TMI Solid Oxide Fuel Cell (SOFC) Systems
A Technology Platform for Economic Development

Building an Advanced Energy Industry in NE Ohio
Cleveland State University
Levin College of Urban Affairs
October 18, 2006

Benson P. Lee
Fuel Cells = “Disruptive Technology”
“Disruptive Technologies”¹

… are ideas, technologies or products which

◆ Have no *measureable* market demands (today)
◆ Take 15-20 years from invention to *prototype*
◆ Have the potential to become mainstream
◆ Can take *another* 10-50 years to penetrate² the marketplace

¹The Innovator’s Dilemma by Dr. Clayton Christensen (Harvard)
² 50%
Examples of Disruptive Technologies

- Telephone
- Airplane
- Electricity
- Full Body CAT Scanning
- $100 toothbrush
- Gas Turbine
- Xerography
- PC
- Cell Phone
- Bone Healing with Electricity
World’s 1st Automatic Wind Turbine for Power Generation
... prototype built in 1887 (Cleveland, Ohio)

- Built by Charles Brush
- 12 kW
- 50’ Diameter
- 144 Blades (made of cedar)
- Operated for 20 years charging batteries
Average time to reach 50% market penetration is 25 years, but decreasing rapidly
Fuel Cells - General
In 1839 Sir William Robert Grove built a device that combined hydrogen and oxygen to produce electricity … the world's first gas battery... later renamed the fuel cell

Not a new discovery …
**Fuel Cell Stack vs. Reformer vs. Hot Assembly**

**Electrochemical Process**
- Quiet
- Clean
- Fuel Efficient
- Scalable/Modular

![Diagram](image-url)

- **Fuel Cell (STACK)**
- **Air Electrode (Cathode)**
- **Fuel Electrode (Anode)**
- **Electrolyte**

**Processes**
- DC Power
- Electrochemical Process
  - $H_2$ (fuel) to $CO_2$ (waste)
  - Water and Heat

**Advantages**
- Quiet
- Clean
- Fuel Efficient
- Scalable/Modular

**Inputs**
- Common Fuel
- $O_2$ (Air)

**Outputs**
- $H_2$ (fuel)
- $CO_2$ (waste)
- Water

**Connections**
- Fuel Reformer
- Hot Assembly

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BPL 9-22-06 /9
## Today’s Cost of Fuel Cell Systems
(from systems demonstration cost data)

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (kW)</th>
<th>$/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Exchange Membrane (PEM)</td>
<td>1-10</td>
<td>$ 5,000</td>
</tr>
<tr>
<td>Phosphoric Acid</td>
<td>200 - 1,000</td>
<td>$ 3,500</td>
</tr>
<tr>
<td>Molten Carbonate</td>
<td>250 - 1,000</td>
<td>$ 3,000 - 4,000</td>
</tr>
<tr>
<td>Solid Oxide (SOFC)</td>
<td>1-250</td>
<td>$ 10,000 - 20,000</td>
</tr>
</tbody>
</table>

Cost Targets: Stationary/Mobile (SOFC) → <$500  
Automobile (PEM) → <$75
Price vs. Power - Applications Map

Source: Product Strategy, March 2002
TMI Fuel Cell Systems
1990 - TMI formed (in Cleveland)
  • Ohio’s 1st independent fuel cell systems company
  • Acquired low cost, solid oxide fuel cell (SOFC) from SOHIO/BP
2006 - Only (stationary) fuel cell systems integrator with all operations exclusively in Ohio
Technology:
  • 10 issued patents (plus international)
  • >200 man years of team experience and know how
Worldwide, one of about 20 SOFC systems developers who have demonstrated complete SOFC systems outside the laboratory, including,
  • GE, United Technologies, Cummins, Delphi, Siemens Westinghouse, General Dynamics, McDermott, Fuel Cell Energy,
  • Rolls Royce (UK), Ceres (UK), Ceramic Fuel Cells (Australia), Sulzer Hexis (Switzerland).
First (known) SOFC company to demonstrate
  • Three 1kW SOFC systems in parallel outside the laboratory
  • Operation on military untreated JP-8 (containing sulfur)
  • Operation on biogas (from anaerobic digesters)
  • Operation on raw vegetable oil (from soybeans)
TMI Solid Oxide Fuel Cell (SOFC) and Stack

Originally developed in the 1980s at SOHIO/BP World R&D Center (Warrensville Heights, Ohio)
TMI Systems Evolution 1985-2006

**Cell Proven (1985)**
(by BP/SOHIO)

**Fuel Reforming Catalyst (1993)**

**Balance of Plant Components (1998)**

1kW (2002)

- Thermally Integrated Hot Assembly (1995)

**Fuels Proven:**
- Natural gas (1997)
- Propane (2002)
- Biogas (1996)
- Ethanol (2002)

**Fuels in Progress:**
- Truck Diesel (2003-6)
- 100% Vegetable Oil (2004-6)

3kW Multi-Module Demonstrated (2006)
TMI 1kW System (May, 2006)

Common Fuel (Propane)

TMI 1 kW System

Typical Load
1st Field Demonstration – Three x 1kW Systems
(October, 2005 @ CEVEC, Mayfield Heights, Ohio)
Classic Hub and Spoke Strategy for Disruptive Technology Commercialization
Kilowatt Class Markets and Applications
(for the Modular TMI SOFC System)

Military (JP-8) & Aeronautics

Off-grid Buildings

Institutional & Commercial

Combined Heat & Power

Remote & Critical Power

Buildings & DG

Rural Electrification

Water Purification & Desalination

Clean Power for Agri-Business

Clean Power for Institutional & Commercial

Clean Power for Village Power/Micro-Utility

Clean Power for Solar/Wind

Telecom Relay Networks

Cell Towers

Natural Gas Pipelines

Tank APU

Mobile Communications

Battery Recharger

Off Road & Class 6

Pleasure Craft

Class 8 Fleets

Municipal Fleets

Recreational

Mobile APU

Class 8 Fleets

Pleasure Craft

Power Supplement for Solar/Wind

Village Power/Micro-Utility

Clean Power for Agri-Business

Clean Power for Institutional & Commercial

Remote & Critical Power

Buildings & DG
Truck APUs (Auxiliary Power Units)

A major source of Ohio air pollution
Idling trucks consume 860 million gallons of fuel per year!
Fuel cells can reduce truck idling fuel consumption from 1 gal/hr to 0.2 gal/hr or 688 million gallons.
Long-haul trucks idle about 1,500 hours per year
Fuel cells can save 1100 gal/year @ $3/gal = $3,300
A $1B market opportunity
Kilowatt Class Markets and Applications
(for the Modular TMI SOFC System)

- Off-grid Buildings
- Institutional & Commercial
- Combined Heat & Power

Remote & Critical Power
- Telecom Relay Networks
- Cell Towers
- Natural Gas Pipelines
- Tank APU
- Mobile Communications

Rural Electrification
- Village Power/Micro-Utility
- Water Purification & Desalination
- Power Supplement for Solar/Wind
- Clean Power for Agri-Business

Military (JP-8) & Aeronautics
- Off-road & Class 6
- Mobile APU
- Battery Recharger
- Pleasure Craft

Mobile APU
- Municipal Fleets
- Recreational
- Class 8 Fleets

Clean Power for Agri-Business
- Institutional & Commercial
- Remote & Critical Power
- Combined Heat & Power
- Off-grid Buildings

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The world’s largest (untapped) market for fuel cells, measured in numbers of systems and not in number of replacement megawatts

…are the world’s “Energy Poor”
…4 billion people with zero electricity,
…dependent on burning biomass
…for boiling water, cooking and warmth
The World’s Energy Poor

Source: IEA analysis.
Solid Oxide Fuel Cell

SUBSTRATES

GAS

Lamp

Gas stove

Dung

Agro-waste

Organic industr. waste

Inlet

Outlet

DIGESTED-SLURRY FERTILIZER

Field

BIOGAS PLANT

有机废物——普遍可用的生物质燃料

有机废物

农业废弃物

有机工业废物
Rural Village - Micro-utility Configuration
(e.g., Community Center, Schools, Health Clinics)

Biomass to Biofuel
(OSU/OARDC)

Animal Waste
Bedding

Food Processing Waste

Fertilizer

Plant Biomass

Aerobic Digester
(small scale)
Methane Ammonia
Hydrogen?

Solids

BIOGAS

Combined Power and Heat
(TMI)

TMI Micro-Utility Plant
(N x 1kW)

Electricity

Surplus Heat

Other Fuels

Ethanol
Biodiesel
Propane
Kerosene

Ancillary Devices

Power conditioners

Distilling, RO Desalination
UV

Absorption Chilling Refrigeration

Heat Exchanger

Clean Energy Services

#1 Clean Water

#2 Refrigeration
- Vaccines
- Food

#3 Heat Source
- Warmth
- Cooking

#4 Electricity
- Battery charging of hand held devices
- Supplement (solar) battery banks
- Lighting
- 7/24 Telecom relay towers

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Fuel Cell Systems
A Catalyst for Economic Development
20 year Product Development Cycle and Role of Manufacturing

Research &
Training

Invention &
Innovation
Universities,
Federal Laboratories,
Corporations

Educated
Workforce

Patents &
Licensing

Consulting

Support Services

Development - Manufacturing - Marketing

OEM Components
- Pumps, Fans,
- Compressors,
- Controllers,
- Sensors

System Components
- Fasteners,
- Fittings/Valves,
- Wire Harnesses,
- Tubing, Etc.

Ancillary Systems
- Power Conditioning,
- Cogen Systems,
- Interconnects,
- Installation Systems

Cells & Stacks

Fuel Processor
& Catalysts

Systems Integration

Prototyping

Raw Materials
- Processed Mats
- Polymers
- Aluminium
- Steels
- Super Alloys

Packaging
- MetaPolymers
- Forming
- Insulation

Mfg. Scale-up
- Engineering
- Pilot Plant
- QC

Applications

Mobile
- Trucks
- Refrig. Trailers
- Buses
- RV, Boats

Stationary
- Commercial Industrial
- Offgrid Buildings

Military
- Silent Watch
- Communications

Accounting
- Legal

Installation
- Maintenance
The mere co-location of companies, suppliers, and institutions creates the potential for economic value; it does not necessarily ensure its realization (Porter 1998)
Who Can Define a New Industry …

- “Systems Commercialization” companies can define an emerging industry:
  - As systems integrators they:
    - Specify materials
    - Select components
    - Specify methods of Manufacture
    - Select suppliers
  - As commercializers of systems they
    - Control marketing strategies
    - Prioritize market segments and locations
    - Target market entry applications/customers
    - Choose strategic partners

- Since none of this knowledge is published or available to the public, supply chain and service companies can only respond to specifications.

- Opportunity: the fuel cell industry is now being defined by systems commercialization companies (like TMI). Regional clusters do not yet exist and can still be “seeded.”
A Technology Model to Create New Ohio Industry

• Build a portfolio of “systems commercialization” companies, meeting the following criteria:
  • Proprietary “Platform Technology”
  • Product prototype at or near field demonstration/test
  • Utilizing regional manufacturing capability and workforce
  • Corporate management
    • In Ohio
    • With relevant (systems commercialization) experience
• Showcase “do-learn-make-sell” applications of platform technology
  • Form 2-3 unique Ohio examples
    • Different end user customers
    • Different distribution channels
  • Maximize use of Ohio supply chain and workforce
  • Competitive in world markets
• Intentionally organize clusters as building blocks for a “new industry”
  • With multiple growth trajectories
  • Serving multiple global markets
  • Which is unique in the world
Example Clusters using TMI Platform Technology
(Small Scale Modular SOFC Systems)

1. Biomass/Bioenergy (Waste-Biogas-Energy)
   - Small Dairy Farms (major industry in Wayne County)
   - Food Processing Plants (Ohio ranks 5th in the nation)
   - Water Treatment Plants (throughout Ohio and Appalachia)
   - Greenhouse industry revival
     - Vegetables (Lorain/Lucas County)
     - Floriculture (Lake/Geauga County)
     - Aquaculture (Cuyahoga)

2. Community-based Micro-Utilities
   - Public School Buildings (start in Cuyahoga)
   - Churches, temples

3. 7/24 Premium Power
   - Fire, safety, airport
   - Telecom Towers
   - Natural Gas Pipelines

4. Mobile Power (Quiet/Non-Polluting) APUs
   - Airport Ground Equipment
   - Truck Anti-idling

5. Cogeneration (combined heat and power)
   - Commercial Scale
   - Residential Scale
Cluster Characteristics (Michael Porter 1998)

- Geographic concentrations of interconnected companies and institutions in a particular field.

- An array of linked industries and other entities important to competition.

- Extend downstream to customers and laterally to manufacturers of complementary products ... and to companies in industries related by skills, technologies, or common inputs.

- Include governmental and other institutions ... that provide specialized training, education, information, research, and technical support.
Start with a Technology Platform

Nucleus
Select Supply Chain Companies

S3

S1

Nucleus

S2

S4

S5
Select Customer Applications

- S3
- S4
- S2
- S5
- Nucleus

- C1
- C2
- C3
- C4
- C5

Diagram showing a network of customer applications with a central 'Nucleus' node connecting to various 'S' and 'C' nodes.
Regional Economic Growth!

Diagram showing relationships between various components labeled S3, S1, S4, S2, S5, G1, C1, C2, C3, C4, and C5 with arrows indicating interactions among them.
Thank you!