Technology Commercialization Showcase 2008
Hydrogen, Fuel Cells & Infrastructure Technologies Program

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Agenda

- Industry Landscape
- Program Objectives
- Technology Commercialization Opportunities
- Emerging Markets and Investment Opportunities
- Appendix

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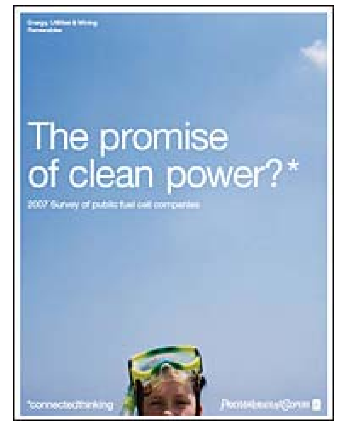
Fuel cell industry begins to see market pull. Investment continues to grow.

- Revenues up 59% to $416M (2005-2006)
- Worldwide Gov't R&D funding of $1B
- Employment up 10% to 3,434
- Market capitalization up 20% to $3.8B
- However, firms share net losses of $644M
- Costs are still high – e.g. $3,000/kW for 5kW PEM fuel cell – though industry reports cost reductions of 10-20%/yr



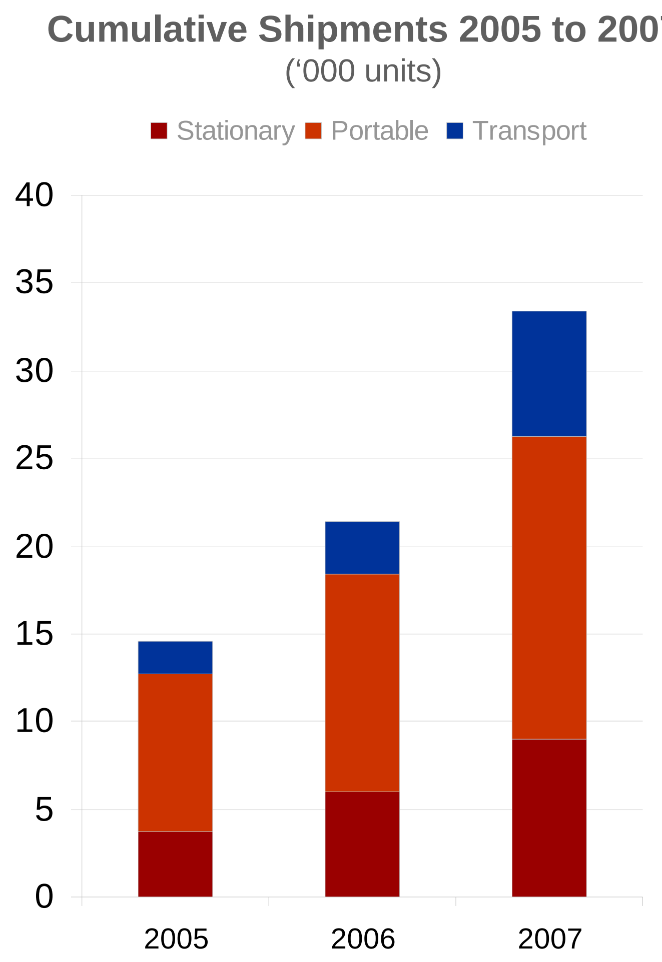
Sources:

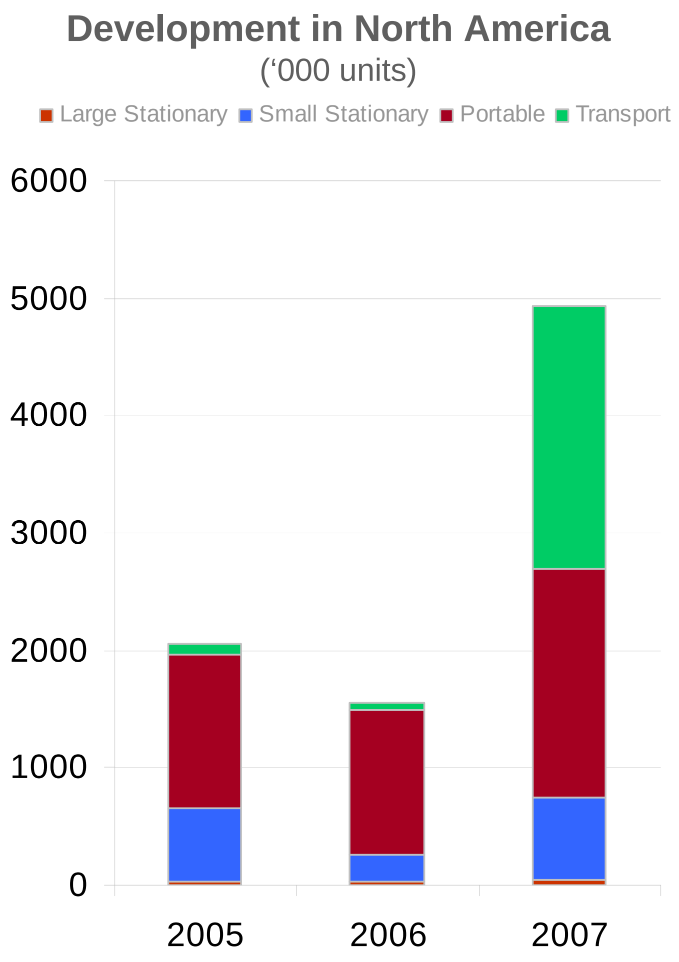
(1) PricewaterhouseCoopers 2007 Survey of Public Fuel Cell Companies*

(2) Fuel Cell Today Industry Review 2008

*OEMs and energy companies not included in this survey

The fuel cell industry has seen an average annual growth of 59% over the past three years. More than 12,000 new units were shipped in 2007



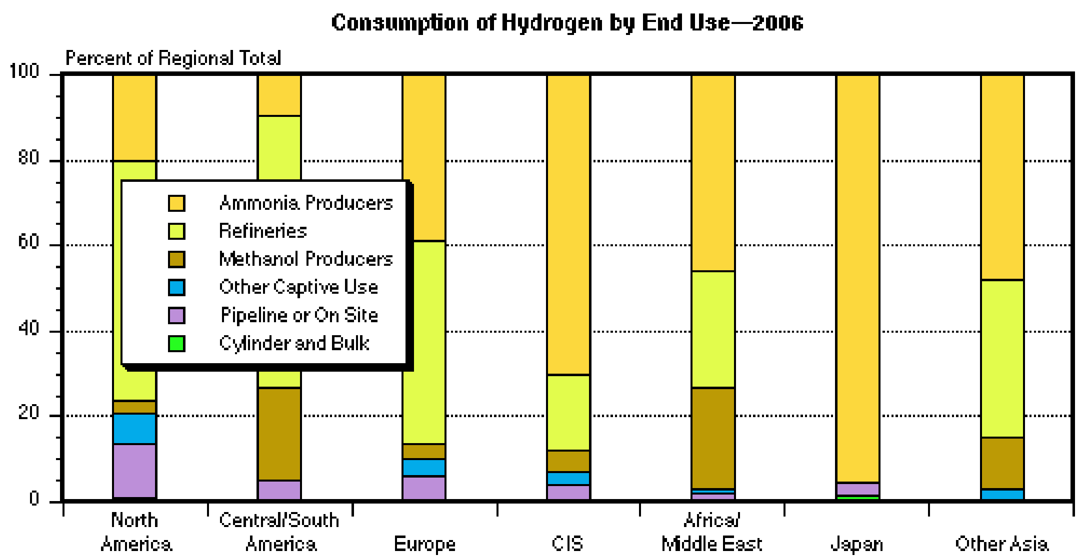


Source: Fuel Cell Today Industry Review 2008

Hydrogen refinery consumption expected to increase by 40% from 2006-2011

Global Hydrogen Trends

- 53 million metric tons consumed 2006
- 80 million metric tons forecasted demand 2011
  - Global environmental regulations and the quality of today's sour crude feedstock will drive consumption in excess of 40% over the next five years
  - Oil-sands processing, gas-to-liquids, and coal gasification projects that are ongoing, require enormous amounts of hydrogen and will boost the size of the market



- *Today ~96% of all hydrogen is from fossil fuels*
  - *~49% from natural gas*
  - *~29% liquid hydrocarbons*
  - *~18% coal with and*
  - *~4% electrolysis and other sources*

U.S. hydrogen production ~ 9 million metric tons

Source: http://www.sriconsulting.com/CEH/Public/Reports/743.5000/

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The program is primarily focused on the research and development of PEM fuel cells.

Polymer Electrolyte Membrane (PEMFC)
- *Pros:* Low temperature operation, quick start, and high power density
- *Cons:* Expensive catalysts
- *Applications:* Transportation, stationary, and portable power

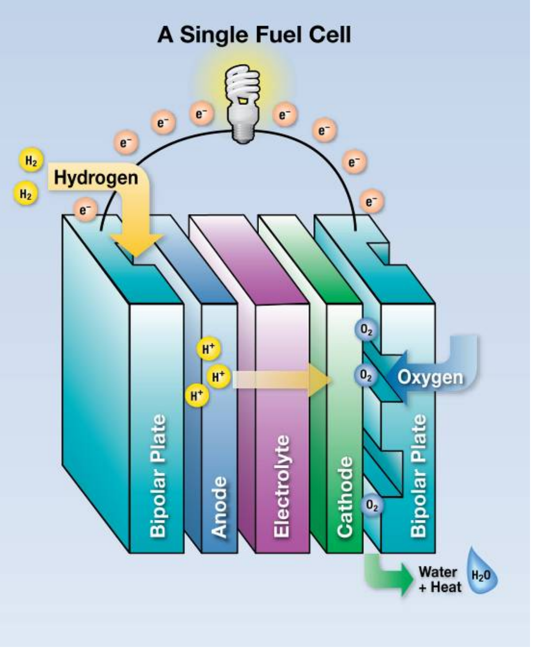
Direct Methanol Fuel Cell (DMFC)
- *Pros:* High energy density
- *Cons:* Expensive materials
- *Applications:* Portable and micro power

Phosphoric Acid Fuel Cell (PAFC)
- *Pros:* Low temperature operation and high efficiency
- *Cons:* Low current and power density
- *Applications:* Distributed generation

Alkaline Fuel Cell (AFC)
- *Pros:* Low temperature operation and high efficiency
- *Cons:* Impurity removal
- *Applications:* Military and space

Solid Oxide Fuel Cell (SOFC)
- *Pros:* Multiple fuel feedstocks, usable waste heat, and cheap catalysts
- *Cons:* Slow start-up, poor transient response, and corrosion issues
- *Applications:* Auxiliary power units and distributed generation

Molten Carbonate Fuel Cell (MCFC)
- *Pros:* Multiple fuel feedstocks and usable waste heat
- *Cons:* Slow start-up and corrosion issues
- *Applications:* Electric utility



Fuel Cells use hydrogen, and oxygen from air to generate electricity through an electrochemical reaction. The only products are water and heat.

The Hydrogen Program is addressing critical barriers to enable the widespread commercialization of hydrogen and fuel cell technologies

Technology Barriers

Hydrogen Cost

Critical Path *Target ($2 – 3 /gge) has been met by distributed reforming of natural gas*)

H_2 Storage Capacity & Cost

(Targets: 2.7kWh/L, 3kWh/kg, and $2/kWh)

Fuel Cell Cost and Durability

(Targets: $30 per kW, 5000-hour durability)

Technology Validation:

(Technologies must be demonstrated under real-world conditions)

Economic & Institutional Barriers

Safety, Codes & Standards Development

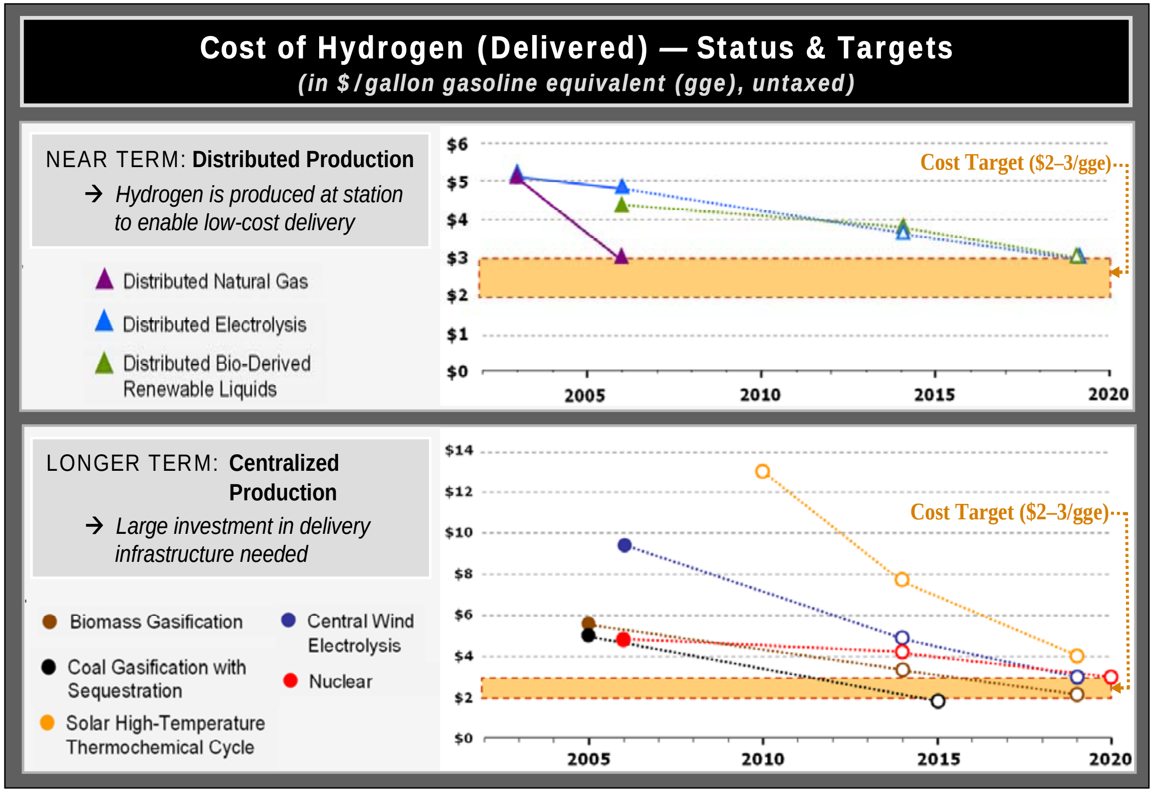
Delivery Infrastructure

Domestic Manufacturing and Supplier Base

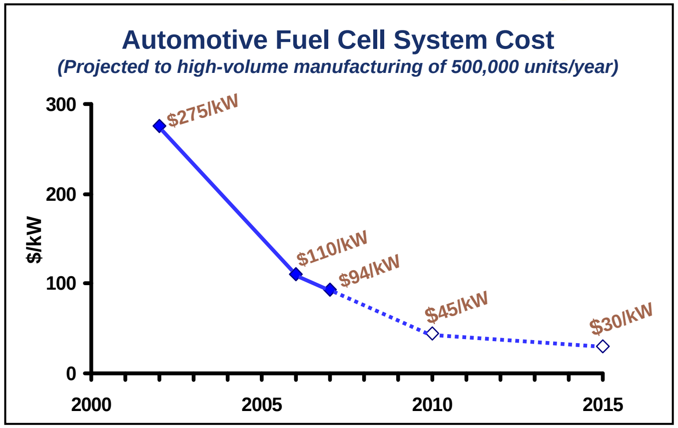
Public Awareness & Acceptance

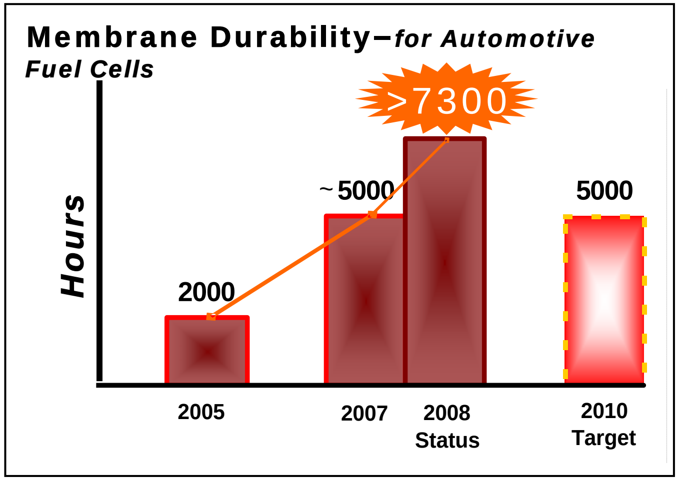
Critical Path Barriers for FCVs

Significant progress has been made as a result of DOE funded R&D



Open symbols for cost reduction targets subject to appropriations





- Reduced high volume automotive fuel cell cost to $94/kW (by 65%)
- Doubled automotive stack durability to 2,000 hrs
- Identified materials with > 50% improvement in storage capacity since 2004
- Demonstrated membrane durability of 7,300 hrs (exceeded 2010 target of 5,000 hrs)

The Program is also facilitating fuel cell opportunities in early markets

Fuel Cells for Backup Power ...

- Provide longer continuous run-time, greater durability than batteries
- Require less maintenance than batteries or generators
- *May provide <u>substantial cost-savings</u>* over batteries and generators

A 1-kW fuel cell system has been providing power for this FAA radio tower near Chicago for more than three years. (*Photo courtesy of ReliOn*)

Fuel Cells for Material Handling Equipment ...

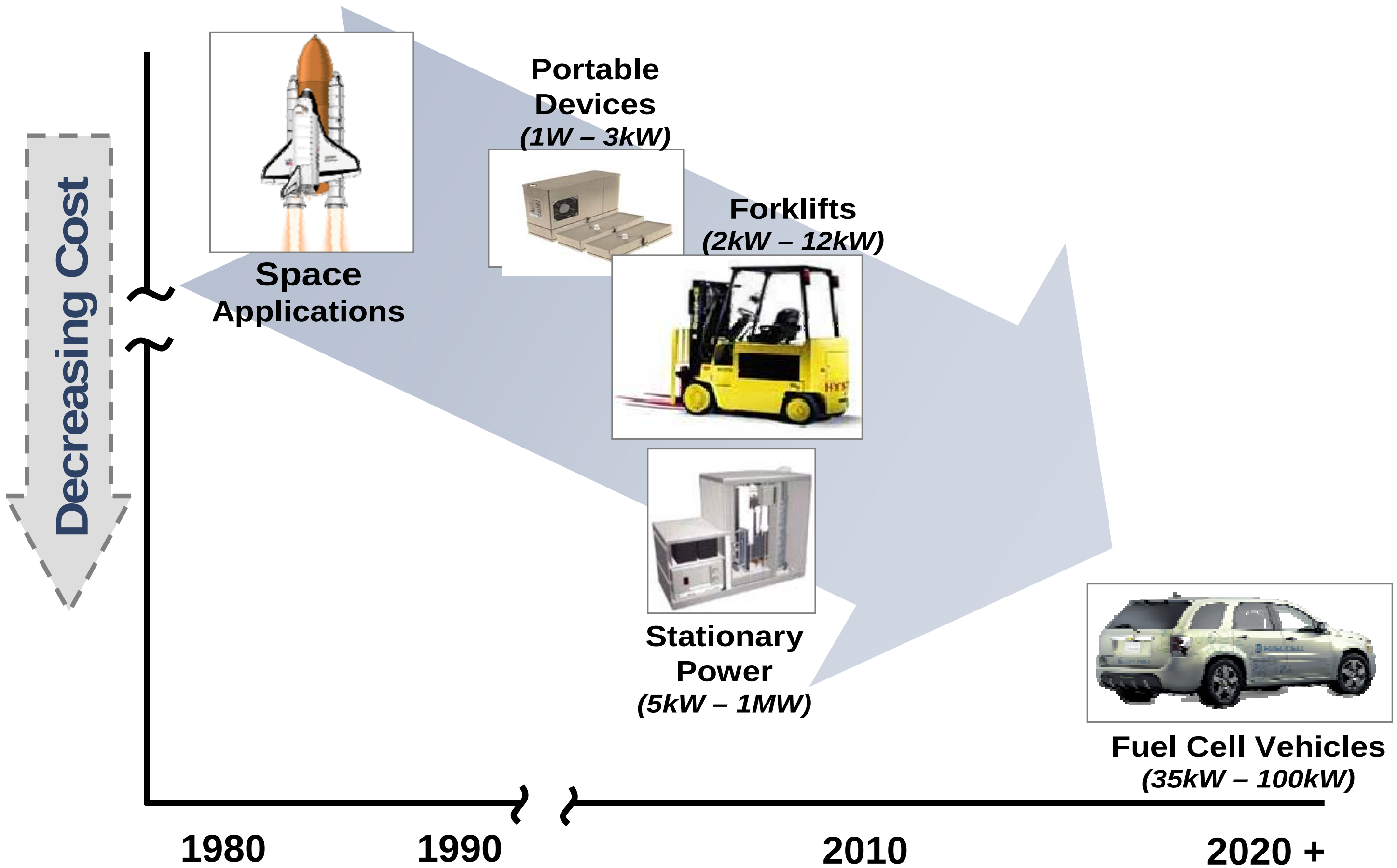
- Allow for rapid refueling — much faster than changing-out or recharging batteries
- Provide constant power without voltage drop
- Eliminate need for space for battery storage and chargers
- *May provide <u>substantial cost-savings</u>* over battery-powered forklifts

Photo courtesy of Hydrogenics

Fuel Cells for Data Centers ...

- Provide high-quality, reliable, grid-independent on-site critical load power
- Improve the effectiveness of data center power use by 40%, with combined heat-and-power (for cooling and heating)
- Produce no emissions
- Have low O&M requirements
- Can be remotely monitored

Early markets in stationary, portable, and niche applications will lower cost and establish a supplier base—to pave the way for the commercialization of fuel cell vehicles



DOE funded component R&D can enable multiple applications

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Investment opportunities exist throughout the hydrogen and fuel cell value chain

Production

- Electrolyzers
- Reformers
- Components
- Converters
- Catalysts
- Membranes

Delivery

- Materials
- Compressors
- Components
- Dispenser technologies

Storage

- Materials
- Carbon fiber tanks
- Conformable designs

Fuel Cells

- Catalysts
- Membranes
- Bipolar plates
- Membrane Electrode Assemblies [MEAs] (Gas Diffusion Layers [GDLs] etc)
- Water management
- Thermal management
- Sensor
- System strategies

Examples of Applications

Stationary

- *Combined heat and power [CHP] (e.g. hospitals)*
- *Uninterrupted power supply [UPS] (e.g. data centers)*
- *Residential*
- *Remote power*
- *Backup power*

Transportation

- *Vehicles*
- *Auxiliary power units*
- *Specialty vehicles (forklifts, marine, RVs)*

Portable

- *Cell phones*
- *Laptops*
- *Military*
- *Toys*

Commercialization Opportunities

Production

- PEM Electrolyzer Incorporating an Advanced Low-Cost Membrane
- Low Voltage Water Electrolyzer
- Compressor-Free High Pressure Electrolytic Hydrogen Fuel Generators
- Renewable-Capable Power Converter for Electrolyzers
- Bio-Oil for Renewable Distributed Hydrogen Production
- Biomass Indirect Gasification

Storage

- Solid State Hydrogen Storage
- Room Temperature Storage Material
- High Strength Carbon Fibers for Hydrogen Storage

Fuel Cells

- Fuel Processor for Fuel Cell Power Systems
- Metallic Bipolar Plates for Fuel Cells
- Bipolar Plates for High Temperature PEM Fuel Cells
- Mobion Direct Methanol Fuel Cells

PEM Electrolyzer Incorporating an Advanced Low-Cost Membrane

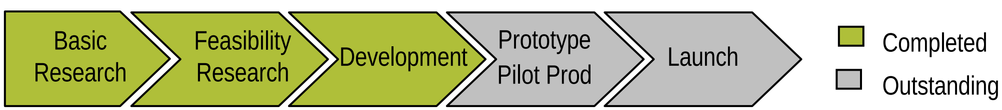
Description

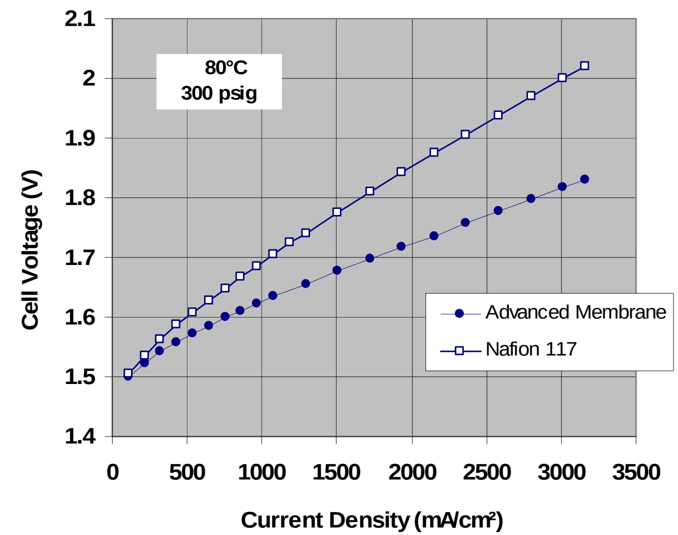
Highly-efficient, low-cost membrane and durable stack design for PEM Electrolyzers

Impact

- Electrolyzer capital and operating cost reductions
- Efficiency improvement: 61% (2003) to 67% (2007)
- Efficiency of 76% with DSM™ membranes

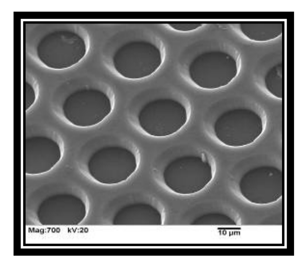
Technology Readiness





Estimated Time to Market

5 to 6 years



DSM™ high-strength, high-efficiency PEM membranes

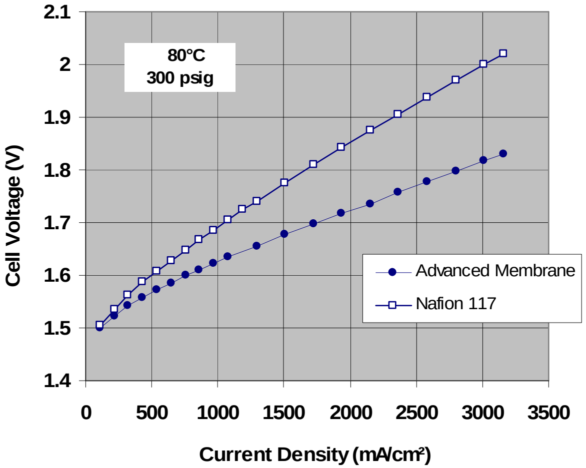
Estimated Commercialization Cost

- $40M: Membrane
  - Demonstrate Performance, Durability, Scale-up, & Manufacturing
- $5-10M: System Life and Field Testing, Agency Approvals
- $15M: System Manufacturing Set-up
  - Modular Electrolyzer Units (1-4 & 5-20kg/hr-H_2)

PEM Electrolyzer Incorporating an Advanced Low-Cost Membrane

- **POTENTIAL:** Significant operating and capital cost reductions are needed. Demand for high-purity hydrogen is increasing in industrial sectors (e.g., microchip manufacturing, ammonia production, metallurgy) as well as among utilities for generator cooling. Utilities are also interested in using electrolysis to capture lost energy from renewables, such as wind during low demand times, for peak shaving.
- **TECHNOLOGY DESCRIPTION:** Improved design, manufacturing techniques, and materials have resulted in a smaller, simpler, more efficient, and less expensive electrolyzers. Present focus is on developing a high-efficiency, low-cost membrane and durable stack design. A prototype system has been demonstrated.
- **IMPACT:** The cost of hydrogen produced by present commercially-available electrolysis systems is estimated to be greater than $5.00/kg-$H_2$, considerably higher than the DOE target of $3.70/kg in 2012 and <$3.00/kg in 2017. Via technology implementation, capital cost is decreased by a significant reduction in part count, lower cost materials, and improved, simpler design. An advanced membrane increases efficiency and reduces the electrical costs required to operate the unit.
- **IP:** 4 patents issued, 5 patents pending for water electrolyzers and electrolyzer systems design. Patents and published patent applications;
  - US 7,261,967, US 7,229,534, US 6,852,441 B2, US 6,500,319 B2
  - 2007/0026283 A1, 2006/0065521 A1
- **TECHNOLOGY STATUS:** Prototype units in the range of 0.25-0.50 kg-H_2/hr, being tested in-house and at NREL, are currently available with no special needs to implement. Funding is required to scale up the technology and further reduce stack and system costs. Capital is required to develop and implement high volume manufacturing.

High Pressure (2000 psig) PEM Electrolyzer with Low Cost Internal Components



Improved Performance over State of the Art Membranes

Low Voltage Water Electrolyzer

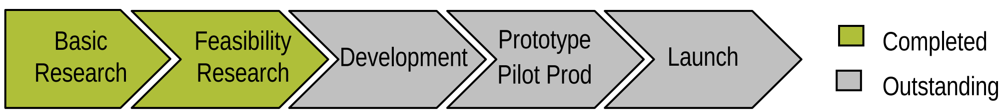
Description

Low Voltage Water Electrolyzer for Thermochemical Production of Hydrogen

Impact

- High efficiency hydrogen production using solar or nuclear energy with no greenhouse gases. Cell voltage of 0.6 V compared to 1.8 V for conventional water electrolyzer.
- Anticipate >30% efficiency improvement
- Simpler process design and lower cost of hydrogen than competing processes

Technology Readiness

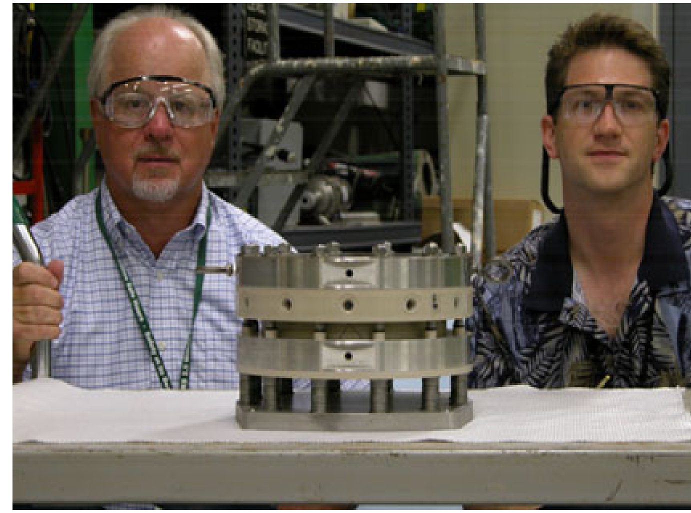


Estimated Time to Market

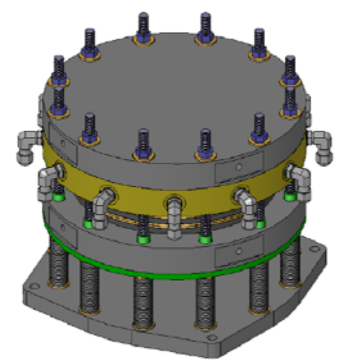
6 to 8 years

Estimated Commercialization Cost

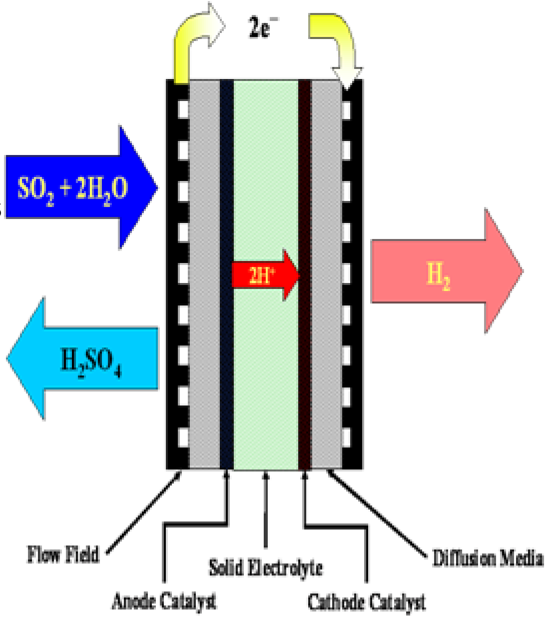
$100M plus balance of plant development - includes scale-up from 160 cm^2 cell area to commercial 1 m^2 (10,000 cm^2) cell area



Three-cell Electrolyzer Stack rated at 100 liters per hour of hydrogen



Low Voltage Water Electrolyzer



- **POTENTIAL:** Thermochemical hydrogen production requires high efficiency water-splitting with either solar central receivers or advanced nuclear reactors to provide high temperature heat. The Hybrid Sulfur (HyS) cycle is the only all-fluid, 2-step thermochemical cycle; it requires an efficient, low-cost water electrolyzer with a sulfur dioxide-depolarized anode.
- **TECHNOLOGY DESCRIPTION**: The SO_2-Depolarized Electrolyzer (SDE) uses a proton exchange membrane and fuel cell-type architecture. It uses SO_2 dissolved in sulfuric acid to depolarize the anode and reduce the cell voltage to less than 1/3 of that required for conventional water electrolysis. The SO_2 is regenerated in a high temperature process using heat from solar or nuclear sources.
- **IMPACT:** Potentially large; the transportation sector would require production facilities of similar capacity to the current national electricity production (400-500 gigawatts). Nuclear hydrogen could provide a large share of this, requiring 100-200 nuclear hydrogen power plants. The capital cost of the electrolyzer systems would be $40-80 billion.
- **IP:** 5 invention records. Patent applications have not been filed yet.
- **TECHNOLOGY STATUS**: Proof-of-concept established; prototype testing on units up to a 3-cell stack and 100 liters per hour hydrogen capacity. Integrated lab-scale experiment combining electrolyzer and balance of system planned for 2009. MW-scale pilot plant in 2012-2015 planned as next major step.
  - **Reduction to practice**: A 3-cell stack with 100 lph hydrogen capacity has been built and tested. Commercial cell performance goal is 600 mV at current density of 500 mA/cm2. Performance to date is 800 mV at 500 mA/cm2. Future development will include operation at higher temperature (120 C versus current 80 C), which is projected to reduce voltage to desired value.
  - **Special needs to implement**: The electrolyzer must be combined with a high temperature sulfuric acid decomposition system to complete the full HyS cycle. Hydrogen production requires high temperature heat from either a solar receiver or an advanced nuclear reactor.

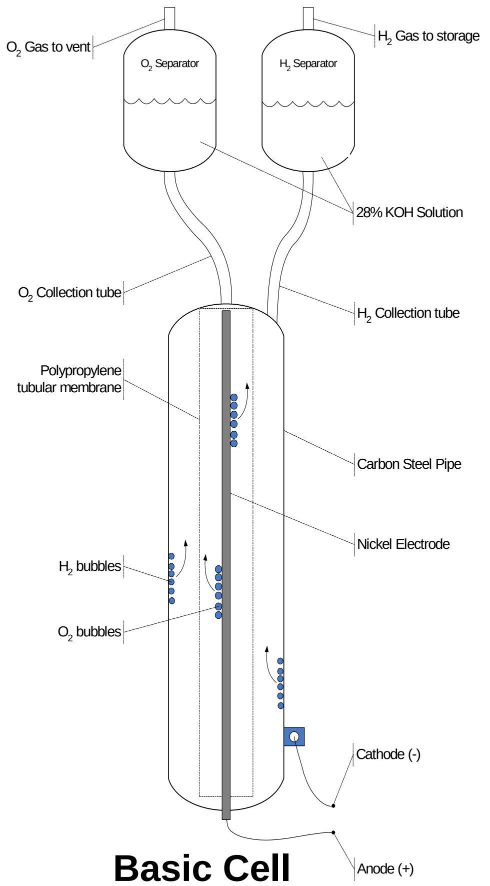
Compressor-Free High Pressure Electrolytic Hydrogen Fuel Generators

Description

Unique cell configuration and pressure control enables direct production of high pressure hydrogen (6500 psi+)

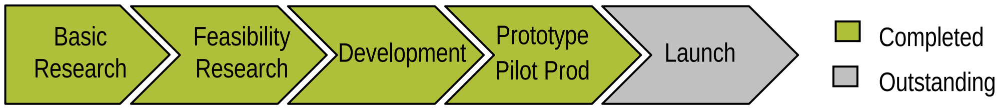
Impact

- Reduces capital costs by up to 50%
- Boosts efficiency up to 15% by eliminating compressors/dryers
- No power conditioning is needed to accommodate fluctuating input power from direct coupled renewable power (e.g. PV, wind)



Basic Cell Configuration

Technology Readiness



Estimated Time to Market

- Custom built units commercially available now
- Standard “certified” 1, 3, 5, and 10 kg/day units available mid-2009

Estimated Commercialization Cost

$5M – Primarily to get standard certifications, perform long term reliability testing, and set up fabrication line and subcontractors

Compressor-Free High Pressure Electrolytic Hydrogen Fuel Generators

- **POTENTIAL:** Current compressor and drier components for storing hydrogen from low-pressure electrolyzer systems are expensive and require significant maintenance.
- **TECHNOLOGY DESCRIPTION:** ***Hydrofiller*** unique cell configuration and pressure control enables direct production of high pressure hydrogen (6500 psi+), reduces capital costs, boosts efficiency by eliminating current costly and unreliable compressor systems. No power conditioning is needed to accommodate fluctuating input power from direct coupled renewable power (e.g. PV, wind).
- **IMPACT:** Will enable low-cost, low-maintenance compressor and drier components for storing hydrogen from low-pressure electrolyzer systems. It will also enable renewable energy use (for peaking power, base load stability, transportation fuel) beyond present practical limit of 15 to 20% Grid Input Power by providing energy storage and dispatchability capability. The global fuel cell/distributed hydrogen market to reach $18B by 2017, PV and Wind Power to reach $130B by 2016. ***(2007 Clean Edge Report)***
- **IP:** Core technology patent pending (PTO #20070151865) in 6 countries or regions; several extensions and fortifications in pipeline, including 300 kg/day design that is key to utility and service station scale application.
- **TECHNOLOGY STATUS:** Core technology performance (high-pressure efficiency and PV integration) documented in DOE-sponsored project.
  - **Reduction to practice:** 4 units in field, 2 in performance testing, 4 in fabrication for early-adopter customers.
  - **Availability:** 1 to 10 kg/day models available now in pre-commercial status; 300 kg/day model being developed with DOE funding.
  - **Special needs to implement:** Inventory of cell core components to reduce delivery schedule, certifications for 1 - 10 kg/day models, accelerated development of & IP protection for 300 kg/day model.

Typical Results – PV Driven Fueler with Integrated Storage and Dispenser

Renewable-Capable Power Converter for Electrolyzers

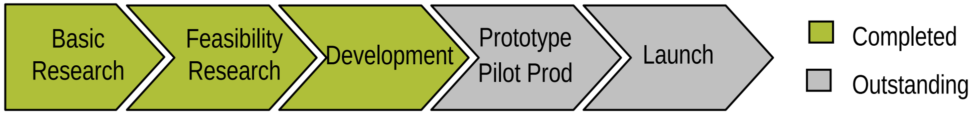
Description

Power converter to transform variable AC current from wind turbines and variable DC current from photovoltaic cells to consistent DC current for use by water electrolyzers to produce hydrogen

Impact

- Enables carbon-free hydrogen for transportation
- Standardizes the power conversion system to make the electrolyzer-energy source interface consistent, which enables improved system efficiency with renewable sources

Technology Readiness

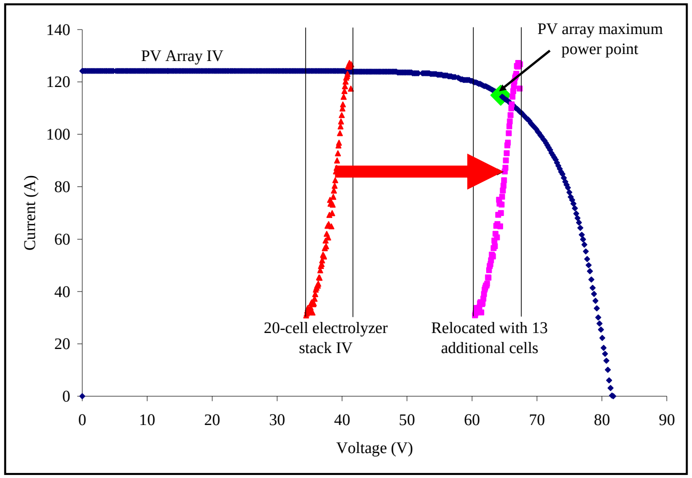


Estimated Time to Market

< 5 years

Estimated Commercialization Cost

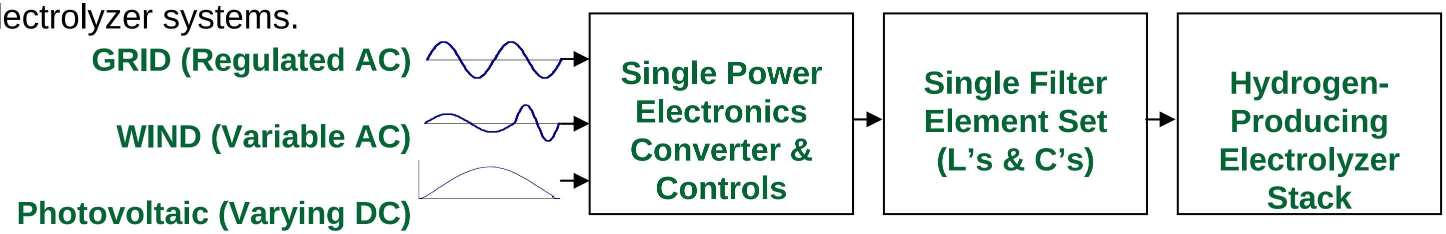
$10M – to fund start-up company to achieve high-volume manufacturing (500 units/yr)



Power electronics can shift the electrolyzer stack operating point in a PV direct-connect (red) configuration to one that controls to operate the stack (pink) near the maximum power point (green).

Renewable-Capable Power Converter for Electrolyzers

- **Potential:** Electrolyzer manufacturers lack low-cost, off-the-shelf power converters for their systems. Also, integration with renewable energy (RE) sources has been limited to small-scale systems incorporating redundant power converters – one for regulating grid alternating current (AC) and another for the RE source. A **single** power electronics converter can account for ~30% of the system cost.
- **TECHNOLOGY DESCRIPTION**: Power converters are required to provide direct current (DC) to the electrolyzer stack to produce hydrogen. Characterizing stack performance under varying input power, enabling multiple RE inputs to the power converter, and embedding algorithms to extract the maximum energy from RE sources can increase system efficiency, reduce system capital costs, and increase reliability by reducing components.
- **IMPACT:** A renewable-capable universal power supply could be widely accepted as early adoption increases and distributed electrolysis expands the market for hydrogen-powered transportation. Also, electrolyzers will act as dispatchable loads for utilities as RE penetration increases. Renewable electrolysis also can develop stranded RE sources where no transmission lines exist and hydrogen fuel is desired.
- **IP:** NREL continues to develop embedded control algorithms for its power converters to improve RE capture, enable multiple RE inputs, and maximize system efficiency with multiple electrolyzer systems. No patents pending, but algorithms used in power converters may be patentable.
- **TECHNOLOGY STATUS**: NREL has designed, built, and tested multiple power converters to improve energy capture from various RE sources tied directly to commercially available electrolyzer stacks.
  - Reduction to practice: NREL has demonstrated improved energy capture from small variable-speed wind turbines and PV sources directly coupled to the stack of polymer exchange membrane (PEM) electrolyzer systems.



Bio-Oils for Renewable Distributed Hydrogen Production

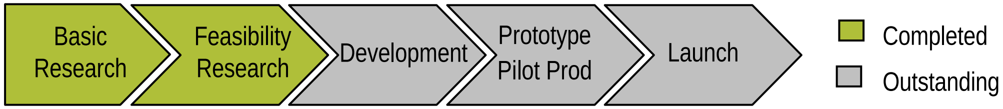
Description

Distributed hydrogen production from biomass-derived pyrolysis liquids (bio-oils)

Impact

- Allows for distributed production of hydrogen from renewable resources
- Potential for using a variety of biomass feedstocks

Technology Readiness

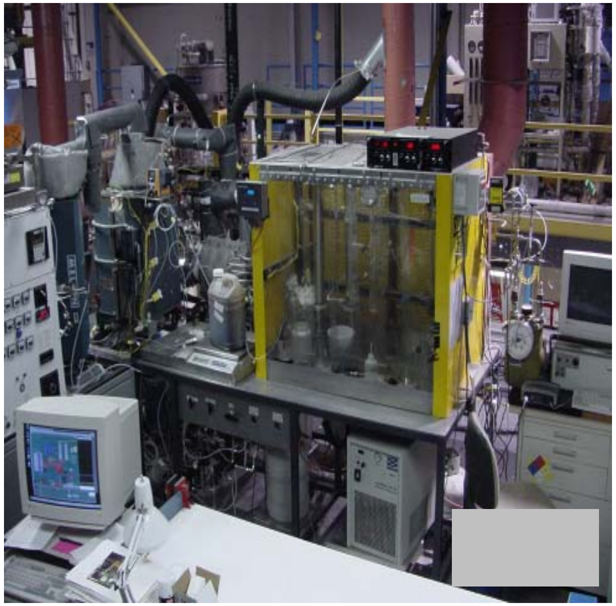


Estimated Time to Market

5 to 7 years

Estimated Commercialization Cost

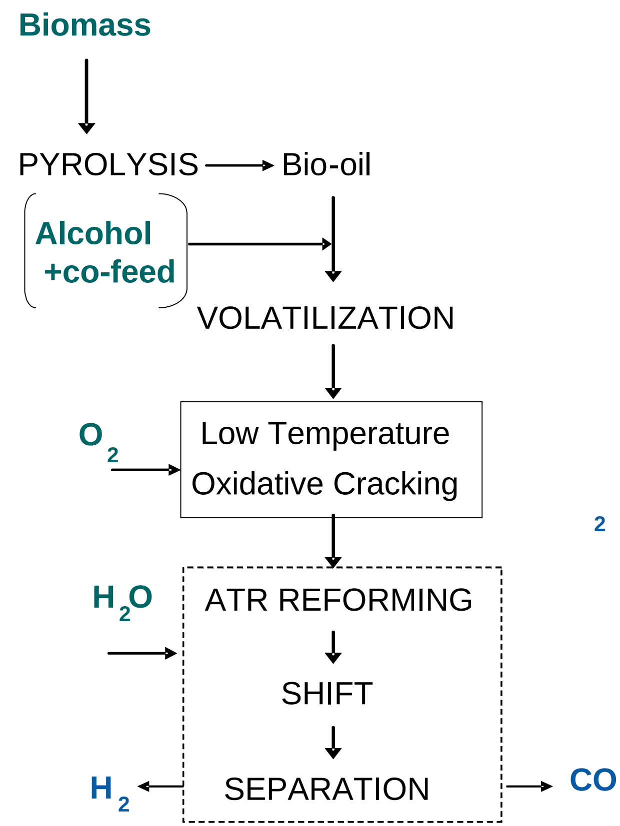
$10M - $20M – to commercialize 1500 kg/day unit



Bio-oil to Hydrogen Experimental System

Bio-Oil for Renewable Distributed Hydrogen Production

- **Potential:** Biomass has significant potential for fuel production, such as hydrogen, but its dispersed nature and low energy density increases cost.
  - Size of Problem: The technical potential of biomass to hydrogen could be over 100 million metric tons annually in the U.S.
- **Description of Technology:** Pyrolysis produces a liquid product in high yields which increases the volumetric energy density and allows autothermal reforming (ATR) operation.
- **Impact:** NREL is investigating a staged approach based on partial oxidation prior to catalytic conversion that could allow the complex mixture to be reformed like simple alcohols.
  - This technology could be used to co-feed other feedstocks (e.g., kerosene) with possible synergistic effects
- **IP:** NREL has established pre-competitive proofs of concept and developed experimental techniques that will allow IP to be developed as the process is further refined and practiced at larger scale.
- **Status:** The progress to date is consistent with the DOE 2012 cost targets, and will be verified using a large scale system, 1 – 2 kg H_2/hour, to be completed in 2008; and a future pilot-scale system, 10 – 20 kg H_2/hour (capital cost to be determined).



Technology Concept

Biomass Gasification

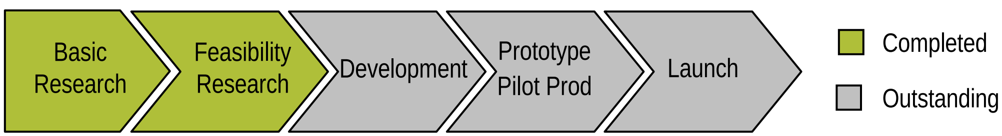
Description

Steam gasification of biomass plus gas cleanup & conditioning, and hydrogen separation

Impact

- Potential to reduced cost of hydrogen by 40-50%
- Hydrogen potential from biomass of 100 million metric tons annually

Technology Readiness



Estimated Time to Market

5 – 7 Years (assuming active commercialization efforts)

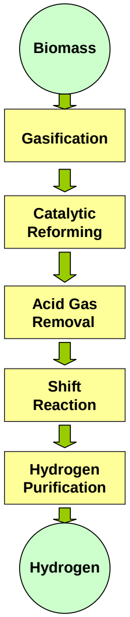
Estimated Commercialization Cost

$200M for RD&D plus balance of plant development – for 2000 ton/day (150-200K kg/day) biomass gasifier

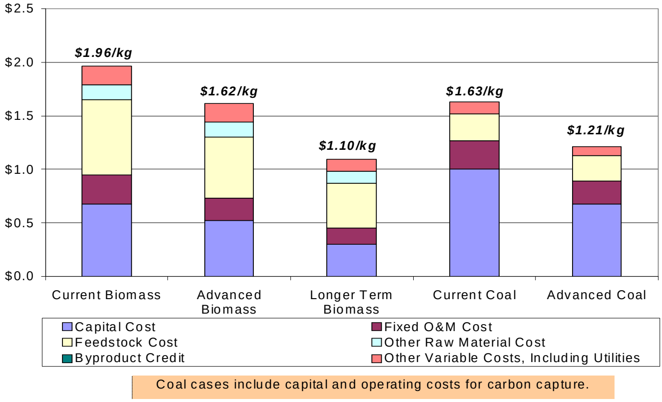
NREL 3 kg H_2/hour Biomass Gasifier

Biomass Indirect Gasification

- **Potential:** Biomass has significant potential for fuel production, such as hydrogen, but its dispersed nature and low energy density increases cost
  - Size of Problem: The technical potential of biomass to hydrogen could be over 100 million metric tons annually in the U.S.
- **Description of Technology:** Steam gasification of biomass, followed by contaminant removal, shift reaction, and hydrogen purification
- **Impact:** NREL is investigating steam gasification followed by catalytic reforming, H_2S removal, and shift reaction to produce a hydrogen rich gas. Preliminary technoeconomic analyses indicate the potential to produce hydrogen at costs lower than competing slagging oxygen gasifier based systems.
- **IP:** NREL has developed experimental techniques and catalyst formulations that will allow IP to be developed as the process is further refined and practiced at larger scale. A patent application has been submitted for the reforming catalyst support. Patent application number 2007/0444009.
- **Status:** The progress to date is consistent with the DOE 2012 (<$1.60/gge H_2)and 2017 plant gate cost targets ($1.10/gge H_2)



Technology Concept



Results

Solid State Hydrogen Storage

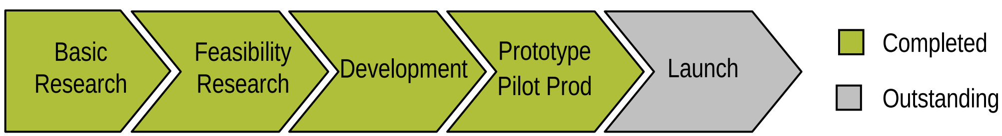
Description

Solid-state hydrogen storage container for stationary and portable fuel cell applications such as back-up power for telecommunication systems and forklifts . When utilized with traditional AB_2 and AB_5 interstitial hydrides can provide 1-1.5 wt.% and 40 - 50 g per liter hydrogen with near ambient temperature operation.

Impact

- Allows for compact hydrogen storage
- Allows for low pressure safe hydrogen delivery and storage

Technology Readiness



Estimated Time to Market

1 to 2 years

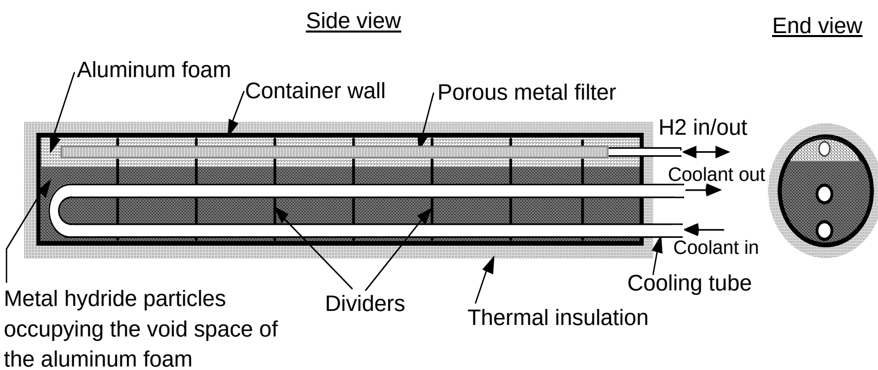
Estimated Commercialization Cost

$20M - $50M for final system design and development costs plus establishing moderate level of production capacity

Hydrogen Storage for Stationary & Backup Power

Solid State Hydrogen Storage

- **PROBLEM:** Today's stationary and portable fuel cell systems need low-cost, safe, and efficient hydrogen storage. High-pressure tanks require too much space, high storage and operating pressures, and additional compression.
- **TECHNOLOGY DESCRIPTION:** A modular system with connected tubes to meet a variety of hydrogen storage or delivery needs. Internal metal foam material increases heat transfer and improves the rate of hydrogen charging and delivery in the system. Overall system specification depends on choice of metal hydride used.



- **IMPACT:** Safe, low-pressure, and compact hydrogen storage can enable new stationary and portable power applications, including indoor and remote applications.
- **IP:** 3 patents (2 U.S., 1 CN, with EU and JP pending).
- **TECHNOLOGY STATUS:** Currently available. Several prototype systems have been built and tested for industrial vehicle, stationary, and backup power applications.
  - **Reduction to practice**: Demonstrated systems include a 15kg system for a hydrogen hybrid ICE transit bus and 2 kg systems for onboard fuel cell industrial vehicles and fuel cell back power systems.
  - **Special needs to implement**: No special needs; choice of metal hydride materials and system configuration are needed for specific markets and applications.

Room Temperature Storage Material

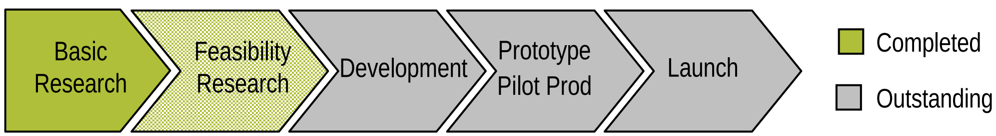
Description

Solid-state hydrogen storage material that can store ~4wt% H_2 at nominally room temperature and < 100 bar pressure

Impact

- Allows for compact hydrogen storage at low pressure and room temperature
- Enables simpler energy management & power-plant integration

Technology Readiness



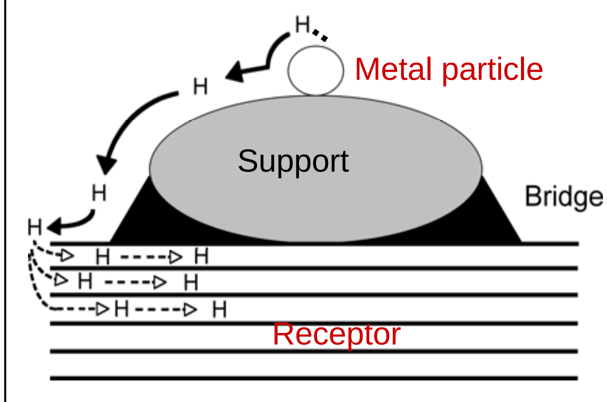
Estimated Time to Market

7 to 10 years

Estimated over next 3-4 years

~$3M for R&D for next 3-4 years to complete feasibility

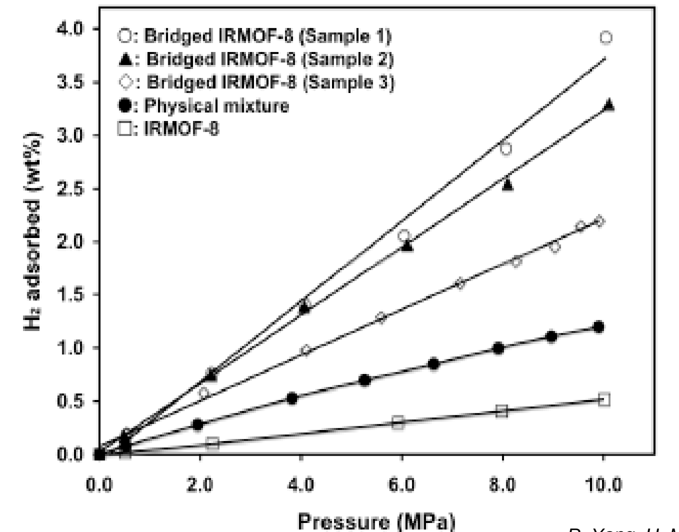
DOE work on "spillover" catalyzed worldwide R&D



R. Yang, U. MI

Room Temperature Storage Material

- **PROBLEM:** Today's vehicular storage systems must meet >300 mile driving range without compromising space, cost, or performance. Room temperature and low pressure options are needed to replace high pressure tanks and simplify the system while maintaining required volumetric & gravimetric capacity and transient performance.
- **TECHNOLOGY DESCRIPTION:** A novel adsorbent material that has been shown to store up to 4 wt% at nominally room temperature and ~100 bar pressure. The lower energy requirements may enable simpler system thermal management.
- **IMPACT:** Safe, low-pressure, and compact hydrogen storage can enable vehicular as well as new stationary and portable power applications.
- **IP:** 1 US patent application and 1 international patent application based on spillover concept.
- **TECHNOLOGY STATUS:** Applied R&D activity
  - Numerous research groups in the world "catalyzed" by this activity
  - R&D emphasizes improving net capacity, transient performance, energy requirements and durability



R. Yang, U. MI

High Strength Carbon Fibers for Hydrogen Storage

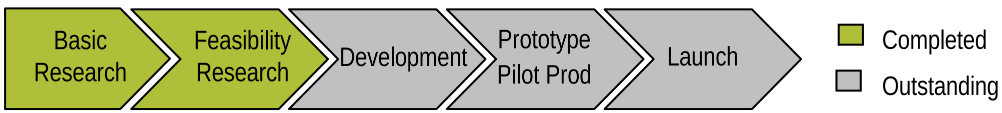
Description

Low cost, high strength carbon fibers

Impact

Can significantly reduce the cost of compressed hydrogen storage vessels

Technology Readiness



Estimated Time to Market

6 to 10 years

Estimated Commercialization Cost

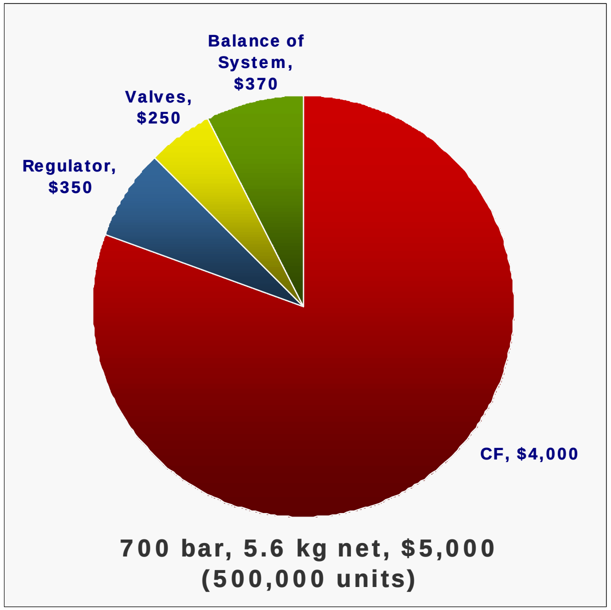
$100M for purchasing, building, and installing pilot line capable of producing 6 million pounds of carbon fiber per year

Conventional pilot line

Advanced, plasma-based conversion process in development

High Strength Carbon Fibers for Hydrogen Storage

- **PROBLEM:** High strength, light weight of carbon fibers (CF) are critical for storing compressed hydrogen onboard a vehicle. Currently this material is too expensive for automotive use.
- **DESCRIPTION:** ORNL is investigating how to produce high strength CF via melt spinnable polyacrylonitrile (PAN) and modified textile grade PAN. ORNL has already achieved breakthroughs in CF conversion processes (e.g., atmospheric pressure plasma processing for oxidation and surface treatment to enhance fiber/resin affinity and adhesion).
- **IMPACT:** These alternative materials and advanced processing methods have been projected to significantly lower the cost per pound of carbon fiber.
- **IP:** ORNL has 20 pieces of IP at various stages.
- **STATUS:** ORNL has established strategic partnerships and unique capabilities including a modular carbon fiber research pilot line and other facilities to support CF development.
  - **Reduction to Practice**: Ongoing.
  - **Next Steps**: Iterations to optimize composition for spinning.



Fuel Processor for Fuel Cell Power Systems

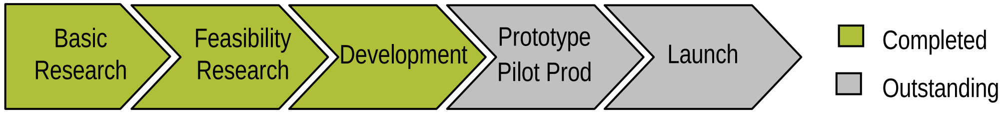
Description

Fuel-flexible, simple fuel processors are required for small-scale (1 to 7 kW_e) distributed fuel cell power systems to become viable. ANL has developed an energy-efficient, simple, compact and fuel-flexible processor that can serve a range of applications and markets.

Impact

- Enables residential combined heat and power
- Facilitates remote stationary applications

Technology Readiness



Estimated Time to Market

2 to 4 years

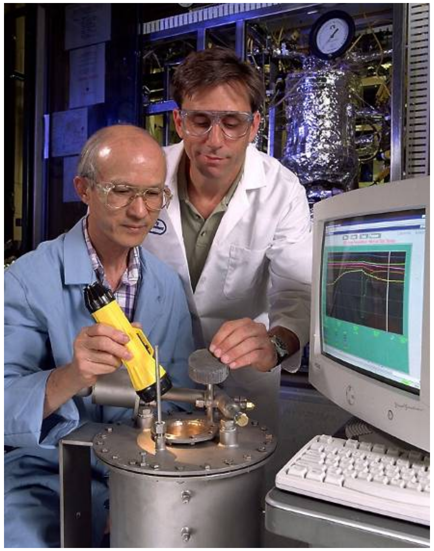
Estimated Commercialization Cost

Commercialization requires prototyping and testing (product design completed for natural gas) and manufacturing process development. $2M to $4M for prototyping in a complete cogeneration system; additional $7M for launch

The reactor vessels above were developed for 1 to 2 kW_e applications, and successfully tested in a breadboard configuration, validating the configurations and catalysts.

Fuel Processor for Fuel Cell Power Systems

- **PROBLEM**: Fuel processors for small fuel cell power systems have high costs, in part because fuel processing technologies have not been flexible enough nor simple enough to gain the cost advantage of serving a wide range of fuel cell markets.
- **DESCRIPTION:** The ANL processor has the following attributes: (1) *simpler, more compact design*—system integration and mass production will be easier and cheaper; (2) *fuel flexibility*—the processor operates well on a range of commercial fuels, maintaining performance even with high-sulfur fuel; and (3) *energy efficiency*—the reactor layout and design complement the various components, which leads to excellent heat recovery and energy efficiency. Overall fuel consumption and operating costs are lower.
- **IMPACT:** Initially, the ANL processor will be used in stationary fuel cell systems (principally residential power). Market projections show potential for sale of ~15,000 units (with 5 to 7 kW_e capacity) in 2010 and more than 400,000 in 2015. Urban residential cogeneration units can be hooked to complement the grid power, while available heat from the unit can be used to produce hot water and space heating. These units are also attractive for remote, stationary applications where other fuels (LPG or liquid fuels) may be preferred.



- **IP:** 9 patents, 4 patent applications.
- **TECHNOLOGY STATUS**:
  - Prototype reformers have been fabricated; patent on fuel-flexible catalyst issued.
  - Residential scale processor with heat recovery product design completed.
  - Market introduction projected 2010-2011.

Metallic Bipolar Plates for Fuel Cells

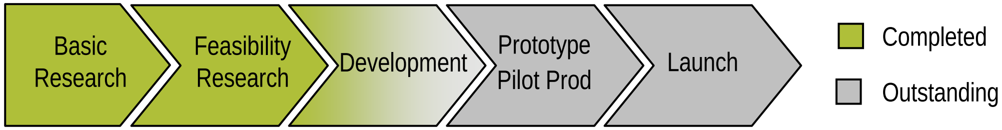
Description

High-volume manufacturing of thin, low-cost, corrosion-resistant bipolar plates is required for cost competitive polymer electrolyte membrane fuel cells. ORNL's development of low-cost base steels and gas nitriding offers a path to meeting industry cost and performance targets in high-volume production

Impact

- Enables highest fuel cell power density
- Facilitates mass manufacture

Technology Readiness



Estimated Time to Market

2 to 3 years: at transition between development and initial prototype production

Estimated Commercialization Cost

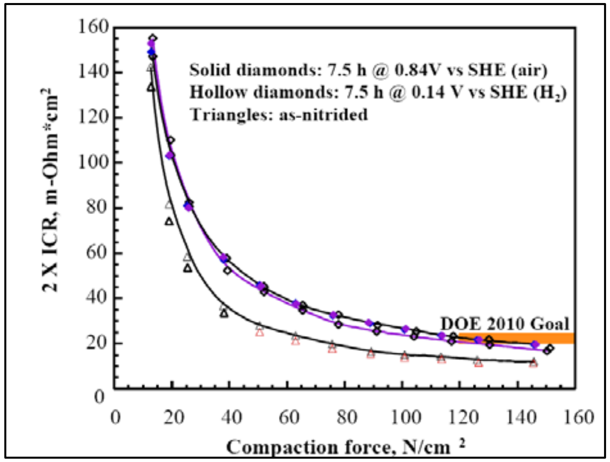
$5M to $10M for application-specific plate design and manufacturing process development and optimization. ($1.3M to develop specific applications in transportation, and distributed power and electrochemical compression for pressurized hydrogen production)

Stamped and nitrided
18 cm^2 active area bipolar plate
(ORNL/GenCell Corp)

Metallic Bipolar Plates for Fuel Cells

- **Problem:** Bulk manufacture of thin, low-cost, corrosion resistant bipolar plates is required for high power density in polymer electrolyte membrane fuel cells for all applications.
- **Description:** Thin, stamped metallic bipolar plates are protected by gas nitriding to form a defect-free Cr-nitride surface layer.
- **Impact:** Metal plates are thinner than conventional carbon or composite plates, leading to increased stack power density and reduced product weight and volume (by approximately 25-30%). The plates can be used in fuel cell applications for transportation, and distributed power and electrochemical compression for pressurized hydrogen production.
- **IP:** 2 patents and 1 patent pending; currently available for licensing.
- **Status:** Developing low-cost Fe-Cr base steels for the stamped bipolar plate that are amenable to the gas nitriding to form Cr-nitride.
  - Reduction to Practice: Fe-20Cr-4V can be manufactured into 4 mil foil and is readily stamped to form flow fields. Fe-Cr plates meet DOE fuel cell performance targets for corrosion resistance and contact resistance. Combined alloy, stamping, and nitriding costs meet DOE cost targets at high volume production.
  - Capital Required: $1.3 M to develop specific application; manufacturing capital requirements depend on product design.

GenCell serpentine flow-field stampings prior to nitridation



Nitrided Fe-20Cr-4V meets interfacial contact resistance target

Bipolar Plates for High Temperature PEM Fuel Cells

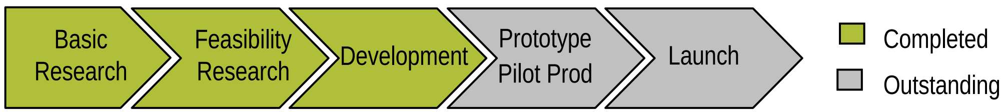
Description

GRAFCELL® flexible graphite bipolar plates for PEM fuel cells can meet or exceed industry cost and performance targets in high-volume production. The technology uses an expanded natural graphite mat that is resin-impregnated, embossed and cured to form the final plate.

Impact

- Enables continuous PEMFC operation at 120°C
- Enables low-cost, high-volume production

Technology Readiness



Estimated Time to Market

2 to 3 years

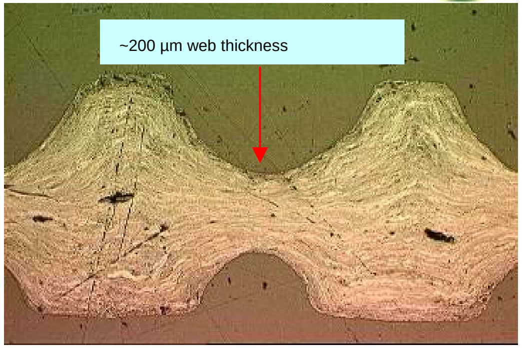
Estimated Commercialization Cost

Commercialization requires manufacturing process development for high production rates and low cost

Molded GRAFCELL® Composite Corrugated Flow Field Oxidant Plate

Bipolar Plates for High Temperature PEM Fuel Cells

- **PROBLEM:** Large-volume manufacturing of thin, gas-impermeable, resin-impregnated, flexible graphite bipolar plates is needed for high-temperature, high-power density PEM fuel cells for various applications.
- **TECHNOLOGY DESCRIPTION:** Expanded natural graphite mat is resin-impregnated, embossed, and cured to make thin, gas-impermeable bipolar plates. The resulting composite material has graphite as its continuous phase, allowing the composite to retain the low contact resistance, high thermal conductivity, and high electrical conductivity of bulk graphite. High temperature resins provide mechanical strength and structural stability while allowing continuous operation of composite bipolar plates at temperatures up to 120°C .



Cross section of composite plate showing minimum web thickness

- **IMPACT:** Resin-impregnated, flexible graphite bipolar plates can be fabricated using high-volume, low-cost manufacturing processes and can meet or exceed DOE cost and performance targets. Plates can be used for transportation, materials handling, and backup and distributed power applications
- **IP:** Numerous patents and patents pending
- **TECHNOLOGY STATUS:** Optimizing processing parameters for fabrication of full-size flow field plates for testing short stack under automotive conditions
  - **Reduction to Practice:** Samples of resin-impregnated flexible graphite composite plates have successfully operated at 120°C for more than 700 hours with no evidence of degradation or drop in performance. Physical properties of sample composite materials are significantly improved or comparable to incumbent GRAFCELL® materials
  - **Special Needs to Implement:** Partners needed for manufacturing process development for scale-up of production quantities and operation speeds
  - **Capital Required:** Final capital requirements will be based on the results of process optimization studies that are still in progress

Mobion Direct Methanol Fuel Cells

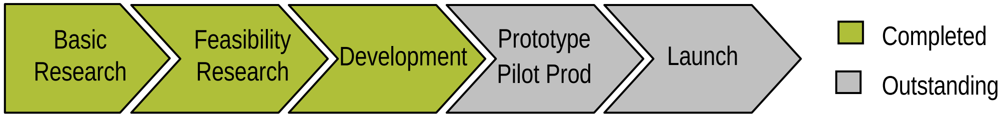
Description

The Mobion Direct Methanol Fuel Cell (DMFC) power system for consumer electronic devices offers higher energy density than state-of-the-art batteries. This new technology simplifies the DMFC system by capturing water in the membrane, enabling elimination of the anode and water circulation pumps.

Impact

- Demonstrates ***2700 hrs of continuous operation*** with less than 15% loss in power
- Enables a broad operating envelope suitable for consumer electronics
- Reduces system complexity and part count

Technology Readiness

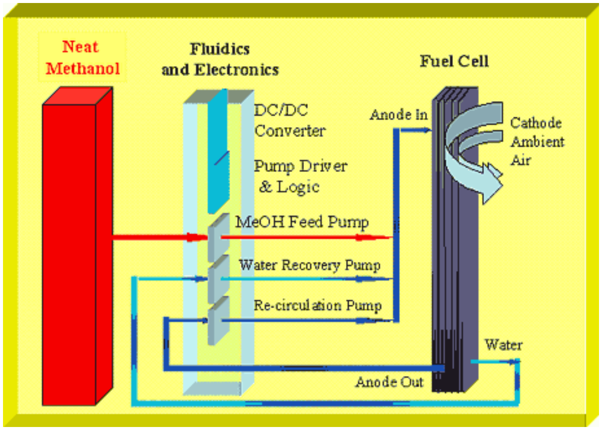


Estimated Time to Market

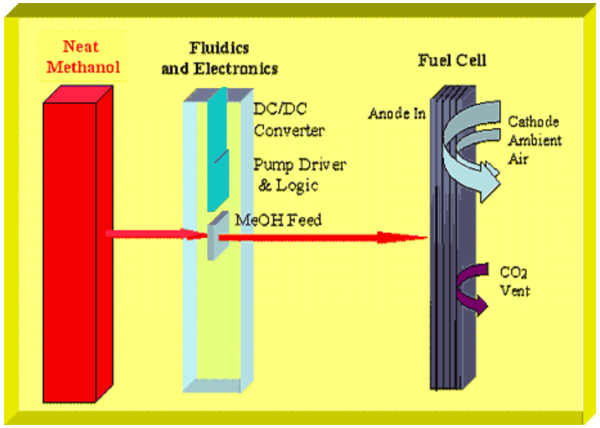
Product launch in 2009

Estimated Commercialization Cost

Commercialization requires further cost reduction, high-volume production processes, and improved ease of assembly



Typical DMFC system



MTI's Mobion technology simplifies system

Mobion Direct Methanol Fuel Cells

- **PROBLEM:** DMFC membranes must remain hydrated. Since water is consumed at the fuel cell anode and produced at the cathode, water is typically carried out with air flowing over the cathode. Water loss from the membrane requires hardware to separate and reclaim water from the cathode exhaust and pump it back to the anode circulation loop. Another pump is then needed to distribute the water (co-flowing with the fuel) over the active anode area.
- **TECHNOLOGY DESCRIPTION:** By capturing water in the membrane, Mobion technology eliminates the need for pumps and hardware to move water from the cathode to the anode loop and subsequent redistribution.
- **IMPACT:** DMFC systems have traditionally had many components and pumps. Significant reductions in system complexity allow a system that is simple enough to be integrated into a handheld device.
- **IP:** 45 patents granted.
- **TECHNOLOGY STATUS:** Several generations of systems have been produced with decreasing size and increasing energy density.
  - **Reduction to practice**: Prototypes have been demonstrated. Continuing to reduce cost and improve ease of assembly / manufacturing.
  - **Special needs to implement**: Use of low-cost, high-volume processes for all components and subsystems. Cell components have been designed and tested for high-volume manufacturing processes such as injection molding, over-molded seals, and stamping.

Injection molded cells:
- **50 mW/cm^2**
- **1.4 Wh/cm^3**

Decreasing system size from prototype to prototype

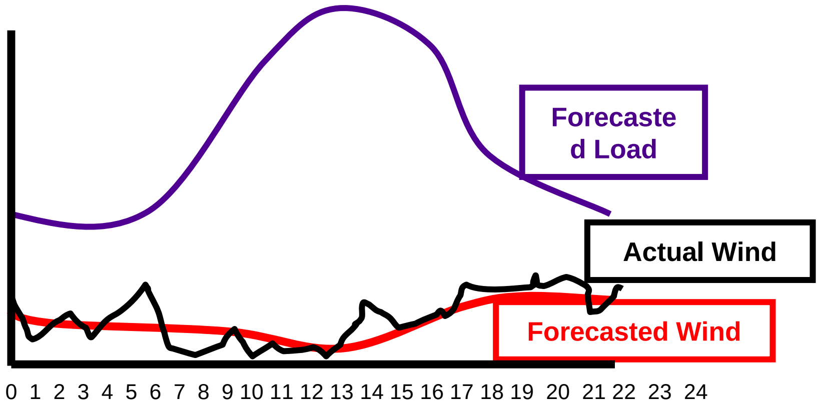
Agenda

- Industry Landscape
- Program Objectives
- Technology Commercialization Opportunities
- Emerging Opportunities
- Appendix

Hydrogen Energy Storage

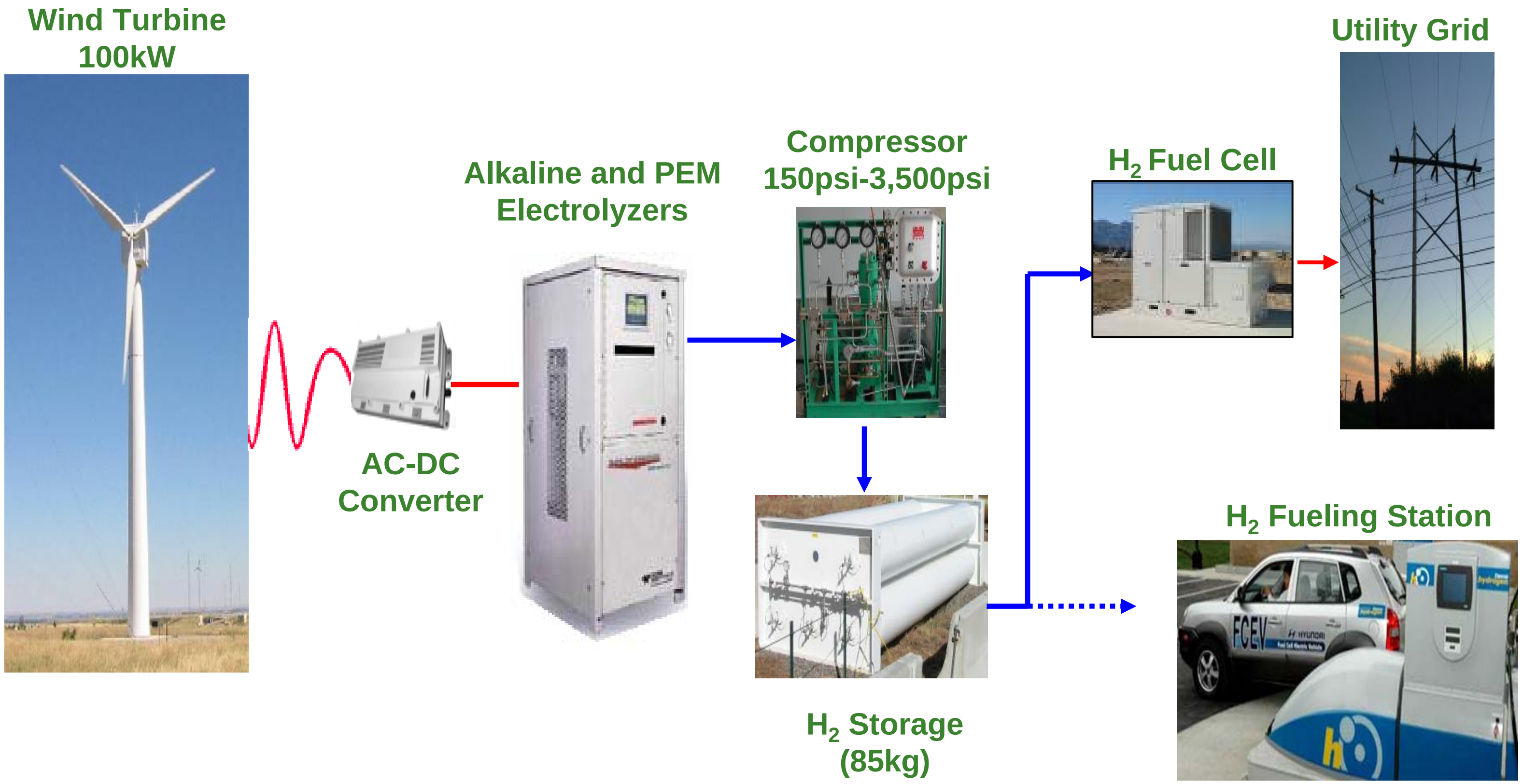
- Wind and solar resources result in variable and seasonal energy production.
- Investment opportunities may exist to enable renewable energy storage and alleviate overloaded transmission lines
- Advantages to this approach:
  - Firming of the grid via time shifting, smoothing, and ramp rate control
  - Reducing power plant cycling and availability requirements minimizing spinning reserve value and operation & maintenance costs
  - Transmission and distribution grid systems support
  - Natural gas price hedge
  - Long term environmental benefits

- Technology Needs
  - Power electronics which can directly convert renewable "wild" AC transmission to usable electric power in an electrolyzer thereby increasing the efficiency while lowering cost.
  - Improved electrolyzers that have larger capacity, increased efficiency, with lower (60-70%) costs.
  - Improve fuel cell durability (40,000 hrs for stationary) and cost (<$750/kW)



Source: National Renewable Energy Laboratory

Xcel-NREL Wind2H2 Project will identify key opportunities and benefits compared to battery storage.



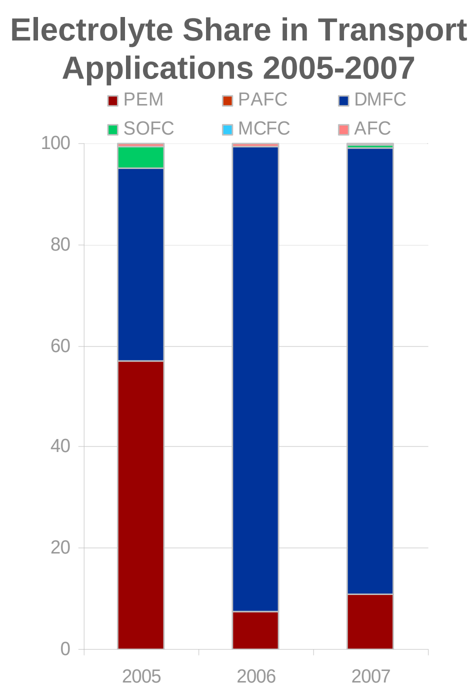
Emerging Opportunities

Bio-Oil as a Syn-gas/Hydrogen Intermediate

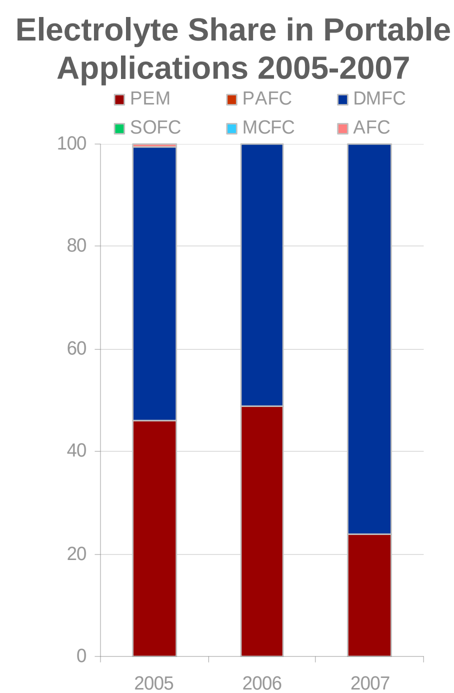
- Bio-Oil is a low cost alternative ($6 – $7.5/GJ) to ethanol (2012 target ~$15/GJ) or sugar solutions (2012 target ~$10/GJ)
  - 5-fold increase in volumetric energy density over biomass.
  - Breakthroughs are needed in physical and chemical properties such as energy density, pH and stability
- Little has been invested in addressing these problems
  - Innovation could enable a variety of opportunities in distributed and centralized biomass
- Near-term niche markets in thermochemical biomass are available and bio-oil to syngas/H_2 needs to be piloted.
  - Gasification for combined heat, power& fuels could be based on pyrolysis technology where bio-oil use is demonstrated
  - Pilot scale systems will provide know-how to the first generation commercial systems

Fuel Cells for Portable Power

- Direct methanol fuel cells have tremendous potential to replace batteries for cell phones, laptop PCs, cameras, and other portable electronic devices.
- High energy density provides a more lightweight system providing a 2-10x longer life than batteries.
- Methanol approval on aircraft enables market opportunities.



* Source: Fuel Cell Today



* Source: Fuel Cell Today

Agenda

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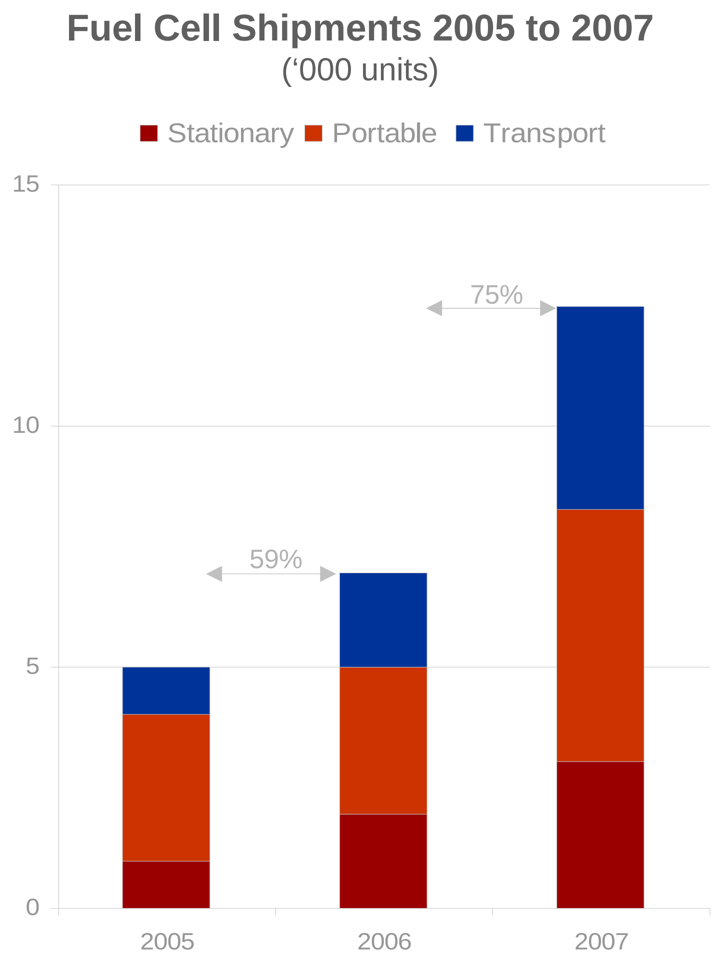
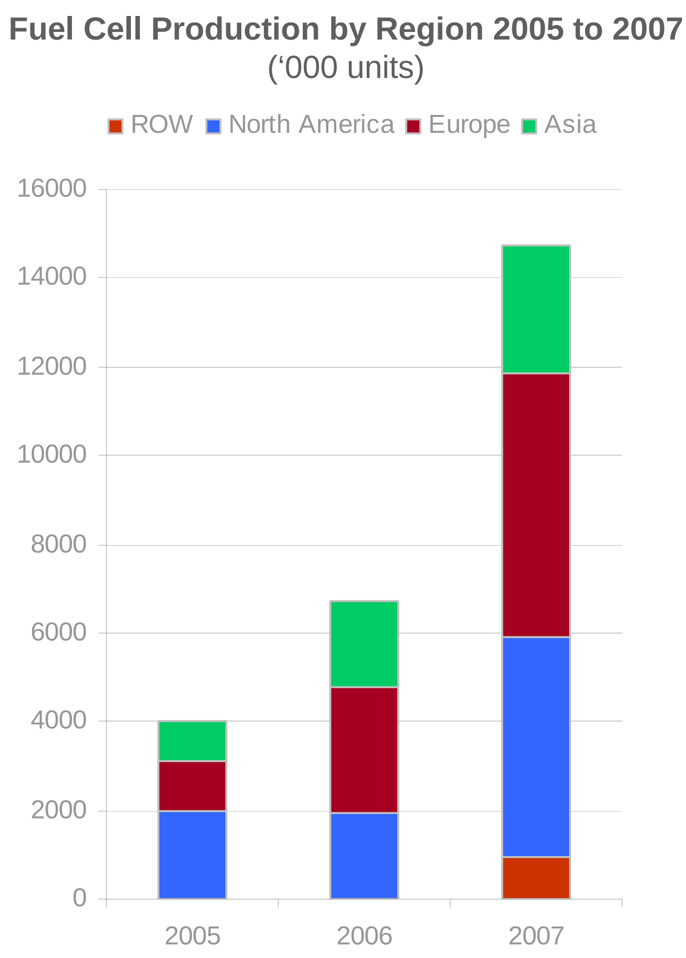
Fuel cell production continues to be centered in North America and Europe.

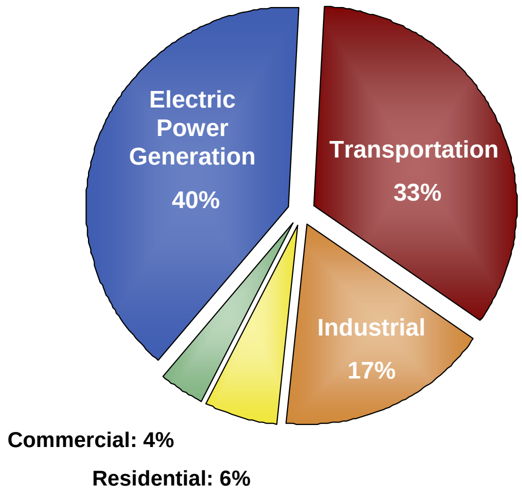




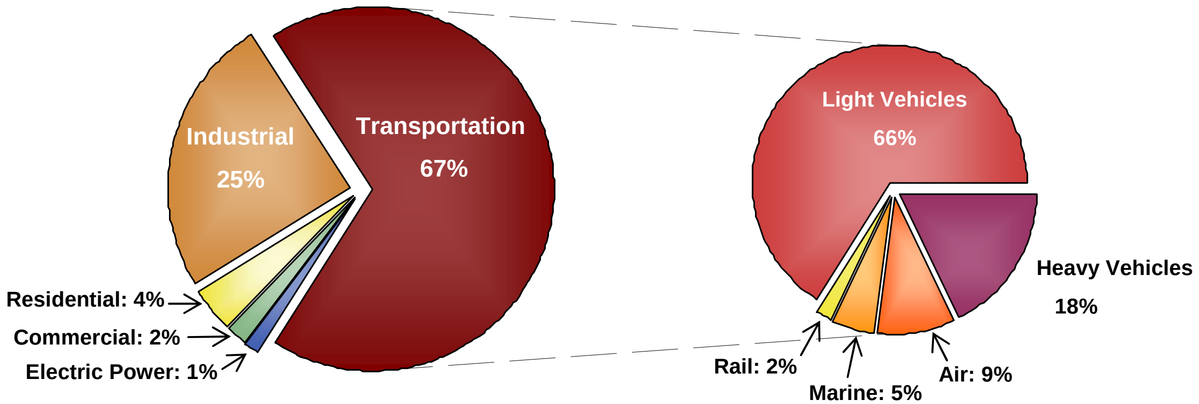
Source: Fuel Cell Today Industry Review 2008

Hydrogen can bring benefits to the two largest energy sectors.

U.S. CO_2 Emissions by Sector (2006)



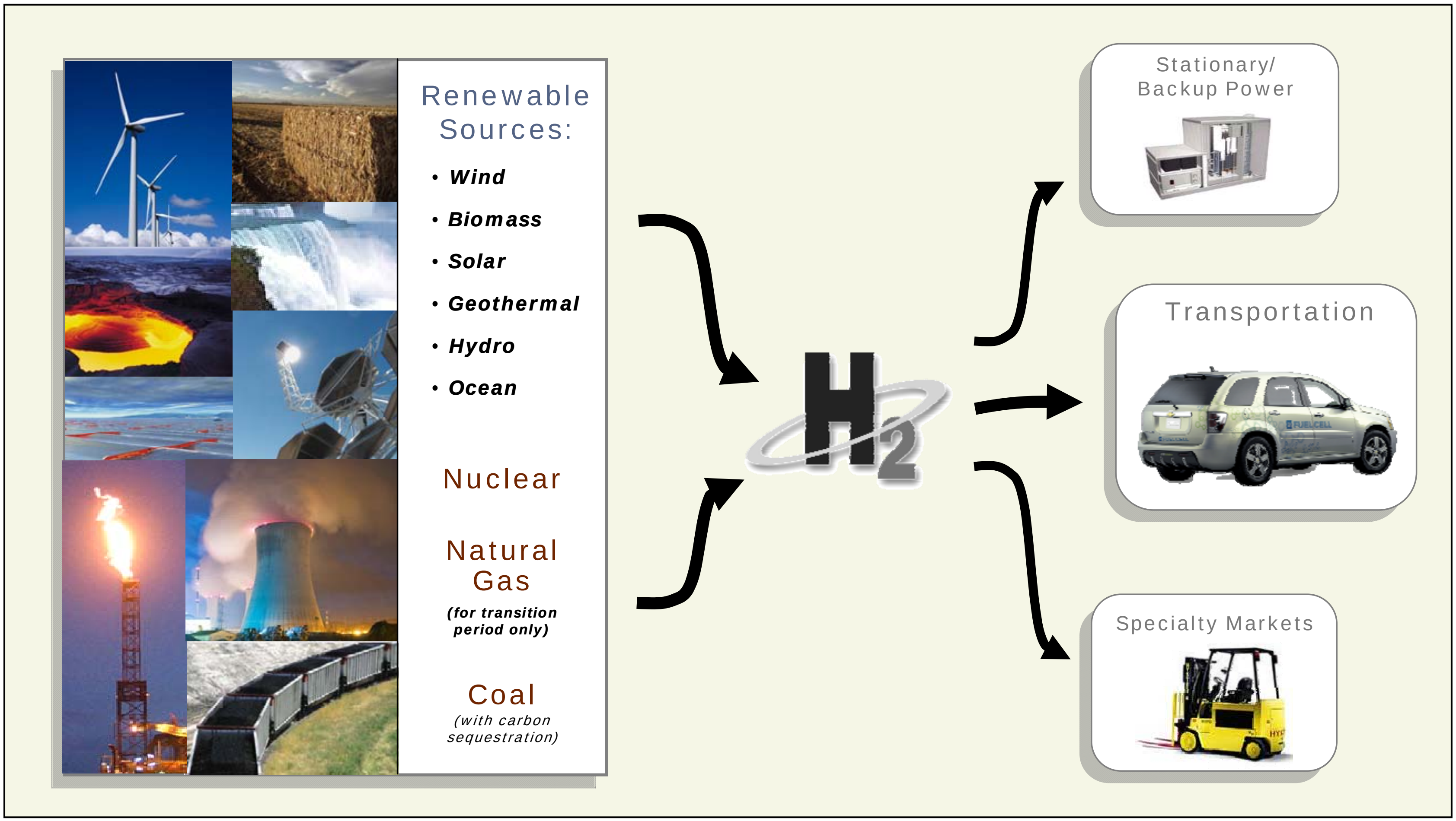
U.S. Oil Consumption (2006)



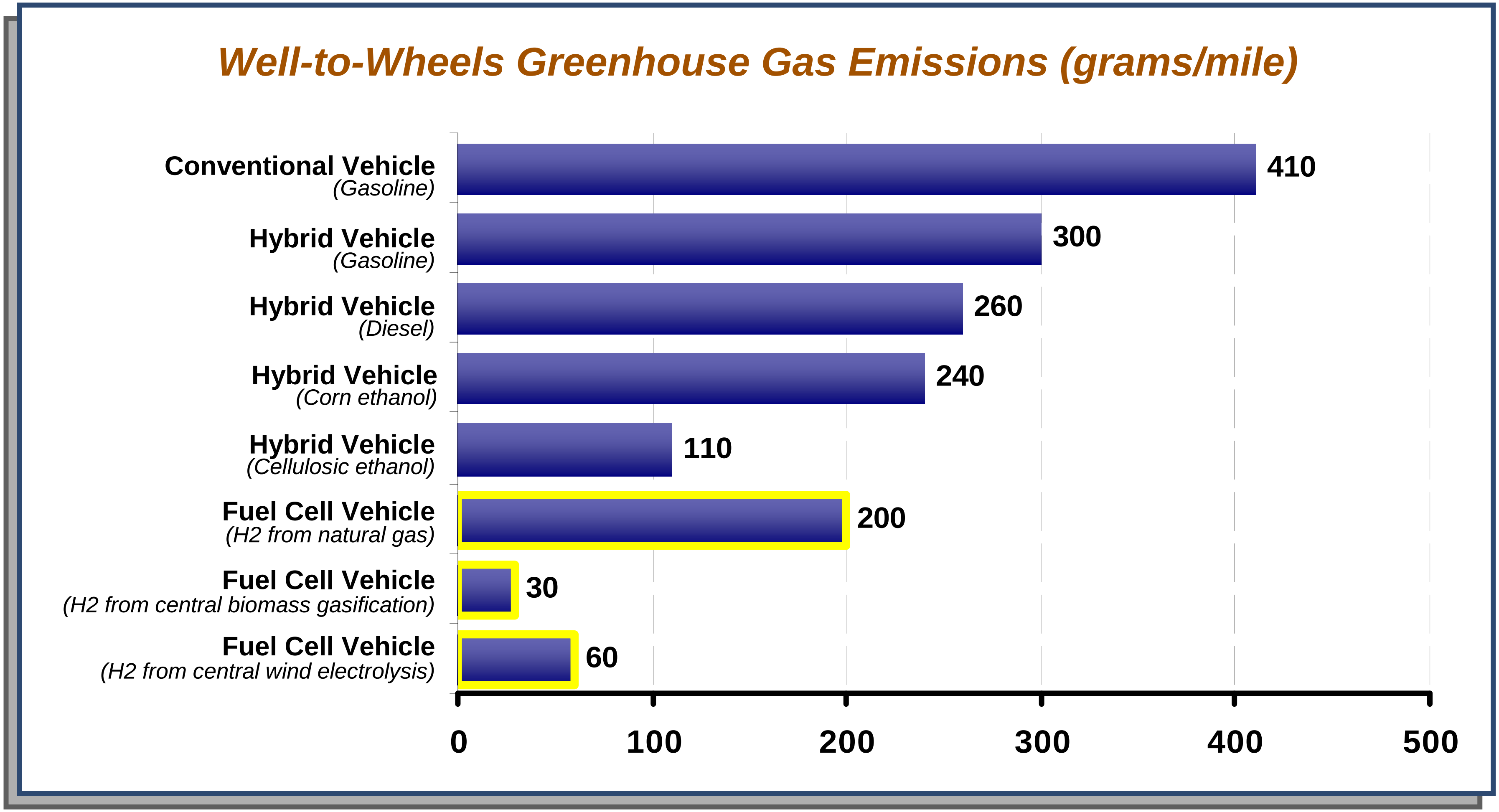
- **Transportation:** Use of hydrogen in fuel cell vehicles can reduce oil use and CO_2 emissions in the transportation sector
- **Power Generation:** Hydrogen can enable clean, reliable energy for stationary and portable power applications

Why hydrogen?

- Diverse domestic resources
- Efficient, reliable power
- Zero/near-zero emissions

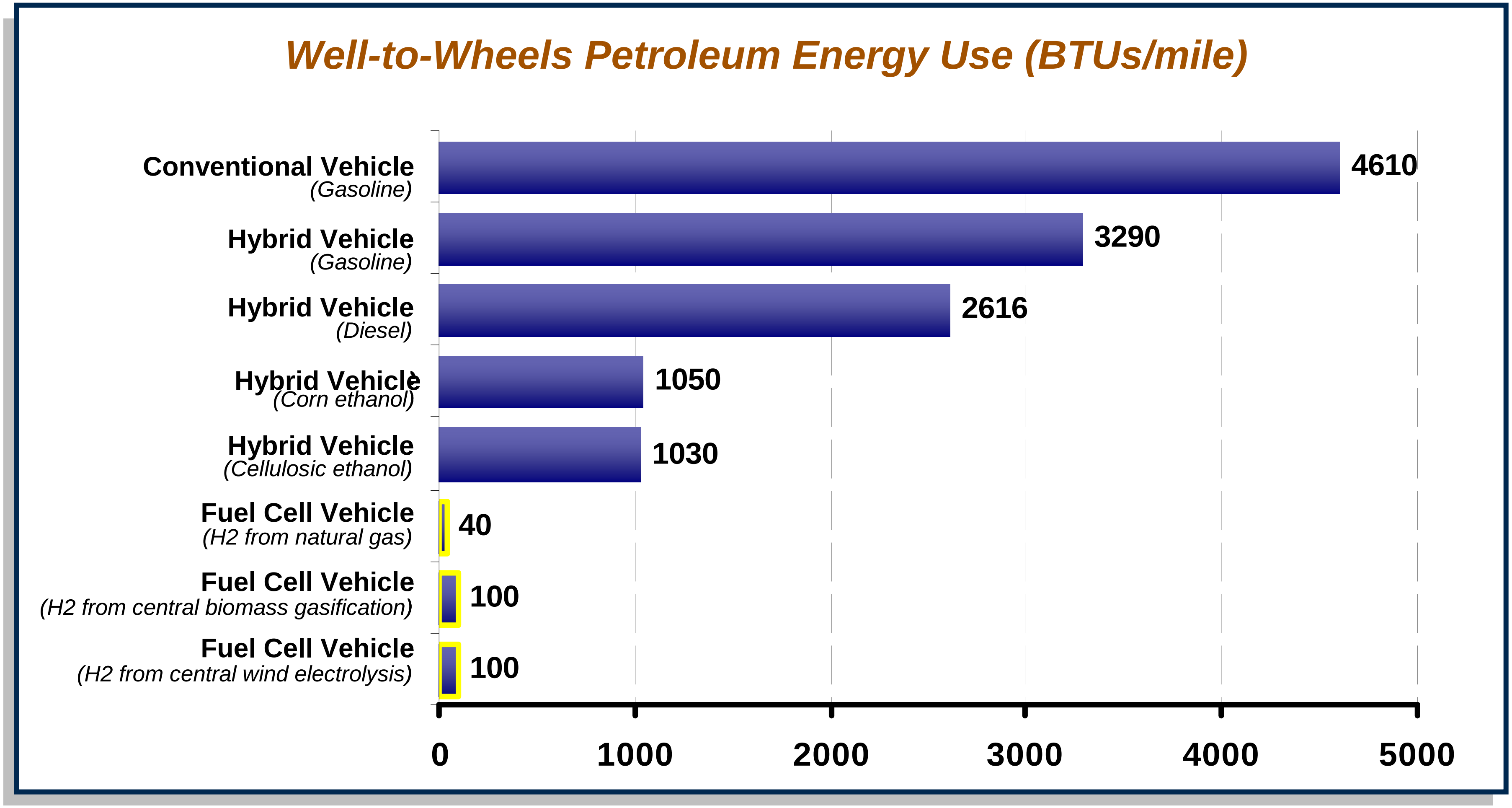


Well-to-wheels analysis* shows that use of hydrogen—from a variety of sources—would reduce greenhouse gas emissions



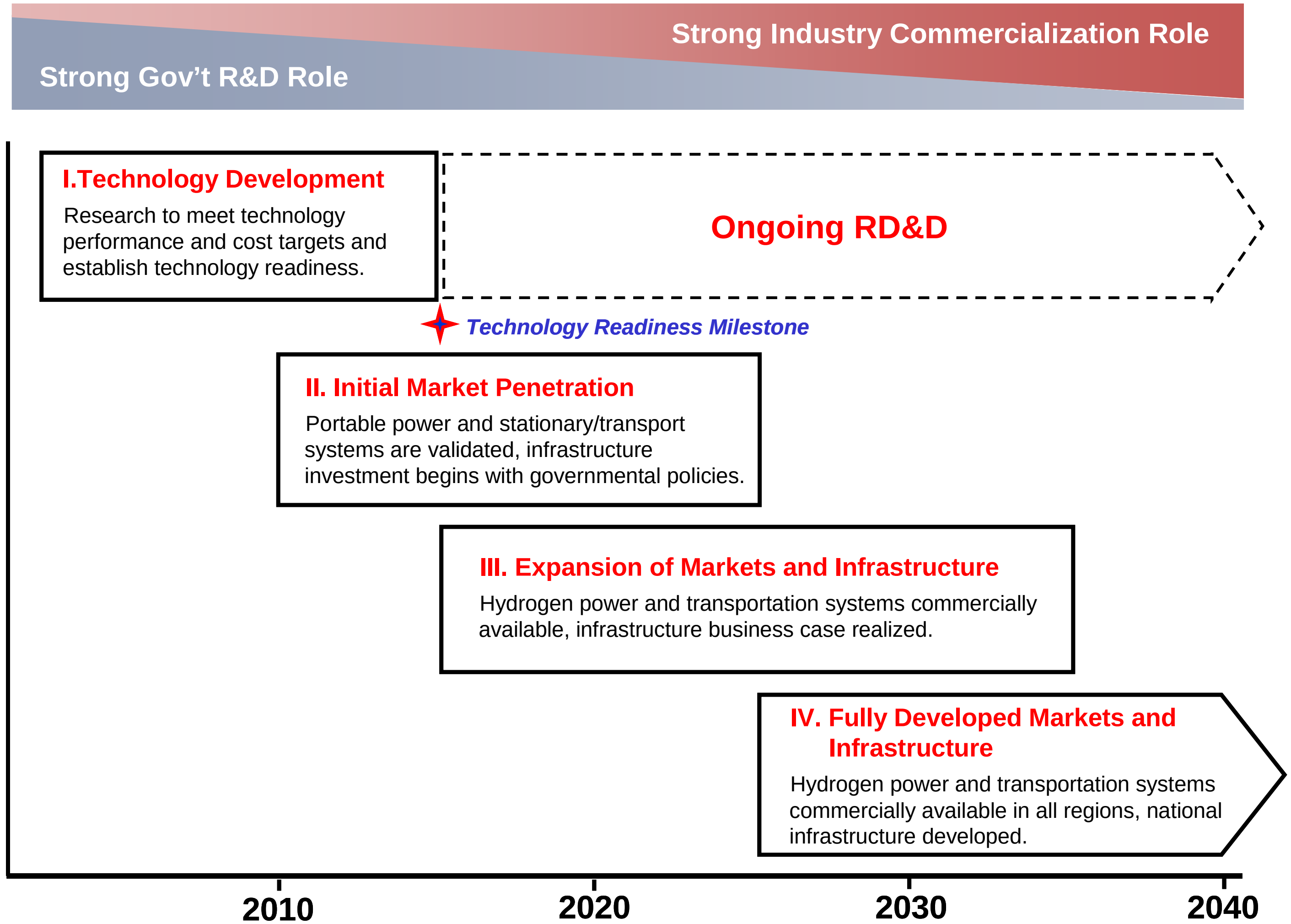
*Analysis based on technologies expected to be available in 2015, except for central hydrogen production pathways, which are based on delivery infrastructure expected in 2030.

Well-to-wheels analysis* shows that use of hydrogen—from a variety of sources—would reduce petroleum gas emissions

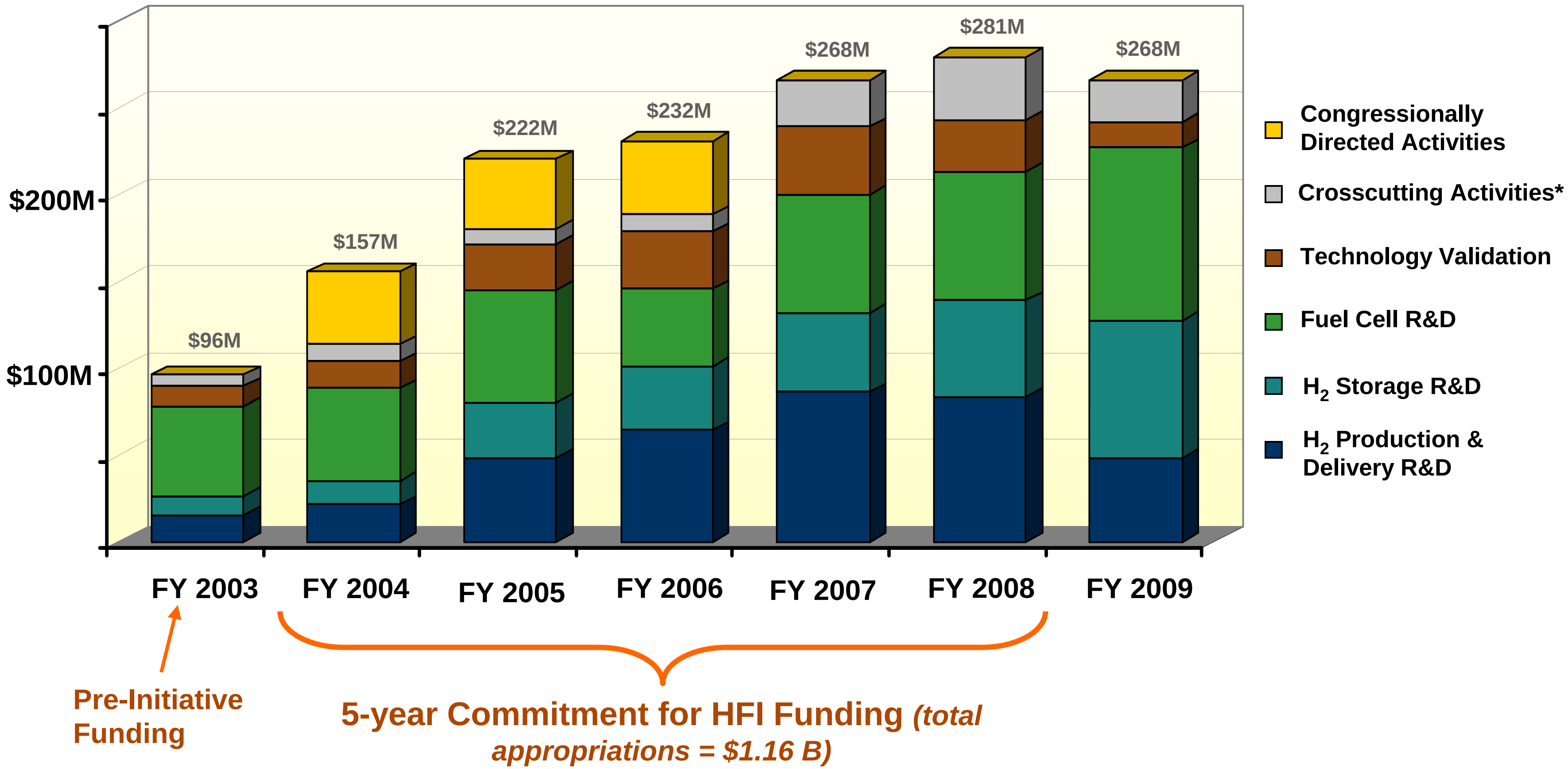


*Analysis based on technologies expected to be available in 2015, except for central hydrogen production pathways, which are based on delivery infrastructure expected in 2030.

Hydrogen Technology Timeline focuses on enabling industry decisions in 2015 time frame for vehicles and supporting infrastructure.



Funding for the Hydrogen Program was significantly ramped up as a result of the President's Hydrogen Fuel Initiative



~ $500M/year across the Federal Government (including HFI)

*These include Safety, Codes & Standards, Education, Systems Analysis, and Manufacturing R&D

FY2008 Technology Funding Breakdown

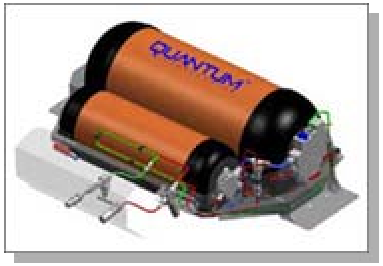
FY2008 Budget: $281 Million

19% Production and Delivery

Low-cost, clean, highly efficient hydrogen production and delivery technologies to enable H_2 from diverse domestic resources, including fossil, nuclear, and renewable sources

21% Hydrogen Storage

Developing on-board vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles.



14% Technology Validation

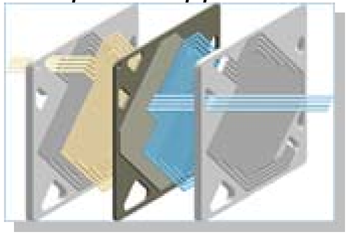
Validate complete systems of integrated hydrogen and fuel cell technologies for transportation, infrastructure and electricity generation applications under real-world operating conditions

17% Cross-Cutting Activities

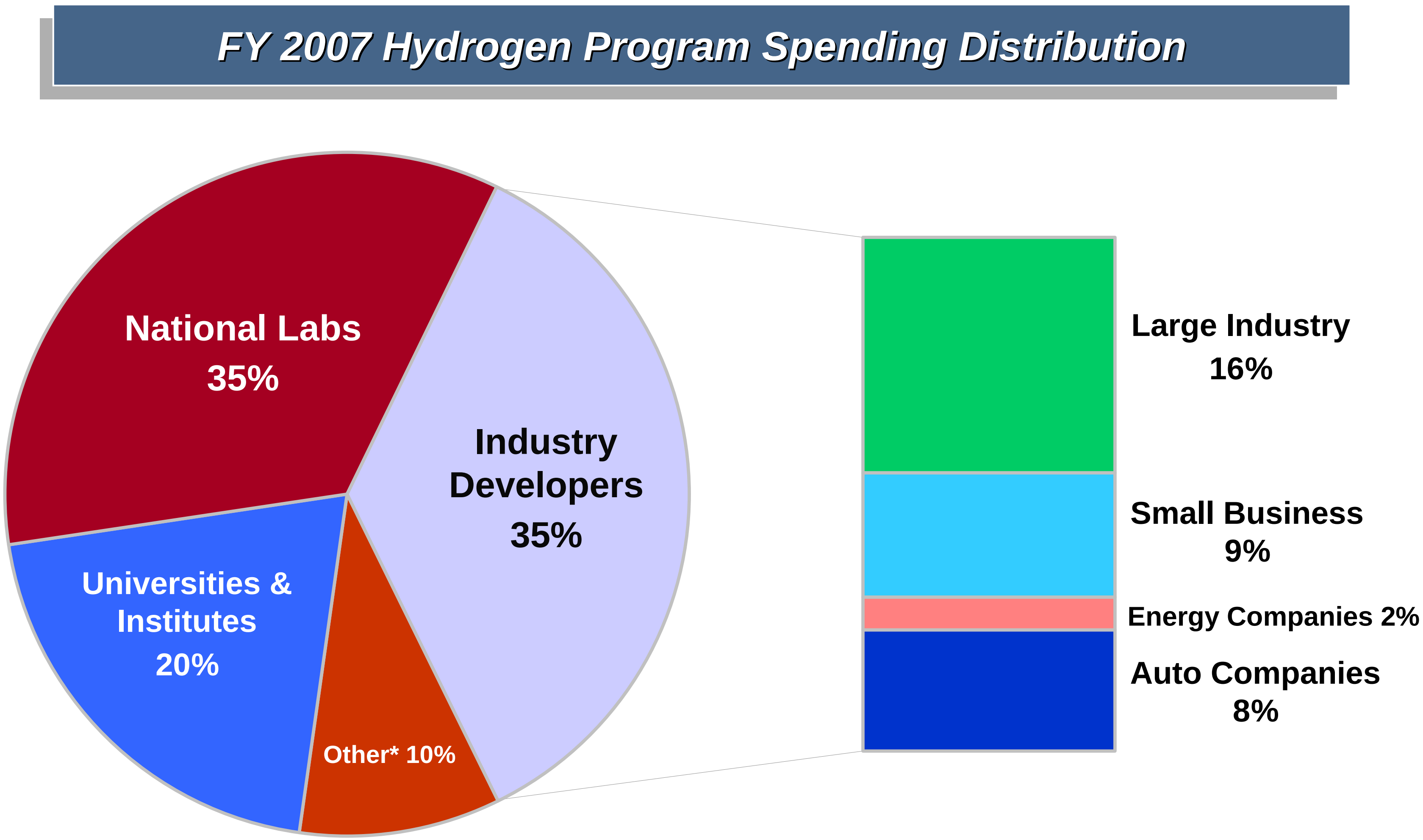
- *Safety, Codes and Standards*
- *Education*
- *Systems Analysis*
- *Manufacturing R&D*

29% Fuel Cells

Developing and demonstrating fuel cell technologies for transportation, stationary, and portable power applications.



Budget Allocation across Partners



** "Other" includes: SBIR/STTR and various crosscutting support activities, such as the Annual Merit Review and required EPAct studies and reports*

Investing Road Blocks

Institutional Barriers

- Safety, Codes And Standards
- Education / Public Awareness
  - Resistance to change
  - Lack of readily-available, objective, technically-accurate and “easily digestible” information
  - Lack of educated trainers and training opportunities

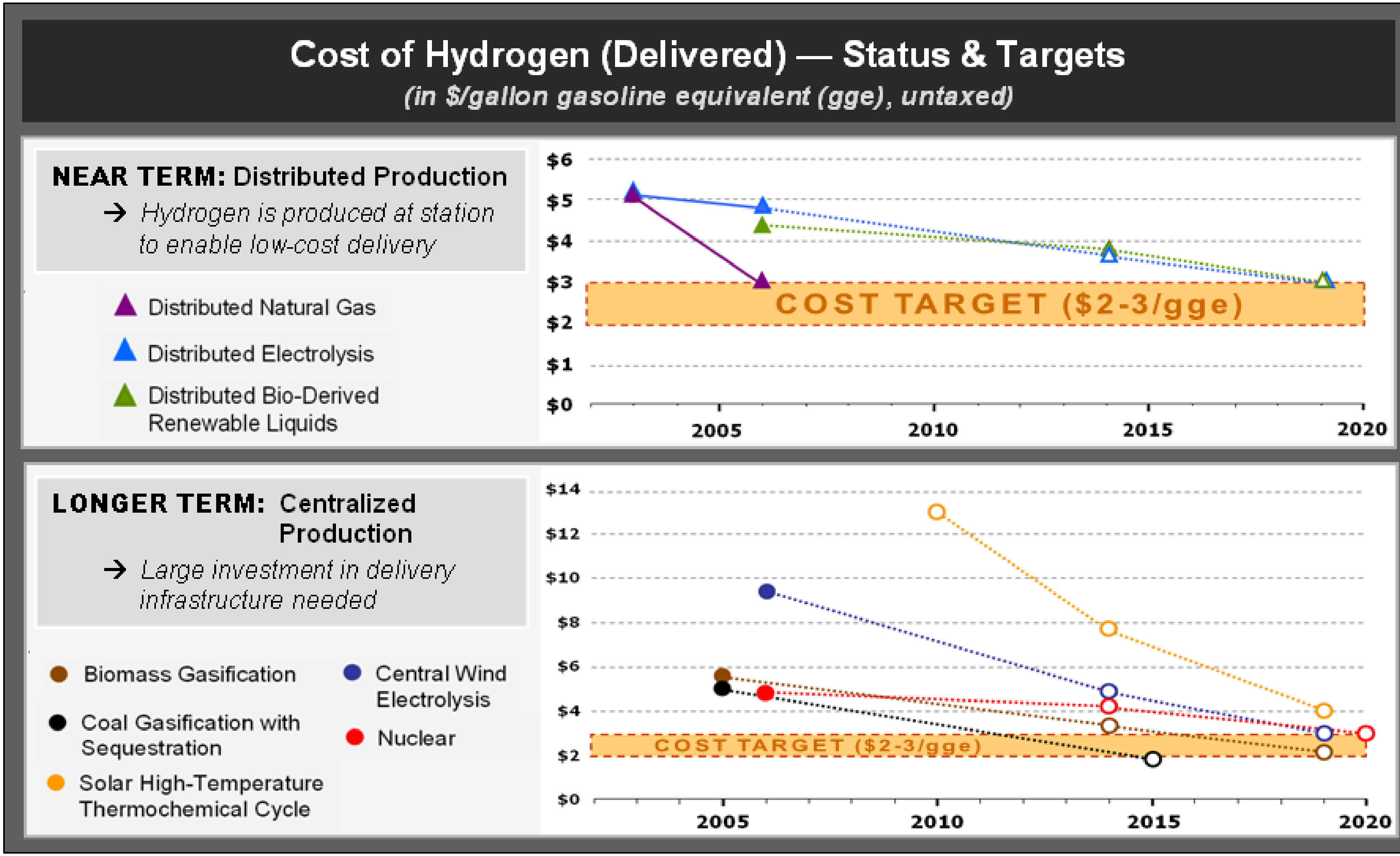
Policy Needs

- Increase and extend existing ($1000/kW) Tax Credit
- Integrated Renewable Power Tax Credit
- Tax Credits for:
  - Hydrogen Fuel from Renewable Sources
  - High Efficiency Combined Heat and Power (CHP)
  - Developing Refueling Infrastructure

Technical Barriers

- Production and Delivery
  - Capital cost
  - Catalyst efficiency
  - Energy efficiency
  - Delivery Infrastructure
- Hydrogen Storage
  - On-board storage for >300 mile range (without compromising space, performance, or cost)
- Fuel Cells
  - Cost
  - Durability
  - Performance

Hydrogen production from distributed natural gas is now competitive with gasoline*.



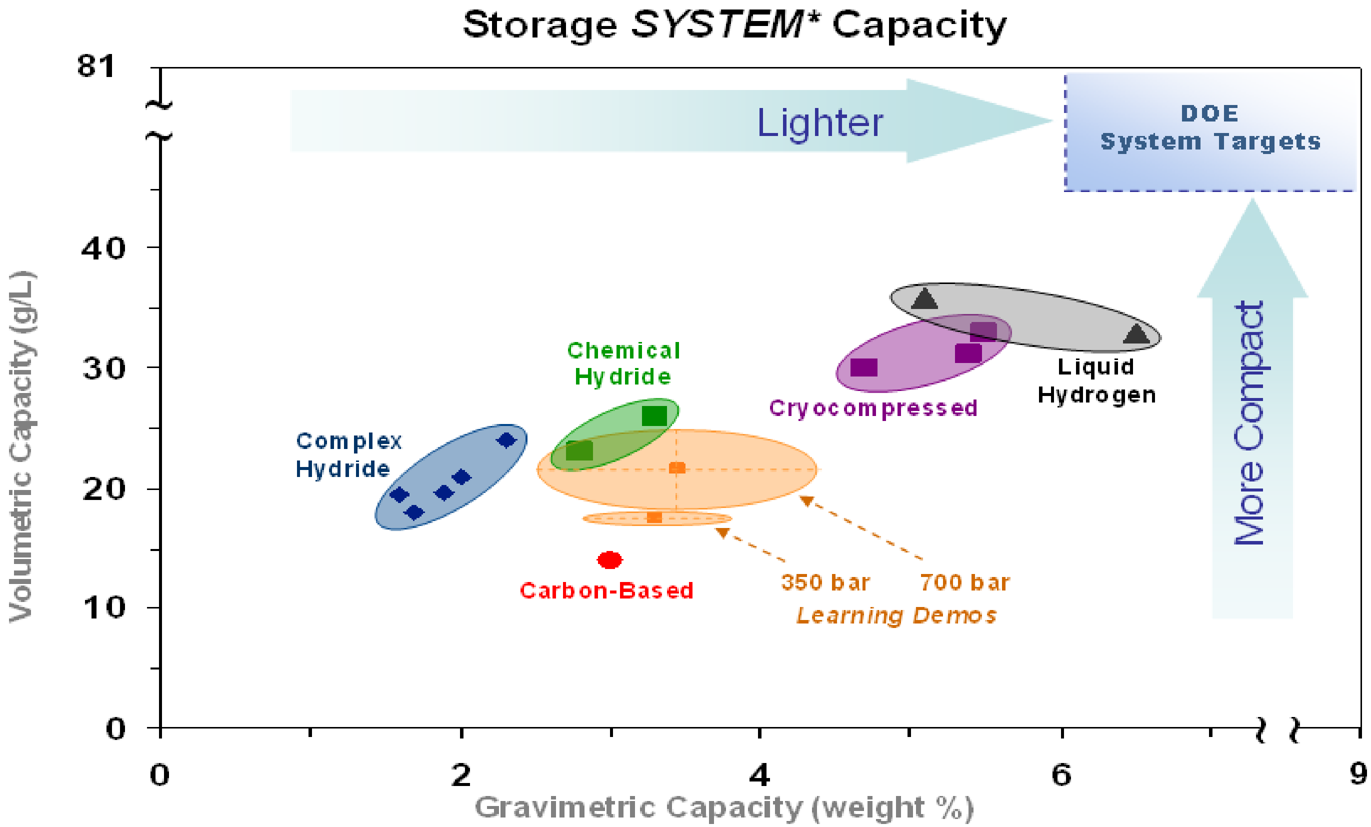
Open symbols for cost reduction targets subject to appropriations

*Projected for 500 units producing at 1500 kg/day

Hydrogen Storage R&D is under way, developing potential materials for storage systems.

DOE targets are set to achieve > 300 mile driving range across different vehicle platforms, *WITHOUT COMPROMISING* ***passenger/cargo space, performance, or cost***

→ *No currently available technology meets these targets*



* System capacity estimates include materials, tanks, and balance of plant

Fuel Cell R&D is focused on the key areas of cost and durability.

Catalysts & Supports | Water Transport | Membranes | Characterization & Analysis

Light-Duty Vehicles

R&D for transportation fuel cells is focused on components rather than systems

KEY TARGETS:

- **$45/kW by 2010; $30/kW by 2015**
- **5,000-hour durability by 2015**
- **60% efficiency**

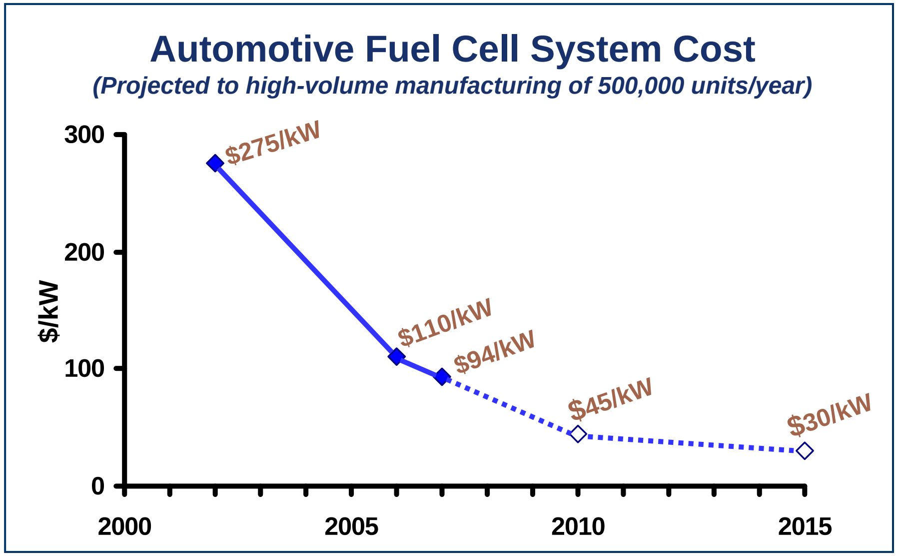
Early Market Applications

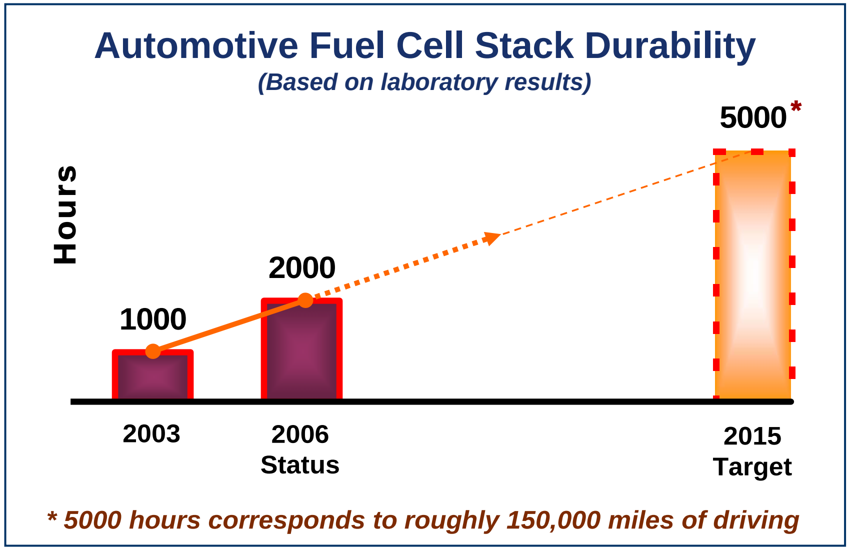
Early markets for stationary, backup power, and specialty applications will lower costs and grow the manufacturing base

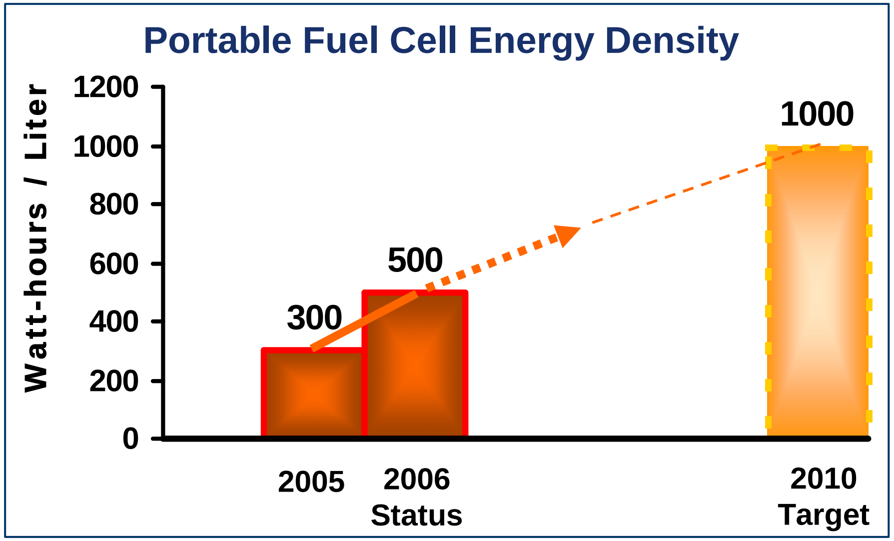
KEY TARGETS:

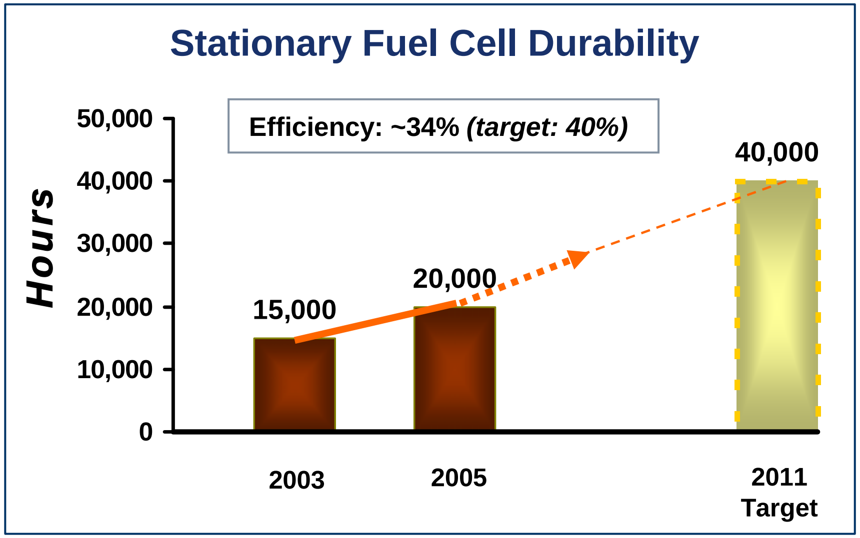
- **Distributed Power:** $750/kW and 40,000-hour durability (with 40% efficiency) by 2011
- **APUs:** Specific power of 100 W/kg and power density of 100 W/L by 2010
- **Portable Power:** Energy density of 1,000 W-h/L by 2010

Fuel cell system cost has been reduced 65%, from $275/kW in 2002, to $94/kW in 2007.









Program Initiatives:

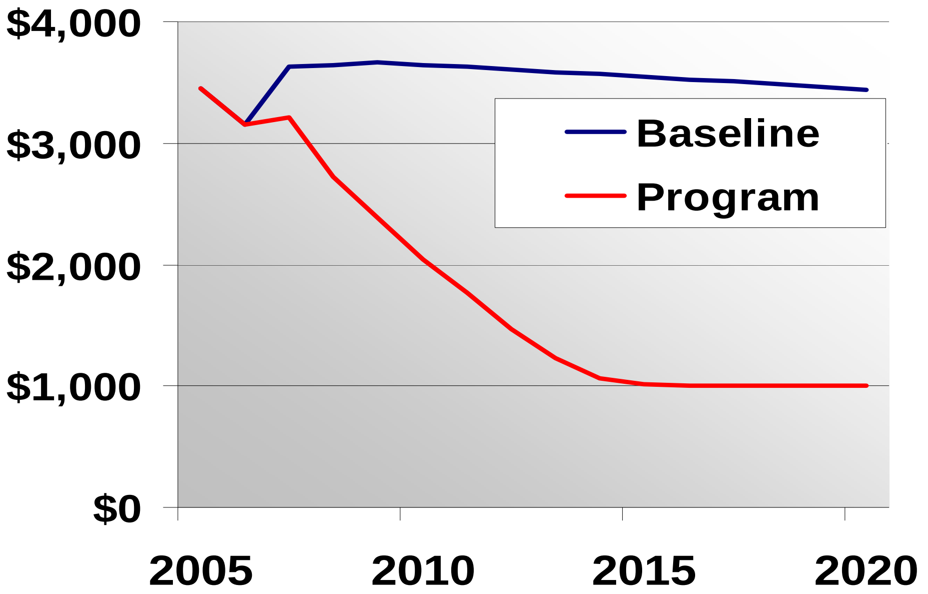
Facilitating Market Transformation

The Program is working to reduce the non-technical barriers facing the commercialization of hydrogen and fuel cell technologies

OBJECTIVES

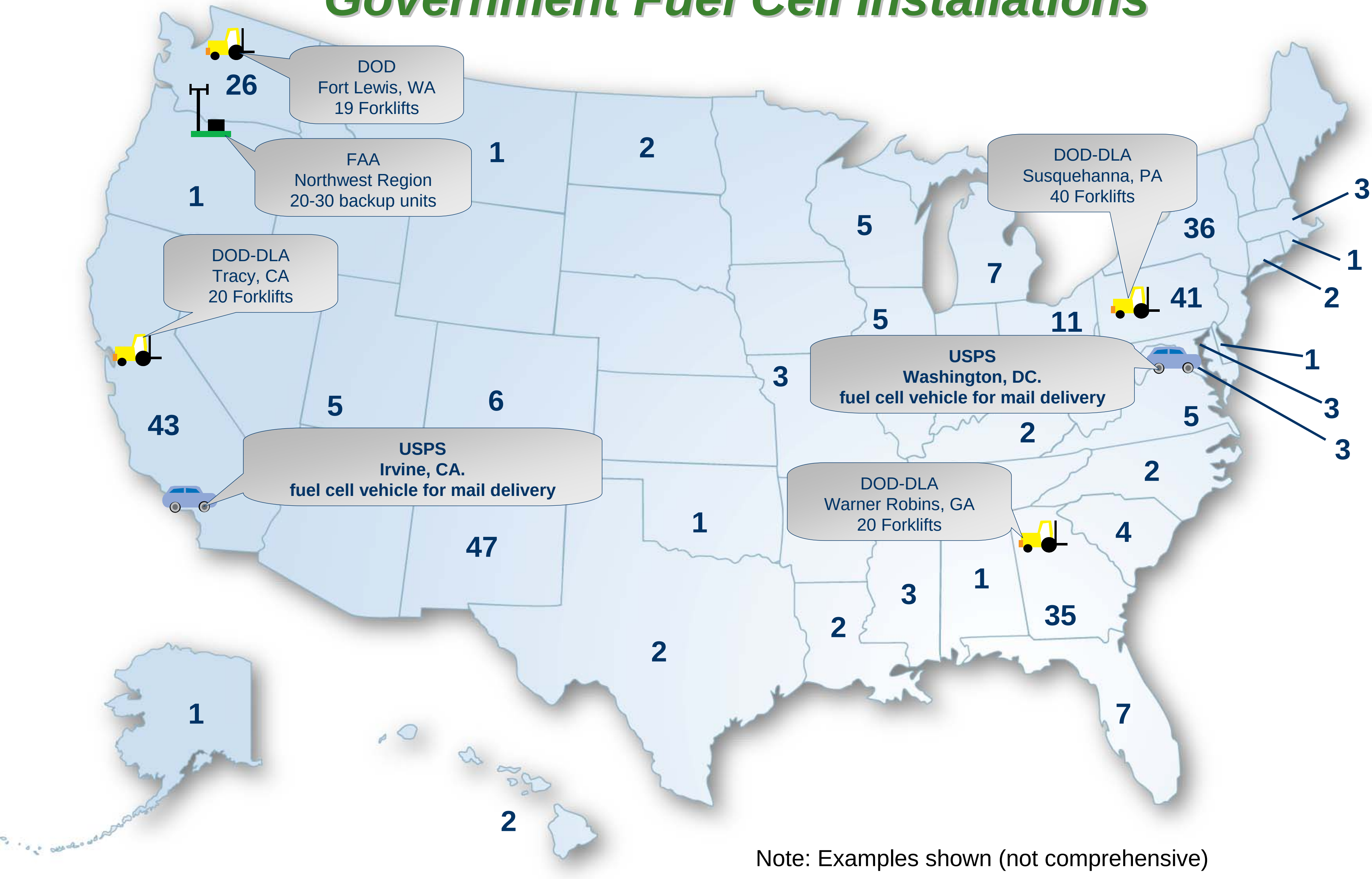
- Assist federal agencies in promoting fuel cell use across the U.S. government to meet the requirements of:
  - EPACT 2005 Sec. 782 and 783
  - Executive Order 13423
- Increase sales & manufacturing volumes of fuel cells to achieve economies of scale
- Support national infrastructure and domestic supplier base development
- Improve user confidence in fuel cell reliability by collecting operations data

Estimated Impact of Government Acquisitions on Fuel Cell Stack Costs *(in $/kW)*



Source: David Greene, ORNL; K.G. Duleep, Energy and Environmental Anaylsis, Inc.

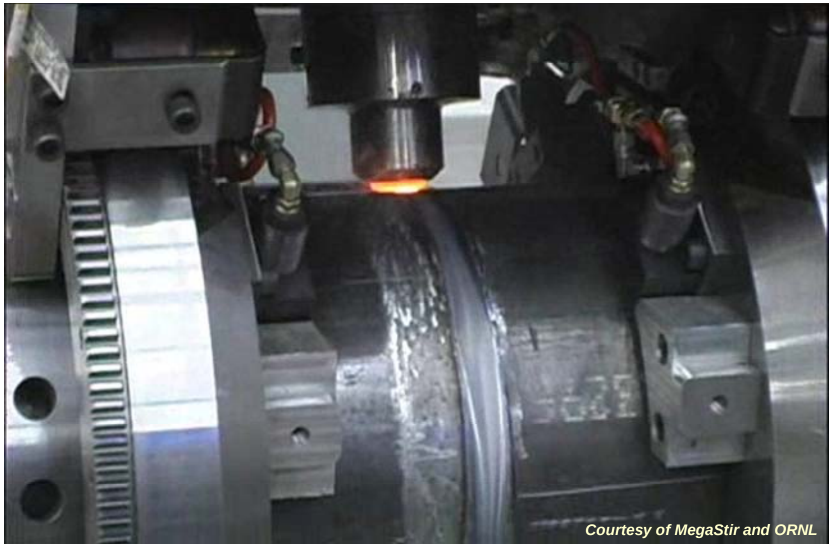
Examples of State and Federal Government Fuel Cell Installations



Note: Examples shown (not comprehensive)

Other Activities

- Manufacturing R&D to reduce cost and increase output of hydrogen and fuel cell components and systems and enable a domestic supplier base
    - Electrode deposition
    - High pressure storage
    - MEA manufacturing
    - Gas diffusion layer fabrication
    - Fuel cell stack testing



Courtesy of MegaStir and ORNL

Other Activities

- Codes and Standards
  - Developed *Technical Reference for Hydrogen Compatibility of Materials*
  - Developed Web-based *Hydrogen Safety Best Practices Manual*
  - 22 hydrogen C&S have been published, 28 are under preparation/review; progress has been made toward an international fuel quality standard
  - Published *Hydrogen Fueling Station Permitting Compendium*
- Education
  - Safety & code officials
    - "Introduction to Hydrogen Safety for First Responders" (>6000 users since launch)
    - Completed draft of "Introduction to Hydrogen for Code Officials"
  - Local communities
    - Radio spots, podcasts, MySpace, Orlando Magic Collaboration
  - State & local government officials
    - 7 new projects awarded for state & local gov't outreach
  - End-users/early adopters
    - Early market fact sheets & case studies
  - Students
    - Reached >6000 teachers through training workshops
    - 5 new university education projects selected

Emerging Markets and Investment Opportunities

Fuel Cells for Material Handling Equipment

- Allow for rapid refueling – quicker than changing-out or replacing batteries
- Provide constant power – without voltage drop
- Eliminate need for space for battery storage and chargers

Photo courtesy of Hydrogenics

	3kW PEM FUEL CELL PAIRED WITH INTEGRAL NiMH BATTERY, FOR PALLET TRUCKS*		
	BATTERY-POWERED (2 batteries per truck)	PEM FUEL CELL-POWERED, WITHOUT INCENTIVE	PEM FUEL CELL-POWERED, WITH INCENTIVE
Net Present Value of Capital Costs	$17,654	$23,835	$21,004
Net Present Value of O&M Costs (including the cost of fuel)	$127,539	$52,241	$52,241
Net Present Value of Total Costs of System	**$145,193**	**$76,075**	**$73,245**

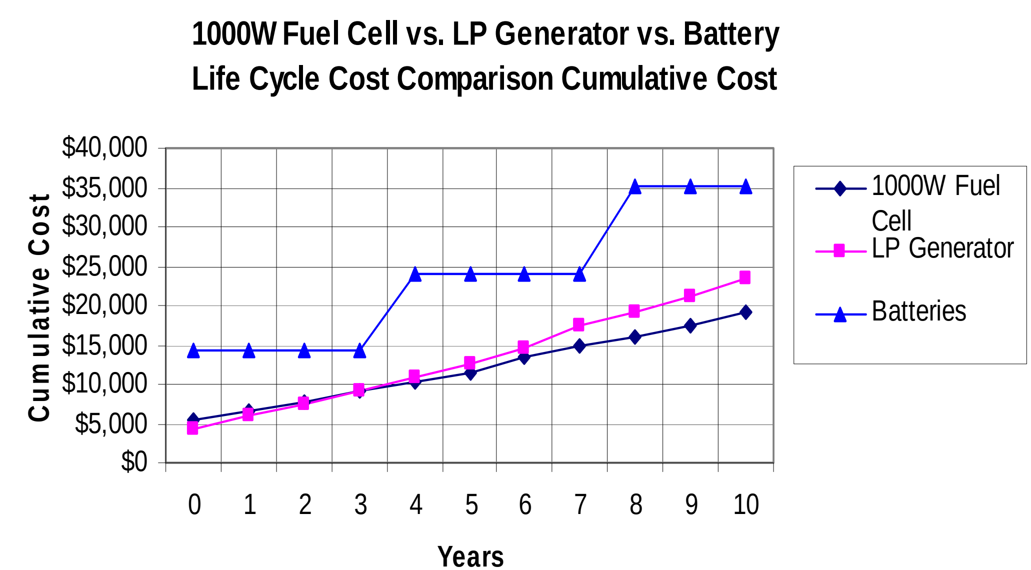
Source: *Identification and Characterization of Near-term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets, Battelle Memorial Institute (April 2007)*

**Assumptions: Operate 7 hours/shift, 3 shifts/day, 7 days/week; batteries changed out every shift, taking about 30 minutes; operator cost $15/hour; PEM fuel cell fork lift uses 3kW stacks with NiMH batteries; PEM fuel cell stack replaced every 5 years at $3,000/kW; batteries replaced every 5 years at $1,800; PEM fuel cell forklift refueled once every shift, refueling time 1 minute; no disposal costs were assumed for any of the technologies.*

Emerging Markets and Investment Opportunities

Fuel Cells for backup power

- **Provide longer continuous run time – greater durability than batteries**
- **Require less maintenance than generators**
- **Offer cost savings over batteries and generators**



Source: *National Weather Service*

	OUTDOOR INSTALLATIONS		
	BATTERY/ GENERATOR	PEM FUEL CELL WITHOUT TAX INCENTIVE	PEM FUEL CELL WITH TAX INCENTIVE
8-hour run time			
52-hour run time	$61,082	$61,326	$56,609
72-hour run time	$47,318	$33,901	$32,014
176-hour run time*	$75,575	$100,209	$95,491

** Additional cost for PEMFCs at 176-hour run time is due primarily to the cost of hydrogen storage*

Source: *Battelle Memorial Institute*

Emerging Markets and Investment Opportunities

About data centers...

- **Large Demand:** 58.7 billion kWh (U.S., 2006) = approx. 5 days of U.S. domestic electricity use.
  - growing 14% annually
- **Low overall grid efficiency:** From the energy source, the fuel efficiency of a data center's computing operations is <15%.
- **Half of the energy consumption of data centers is used for cooling:** Power requirements are proportional to cooling requirements

Fuel Cells for Data Centers…

- **Provide high-quality, reliable, grid-independent on-site critical load power**
- **Improve the effectiveness of data center power use by 40% (CHP)**
- **Produce no emissions**
- **Have low O&M requirements**
- **Can be remotely monitored**

Commercialization Opportunities:

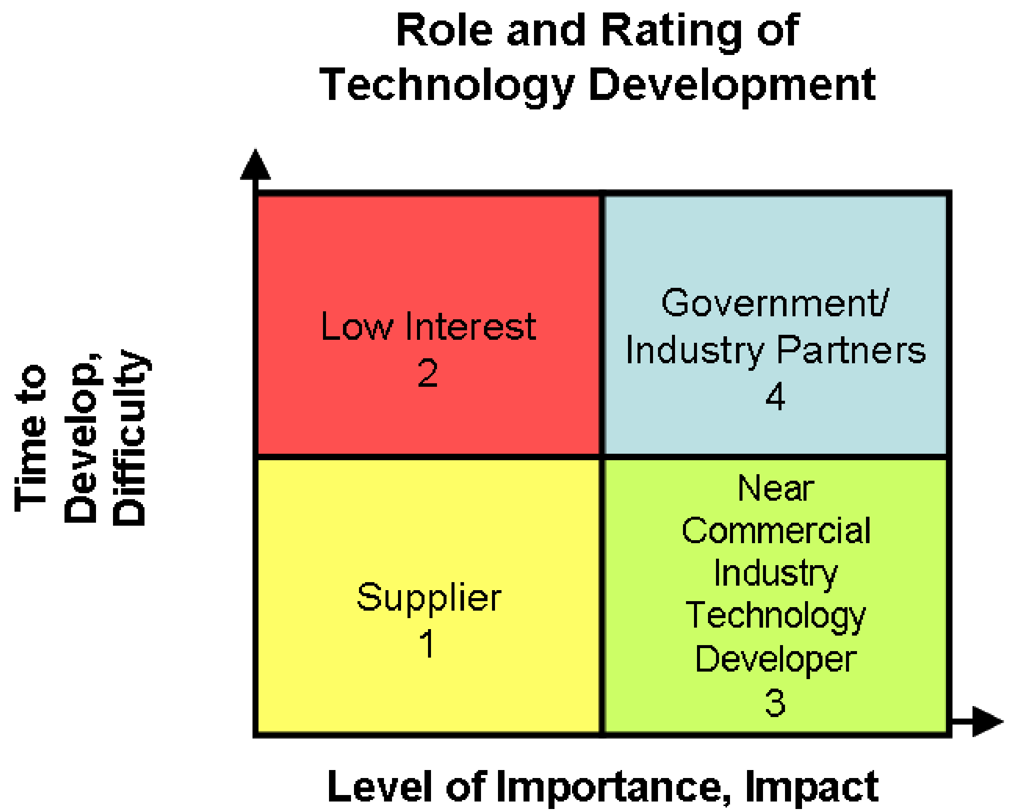
FY2008 Funding to the National Labs

National Lab	Funding ($ in thousands)					
	Fuel Cells	Storage	Production and Delivery	Technology Validation	Crosscutting*	TOTAL
Idaho	-	200	-	-	-	200
Argonne	7,952	1,366	2,450	260	2,779	14,807
Lawrence Berkeley	1,250	483	-	-	200	1,933
Brookhaven	675	1,125	-	-	400	2,200
Pacific Northwest	1,775	2,580	1,370	-	2,575	8,300
Oak Ridge	3,480	2,670	2,360	-	1,510	10,020
Savannah River	275	1,600	500	-	-	2,375
National Renewable Energy Laboratory	1,225	4,135	9,948	900	8,679	24,887
Lawrence Livermore		1,532	900	450	683	3,565
Los Alamos	8,061	3,880	300	-	1,960	14,201
Sandia	250	3,720	1,977	150	4,822	10,919
Technology Focus TOTAL	24,943	23,291	19,805	1,760	23,608	93,407

***These include Safety, Codes & Standards, Education, Systems Analysis, and Manufacturing R&D**

"Outcome Maps" identify potential opportunities across the R&D pipeline

Pre-decisional Draft

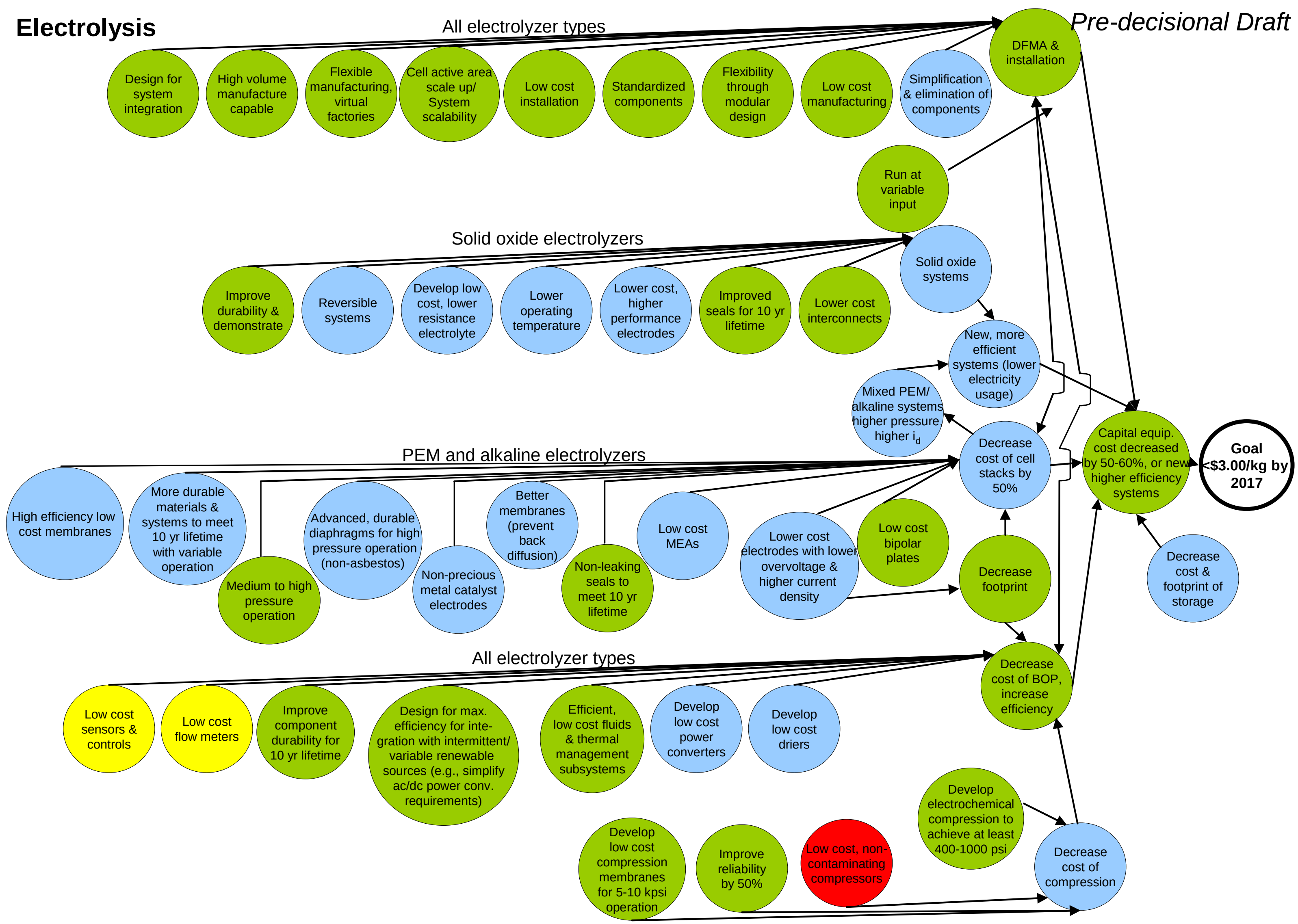


Role and Rating of Technology Development Descriptions

- **Supplier** – Low level of importance and short development time of less than 5 years
- **Low Interest** – Low level of importance and long term development of more than 5 years
- **Industry Technology Developer** – High level of importance with a short development time of less than 5 years. This task is critical to reaching the final outcome
- **Government/Industry** – High level of importance but with difficult and long term development time of more than 5 years. This task is critical to reaching the final outcome

Example of “Outcome Map” for hydrogen production by electrolysis. Identifies potential opportunities.

Pre-decisional Draft



Example of mapping R&D portfolio & requirements to targets. Helps identify opportunities for investment.