built with our patented solid oxide fuel cell technology, Bloom's Energy Server™ is a new class of distributed power generator, producing clean, reliable, affordable electricity at the customer site.”



http://www.bloomenergy.com
/products/architecture/

What is a Fuel Cell?

- Converts chemical energy (fuel) directly to electrical energy.
- A battery with a constant flow of reactant.
- Reactant and product are separated by an electrolyte that selectively allows charged ions (O^{2-}, H^{+}) to pass through. If an electrical conductor is used to complete the circuit, electrons will flow through the conductor to maintain charge balance and promote the reaction.



Types of Fuel Cells

- Phosphoric Acid
  - ion = H^+
  - $O_2 + H_2 = H_2O$
- Molten Carbonate
  - ion = CO_3^{2-}
  - $O_2 + CO_2 + H_2 = CO_2 + H_2O$
- Proton Exchange Membrane (PEM)
  - ion = H^+
  - Fuel processing: $CH_3OH + H_2O = H_2 + CO_2$
  - $O_2 + CH_n = CO_2 + H_2O$
- Solid Oxide
  - ion = O^{2-}
  - *Fuel processing: $CH_4 + 2H_2O = 4H_2 + CO_2$*
  - $O_2 + CH_n = CO_2 + H_2O$

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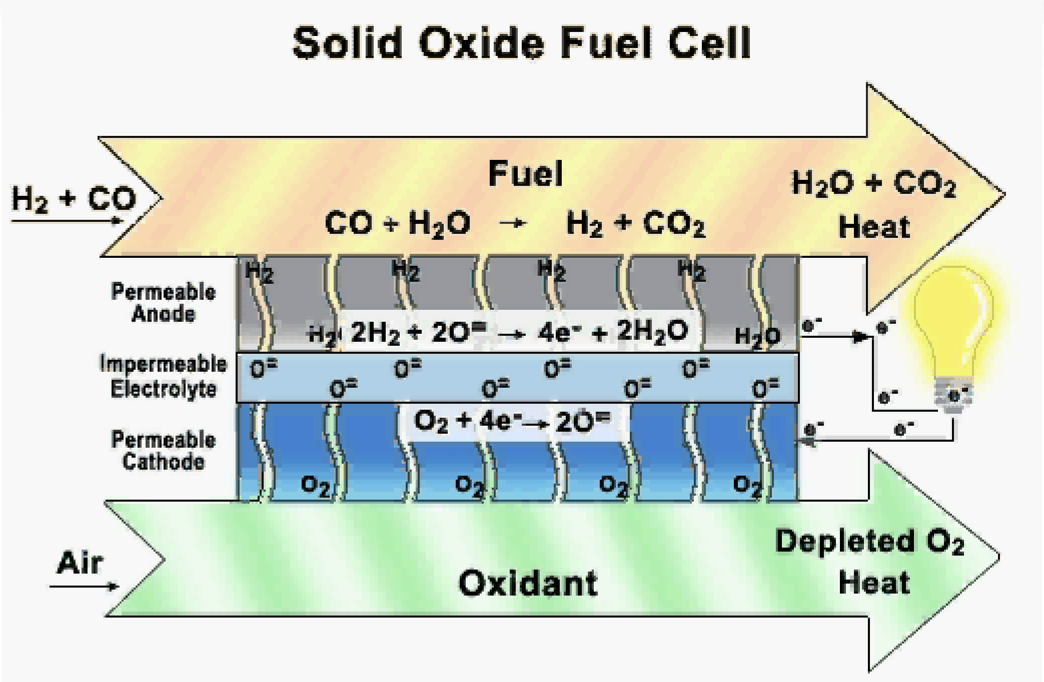
Solid Oxide Fuel Cells



- **Convert chemical energy directly to electricity**
  - **Efficient.**
  - **Reduced emissions, especially NO_x and SO_x.**
  - **Flexible fuel supplies.**

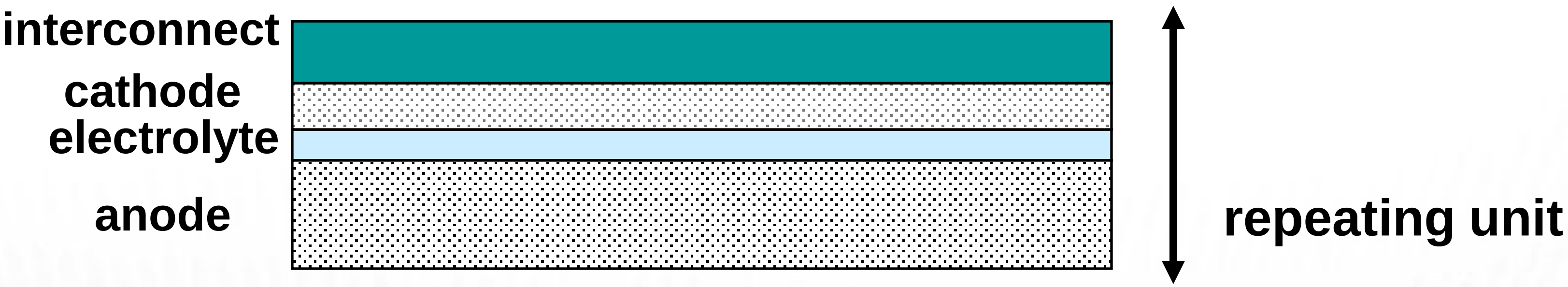
Illustration from: http://www.seca.doe.gov

Solid Oxide Fuel Cells - materials

- **Electrolyte**
  - **Pure ionic conductor, dense**
  - **Zirconia (ZrO_2), ceria (CeO), lanthanum gallate ($LaGaO_3$).**
- **Cathode**
  - **Catalyst for electrochemical reduction of oxygen, gas transport, electrical conduction, stable in oxidizing environments**
  - **$LaM_{1-x}Mn_xO_3$ (M=Mn, Cr), $LaCoO_3$**
- **Anode**
  - **Catalyst for electrochemical oxidation of fuel, gas transport, electrical conduction, stable in reducing environments**
  - **Porous Ni/Yttria-stabilised ZrO_2 cermet**

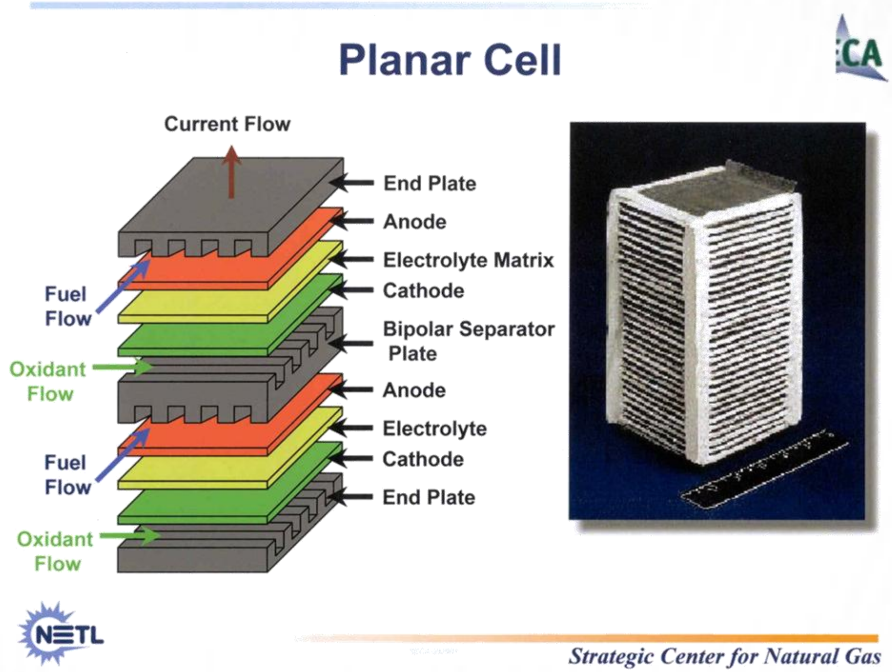
Solid Oxide Fuel Stacks - materials

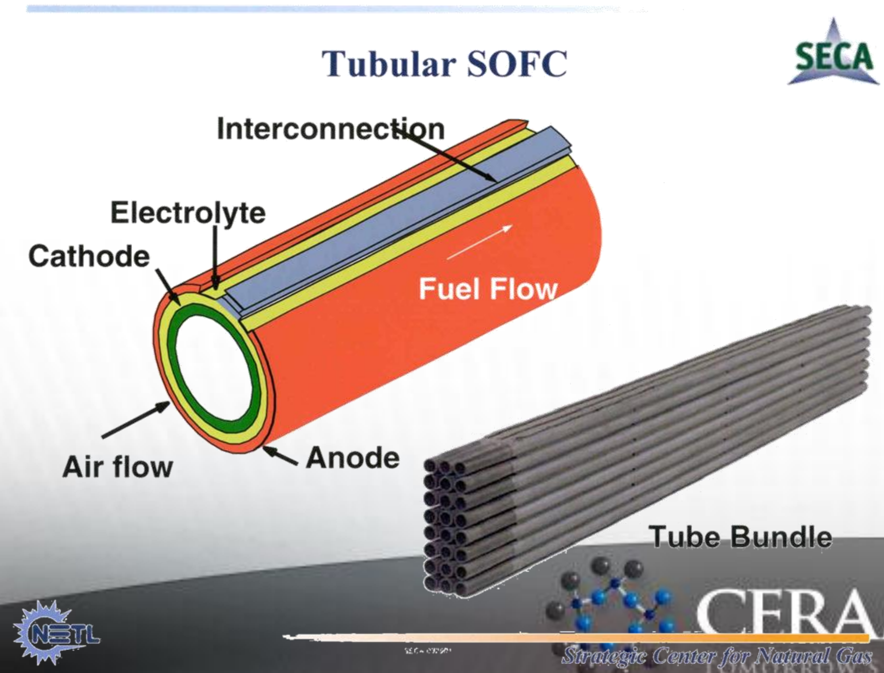
- **Interconnect**
  - **Pure electronic conductor, dense, stable in reducing and oxidizing environments**
  - **$LaCrO_3$, metals.**



Solid Oxide Fuel Cells - designs

Migration Path
- Cost
- Efficiency
- Footprint





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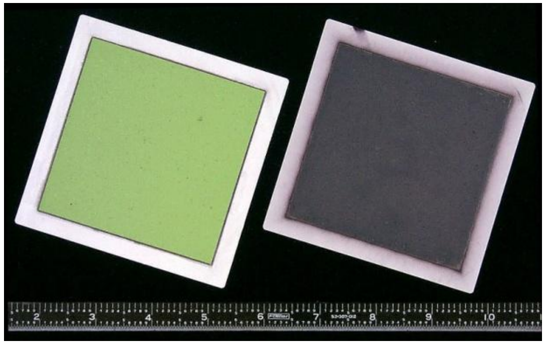
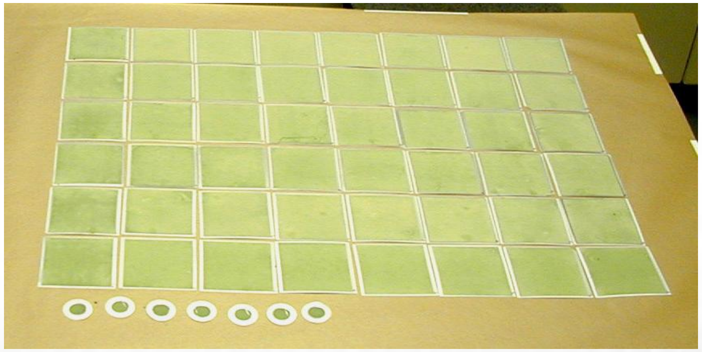
Planar SOFC design options

- Co-fired cells
  - **Anode-Electrolyte-Cathode sintered in a single step**
- Electrolyte supported cells
  - **Zirconia (YSZ) electrolyte sintered first, followed by application and sintering of electrodes**
- Anode supported cells
  - **Thin YSZ deposited on thick anode; bilayer sintered followed by application and sintering of cathode**





Design issues

- **High oxygen flux through electrolyte**
  - **Thin membrane**
  - **High temperature**
- **Effective gas transport**
  - **Porous electrodes**
  - **Interconnects with integral gas channels**
  - **Planar vs tubular**
- **Structural reliability**
  - **Uniform temperature distribution**
  - **CTE match between components**
  - **Strong electrolyte**
- **Seals**
  - **Ceramic-ceramic**
  - **Ceramic-metal**

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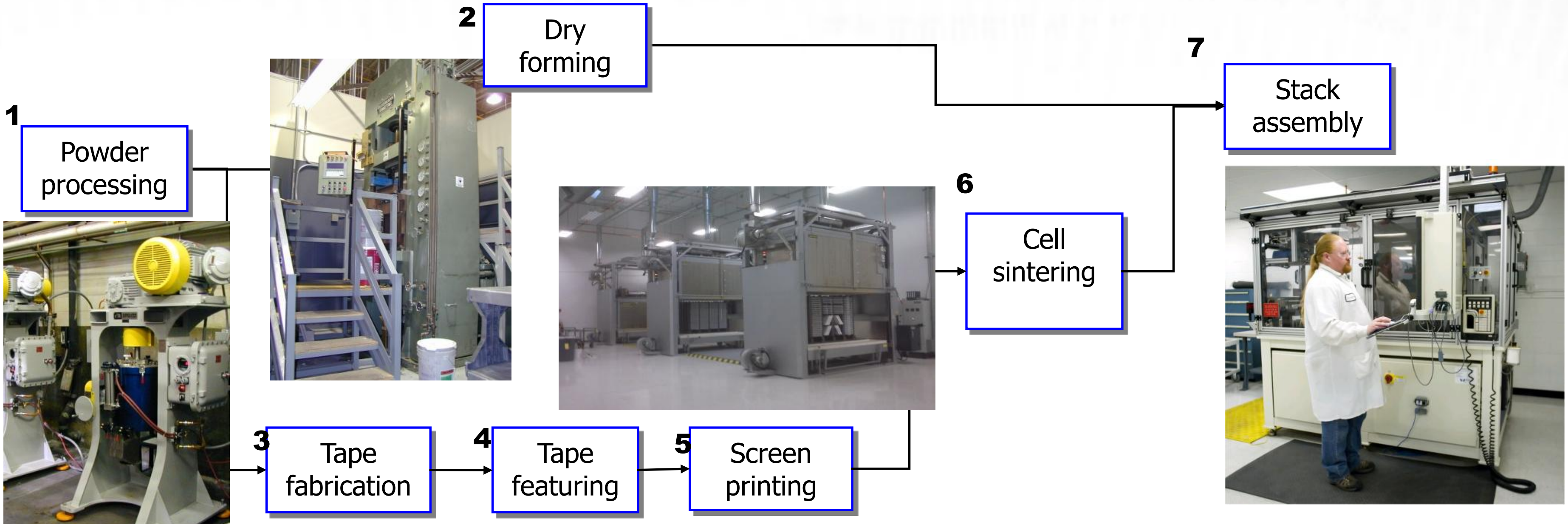
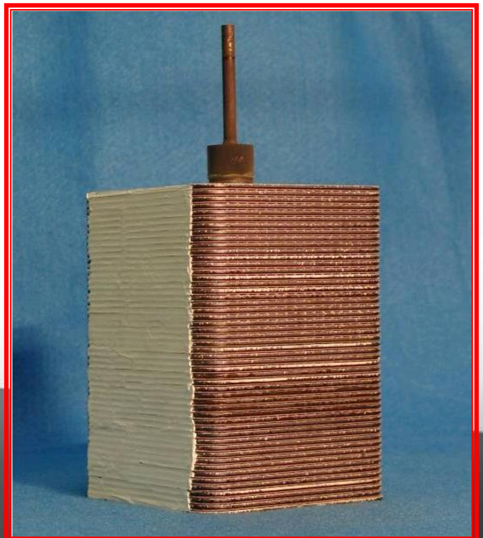
Fuel Cell Manufacturing





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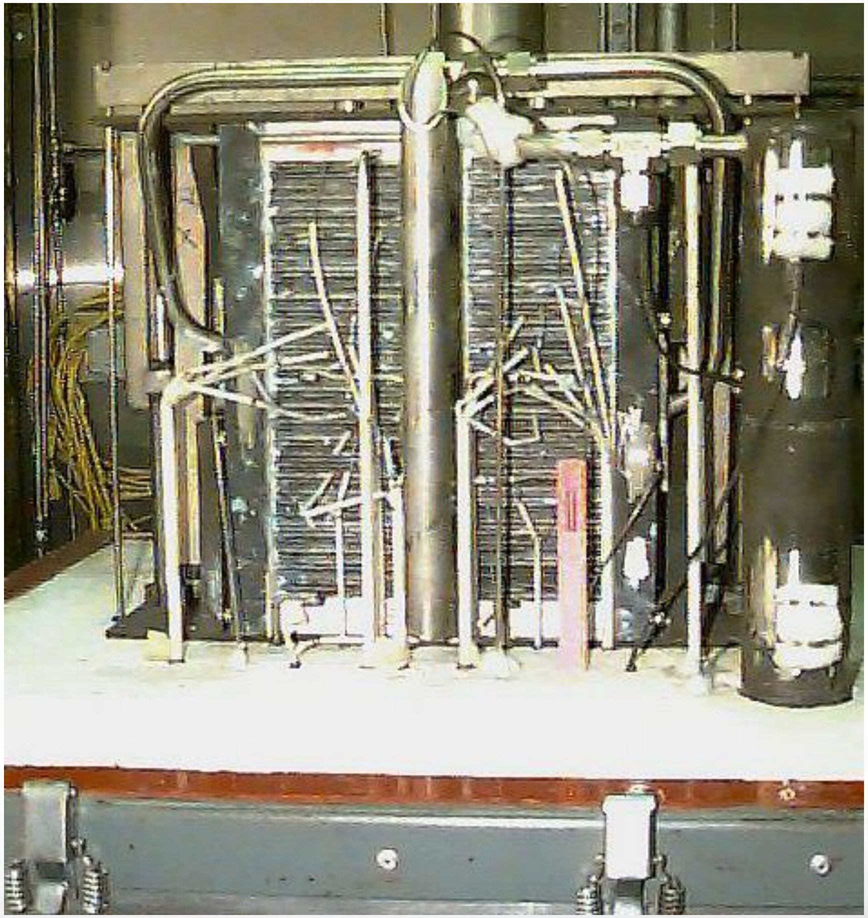
Fuel Cell System

- Air cleanup
- Heat Exchanger/Recuperator
- Fuel reformer
- Stack
- Power control system
- After-treatment
- Recuperator



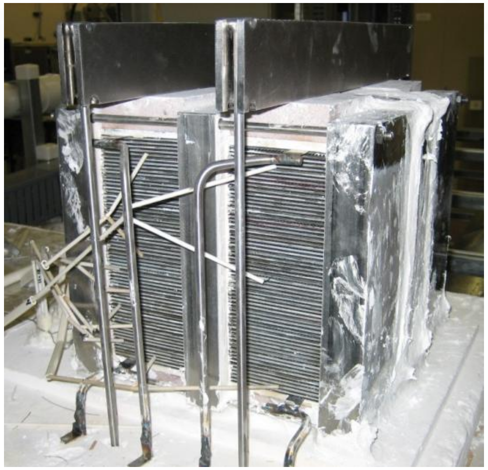
1.2 kW unit operated on POx-Reformed JP-8

Solid Oxide Fuel Cells/Fuel Reformer

Technology Description:

- Fuel to electricity + heat
- Fuel reformed to syngas (H_2+CO) and fed to fuel cell
- Fuel source flexibility (coal, bio, fossil) to reformer
- Integration of reformer + SOFC

4x60 cell module: ~ 3 kW



Results to Date:

- Sulfur tolerance of anode and reformer
- Cell operation on direct diesel reformate
- Present Scale ~ 2 kW
- Scalable to 5 - 10 kW demo with current fabrication infrastructure

Potential Applications:

- DOD portable powder (sub-kW)
- Remote power
- Stand-alone reformer for heavy fuel for syngas or hydrogen generation

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Environmental Benefits of SOFC

Reduced GHG emissions

- **Efficient energy conversion – low CO_2/kw_e**

Neutral GHG emissions

- **Renewable, sustainable bio-fuel**
- **Use as electrolysers, to produce hydrogen, with renewable energy sources (PV, wind) and fuel cells with stored hydrogen.**
- **CO_2 fuel cycle: convert renewable energy into liquid fuels**

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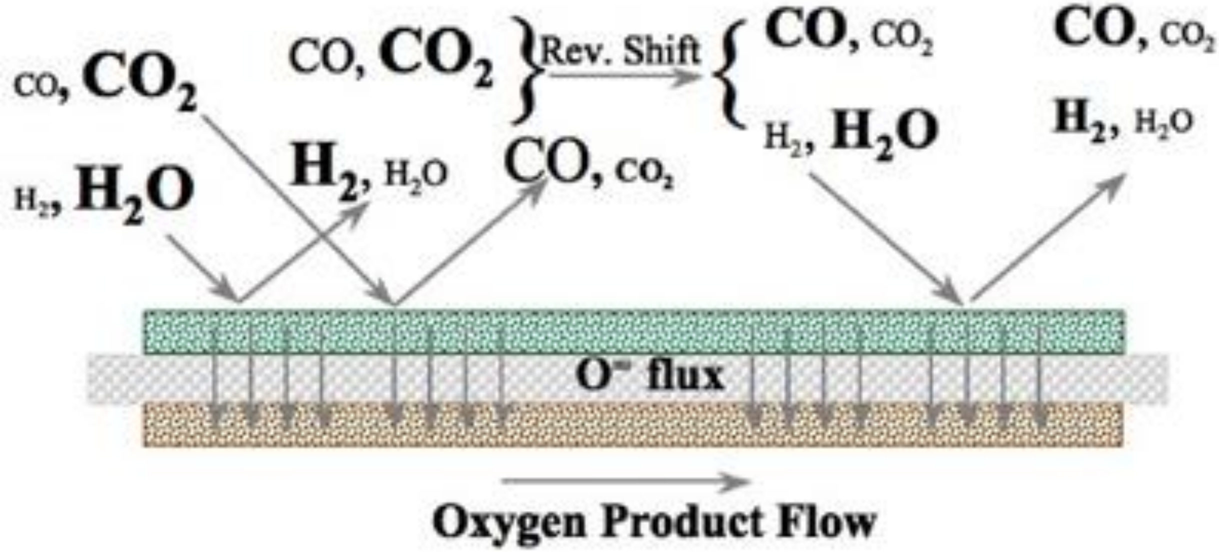
Zero GHG emissions: Synfuel Production



- Renewable energy reduces CO_2 and H_2O to CO and H_2.
- CO and H_2 can be compressed and reacted to form methane or liquid synfuel (diesel).

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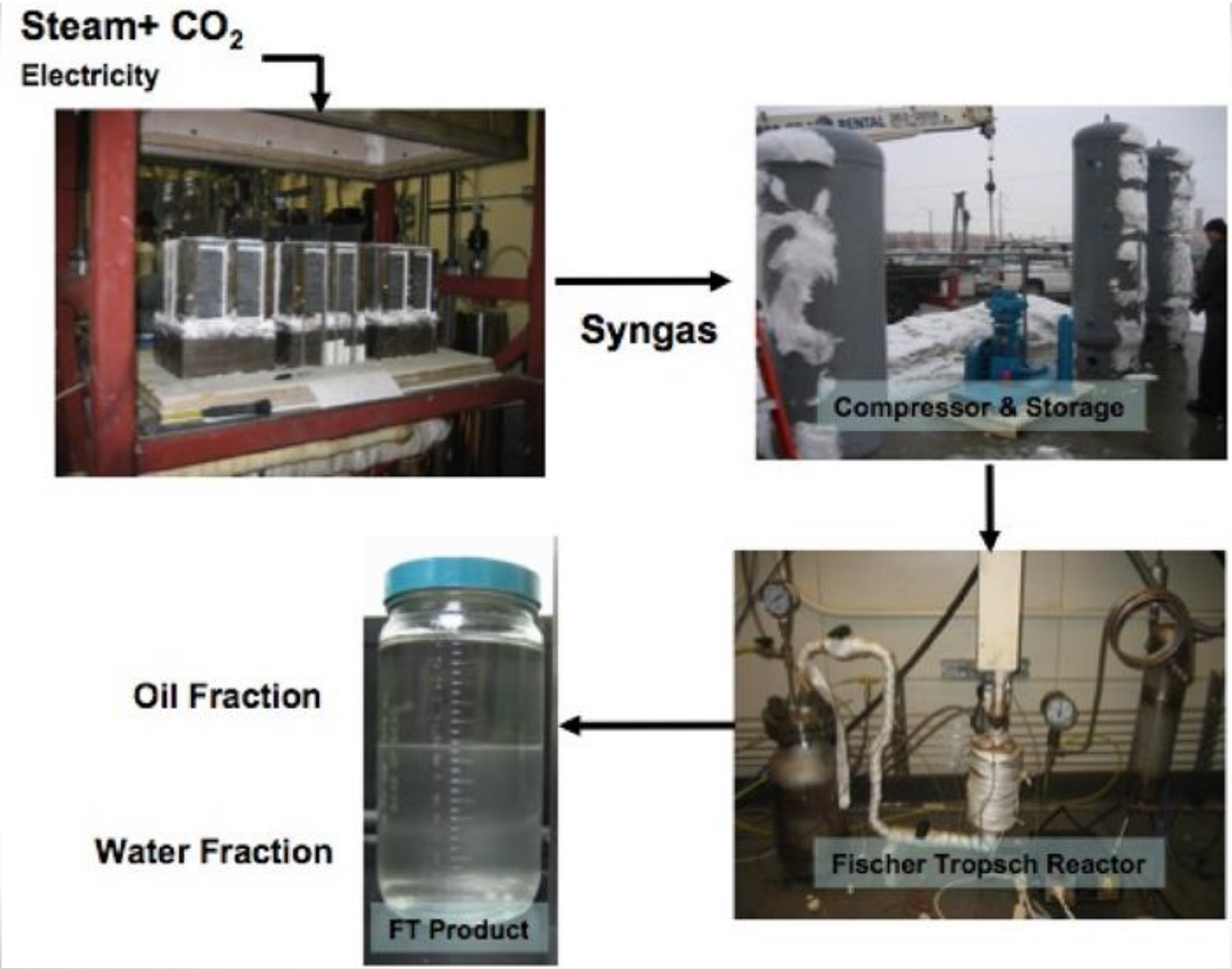
Zero GHG emissions: H_2 Production

- 5700 liters/hr H_2
- Same cells can covert CO_2 to syngas

Zero GHG emissions: Synfuel Production



SOFC technical challenges

- **Manufacturing cost.**
- **Reliability.**
- **Balance-of-plant: temperature and materials compatibility.**
  - **Lower temperature electrolytes.**
  - **Higher temperature interconnects.**
  - **Seals, especially capable of surviving thermal cycles.**

Fuel Cells

http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

DOE Hydrogen Program

Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	System Output	Electrical Efficiency	Combined Heat and Power (CHP) Efficiency	Applications	Advantages
Polymer Electrolyte Membrane (PEM)*	Solid organic polymer poly-perfluorosulfonic acid	50 - 100°C 122 - 212°F	<1kW – 250kW	53-58% (transportation) 25-35% (stationary)	70-90% (low-grade waste heat)	• Backup power • Portable power • Small distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 - 100°C 194 - 212°F	10kW – 100kW	60%	>80% (low-grade waste heat)	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to higher performance • Can use a variety of catalysts
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150 - 200°C 302 - 392°F	50kW – 1MW (250kW module typical)	>40%	>85%	• Distributed generation	• Higher overall efficiency with CHP • Increased tolerance to impurities in hydrogen
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C 1112 - 1292°F	<1kW – 1MW (250kW module typical)	45-47%	>80%	• Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP
Solid Oxide (SOFC)	Yttria stabilized zirconia	600 - 1000°C 1202 - 1832°F	<1kW – 3MW	35-43%	<90%	• Auxiliary power • Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces electrolyte management problems • Suitable for CHP • Hybrid/GT cycle

**Direct Methanol Fuel Cells (DMFC) are a subset of PEM typically used for small portable power applications with a size range of about a subwatt to 100W and operating at 60 - 90°C.*

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U.S. DEPARTMENT OF ENERGY

U.S. Department of Energy Hydrogen Program
www.hydrogen.energy.gov

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Fuel Cells

	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Proton Exchange Membrane (PEM)	Solid Oxide (SOFC)
Fuels	H_2	Methane (natural gas), H_2, various	H_2, Methanol	Methane (natural gas), H_2, various
Efficiency	37-42%(85% w/CHP)	60-85%	40-60%	50-85%
Cost	4-5$/W (operating)	6-7 $/W	30-35 $/W	~ 100 $/W (Bloom: 7-8 $/W)
Applications	stationery power/heat (200kW – 400 kW)	stationery power, power/heat (250kW – 1 MW)	stationery power, portable power, transportation (10-100 kW)	stationery power, power/heat (50-200 kW)

Summary

- SOFCs can be used to improve the efficiency and environmental impacts associated with producing electricity.
- SOFCs operate at high temperature making them suitable for integration with heating uses.
- SOFCs are flexible systems that can produce hydrogen or utilise CO_2 to make liquid fuels, when run in reverse.
- Several materials and design challenges remain to be solved for commercial implementation of SOFCs:
  - Manufacturing cost
  - Interconnect materials
  - Lifetime and reliability

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