LANL Fuel Cell Program

Hydrogen, Hydrogen production, and Hydrogen for transportation

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Operated by Triad National Security, LLC for DOE/NNSA

'LA-UR-21-31888'

Questions

1. Why hydrogen? Why now?

   In part: See slide 5. See slides 4,6,7 etc. plus 15
   In part: this is sort of asking, why deal with Climate Change now.

2. What does the Hydrogen Hub Act aim to accomplish?

   This is not my question to answer. My role is as a scientist; not to make policy. However, it supports the Federal Infrastructure bill.
   In the Infrastructure Bill, H2 starts on page 577; the HUB call specifically starts on SEC. 813, page 580.

From: H. R. 3684 Infrastructure Investment and Jobs Act

‘‘SEC. 813. REGIONAL CLEAN HYDROGEN HUBS.

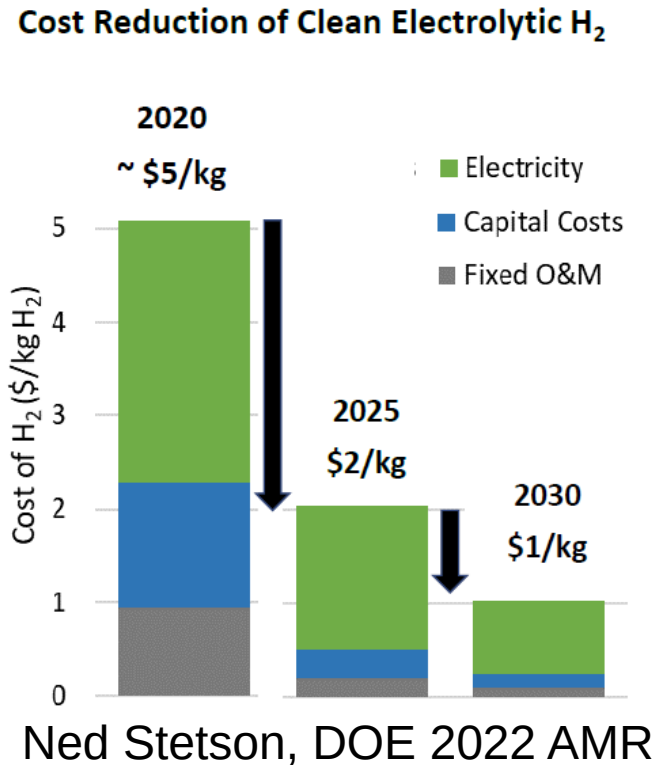
‘‘(a) DEFINITION OF REGIONAL CLEAN HYDROGEN HUB.—In this section, the term ‘regional clean hydrogen hub’ means a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity.

‘‘(b) ESTABLISHMENT OF PROGRAM.—The Secretary shall establish a program to support the development of at least 4 regional clean hydrogen hubs that—

‘‘(1) demonstrably aid the achievement of the clean hydrogen production standard developed under section 822(a);

‘‘(2) demonstrate the production, processing, delivery, storage, and end-use of clean hydrogen; and

‘‘(3) can be developed into a national clean hydrogen network to facilitate a clean hydrogen economy.



Ned Stetson, DOE 2022 AMR

3. How would you respond to those who would characterize the Hydrogen Hub Act as a life line to NM's oil and gas industry, in that the Act would shift the industry's emphasis to grey or blue hydrogen without transitioning the state away from its dependence on oil and gas revenues?

   My role is as a scientist; not to make policy. I will try to answer technical questions.
   However, I would suggest that the NM HUB act is NM legislation to help the state of NM and the industries within to work with the Federal government to transition to energy technologies that will decarbonize the energy infrastructure. Renewable energy is growing. However, fossil fuels will be used for the foreseeable future in tandem (in my opinion). Thus jumping from our current energy infrastructure to full renewable & hydrogen seems like a leap when you consider economics. See graph.

Questions

4. What is hydrogen's role in the quest to decarbonize our economy?

See slide 5

5. Is there a risk that a push toward using hydrogen will distract from the pathways toward electrification of building heating, vehicle driving, and water heating?

In my opinion, these are coupled together and of mutual interest.
Electric vehicles include BEV and FCEV – both are EVs

6. Is there a way to use existing fossil fuel infrastructure - pipelines, power plants and the like - to create and move hydrogen?

In part, the answer is yes. In part, the answer is that this is an area of study and projects.

7. How much of a role can hydrogen play in powering industries such as aviation, cement, steel, and others hard to convert to renewables?

See slide 5, and H2 projects.
There are at least a couple of projects working on ~ commuter aircraft. NASA explored airliners decades ago. Germany has a demo plant related to steel.

Biden Administration Targets CO2 Emissions

April 22, 2021

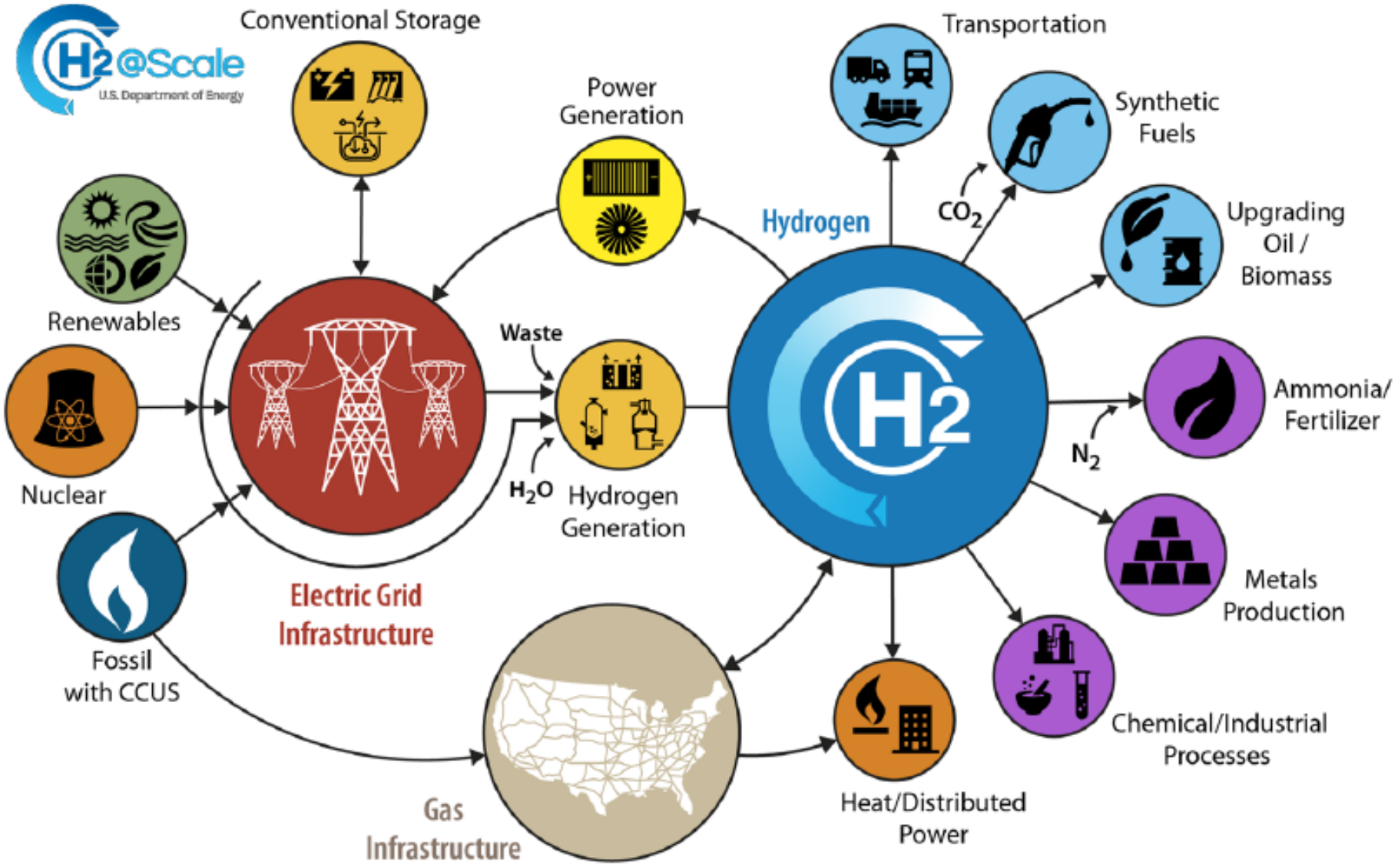
FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies

Building on Past U.S. Leadership, including Efforts by States, Cities, Tribes, and Territories, the New Target Aims at 50-52 Percent Reduction in U.S. Greenhouse Gas Pollution from 2005 Levels in 2030

On Day One, President Biden fulfilled his promise to rejoin the Paris Agreement and set a course for the United States to tackle the climate crisis at home and abroad, reaching net zero emissions economy-wide by no later than 2050. As part of re-entering the Paris Agreement, he

Conceptual H_2 at Scale Energy System*

Decarbonize the Three Energy Sectors Simultaneously



Potential

- 10 MMT of H_2/yr produced today with scenarios for ~5X growth
- 10 MMT H_2 would ~ double today's solar or wind deployment
- Industry study shows potential for $140B in revenue, 700K jobs, 16% GHG reduction. Analysis underway, including on export potential.

*Illustrative example, not comprehensive

President Biden and Energy Secretary Granholm at Climate Summit

"...I've asked the Secretary of Energy to speed the development of critical technologies to tackle the climate crisis. No single technology is the answer on its own because every sector requires innovation to meet this moment."

President Joseph R. Biden
April 23, 2021

Launch of Hydrogen Energy Earthshot
First of the Energy Earthshots
June 7, 2021
at DOE Hydrogen Program AMR

Secretary Jennifer Granholm
June 7, 2021

Hydrogen Earth Shot Summit: August 31 and September 1, 2021

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Hydrogen Shot's "1 1 1" goal of $1 for 1 kg of clean hydrogen in 1 decade.

Jennifer M. Granholm
Secretary, U.S. Department of Energy

David M. Turk
Deputy Secretary, U.S. Department of Energy

John Kerry
Special Presidential Envoy for Climate

Joe Manchin
U.S. Senator (D-WV)

Michelle Lujan Grisham
Governor (D-NM)

Bill Gates
Founder, Breakthrough Energy

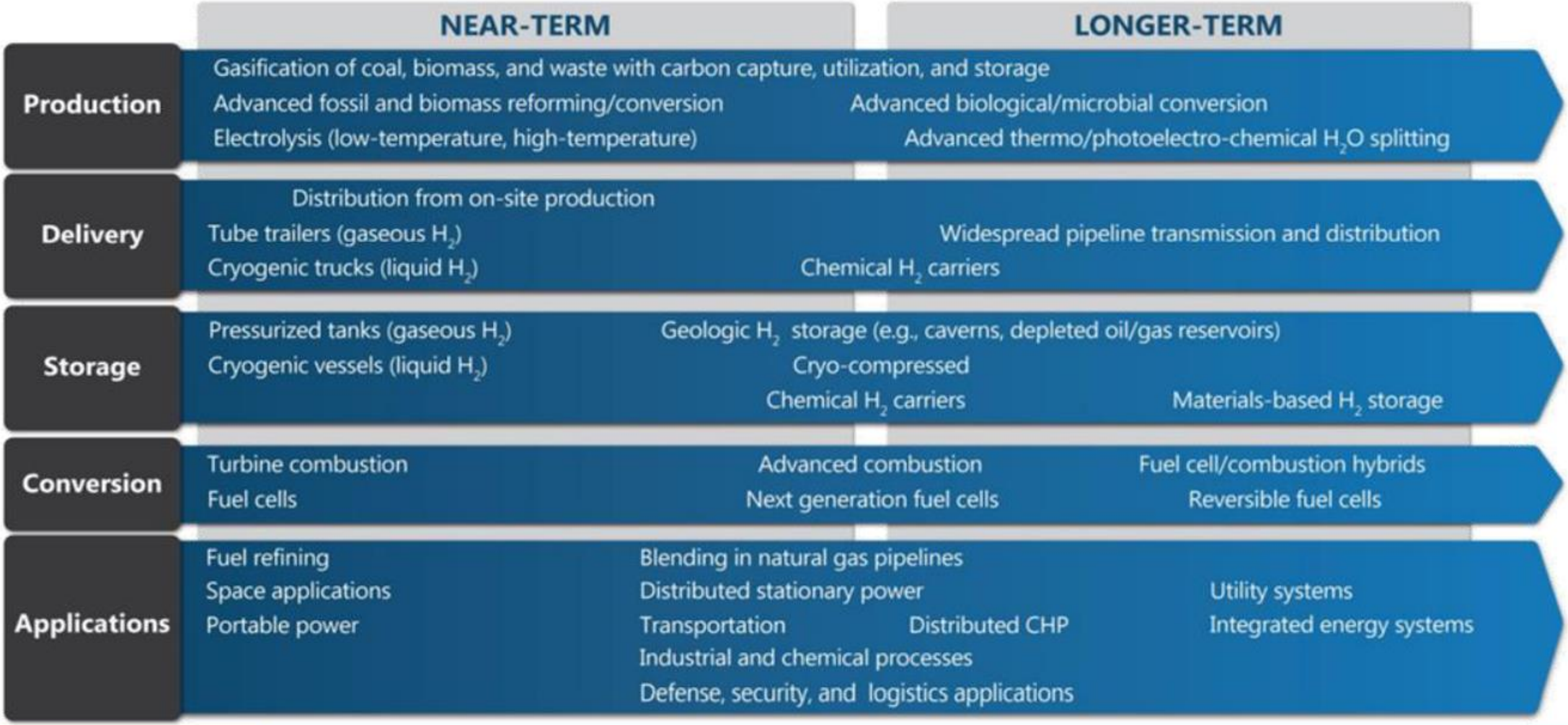
Paul Tonko
U.S. Representative (D-NY)

Greg Pence
U.S. Representative (R-IN)

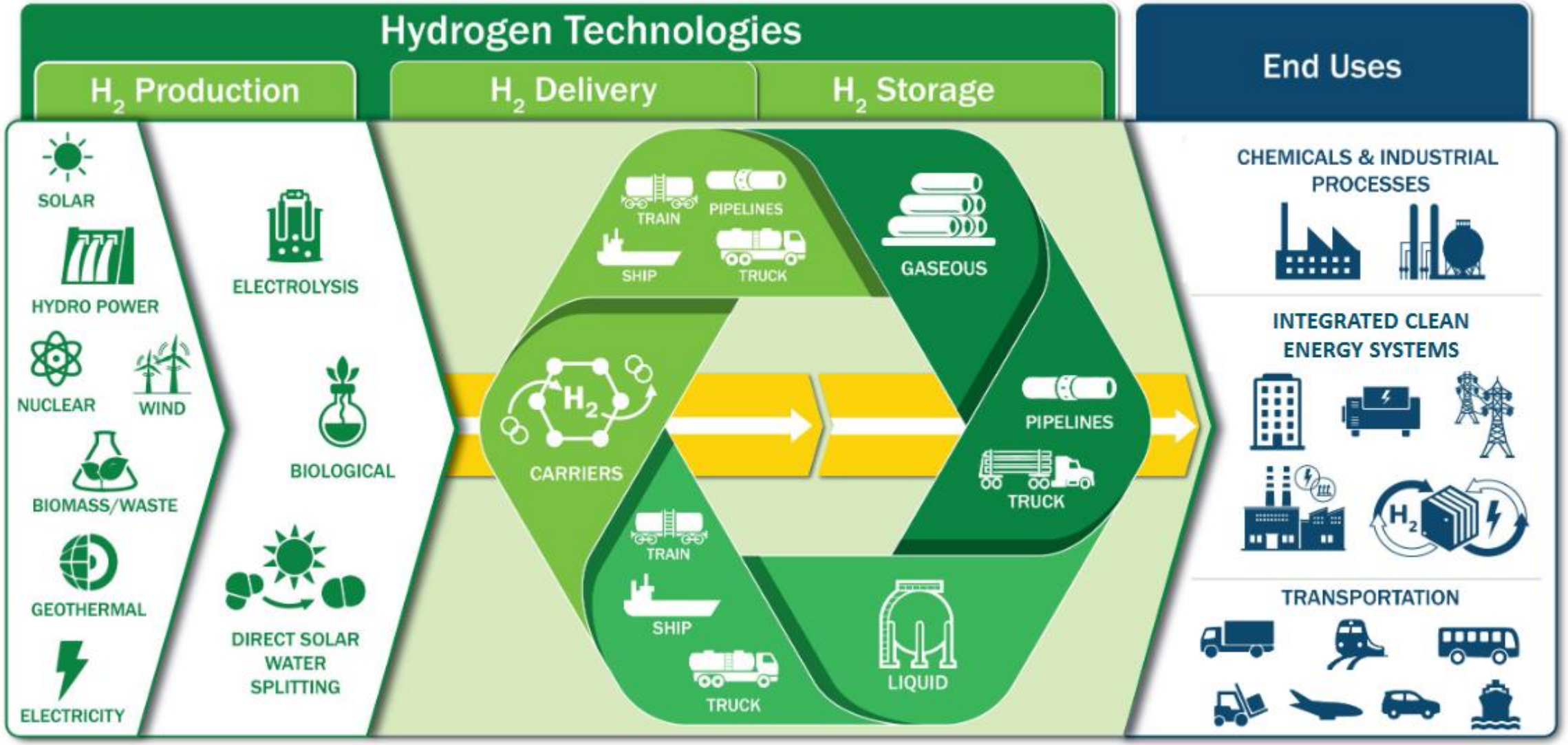
Robert Walker
Former U.S. Representative (R-PA)

Bill Cassidy
U.S. Senator (R-LA)

Comprehensive DOE Strategy Across the Hydrogen Value Chain

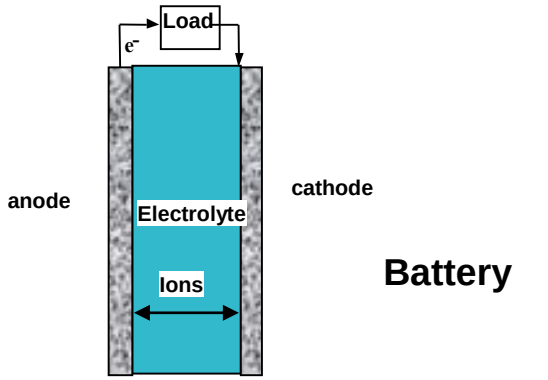


Hydrogen Technologies Program

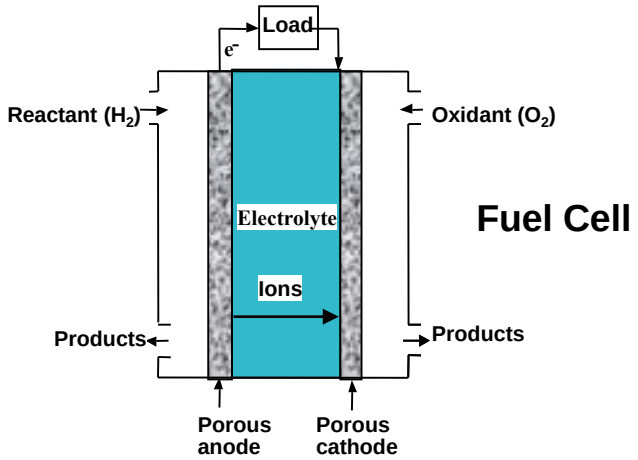


From producing hydrogen molecules through dispensing to end-use applications

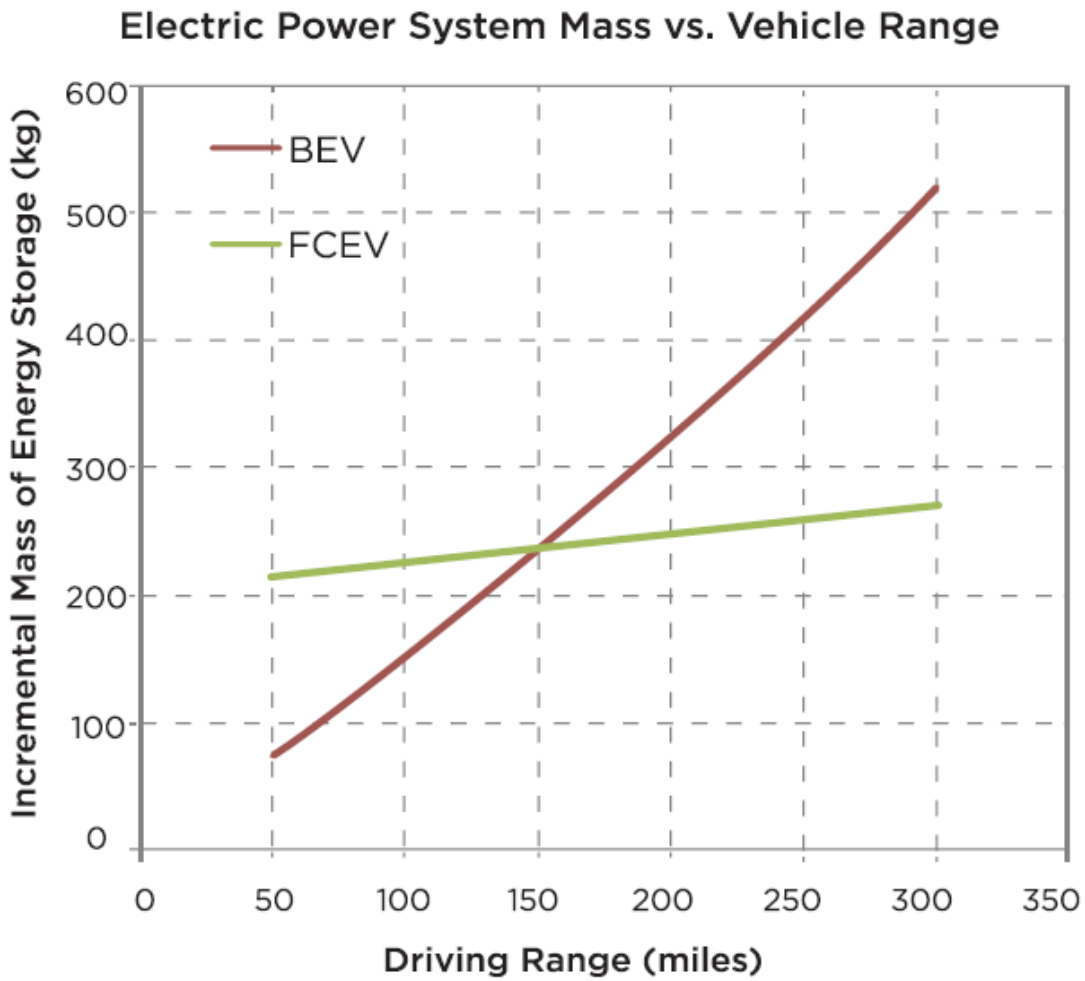
Range of Fuel Cell vs. Battery



Battery

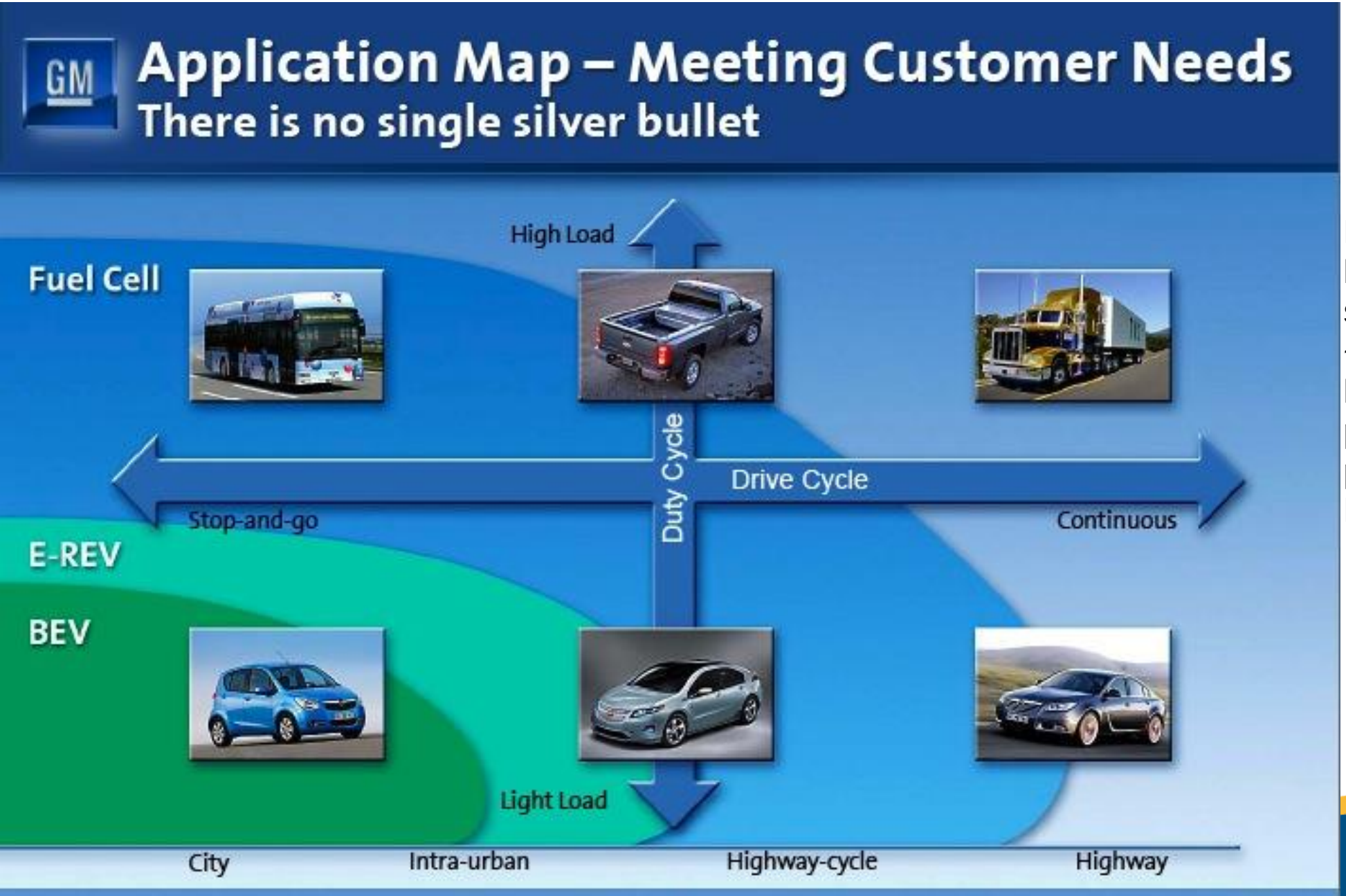


Fuel Cell



Advantages: energy density (up to >6000 Whr/kg based on fuel, batteries up to 150 Whr/kg), refuel versus recharge

Major Auto OEMs Developing PEM Fuel Cells



Daimler, Nissan, Toyota have shown similar strategies

~ All major auto companies have fuel cell vehicle programs including above, plus BMW, Volkswagen, Ford, Honda, Hyundai, ….

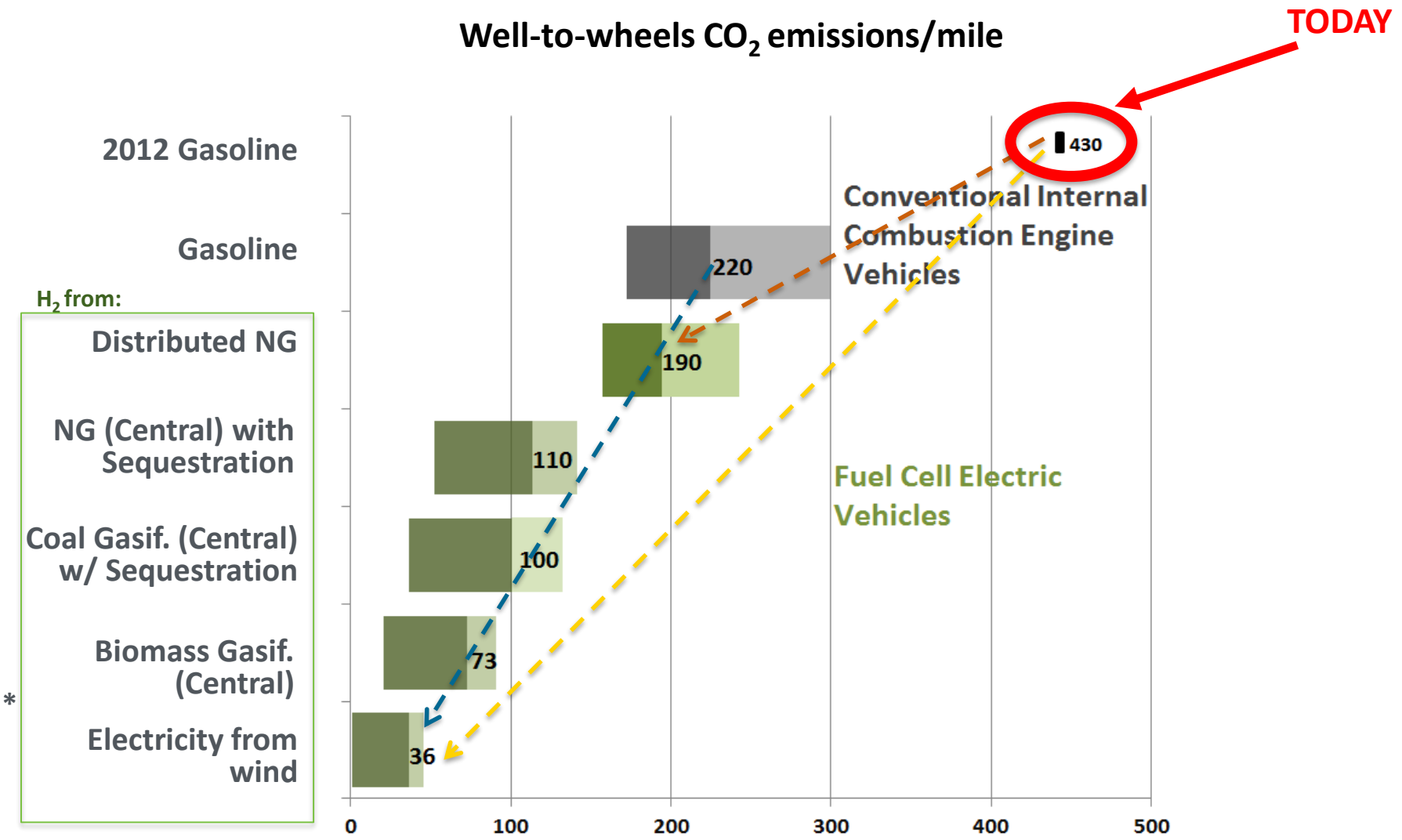
FCEVs Reduce Greenhouse Gas Emissions

>50% with H_2 from Distributed Natural Gas*

>80% with H_2 from Renewables* (Wind)

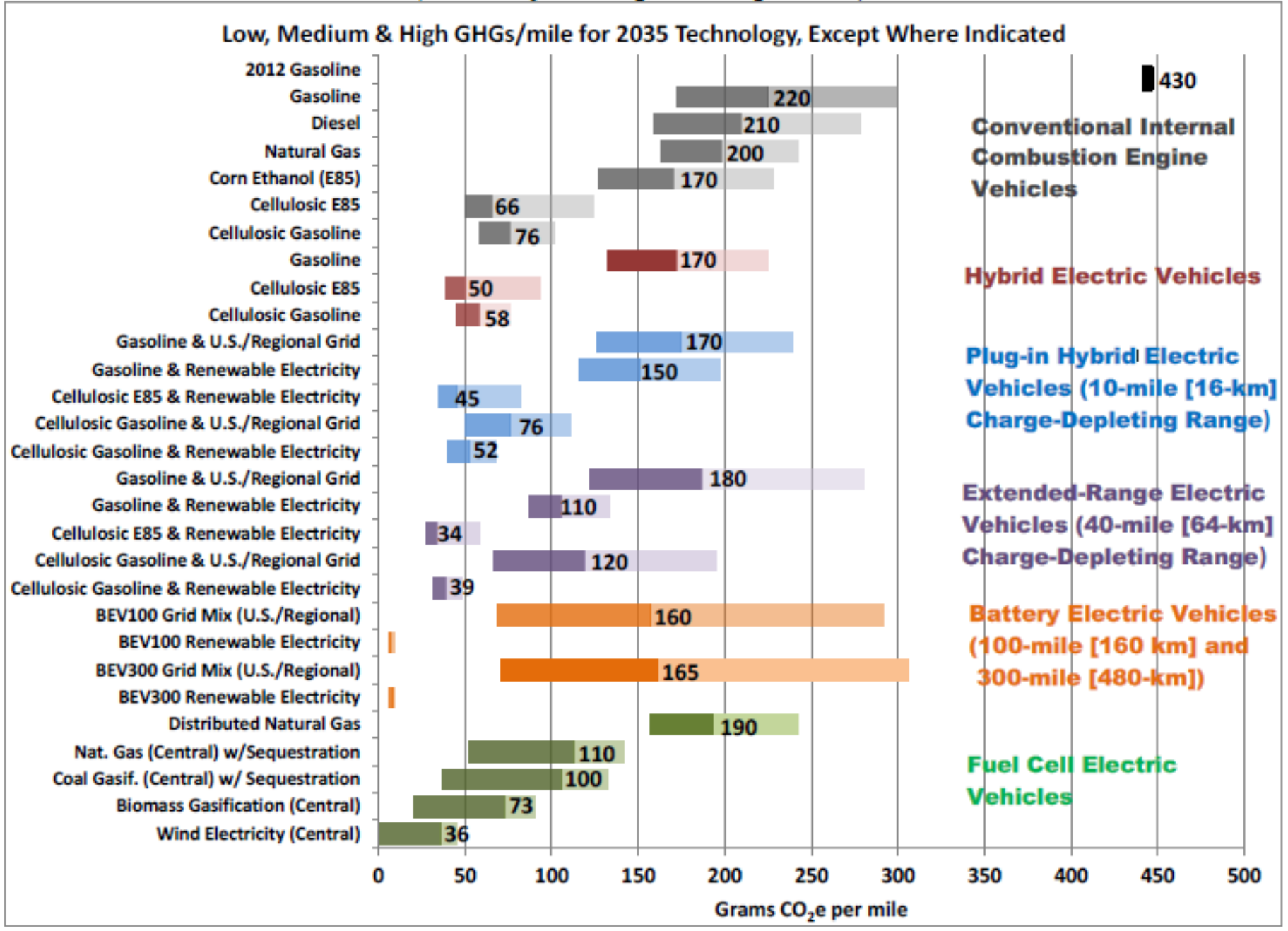
>90% with H_2 from Renewables** (Wind)

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



Source: http://hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf
Advanced 2035 technologies

Substantial GHG reductions with H_2 produced from renewables



Low/medium/high: sensitivity to uncertainties associated with projected fuel economy of vehicles and selected attributes of fuels pathways, e.g., electricity credit for biofuels, electric generation mix, etc.

What is best for society?

- Hybrid electric vehicles?
- Plug-in hybrids?
- Biofuels?
- Fuel cell vehicles?

…….or all of the above!

Zero-Emission Vehicles Legislation

- Norway 2025, Denmark 2030, Netherlands 2030, Sweden 2030, India 2030, France 2040, United Kingdom 2040, Sri Lanka 2040, China (no date set), Canada - British Columbia (2040). In the United States, municipalities such as Seattle (2030) and Los Angeles (2030) have announced bans.
- California initially announced Zero-Emissions Trucks – June 2020.
- California rapidly expanded it to cars after the California wild-fires – September 2020.

The New York Times

New Rule in California Will Require Zero-Emissions Trucks

More than half of trucks sold in the state must be zero-emissions by 2035, and all of them by 2045.

An Amazon warehouse in the Inland Empire of California last year. Philip Cheung for The New York Times

June 2020

The New York Times

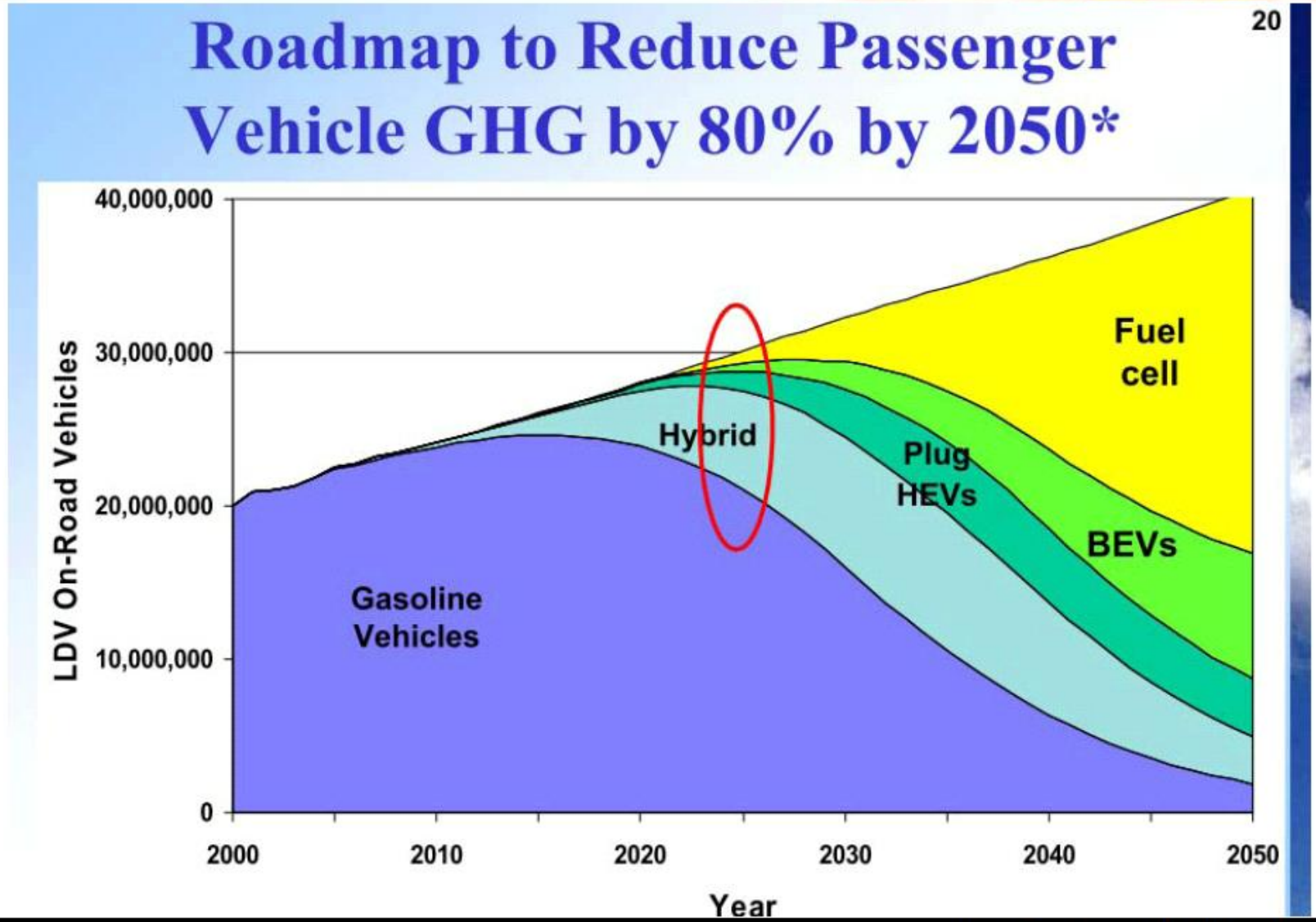
California Plans to Ban Sales of New Gas-Powered Cars in 15 Years

The proposal would speed up the state's efforts to fight global warming at a time when California is being battered by wildfires, heat waves and other consequences of climate change.

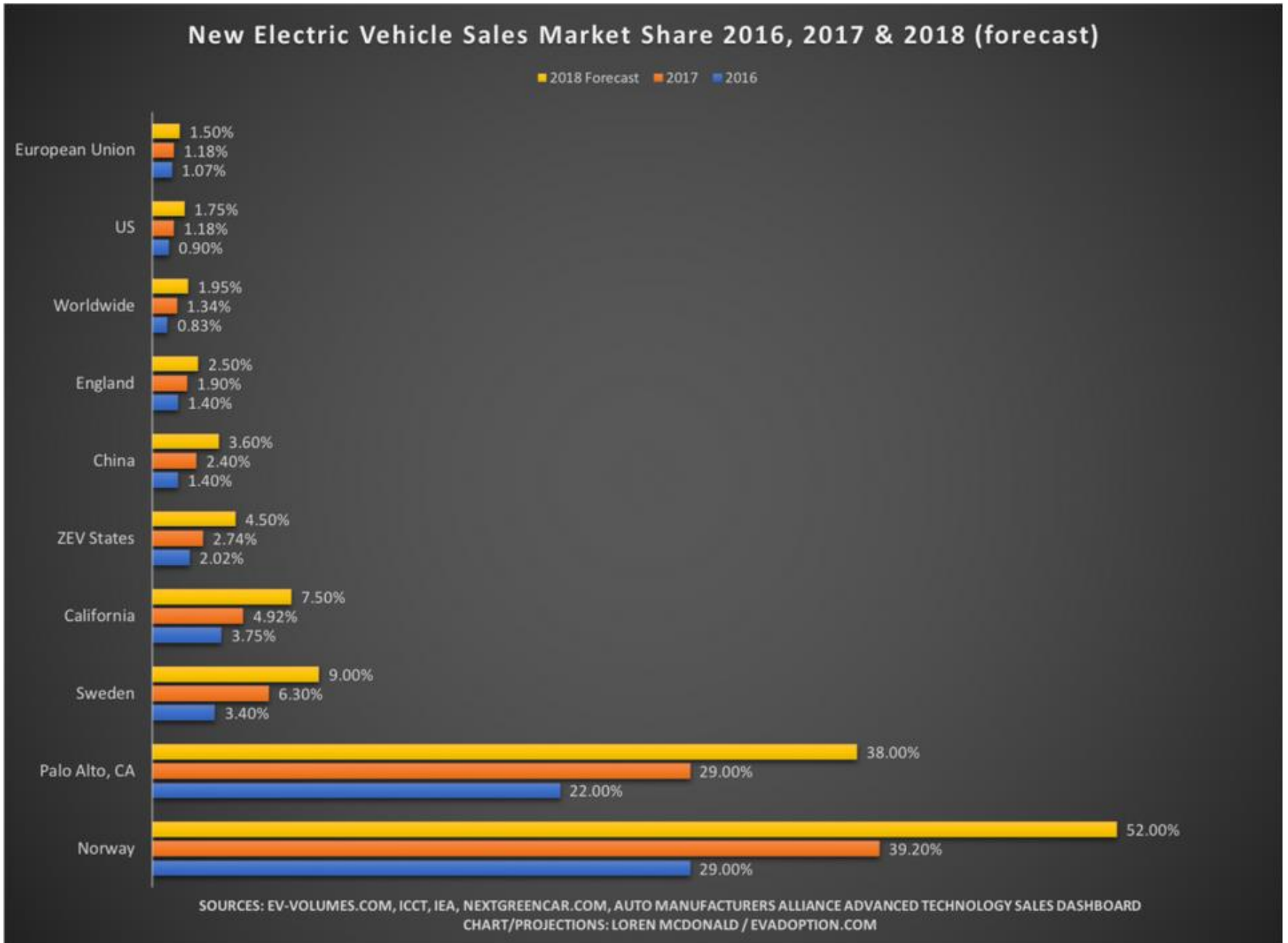
Transportation remains California's largest source of planet-warming emissions, accounting for roughly 40 percent of the state's greenhouse gases from human activity. Ben Margot/Associated Press

September 2020

CARB's Vehicle ROADMAP
(Source Tom Cackette)



New Electric Vehicle Sales Market Share for 2016, 2017 and Forecast for 2018 (full year) for Selected Markets



Hybrid vehicles:

- **4.9 percent**

BEV market share:

- 1.5% in 2020
- 2.3 - 2.5% in H1 2021

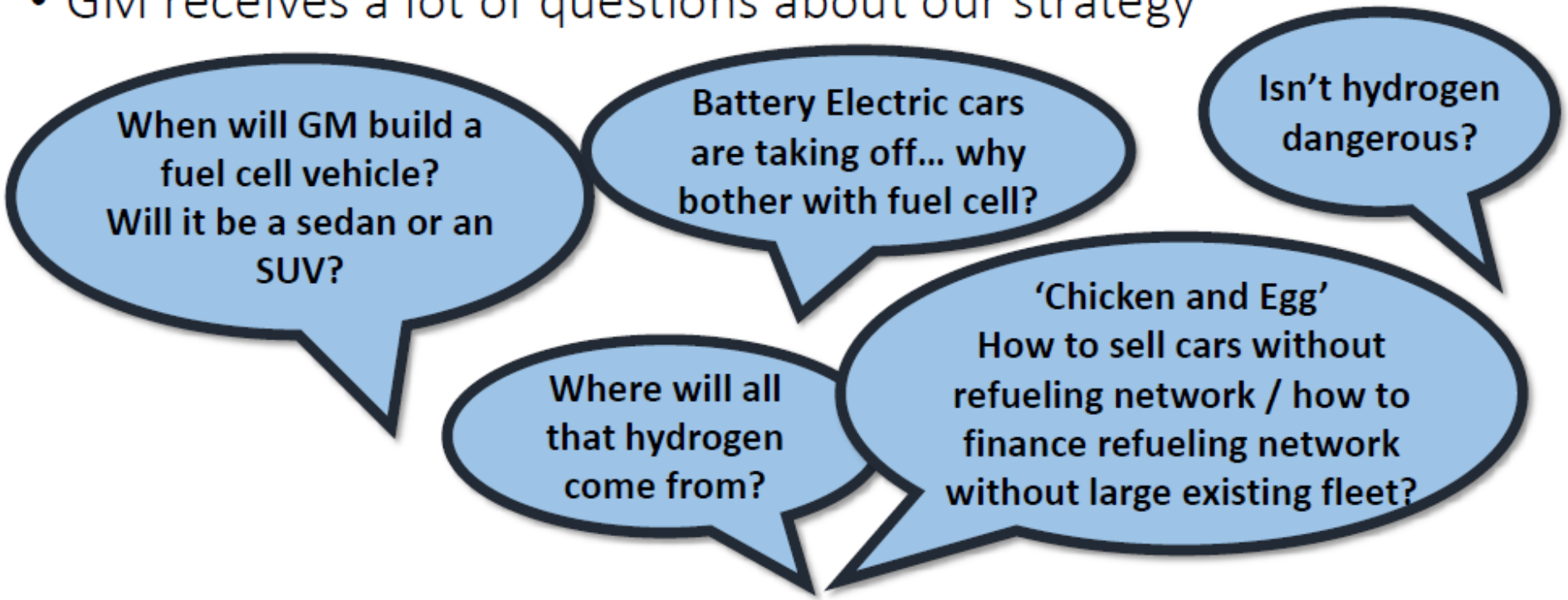
- one in 40 new cars

Biden pushes for electric vehicles to make up half of U.S. auto sales by 2030

HYDROTEC
GENERAL MOTORS

Inconsistent Fuel Cell Interest among Automakers

- GM is increasing our commitment to fuel cell technology
- While most major automakers are active in fuel cell, few are committed
- GM receives a lot of questions about our strategy



Kurt Wellenkotter, General Motors, 232rd Meeting of the Electrochemical Society (2017)

HYDROTEC
GENERAL MOTORS

Fuel cell and BEV have different strengths that complement each other

When will GM build a fuel cell vehicle? Will it be a sedan or an SUV?

Early 2020's

Stay tuned!

Battery Electric cars are taking off… why bother with fuel cell?

All fuels requires care

Isn't hydrogen dangerous?

'Chicken and Egg' How to sell cars without refueling network / how to finance refueling network without large existing fleet?

Fuel cell deployment will spread through products and market segments as it solves problems

Where will all that hydrogen come from?

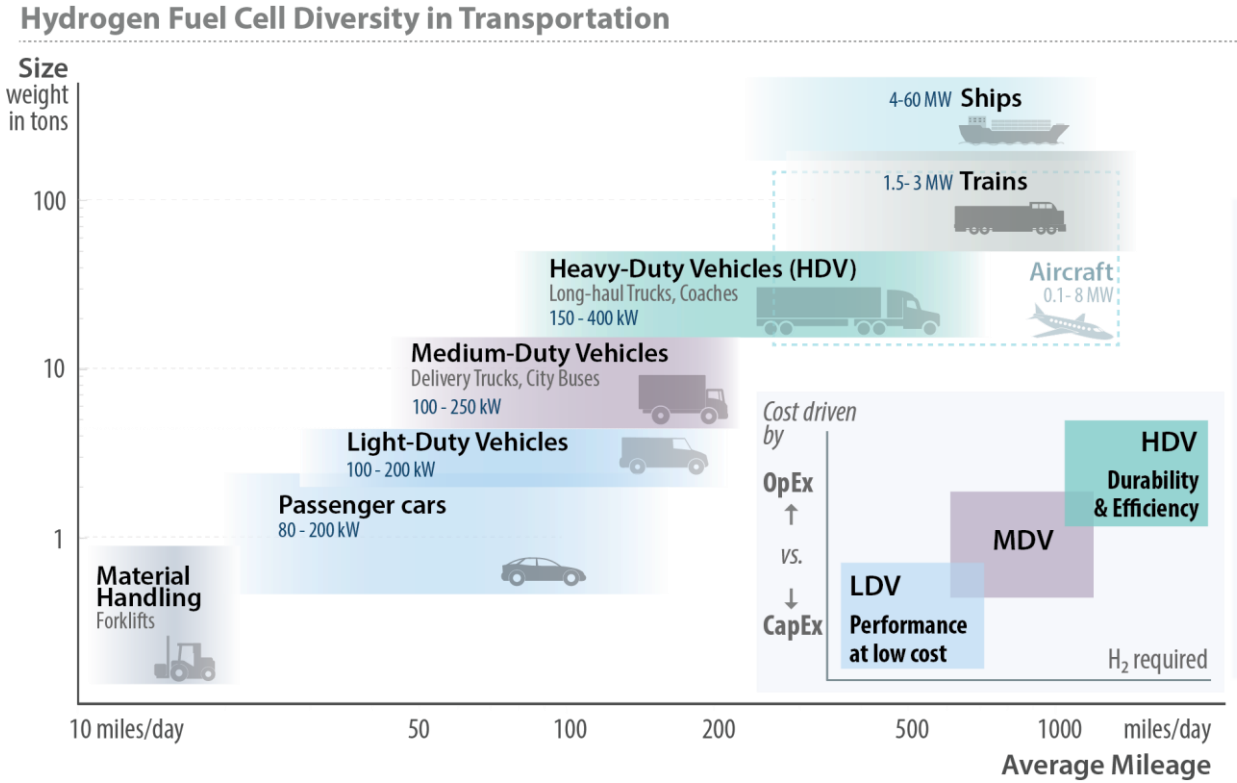
New channels and potentially new sources

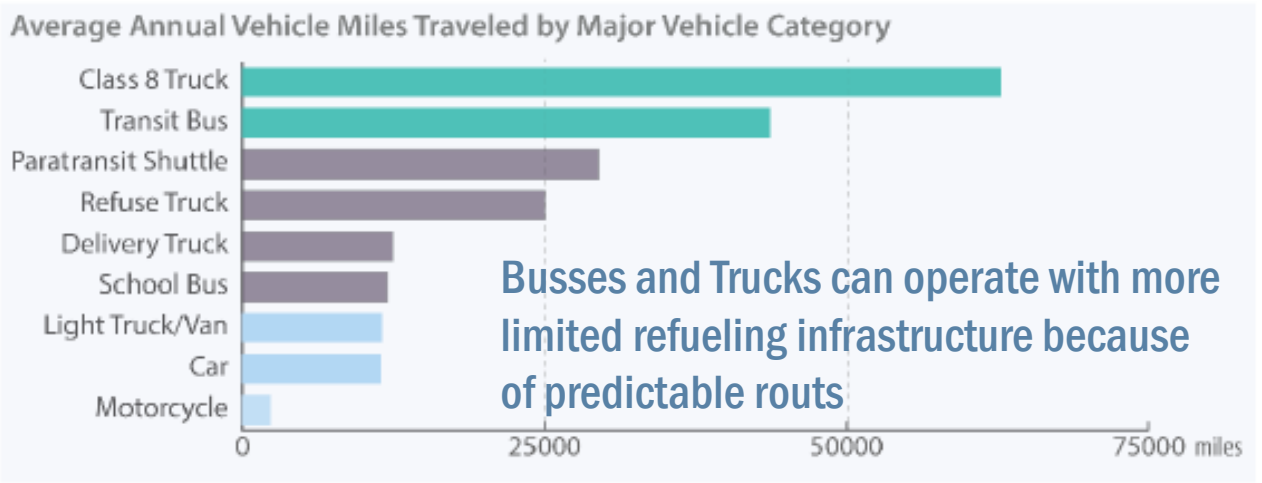
Why does it take so long to charge batteries?

Fueling Time Analogy

- Pumping 14 gallons of gasoline in 3 minutes is equivalent to 10 Megawatts of power
- The average hydrogen power flow in 27,000 hydrogen FCEV fueling events monitored by NREL was 1.82 MW
- A home 120V/20A circuit has a maximum power rating of 1.9 kW, which is 5,300 times slower than pumping gasoline and 950 times slower than pumping hydrogen
- A Type-2 240V 40A circuit has 7.7 kW power, or 1,300 times slower than gasoline and 240 times slower than hydrogen.

Hydrogen for Transportation: Fuel Cell Vehicles Target Comparison between Light- and Heavy-Duty





- Heavy-duty market is a critical market for reducing energy consumption and emissions
  - Medium- and heavy-duty trucks consume 25% of the total annual vehicle fuel use and produce 23% of the total CO_2 emissions in the US today
  - Annual freight truck miles traveled is projected to increase by 54% by 2050.

Payload Impact

Payload and Energy Density

One Day of Regional Haul = 350 miles on 2 Shifts

Diesel		Compressed Hydrogen		Battery	
Fuel Amount:	70 gallons	Fuel Amount:	55 kgs	Energy Amount:	900 kW-hrs
Fuel Weight:	500 lbs	Fuel Weight:	120 lbs	Fuel Weight:	0
Tank Weight:	150 lbs	Tank Weight:	4,200 lbs	Battery Weight:	16,800 lbs
Total Weight:	650 lbs	Total Weight:	4,320 lbs	Total Weight:	16,800 lbs

Slide 4 of 9

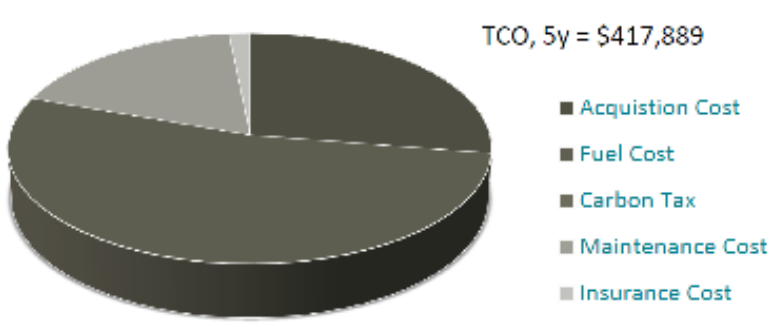
Brian Lindgren, **Kenworth Truck Company,** California Hydrogen Business Council (CHBC)**,** April 14, 2020

Total cost of ownership, regional delivery application

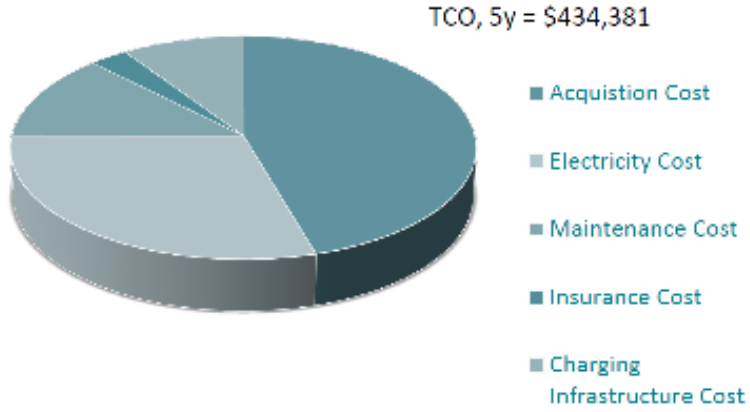
Example TCO for Regional Haul

diesel, $/gal	battery, $/kWh	H2 tank, $/kWh	FCM, $/kW
$3.00	$160	$15	$250

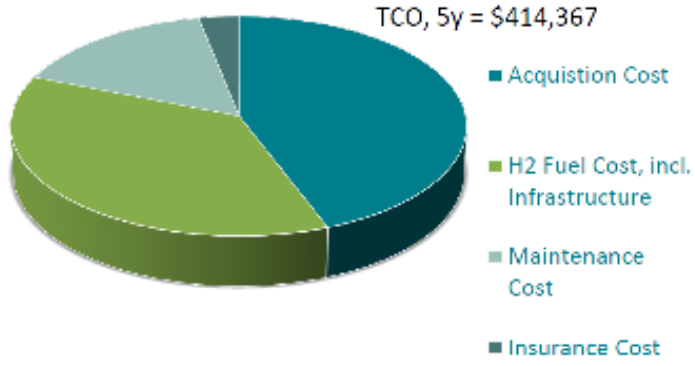
Diesel truck, regional delivery



Battery truck, regional delivery



Fuel cell truck, regional delivery



Fuel cell truck at TCO parity with diesel truck and lower cost than battery truck

For Sale

For Lease

Honda Clarity

General Motors, Daimler, Volkswagen, Ford, Nissan, BMW, SAIC

Heavy-Duty Trucks & Buses

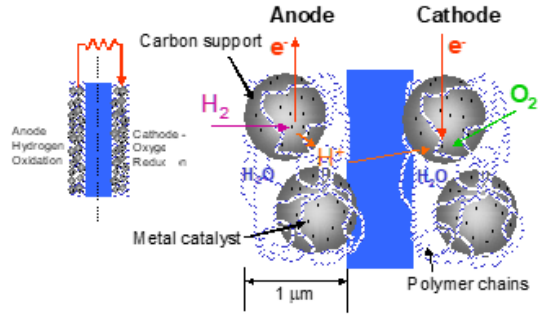
Toyota, Hyzon, Nikola, Cummins, Ballard (Supplier)

Fuel Cell R&D at Los Alamos

Rod Borup: Borup@lanl.gov

- One of longest running non-weapons programs at LANL (since 1977)
  - **The first fuel cells for transportation program**
- The **current DOE HFTO program grew out** of the original Los Alamos program
- **LANL has the top world-wide citation record in Fuel Cell R&D**
- Cost and durability remain the biggest barriers to commercialization
- Program focus is obtaining fundamental understanding to enable “knowledge-based innovation,” and subsequent materials and process development
- Scientists with over **200 years of experience** related to fuels cells and over 25 Ph.D.’s

LANL Enabling Breakthrough Thin Film Electrode



An electrochemically active reaction site must have reactant access to catalyst, available electronic and ionic conduction paths, and manage water

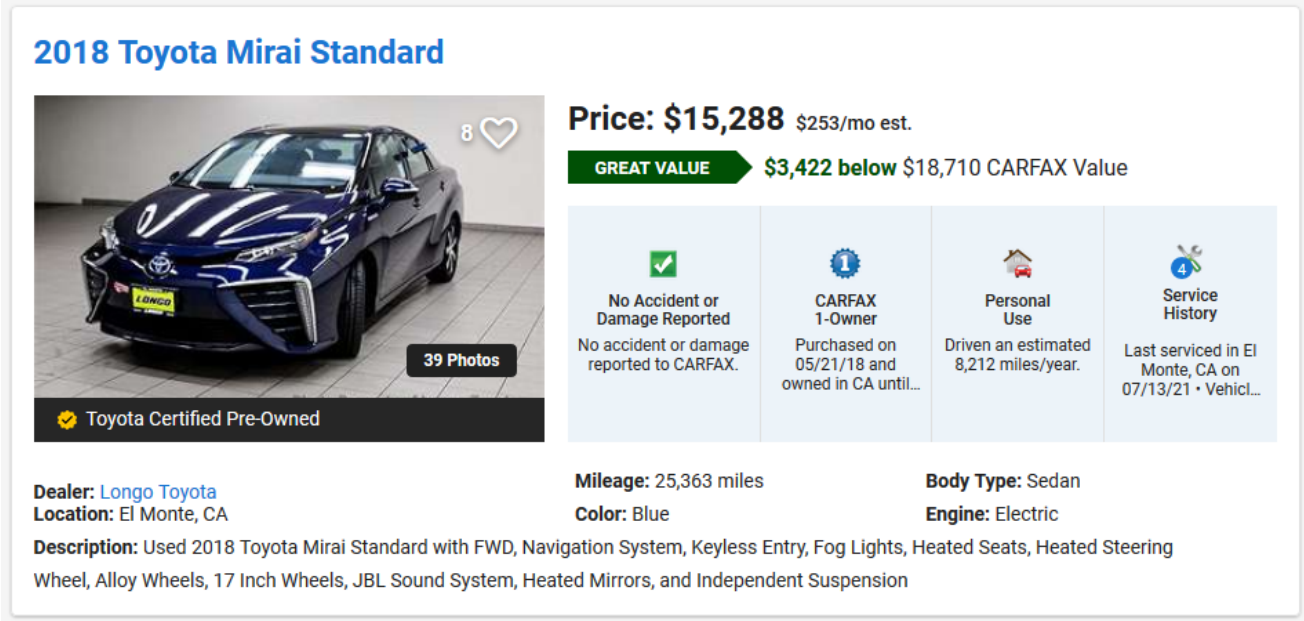
US Patents #4,876,115, #5,211,984 and #5,234,777

LANL’s innovation in fuel cells technology has played a critical role in the technical viability of fuel cell stacks for FCEVs.

→ Every Fuel Cell Vehicle relies on technology developed at LANL

Summary Comments and Opinions

- Huge (recent) interest in H_2
- Comments on CO_2 Reduction
- Comments on Economic competitiveness
- LANL Movement on H_2
- Infrastructure Bill
  - $8B for 4 H_2 HUBs
- New Mexico Interest in H_2
- Ca's Hydrogen Highway
- Nikola's Business Plan
  - Coupling vehicle sales and H_2



Back-up Slides

H2 and Water

Section 3. Hydrogen Hub Act – Standards.

1. For the purpose of compliance with this Act, qualifying hydrogen and clean hydrogen shall meet the following carbon intensities: a. Upon the effective date of the Act, qualifying hydrogen means hydrogen produced with a carbon intensity equal to or less than nine kilograms of carbon dioxide equivalent per kilogram of hydrogen produced. As of July 1, 2024, qualifying hydrogen means hydrogen produced with a carbon intensity equal to or less than seven kilograms of carbon dioxide equivalent per kilogram of hydrogen produced. As of July 1, 2026, qualifying hydrogen means hydrogen produced with a carbon intensity equal to or less than five kilograms of carbon dioxide equivalent per kilogram of hydrogen produced. As of July 1, 2028, qualifying hydrogen means hydrogen produced with a carbon intensity equal to or less than three kilograms of carbon dioxide equivalent per kilogram of hydrogen produced. After July 1, 2030, the secretary of the Environment Department may, through administrative rule, lower the carbon intensity of qualifying hydrogen for a period of two years. Hydrogen meeting the definition set forth herein shall qualify for certain incentives as set forth in this Act provided the hydrogen molecule is not directly derived from fresh water.

Hydrogen production in 2050: how much water will 74EJ need?

July 22, 2021 by Herib Blanco

energypost.eu
THE BEST THINKERS ON ENERGY

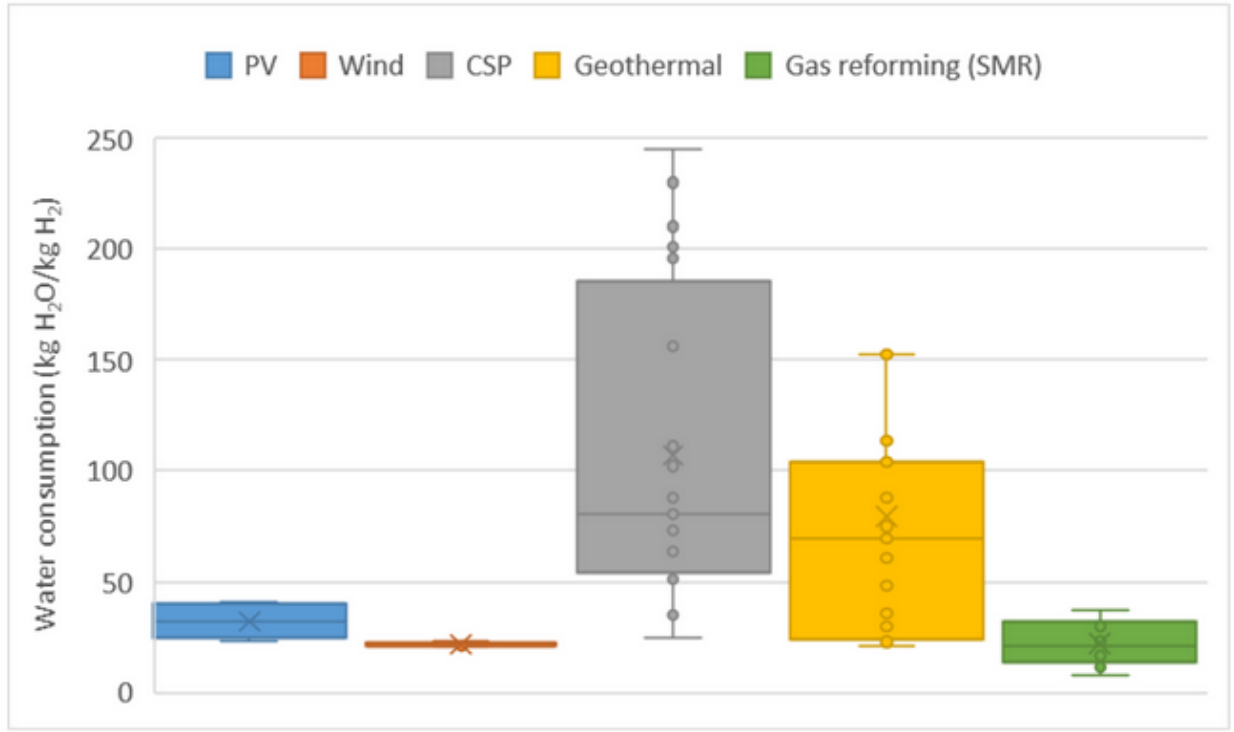


Figure 1. Lifecycle water consumption for various hydrogen production pathways / Sources: [2, 3].

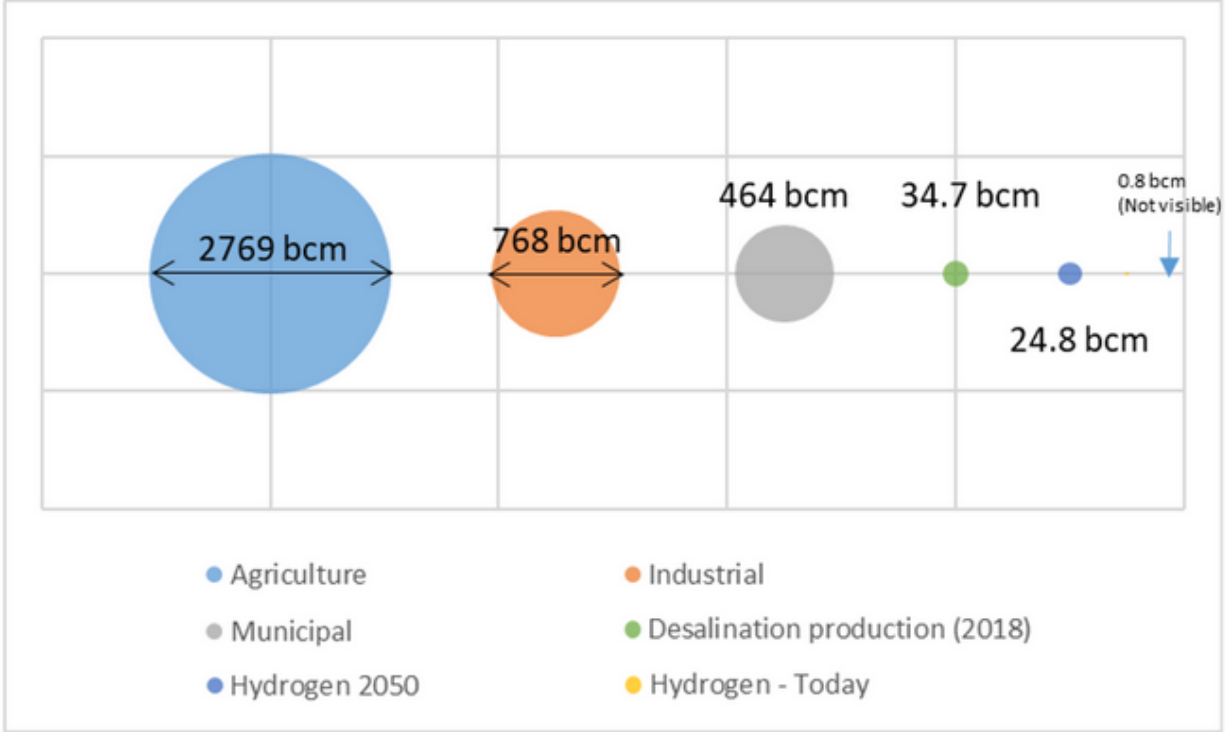


Figure 2. Water consumption by application (circle size is proportional to water use in each application with agriculture at almost 2,800 km3/yr) / Sources: [7-9].

Electrolysis

- **Consumes 27 gallons of water as a feedstock and coolant for every kilogram of hydrogen that is produced using an electrolyzer that has an efficiency of 75%.**
- **A Toyota Mirai fuel cell car holds: 5.6 kg H2**
  - **So ~ 151 gal H2O per full car refill (1 gal = 3.79 kg)**
    - **Average refill is actually close to 3 kg H2**

- **Roughly 80% of hydrogen refueling stations now have a capacity of 150 to 200 kilograms of hydrogen.**
  - 5400 gal H2O per station at 200 kg
  - (Obviously) Water consumption depends upon H2 consumption

- **520-MW coal-fired power plant uses about 12 million gallons of water per hour.**

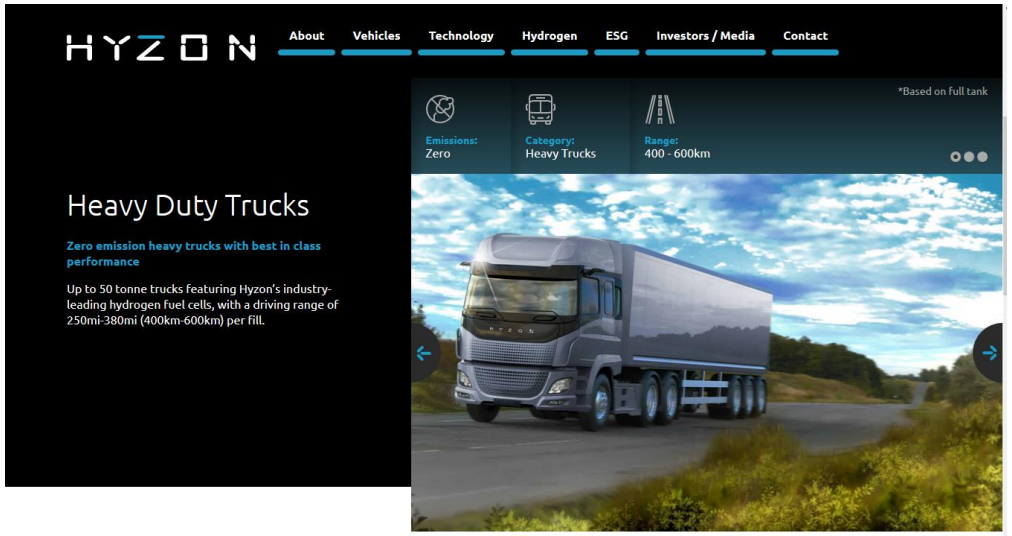
U.S. Energy Related Carbon Dioxide Emissions by Sector

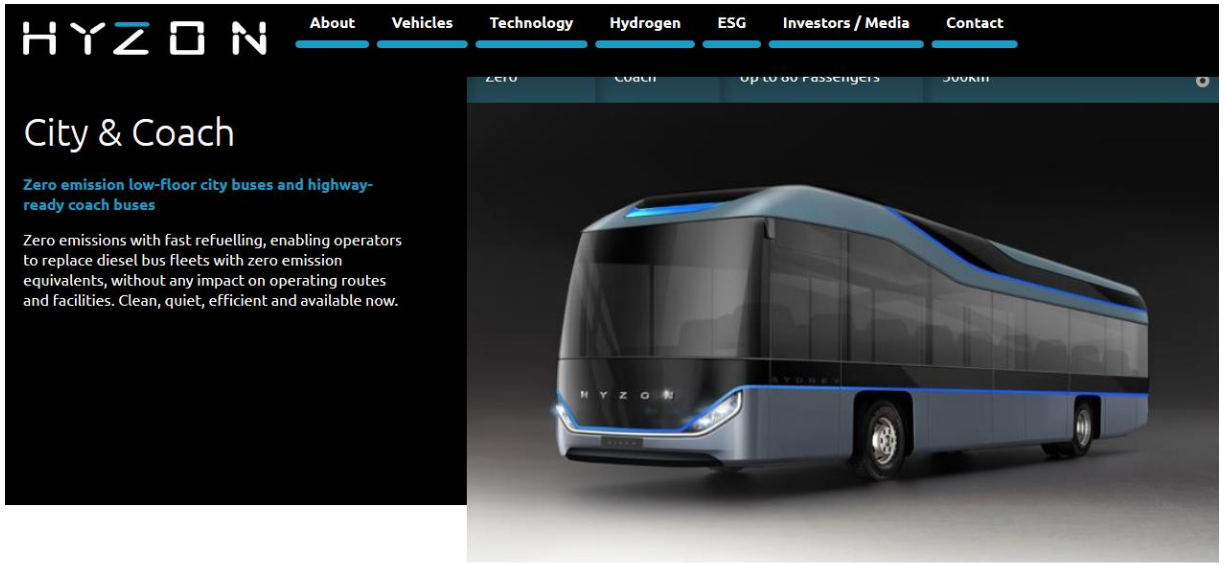
Need to address all sectors with portfolio approach

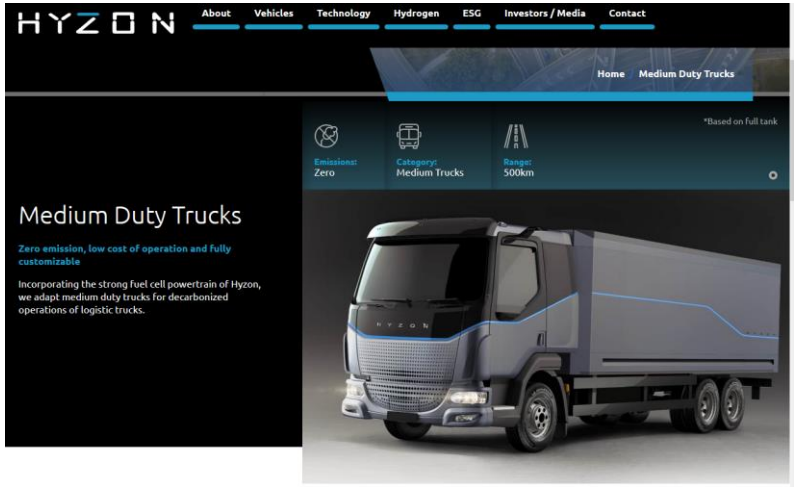
Hydrogen can provide benefits particularly in hard to decarbonize sectors: industry, heavy duty transport, energy storage, etc.

Source: M. Koleva, DOE HFTO, NREL, adapted from EPA, Sources of Greenhouse Gas Emissions | Greenhouse Gas (GHG) Emissions | US EPA

Hyzon – Retrofits vehicles for fuel cells
Concentration on HDV and Full-Sized buses







Ballard

The Future of Clean Transit is Electric

Public transit leaders know that zero-emission buses are critical to the future of transit. Many regions around the world are setting goals and mandates to convert entire fleets to electric buses.

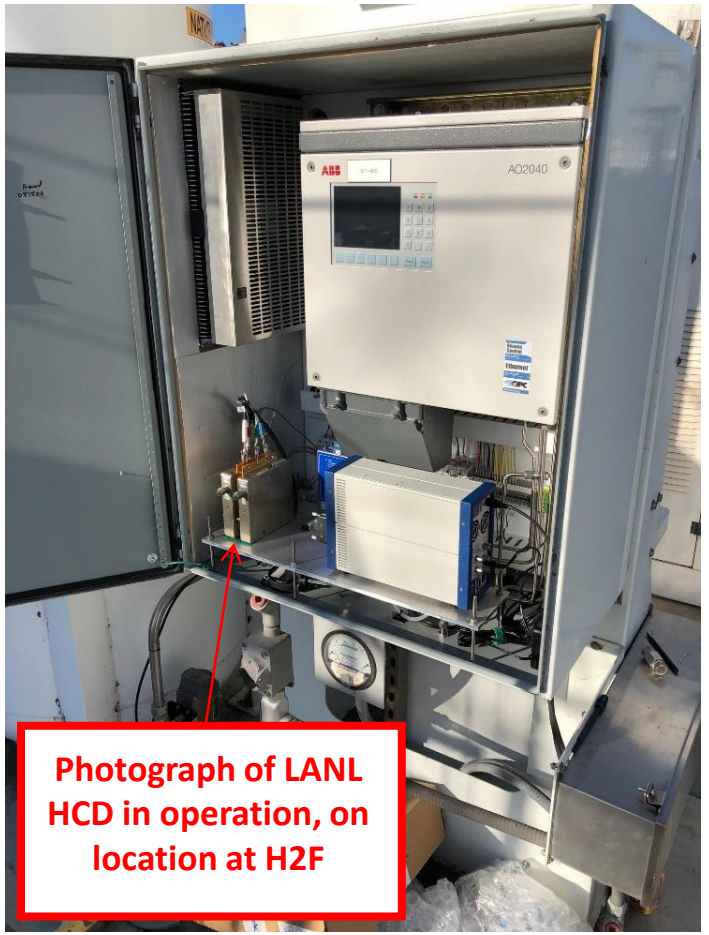
Hydrogen Fuel Cell Buses are Electric Buses

ONEH2

<dan.poppe@oneh2.com>

For a 200 kg a day generation, storage and dispense system for both 700 and 350 it is @3 million USD
For 400 a day 4 mil USD.
If these numbers are in your range I can provide more details.
Generation is SMR tech, feedstock natural gas
Note: Toyota Mirai holds 5.6 kg H2

Sulphur and odorants are trapped in a vessel with catalysts. Changed every 6 months to a year depending on thru put.



H2 Frontier Inc
Hydrogen Generation, Storage & Delivery Systems

SimpleFuel

SimpleFuel is our prize winning refueling system that we installed at the DC station at NPS's Brentwood. The cost vary but I am told a ~$300k/ year lease is possible. Its an electrolysis system producing 2-5 kgs/day

The second commercial installation of SimpleFuel in Japan is at the Toyota Motomachi Plant! Read more here...

Toyota:
Regarding Colorado, we are focused on education/outreach to establish policies to support H2 refueling stations (HRS) with a near-term goal of getting a few HRS built to support pilots that would demonstrate the technology and its potential – we have found that "seeing is believing" when it comes to H2/FCEV. These activities are intended to garner support (from local government and private companies / investors) for a broader HRS rollout that would enable high-volume deployment of FCEVs. Starting from a point of zero awareness of H2/FCEV 1-2 years ago, these efforts have built significant momentum behind H2, including:

•Colorado Hydrogen Network
- Non-profit that convenes companies, local governments, and universities interested in H2 to facilitate education and networking amongst members as a means of fostering H2 pilot project development

•Colorado Motor Carriers Association working group
- CMCA recognized the critical need for H2/FCEV technology to take trucking ZEV in CO and convened this group consisting of CMCA members, various Colorado state regulatory agencies, and private companies interested in H2 deployment (e.g., Xcel Energy, Toyota)
- Working group helps guide CMCA's strategy for H2/FCEV advocacy in medium-/heavy-duty trucking applications, including educating CMCA members, engaging with state legislators and regulators, etc.

•Current legislative proposals
- Massive transportation bill that would unlock ~$700M for refueling of BEVs and FCEVs – narrative has shifted in CO away from ZEV=BEV to ZEV = BEV & FCEV with recognition that both technologies are needed to decarbonize transportation
- Separate bill that would provide ~$5M/year funding for H2 stations

•H2 infrastructure pilots
- New Day Energy (startup) is collaborating with Colorado State University to establish a publicly-accessible demonstration HRS on CSU's campus in Fort Colins
- Roaring Fork Transit Authority (RFTA) is actively seeking grant funding to build an HRS at their facility to support deployment of FC buses
- Xcel Energy is the largest utility in CO and has been vocal about supporting H2 production and distribution – no concrete activities publicly disclosed yet, but it sounds like they are seriously considering a multi-MW electrolyzer deployment in CO in the near future

Toyota:
Regarding the General Services Administration, I think we have investigated participating in it previously, but ultimately decided against it at the time (of the major automotive companies, Toyota has one of the lowest % fleet sales). Your recommendation is great and I think we should reevaluate internally whether our previous conclusion is still valid. That said, I do not think anything would preclude us from working through the Toyota of Santa Fe dealership to provide FCEVs to Los Alamos.

Federal Contract Opportunity for FY2022 Electric, Hydrogen Fuel Cell, and Other Clean Emission Vehicles Request for Information 47QMCA21R0004. The NAICS Category is 336111 - Automobile Manufacturing. Posted Jan 12, 2021. Due Mar 5, 2021. Posted by the Federal Acquisition Service (GSA). The work will be performed at Washington, DC 20405, USA

Our Summary

U.S. General Services Administration FY2022 Battery Electric and Hydrogen Fuel Cell Vehicles Request for Information The U.S. General Services Administration (GSA) Office of Fleet Management (GSA Fleet) is seeking information from industry on commercially available battery electric and hydrogen fuel cell vehicles that can be provided to GSA Fleet for sale and/or lease to eligible GSA customers. These vehicles must meet or exceed current Federal Vehicle Safety Standards for Domestic use, and all vehicles produced for other global regions are to comply with safety and emission standards for the countries they are intended for sale outside the United States. GSA Fleet will use the information provided by industry to determine if the market can meet customer demand for battery electric and hydrogen fuel cell vehicles. GSA Fleet's intent is to develop a comprehensive, industry-informed requirement and acquisition strategy to pursue battery electric and hydrogen fuel cell...more

Original Description Show Most Recent (2 months ago)

Show & Tell

- **Several versions of Fuel Cell Stacks**
  - MicroWatt Power
  - Watt Power
  - Small stack parts (plates, gaskets)
- **Cells from commercials stacks (kilowatt power)**
- **Membrane**
- **Membrane – Electrode – Assembly (MEA)**
- **Catalyst (?)**

Strong record of national and international collaborations with other labs, academia, and industry

Rodney Borup (co-lead with LBNL)
Million Mile Fuel Cell Truck (M2FCT)

- Enhancing the performance and durability of polymer electrolyte membrane fuel cells while simultaneously reducing their cost
- Demonstrate world-class improvements in fuel cell performance and durability that exceed the targets set by the U.S. DOE
- International collaborations: EU funded IMMORTAL, ID-FAST, Japan FC-CUBIC

Piotr Zelenay (co-lead with ANL)
ElectroCat 2.0: Energy Materials Network Consortium

- Accelerating development and deployment of platinum group metal-free electrocatalysts in fuel cells and electrolyzers
- Systematic approach combining experiment, theory, machine learning (ML), high-throughput and combinatorial techniques, advanced materials characterization
- International collaborations: PEGASUS, CRESCENDO, IFCC, universities (including in France, Germany, Israel, Italy, Poland)

Los Alamos Interacts Heavily with other National Labs and Industry

Partners for Million Mile Fuel Cell Truck (M2FCT) Consortium

Primary Laboratories

- Berkeley Lab
- Los Alamos National Laboratory
- Argonne National Laboratory
- Oak Ridge National Laboratory
- NREL National Renewable Energy Laboratory

Affiliate Laboratories

- Pacific Northwest National Laboratory
- NIST National Institute of Standards and Technology
- Brookhaven National Laboratory

- **Heavy duty MEA**
  - GM
  - 3M
  - Mines
  - Cornell University
  - Pajarito Powder
  - Carnegie Mellon University Tartans
  - Chemours
  - Ballard
  - Nikola
  - Georgia Tech
  - Northeastern University
  - Carnegie Mellon University Tartans

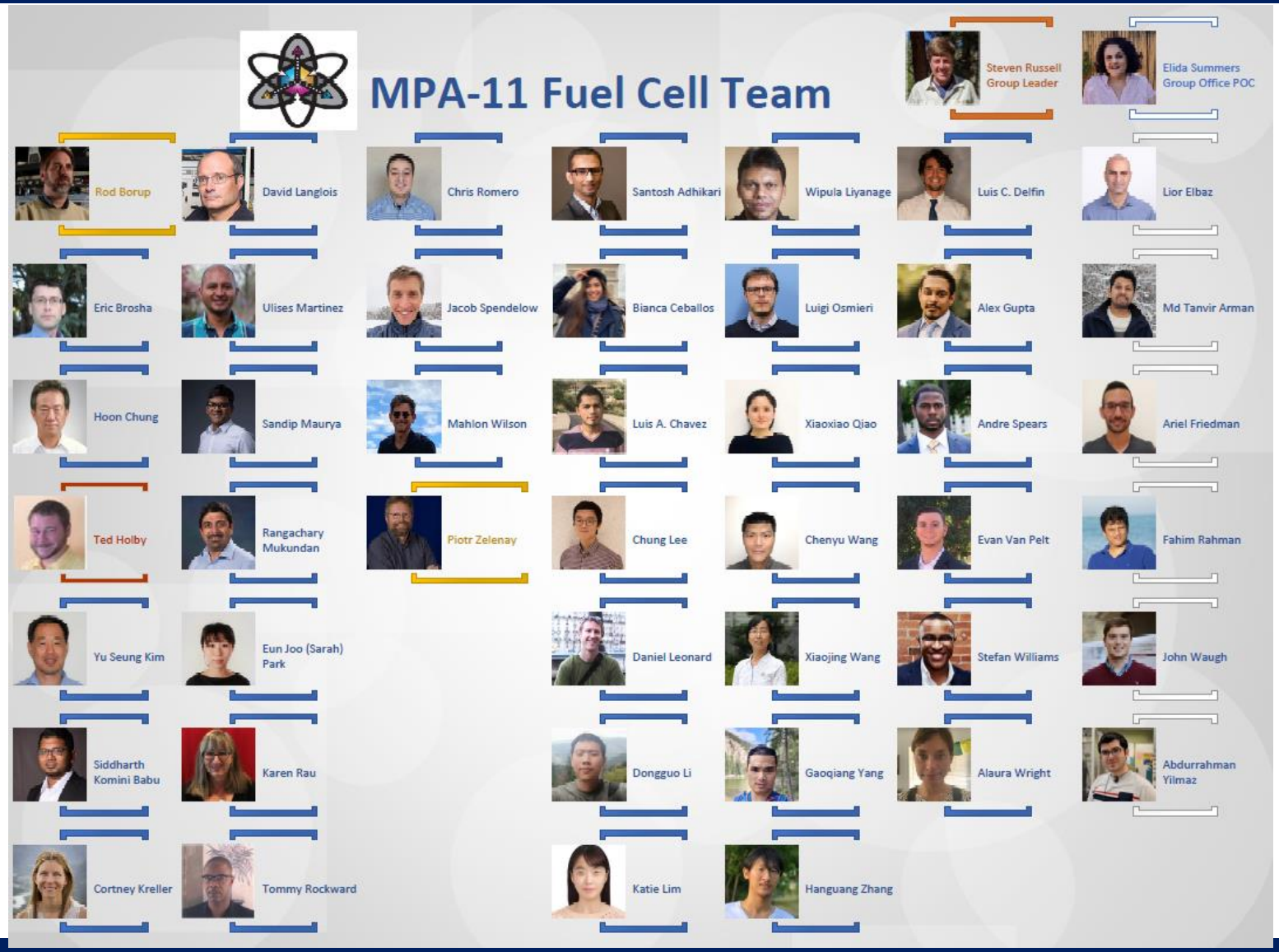
- **High temperature membrane**
  - The University of Tennessee Knoxville
  - Oak Ridge National Laboratory
  - Kodak
  - Akron Polymer Products, Inc.
  - 3M
  - GM
  - NREL
  - Lubrizol
  - NREL
  - Nikola
  - Chemours

Domestically manufactured stacks

- Cummins
- Plug Power

Fuel Cell People

- **Expertise from Chem. Eng., Chemistry, Material Sci., Mech. Eng. & Physics**
- **Scientists with over 200 years of experience fuels cells and over 25 Ph.D.'s**



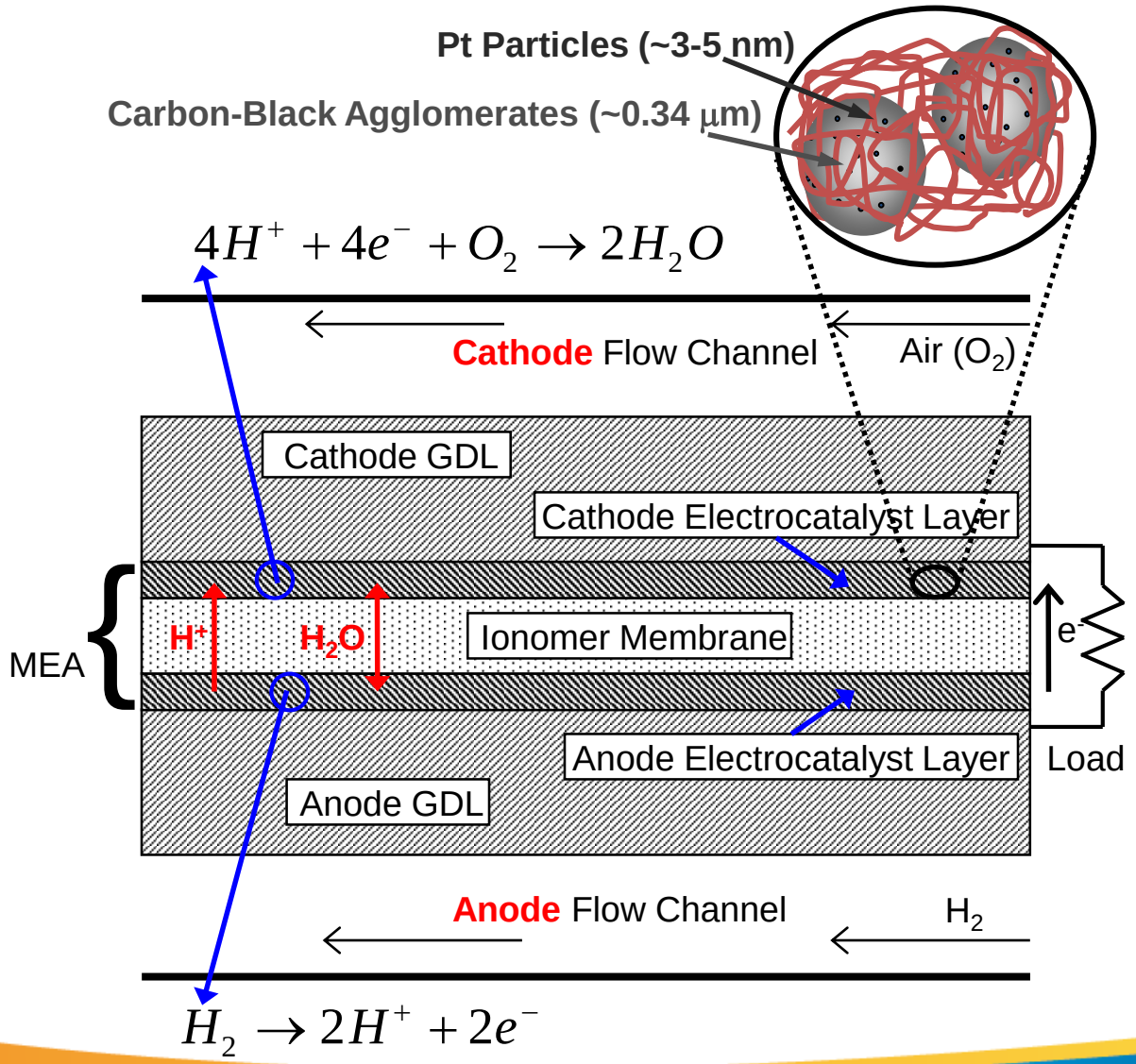
People

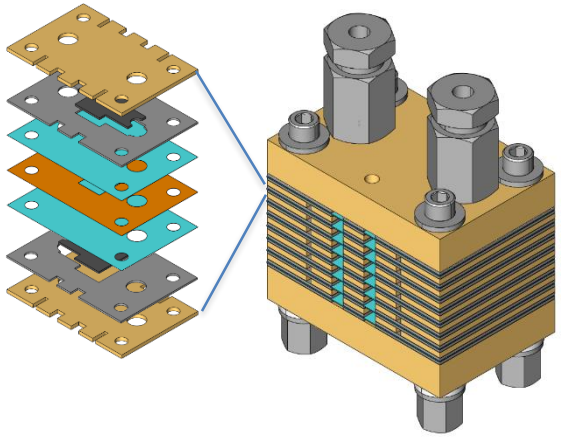
Fuel Cell Program has an extensive record of students and post-docs

Funding

- DOE EERE HFTO
- (Energy Efficiency and Renewable Energy – Hydrogen Fuel Cell Technologies Office)
- NNSA
- ARPA-E
- CRADAs
- LDRD
- OE
- BES

Components: Polymer Electrolyte Membrane Fuel Cell (PEMFC)





Membrane: Perflourosulfonic acid (10 – 25 micron)

Catalysts:

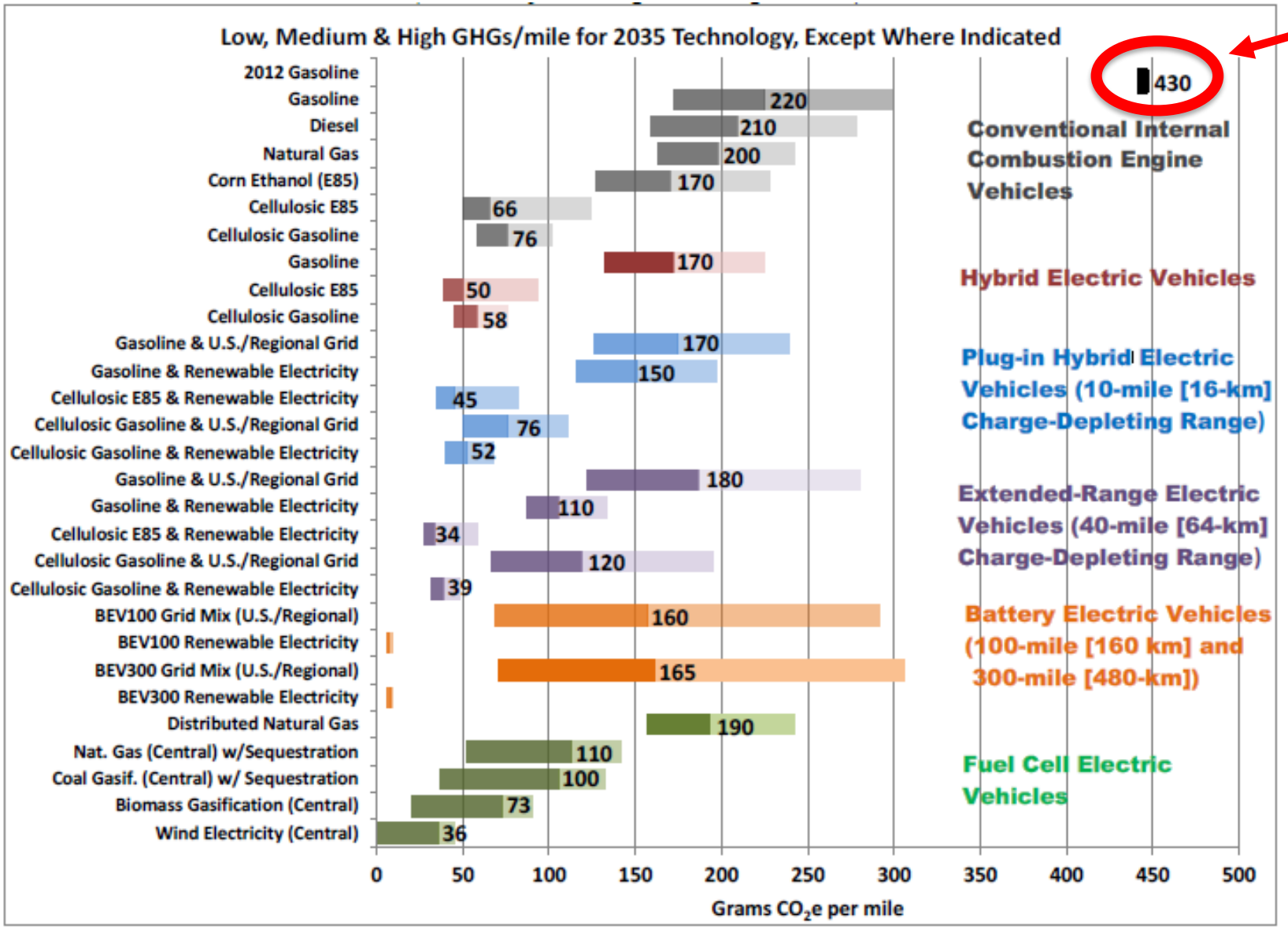
- Anode: Pt
- Cathode: Pt, PtCo, PtNi …

Catalyst Support: Carbons

Gas Diffusion Layer: Carbon fiber with micro-porous layer

Bipolar Plate: Carbon Composite, Coated Metal

Well-to-Wheels Greenhouse Gases Emissions for 2035 Mid-Size Car

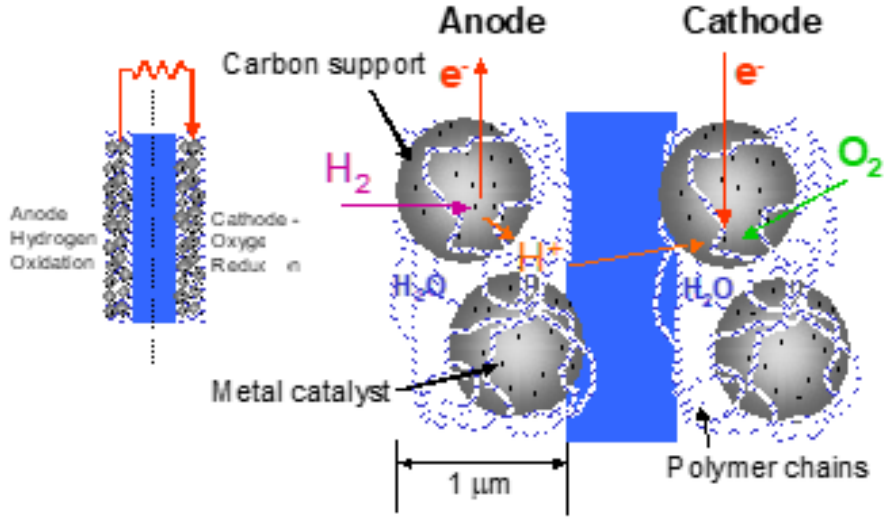


Low/medium/high: sensitivity to uncertainties associated with projected fuel economy of vehicles and selected attributes of fuels pathways, e.g., electricity credit for biofuels, electric generation mix, etc.

Fuel Cell R&D at Los Alamos
Breakthrough MEA: Membrane Electrode Assembly

- longest running non-weapons programs at LANL (since 1977)
  - **The first fuel cells for transportation program**
- The current DOE HFTO program grew out of the Los Alamos program
- Primarily polymer electrolyte membrane (PEM) technology
- Cost and durability are biggest barriers to commercialization
- Program focus is obtaining fundamental understanding to enable “knowledge-based innovation,” and subsequent materials and process development

LANL Enabling Breakthrough Thin Film Electrode



An electrochemically active reaction site must have reactant access to catalyst, available electronic and ionic conduction paths, and manage water

US Patents #4,876,115, #5,211,984 and #5,234,777