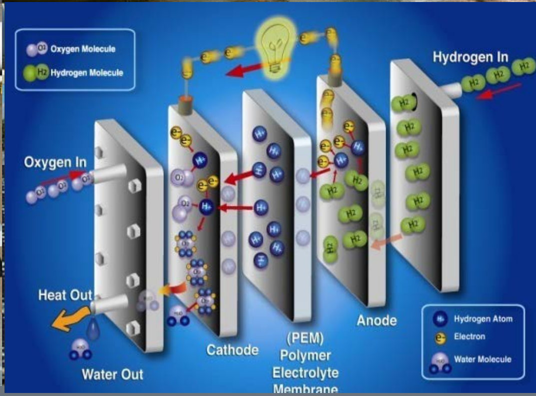
DOE Workshop Overview and Purpose

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



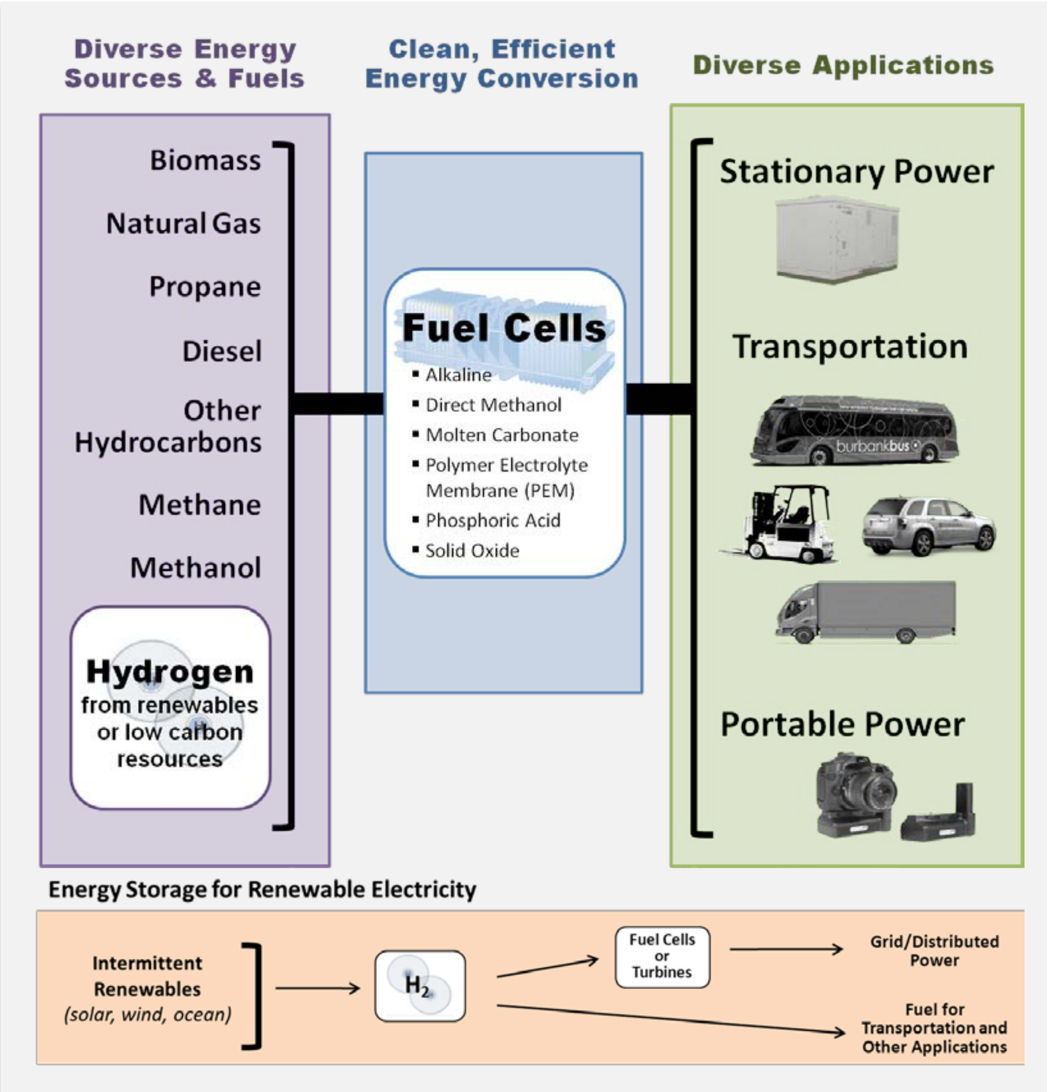
Workshop on Gas Clean-Up for Fuel Cell Applications

3/6/2014, Argonne National Laboratory

Dr. Dimitrios Papageorgopoulos

Fuel Cells Program Manager
Fuel Cell Technologies Office
U.S. Department of Energy

The Role of Fuel Cells



Key Benefits

Very High Efficiency

- **> 60%** *(electrical)*
- **> 70%** *(electrical, hybrid fuel cell / turbine)*
- **> 80%** *(with CHP)*

Reduced CO_2 Emissions

- **35–50%+ reductions** *for CHP systems (>80% with biogas)*
- **55–90% reductions** *for light-duty vehicles*

Reduced Oil Use

- **>95% reduction** *for FCEVs (vs. today's gasoline ICEVs)*
- **>80% reduction** *for FCEVs (vs. advanced PHEVs)*

Reduced Air Pollution

- **up to 90% reduction in criteria pollutants** *for CHP systems*

Fuel Flexibility

- **Clean fuels** — *including biogas, methanol, H_2*
- **Hydrogen** — *can be produced cleanly using sunlight or biomass directly, or through electrolysis, using renewable electricity*
- **Conventional fuels** — *including natural gas, propane, diesel*

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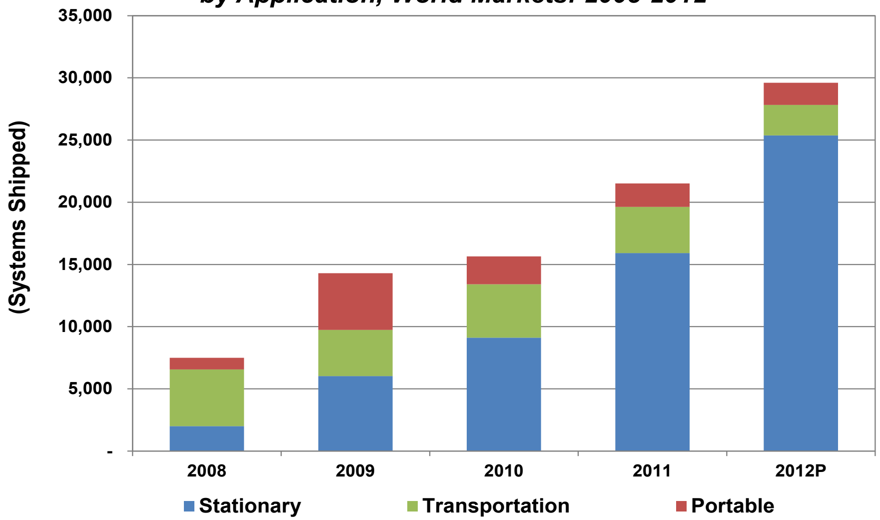
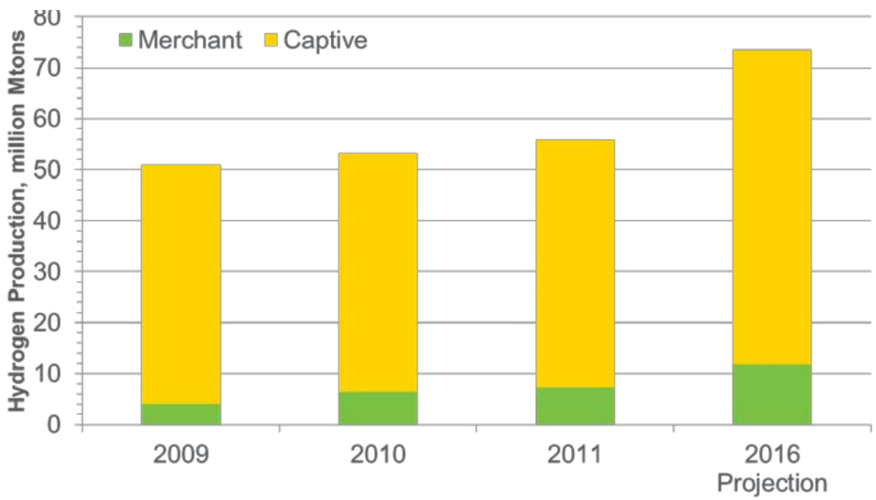
Fuel Cell Market Overview

Fuel Cell Systems Shipped
by Application, World Markets: 2008-2012



Global Hydrogen Production Market 2009 – 2016
(million metric tons)



Market Growth

Fuel cell markets continue to grow

48% increase in global MWs shipped

62% increase in North American systems shipped in the last year

The Market Potential

Independent analyses show global markets could mature over the next 10–20 years, with potential for revenues of:

- **$14 – $31 billion/year for stationary power**
- **$11 billion/year for portable power**
- **$18 – $97 billion/year for transportation**

The global hydrogen market is also robust with over 55 Mtons produced in 2011 and over 70 Mtons projected in 2016, a > 30% increase.

Several automakers have announced commercial FCEVs in the 2015-2017 timeframe.

For further details and sources see: ***DOE Hydrogen and Fuel Cells Program Plan,*** **http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf; FuelCells 2000, Fuel Cell Today, Navigant Research, Markets & Markets**

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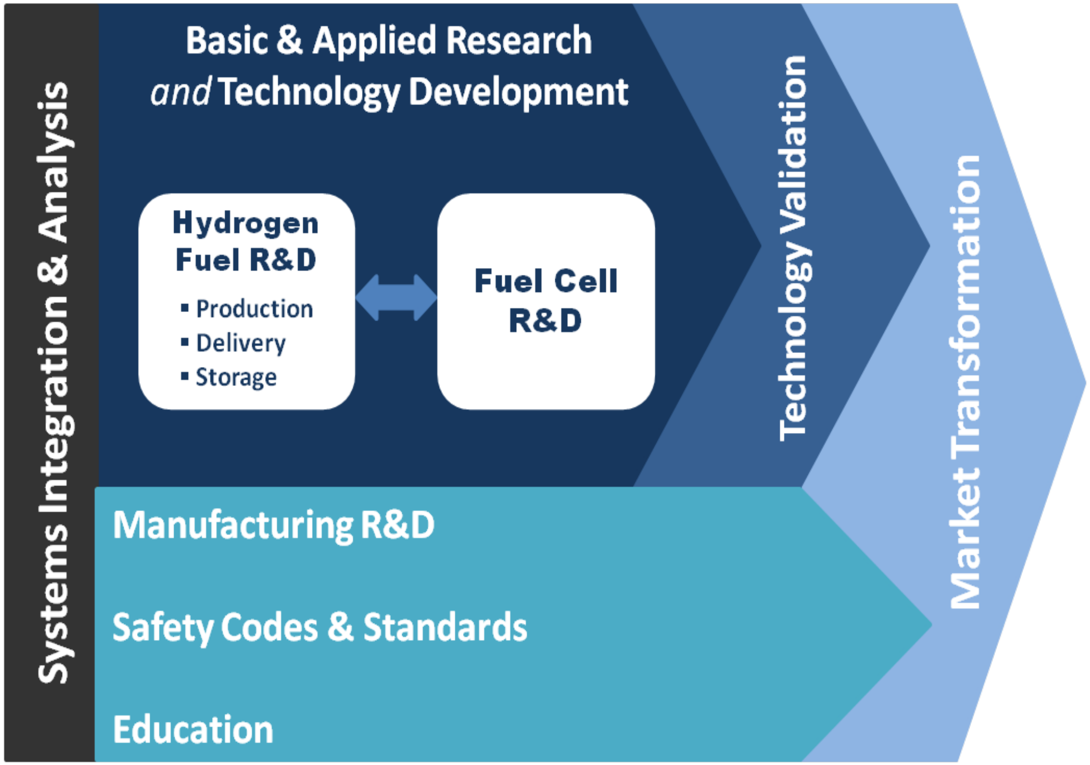
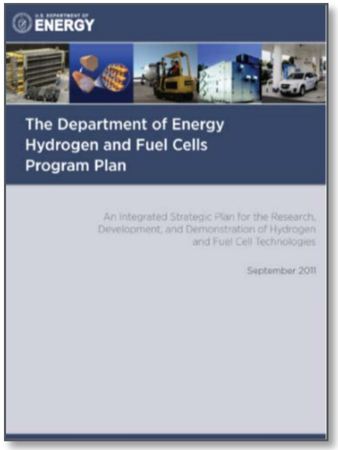
DOE Program Overview

- The Program is an integrated effort, structured to address all the key challenges and obstacles facing widespread commercialization.



WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS

- Transportation
- Stationary Power
- Auxiliary Power
- Backup Power
- Portable Power



Released September 2011
Update to the Hydrogen Posture Plan (2006)
Includes Four DOE Offices
EERE, FE, NE and Science

More than 200 projects currently funded at companies, national labs, and universities/institutes

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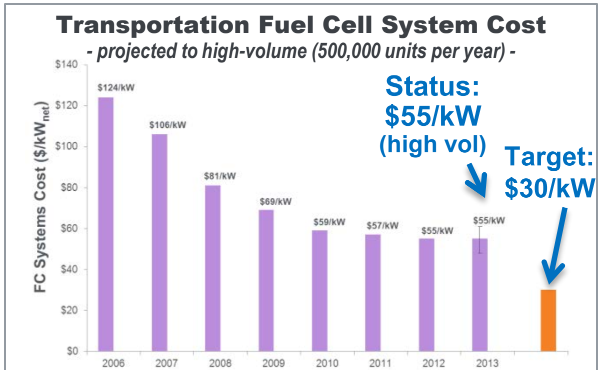
DOE Program: RD&D to Deployments

DOE R&D

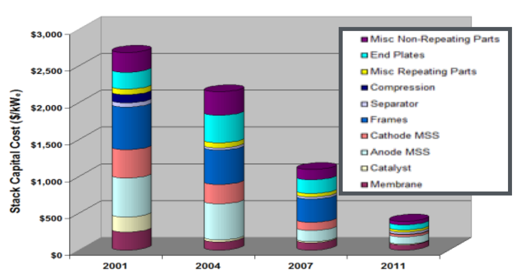
- *Reduces cost and improves performance*

Examples of progress:



→ *Reduced cost of fuel cells 50% since 2006*

→ *2020 target $40/kW, ultimate target $30/kW*



→ *Reduced cost of electrolyzer stacks 60% since 2007*

DOE Demonstrations & Technology Validation

- *Validate advanced technologies under real-world conditions*
- *Feedback guides R&D*

Demonstrated >180 FCEVs, 25 stations, 3.6 million miles traveled

Examples—validated:

- *59% efficiency*
- *254 mile range (independently validated 430-mile range)*
- *75,000-mi durability*

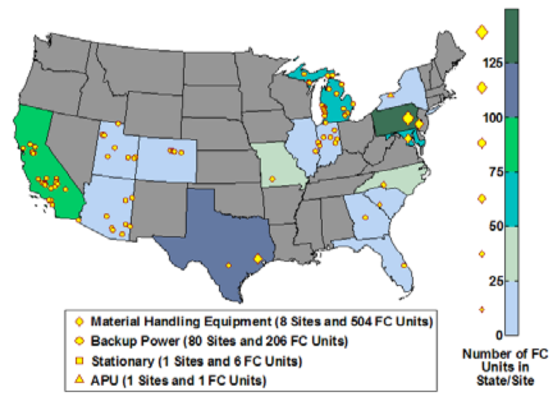
Demonstrated **world's first tri-gen** station (250 kW on biogas, 100 kg/d)

Program also includes enabling activities such as codes & standards, analysis, and education.

Deployments

- *DOE Recovery Act and Market Transformation Projects*
- *Government Early Adoption (DoD, FAA, California, etc.)*
- *Tax Credits: 1603, 48C*

Recovery Act & Market Transformation Deployments



Nearly 1,600 fuel cells deployed

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Opportunities for Distributed Generation (DG) and Efficient use of Natural Gas

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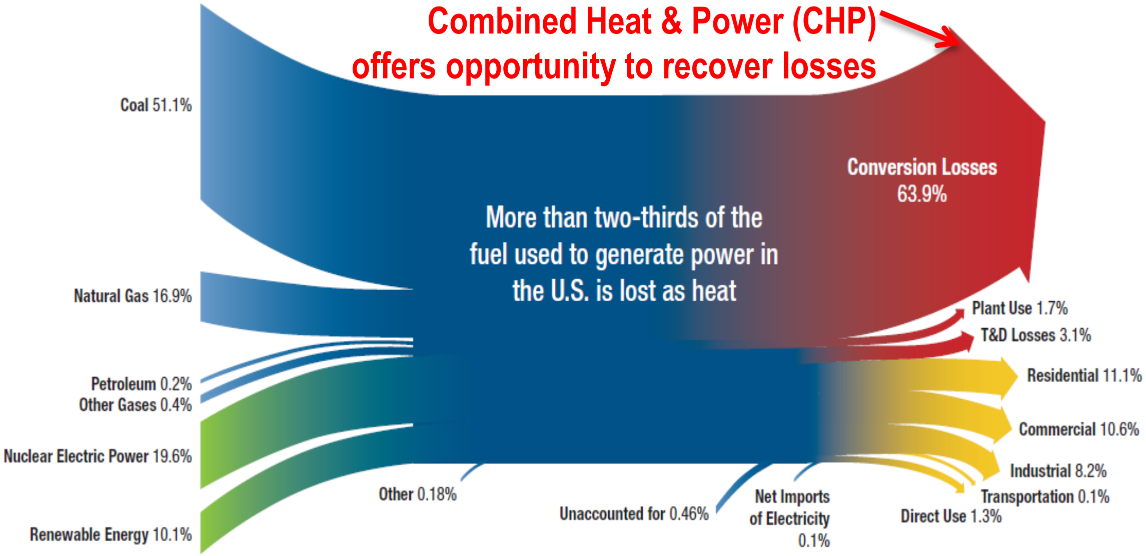
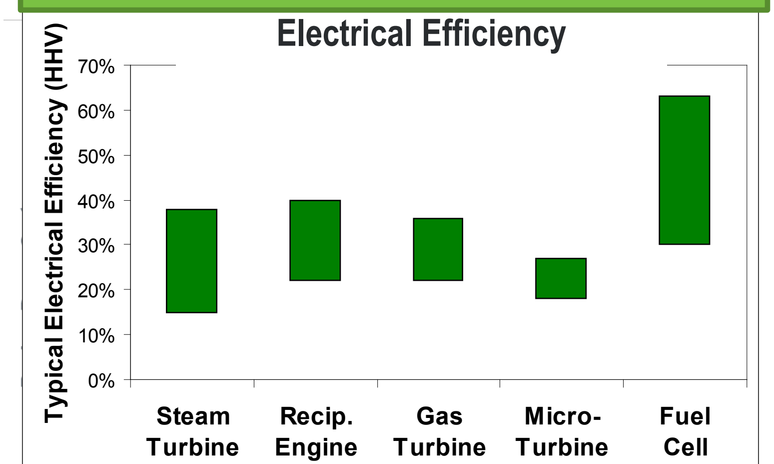


Source: http://www.chpcenterse.org/pdfs/ORNL_CHP_Report_Dec_2008.pdf

Range of electrical efficiencies for DG technologies



Source: EPA, Catalog of CHP Technologies, December 2008

Examples of fuel cell deployments using natural gas

Supermarkets *one of several in the food industry interested*

Critical Loads- e.g. banks, hospitals, data centers

New World Trade Center will use ***12 fuel cells totaling 4.8MW***

During Hurricane Sandy, fuel cells were instrumental in providing backup power for many in NY, NJ, and CT.
>60 fuel cells acted as backup power for cell phone towers.
>20 fuel cells systems provided continuous power to buildings

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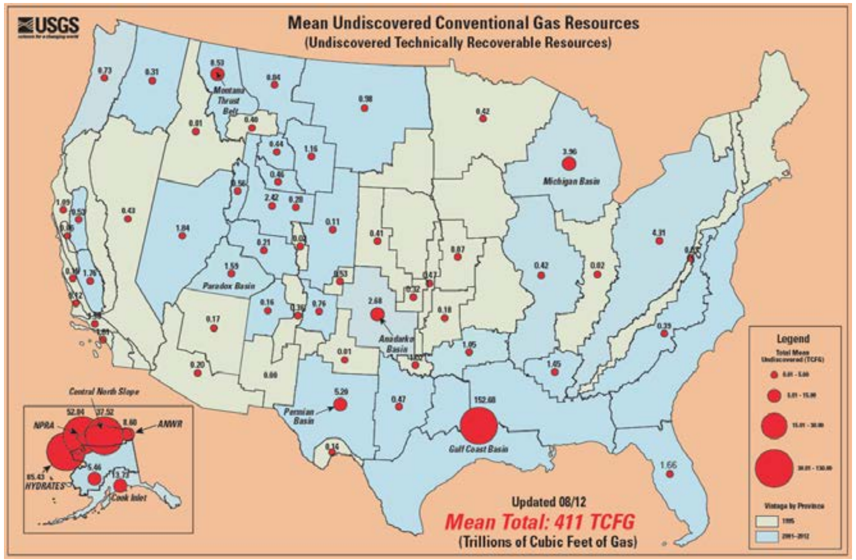
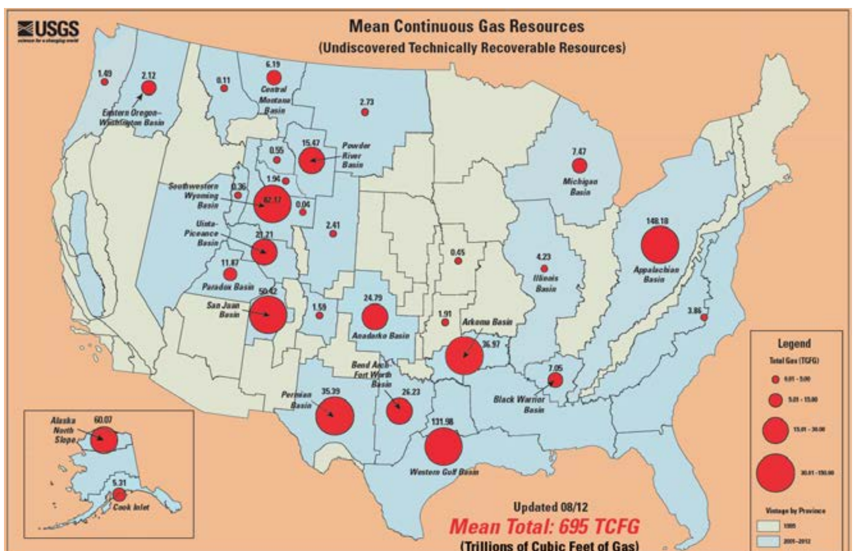
Natural Gas Resources

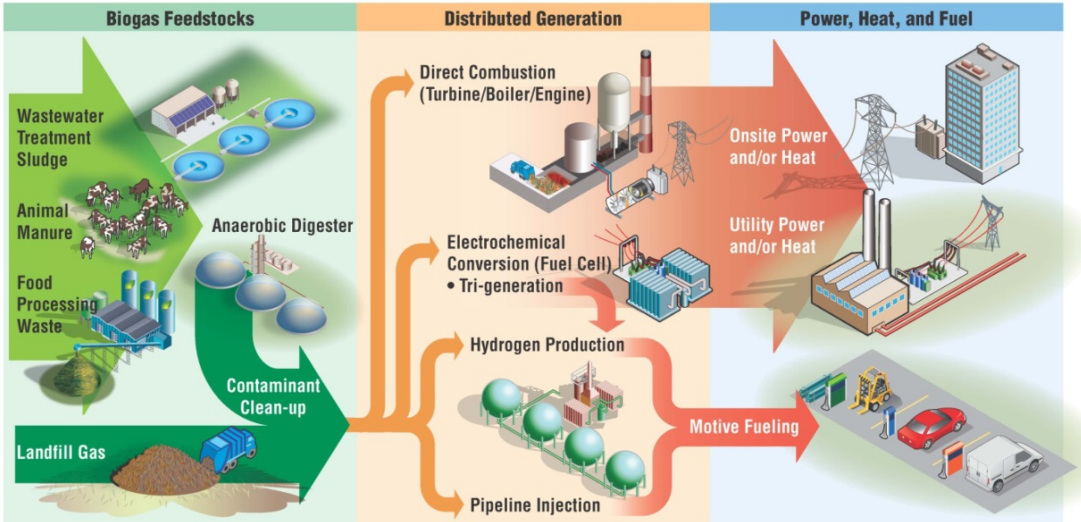




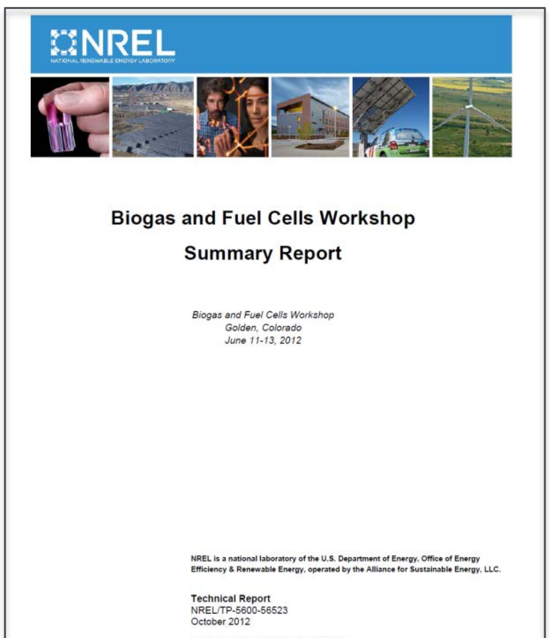
- 304.6 trillion scf in 2010 for proven reserves
  - 61% comes from tight gas, shale gas, and coalbed methane
- 1,930 trillion scf estimate for unproved natural gas reserves
  - 25% shale gas, 22% tight gas, 14% offshore of the lower 48 states, and 14% on- and offshore in Alaska
- Estimates for natural gas shale reserves have grown rapidly, increasing by a factor of 4 between 2008 and 2010
- Adding unproven reserves yields an estimate for total technical and economic potential for natural resources of ~2,200 trillion scf

Source: NREL, Resource Assessment for Hydrogen Production http://www.nrel.gov/docs/fy13osti/55626.pdf

Biogas Opportunities for Fuel Cells



Biogas fuel cell projects are being demonstrated in real world conditions and provide a foundation for growth


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Biogas and Fuel Cells Workshop

Summary Report

Biogas and Fuel Cells Workshop
Golden, Colorado
June 11-13, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-56523
October 2012

Contract No. DE-AC36-08GO28308

2012 Biogas and Fuel Cells Workshop discussed :

- state-of-the-art of biogas and waste-to-energy technologies for fuel cell applications
- challenges preventing or delaying widespread deployment of biogas fuel cell projects and opportunities to address those challenges
- strategies for accelerating the use of biogas for stationary fuel cell power or hydrogen fueling infrastructure for motive power fuel cells

Contaminant issues were also highlighted

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_report.pdf

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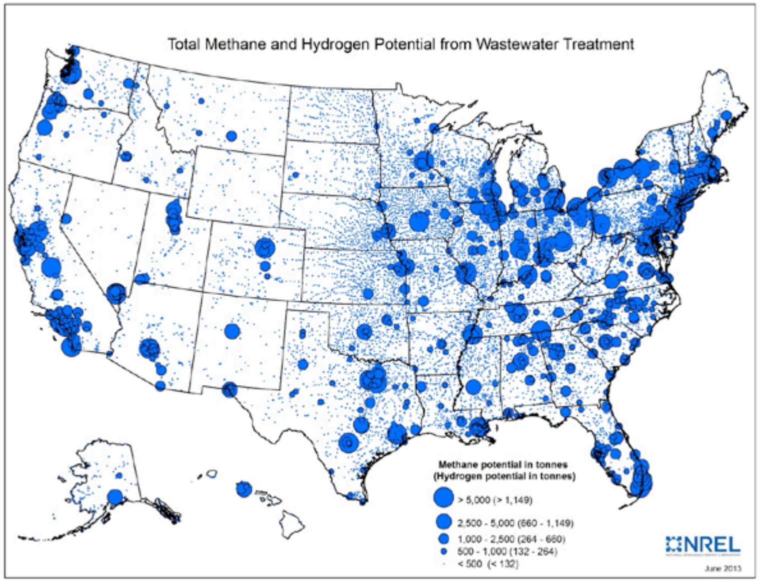
Biogas as an Early Source of Renewable Hydrogen and Power- Preliminary Analysis

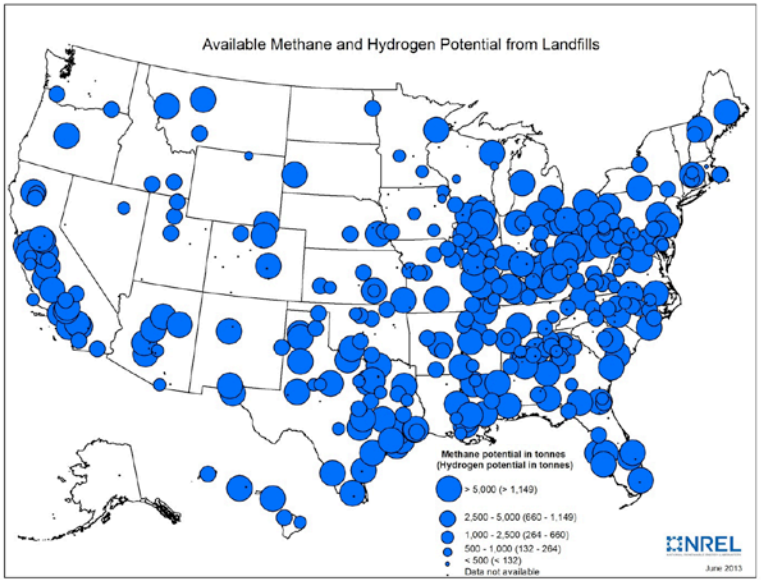
- ***The majority of biogas resources are situated near large urban centers—ideally located near the major demand centers for hydrogen generation for hydrogen fuel cell vehicles (FCEVs) and power generation from stationary fuel cells.***
- ***Hydrogen can be produced from this renewable resource using existing steam-methane-reforming technology.***

Hydrogen generated from biogas can fuel ~11M FCEVs per year.
Hydrogen from landfills can support more than 3M FCEVs annually.

- 1.9 MT per year of methane is available from wastewater treatment plants in the U.S.
- Potential to provide **509,000 tonnes/year** of hydrogen.



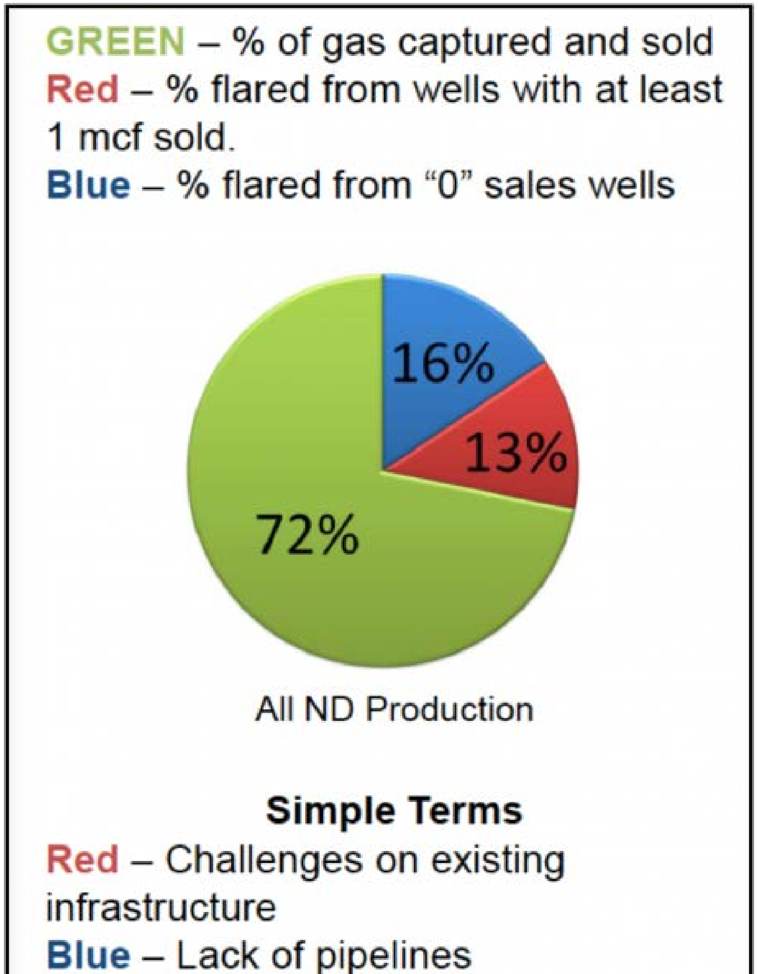
- 2.5 million MT per year of methane is available from landfills in the U.S.
- Potential to provide **648,000 tonnes/year** of hydrogen.



Source: NREL Renewable Hydrogen Potential from Biogas in the United States, in press

Fuel Cells could play a role in addressing APG flaring

Example: Bakken deposits in ND



- In February 2013, over 30% of APG gas produced from the Bakken deposits was flared – the highest of any US basin

http://www.rbnenergy.com/set-fire-to-the-gas-the-fight-to-limit-bakken-flaring

- In 2011, the US flared 0.25 trillion scf of APG, which could provide up to 8 GW of CHP

http://www.worldbank.org/en/news/press-release/2012/07/03/world-bank-sees-warning-sign-gas-flaring-increase

- North Dakota accounts for almost 30% of total US APG flaring

http://northdakotapipelines.com/natgasfacts/

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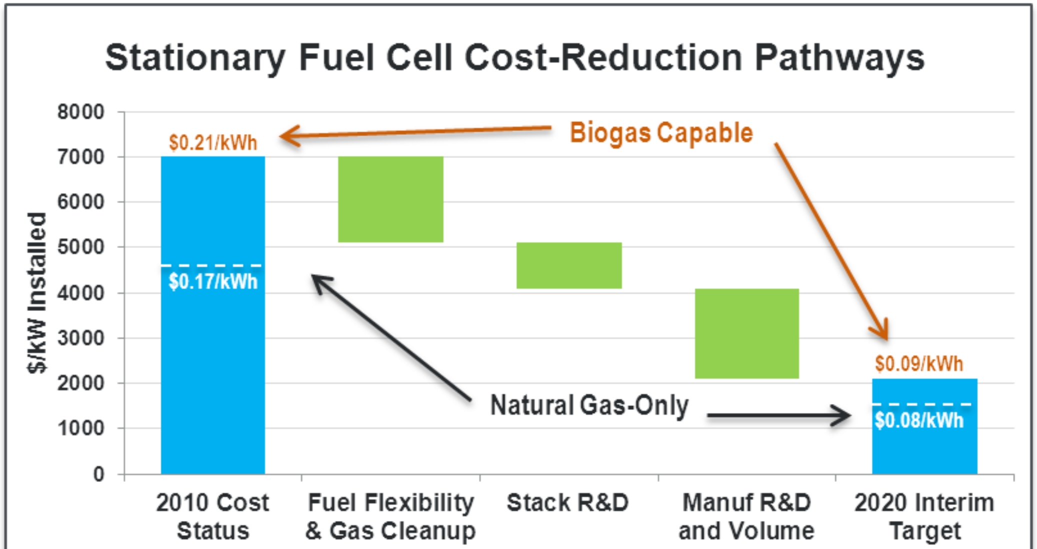
Challenges and Strategy: Stationary Applications

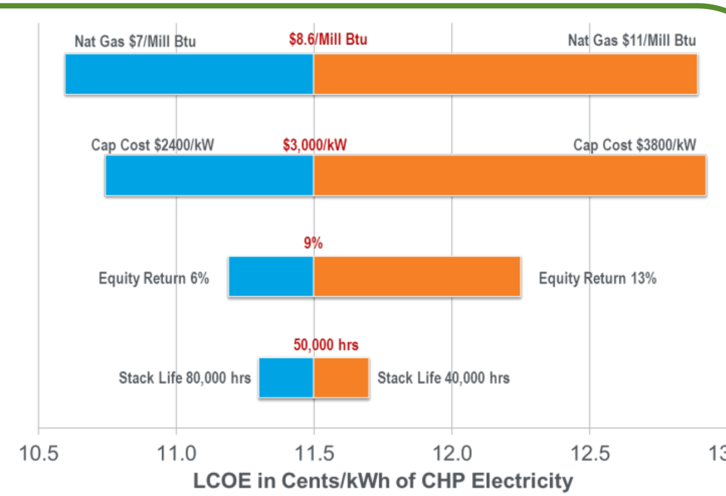
Further reduction in capital cost of medium scale distributed generation/CHP need to be pursued to facilitate widespread commercialization



- Further reduction of fuel cell system cost required to expedite commercialization
- Natural gas availability and fuel cell performance (efficiency) gains will enhance the technology's market attractiveness
- Development of a cost-effective process for removing fuel contaminants would allow for fuel flexibility
- Also applicable for tri-gen (H_2 production)

Sensitivity analysis around 2015 targets assesses impact of fuel cell system cost and durability on commercialization prospects

Technical Parameters (2015)	
Electric Efficiency (LHV)	45.0%
Combined Effic.(LHV)	87.5%
Size, MWe	1
Operating Life, years	20
Equipment, $/kWe	2,300
Engineering& Installation, $/kWe	700
Fixed O&M, $/MWh	13
Variable O&M, $/MWh	8.0



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Impurities increase cost

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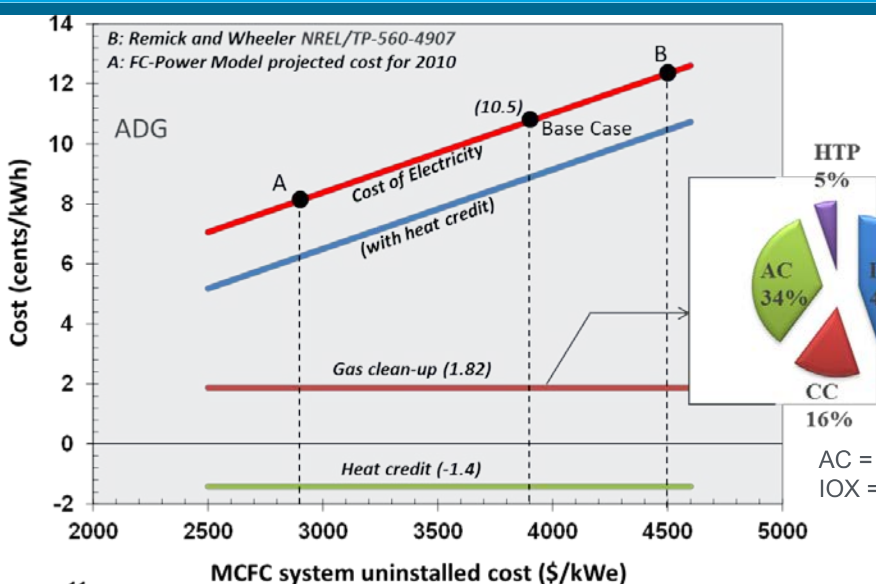
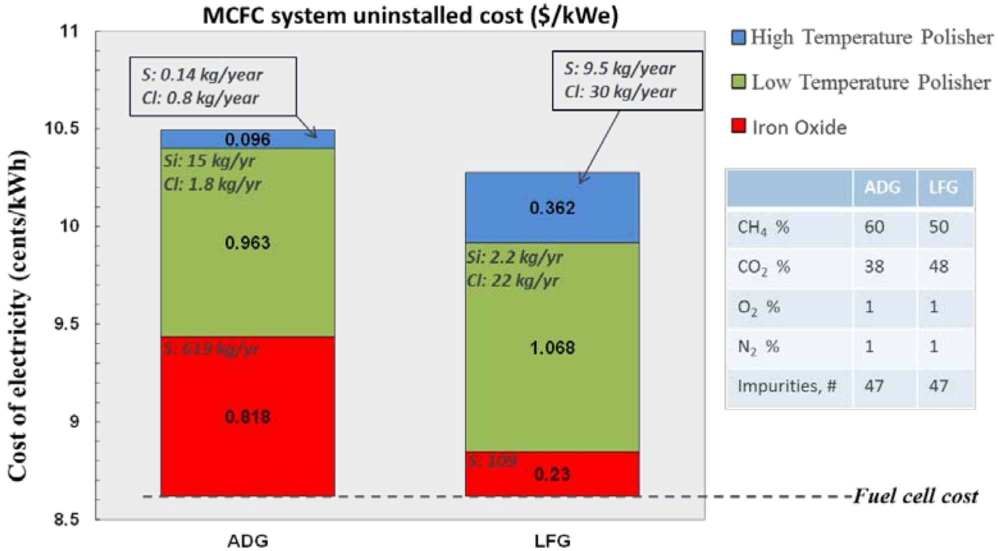
Seeking removal strategies that can reduce plant complexity, reduce cost, and improve plant durability



AC = Activated Carbon, CC = Chiller-Condenser
IOX = Iron Oxide, HTP = High Temp. Polisher

- Sulfur, organosilicon, and halocarbons are known to damage fuel cells
- There are technology options for removing the impurities
- Model estimates that (LFG, ADG) clean-up adds ~2 cents per kWh_e



	ADG	LFG
CH_4 %	60	50
CO_2 %	38	48
O_2 %	1	1
N_2 %	1	1
Impurities, #	47	47

- The carbon beds in the low temperature polisher dominate the cost of clean-up.

Argonne National Laboratory

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Key Report: Biogas in Stationary Fuel Cells

Argonne NATIONAL LABORATORY

ANL/CSE/FCT/FQ-2011-11

Fuel Quality Issues in Stationary Fuel Cell Systems

Chemical Sciences and Engineering Division

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fuel_quality_stationary_fuel_cells.pdf

Sulfur, siloxanes, and halides are impurities of particular concern because of their significant harmful effects on the performance and durability of fuel cell systems.

Further technological development is necessary to help accelerate the deployment of biogas based fuel cell power generation developments.

- Development of continuous monitoring devices for siloxanes would allow better use of the sorbent beds.
- Development of sorbents for these species that have high sorption capacities would facilitate internal reforming.
- Data on adsorption properties of impurities on common sorbents would help in predicting impurity breakthrough and sorption capacity of these sorbents.

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Workshop Objective

- Exchange information
- Discuss research and development (R&D) needs
  - to reduce the cost and complexity of removing impurities from natural gas, LPG, biogas, associated petroleum gas (APG), diesel, and biodiesel for fuel cell applications

Approach

- Identify the impurities
- Identify the removal technologies, their advantages and limitations
- Recommend R&D to improve impurity management
- Identify opportunities to avoid gas emissions and flaring of APG

Participants

- Industry, Academia, National Labs, Government agencies and other stakeholders

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Thank you

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www.hydrogenandfuelcells.energy.gov

Back Up

Micro-CHP Market Outlook

- Until 2012, global micro-CHP market was dominated by products powered by combustion engines.
- Residential fuel cells now account for **64%** of global unit sales (doubling of technology's market share since 2011).

Source: "Fuel Cells Now Outselling Conventional Micro-CHP Technologies," FuelCell Today, July 11, 2013, ***http://www.fuelcelltoday.com/news-events/news-archive/2013/july/fuel-cells-now-outselling-conventional-micro-chp-technologies***

Tri-Generation

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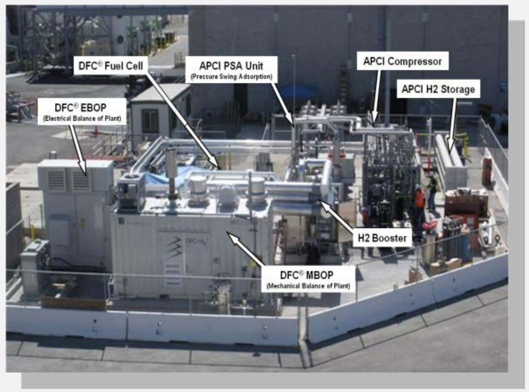
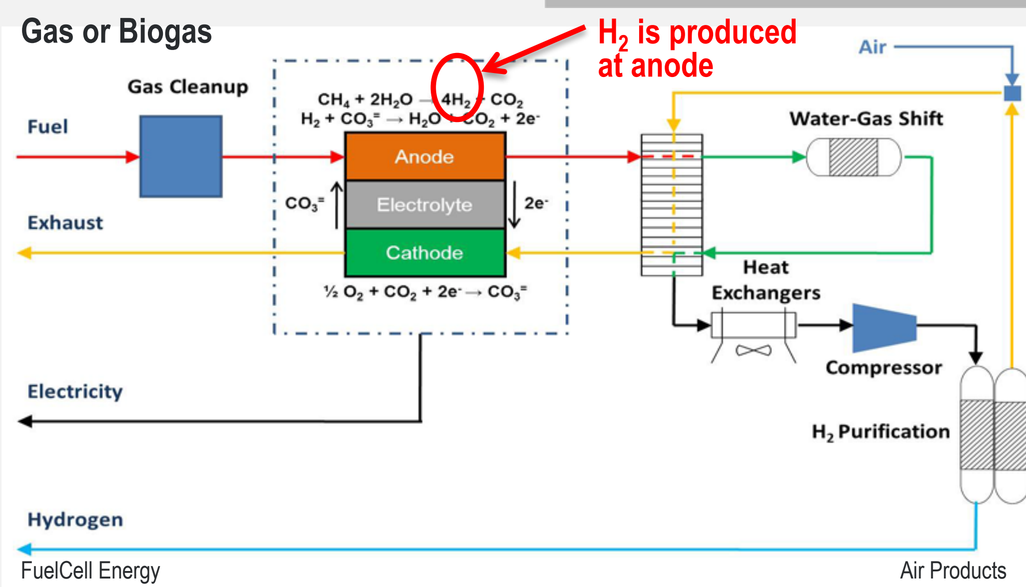
Tri-Generation co-produces power, heat and hydrogen. World's First Fuel Cell and Hydrogen Energy Station demonstrated in Orange County (DOE/FCT project)

Demonstrated world's first Tri-generation station

- Demonstrated co-production of electricity and hydrogen with 54% efficiency
- Uses biogas from wastewater treatment plant





Co-funded by DOE/FCT and multiple partners

Fountain Valley demonstration

- ~250 kW of electricity
- ~100 kg/day hydrogen capacity (350 and 700 bar), enough to fuel 25 to 50 vehicles.

- ***Sulfur***
  - Corrosive, affects catalyst and electrolyte
  - Rapid initial followed by slower voltage decay
  - More severe effect with CH_4/CO rich fuels to Fuel Cell and anode recirculation
  - Tolerance limits 0.5-5 ppm
  - Effect may be recoverable
- ***Siloxanes***
  - Fouls surfaces (HEx, sensors, catalysts)
  - Thermally decompose forming glassy layers
  - Few studies on the effects on FC's, but tolerance limits may be practically zero
- ***Halogens***
  - Corrosive, affects electrolyte
  - Long term degradation effect
  - Tolerance limits, 0.1-1 ppm

Impurity	Tolerance		Reference
Molten Carbonate Fuel Cells			
H_2S	0.1 0.5 0.1-5	ppm	(Tomasi, *et al.*, 2006) (Abe, Chaytors, Clark, Marshall and Morgan, 2002) (Moreno, *et al.*, 2008) (Desiduri, 2003)
COS, CS_2, mercaptan	1	ppm	(Tomasi, Baratieri, Bosio, Arato and Baggio, 2006)
Organic Sulfur	<6	ppm	(Lampe, 2006)
H_2S, COS, CS_2	0.5-1 <10	ppm	(Cigolotti, 2009) (Lampe, 2006)
Halogens (HCl)	0.1-1	ppm	(Moreno, McPhail and Bove, 2008) (Desiduri, 2003), Lampe, 2006) (Abe, Chaytors, Clark, Marshall and Morgan, 2002)
Halides: HCl, HF	0.1-1	ppm	(Cigolotti, 2009)
Alkali Metals	1-10	ppm	(Tomasi, Baratieri, Bosio, Arato and Baggio, 2006) (Moreno, McPhail and Bove, 2008)
NH_3	1 1-3	%	(Moreno, McPhail and Bove, 2008) [Desiduri, 2002], [Fuel Cell Handbook, 2002] (Cigolotti, 2009)
[illegible]	[illegible]		(Moreno, McPhail and Bove, 2008)
Siloxanes: HDMS, D5	10-100 <1	ppm	(Cigolotti, 2009) (Lampe, 2006)
Tars	2000	ppm	(Cigolotti, 2009)
Heavy Metals: As, Pb, Zn, Cd,Hg	1-20	ppm	(Cigolotti, 2009)
Solid Oxide Fuel Cells			

Energy 44 (2012) 257-277