Medium- and Heavy-Duty Fuel Cell Electric Vehicles

Technology Assessment

September 2, 2014
Sacramento, California

California Environmental Protection Agency
Air Resources Board

Outline

- Background
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Fuel Cell Electric Vehicle (FCEV) Applications
- Hydrogen On-Board Storage
- Fuel Cell Electric Vehicle Demonstrations
- Hydrogen Fueling Station Design
- Conclusions and Next Steps

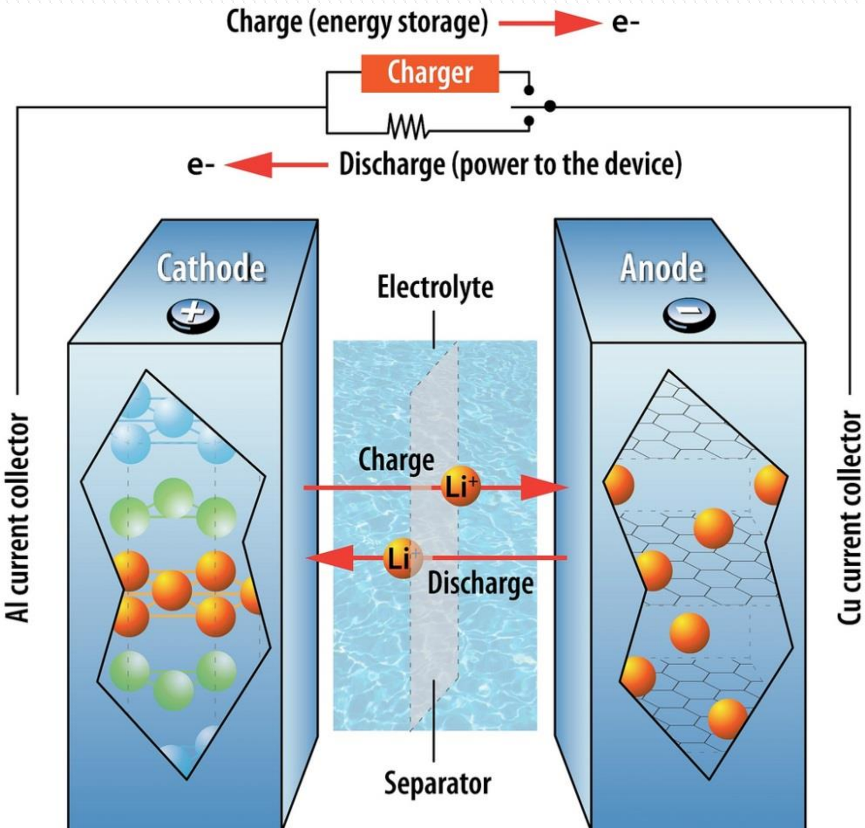
Background

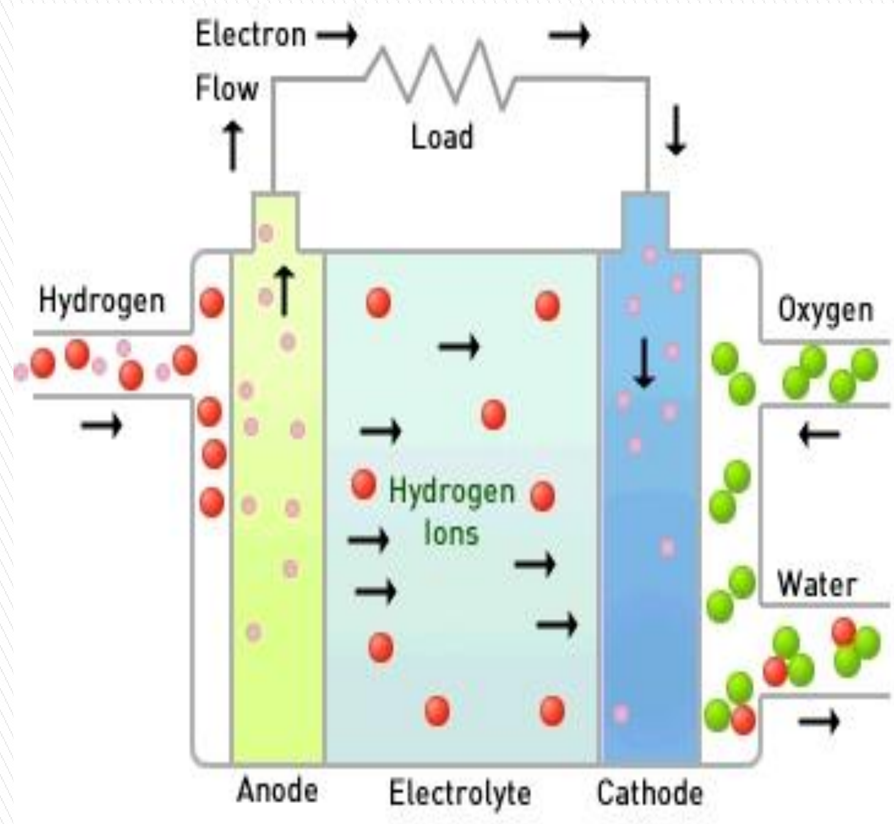
- Fuel Cell History and Technology

Fuel Cells in Transportation

- Fuel cell material handling and backup power have reached commercial volumes
- Fuel cell passenger vehicle early commercialization beginning 2014/2015
- Small scale pilots in transit buses
- Fuel cells are being demonstrated in other modes of transport, including:
  - Trucks
  - Ocean going vessels
  - Aviation auxiliary power units
  - Locomotives

Batteries Compared to Fuel Cells





Battery

Fuel Cell

FCEV Benefits

- Zero tailpipe greenhouse gas and criteria pollutant emissions
- Quiet operation
- Quick and smooth acceleration
- High fuel efficiency
- Range and performance comparable to conventional vehicles
- Refueling time similar to conventional liquid fueling

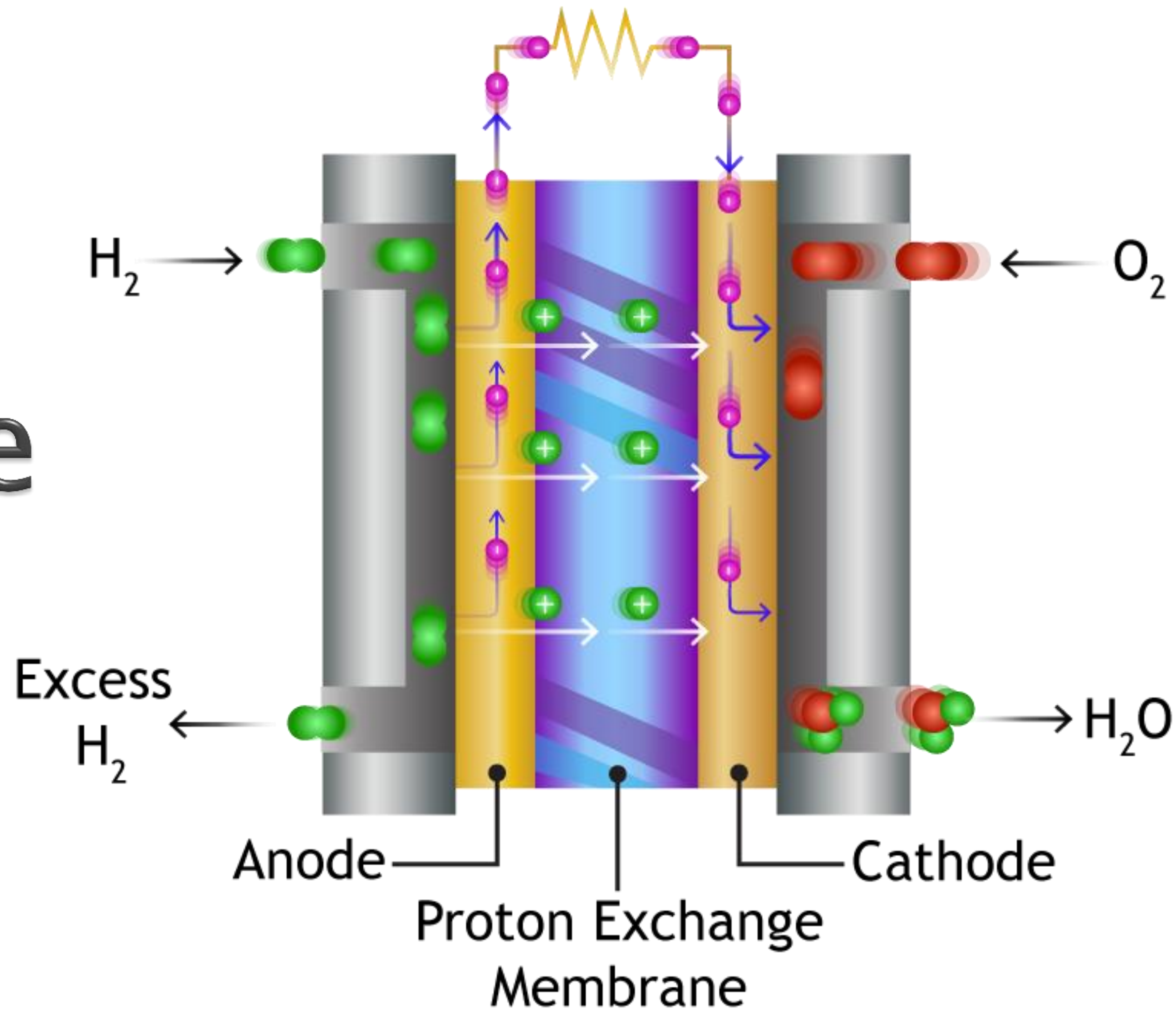
Fuel Cells in Transport

- PEMFC most compatible fuel cell for motive application because:
  - Thermally compatible (low operating temperature)
  - Highest power density of all fuel cell types
  - Best start-stop and dynamic load following characteristics
  - 2-3X more efficient than conventional combustion technologies
- Focus on single electrochemistry for fuel cells in transport has allowed for substantial technological advancements

Proton Exchange Membrane Fuel Cell Technology

- Characteristics and Technology Status

Proton Exchange Membrane Fuel Cell (PEMFC)



PEMFC Characteristics

- **Electrolyte:** Perfluorinated sulfonic acid polymer
- **Anode & cathode materials:** Carbon paper or cloth
- **Anode & cathode catalyst:** Platinum Group Metals (PGM) and PGM-alloy
- **Operating temperature:** 80–100 °C
- **Efficiency:** 48–59 %

Urban Transit Bus Targets

	Current Status	Target
Stack Durability	17,500 hours[1]	25,000 hours[2]
System Power	200–550 W/kg	650 W/kg[3]
Power Density	200–300 W/ℓ	650 W/ℓ[3]
Volume	Equivalent to diesel[4]	Equivalent to diesel

1. AC Transit fuel cell electric bus operational hours
2. DOE Target for Transit Buses
3. DOE 2017 Target for 80 kW fuel cell system
4. (2013) Zero emission trucks: An overview of state-of-the-art technologies and their potential" E. den Boer, S. Aarnink, F. Kleiner, J. Pagenkopf, Delft, CE Delft, July 2013.

- ARB/EPA diesel engine durability standard
  - Heavy heavy-duty engine: 435,000 miles
  - Medium heavy-duty engine: 185,000 miles

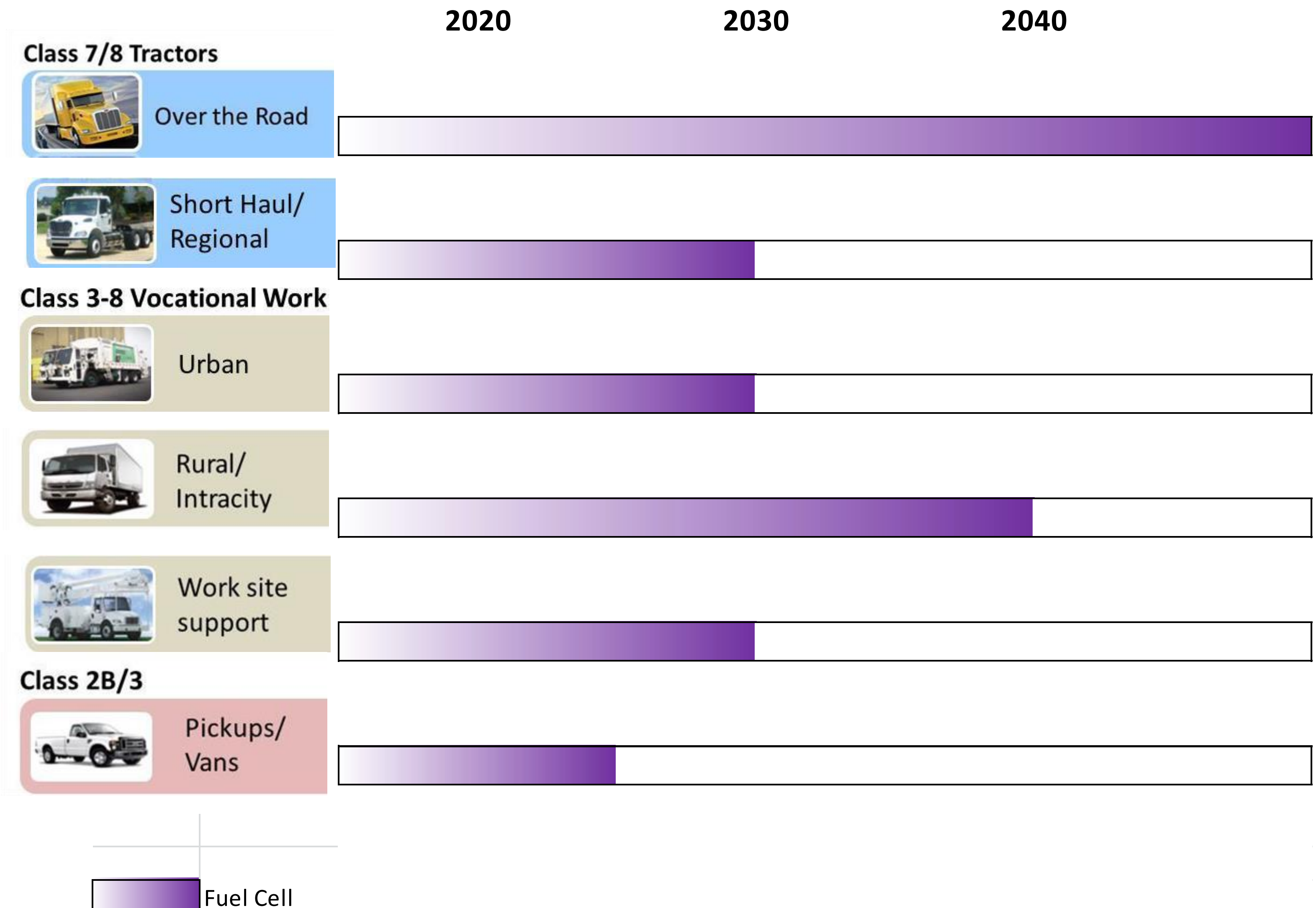
PEMFC Manufacturers

- Ballard
- Hydrogenics
- Nuvera
- PlugPower
- PowerDisc
- US Fuel Cells

Fuel Cell Electric Vehicle Applications

- Trucks and Buses

Advanced Tech MD/HD Applications Potential Pilot Deployments



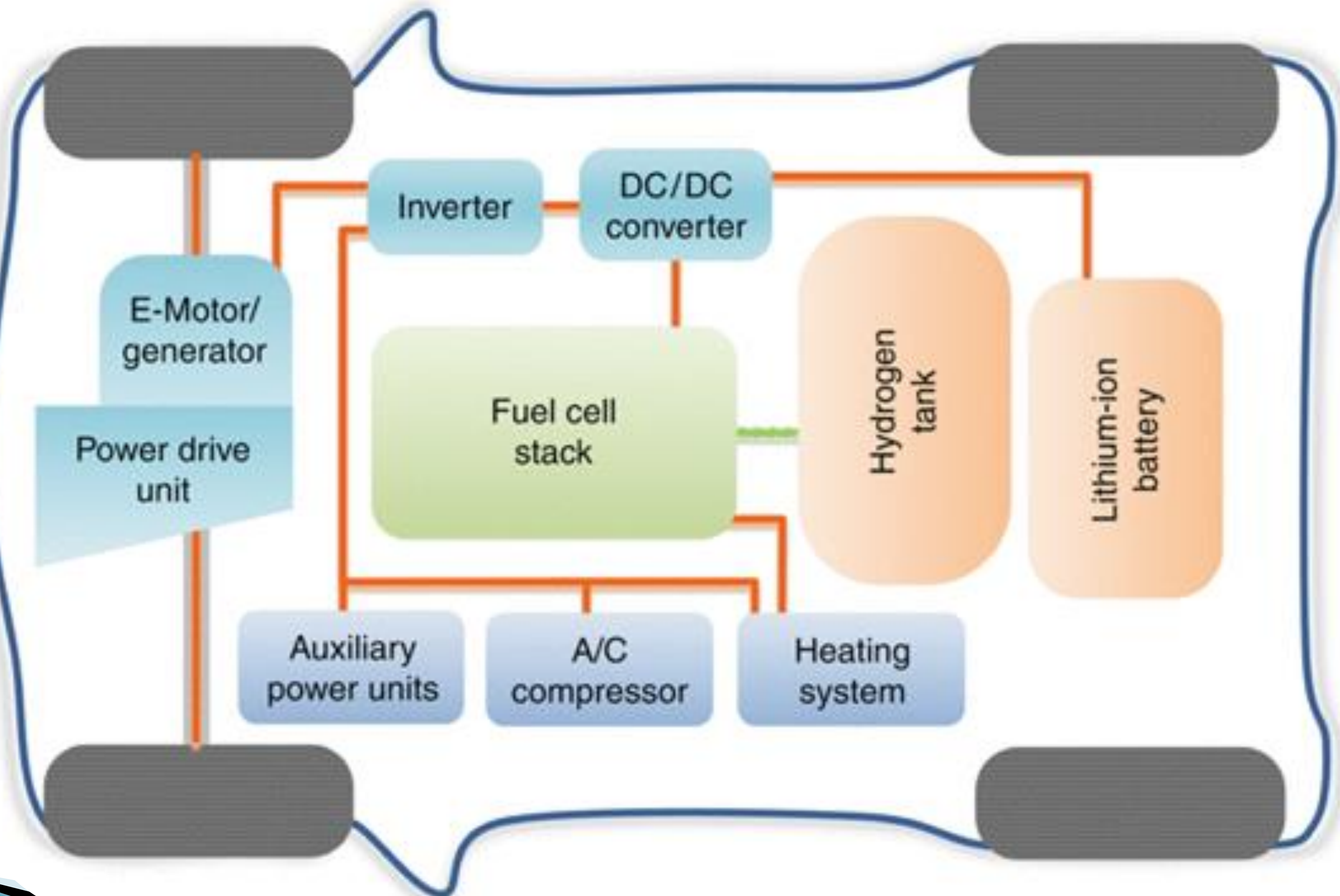
Currently Demonstrated MD/HD Fuel Cell Powered Vehicles

- Early Pilot
  - Transit buses
- Demonstrations
  - Port and drayage
  - Parcel and urban delivery
  - Utility
  - Refuse

Fuel Cell System Configurations

- Prime Power
  - Fuel cell acts as prime mover with smaller energy storage system for regenerative energy capture and launch assist
- Range Extension
  - Smaller fuel cell provides additional power to a energy storage system, such as a battery, to extend the range of the vehicle
- Auxiliary Power Unit (APU)
  - Fuel cell supports auxiliary vehicle loads

Basic Drivetrain



On-Board Hydrogen Storage

- Current and Future Status, Safety

Current On-Board Physical Hydrogen Storage Tanks

- High-pressure compressed gas cylinders
  - Type IV hydrogen canister
  - Materials: composite such as carbon fiber with a polymer liner
  - Pressure: 350–700 bar
  - Temperature: −40 °C to ambient
- Cryogenic liquid tank
  - Materials: composite with perlite-packed vacuum or laminated multilayer vacuum insulation
  - Pressure: 6–350 bar
  - Temperature: −253 °C and below

Future On-Board Hydrogen Storage Tanks

- Improved efficiency of conventional physical storage (compressed gas and liquid)
  - Reduce cost, weight, volume

- Materials-based storage:
  - Reversible metal hydrides
  - Hydrogen sorbents
  - Regenerable chemical hydrogen

On-Board Hydrogen Storage Safety

- Tanks undergo rigorous testing to validate safety under severe or unusual conditions to meet Federal Motor Vehicle Safety Standards

- Tanks are designed to withstand twice the maximum pressure to avoid rupture

- Sensors are located on the vehicle in the unlikely event of a hydrogen leak

Fuel Cell Electric Vehicle Pilots/Demonstrations

- Buses and Trucks

Fuel Cell Electric Bus Pilots and Demonstrations

- Over 320 fuel cell electric buses (FCEB) deployed worldwide since 1991

Active U.S. FCEB Demonstrations

Bus Operator	Location	Total Buses
ZEBA	San Francisco Bay Area, CA	12
SunLine Transit	Thousand Palms, CA	4
Capital Metro/University of Texas	Austin, TX	1
University of Delaware	Newark, DE	2
Greater New Haven Transit District	New Haven, CT	1
CTTRANSIT, Nutmeg	Hartford, CT	1
	Total	**22**

U.S. FCEB Configurations

Bus Manufacturer	Fuel Cell System	Hybrid System	Prime Power	Number Deployed
Van Hool	US FuelCell (UTC Power)	Siemens ELFA integrated by Van Hool	Fuel Cell	16
ElDorado	Ballard	BAE Systems	Fuel Cell	7
ElDorado	Ballard	BAE Systems	Battery	1
New Flyer	Ballard	Siemens ELFA integrated by Blueways	Fuel Cell	1
Proterra	Hydrogenics or Ballard	Proterra	Battery	3
DesignLine	Ballard	DesignLine	Battery	1
Ebus	Ballard	Ebus	Battery	2
EVAmerica	Ballard	EVAmerica	Battery	1

Buy America Compliant FCEBs

- Proterra
  - Hydrogenics Fuel Cell
- American Fuel Cell Bus
  - El Dorado OEM
  - Ballard Fuel Cell
  - BAE integrator
- New Flyer
  - Ballard
- Bus repowers
  - Ballard
  - Hydrogenics
  - US Hybrid

AC Transit FCEB Performance

Criteria	2011	2012	2013	2013-Diesel
Availability	63 %	56 %	82 %	76 % – 84 %
Maintenance Cost	$ 1.51 / mi	$ 1.31 / mi	$ 0.67/mi	$ 0.21 – 1.03 / mi
Fuel Cost	$ 1.49 / mi	$ 1.40 / mi	$ 1.41 / mi	$ 0.75 – 0.79 / mi
Operational Costs	$ 3.01 / mi	$ 2.71 / mi	$ 2.08 / mi	$ .97 – 1.82 / mi

- Bus prices have declined by 70%
- Maintenance costs decreased by 50%
- Operational costs decreased by 30%

FCEB Accomplishments

- Fuel cell electric bus development over the 10+ years have provided:
  - Technological advancements
  - Cost reductions
  - Lessons learned
  - Codes and standards development
  - Data validating strong performance
  - Legislative and regulatory support

Technology Transfer

- Fuel cell electric bus development and deployment serves as a foundation for other MD/HD applications
  - Hydrogen fueling protocols for stations fueling more than 10 kg
  - Growing supply chain
  - Greater insight into platform configurations
  - Standardization of MD/HD fuel cell size
  - Safety standards

Class 3-8 FCEVs

Transit Buses

Drayage Trucks

Shuttle Buses

Delivery Vans

Class 3-6 FCEVs

- US Hybrid H2Cargo Fuel Cell Plug-in Step Van
- FEDEX Express Fuel Cell Range Extender Delivery Truck
- UPS Fuel Cell Range Extender Walk-In Delivery Van
- US Hybrid H2Ride Fuel Cell Plug-In Shuttle Bus
- US Hybrid Fuel Cell Plug-In Hybrid Electric Re-Fueler (R12)

Class 7-8 FCEVs

- US Hybrid Fuel Cell Plug-In Hybrid Electric C-17 Tow Tractor
- US Hybrid Fuel Cell Plug-In Hybrid Refuse Truck
- Vision Industries Tyrano Fuel Cell Plug-In Hybrid Electric Drayage Truck
- Vision Industries Zero-TT Fuel Cell Plug-In Hybrid Electric Terminal Tractor
- Vision Industries Fuel Cell Plug-In Hybrid Electric Refuse Truck

Transferability between Light-Duty and Medium/Heavy-Duty

- Commercial launch of LD FCEVs 2014/2015
- Across all vehicle classes, same fuel cell technology utilized: PEMFC
  - Advancements in PEM for LD application benefits MD/HD market directly
- Other major components are not immediately transferable and may require different codes and standards
  - Fuel cell rated power varies on application
  - Hydrogen storage tanks in LD are not easily transferred to MD/HD FCEVs

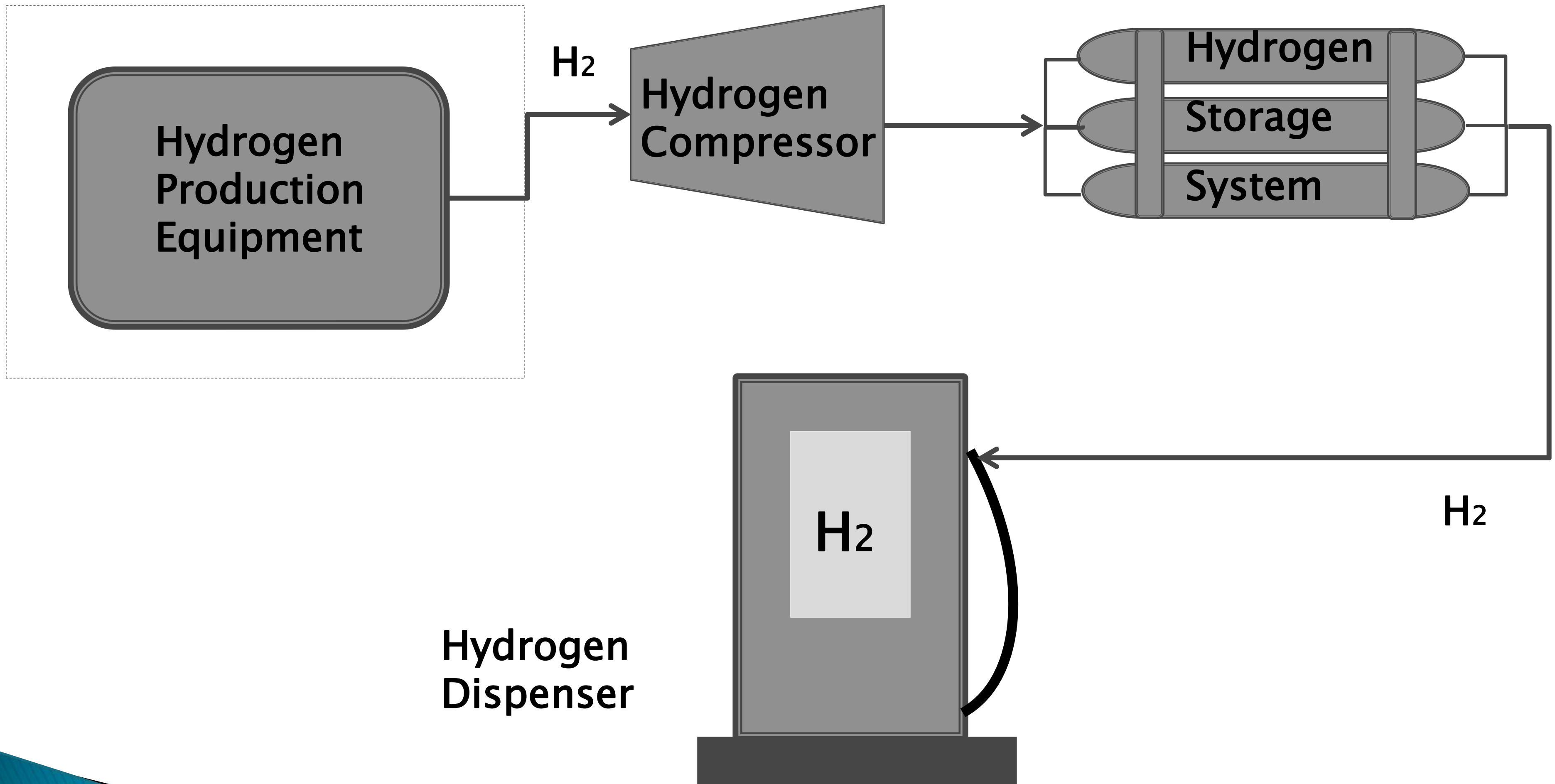
Hydrogen Production and Fueling

- Production, Compression, Storage, Dispensing

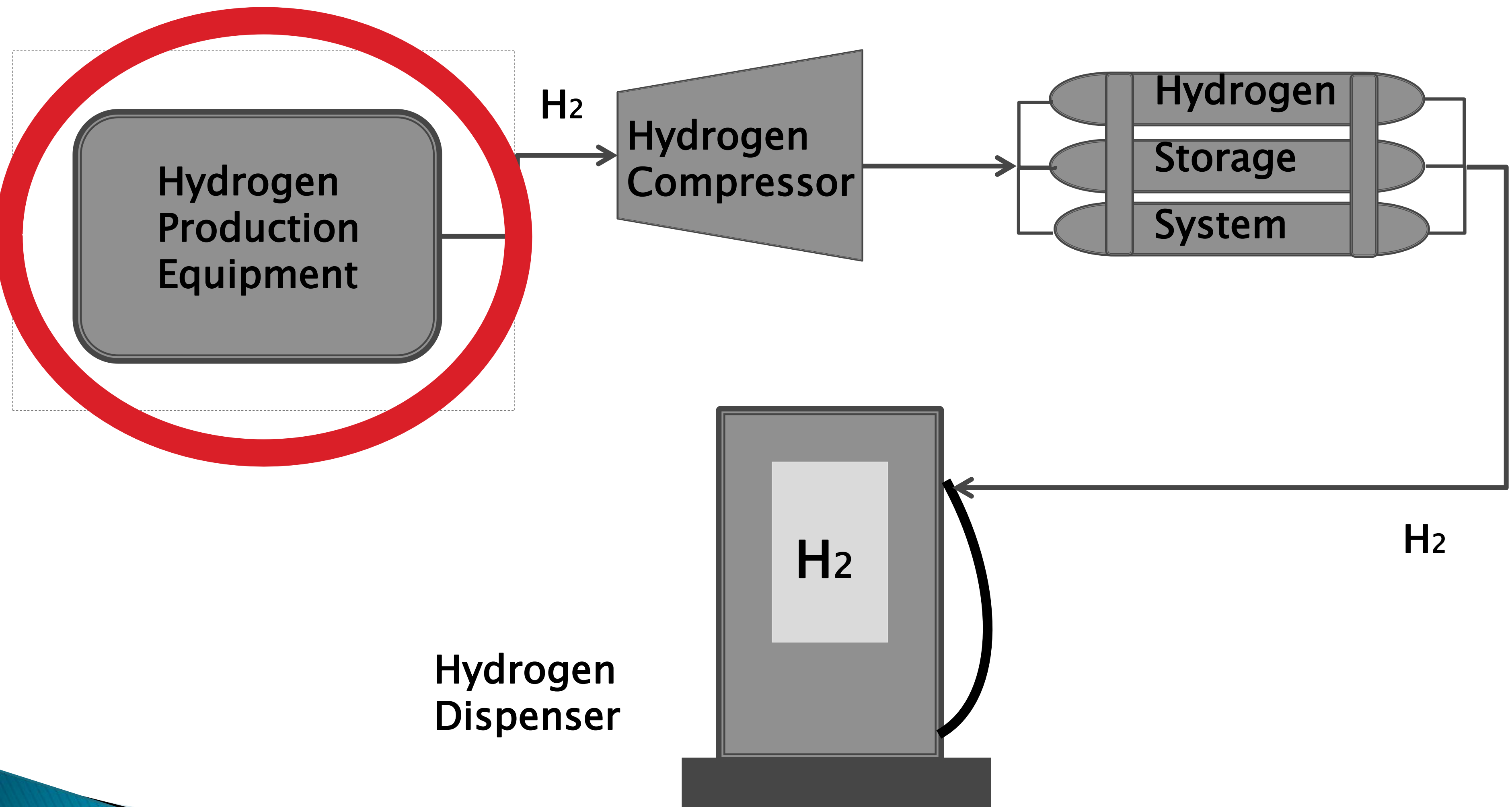
Hydrogen Production

- U.S. produces 9M tonnes of H_2 gas
  - 95% produced via steam-methane reformation (SMR) at central plants derived from fossil fuels
- CA Senate Bill 1505
  - Requirement for 33% renewable hydrogen at state funded stations
  - When 3,500 metric tons dispensed, all stations must meet requirement
- Renewable hydrogen can be generated from biofuels or electricity

Hydrogen Station Schematic



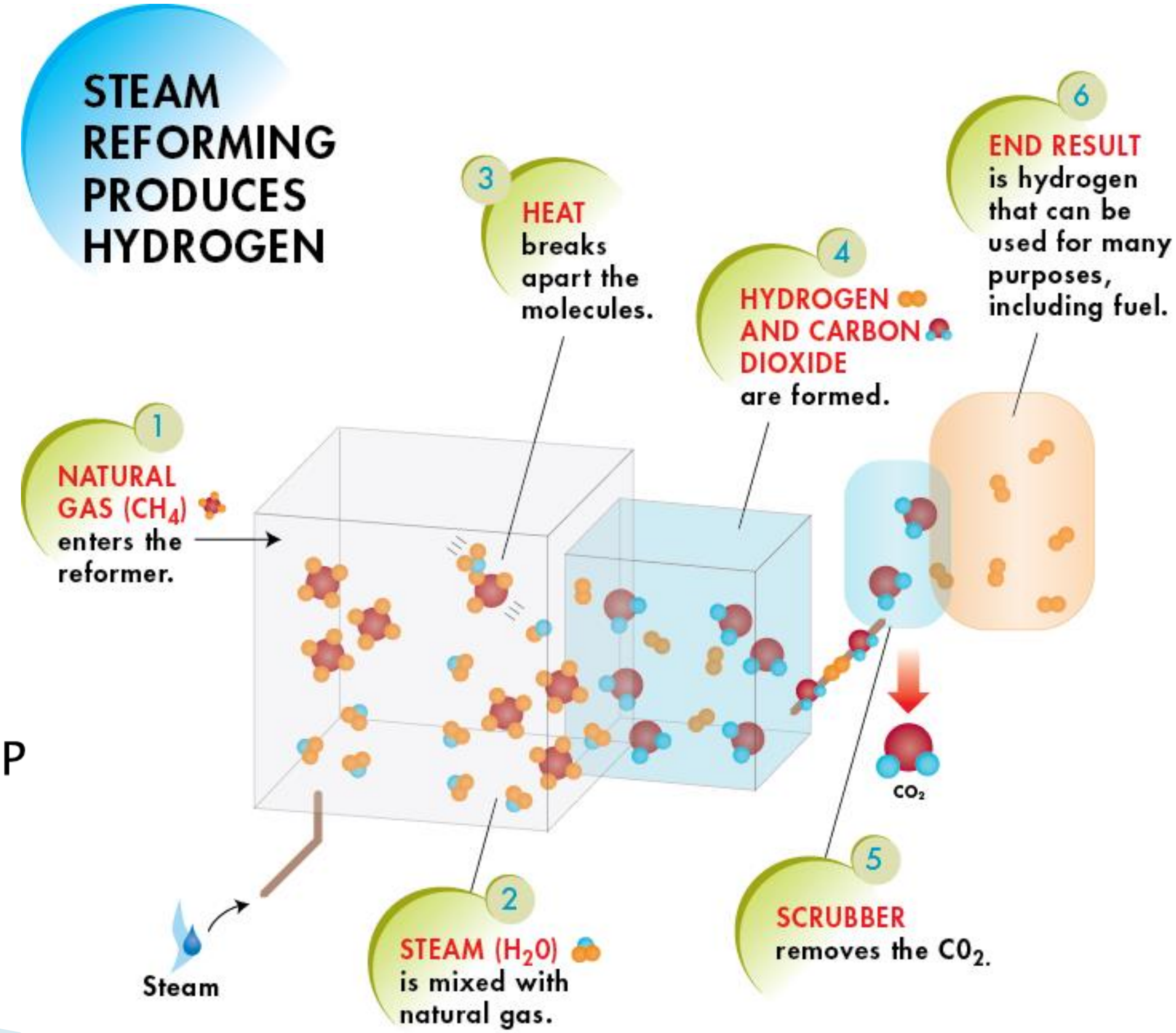
Hydrogen Station Schematic



On-Site Hydrogen Production

- Hydrogen may be produced at the hydrogen station site
- Common hydrogen production methods employed at stations:
  - Steam-methane reformation (SMR)
    - Today: Natural gas feedstock
    - Future: Biomethane feedstock
  - Electrolysis
    - Today: Electricity from the grid and water
    - Future: Renewable electricity (solar/wind) and water

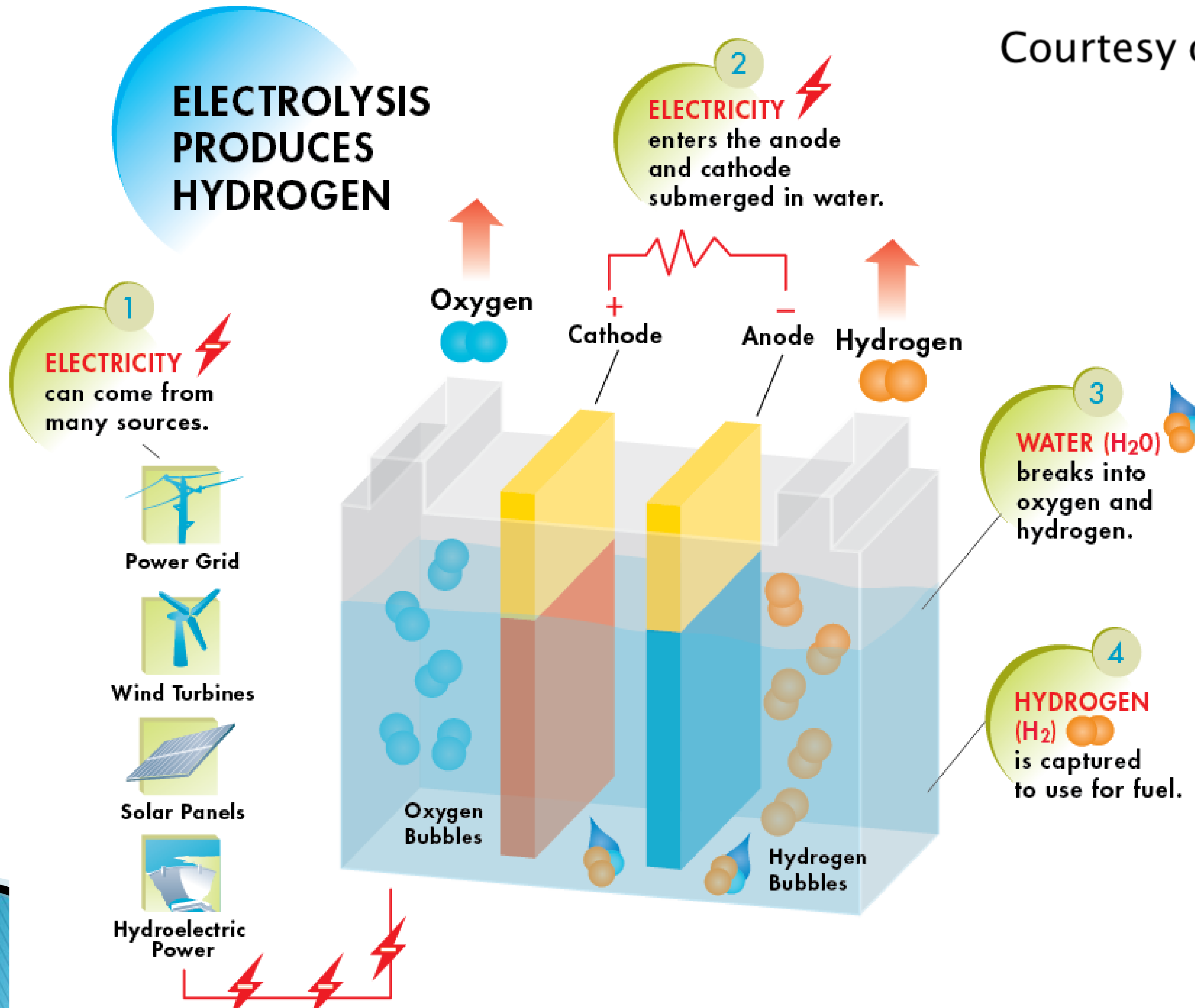
Steam-Methane Reformation



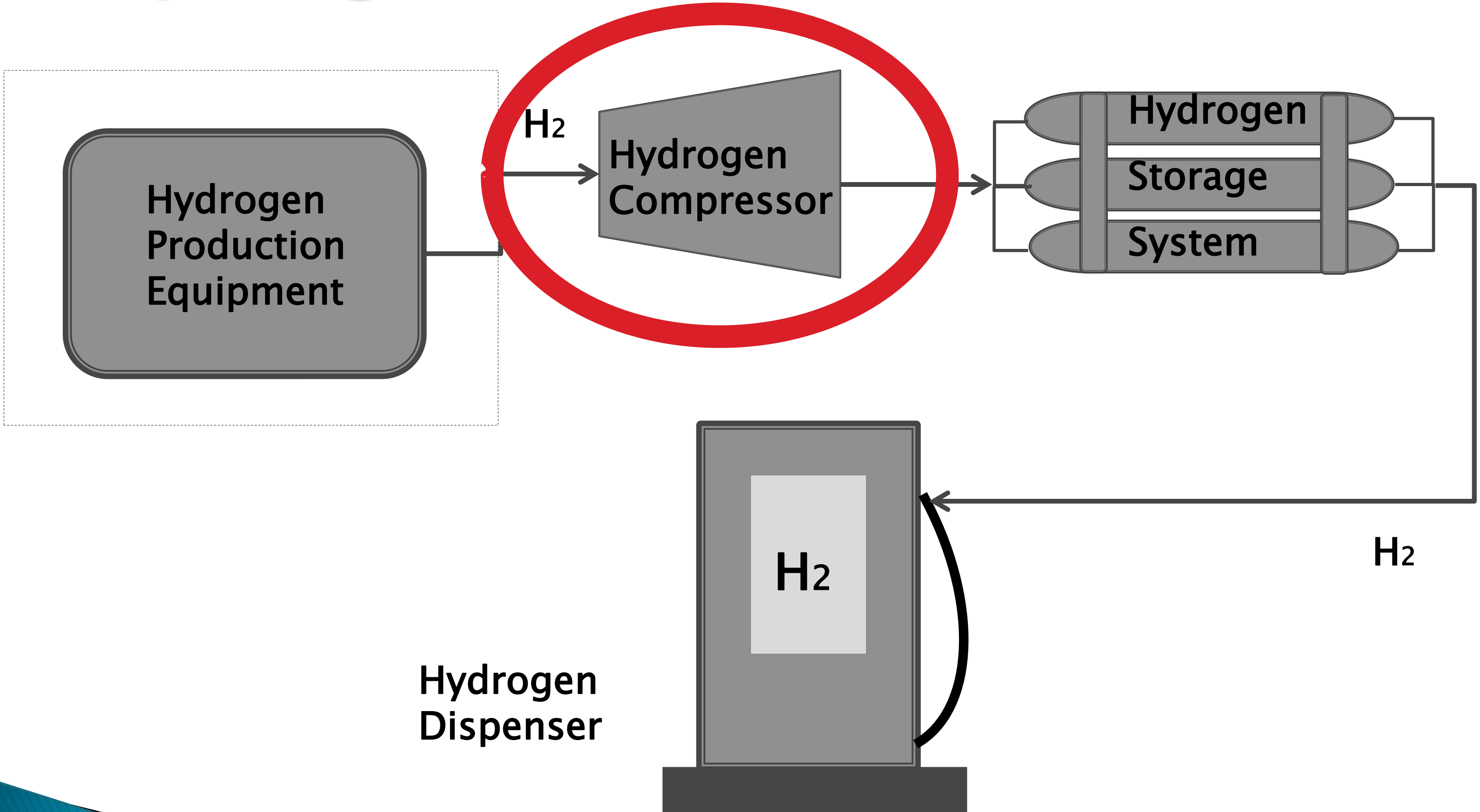
Courtesy of CaFCP

Electrolysis

Courtesy of CaFCP



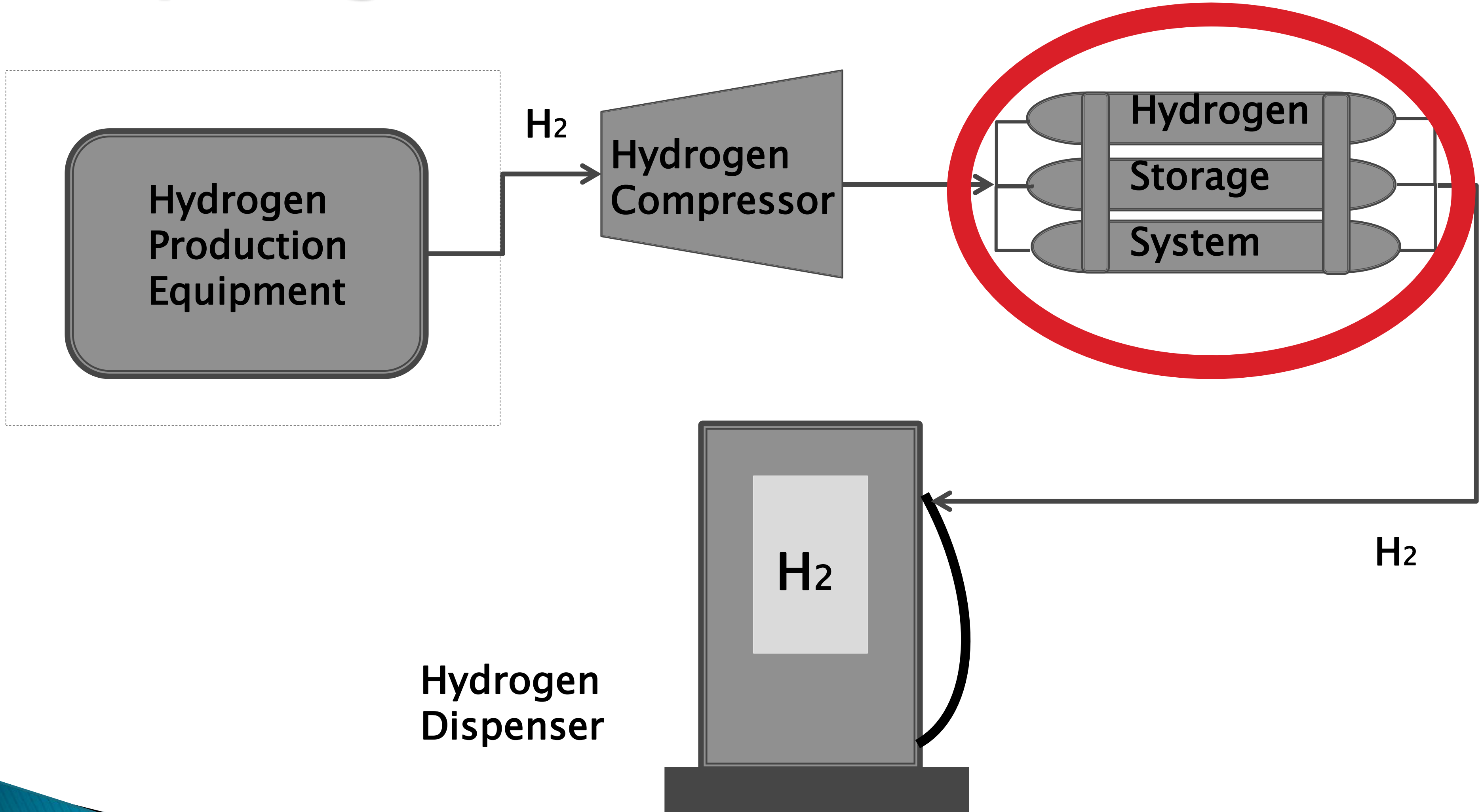
Hydrogen Station Schematic



Hydrogen Compression

- Typically compression is the largest contributor to station costs (capital, energy consumption, and operations and maintenance)
- Compression efficiency:
  - Min: 50%; Max 80%
  - 2-4 kWh/kg for 350-bar refueling
- Multiple compressors needed to reach 350 or 700 bar pressure
- Spare compressor often needed

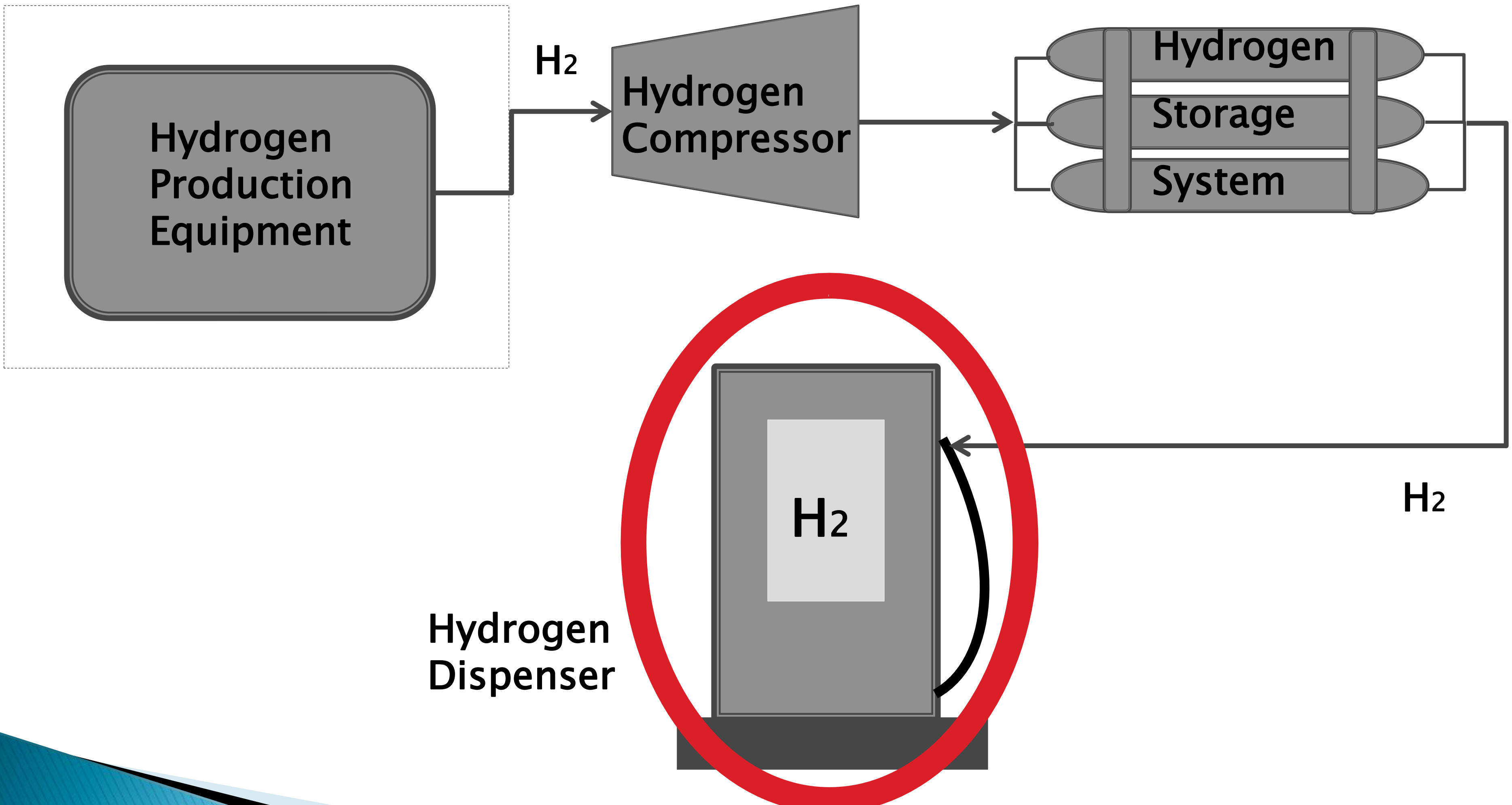
Hydrogen Station Schematic



Hydrogen Storage

- Off-board storage requirements differ from on-board storage
- Physical storage most mature technology
  - High-pressure compressed gas cylinders
  - Cryogenic liquid tanks

Hydrogen Station Schematic



Hydrogen Dispenser

- Typical MD/HD FCEV fills with hydrogen at 350 bar
- Hydrogen fuel quality for LD and HD identical—SAE J2719
- Hydrogen fueling protocol developed for MD/HD FCEV—SAE J2601-2

HD Hydrogen Fueling Protocol

- SAE J2601-2: Anticipated publication August/September 2014
- Universal fueling protocol establishes safety limits and performance requirements for heavy duty vehicle fueling
  - Storage capacity > 10 kg
  - 350 bar gaseous hydrogen
  - Reach full tank or 100% high state of charge (SOC) within a reasonable amount of time
    - Fueling rate: 1.8-7.2 kg/min depending on on-board tank configuration
  - Avoid exceeding temperature, pressure, and density limits for the storage system

Complementary Momentum: LD & HD Hydrogen Stations

- Standardization of station design for all vehicle types courtesy of LD station build-out
- Cost reductions and supply chain expansion expected as a result of LD station volumes increasing in upcoming years
- Codes and standards for LD fueling protocols paved way for HD protocols, which were established in significantly less time
- HD fueling may provide lessons learned for future expansion of LD station capacity

Conclusions and Next Steps

- Deployment Challenges, Next Steps, Conclusions, Contacts

Conclusions

- Fuel cells show potential in many applications
  - Zero tailpipe emissions with potential for deep carbon reductions
  - Quiet operation with full range and performance
- Early commercialization in cars, forklifts, stationary generators
- Early pilots in transit buses
- Demonstrations in off-road and truck applications

Team Contacts

- Fuel Cell EV Tech Assessment Team:
  - Roxana Bekemohammadi
    - Fuel Cell Electric Vehicle Team Lead
    - rbekemoh@arb.ca.gov
    - (916) 323.2803
  - Kim Heroy-Rogalski
    - Manager of Truck Technology Assessment
    - kheroyro@arb.ca.gov
    - (916) 327.2200

- Submit comments by Oct. 1 to: http://www.arb.ca.gov/msprog/tech/comments.htm