UNIVERSITY OF CALIFORNIA Berkeley
Transportation Sustainability
RESEARCH CENTER

Hydrogen Fueling Stations for Fuel Cell Vehicles: Status of Recent California and International Efforts

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Presentation Outline

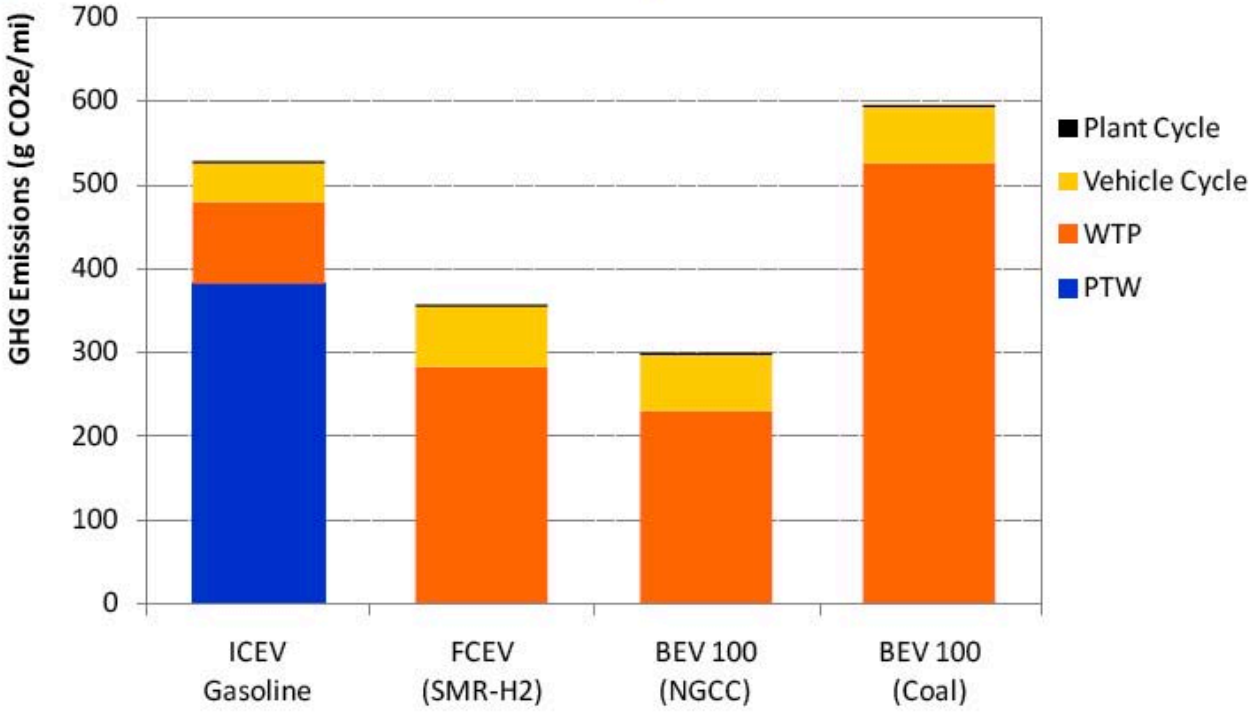
- Latest fuel cell system and vehicle progress
- Hydrogen production pathways
- Hydrogen station concepts
- California, U.S., and international H2 infr. efforts
- UC Berkeley research program:
  - 700-bar station operation (3 years)
  - “Real world” testing of 8 FCHV-adv Toyota Highlanders
  - Toyota FCHV-adv driver response
  - Fuel cell bus driver study
- Additional Q&A and discussion

A Few Key Points

- Electric vehicle technologies (batteries, fuel cells, and hybrids) are synergistic rather than opposed – room for more than one "alternative fuel" option
- With minimal public and mostly automaker support, hydrogen fuel cell technologies for light, medium, and heavy-duty applications have seen great improvements in recent years
- PHEVs and FCVs are showing very good to excellent initial "consumer acceptance" – not just green cars but better cars!
- Hydrogen is a low carbon fuel, even if made with natural gas SMR -- and esp. with a 33%+ renewables component
- Recent progress in CA/state, U.S., and International efforts
- However, many challenges remain on the hydrogen infrastructure "half of the puzzle"

Overall Impacts Incl. Vehicle and Plant

Overall, Emissions from Plant Construction Are Negligible Compared to Fuel- and Vehicle-Cycle Emissions

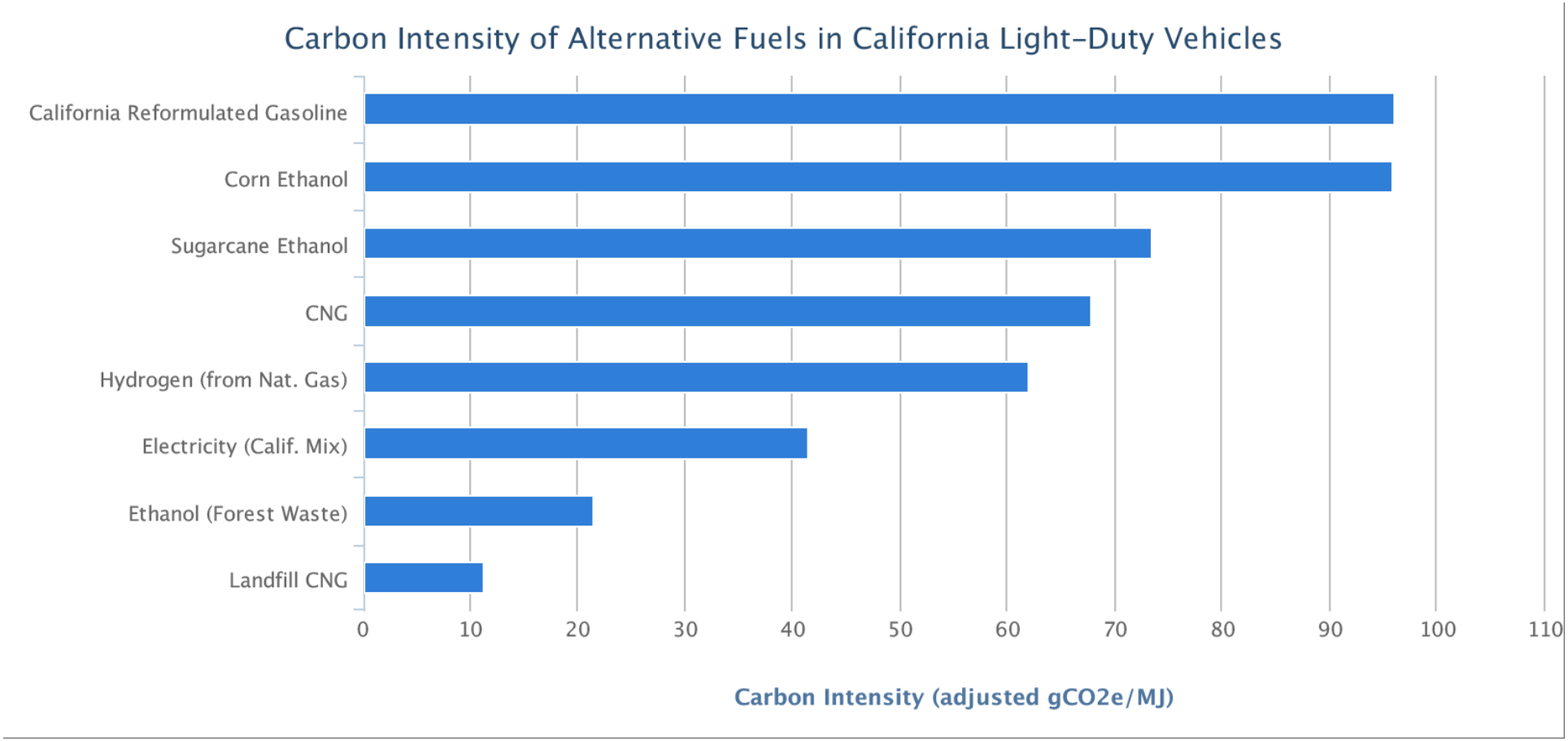


	Gasoline ICEV	H_2 FCEV	BEV 100
Fuel Economy (mpgge)	23	54	80*

*from wall outlet (assuming 85% charging efficiency)

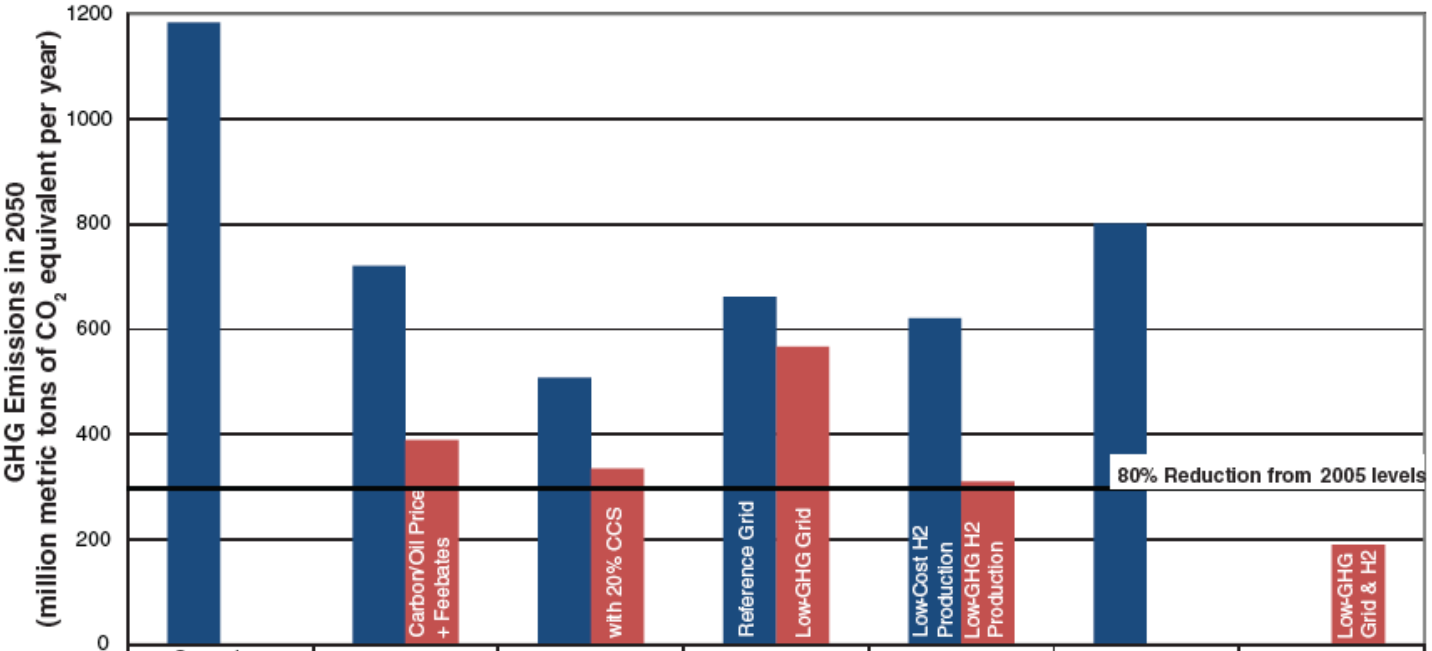
14

California Emissions Scenario



Source: DOE NREL

GHG Emissions from NRC Strategies

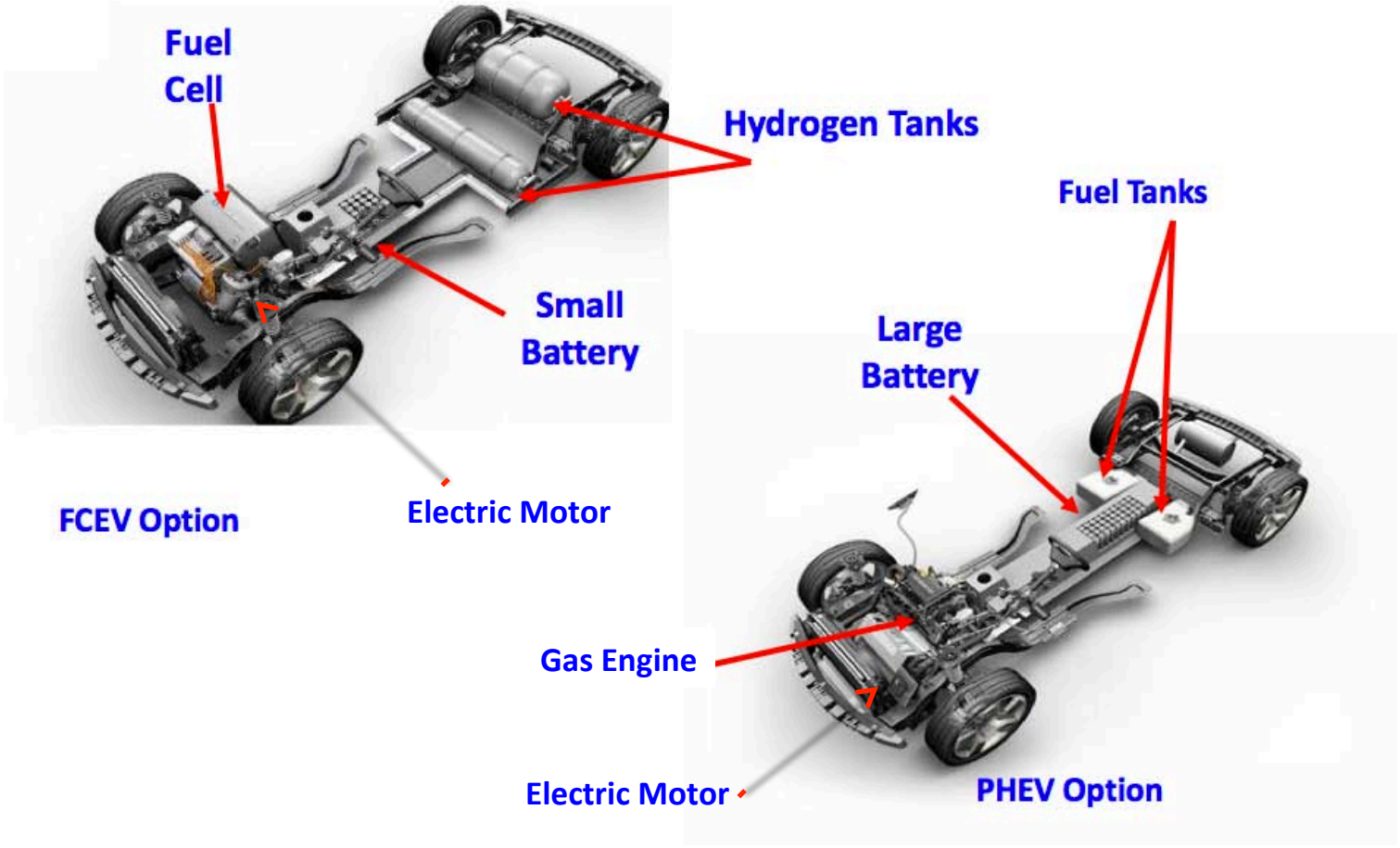


	Committee Reference (Current Policies)	Efficiency	Efficiency + Biofuels	Plug-In Electric Vehicles (PEVs)	Fuel Cell Electric Vehicles (FCEVs)	Natural Gas Vehicles	PEVs + FCEVs + Biofuels
Reference Production	1184	721	508	662	621	801	
Low-GHG Production		389	335	567	310		190

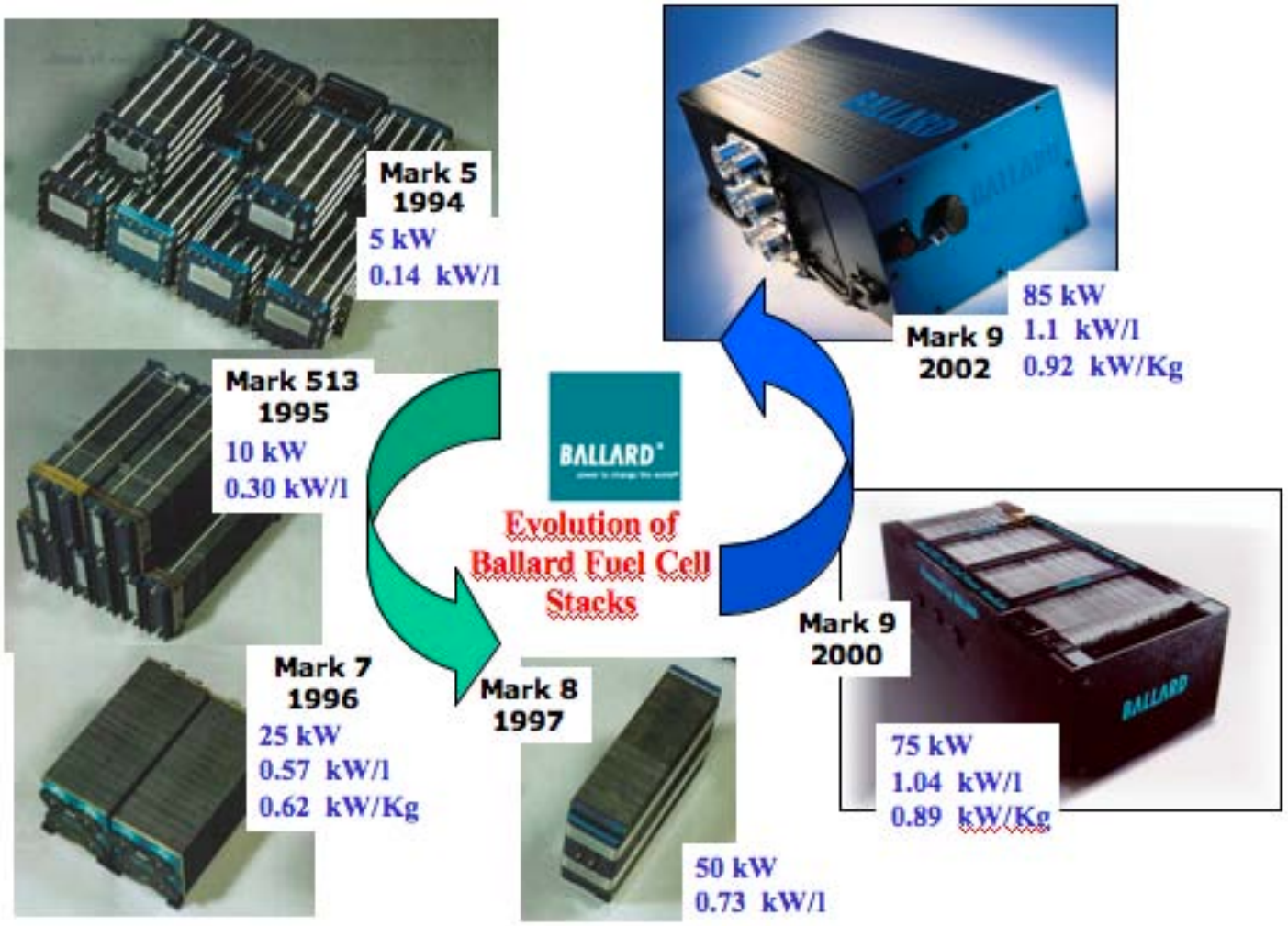
FIGURE S.2 Estimated U.S. LDV GHG emissions in 2050 under policies emphasizing specific technologies. All scenarios except the Committee Reference Case (current policies, including the fuel economy standards for 2025) include midrange efficiency improvements. Fuel production for these scenarios is assumed to be constrained by policies controlling GHG emissions (low GHG production).

Source: NRC 2013

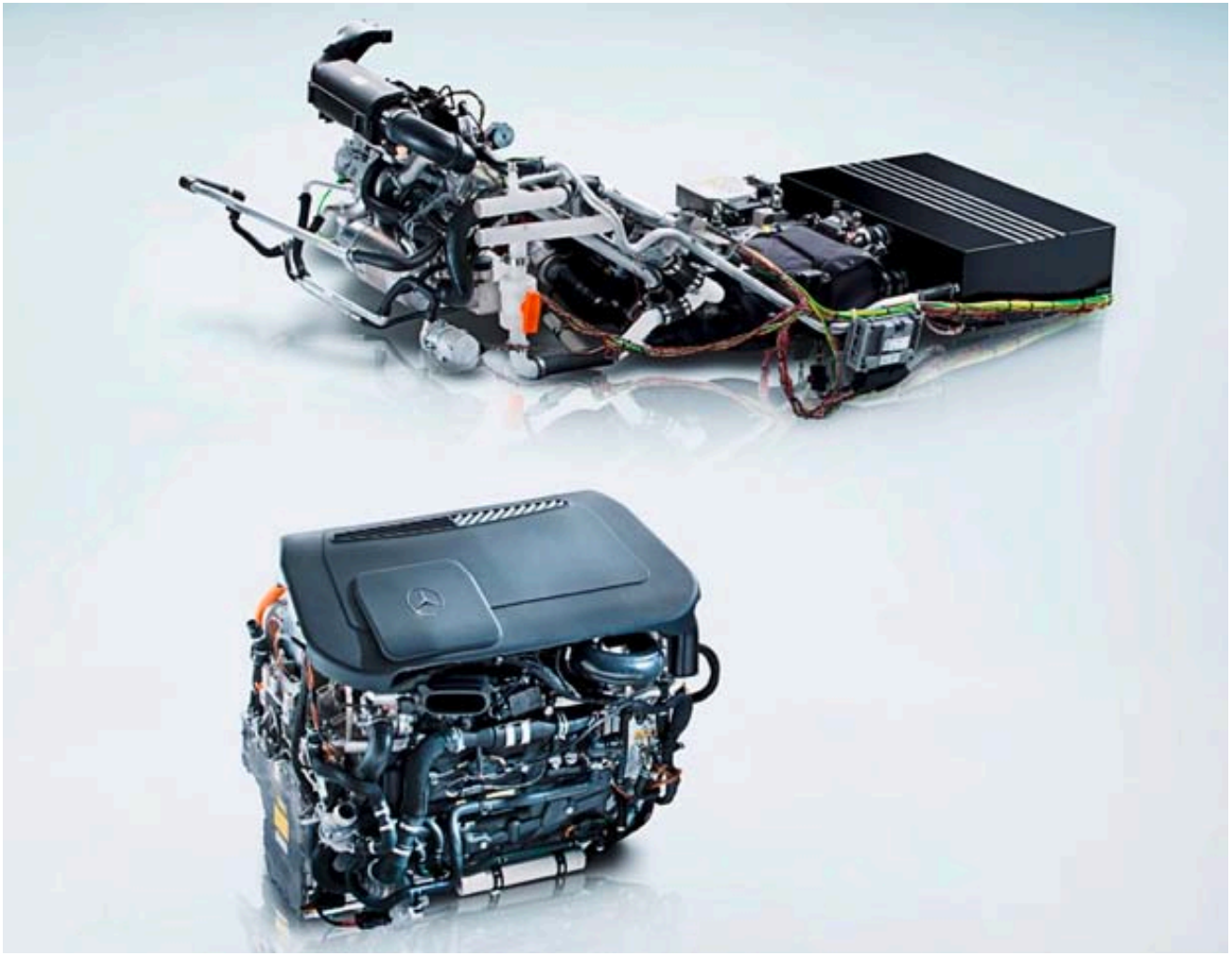
PHEV and FCEV Architectures



Historical Hydrogen Fuel Cell Progress



Latest Daimler Benz Fuel Cell Systems



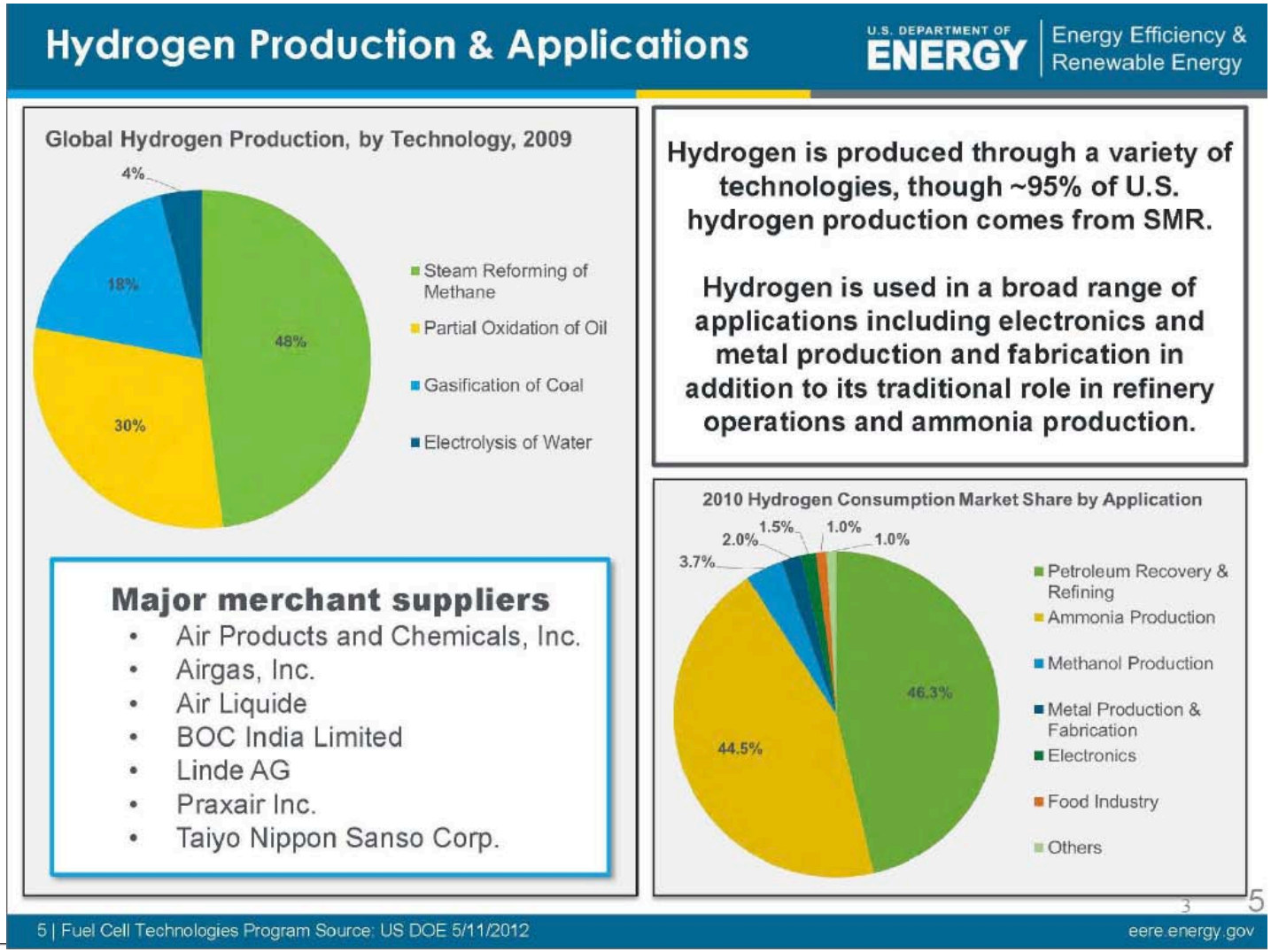
Current Early Market FCVs

Note: clockwise from top center: GM Equinox, Hyundai ix35, Nissan TeRRA, Toyota FCV Concept, Honda Clarity, Daimler F-Cell

Hydrogen Fuel Cell Buses – Great Progress

- Fuel cell buses in operation at AC Transit since 2005
- Current fleet of 12 buses (240 miles range)
- Lead fuel cell bus with 16,500+ hours of operation
- Nearly one million miles of service for AC Transit and over 3 million passengers carried
- Emeryville station has dispensed over 100,000 kg of fuel
- Oakland station online this summer

Hydrogen Production Today



Hydrogen Production Pathways

The Sustainable Hydrogen Economy

The production of hydrogen, primarily from water, its distribution and utilization as an **energy carrier and feedstock.**

Note: The energy generation and the feedstock must be sustainable

Energy Generation
- Biomass
- Nuclear
- Geothermal
- Sustainable e-
  - Solar
  - Wind
  - Hydro
  - Other

Production
- Electrolysis
- Thermolysis
- Conversion

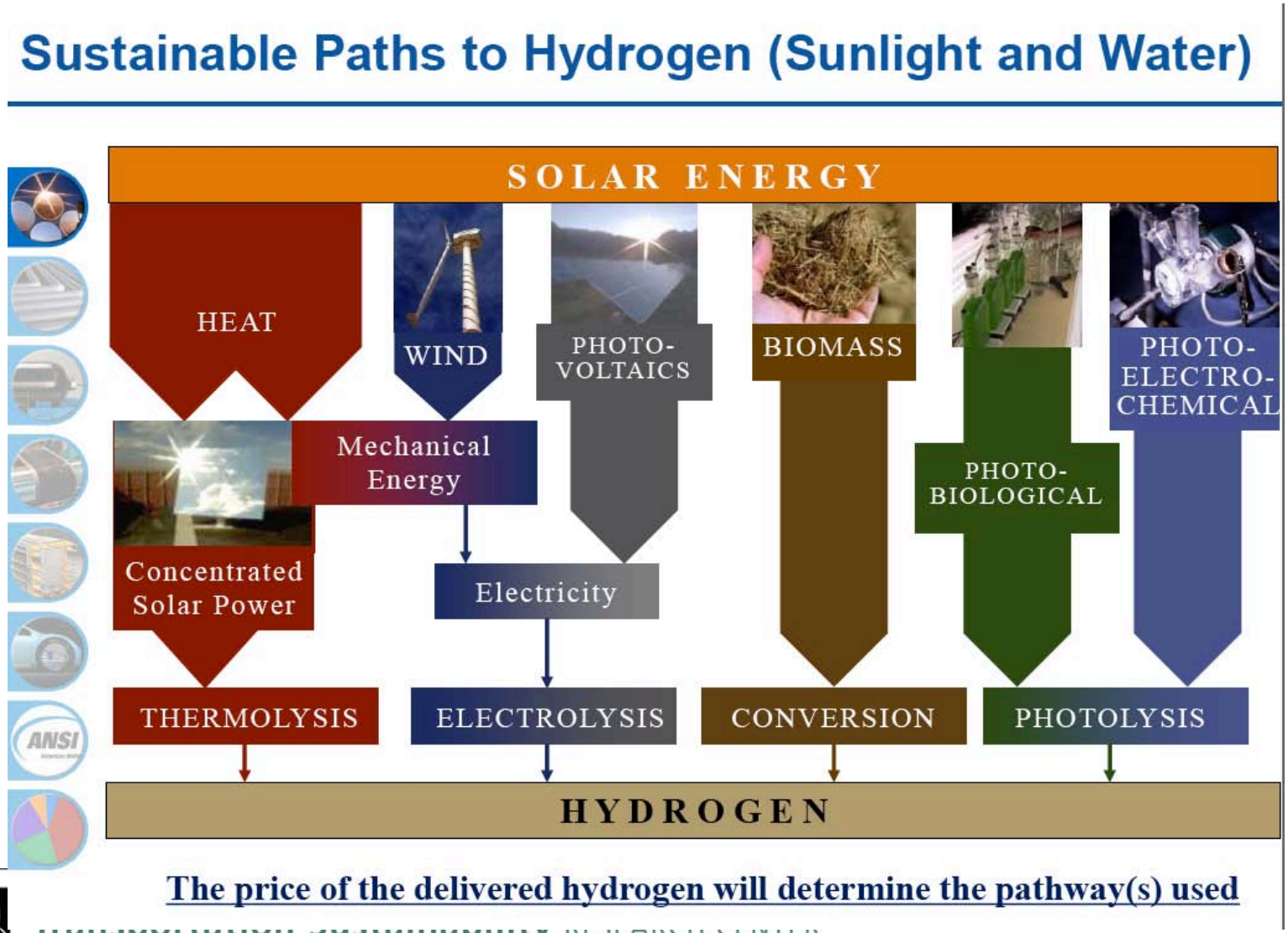
Feedstock
- Water
- Biomass

Distribution
- Used onsite
- Pipelines
- Compressed gas
- Liquid

Utilization
- Fuel cells
- Turbines
- IC Engines
- Synthesis

Transportation fuel Ammonia and Energy Storage.

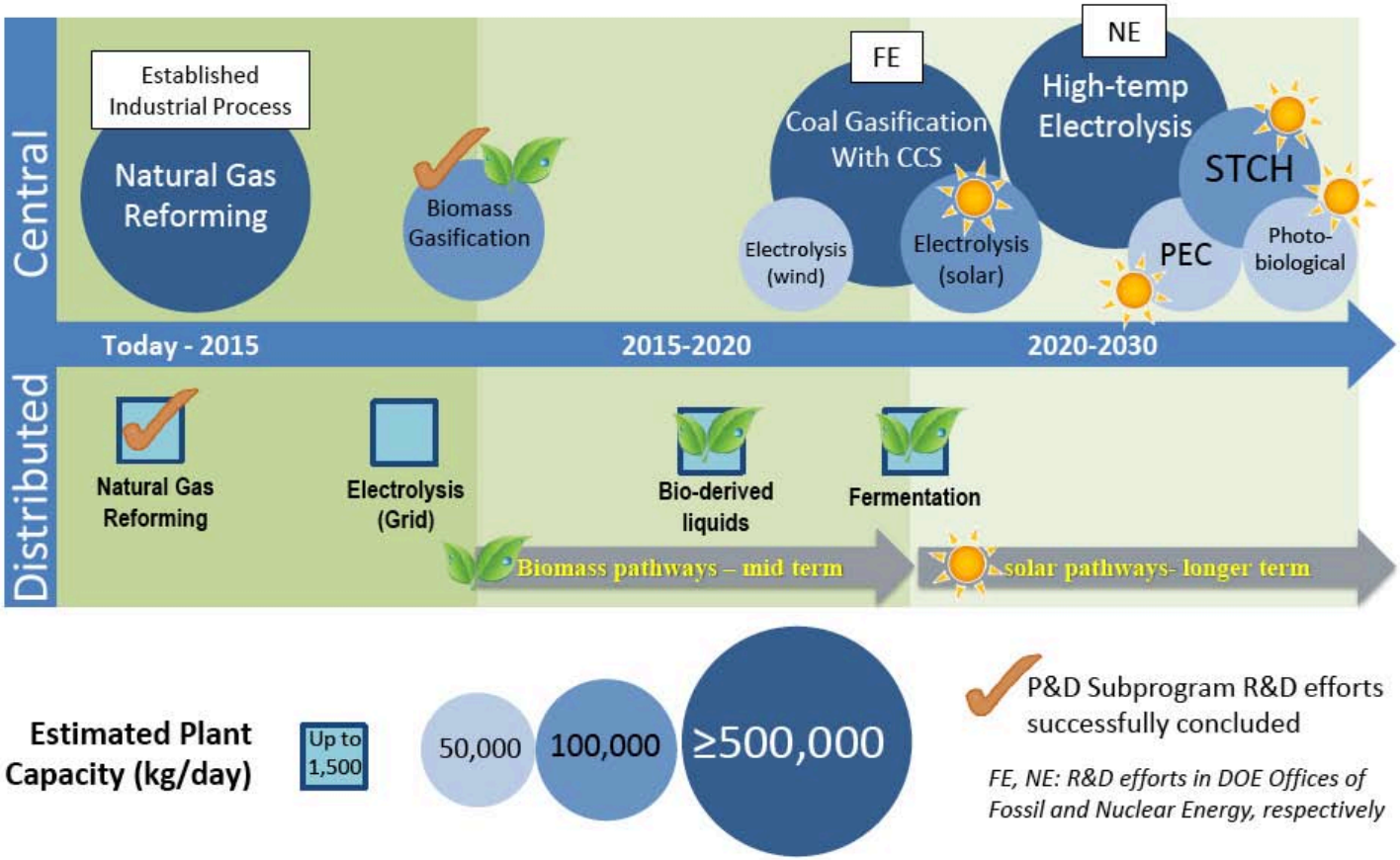
Hydrogen Production Pathways



Hydrogen Production Pathways

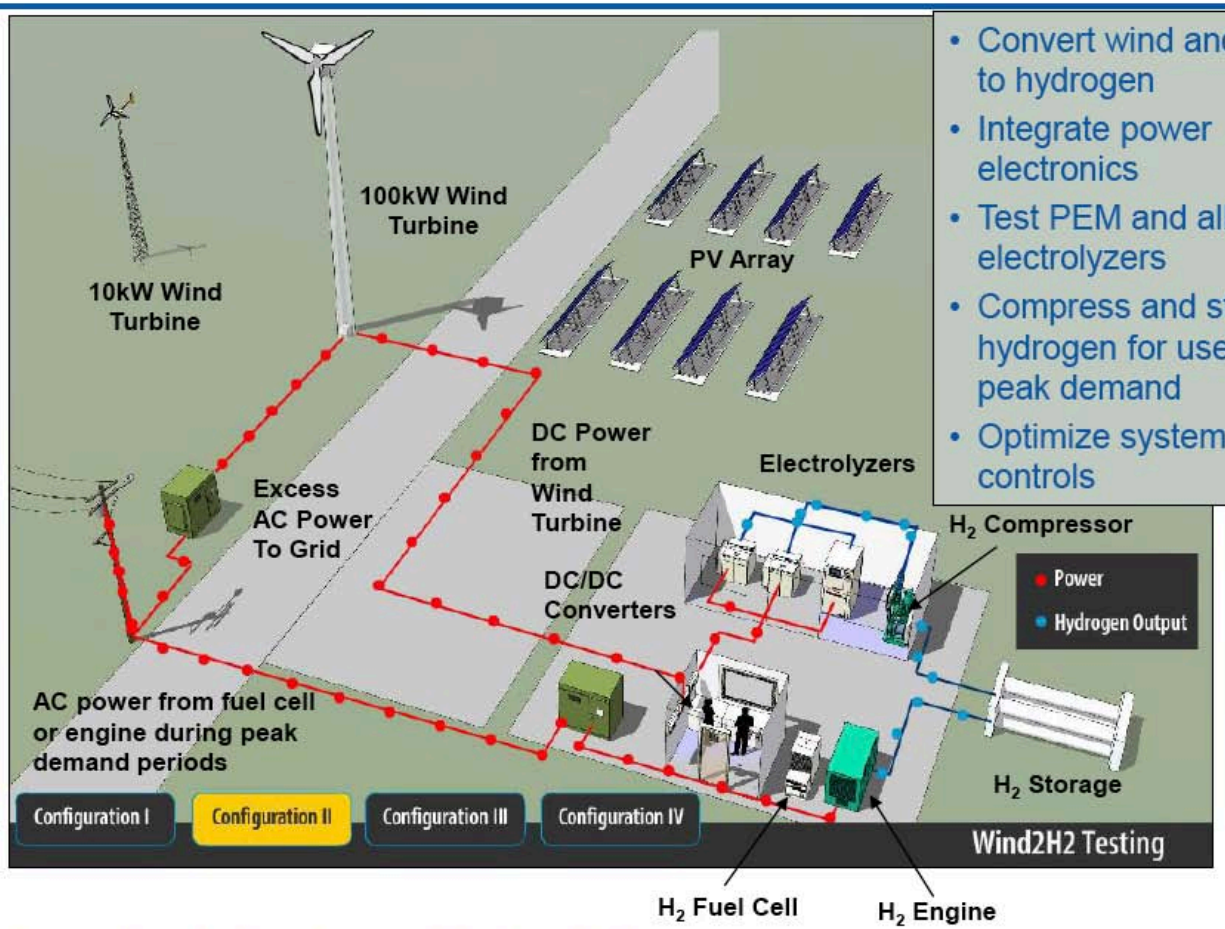
Hydrogen Production - Strategies

Technology Readiness of DOE Funded Production Pathways



Hydrogen Production Pathways

NREL/Xcel Wind-to-Hydrogen Project

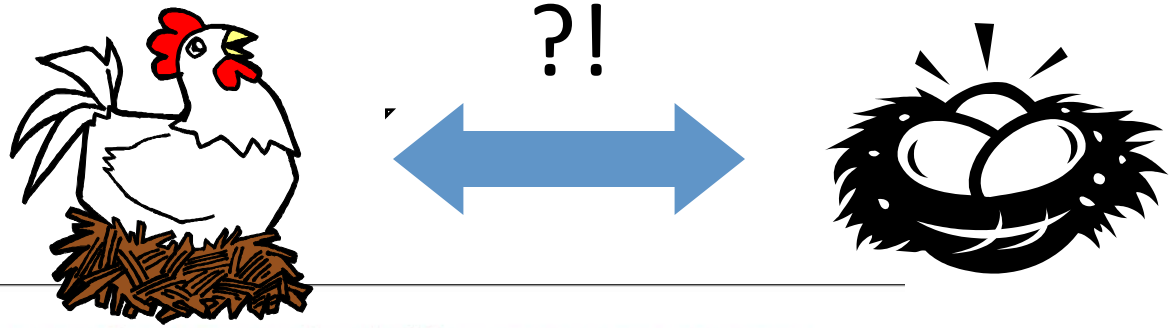


- Convert wind and solar to hydrogen
- Integrate power electronics
- Test PEM and alkaline electrolyzers
- Compress and store hydrogen for use during peak demand
- Optimize system controls

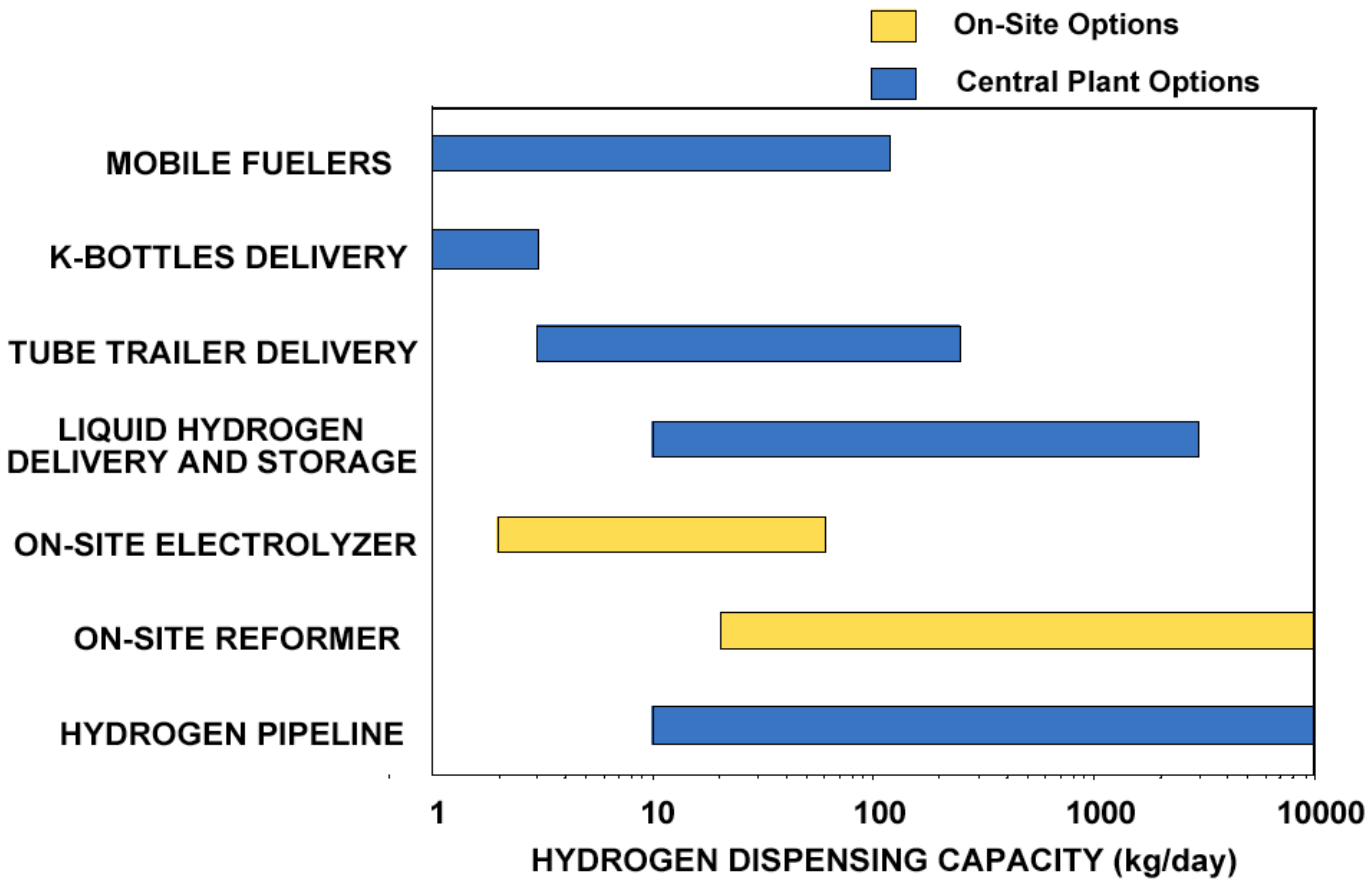
http://www.nrel.gov/hydrogen/proj_wind_hydrogen.html

Here's the Key Alt. Fuels Dilemma...

- Fundamental "Chicken or the Egg" Question
  - Private consumers will not buy vehicles without significant refueling infrastructure
  - Energy companies reluctant to invest in infrastructure without a clear business case
  - Economics of hydrogen production/ distribution for low levels of vehicle demand are challenging



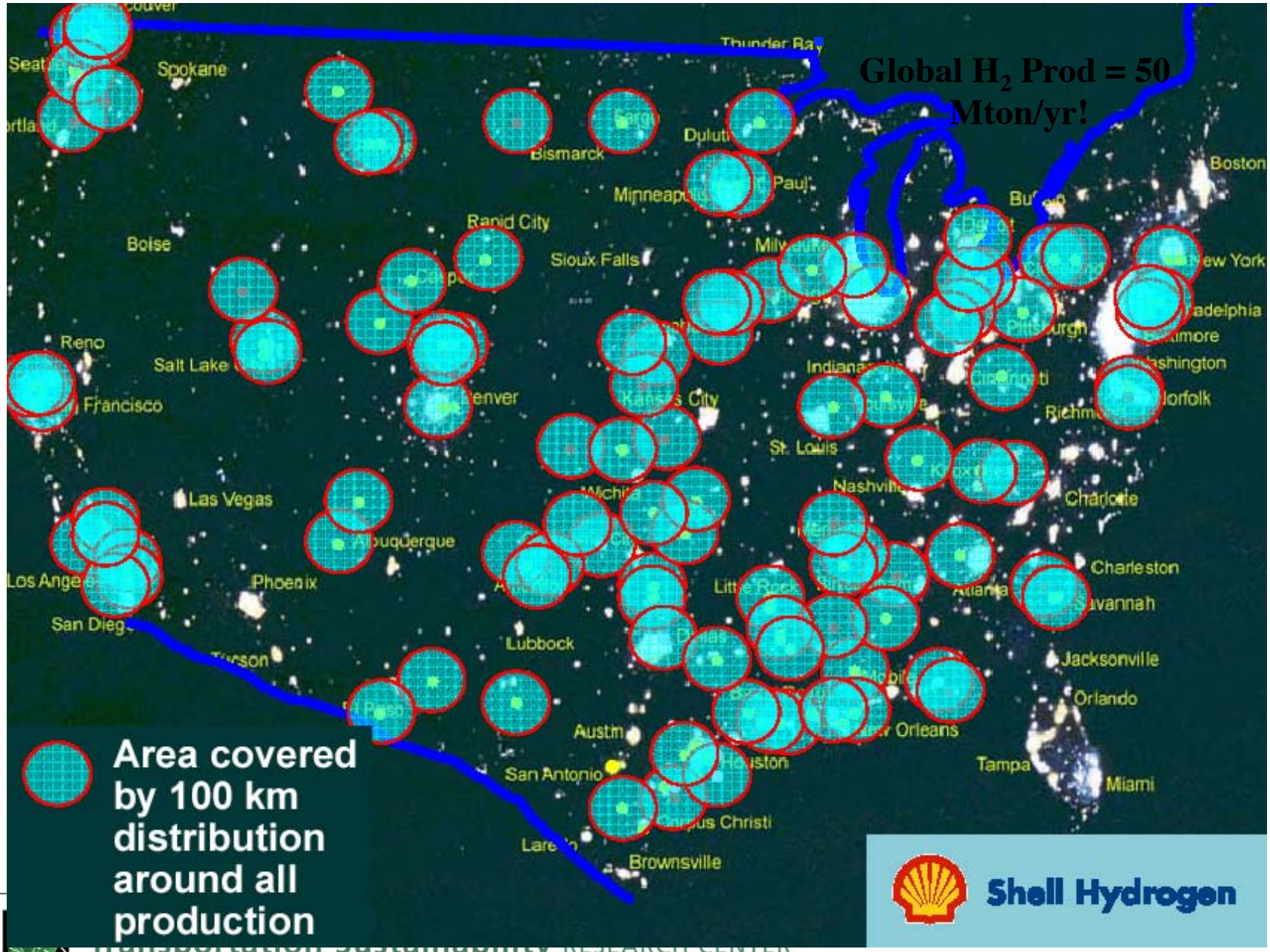
Primary H_2 Distribution Options



Mobile Hydrogen Refuelers Are An Interim Option

- Use Within ~100-150 km of Production Facilities


Seattle
Spokane
Billings
Fargo
Duluth
Bismarck
Minneapolis
St. Paul
Rapid City
Boise
Sioux Falls
Casper
Milwaukee
Chicago
Cleveland
Boston
New York
Philadelphia
Baltimore
Washington
Pittsburgh
Omaha
Reno
Salt Lake City
Indianapolis
Cincinnati
San Francisco
Denver
Kansas City
Louisville
Richmond
Norfolk
St. Louis
Knoxville
Nashville
Wichita
Charlotte
Las Vegas
Tulsa
Memphis
Albuquerque
Oklahoma City
Charleston
Los Angeles
Phoenix
Amarillo
Little Rock
Birmingham
Atlanta
Savannah
Lubbock
Dallas
Jacksonville
Mobile
Baton Rouge
Orlando
El Paso
Austin
New Orleans
San Antonio
Houston
Tampa
Miami
Corpus Christi
Brownsville
USA at night
Shell Hydrogen

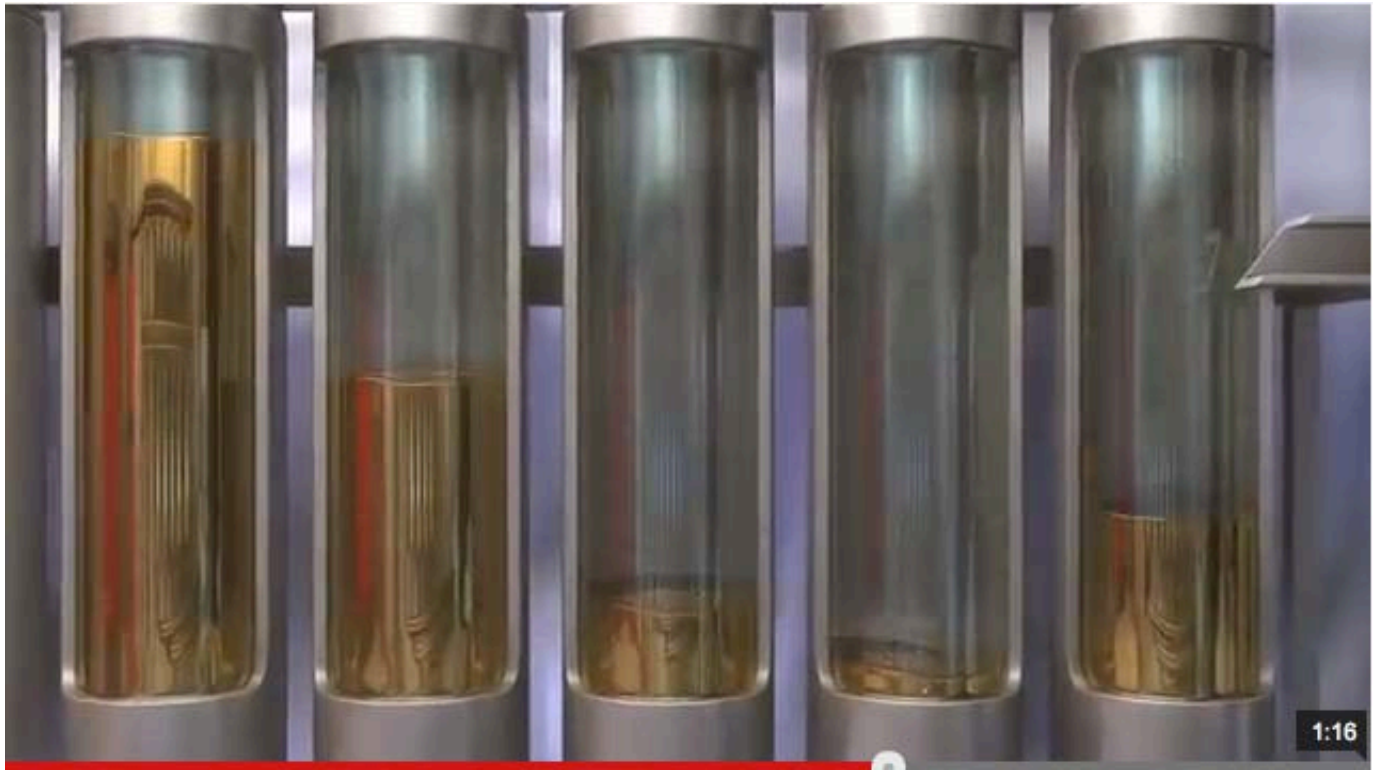

Global H_2 Prod = 50 Mton/yr!
Area covered by 100 km distribution around all production
Shell Hydrogen
Spokane
Bismarck
Boise
Rapid City
Sioux Falls
Reno
Salt Lake
Francisco
Las Vegas
Phoenix
San Diego
Lubbock
Austin
San Antonio
Brownsville
Corpus Christi
St. Louis
Charlotte
Charleston
Jacksonville
Orlando
Tampa
Miami
Boston

Hydrogen Fueling Facility at RFS

Emeryville Hydrogen Fueling Station

Hydrogen Station in Emeryville

http://www.youtube.com/watch?feature=player_embedded&v=difhN1Lpnbk

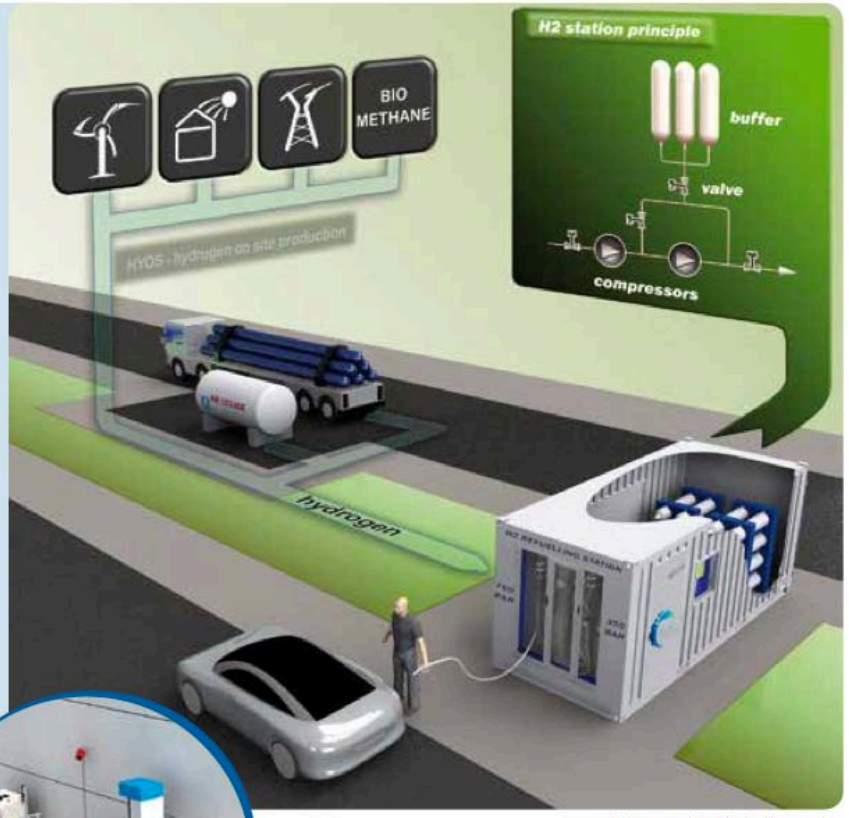


Modern Hydrogen Station Layout

Air Liquide provides a complete range of hydrogen refuelling stations from 350 up to 700 bar and offers comprehensive turnkey solutions to fill vehicle tanks (buses, cars, forklifts...) with hydrogen, quickly and safely.

With over 40 years of technical and industrial experience in hydrogen, and more than 15 years specifically on hydrogen refuelling stations, our teams propose standardised products and tailor-made solutions to meet specific customer needs.

Air Liquide supports all phases of your project from design to operation, including integration, manufacturing, start-up, training and maintenance.



Buses and cars'refuelling station

Forklifts'refuelling station

Source: Air Liquide

New APCI Inc. Dual-Pressure Dispenser

Dispenser features

1. Valence with gas detection sensors for immediate leak detection
2. Enclosed and shrouded breakaway connectors
3. Reinforced polycarbonate upper door with ergonomic design to provide simple, customer-friendly user interface
4. Energy-efficient display panel with LED backlighting for clear visibility of display in all lighting conditions; all displays equipped with clear, hard-coated sacrificial lenses for increased durability and extended life
5. Debit payment system and 5.7" color LED display with on-screen training instructions for first-time users
6. Durable EPP/TDS keypad
7. Credit card reader
8. Emergency stop button and operating instructions
9. H70 and H35 unit price displays
10. Unique fueling pressure selection buttons with no moving parts for unmatched durability
11. Lower door assembly
12. RFID (radio frequency identification detector) reader for vehicle identification and communications
13. Universal metal nozzle boot—the industry's most durable
14. Protective jackets over hoses

Source: APCI Inc.

Older Chevron “Energy Station” Concept

Hydrogen Delivery+Dispensing Costs

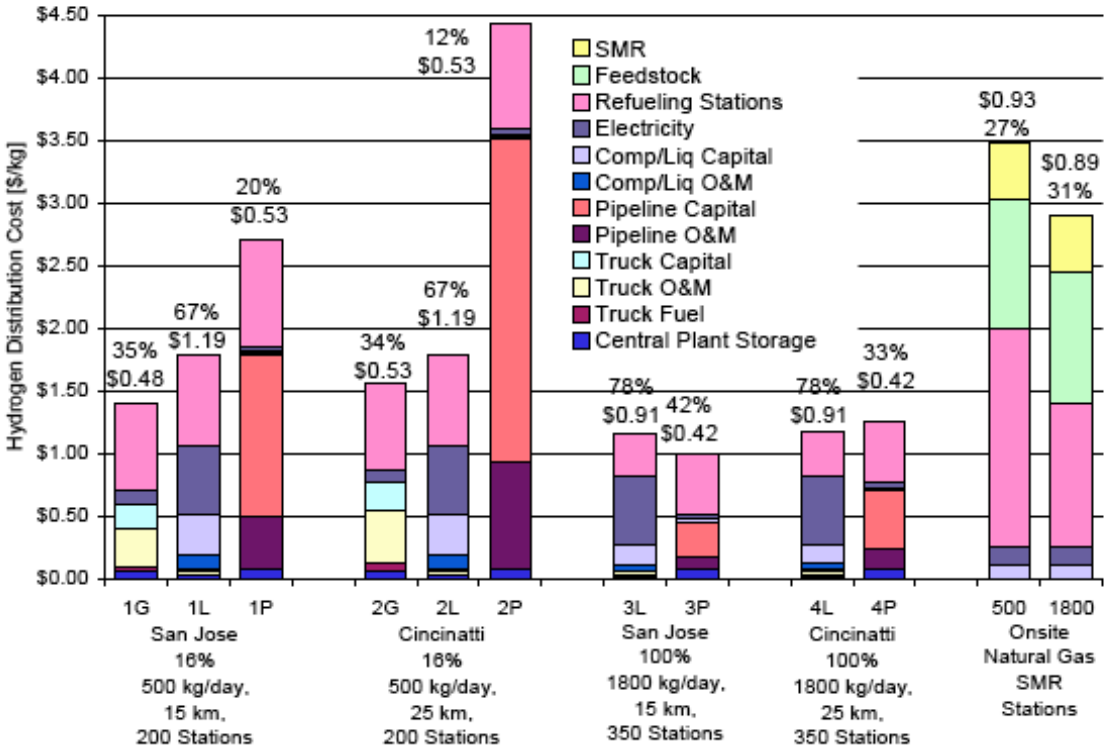
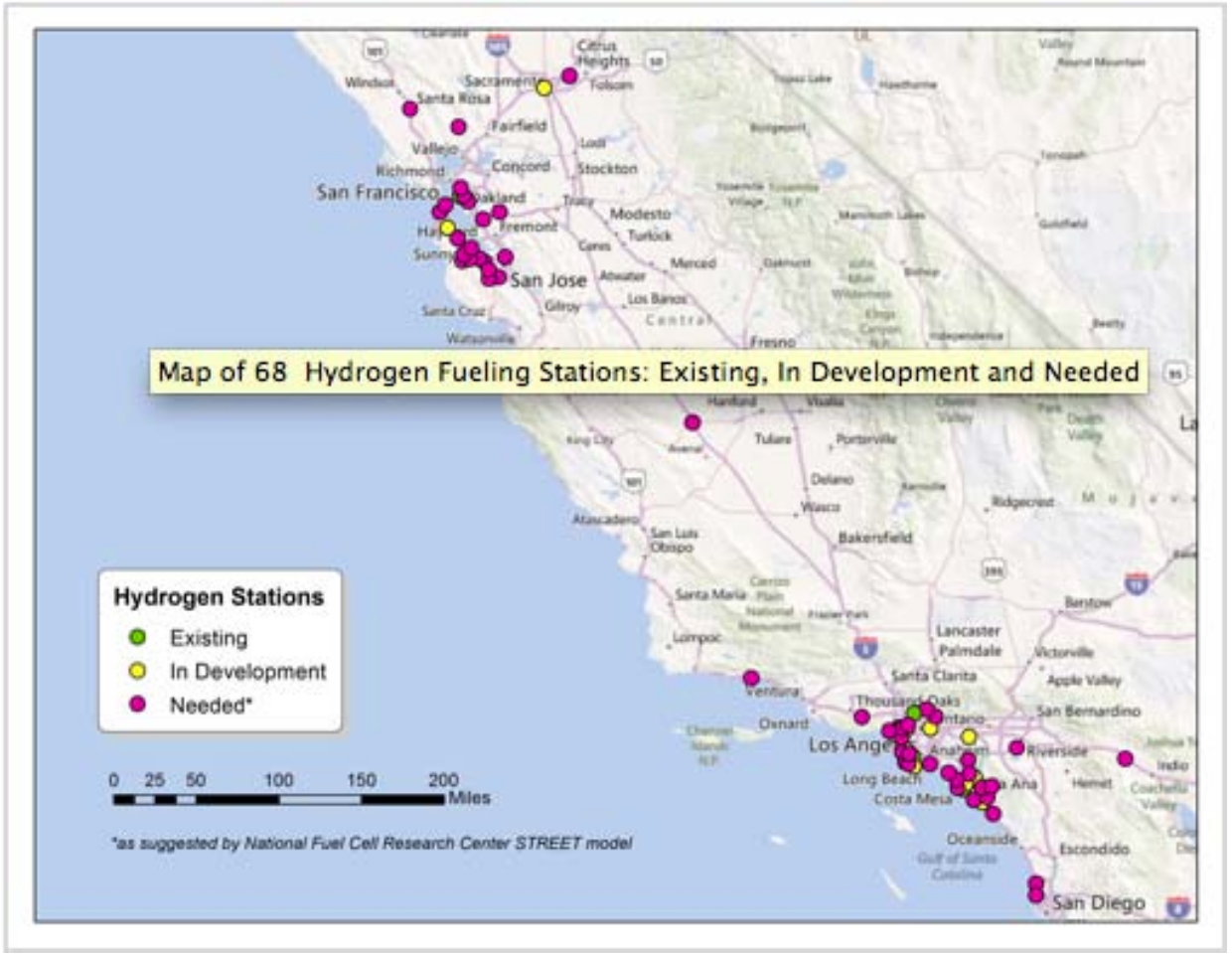


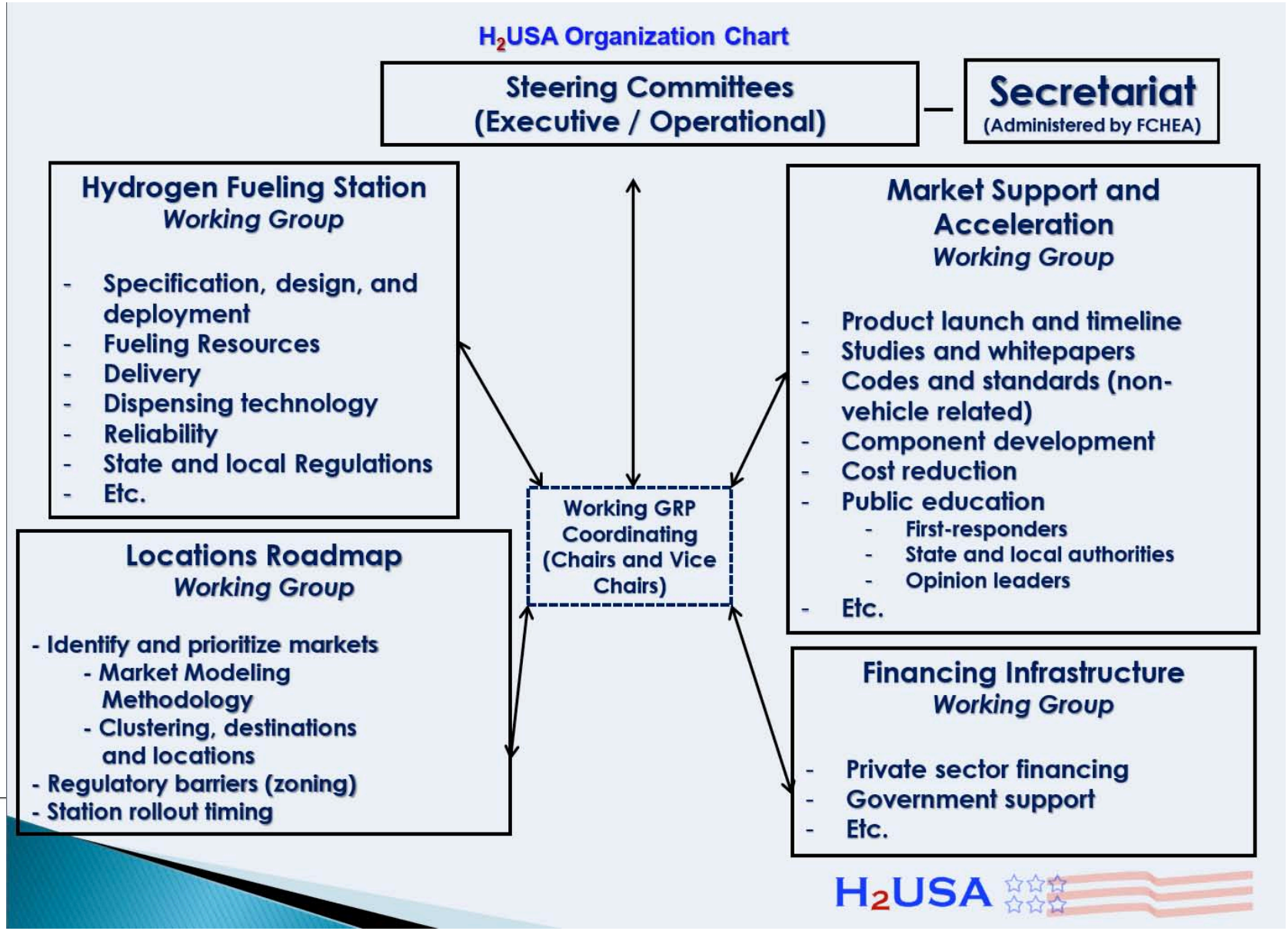
Figure 5. Levelized cost of hydrogen delivery and refueling stations ($/kg) for two cities San Jose and Cincinnati, for market fractions of 16% and 100% . The delivered cost of hydrogen is shown for onsite SMR stations producing 500 and 1800 kg/day. The components of the cost are shown, and the fraction due to storage is indicated at the top of each bar.

Source: Ogden and Yang, 2008

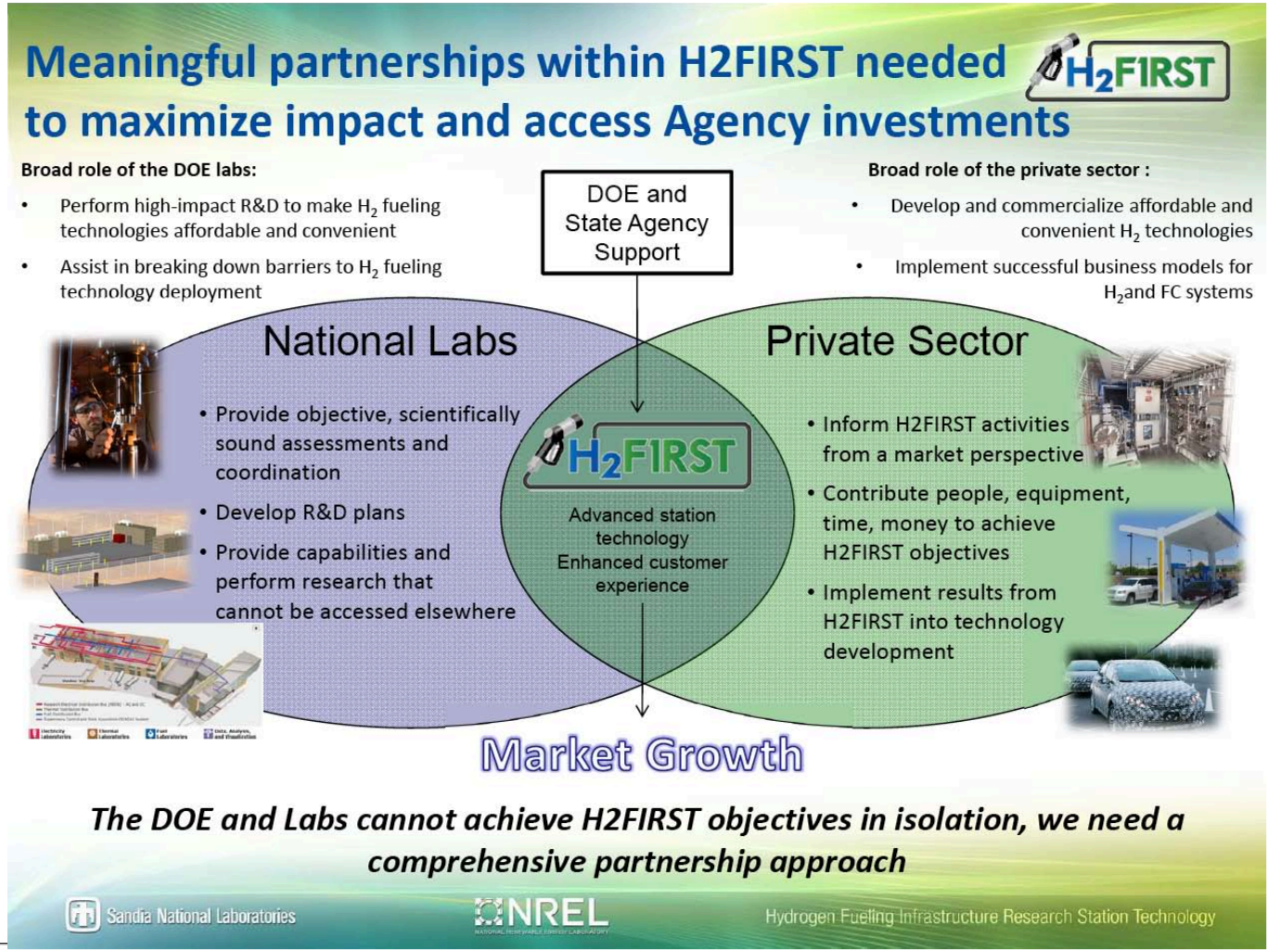
California Hydrogen Station Plan



U.S. National H2 Infrastructure Efforts: "H2USA"



U.S. National H2 Infrastructure Efforts: "H2FIRST"



International H2 Infrastructure Efforts

Germany Agrees Action Plan For Hydrogen Refuelling Network

01 OCT 2013

The six partners in the H2 Mobility initiative – Air Liquide, Daimler, Linde, OMV, Shell and Total – have set up upon a specific action plan for the construction of a nationwide hydrogen refuelling network for fuel cell powered electric vehicles. By the year 2023 the current network of 15 hydrogen refuelling stations (HRS) in Germany shall be expanded to about 400, with an initial intention to install 100 HRS over the next 4 years, establishing a demand for fuel cell electric vehicles. An agreement in principle has been signed by representatives of all the partners involved.

Japan & Germany Revving Up for More Hydrogen Fueling Stations

Posted on January 15th, 2013 by Hydro Kevin

Japan and Germany are both once again putting the pedal to the metal in regard to building more hydrogen fueling stations by 2015. This is the rollout date agree to by all of the major automakers for their commercial hydrogen fuel cell cars.

According to Fuel Cell Today (courtesy Nikkei), "The Nikkei reports that JX Nippon Oil & Energy Corp. plans to open 40 hydrogen refuelling stations by 2015, when automakers will launch commercial fuel cell electric vehicles (FCEV). In January 2011, thirteen automakers and energy companies signed up to a target of 100 hydrogen refuelling stations in Japan by 2015.

Hydrogen in Finland ≤ 2020 2/2

Domestic pioneers invest now

Proposal COM(2013)18
→ EU Direktive 4/2014

By 2020 hydrogen stations:
1/300 km + 1/250 000

Commission proposal 01/2013

Parliament draft 07/2013

Parliament desicion 04/2014

Tekes 12

TSRC FCV Research

- 2006-07: Daimler F-Cell “longitudinal” (multi-month) study
- 2007: F-Cell “drive clinics” at RFS (Richmond) and at CAFCP (~200 participants)
- 2008-2010: Sequential HEV/PHEV/FCV study under AB1811 (replicated in N./S. Cal)
- 2010-present: FCHV-adv study (8-9 vehicles)
- 2011-present: Operation of 700-bar station
- 2008-present: Ongoing H2 infrastructure studies

FCV Drive Clinic in 2007

2012-13 FCHV-adv Study

- Each participant completes 2 online surveys:
  - Initial – completed before driving the FCHV-adv and receiving driver training
  - Final – completed at the end of the four-week driving period
- Initial survey collects data about driver:
  - vehicle ownership and preferences, driving habits, exposure to alternative-fueled vehicles, attitudes toward environmental subjects, and demographics.
- Final survey collects data about driver:
  - FCHV-adv driving habits, fueling experience, safety perceptions, use of HOV stickers, etc.

UCB FCHV-Adv Program Stats

- ~80,000 miles driven from 2/1/13 to 3/31/14 on 8 project vehicles
- Goal is 120,000+ miles by end of 2014
- Seeing about 53-60 miles per kg (in a Highlander “medium SUV” weighing 1,880 kg), depending on driving patterns and habits
- Perfect safety record thus far…knock on wood

Preliminary Station and Vehicle Performance Data

- Full fills (4-5 kg) take from approx. 12 min. to ~20 min. with pre-cooling
  - Higher ambient temperatures increase fueling times
  - Sequential fills increase fueling times
- "Estimated Ranges" and actual ranges on vehicles fluctuated
  - 260 miles/full-tank to 340 miles/full tank
  - Variations due to individual driver style are evident
  - Vehicle to vehicle variations have also been observed to some extent

Hydrogen Fuel Dispensed - RFS

- Individual fill data are logged and stored
  - From 6/9/2012 – Present
  - Provides complete fill profile information
- Over 300 successful fills
- Over 1,000 kg of fuel dispensed across all vehicles
- H2 Dispensed:
  - Avg. of 3.39 kg / fill
  - Max fill = 5.3 kg

"Lessons Learned" Paper

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 38 (2013) 15868–15877

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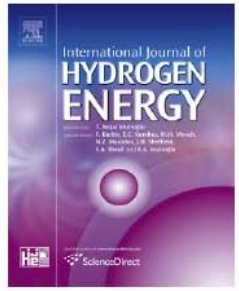

Lessons learned from the installation and operation of Northern California's first 70-MPa hydrogen fueling station

*Timothy Lipman**, *Maggie Witt*, *Matthew Elke*

University of California – Berkeley, Transportation Sustainability Research Center, 2150 Allston Way, Suite 280, Berkeley, CA 94704, USA

Hydrogen Metrology Testing

2013-14 FCHV-adv Study

- Each participant completes 2 online surveys:
  - Initial – completed before driving the FCHV-adv and receiving driver training
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- Initial survey collects data about driver:
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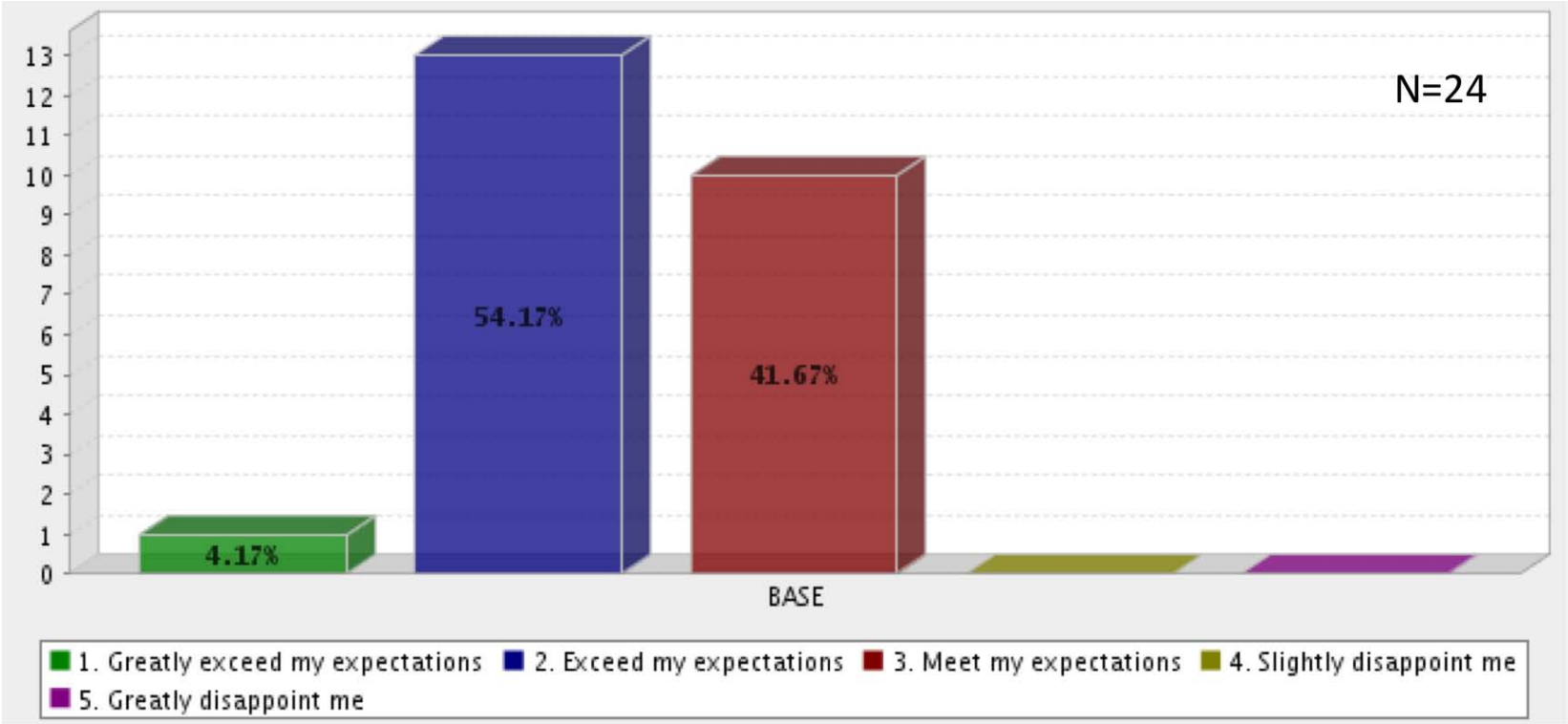
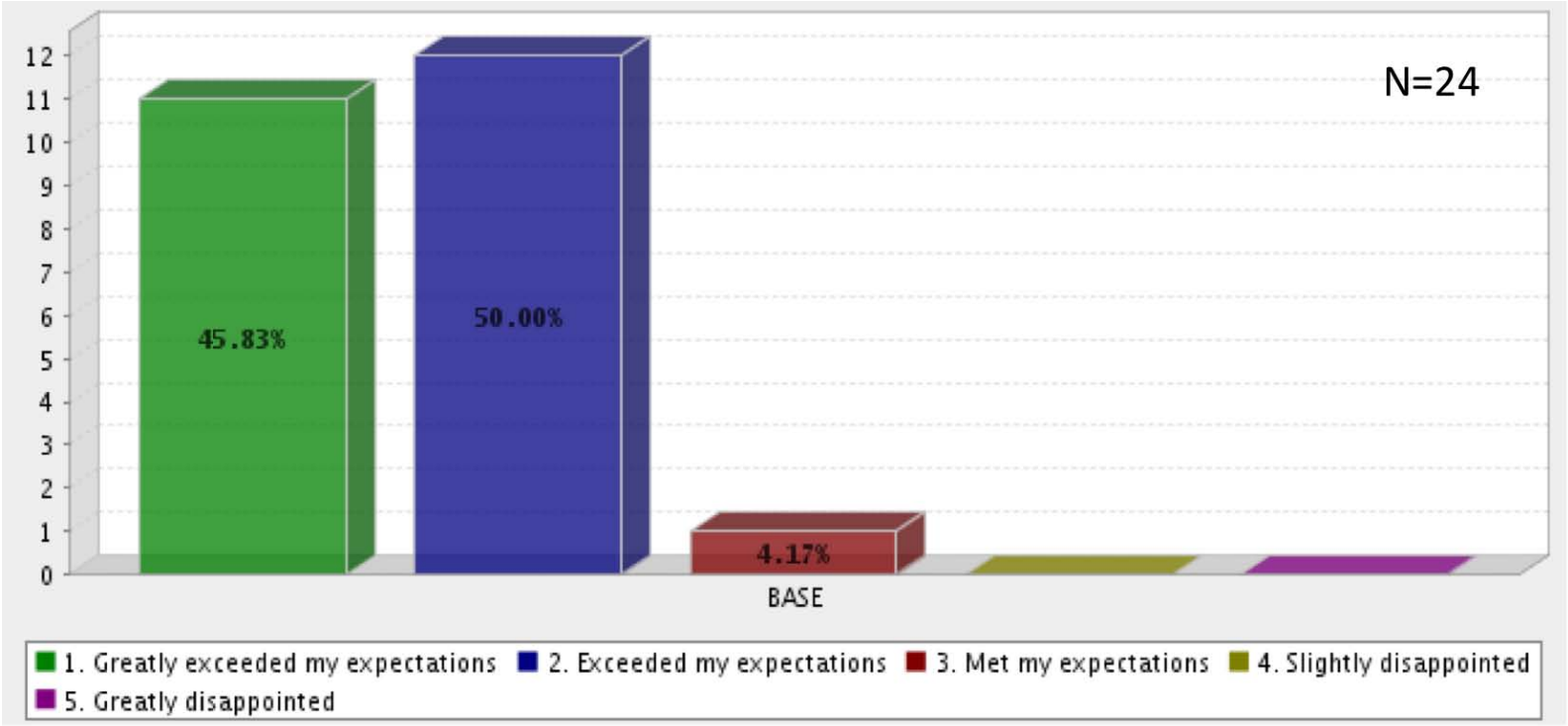
- Final survey collects data about driver:
  - FCHV-adv driving habits, fueling experience, safety perceptions, use of HOV stickers, etc.

Overall Impression of FCHV-adv: Initial



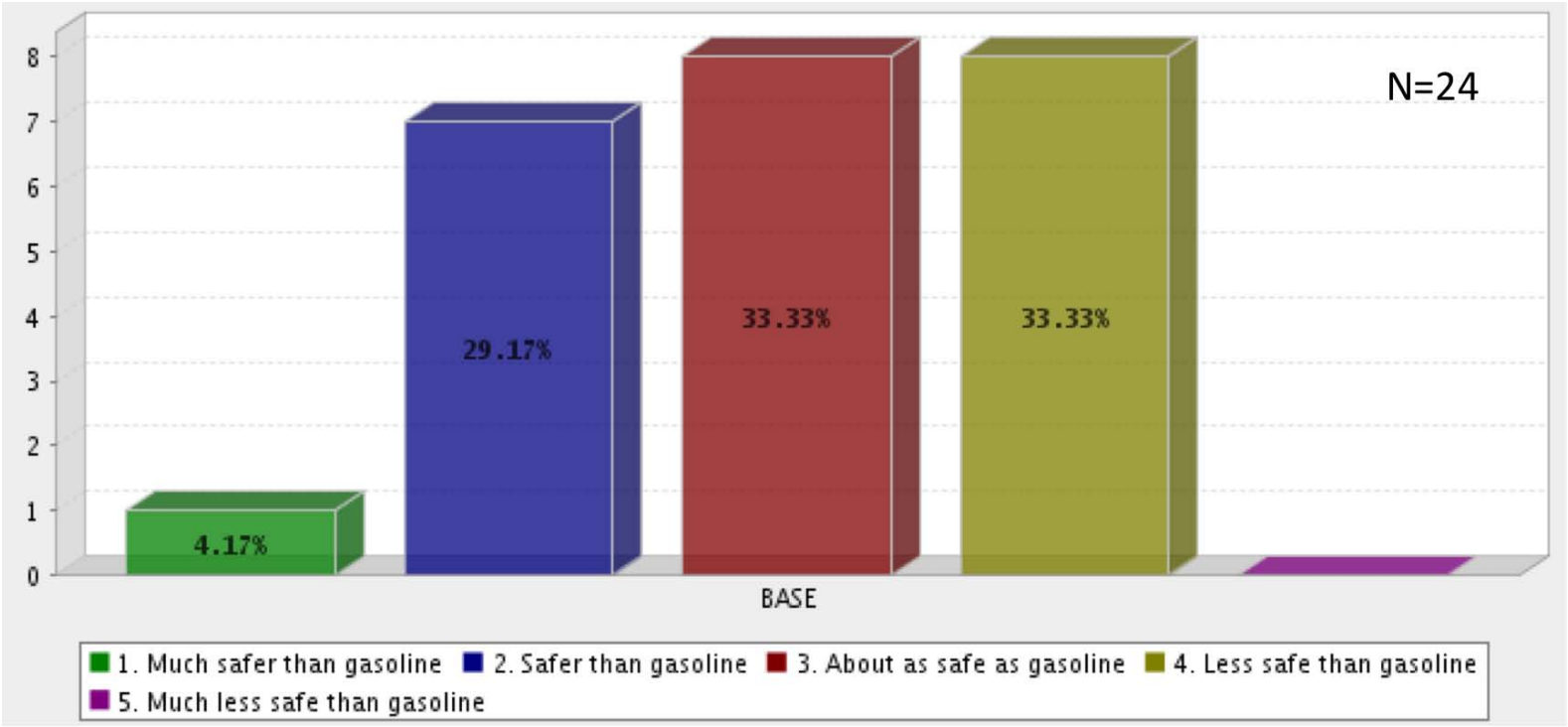
Before you drive the FCHV for the next month, how do you expect it to meet your expectations relative to other vehicles you have driven in terms of its overall performance? (Please select one response.)

Overall Impression of FCHV-adv: Final



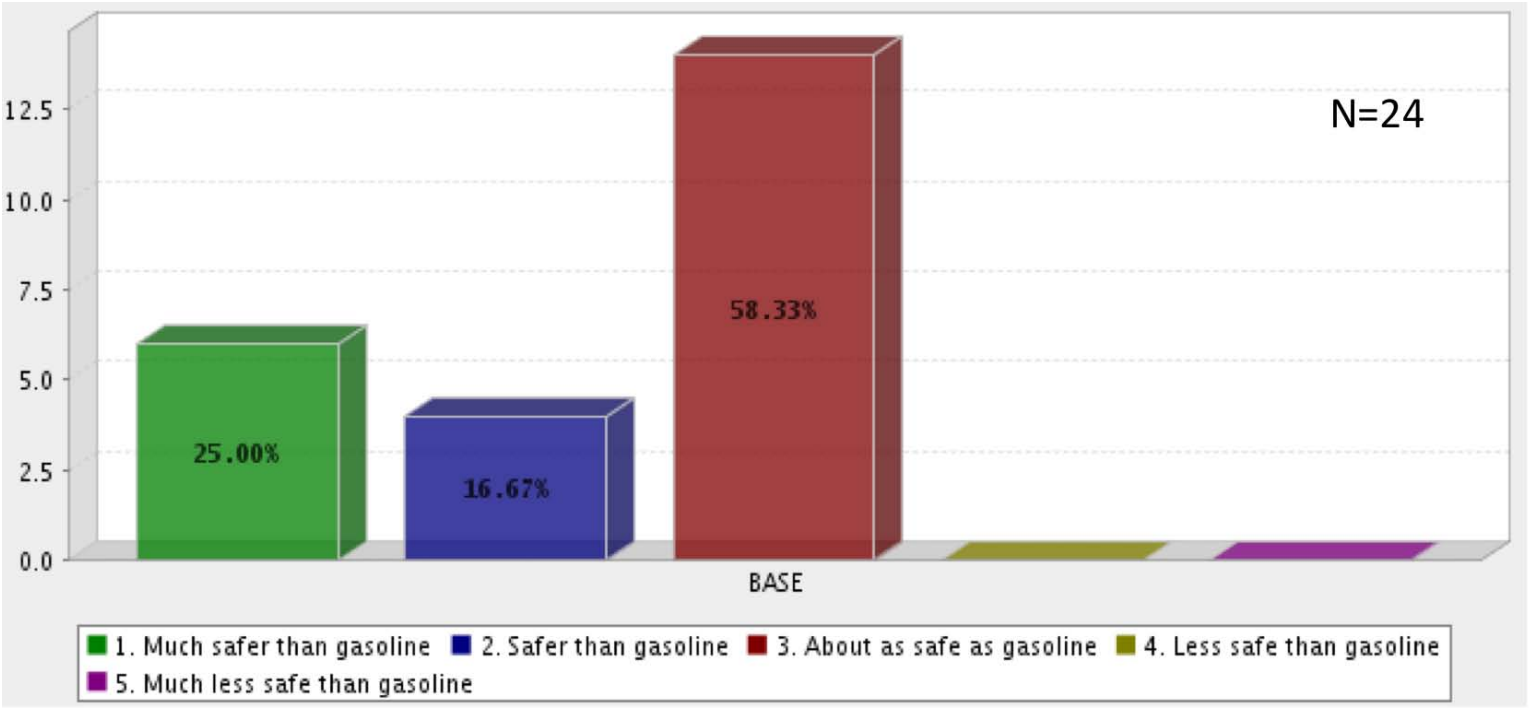
Overall, how has the FCHV met your expectations? (Please select one response.)

Perceived H_2 Fueling Safety: Initial



Before you fuel up the FCHV, what are your perceptions of hydrogen fueling safety? (Please select one response.)

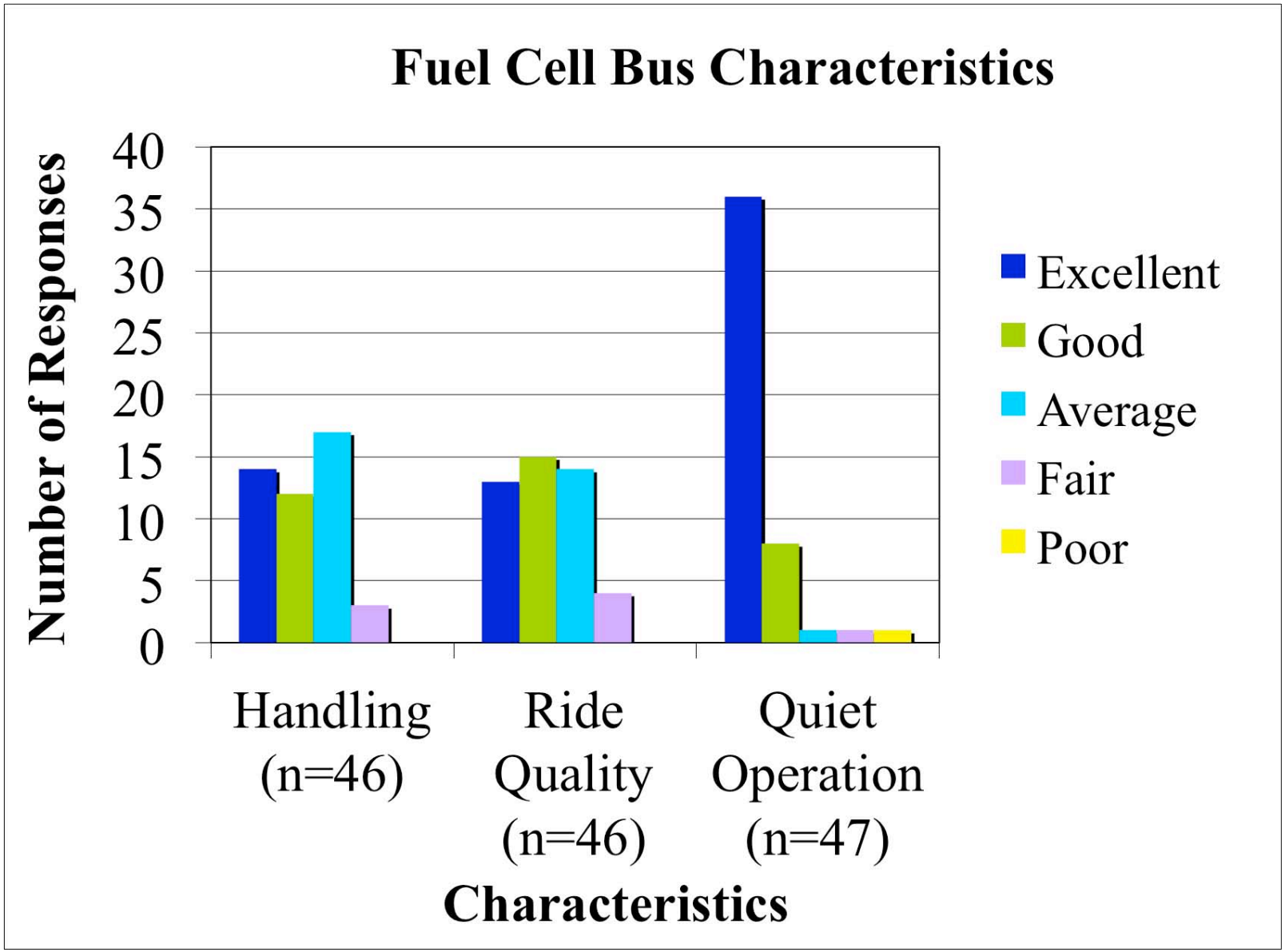
Perceived H_2 Fueling Safety: Final

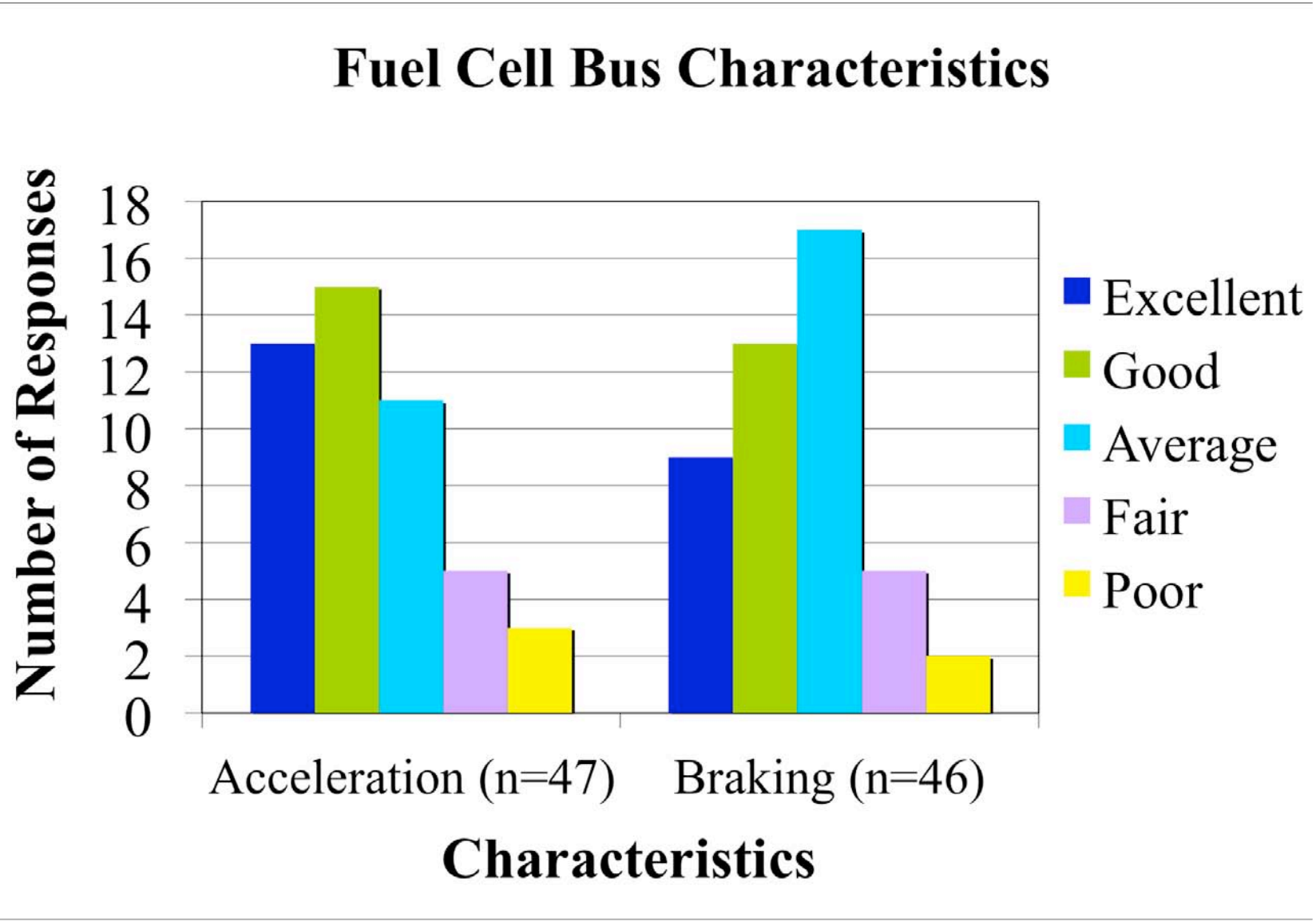


Based on your experience with hydrogen refueling, what are your perceptions of hydrogen fueling safety? (Please select one response.)

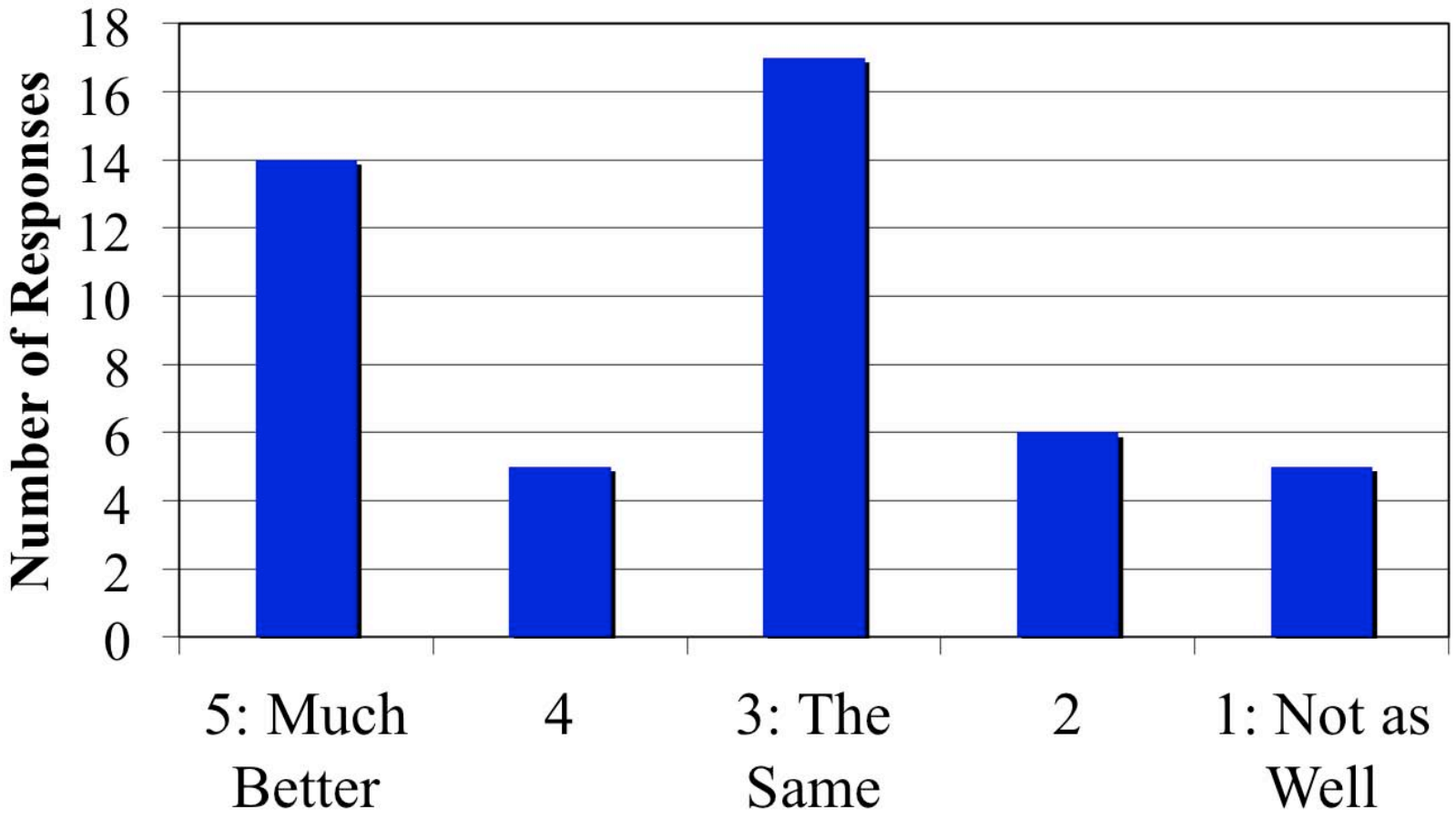
FCV Bus Driver Study

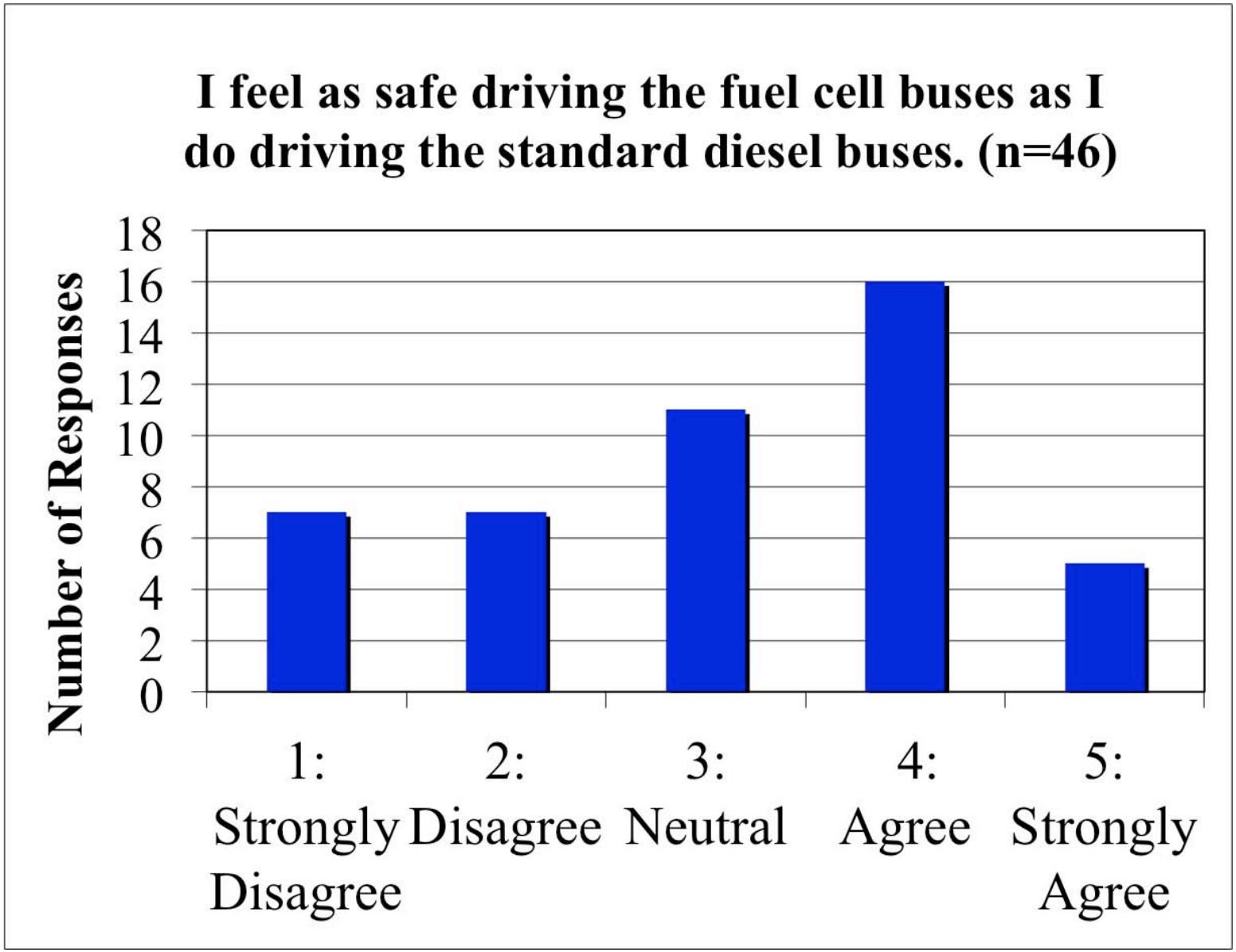
- Survey conducted of AC Transit and Golden Gate Transit fuel cell bus drivers during Summer 2013
- Approximately 140 surveys issued and 47 returned (total "n"=47) for 33% response rate
- 3-page written survey with last page for "open ended" responses
- No incentive except drivers paid 15 minutes of overtime for completing survey
- Questions asked about bus performance, perceived safety, and demographics / attitudes


Fuel Cell Bus Characteristics
Number of Responses
40
35
30
25
20
15
10
5
0
Handling (n=46)
Ride Quality (n=46)
Quiet Operation (n=47)
Characteristics
Excellent
Good
Average
Fair
Poor


Fuel Cell Bus Characteristics
Number of Responses
18
16
14
12
10
8
6
4
2
0
Excellent
Good
Average
Fair
Poor
Acceleration (n=47)
Braking (n=46)
Characteristics

Overall, how do you like the new fuel cell bus compared to other buses you have driven? (n=47)




I feel as safe driving the fuel cell buses as I do driving the standard diesel buses. (n=46)
Number of Responses
18
16
14
12
10
8
6
4
2
0
1: Strongly Disagree
2: Disagree
3: Neutral
4: Agree
5: Strongly Agree

Refueling Station of the Future?

Source: Wired Magazine, 2008

Thanks! Questions?

tsrc.berkeley.edu