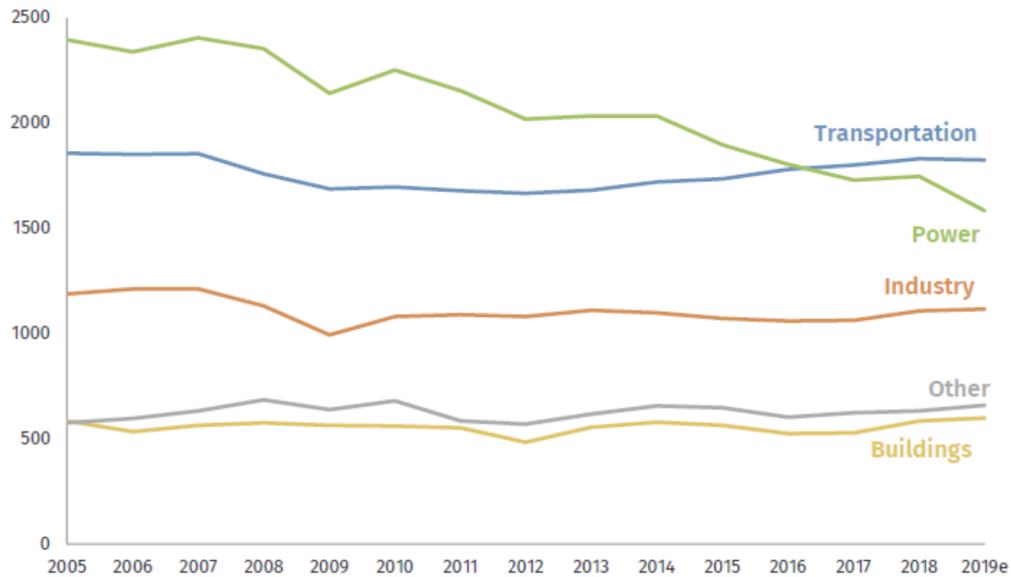


The Next Frontier of Transport Decarbonization: Transitioning Medium/Heavy Duty Sector to Zero Emission

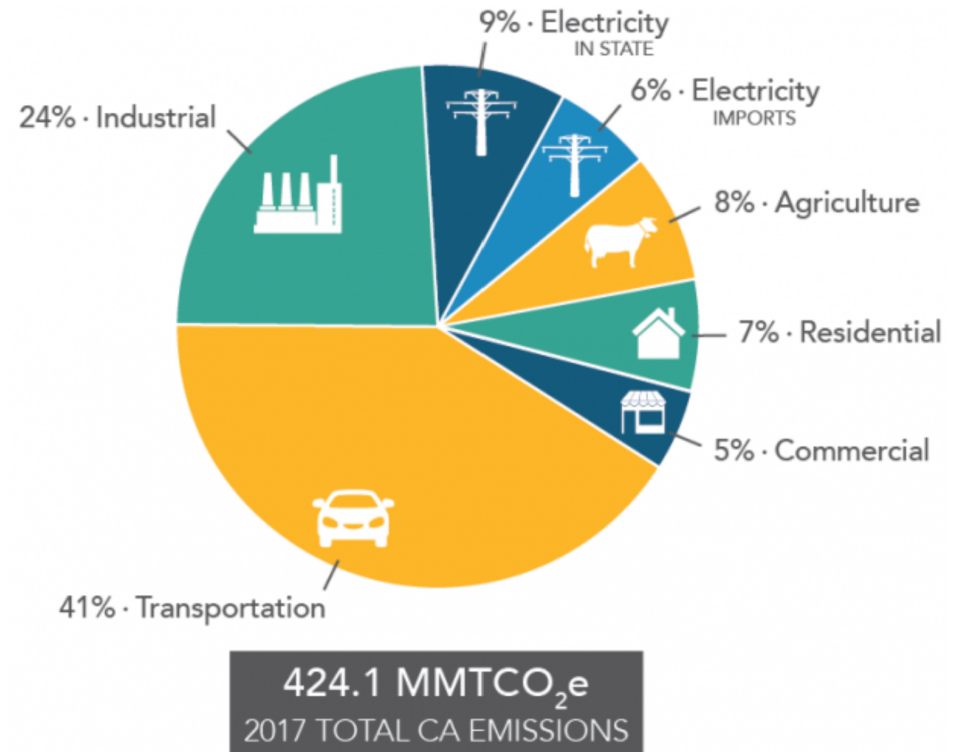
Anish Kumar Sinha

Where are we headed?

FIGURE 2
Net US GHG emissions by sector
Million metric tons CO₂e, IPCC definitions, excludes international bunkers



Source: Rhodium Climate Service



Courtesy of California Air Resources Board

Big questions

How soon can the medium/heavy duty sector start to transition towards decarbonization?

What are the challenges in this transition?

- Technological
- Economical
- Infrastructural

Which vehicles are the low hanging fruit?

Project outline

Vehicle simulations for both battery-electric and H2 fuel cell vehicles

6 different vehicle types

- City Delivery Truck
- City Transit Bus
- Intercity Bus
- Long Haul Truck
- Short Haul Truck
- HD Pickup truck

Battery capacity & weight, effects on payload capacity

Total cost of ownership (TCO)

Charging and refueling infrastructure

Carbon intensity

The problem with range

Can the range be reliable throughout:

- Reasonable road grades?
- All weather conditions?
- Over the lifetime of the vehicle?

For BEVs this means almost doubling the battery size

For FCVs, this factor is 1.6

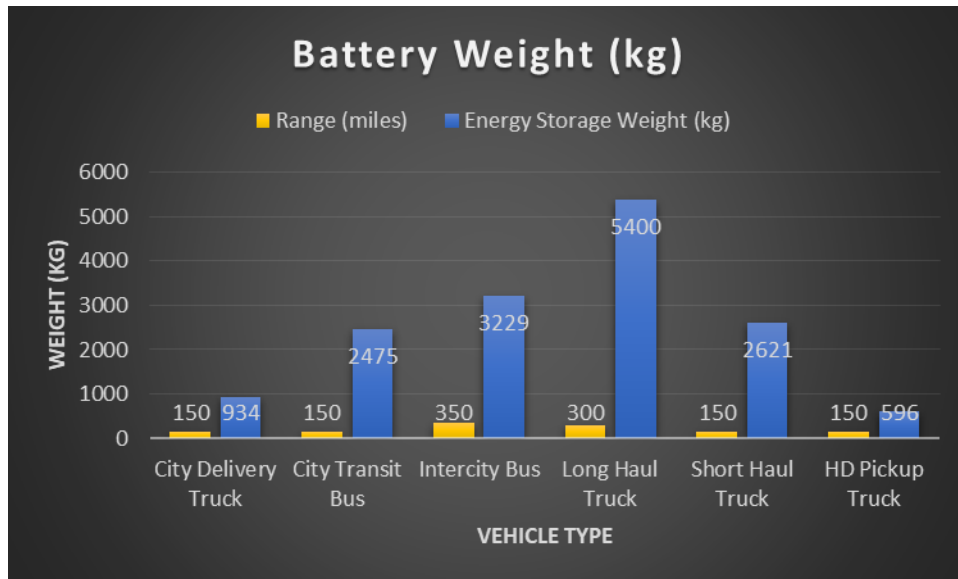
| Long Haul Electric Truck Energy Consumption (kWh/mi) | | | |
|--|-----------|-----------|----------|
| Driving cycle | 0.0 Grade | ½ % grade | 1% grade |
| WVintercity | 1.97 | 2.84 | 3.78 |
| Interstate Highway Up to 75 mph | 2.42 | 3.36 | 4.36 |
| Constant speed 65 mph | 1.78 | 2.69 | 3.89 |

| Design factor | Percentage increase of battery energy (%) |
|---|---|
| Usable battery energy | 20 |
| Battery degradation | 20 |
| Additional energy needed under adverse conditions | 30 |
| Total | 87 |

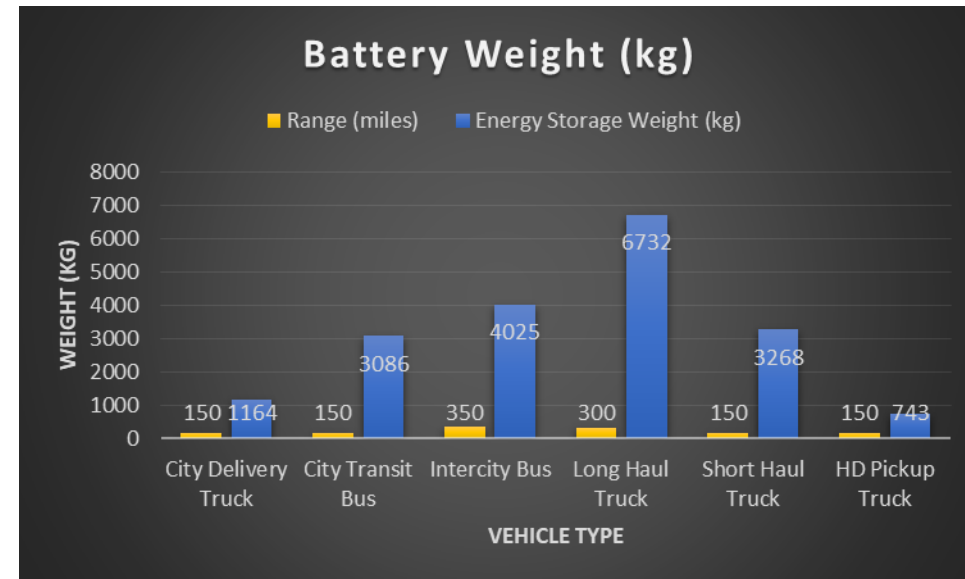
Weight problems?

Battery energy density of 200 Wh/kg

Oversize Factor = 1.5



Oversize Factor = 1.87



Effect on payload

For long haul with 300 mile range

- Payload is reduced by 10%

For short haul with 150 mile range

- Payload is increased by 5%

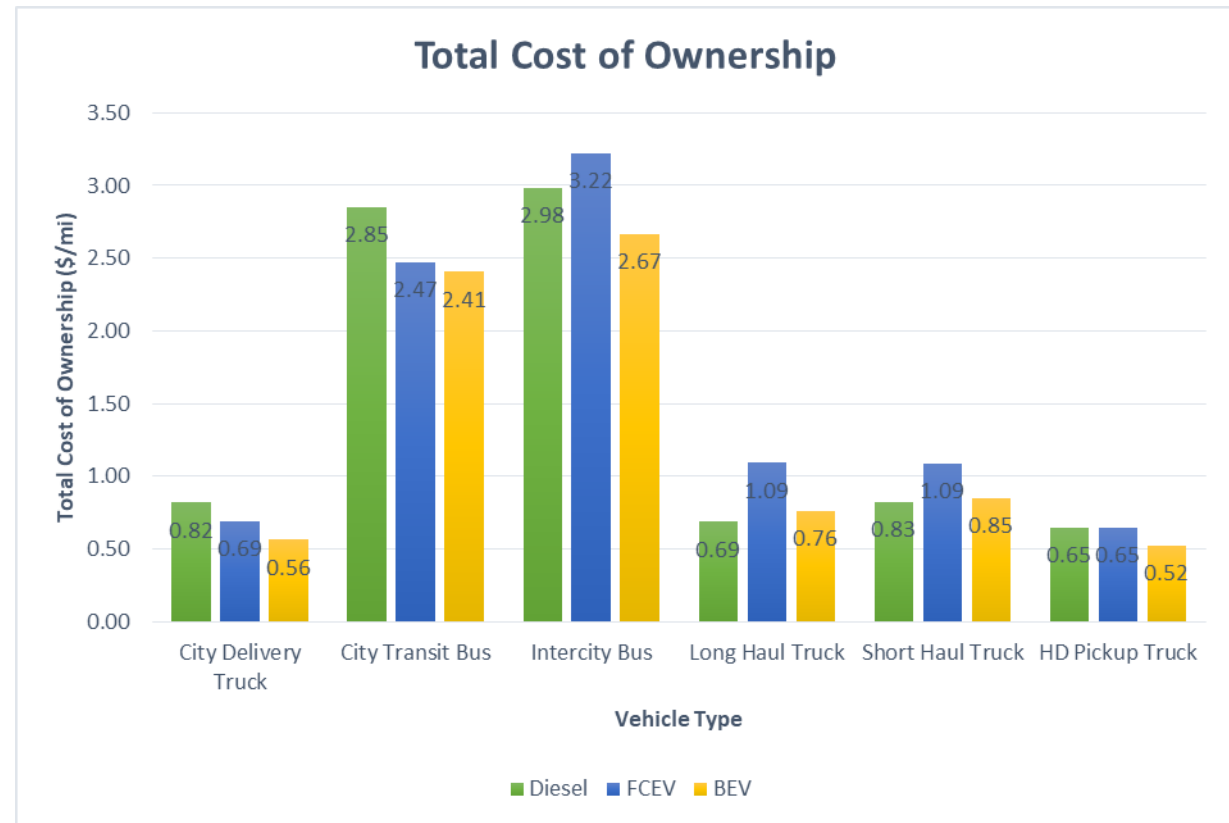
For delivery trucks with 150 mile range

- Payload is increased by 11%

Total Cost of Ownership

Low hanging fruits

- Delivery Trucks
- Buses
- Pickup Trucks



Charging infrastructure for BEVs

What are the infrastructure and operating cost for BEV chargers?

Example of short haul truck – the bigger the charger, the better

| Infrastructure Capital Expenses | | | | | | | | | | | | |
|---------------------------------|-------------------------|-----------------------------|-------------------------|--------------------------|------------------------|---|---|----------------------------|-----------------------------|---------------------------------|--------------------------|---------------------------|
| Battery Size (kWh) | Max Charging Power (kW) | No of vehicles in the fleet | Charger Power (kW) | Time to charge (hrs) | No of ports | Number of free hours to charge vehicles (hrs) | Number of vehicles that can be charged on one charger | Cost of one charger (\$) | No of chargers required | Cost of charging infrastructure | Charging Power/Day (kW) | Charging Energy/Day (kWh) |
| 524 | 250 | 50 | 50 | 2.10 | 0.20 | 10 | 1 | 40000 | 52 | 2096000 | 2620 | 26200 |
| | 250 | 50 | 100 | 2.10 | 0.40 | 10 | 2 | 50000 | 26 | 1310000 | 2620 | 26200 |
| | 250 | 50 | 150 | 2.10 | 0.60 | 10 | 3 | 65000 | 17 | 1135333 | 2620 | 26200 |
| | 250 | 50 | 250 | 2.10 | 1.00 | 10 | 5 | 80000 | 10 | 838400 | 2620 | 26200 |
| | 250 | 50 | 350 | 2.10 | 1.40 | 10 | 7 | 100000 | 7 | 748571 | 2620 | 26200 |
| | 250 | 50 | 500 | 2.10 | 2.00 | 10 | 10 | 150000 | 5 | 786000 | 2620 | 26200 |
| | 250 | 50 | 1000 | 2.10 | 4.00 | 10 | 19 | 300000 | 3 | 786000 | 2620 | 26200 |
| Operating Expenses | | | | | | | | | | | | |
| No. of days | Charging Power/day (kW) | Charging Energy/day (kWh) | Energy Charges (\$/kWh) | Fixed Charges (\$/month) | Demand Charges (\$/kW) | Monthly Energy Charges (\$) | Monthly Demand Charges (\$) | Total Monthly Charges (\$) | Energy Consumption (kWh/mi) | Range (mi) | Monthly Fleet Range (mi) | Operating Cost (\$/mi) |
| 30 | 2620 | 26200 | 0.15 | 100 | 15 | 117900 | 39300 | 157300 | 2.33 | 180 | 269871 | 0.58 |

BEV Charging

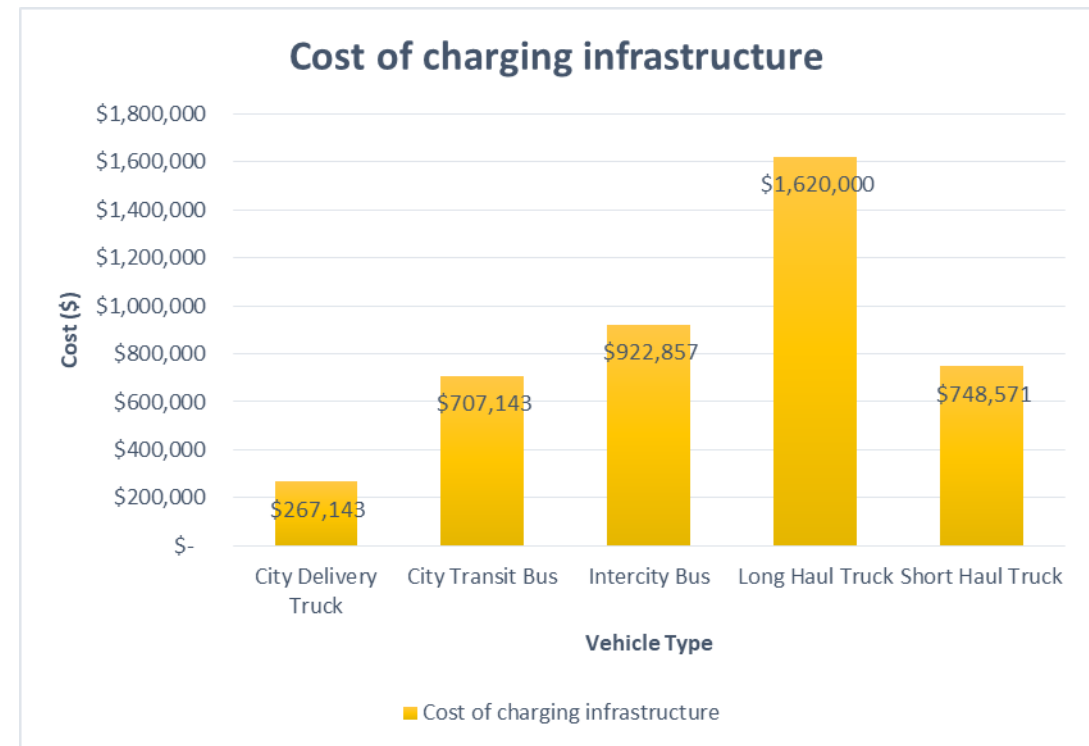
Assuming an average charge time to be about 2 hours

50 vehicles in the fleet

Available time to charge 10 hours

350 kW charger seems most optimal

Except long haul which has 500kW/1000kW



Refueling infrastructure for FCEVs

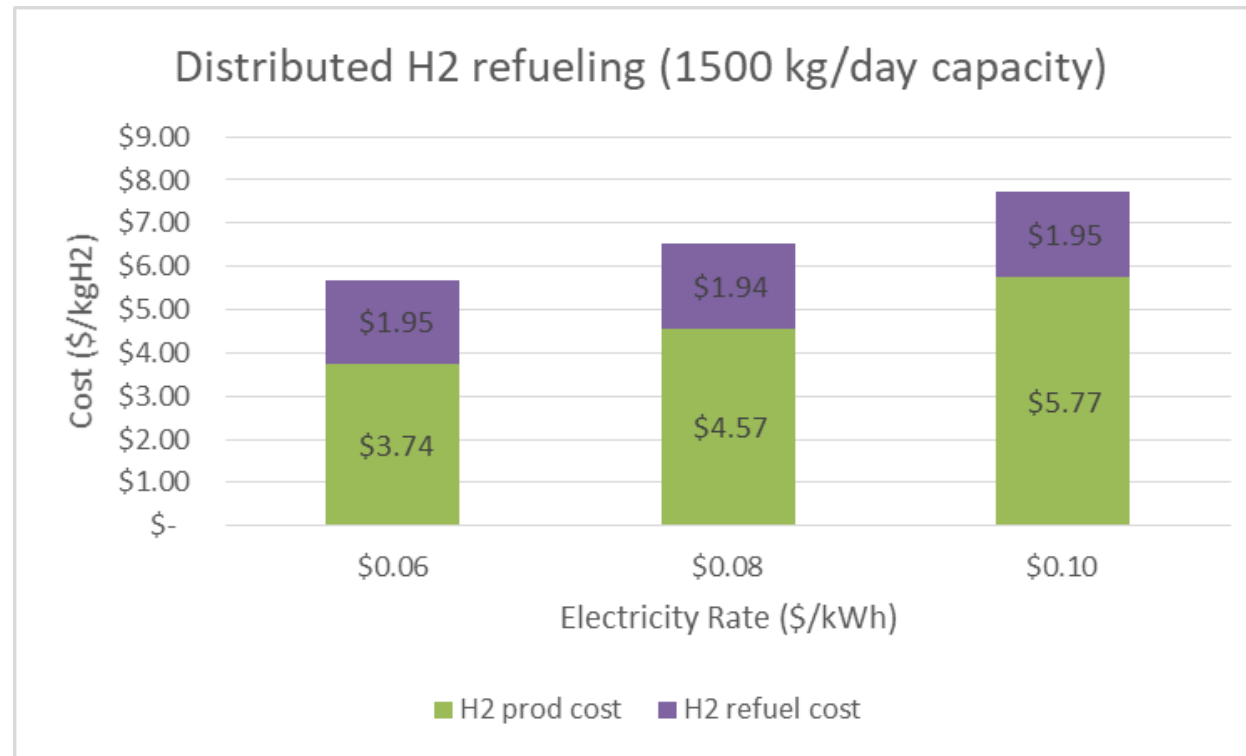
- Breakdown of components costs for a H2 refueling station
- 500 trucks per day per station, 35 Tonnes H2 per day, 20 hoses per station

| Component | Unit cost | Size parameter | Cost \$million |
|--|-----------------------------|--|--------------------------------------|
| Electrolyzer | \$800/kW | 50 MW | 40 |
| Low pressure Storage | \$725/kgH ₂ | 17500 kgH ₂ | 12.7 |
| Low pressure compressor | \$700/ kgH ₂ /hr | 1500 kgH ₂ /hr | 1 |
| High pressure Storage | \$1000/ kgH ₂ | 3500 kgH ₂ | 3.5 |
| High pressure compressor | \$2000/kgH ₂ /hr | 3500 kgH ₂ /hr, 900 atm. | 7 |
| Dispenser hoses and pre-cooling | \$430,000 for 3 hose unit | 5 kgH ₂ /min., -40C 20 hoses | 3 |
| | | | |
| Total w/o installation | \$1900/kgH ₂ | | 67 |
| Total with installation | \$2127/ kgH ₂ | | 75 |
| Present value (10%, 10 yr) | | | 177 |
| | | | |
| Electricity for hydrogen compression (4kWh/ kgH ₂) | 70 kgH ₂ | 280 kWh | .4/ kgH ₂ (\$0.10/kWh) |
| Electricity for producing hydrogen by electrolyzer | 70 kgH ₂ | 3597 kWh | \$5.1/ kgH ₂ (\$0.10/kWh) |



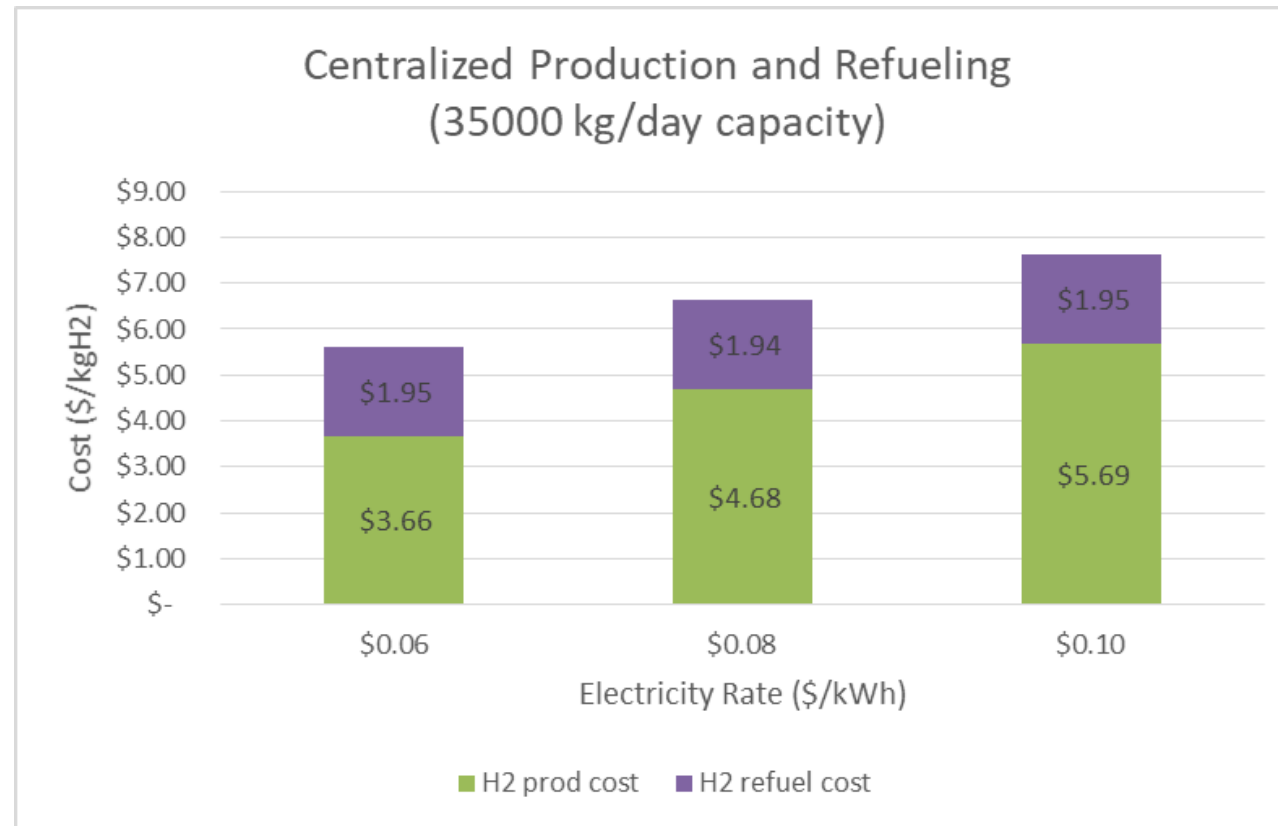
H2 Refueling at fleet depot

Distributed production and refueling



H2 refueling at public highway

Centralized production of H2 and refueling



Carbon Intensity

Carbon intensity of H₂ production varies a lot depending on the method of production

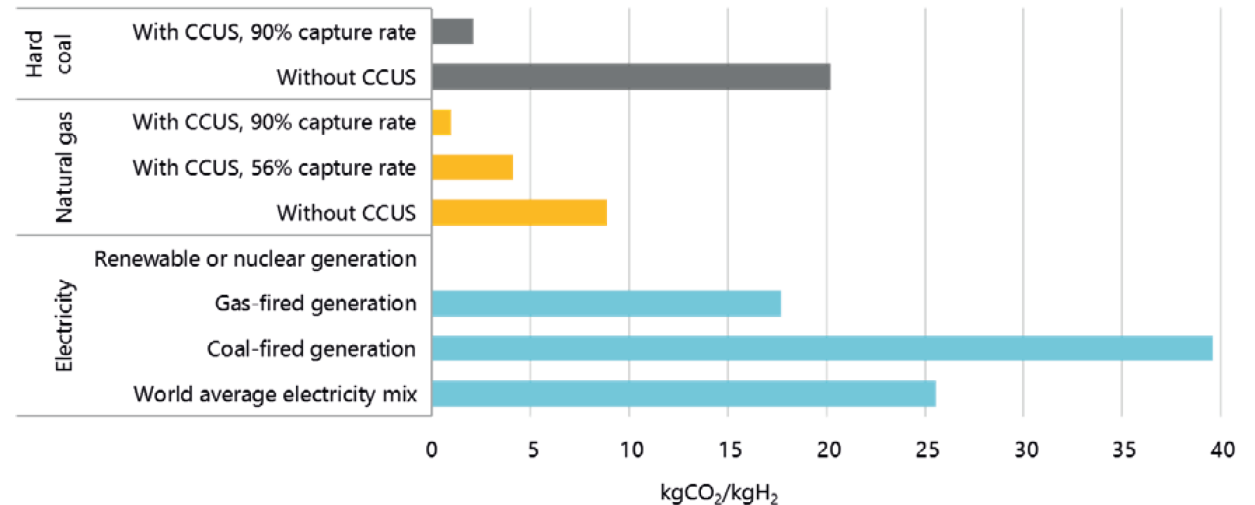
CA grid avg. CI = 222 gCO₂/kWh

H₂ production from NG w/o CCUS:

- CI = 250 gCO₂/kWh of H₂

Efficiency of BEV almost twice of FCV

Figure 17. CO₂ intensity of hydrogen production



Notes: Capture rate of 56% for natural gas with CCUS refers to capturing only the feedstock-related CO₂, whereas for 90% capture rate CCUS is also applied to the fuel-related CO₂ emissions; CO₂ intensities of electricity taking into account only direct CO₂ emissions at the electricity generation plant: world average 2017 = 491 gCO₂/kWh, gas-fired power generation = 336 gCO₂/kWh, coal-fired power generation = 760 gCO₂/kWh. The CO₂ intensities for hydrogen also do not include CO₂ emissions linked to the transmission and distribution of hydrogen to the end users, e.g. from grid electricity used for hydrogen compression. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source: IEA 2019. All rights reserved.

Takeaways

Medium duty vehicles can start to transition right away

- Battery weight in favor
- TCO in favor

Heavy duty will need batteries to become more energy dense

FCVs don't seem better for any vehicle type but

- Can become suitable for long haul – refueling cost come down well below \$5/kgH₂

The biggest uncertainty in this transition is the deployment of charging/refueling infrastructure

- Fleet owned/public owned?

For truly zero carbon, H₂ production cost from electrolysis needs to come down to \$2-\$3/kgH₂

- Otherwise BEVs will continue to increase market share

Next steps

Analysis of more different MD/HD truck types – eg drayage, forklifts

Updates of performance and costs for batteries and fuel cell systems for truck applications

Continued analysis of the cost of renewable H2 from different sources

Road terrain and climate condition effects on ZEV truck economics

Infrastructure projections for large battery-electric and fuel cell fleets – costs, land footprint requirement, fuel distribution considerations

importance of charging/refueling time and fleet size

Questions?