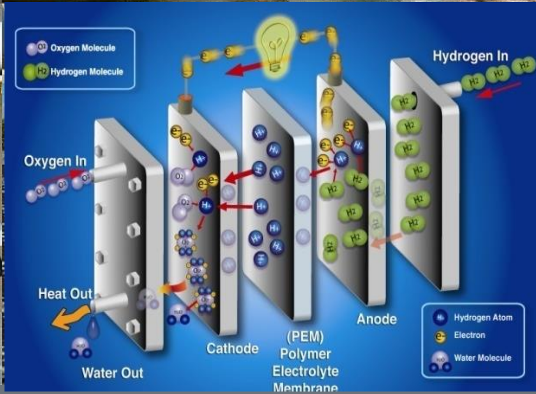
U.S Department of Energy Fuel Cell Technologies Office Overview

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



Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop

Washington, DC

March 18, 2015

Dr. Sunita Satyapal

Director
Fuel Cell Technologies Office
Energy Efficiency & Renewable Energy

All-of-the-Above Energy Strategy

"We've got to invest in a serious, sustained, ***all-of-the-above energy strategy*** *that develops every resource available for the 21st century."*

- President Barack Obama

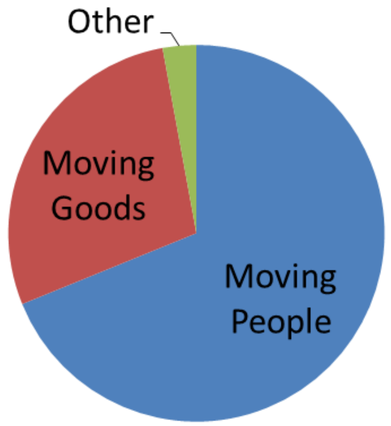
"As part of an all-of-the-above energy approach, fuel cell technologies are paving the way to competitiveness in the global clean energy market and to new jobs and business creation across the country."

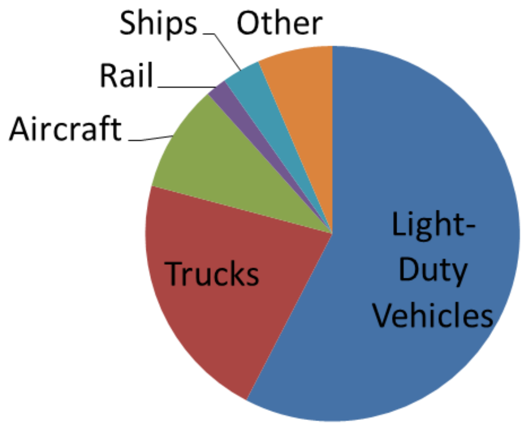
- Secretary Moniz,
U.S. Department of Energy

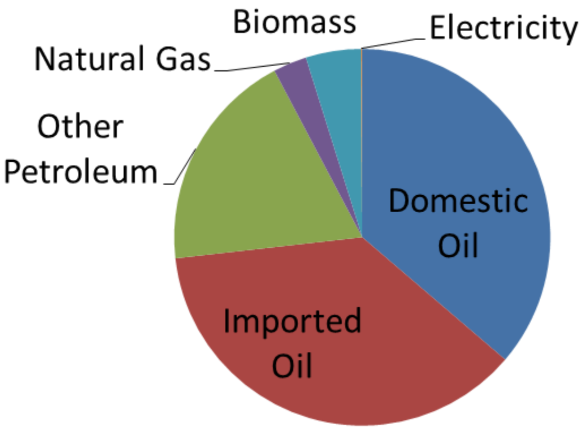
Secretary Moniz at DC Auto Show

Transportation Overview

- **Transportation sector:**
  - **is 93% petroleum dependent**
  - **represents 70% of all U.S. petroleum use**
  - **produces 27% of U.S. emissions**
- **The U.S. uses 21% of the world's oil supply**
  - **accounts for 11% of the world's production**
  - **has just 2% of the world's proven oil reserves**







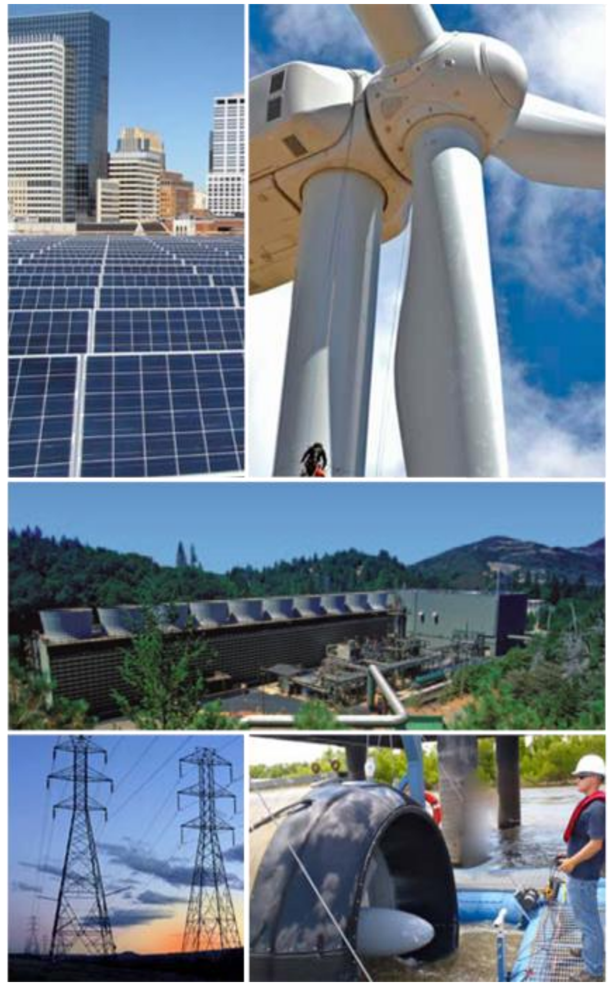
26.8 Quadrillion Btu of transportation energy use

(note: does not include approximately 2.2 quadrillion Btu for offroad equipment)

Office of Energy Efficiency & Renewable Energy

Sustainable TRANSPORTATION

Renewable ELECTRICITY GENERATION



Energy Saving HOMES, BUILDINGS, & MANUFACTURING

Sustainable TRANSPORTATION

- Transportation Efficiency
- Diverse Fuel Sources
- Domestic & Renewable

Hydrogen and Fuel Cells

Vehicles

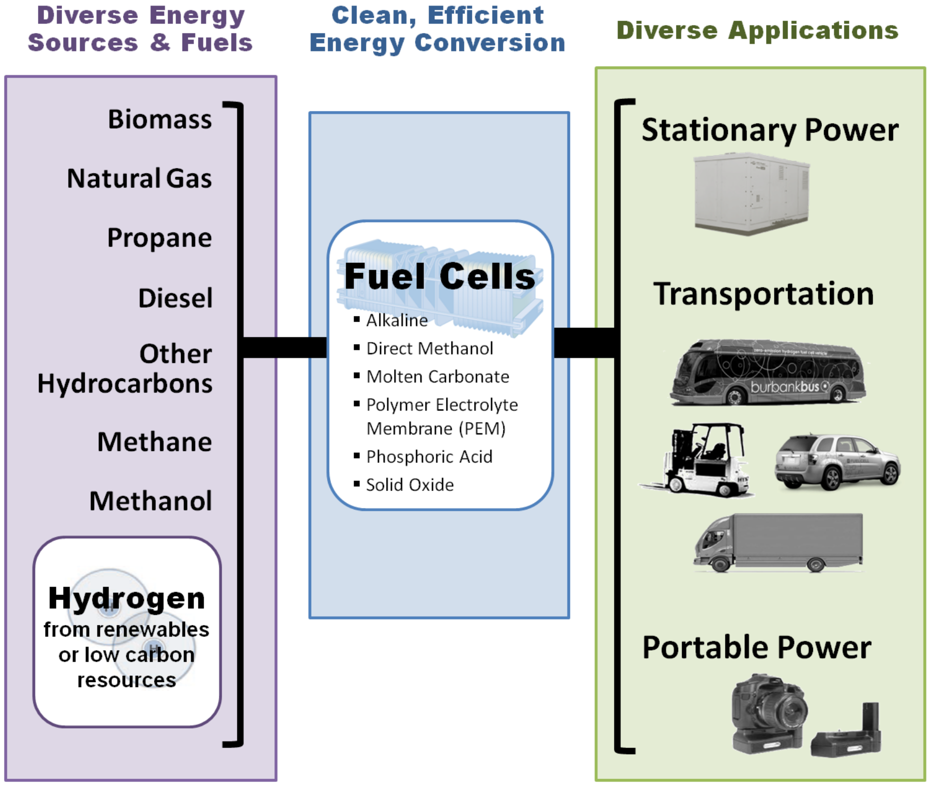
Bioenergy

National Energy Goals & Climate Action Plan

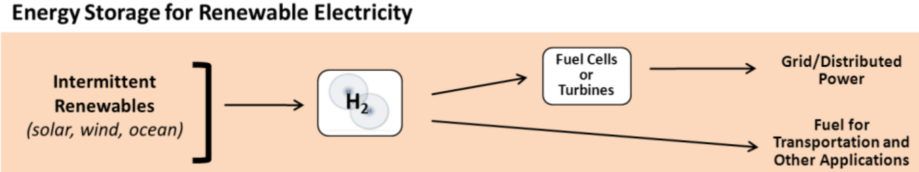
Net Oil Imports	GHG Emissions
↓ 50% by 2020	↓ 17% by 2020 >80% by 2050

Background on Fuel Cells

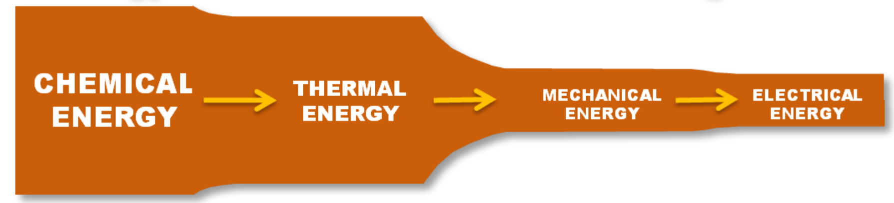
The Role of Fuel Cells



Energy Storage for Renewable Electricity



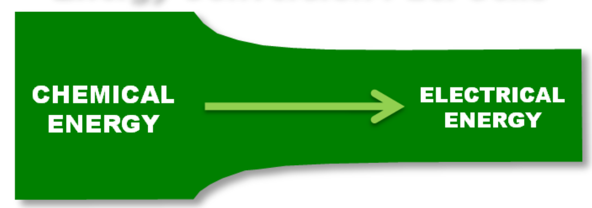
Energy Conversion in Combustion Engines



15 – 40% efficiency

Combustion Engines — convert chemical energy into thermal energy and mechanical energy, and then into electrical energy.

Energy Conversion Fuel Cells



60%+ efficiency possible

Fuel cells — convert chemical energy directly into electrical energy, bypassing inefficiencies associated with thermal energy conversion.

Fuel cells convert chemical energy directly to electricity without the need for combustion and are more efficient than conventional technologies

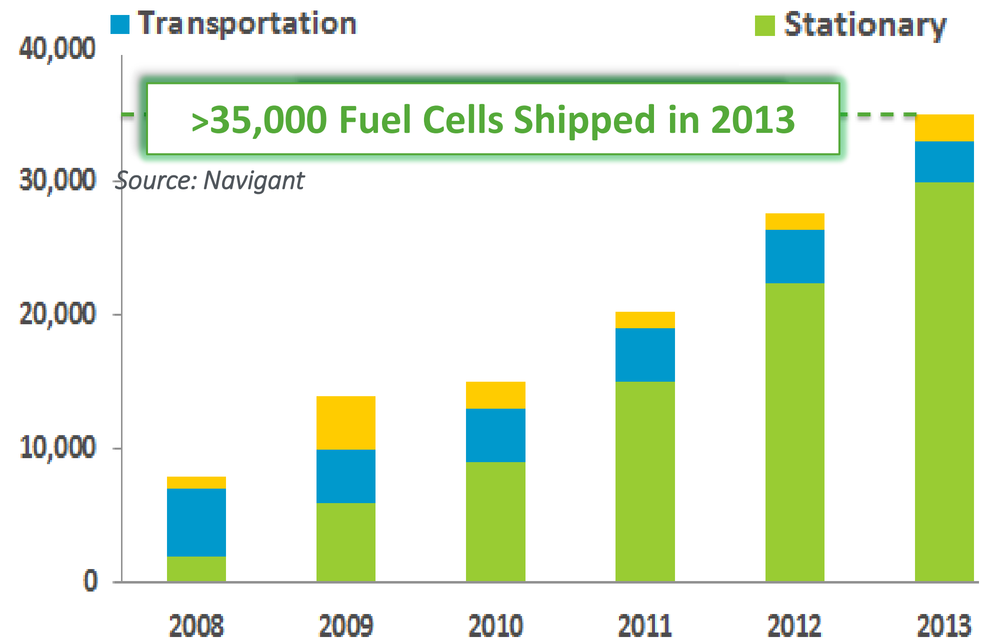
Fuel Cells- An Emerging Industry

Steady Market Growth

~30% annual growth in global systems shipped since 2010.

Global market potential in 10–20 yrs:

- $14 – $31 billion/yr- stationary power
- $11 billion/yr- portable power
- $18 – $97 billion/yr- transportation



FCEV Commercial Launch

Several automakers have announced plans for commercial FCEVs (Hyundai, Toyota, Honda, GM, Daimler, Nissan, Ford, BMW, etc.)

Recent FCEV announcements- 2014-2015

H_2USA to address H_2 Infrastructure Challenges

H_2USA

U.S. Department of Energy
The Great Seal of the State of California
Global Automakers
NESCAUM
Fuel Cell & Hydrogen Energy Association
AGA American Gas Association
California Fuel Cell Partnership – Driving for the Future
GM
Honda – The Power of Dreams
Hyundai
Mercedes-Benz
Nissan
Toyota
Volkswagen
Air Liquide
arc:Hydrogen
Argonne National Laboratory
EDTA – Electric Drive Transportation Association
HNEI
Hydrogenics – Advanced Hydrogen Solutions
Intelligent Energy
ITM Power – Energy Storage | Clean Fuel
Kobelco – Kobelco Compressors (America), Inc.
The Linde Group – Linde
Massachusetts Hydrogen Coalition
NACS
NREL – National Renewable Energy Laboratory
Nuvera – Making hydrogen make sense.
Pacific Northwest National Laboratory
PDC
Plug Power
Proton – The Leader in On Site Gas Generation
Sandia National Laboratories
SRNL – Savannah River National Laboratory
SCRA
INL – Idaho National Laboratory
FCA – Fiat Chrysler Automobiles

*Representative sample of member logos

Public-Private Partnership with 3X increase in partners since 2013

H_2 Infrastructure Development and Status

Nationwide

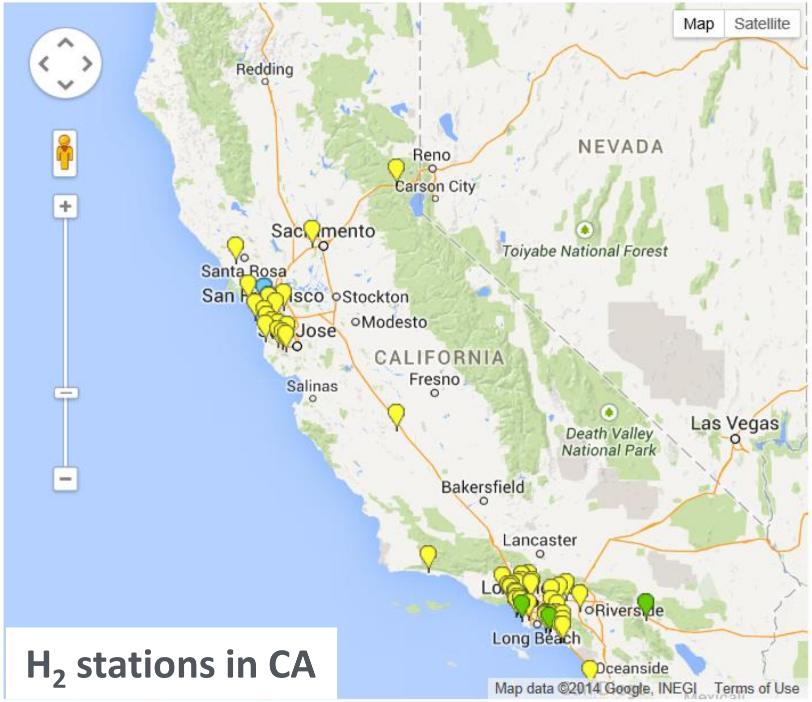
- **1,500 mi.** of H_2 pipeline
- **>9M** metric tons produced/yr
- **~50 stations** (~10 public)

Other States

- **8-State MOU Members:** CA, CT, NY, MA, MD, OR, RI and VT
- **MA, NY, CT:** Preliminary plans for H_2 infrastructure and FCEVs deployment in metro centers in NE states.
- **Hawaii:** Public access refueling infrastructure on Oahu by 2020

California

- **100 stations** - Goal
- **>~$70M** awarded
- **~$100M** planned through **2023**

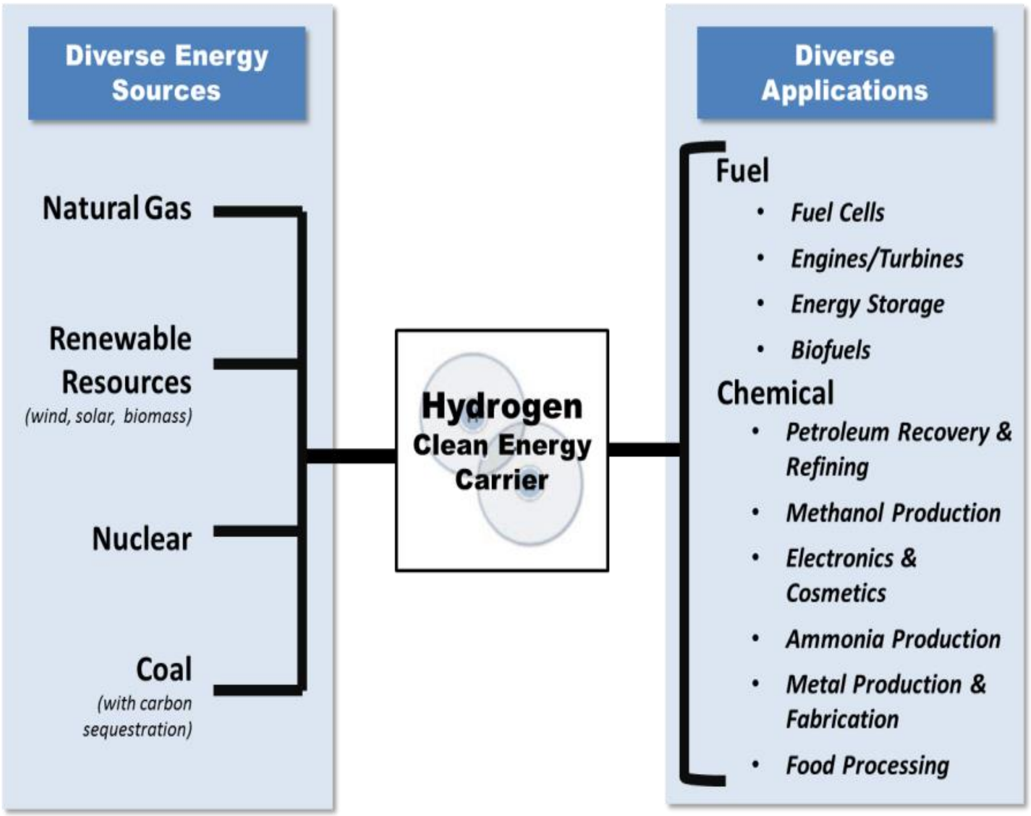


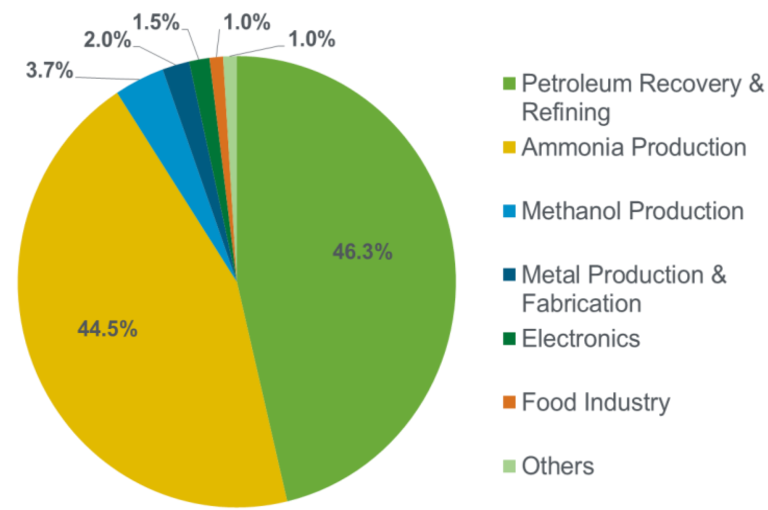
H_2 stations in CA

Filter by: All (60) | Open (9) | In Development (49) | Bus (2)

NE states, California and Hawaii have H_2 infrastructure efforts underway

Hydrogen Production and Use





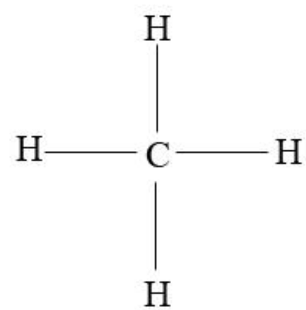
2010 hydrogen consumption market share by application

Hydrogen can be produced from diverse, domestic resources and is used in numerous applications

Hydrogen vs. Hydrogen vs. Hydrocarbons

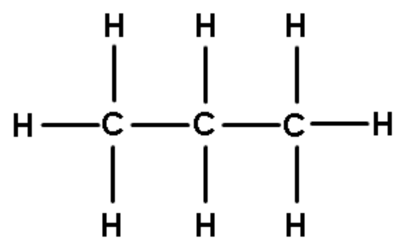
Increasing specific energy

120 MJ/kg

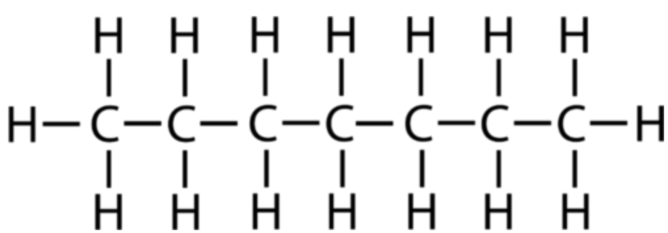


~ 43 MJ/kg

8.5 MJ/L (l)
4.8 @ 700 bar



Increasing energy density



similar components in gasoline

~32 MJ/L

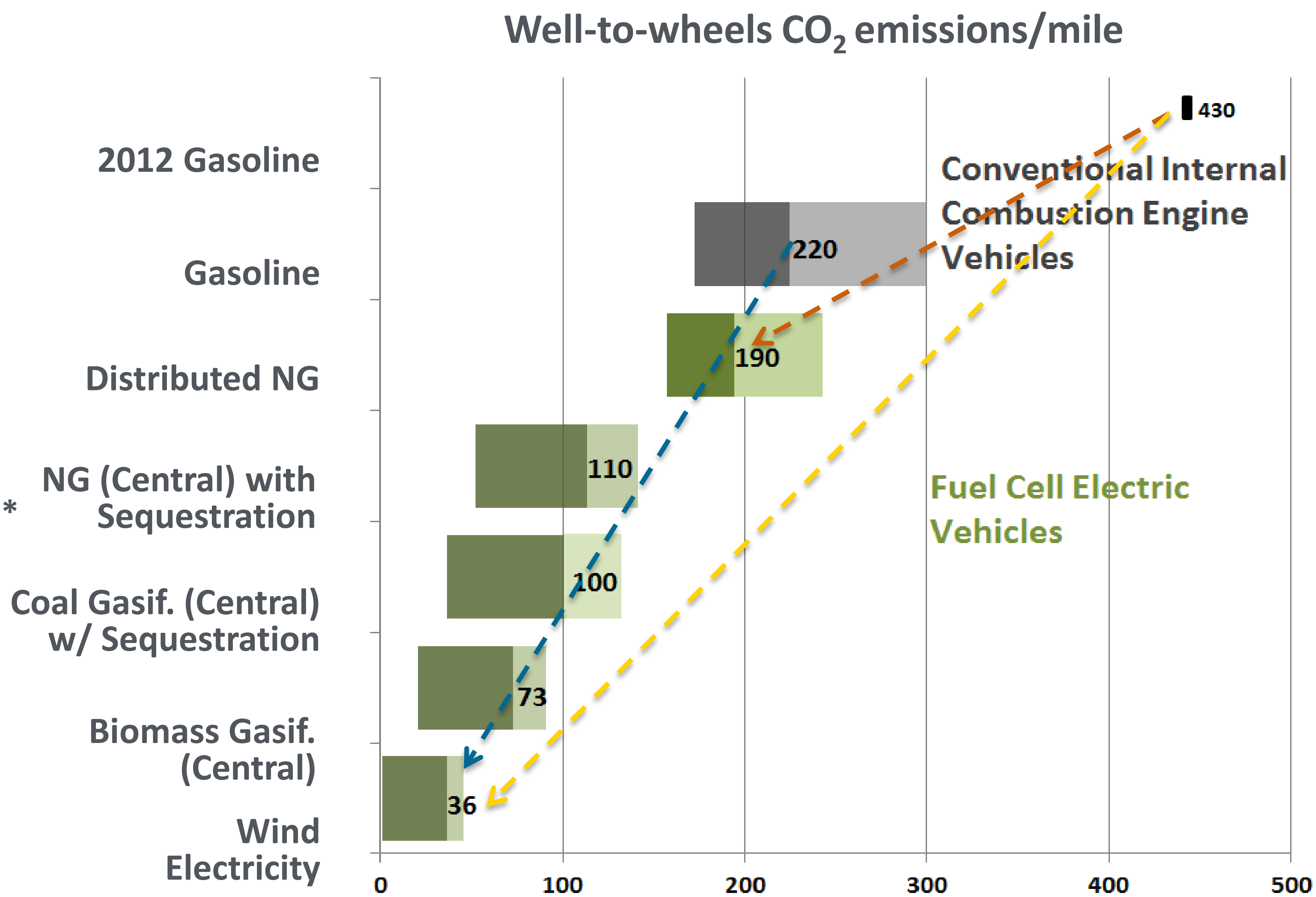
Hydrogen has the highest energy content by mass but low energy density

FCEVs Reduce Greenhouse Gas Emissions

>50% from Distributed Natural Gas*

>80% from Renewables** (Wind)

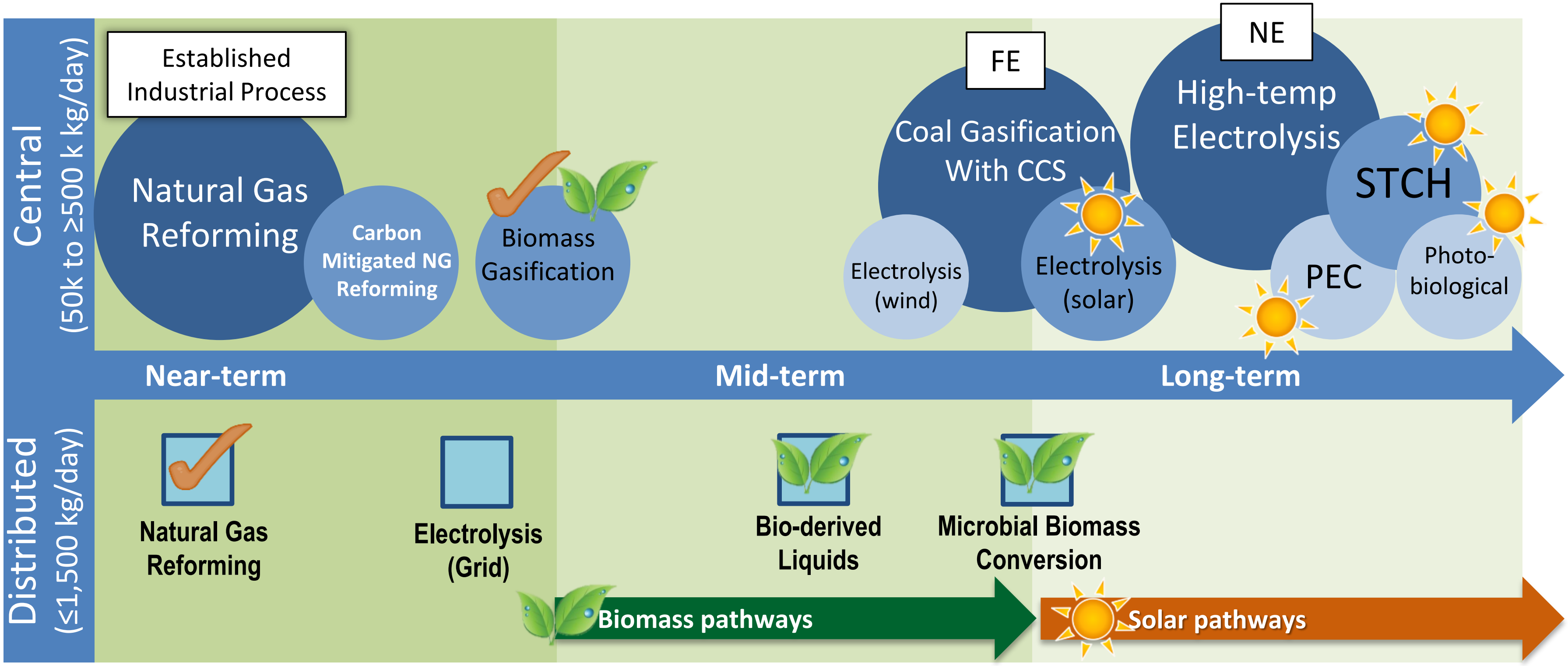
>90% from Renewables* (Wind)



*Compared to 2012 gasoline vehicle
**Compared to 2035 gasoline vehicle

Substantial GHG reductions with H_2 produced from renewables

Hydrogen Production - Strategies



✓ P&D Subprogram R&D efforts successfully concluded

FE, NE: R&D efforts in DOE Offices of Fossil and Nuclear Energy, respectively

Objective: Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of < $4/kg H2 by 2020

Hydrogen Production Cost

Current Technology

- Natural Gas (D/C)
- Electrolysis (D)

Near to Mid-Term:

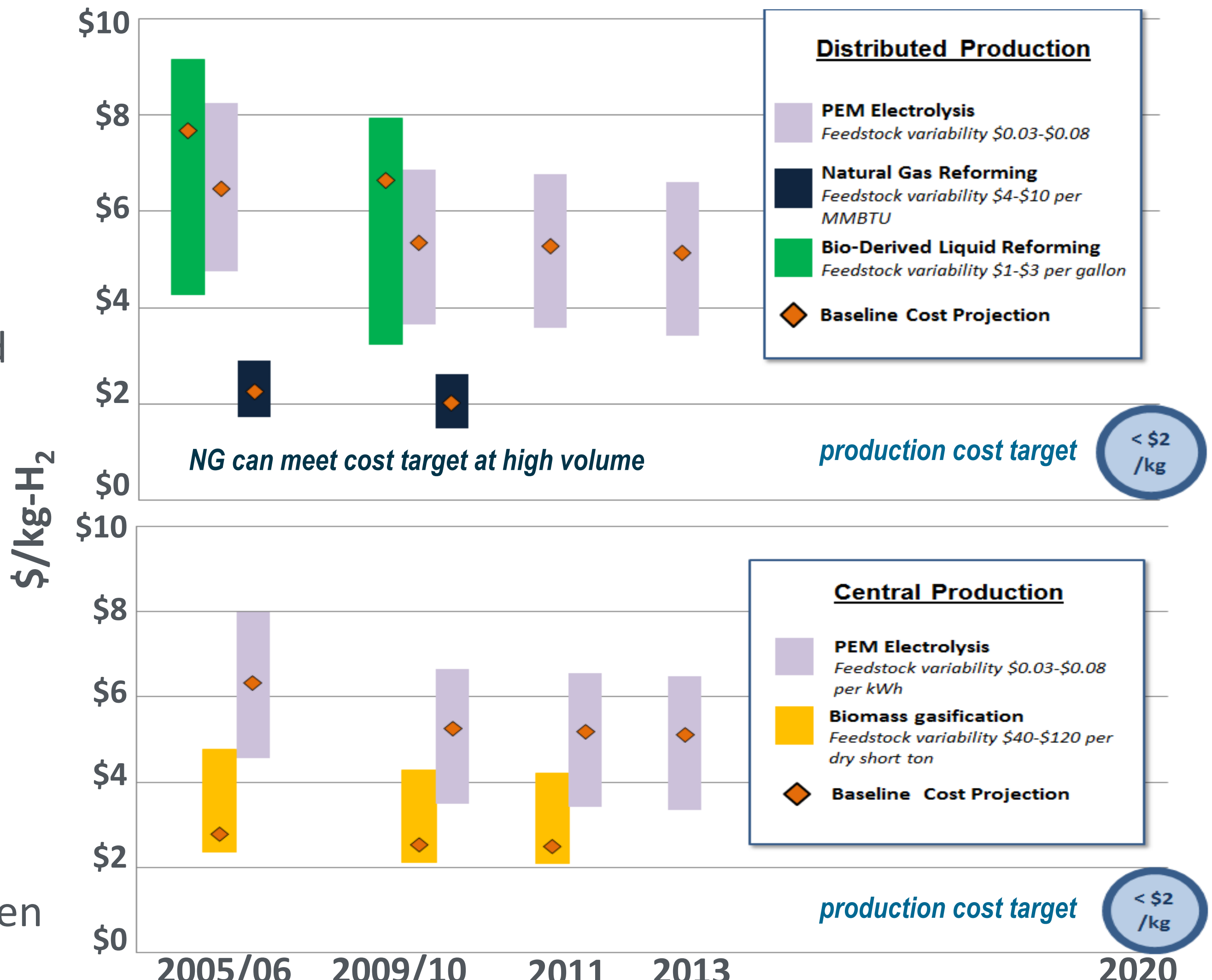
- Electrolysis- Wind and Solar Powered (D/C)
- Bio-derived Liquids (D/C)
- Fermentation (D/C)

Long-Term (not shown):

Central Renewable H_2

- Solar-based water splitting
- Photolytic Bio-hydrogen

D- Distributed C- Central

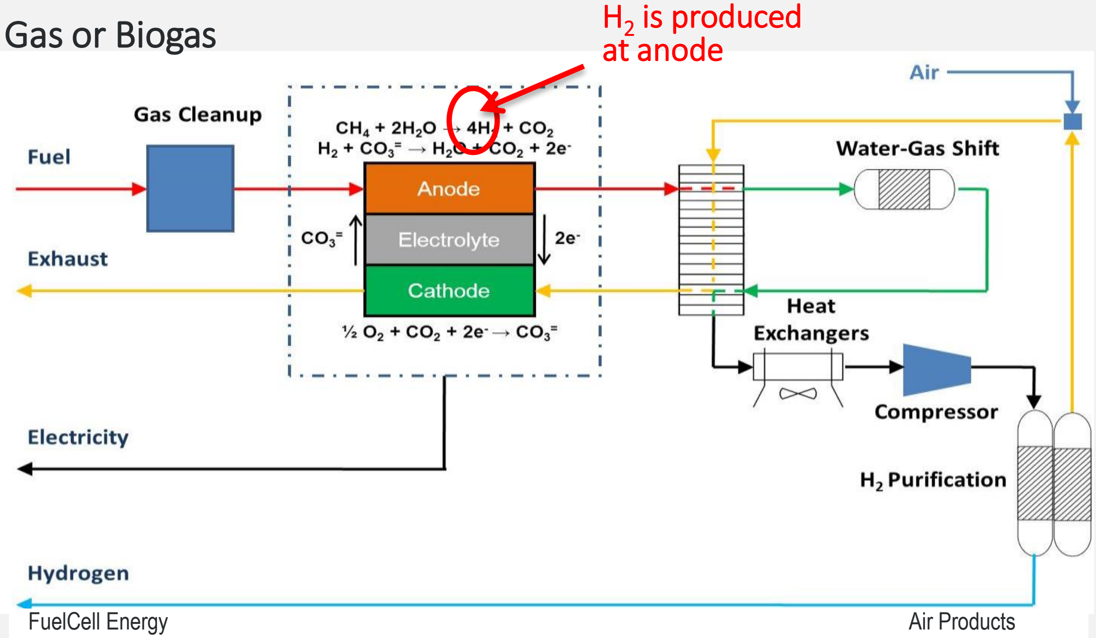


Current renewable H_2 costs do not meet $2/gge target. Challenges include capital cost, feedstock issues, durability, efficiency.

Example of Innovation: Tri-Generation

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

Gas or Biogas



Co-funded by DOE/FCTO 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.

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

Wastewater- Challenges & Opportunities

Cost of U.S. water treatment

- $7.5 billion per year for wastewater treatment, safe drinking water
- ~ 30 TWh/yr for wastewater treatment
- ~0.8% of total U.S. electricity consumption used by wastewater industry

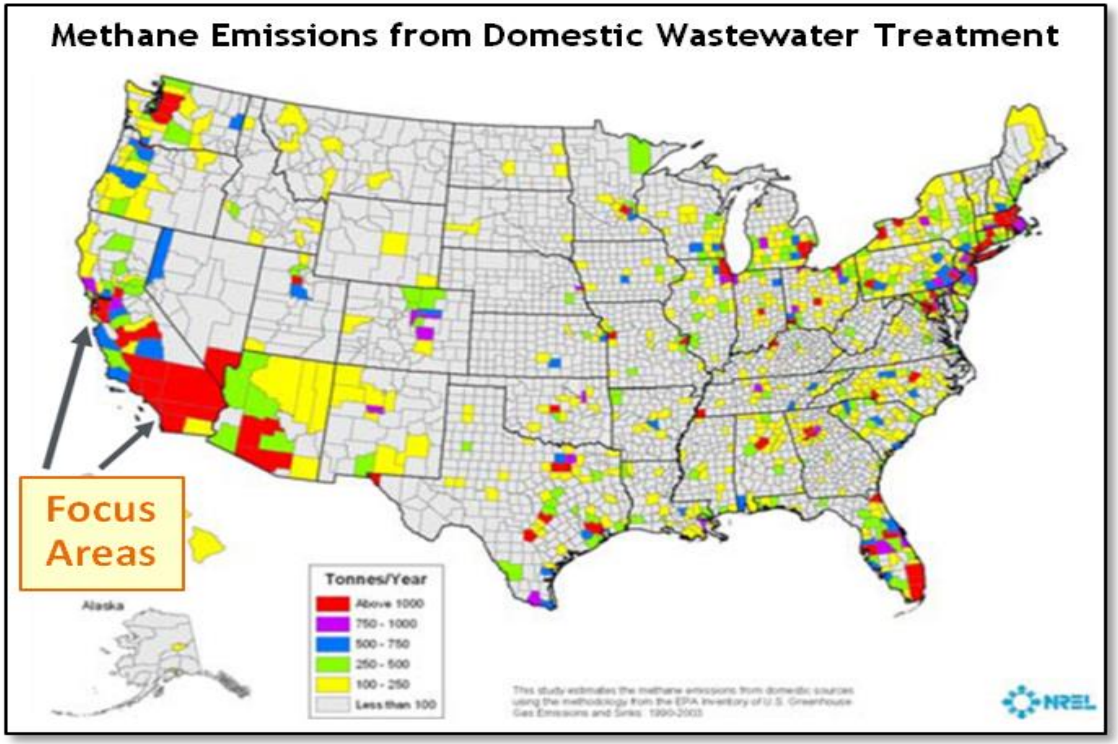
Warren Gretz / NREL

Wastewater and biosolids contain energy far exceeding what is required for treatment (~9 fold)

Improved treatment methods that provide additional product streams can reduce costs and meet environmental regulations: Opportunity for MxCs & AnMBRs?

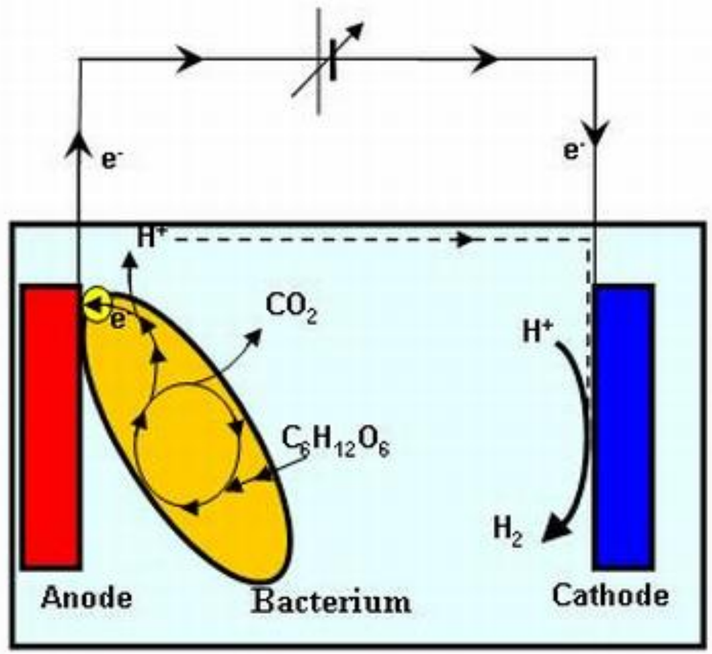
Biogas: Early Source of Renewable H_2 and Power

- Majority of biogas resources are near large urban centers, ideally located near the major demand centers for FCEVs and power
- Hydrogen can be produced using existing steam-methane-reforming technology
- Power can be produced by stationary fuel cells



Wastewater treatment plants alone have the potential to provide enough hydrogen to support ~1-3M FCEVs/yr

Microbial Fuel Cell-based technologies (MxCs) couple microbial metabolism with electrochemical reactions

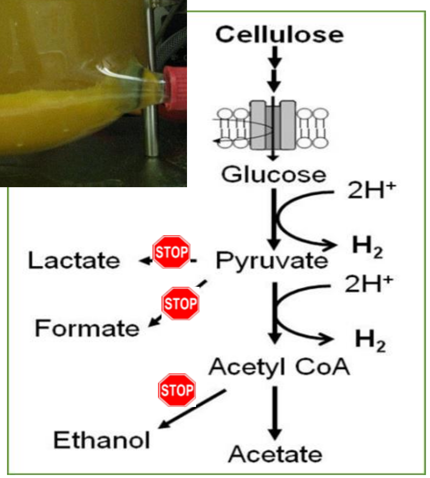


Products include:

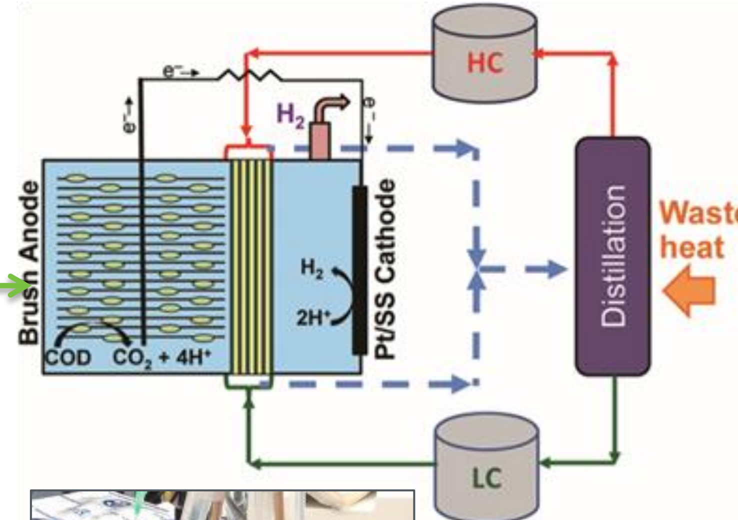
Electricity
Hydrogen
Methane
Ethanol
Formate
and others

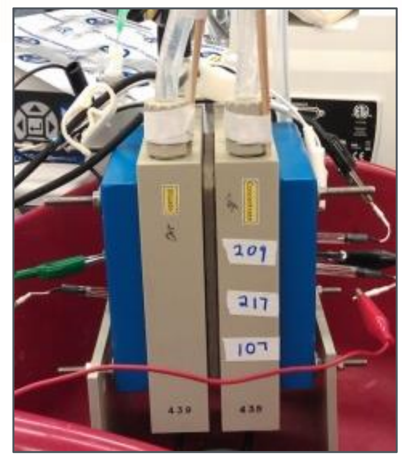
Low-energy input water treatment with range of products

Fermentation and Electrohydrogenic Approaches to Hydrogen Production



Fermentation waste water used as feedstock for MREC





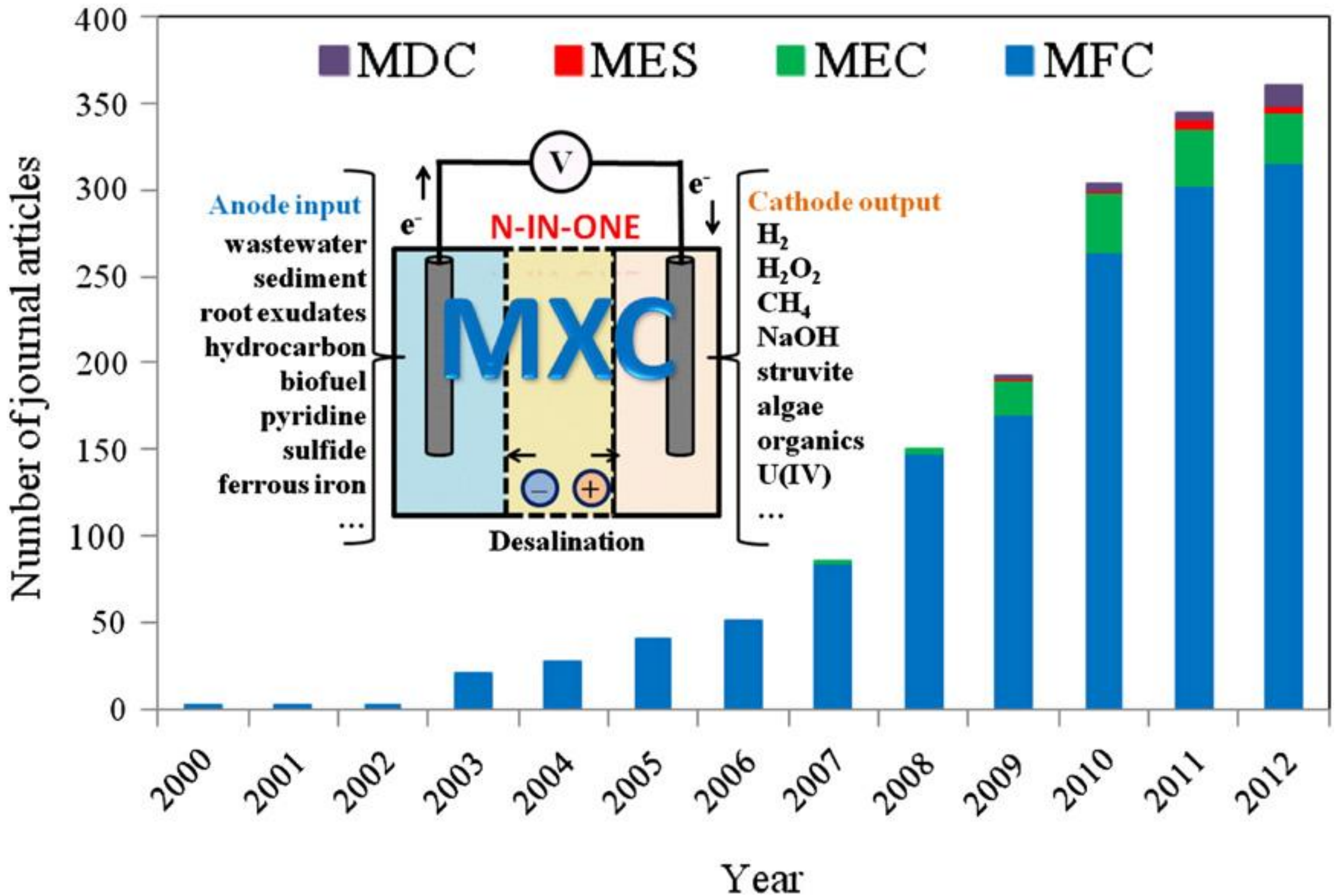
Pin-Ching Maness,
National Renewable Energy Laboratory

Improving fermentative hydrogen production from pretreated corn stover

Bruce Logan, Penn State

Microbial Reverse Electrodialysis Cells for hydrogen production

MxCs: A Rapidly Growing Field



Source: H.Wang, Z.J. Ren / Biotechnology Advances 31 (2013) 1796–1807

Examples of H_2 production rates

Hydrogen Production Rate for Various Bio-hydrogen Production Approaches

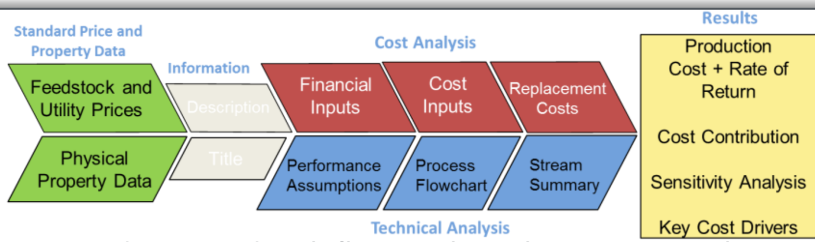
Bio-hydrogen system	H_2 synthesis rate (reported units)	H_2 synthesis rate (converted units)	Bio-reactor volume (m^3) for 5 kW PEMFC
Direct photolysis	4.67 mmol H_2/(180 h)	0.07 mmol H_2/(l h)	1707
Indirect photolysis	12.6 mmol H_2/(μg protein h)	0.355 mmol H_2/(l h)	337
Photo-fermentation	4.0 ml H_2/(ml h)	0.16 mmol H_2/(l h)	747
WGS	0.8 mmol H_2/(g cdw min)	96 mmol H_2/(l h)	1.24
Dark fermentation	Various	8.2–121 mmol H_2/(l h)	1–14.75
MEC	3.12 $m^3 H_2$/(m^3 reactors day)	5.8 mmol H_2/(l h)	21
Multi-stage	Not available, but assumed higher than individual stages		

Source: J. Holladay, et al, Catalysis Today, 139 (2009), 244-260 and references therein

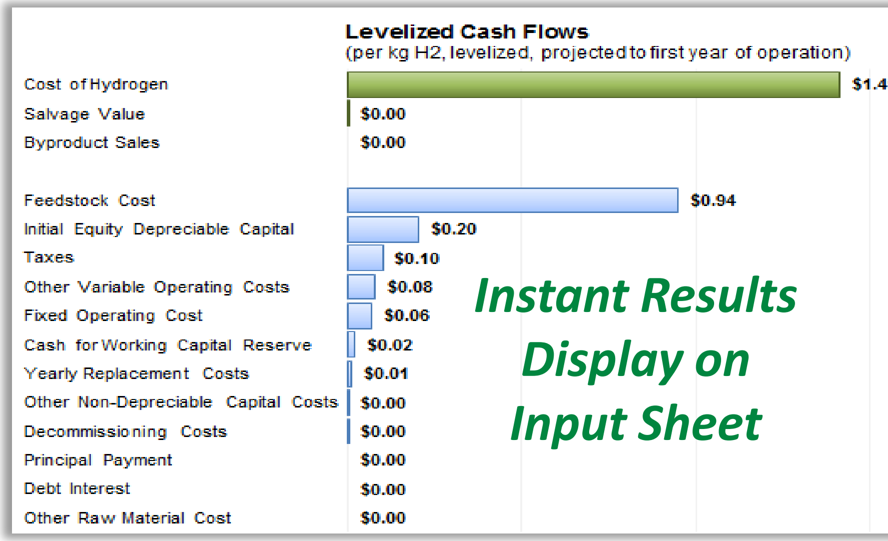
Hydrogen production rates are critical

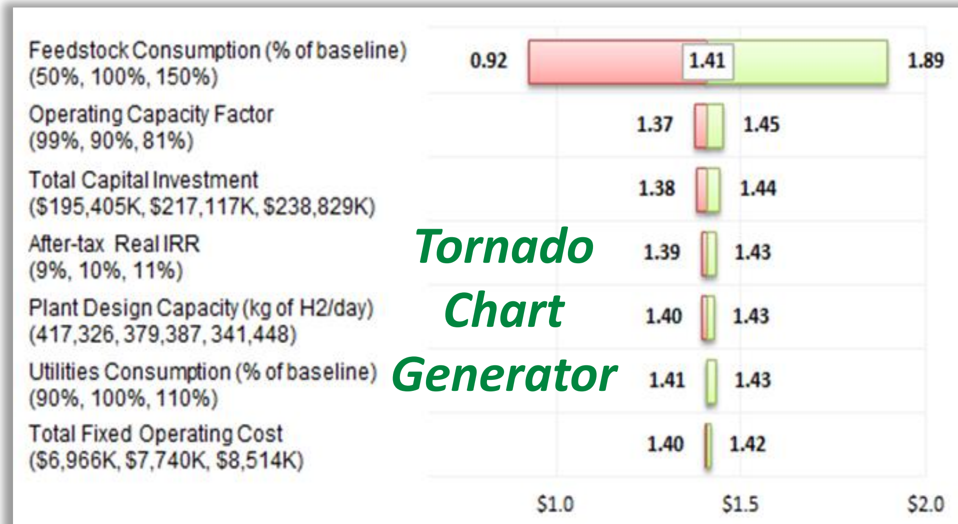
MECs, dark fermentation and WGS have shown higher rates

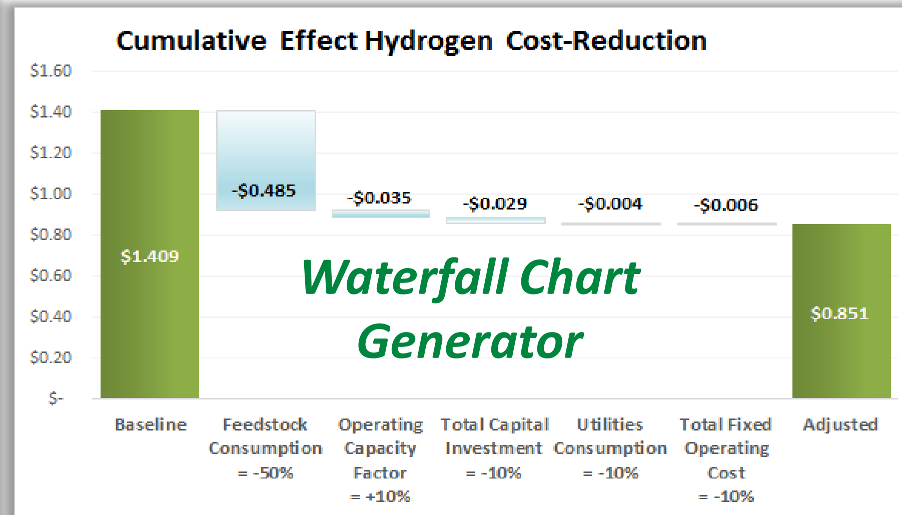
DOE's H2A Techno-economic Analysis Tool



- **H2A is a discounted cash flow analysis that computes the required price of H_2 for a desired after-tax internal rate of return**
- **Developed by NREL and DOE EERE-FCTO**
- **H2A Production Analyses Objectives:**
  - Establish a standard format for reporting the production cost of H_2, to compare technologies and case studies
  - Provide transparent analysis
  - Provide consistent approach
  - Prioritize research and development efforts







Continued updates to the H2A tool & development of technology case studies are vital to P&D portfolio evolution

2013 FCTO Biological H_2 Workshop

http://energy.gov/eere/fuelcells/biological-hydrogen-production-workshop

MxC Hydrogen Production R&D Needs	
Near-term	• Cathode improvements • Precisely characterize performance • Precisely quantify each step of potential loss that leads to overpotential • Characterize mechanisms of "potential" loss (sources of overpotential) • Fermentation + MEC integration to optimize performance • Standardized metrics • Develop scale-up designs • Improved proton exchange membranes • Technoeconomic analysis
Mid-term	• Improved anode organisms • Development of high-temp (~60°C) low-pH (~5) biofilm • Develop improved H+ transfer systems • Develop improved cathode catalyst • Scale-up – longevity, cost reduction
Long-term	• Durability and stability • Improve anode with microbe engineering (metabolic/system synthetic) • Microbial metabolism understanding

Identified near, mid and long term R&D needs to overcome MxC barriers

H2 Refuel H-Prize

H2 refuel
U.S. Department of Energy

$1 million competition for on-site home and community-scale H_2 fueling systems.

1st Year
2nd Year
Late 2016
Award

Teams form and submit designs → Selection of finalists and testing → Technical and cost analysis to select winner → $1M

Promoting H_2 fueling system development in the community
Visit http://hydrogenprize.org/

Thank You

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