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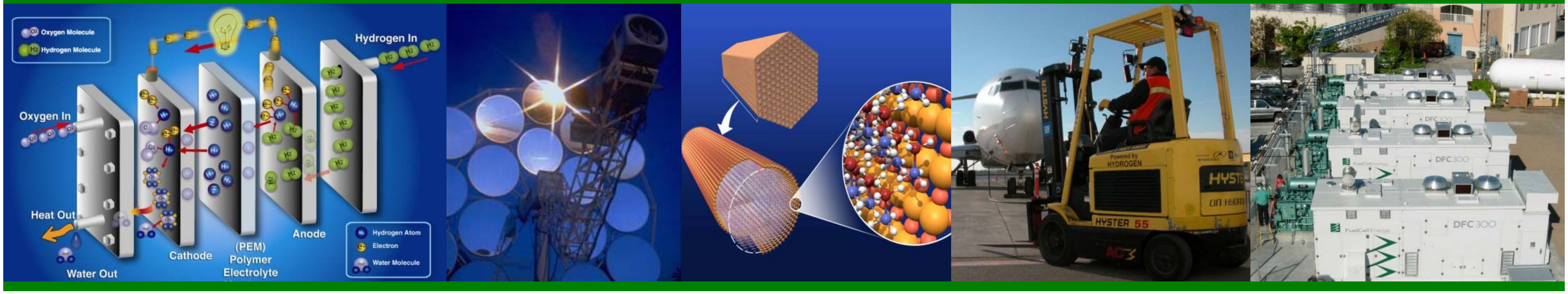

Benefits and Challenges of Biogas Resources

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Program Mission

The mission **of the Fuel Cell Technologies Program is to enable the widespread commercialization of fuel cells, through applied R&D to overcome technical barriers and through efforts to reduce institutional and market barriers.**

→ ***This mission supports the broad national goals of reducing petroleum use, greenhouse gas emissions, and air pollution; developing a more diverse and efficient energy infrastructure; and creating high-skilled jobs in emerging technical fields.***

The key objective **is to make fuel cells competitive with incumbent technologies and other advanced technologies in terms of lifecycle cost, performance, and market acceptance.**

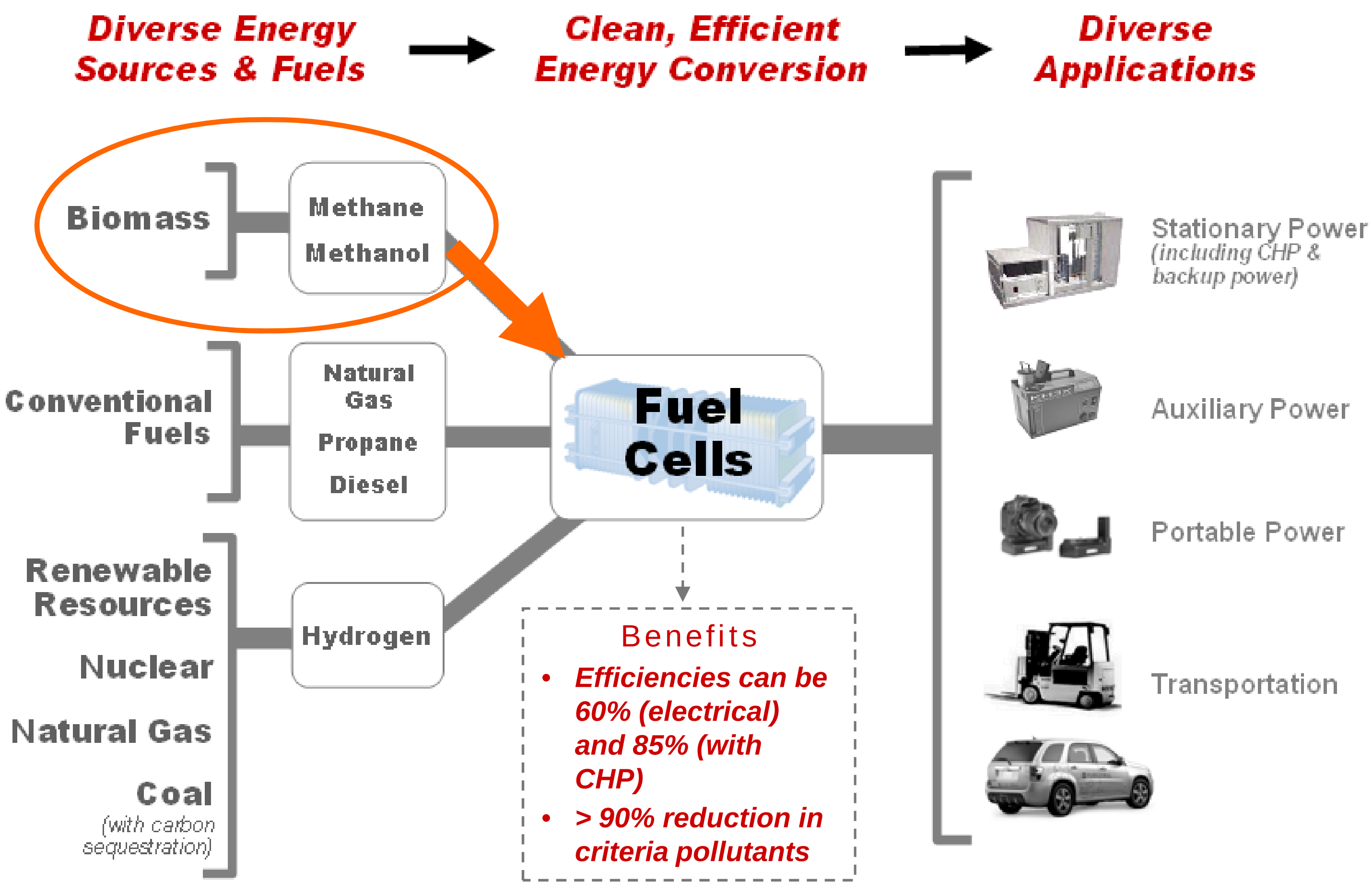
Fuel Cells Technologies (FCT) Program

Energy Efficiency and Resource Diversity

→ ***Fuel cells offer a highly efficient way to use diverse fuels and energy sources.***

Greenhouse Gas Emissions and Air Pollution:

→ ***Fuel cells can be powered by emissions-free fuels that are produced from clean, domestic resources.***



Key Challenges of FCT Program

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The Program has been addressing the key challenges facing the widespread commercialization of fuel cells.

Technology Barriers*

Fuel Cell Cost & Durability

Targets*:

Stationary Systems: **$750 per kW, 40,000-hr durability**

Vehicles: **$30 per kW, 5,000-hr durability**

Hydrogen Cost

Target: $2 – 4 /gge, delivered

Hydrogen Storage Capacity

Target: > 300-mile range for vehicles—without compromising interior space or performance

Technology Validation:

Technologies must be demonstrated under real-world conditions.

Economic & Institutional Barriers

Safety, Codes & Standards Development

Domestic Manufacturing & Supplier Base

Public Awareness & Acceptance

Hydrogen Supply & Delivery Infrastructure

Market Transformation

Assisting the growth of early markets will help to overcome many barriers, including achieving significant cost reductions through economies of scale.

***Metrics available/under development for various applications**

Bio-methane from Biogas

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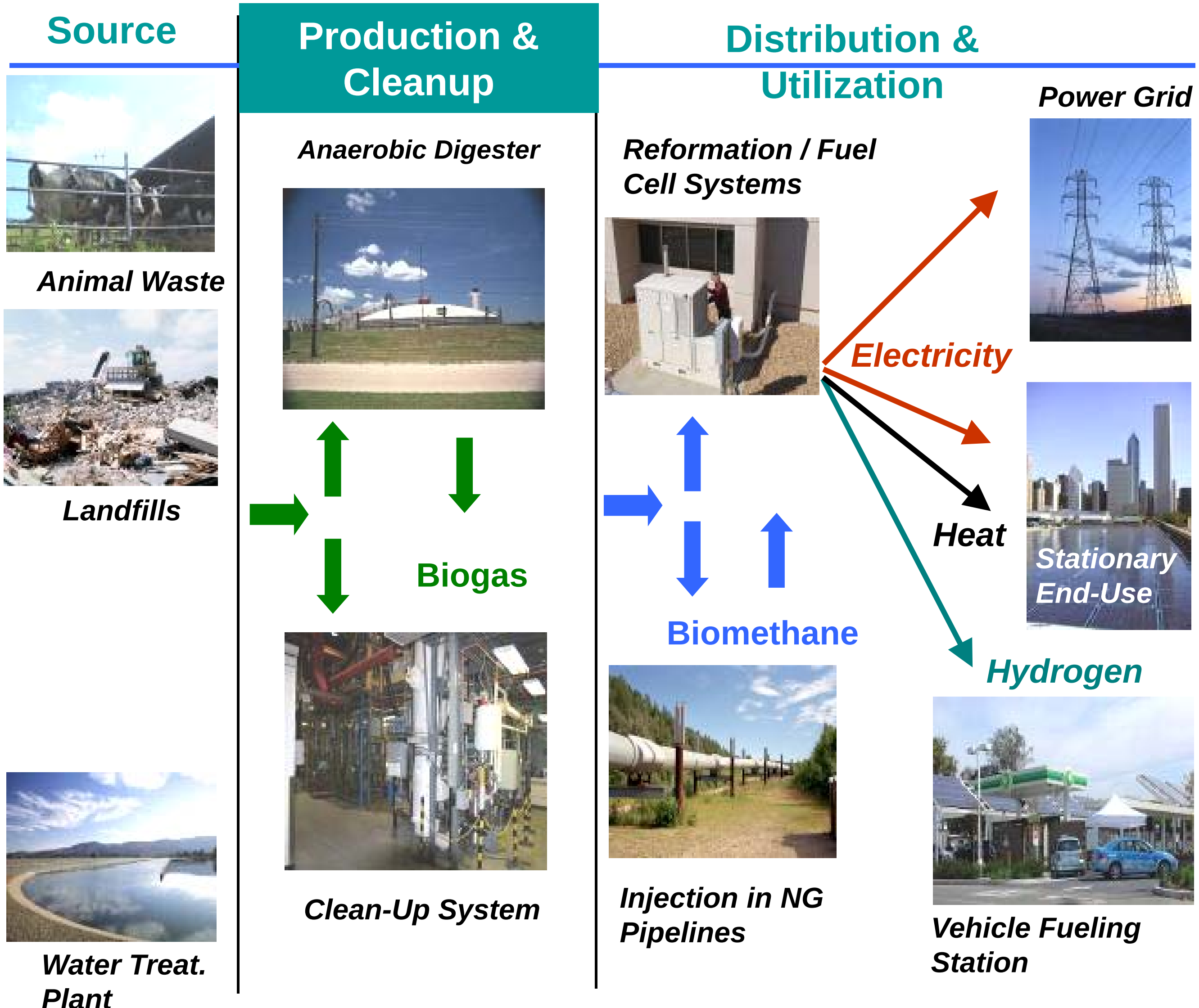
Fuel cells operating on bio-methane or hydrogen derived from bio-methane can mitigate energy and environmental issues and provide an opportunity for their commercialization. Other drivers are: need for fuel diversity/flexibility, evolving policies for renewables, and related incentives.



Source: National Renewable Energy Laboratory

H2A Production Model
Platform for new cost analysis model aimed at calculating levelized cost of bio-methane (from biogas).

Fuel Cell Power Model
Analysis of stationary fuel cell systems—in standalone and combined heat, hydrogen, and power (CHHP) models.

SERA Model
Optimization tool, may also be used for related infrastructure analysis upon modification.

Biogas Resource: Methane from Landfills

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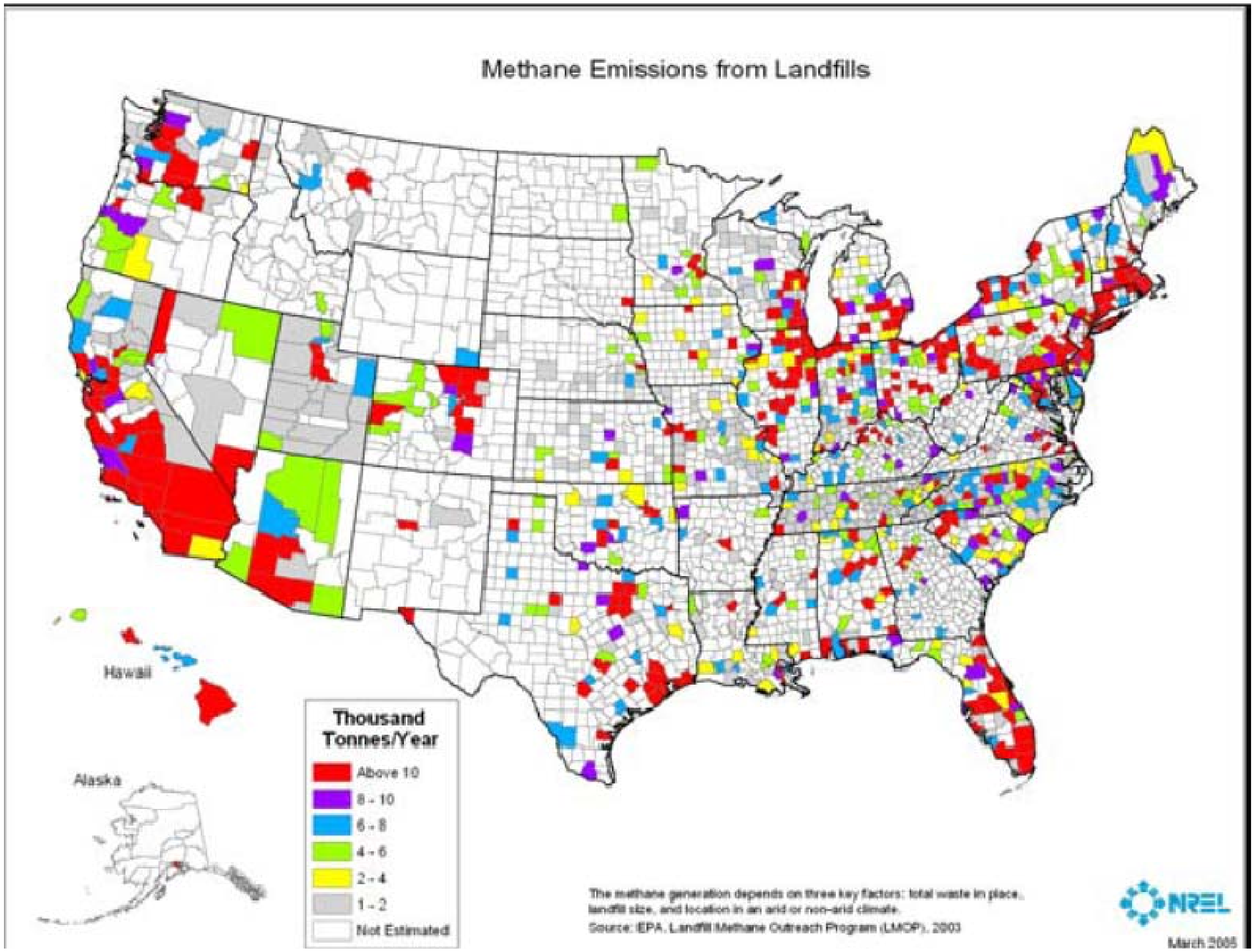
Biogas from landfills are located near large urban centers and provide enough renewable resource to fuel ~17 million fuel cell vehicles per day.



- **12.4 million MT per year of methane available from landfills in U.S.**
- **Majority of resource located near urban centers.**
- **Bio-methane could be used to produce ~17 million kg/day of renewable hydrogen from steam methane reforming.**
- **Renewable hydrogen is enough to fuel ~17 million fuel cell vehicles per day.**
- **Potential oil savings of ~1,000,000 B/D.**

Source: NREL report *A Geographic Perspective on Current Biomass Resource Availability in the United States*, 2005

Biogas Resource:
Methane from Waste Water Treatment Plants

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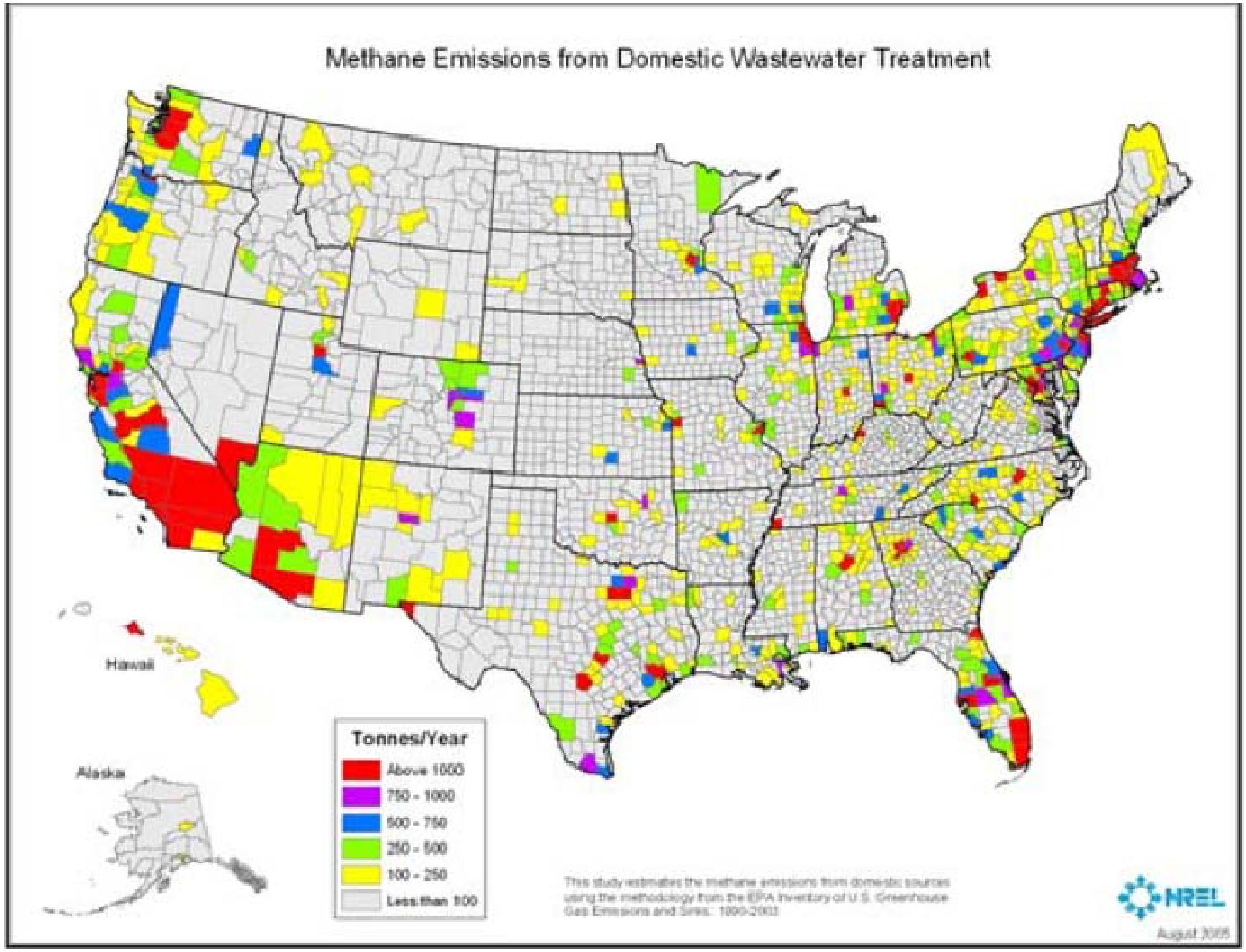
Biogas from waste water treatment plants is ideally located near urban centers to supply hydrogen for fuel cell vehicles.



Source: NREL report *A Geographic Perspective on Current Biomass Resource Availability in the United States*, 2005

- **500,000 MT per year of methane available from waste water treatment plants in U.S.**
- **Majority of resource located near urban centers.**
- **Bio-methane could be used to produce ~680,000 kg/day of renewable hydrogen from steam methane reforming.**
- **Renewable hydrogen is enough to fuel ~680,000 fuel cell vehicles per day.**
- **Potential oil savings of 40,000 B/D.**

Biogas Application for Combined Heat, Power and Hydrogen

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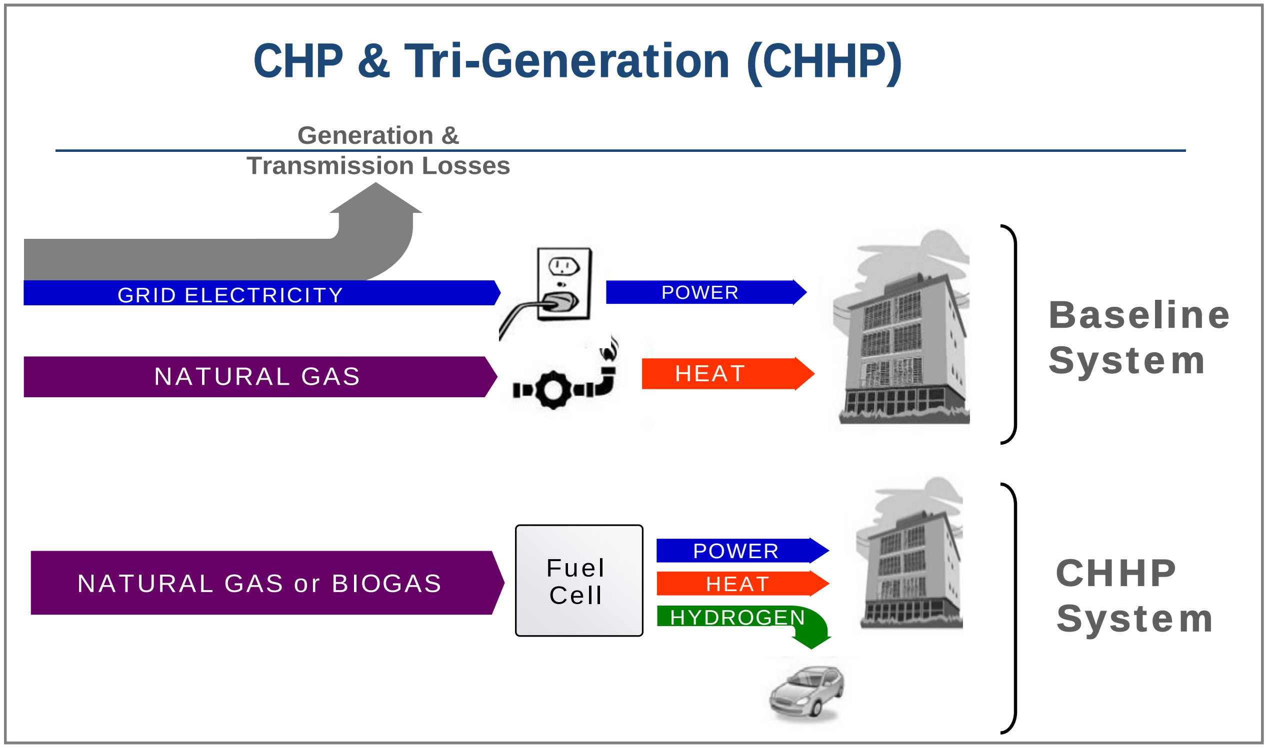
Biogas resource can produce a significant amount of power from Combined Heat and Power units.



Combined heat, hydrogen, and power systems can:

- ***Produce clean power and fuel for multiple applications***
- ***Provide a potential approach to establishing an initial fueling infrastructure***

Combined bio-methane resource from landfills and waste water treatment plants could provide enough energy to produce 9.3 Giga Watts of power from Combined Heat and Power Units.

Biogas Benefits

Preliminary Well to Wheels Analysis Results

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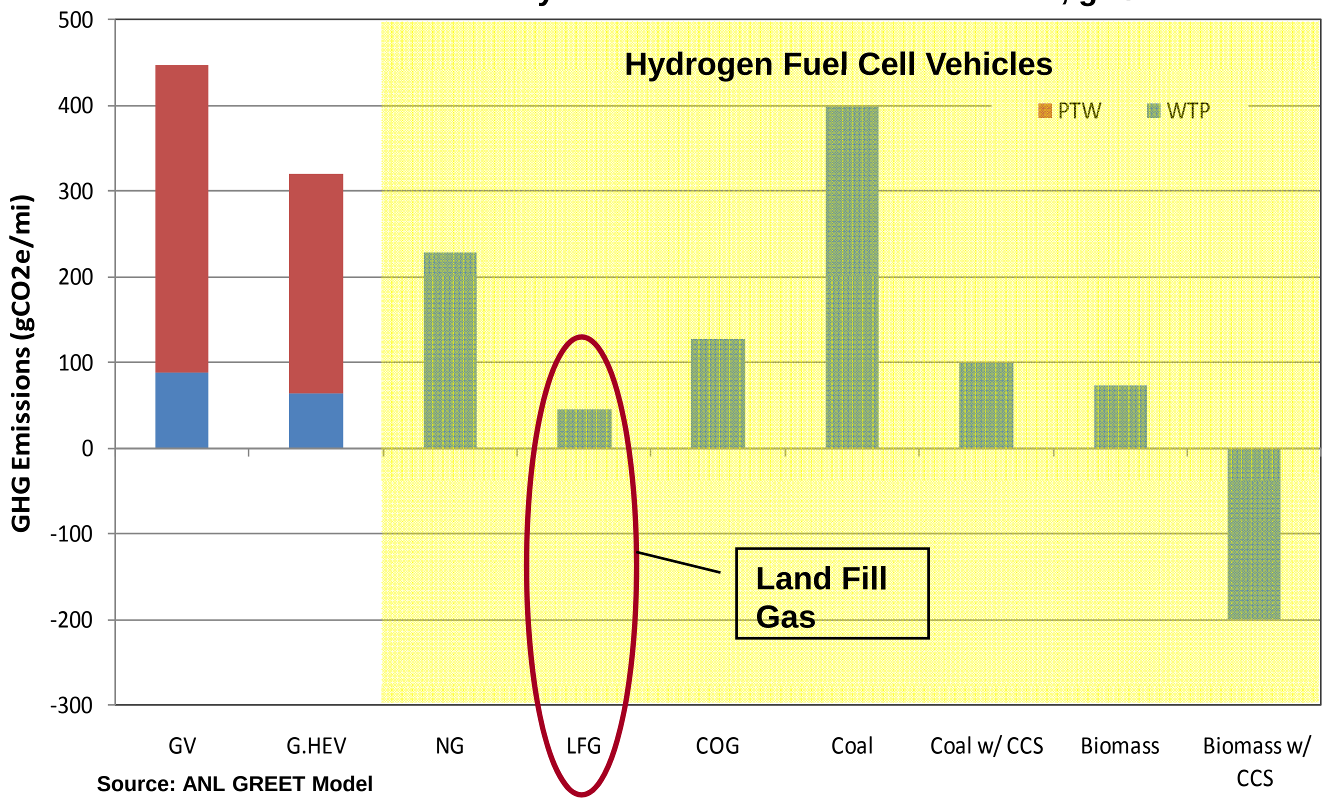
Fuel cell vehicles utilizing hydrogen produced from landfill gas is a renewable pathway with low carbon emissions.

Well to Wheels Analysis – Greenhouse Gas Emissions, gm/mile



Source: ANL GREET Model

Legend

GV – Gasoline Vehicle

GHEV – Gasoline Hybrid Electric Vehicle

NG – Distributed Natural Gas Hydrogen Fuel Cell Vehicle

LFG – Land Fill Gas Hydrogen Fuel Cell Vehicle

COG – Coke Oven Gas Hydrogen Fuel Cell Vehicle

CCS – Carbon Capture and Sequestration

WTP – Well to Pump

PTW – Pump to Wheels

Notes:

- **Information for H2FCV with hydrogen from landfill gas is based on ANL GREET model and analysis.**
- **The landfill gas is assumed to be flared in this scenario.**
- **For carbon capture and sequestration (CCS), 90% carbon capture rate was assumed; electricity use for capture and transmission of CO2 was considered.**

Vehicle Fuel Economy Assumptions			
	Gasoline ICE	Gasoline HEV	Fuel Cell Vehicle
MPGGE	25	34	58

Biogas Benefits

Preliminary Well to Wheels Analysis Results

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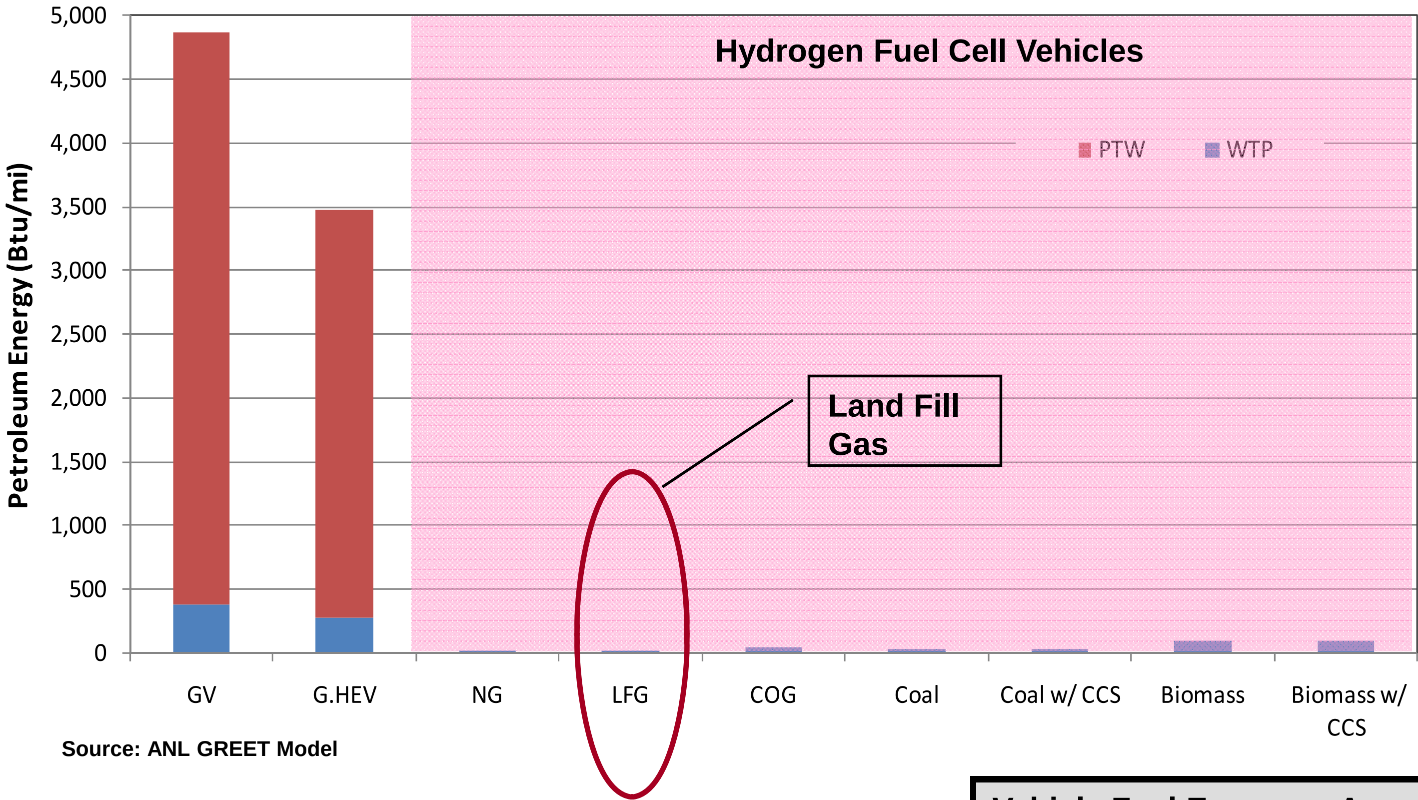
The fuel cell vehicles fueled with hydrogen produced from landfill gas will reduce light duty vehicle petroleum use.

Well to Wheels Analysis – Petroleum Use, Btu/mile



Source: ANL GREET Model

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Biogas Challenges

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Use of biogas for hydrogen production and stationary fuel cells will be impacted by contaminant content and cleanup costs.

Challenges

High level of contaminants

High variability of contaminant concentrations

High capital cost for contaminant removal

Low experience level with biogas cleanup

Location of resources relative to demand centers and understanding cost impacts of transportation

Pipeline restrictions for transport of biogas from source to demand center

Activities to Address Challenges

Project established with ANL to understand impact of biogas impurities on stationary fuel cell performance

Project established with NREL to identify locations of biogas resources and develop biogas H2A model for biogas cost analysis

Held workshops to understand gaps for utilizing biogas for hydrogen and power production

Biogas Contaminant Content

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Landfill gas contains a wide variety of species at concentrations of less than 0.05% that vary widely among landfill sites.

Landfill Gas Analysis

Paraffins	ppm
Isobutane	<100
Isopentane	<970
N-Pentane	<180
Hexanes	<390
Sulfur	
Hydrogen Sulfide	<280
Methyl Mercaptan	<0.5
Ethyl Mercaptan	<8
Dimethyl Sulfide	<0.02
Carbon Disulfide	<0.5
Methanethiole	<0.5
Cyclics	
Pinene	<86
Limonene	<25

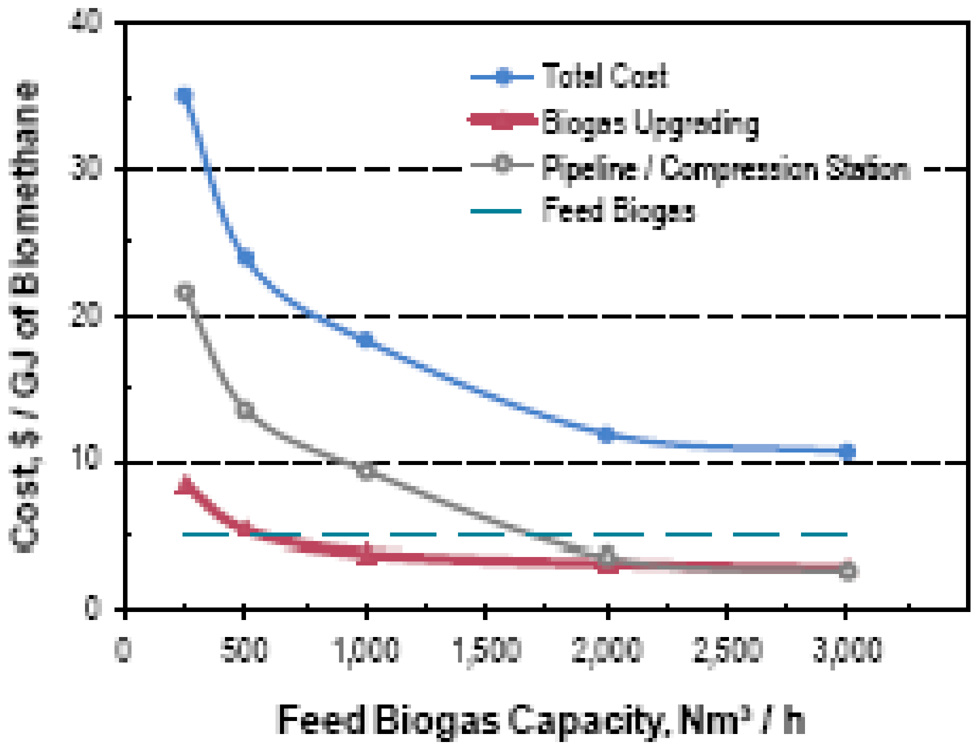
Aromatics	ppm
Isopropylbenzene	<6
Benzene	<5
Toluene	<21
Xylene (and isomers)	<45
Styrene	<0.5
Ethylbenzene	<13
Trimethylbenzene	<14
Halides	
Chlorobenzene	<1
Dichloroethene	<33
Dichloroethane	<0.25
Cis-1,2 Dichloroethane	<5
Methylene Chloride	<12
Trichloromethane	<0.6
Trichloroethene	<6.3
Vinyl Chloride	<1.4
Organic Silicon	
Siloxane (D3, D4*, D5, L2, L4)	<15*
Trimethylsilanol	<12

Source: ANL 2010 Annual Merit Review Presentation

Biogas Cost Challenge

Biogas Cleanup could be ~30% of Biogas Cost

Costs for Biogas from Dairy Farm/s



- **Costs reflect upgrading and transport of biogas from a dairy farm/s.**
- **Cost of biogas upgrading and transport decrease with increase capacity.**
- **For comparison, natural gas cost is ~$11/GJ.**

Source: NREL report for 2010 Annual Merit Review

Summary

- **Biogas from landfills and waste treatment is a domestic, renewable resource strategically located near large urban centers.**
- **Biogas quantities are large enough to produce hydrogen fuel to support fuel cell vehicle rollout strategies.**
- **The hydrogen production pathway utilizing biogas has lower greenhouse gas emissions than conventional gasoline vehicles.**
- **Fuel cell vehicles utilizing hydrogen from biogas will reduce petroleum use for light duty vehicles.**
- **Biogas applications face cleanup challenges of a wide range of contaminants with variable concentrations that could increase the cost of biogas by ~30%.**
- **Fuel Cell Technologies Program is incorporating this feedstock in program benefits modeling and analysis to further understand cost and quality constraints.**

Thank You

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Supporting Slides

Sulfur Impurity of Landfill Gas

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- Sulfur is removed by HDS, Adsorption, Absorption, Oxidation

Example of medium used for H_2S and mercaptan removal*

Sulfur Removal Medium	Regeneration	Capacity	$/kg of H2S
Iron Sponge (Iron Oxide)	2-3 X	2.5 kg-H_2S/kg-Fe_2O_3	0.35-1.35
Sulfa Treat® (Iron Oxide	No	0.5-0.7 kg-H_2S/kg-Fe_2O_3	4.85-5.00
Media G2® (Iron Oxide)	15 X	0.5 kg-H_2S/kg-Fe_2O_3	2.90-3.00
Impregnated activated carbon	Yes	0.12 g-S/g-C	1.75-2.00

- Pressure swing adsorption is very effective for most impurities
- Membrane permeation (H_2) is effective but the membrane is vulnerable to poisoning by sulfur
- Phase separation is used for the removal of moisture, ammonia, metals

**Zicari, S (2003). M.Sc Thesis - Cornell University; Spiegel et al (2003). Waste Management, 23, 709-717*

Siloxane Impurity of Landfill Gas

- Landfill gas contains siloxanes
  - Siloxanes oxidize to form silica that deposits on surfaces
  - Siloxanes can be removed by sorbents (e.g., silica gel, bentonite, etc.)
  - Removal is affected by siloxane type, sorbent used, and the nature of the other impurities (e.g, water)
  - Sorbent beds are often staged
  - Life / capacity are generally low

Siloxane Uptake Capacity of Silica Gel*

Rel. Humidity, %	L2	D5
0	11	10
10	10	8.4
20	6.2	4.6
30	1.8	1.0
50	0.8	0.6

**Schweigkofler et al (2001), Journal of Hazardous materials B83 183-196*

Source: ANL Presentation at 2010 Annual Merit Review