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Decarbonizing Heavy-Duty Transportation

WORKSHOP BRIEF

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A report by
Stanford | ENERGY

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The Stanford Hydrogen Focus Group, a joint effort of the Natural Gas Initiative (NGI), Stanford Energy Corporate Affiliates (SECA), and SUNCAT Center for Interface Science and Catalysis, hosted a workshop in April 2021 to discuss decarbonizing heavy-duty transportation. This report is a summary of the workshop discussions. We gratefully acknowledge the participants who contributed to the discussions as moderators, panelists and speakers.

Rasmus Bach Nielsen, Trafigura

Jeremy Baines, Neste

Raymond Bergmann, Shell

Jim Chen, Stanford University

Al Cioffi, Plug Power

Ash Corson, Toyota

Yi Cui, Stanford University

Ben De Alba, California Energy Commission

Brian Ehrhart, Sandia National Lab

Amgad Elgowainy, Argonne National Lab

Aaron Gillmore, BYD Motors

Noah Heulitt, Alstom

Andreas Hoffrichter, Deutsche Bahn Engineering & Consulting USA Inc.

Patrick Huber, H2energy

Tom Jaramillo, Stanford University

Brian Lindgren, PACCAR

Salvador Llamas, AC Transit

Jennifer McNeill, NFI Group

Rachael Nealer, White House Council on Environmental Quality (formerly at Department of Energy at time of workshop)

Fritz Prinz, Stanford University

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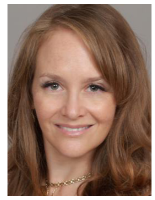
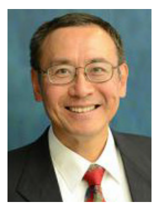
D'ARCY BIDDLE SEAMON is in her senior year at Stanford University studying Engineering Physics and co-terming in Energy Resources Engineering. Her research interests are centred around energy storage, particularly the role it will play in accelerating the transition to a zero-emission economy. Hydrogen's potential as a method for energy storage in long haul transportation is what initially sparked her interest in the field however it has since expanded to an overall respect and excitement for hydrogen as an energy source.

JUSTIN BRACCI received his BS in Environmental Engineering from SUNY Buffalo in 2019. He is currently a first year PhD student in the Energy Resources Engineering Department at Stanford University. Justin works with Dr. Sally M. Benson on decarbonizing the heavy-duty transport sector in California.



NAOMI BONESS is the managing director of the Natural Gas Initiative at Stanford University, co-managing Director of the Stanford Hydrogen Focus Group and a co-instructor of a graduate seminar class on the Hydrogen Economy. She is an experienced practitioner in the energy sector with a focus on natural gas, hydrogen and decarbonization in both the developed and the developing world. Prior to Stanford, she held a variety of technical and management positions at Chevron. Naomi is also a Director for a renewable fuels company and an advisor for a hydrogen startup. As an advocate for women and gender equality, she is a member of the organizing committee for the Women in Clean Energy, Education and Empowerment (C3E) Initiative. Naomi holds a Ph.D. in geophysics from Stanford University, a M.Sc. in geological sciences from Indiana University and a B.Sc. in geophysics from the University of Leeds.



JIM CHEN is the managing director of the Stanford Energy Corporate Affiliates at Stanford University, co-managing director of the Stanford Hydrogen Focus Group and a co-instructor of a graduate seminar class on the Hydrogen Economy. He is responsible for developing and managing engagements for corporations and other organizations that have an interest in Stanford's research, faculty, and graduate students in energy and energy-related areas. He has a broad background in energy and technology, specializing in technology and product development. He has held technical positions at Lawrence Berkeley Labs, GTE Labs, and AT&T Bell Labs, and technology executive positions at both start-ups and Fortune 500 companies, including FormFactor and Eaton. He received his PhD degree from MIT and his MS degree from the University of California, Berkeley both in materials science and engineering, and his BS degree from the University of California, Berkeley in electrical engineering.

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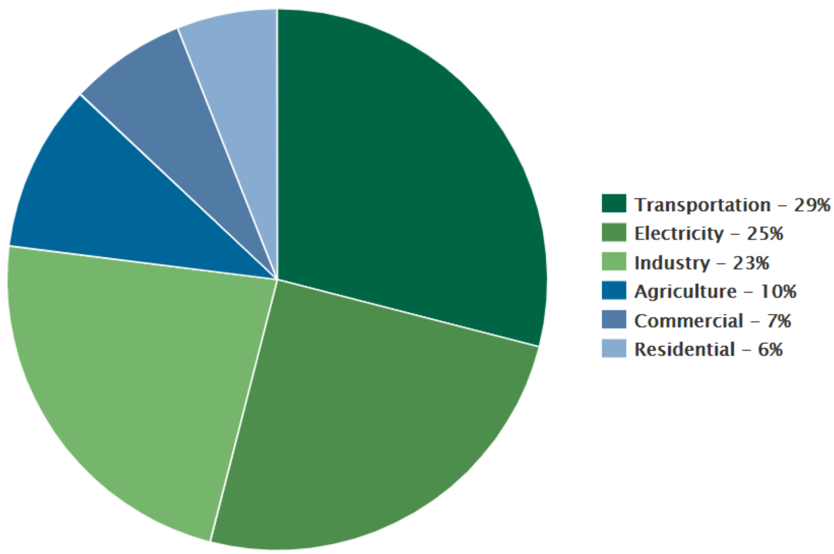
Introduction

With increasingly present drought, wildfires, hurricanes and other natural disasters around the globe, the necessity to decarbonize is reaching a critical tipping point. The transportation sector is a major emitter of greenhouse gas emissions today because of its continued reliance on fossil fuels. In the United States, 29% of greenhouse gas emissions are from the transportation sector (Figure 1). Heavy-duty transport vehicles make up a disproportionate share of these emissions because of their extended travel times, high payloads, and high vehicle weights.

Figure 1: 2019 U.S. Greenhouse Gas Emissions by Sector[1]



The primary options for zero emission vehicles (ZEV) include battery electric vehicles (BEV) and hydrogen fuel cell electric vehicles (FCEV). These technologies are still in the early stages of development and have yet to significantly penetrate the market. Today, most experts see BEV market growth occurring in lighter vehicles with low daily use, and FCEV market growth in heavier vehicles with high daily use (Figure 2). However, these technologies have unique trade-offs across cost and performance making it a challenge to determine the optimum decarbonization pathway for each type of vehicle or vessel. These trade-offs are a key point of discussion throughout the workshop.

In addition to transport applications, hydrogen and batteries also have other applications that will help to decarbonize the global energy system. For example, both batteries and hydrogen can be used for energy storage solutions. This will become increasingly important as renewable generation continues to grow. Hydrogen also has applications in the industrial sector, from fertilizers to potential use in steelmaking and cement. These synergies can be exploited to enable an effective transition to zero emission technology in the heavy-duty transport sector. Consideration should also be given to having a diverse set of solutions, for both transportation and the broader energy system, to provide energy resilience and security.

This brief details the current state of the transition to zero emission in the heavy-duty transport sector. Specifically, academics, companies and government agencies working to decarbonize trucks, buses, trains, ships, and planes discuss the challenges and opportunities to further develop zero emission technologies and fulfill sustainable development scenarios (Figure 3).

1 https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

Figure 2: Application Space for Hydrogen Fuel Cell vs. Battery

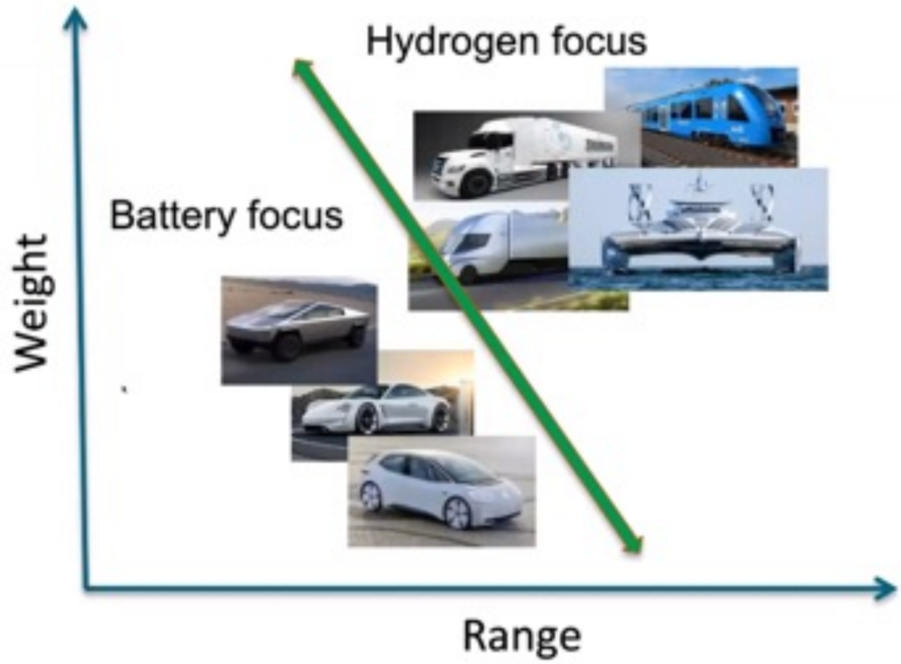
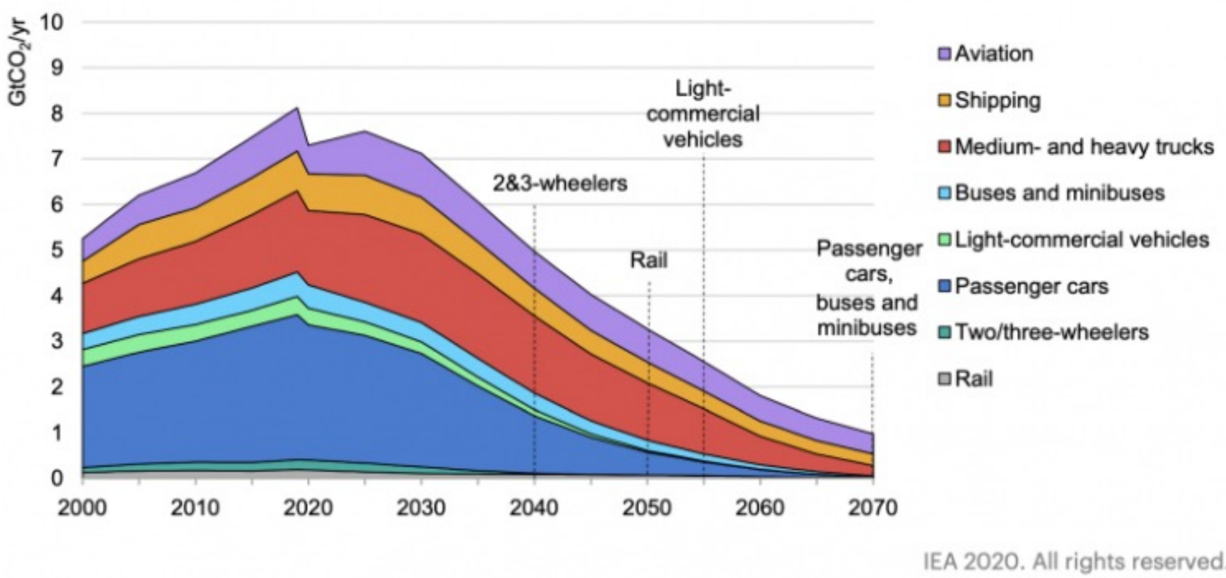


Figure 3: Global CO_2 Emissions from Transport in the IEA's Sustainable Development Scenario to 2070[2]



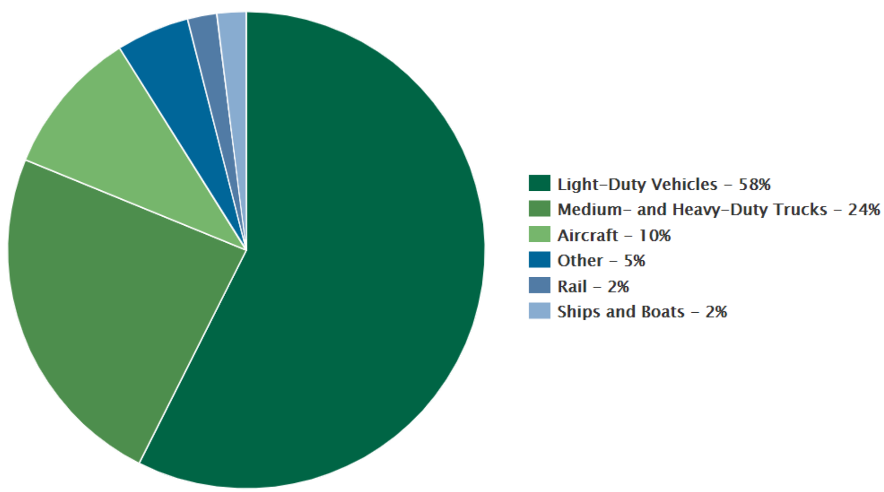
2 IEA (2020), Energy Technology Perspectives 2020, IEA, Paris.

Trucks and Buses

INTRODUCTION

Of the 29% of GHG emissions in the United States that come from the transportation sector, over 80% come from on-road vehicles (Figure 4). The medium- and heavy-duty vehicles represent 24% of the transportation emissions and emit a disproportionate share of the on-road GHG emissions due to their low fuel economy. They also emit higher concentrations of nitrogen oxides and particulate matter due to their heavy reliance on diesel powertrains. Today, China is leading the way in decarbonizing heavy-duty vehicles (HDV) having deployed over 350,000 zero emission buses (ZEB) and 12,000 ZEV trucks[1]. The United States, European Union, Japan, China, and India have HDV fuel consumption standards in place but still lag behind China on infrastructure buildout. Within the United States, California has the strictest regulations for HDV ZEV adoption. The California Air Resources Board (CARB) Innovative Clean Transit Regulation (ICT, 2018) mandates transit agencies to purchase only zero emission bus sales starting in 2029[2]. The CARB Advanced Clean Truck Regulation (ACT, 2020) mandates an increment in percent of zero-emission truck sales each year from 2024 to 2035[3]. Governor Newsom issued Executive Order N-79-20 that requires 100% of medium- and heavy-duty vehicles in CA to be zero-emission by 2045 where feasible, with all drayage trucks zero-emission by 2035 where feasible[4]. This panel discussion highlights the current state of the transition to ZEV trucks and buses in the United States and California, focusing on both fuel cell and battery technologies and the challenges and opportunities with each.

Figure 4: 2019 U.S. Transportation Greenhouse Gas Emissions[5]



1 https://www.iea.org/reports/trucks-and-buses
2 https://ww2.arb.ca.gov/resources/fact-sheets/innovative-clean-transit-ict-regulation-fact-sheet
3 https://ww3.arb.ca.gov/regact/2019/act2019/fro2.pdf
4 https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-text.pdf
5 https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

COMPANY PROFILES

Toyota is one of the major vehicle manufacturers currently deploying ZEV technology to market. They are focused on a portfolio approach to ZEV deployment as the diversity of customer needs requires a matching diversity of ZEVs to meet desired customer applications. Their focus has been on light-duty ZEVs, including hybrid electric vehicles (HEVs), BEVs, and FCEVs like the fast-filling, long-range Toyota Mirai. Given the high productivity potential of FCEVs, Toyota is also applying their modular, scalable, and durable fuel cell electric technology to the ZEV heavy-duty vehicle space. In addition to commercial bus and materials handling applications, Toyota has introduced their fuel cell electric system into Class 8 heavy-duty trucks including 10 “Ocean” FCEV trucks in collaboration with Kenworth, Shell, the Port of Los Angeles, and the State of California. The power and efficiency of Toyota’s fuel cell electric powertrains allow these FCEV trucks to achieve over 300 miles of fully loaded 80,000 pound gross-weighted range with refueling times equivalent to diesel. This enables versatile, high-uptime, zero-emission transport that bypasses constraints that big batteries face for heavy-duty freight movement. Ocean trucks are also operating across multiple fleets and duty cycles, including the rugged, demanding, and high-variability port drayage duty cycle. The severity and broad needs spectrum of the drayage duty cycle has traditionally made these vehicles especially difficult to decarbonize, but the flexibility, capability, and range of FCEV trucks are proving to provide a versatile zero-emission solution.

While Toyota has focused on hydrogen fuel cell electric trucks, **BYD** has focused on battery electric trucks and buses. BYD is the number one commercial ZEV manufacturer and has sold over 13,000 electric trucks and 65,000 electric buses worldwide. BYD utilizes iron phosphate batteries for heavy-duty trucking and busing applications because these batteries are safe, have a high energy density, can operate at a wide range of temperatures, and contain both battery thermal management and water cooling systems to maintain high efficiency. BYD offers diverse charging infrastructure as well. There are AC and DC plug-in charging options, as well as induction charging options for both trucks and buses. Additionally, they offer overhead charging options for their buses. BYD has focused on fitting duty cycles to the vehicle type and vocation. These vocations include operations, refuse collection, and distribution and logistics. Overall, BYD trucks are well suited to meet required duty cycles. While electrification of refuse trucks dramatically improves energy efficiency given very frequent idling at stops, adding battery weight reduces the allowable payload for BEV versions. FCEV may therefore have an advantage for these applications.

Kenworth, part of **PACCAR** group, is another major heavy-duty truck manufacturer working to add more zero-emission trucks to its portfolio. While continuing to offer near-zero emission natural gas engines in their trucks, Kenworth is primarily focused on zero-emission technology for Class 8 tractor trailers and is considering both fuel cell electric and battery electric options. As a general rule, for Class 8 trucks traveling under 100 miles per day, battery electric may be the more economical option, but for travel distances closer to the 200-400 miles per day range, fuel cell electric vehicles make more sense. This is consistent with the Department of Energy (DoE) assessment of ZEV choice with different levels of daily fuel use (Figure 5). Figure 5 does not take into account the long charging times for battery electric trucks and the comparable refueling times of fuel cell trucks to diesel Class 8 trucks which would also tend to favor FCEVs for high daily fuel consumption applications (Figure 6). FCEVs using compressed gas storage and BEV Class 8 trucks both have onboard energy density limitations, resulting in less allowable payload than typical diesel trucks with BEV trucks having the more significant payload impact (Figure 7). In terms of the capital cost of Class 8 tractor trailers, hydrogen and battery electric options have also yet to reach parity with diesel (Figure 8). Vehicle operators looking to buy these zero-emission trucks may also be required to pay for charging or refueling infrastructure as well, which may sway them away from these new technologies.

On the fuel cell electric side, Kenworth is assessing the overall effectiveness of different sized complementary battery systems. While smaller battery options have benefits of lower weight and modularity, they suffer from reduced regenerative braking and grade duration capabilities. One major challenge that Kenworth is seeing with Class 8 zero-emission truck manufacturing is that components are hard to come by with the supply base still developing. Many times the components they do get are not plug and play with current heavy-duty truck systems. In addition, once these zero-emission trucks are on the road there will be a learning curve for truck operators to operate these vehicles. Going forward Kenworth will look at new truck designs to accommodate vocational vehicles and will continue to look at pathways to improve costs for the zero-emission truck components.

Figure 5: Cost Comparison of ZEVs with Variable On-Board Storage

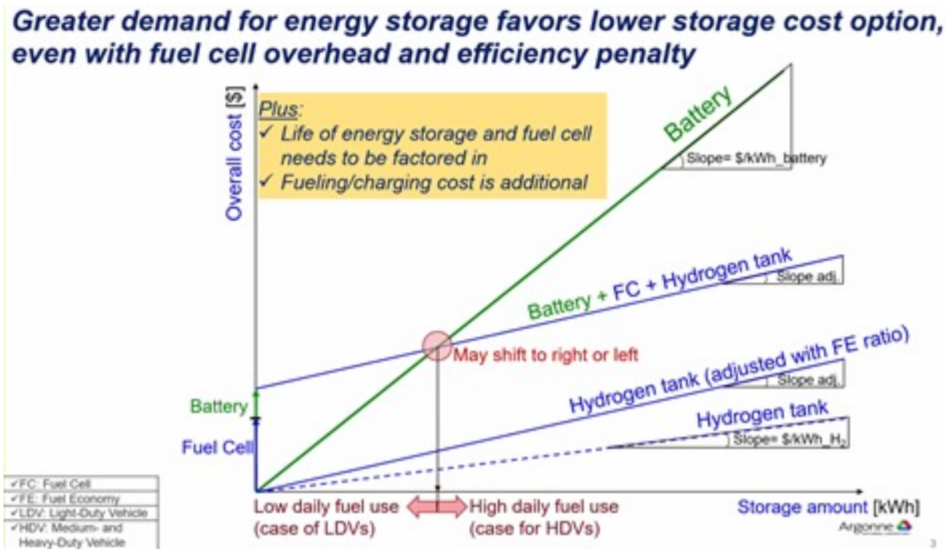


Figure 6: Class 8 Truck Refueling Time Comparison

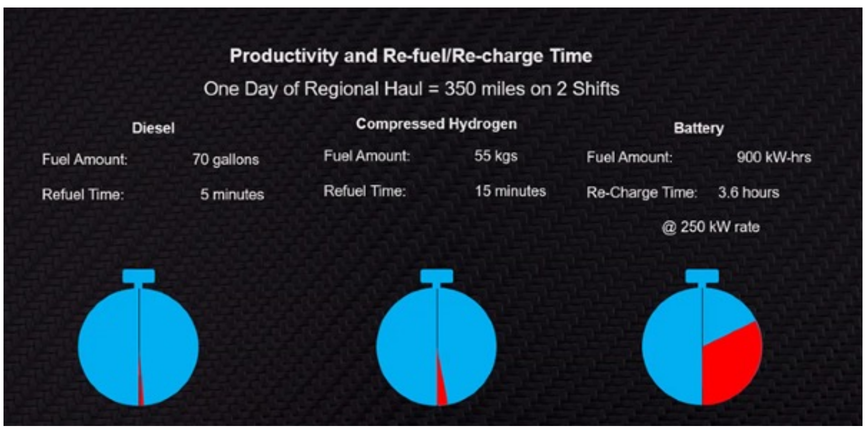


Figure 7: Class 8 Truck Payload and Energy Density Comparison

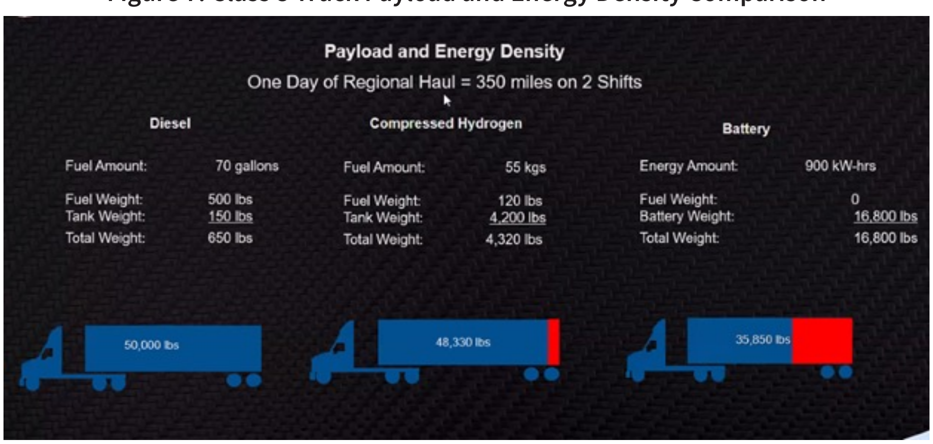
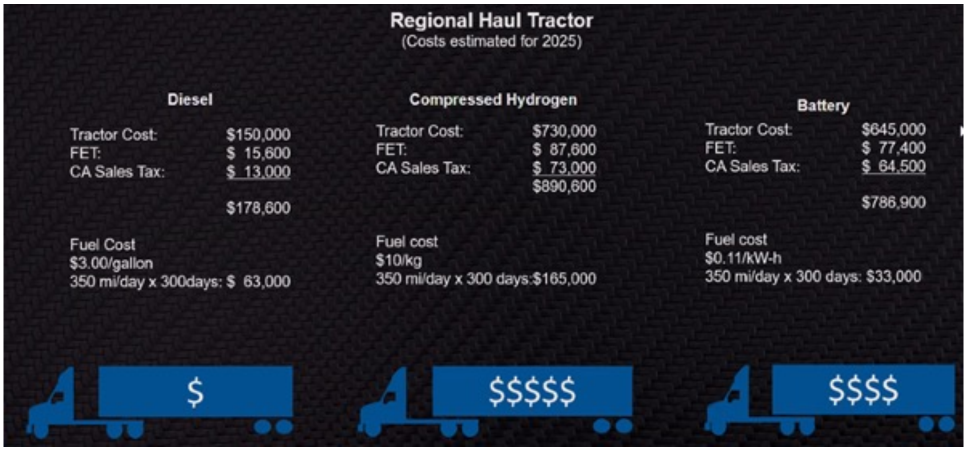


Figure 8: Class 8 Truck Capital and Fuel Cost Comparison



NFI Group, previously New Flyer Industries Inc., is a family of major bus manufacturers that have deployed over 750 ZEBs in 40 cities across North America. These buses aid in getting people out of CO_2 emitting light-duty vehicles and into zero-emission public transit, and also help to reduce traffic congestion and improve air quality where they are deployed. NFI Group uses batteries from ethically sourced materials and their buses store batteries in the roof or in engine compartments of ZEBs. Their fuel cell electric buses (FCEBs) use Ballard Power fuel cells and are battery dominant with hydrogen used to charge batteries and extend vehicle range. The fuel consumption of the ZEV transit buses will depend on climate, topography, duty cycle, and driving techniques. These factors may also impact the range requirement of the transit bus and will impact the choice of a BEB or FCEB. In general, FCEBs have better range than BEBs today but both can usually meet range requirements for a bus duty cycle (Figure 9). The prices for NFI Group BEBs and FCEBs are variable but are still high in comparison to diesel or compressed natural gas buses (Figure 10). Encouragingly, prices for both types of NFI Group ZEBs are dropping as fuel cell costs are decreasing and battery chemistries advancements are occurring to increase battery energy density (Figure 11). NFI Group also introduced a new service called Infrastructure Solutions in January 2019 focused on ZEV mobility infrastructure planning and buildout[6]. This service division has already installed over 200 BEB chargers across North America and is helping to provide a cohesive transition for fleets to zero-emission technology.

Figure 9: Bus Range Comparison

Range Comparisons at Altoona Test Track

	Fuel Cell Electric	Battery-Electric			Diesel
	Standard Grade Motor	Standard Grade Motor	Standard Grade Motor	Standard Grade Motor	N/A
ESS (kWh)	100	350	440	525	125 Useable US Gal
Range (miles)	305	174	213	251	CBD: 492.5 ART: 560 COM:1,025 TOTAL: 602.5 **APTA SBPG: 350**

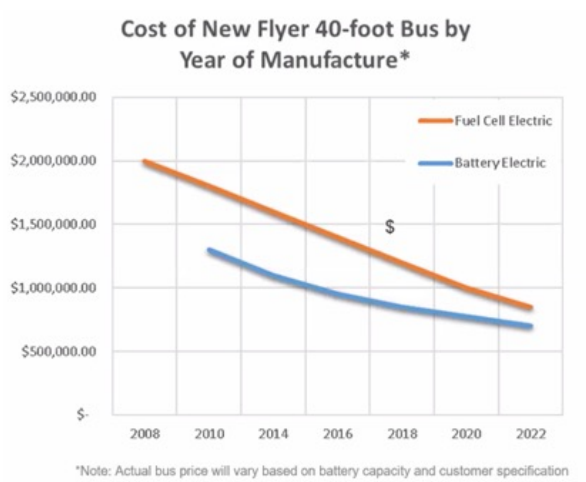
*BAC (Business, Arterial, Commuter) duty cycle

Figure 10: NFI Group Bus Price Comparison

2021 Bus Price	Battery-Electric	Fuel Cell Electric	Diesel-Electric Hybrid	CNG	Diesel
40' Xcelsior Transit Bus*	$804,990 (388 kWh)	$1,086,990	$596,990	$489,990	$434,990

Source: Washington Department of Enterprise Services Contract

Figure 11: NFI Group ZEB Bus Price Decline



6 https://www.newflyer.com/parts-support/infrastructure-solutions/

The bus transit agency, **AC Transit**, is the largest public bus-only transit agency in California and has been serving the San Francisco East Bay since 1960. With its headquarters office in Oakland, Alameda County, AC Transit has a long-standing commitment to preserving and improving the quality and quantity of transit service for 1.5 million East Bay passengers that populate their 364 square mile service area. AC Transit is currently operating 21 FCEBs (11 are from the NFI Group), and 7 BEBs in the Bay Area and have recently been awarded a contract for 20 more FCEBs and 21 more BEBs. To support their ZEB fleet, AC Transit has hydrogen refueling stations and charging stations at both their Emeryville and Oakland facilities. The Emeryville hydrogen station was recently upgraded from compression dispensing to cryogenic pumping which has significantly improved refueling times for bus fleets. At the Oakland facility, there are 5 depot DC-fast charging stations and plans to build charging infrastructure for up to 50 buses. In Emeryville, a project is underway to install up to 16 depot DC-fast charging stations. Looking toward the future, AC Transit has implemented a rollout plan with targets for a 100% zero-emission bus fleet by 2040[7]. This rollout plan maximizes AC Transit's unique opportunity, based on more than 20 years of experience deploying ZEBs, to operate a mixed fleet of BEBs and FCEBs. As part of their rollout studies, AC Transit is currently conducting a Zero Emission Transit Bus Technology Assessment, in collaboration with a Stanford University team, coined the "5x5 study", where 5 different kinds of buses, 5 buses of each kind, are being examined for their operational, financial, and social metrics. AC Transit's goal with this report is to have a true, side-by-side evaluation of ZEB technologies operated by the same Agency, in the same service environment, from the same ZEB manufacturer, and compare that to conventional fleets. As they move ahead with a fleet transition, AC Transit plans to prioritize ZEB services in disadvantaged communities to help improve air quality and reduce traffic congestion in these communities. An interim report of this "5x5 study" is currently available.

TRUCK AND BUS DISCUSSION

As shown in Figures 8 and 10, BEV and FCEV trucks and buses are still more expensive than their internal combustion engine counterparts. Interestingly, the electric powertrain of both FCEVs and BEVs is cheaper than the diesel powertrain today. It is the batteries and fuel cells, and supply chain limitations that drive up the cost of these zero emission vehicles. As production of ZEV trucks and buses scales, costs are expected to drop closer to that of diesel trucks. If possible, vehicle manufacturing companies can even take advantage of their current vehicle backbone to make ZEV versions. This will help keep assembly line efficiencies high and reduce production costs. In addition, as ZEV costs are expected to decline over time, diesel truck and bus costs are expected to increase due to stricter emission regulations. Cost parity with diesel trucks and buses is expected in the 2030 time frame. Finally, the total cost of ownership (TCO) needs to be considered. ZEVs can have second or third use applications and can also be used for vehicle-to-grid offload for an extra revenue stream. Batteries from a ZEV can also be repurposed for energy storage applications. With all this in mind, indications are that by 2030 the cost of ZEV trucks and buses will be on par with their diesel counterparts. The economic drivers will then be in place for decarbonizing trucks and buses, along with environmental and social benefits. Until that time, purchase incentives will be necessary (see Government Involvement below).

FUEL DISCUSSION

As shown in Figure 8, the fuel cost of hydrogen is a significant contributor to the total cost of ownership of a FCEV truck or bus. On a levelized cost of driving basis, fuel costs for heavy-duty vehicles are actually higher than the capital cost of the vehicle. Interestingly, hydrogen production is quite cheap today as it is mostly generated from natural gas, but has an associated carbon dioxide emissions stream. The cost of new infrastructure for delivering and dispensing hydrogen is what keeps prices high. To keep these costs low, it is important to make sure that hydrogen supply and demand are in close proximity to reduce or eliminate the cost of transporting hydrogen. As FCEVs penetrate the market, hydrogen fuel costs will be driven down as existing refueling stations will operate at higher capacity factors and new refueling stations are built with higher dispensing volumes. Department of Energy research suggests delivering liquid hydrogen to refueling stations instead of gaseous hydrogen will also bring down fuel costs because refueling stations will require less equipment (Figures 12 and 13). However, there is a corresponding energy and emissions penalty to making liquid hydrogen that needs to be considered. Another factor that plays a role in hydrogen fuel costs is the fuel economy of fuel cell trucks and buses in comparison to their gasoline or diesel counterparts. The ratio between the two is called the fuel economy (FE) ratio and depends on the vocation of the vehicle. Typically, vehicles with higher daily vehicle miles travelled (VMT) and less idle time

7 https://cafcp.org/sites/default/files/AC_Transit_ZEB_Assessment_18-134%20_27Jun18_2020.pdf

will have lower fuel economy ratios than vehicles with lower daily VMT and high idle times[8]. A higher FE ratio indicates a FCEV truck or bus uses its fuel much more efficiently than a comparable ICE truck or bus. This means that fuel costs for an FCEV with a higher FE ratio will be less than for an FCEV with a FE ratio closer to one (Table 1).

Figure 12: Refueling Station Configuration for Gaseous (left) and Liquid (right) Hydrogen Delivery to Station[9]

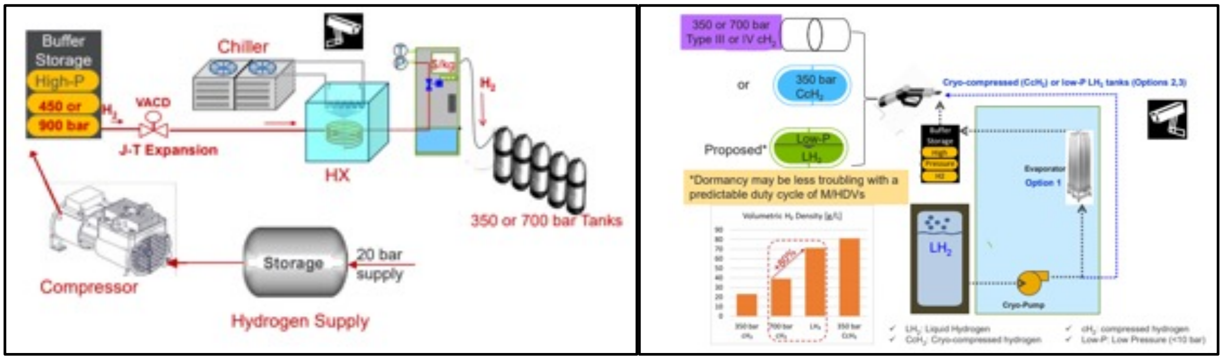
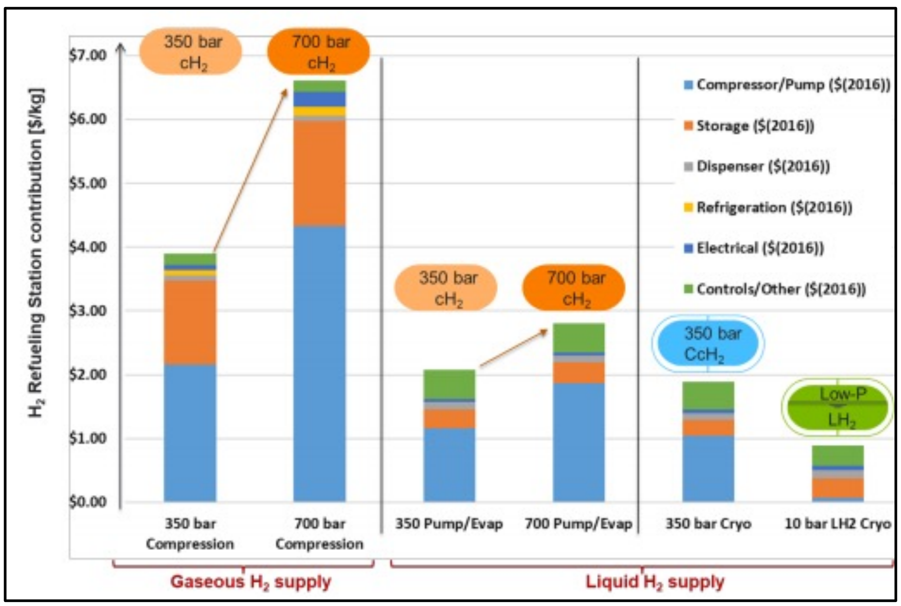


Figure 13: Refueling Station Contribution to Hydrogen Costs under Different Supply and Dispensing Conditions (in this scenario levelized costs are for a 30 bus fleet that have 35 kg tanks and fill up back-to-back at one dispenser)[10]



8 https://www.sciencedirect.com/science/article/pii/S0378775318304737
9 https://hdsam.es.anl.gov/index.php?content=hdrsam
10 https://hdsam.es.anl.gov/

Table 1: Fuel Economy Ratio Effect on Hydrogen Fuel Costs

	Passenger Car		Line Haul HDV	
	Gasoline ICEV	H_2 FCEV	Diesel ICEV	H_2 FCEV
Fuel Economy	25 mpgg	60mi/kg (~60 mpgge)	6 mpgd	7 mi/kg (6 mpgde)
Fuel Economy Ratio	2.4		1.0	
Equivalent Fuel Cost	$2/gal	$4.8/kg	$2/gal	$1.8/kg
	$3/gal	$7.2/kg	$3/gal	$2.7/kg
	$4/gal	$9.6/kg	$4/gal	$3.6/kg

Another impact of the fuel economy ratio is the well-to-wheel emissions of both BEVs and FCEV fuels. Because of the low FE ratio for large long-haul vehicles, these vehicles actually have similar GHG emissions as their internal combustion engine vehicle counterparts (Figures 14 and 15). This illustrates there is still work to be done to decarbonize the hydrogen and electricity generation, storage, and distribution practices.

Figure 14: WTW GHG Emission Comparison for BEVs using 2019 U.S. Grid Mix[11]

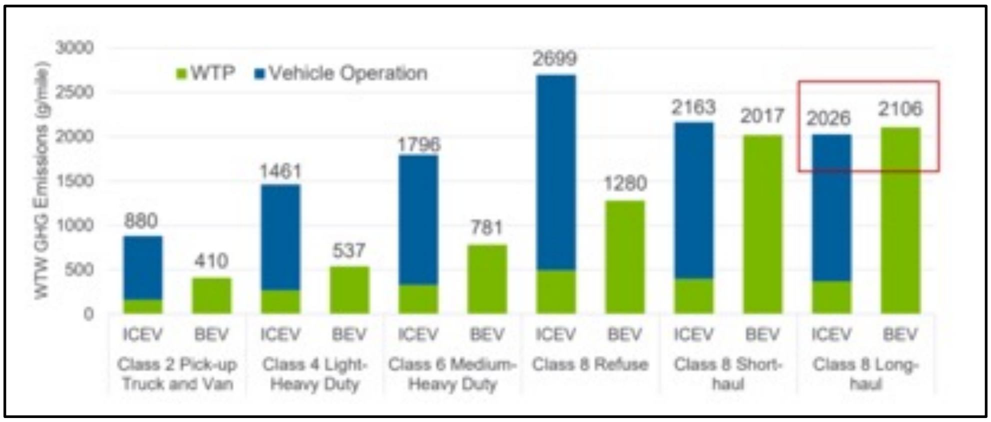
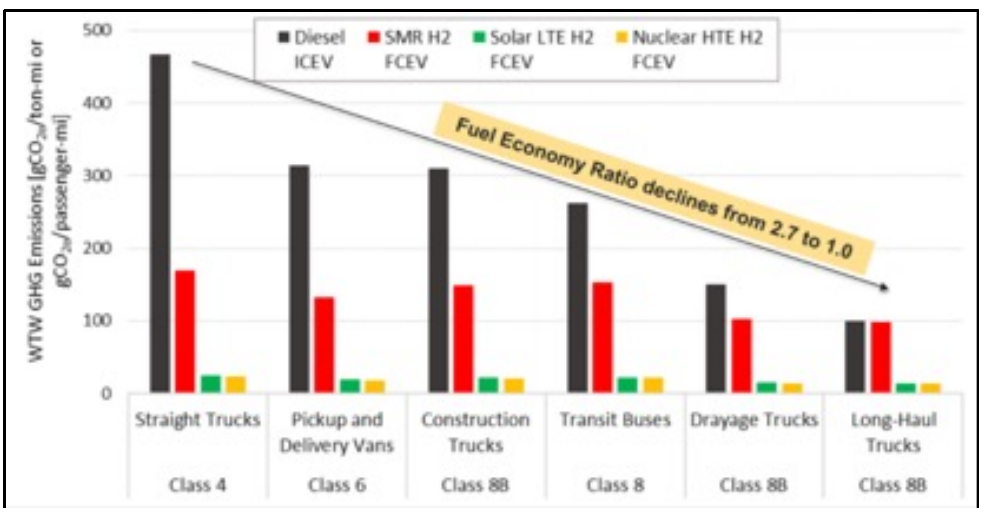


Figure 15: WTW GHG Emission Comparison for FCEVs



11 https://greet.es.anl.gov/

Although Figure 8 indicates fuel costs for BEV trucks and buses are less than for FCEV, and possibly even incumbent diesel and gasoline models, there are still challenges with obtaining reliable, low cost electricity. Electricity rates vary throughout the US so BEV fuel costs may be more expensive in one part of the country than another. Also, many utilities have time-of-use rate structures and demand charges so fleet operating companies could deploy charge management systems to optimize fuel costs by spreading out charging times, which may reduce the number of chargers required for the fleet. Another option fleet operators have is to "load balance", ie. to sell the extra state of charge from their vehicles when the grid needs it, and charge the vehicles when the electricity prices and demand on the grid are low. There is also a question of reliability when it comes to electricity for vehicle charging. When there are public safety shutdowns or power failures, BEV fleet operators need to make sure they have back-up options to continue vehicle operations. One of the options mentioned was to charge vehicles with distributed renewables. This approach would also put less demand requirements on the grid even when it is not shut down. As a key takeaway, each business will have a different optimal solution for getting electricity delivered to their vehicle in a low cost reliable fashion.

TRUCKS AND BUS INFRASTRUCTURE DISCUSSION

When it comes to charging and refueling infrastructure for ZEV trucks and buses, FCEV infrastructure is more similar to what is currently used today for compressed natural gas and diesel trucks and buses. This is more favorable and familiar for employees refueling trucks and buses at a depot as they will not have to deal with charging time constraints that come about with BEVs. Fast chargers for BEVs will alleviate charging time constraints but are very expensive (around $150,000 to $300,000 per charger to start). One way to limit costs associated with chargers is to have one big charger that delivers power to many dispensers at the same time instead of buying chargers for each dispenser. However, this set-up would only be feasible for some fleet sizes and duty cycles. For BEBs, induction charging at bus stops is a potential method to increase range and reduce downtime for charging. Currently, the BEV "behind the meter" infrastructure appears to have a lower initial cost, especially for a low number of vehicles, because of the existing electricity infrastructure, whereas the FCEV infrastructure will have a higher initial cost, but will scale more easily and cheaper for fleets given their faster fueling time. [12 13]

One difficulty with building out charging and refueling station infrastructure in the depot setting is space constraints. Some depots do not have space for chargers or a refueling station. For these depots, a FCEV fleet may be the best option as low footprint, mobile hydrogen refueling trucks could be used to dispense hydrogen to the fleet.

Another important point on infrastructure development is that both depot and public refueling and charging stations will need to be put in to support ZEV trucks and buses. Many independent truck operators keep vehicles at their homes overnight and will need access to public stations so as not to get off schedule with their deliveries.

Significant cost decline of infrastructure has occurred over the last several years. Back in 2012, AC Transit paid about $6 million for a refueling station for a fleet of 13 buses. Today, a refueling station for a fleet of 200 buses would be about $12-15 million using cryogenic pumping. How hydrogen is supplied and dispensed at a refueling station also plays a role in the cost. This is highlighted in Figure 13. On the battery electric side, AC Transit invested $900,000 for 5 chargers. As mentioned, a cost challenge for battery electric is obtaining reliable electricity at optimal cost.

GOVERNMENT INVOLVEMENT

Although progress has been made in recent years, the primary considerations holding back widespread adoption of ZEV trucks and buses is the cost of the vehicles, fuel, and infrastructure. Vehicle sales regulations are a tool utilized in California to push ZEV adoption for trucks and buses. In addition, levers such as CO_2 emission regulations and a company's green image can help to spur continued market penetration. However, panelists see government action, primarily incentives and funding, playing the biggest role in accelerating adoption. Local, state, and federal governments should start providing funding for bus transit and trucking companies looking to start pilot projects across the United States as this will help to drive down the cost of the ZEVs. Governments can also put in place incentives for ZEV truck and bus manufacturers so as to ensure they are getting a high return on investment. There are also opportunities to incentivize independent operators using high-emitting 2nd and 3rd hand trucks to switch to zero-emission trucks. Smaller

12 https://cafcp.org/sites/default/files/07-24-2020-Foothill-ZEB-Update-to-Board.pdf

13 https://metro.legistar.com/LegislationDetail.aspx?ID=4062439&GUID=7C3E86D2-9132-4368-9901-AC6AEAE36D84

ways the government can facilitate ZEV adoption is by giving tax rebates or Federal Excise Tax exemption for ZEV trucks and buses sold and making it easier for depot expansions to accommodate charging or refueling infrastructure. Pushing adoption for ZEV trucks and buses now implies lower sales of new diesel trucks that will be in operation for another 15-20 years. As a key takeaway, government support is necessary in the shorter term to enable long-term sustainability.

THE ROLE OF ACADEMICS

Trade schools and research universities also play a role in the transition to ZEVs. Trade schools will be a place to educate technicians to repair/maintain this new technology while research universities can educate future policymakers, engineers, and researchers to help further facilitate a transition to zero-emission trucks and buses. Stanford as well as other research universities could look for ways to reduce fuel cell costs, store hydrogen on-board vehicles in a more cost effective manner, and increase battery energy density. Advancements in artificial intelligence can also be utilized to intelligently optimize the energy systems of the future, including charging systems for battery electric vehicles.

TRUCKS AND BUSES SUMMARY

Key messages are:

- There is no “silver bullet” solution to decarbonizing the heavy-duty transport sector, all technology options must be explored;
- Total cost of ownership for FCEV and BEV trucks and buses, are still more expensive today than diesel trucks and buses on the road today;
- Government incentives will play a key role in accelerating ZEV truck and bus adoption;
- ZEV adoption is a choice society has to make. In the short term it will be costly, but the long-term air pollution and climate benefits it will bring about is worth the investment.

Infrastructure

INTRODUCTION

To support a ZEV fleet across the world, significant infrastructure developments need to be made. The electric grid of today is well developed in comparison to hydrogen infrastructure, and importantly it is able to support the BEVs on the road today. In California, a national leader in hydrogen infrastructure, there are less than 100 hydrogen refueling stations compared to roughly 10,000 gas stations. However the current electric grid cannot support an entire fleet of BEVs, especially not one that includes heavy-duty BEVs. Across the world there is growing recognition that hydrogen is a potential solution to reduce transportation emissions by replacing current heavy-duty vehicles with FCEVs powered by hydrogen. It is important to recognize that FCEVs and BEVs should not be in competition with each other, but rather work in parallel to create a zero emission transportation sector.

However a ‘chicken and the egg’ problem presents itself here: to justify investment in hydrogen fueling stations and associated infrastructure, there should be a guarantee that these stations will be used by a large enough number of FCEVs. On the other hand, for customers to invest in FCEVs, they want a guarantee that there is infrastructure in place to refuel their vehicles at reasonable cost. Both government agencies and private companies are aware of this issue, and are exploring different solutions where the necessary infrastructure is developed to support the expansion of the FCEV industry.

COMPANY PROFILES

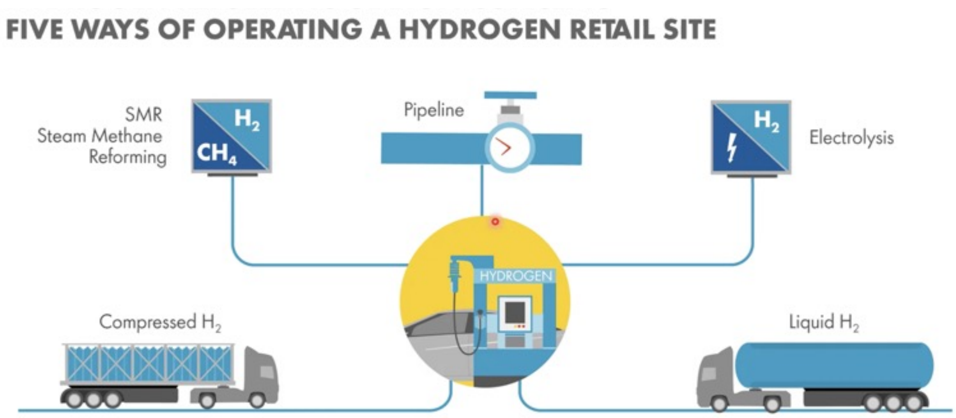
Shell is exploring different options for transporting hydrogen to support a network of hydrogen refueling stations across America. Current options for storing hydrogen for transportation include as a compressed gas at 350 and 700 bar, as a liquid, or through molecular carriers such as liquid organic hydrogen carriers (LOHC) or ammonia.

Figure 16: Trailer options for transporting hydrogen

There are 5 options to deliver low carbon hydrogen to refueling stations:

1. If the station is connected directly to the gas grid, steam methane reforming can be done onsite with some form of carbon capture, storage and/or utilization.
2. Hydrogen pipeline access. For long distance transport, pipelines are the ideal method especially in countries that have existing hydrogen pipelines from chemical factories and refineries; in America, there are 2608km of hydrogen pipeline connecting mostly from chemical factories or refineries.
3. Direct electrolysis on site at the refueling station using electricity from the power grid.
4. Compressed hydrogen delivered by truck (Figure 16).
5. Liquid hydrogen delivered by truck (Figure 16).

Figure 17: Hydrogen Refueling Station Concepts



There are also several different designs to construct a refueling station. The electrolyzer could be onsite or upstream to produce the hydrogen. This hydrogen would then enter low pressure storage, followed by a compressor, a cooling system, and then finally enter a dispenser. Refueling stations may also need to take into account who their customer base is, as hydrogen refueling stations for heavy-duty vehicles require a much larger supply volume. Shell has three different examples of how light-duty vehicle refueling stations would be structured in comparison to heavy-duty stations (see Figure 18).

Figure 18: Size Options for Hydrogen Refueling Stations

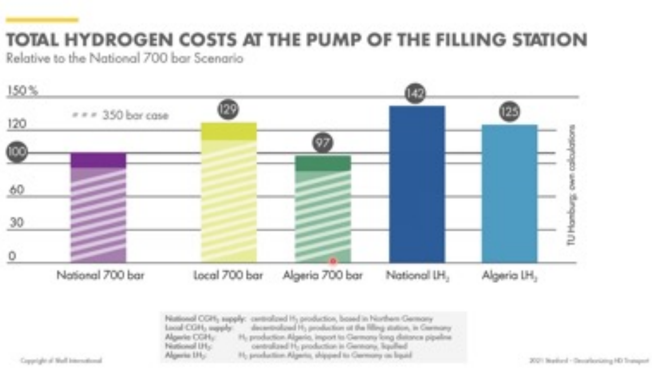
SIZE OF HYDROGEN REFUELING STATIONS

	PC Station Small	PC Station Large	Truck Station Small
No. of Dispensers	1	4	4
Max throughput [kg p.d.]	212	1.000	9.000
Max # of refuelings	38	180	110
Max # of FCEV supplied	400	1.600	110
Typical filling time [min]	3-5	3-5	10

Shell investigated the efficiency and cost of 5 different methods to supply Europe with hydrogen:

1. National compressed gaseous hydrogen pathway (National CGH2): Hydrogen would be produced through electrolysis powered by renewables, for example a wind or solar farm. This hydrogen is then compressed for transport through a pipeline, then further compressed from the pipeline terminal to a truck where it is delivered to a refueling station. The multiple compression stages detract from the efficiency of the system, but this is compensated by the low cost as it would use cheaper electricity produced on a large, national scale.
2. Local compressed gaseous hydrogen, or Local CGH2: This would include an electrolyzer on a refueling station, so the hydrogen is produced onsite. This is the most efficient option as less transport, and therefore less compression, is required.
3. Algeria Supply Chain: The hydrogen would be produced in Algeria where renewable resources are abundant and the cost of renewable electricity is relatively cheap, then transported via a compressed gaseous hydrogen pipeline to the market. Although the longer supply chain and loss of ~8-10% efficiency along the pipeline does increase the cost, this option is still competitive with the National CGH2 option.
4. National liquid hydrogen pipeline: The hydrogen would be produced through national electricity, similar to Option 1), and then would be liquefied and transported to refueling stations. However liquefaction is very energy intensive and expensive, further reducing the efficiency and viability of this option.
5. Algeria Liquid Hydrogen Supply Chain: Similar to Option 3) the hydrogen would be produced in Algeria and then transported via ship to European markets.

Figures 19 & 20: Hydrogen Supply Chain Scenarios



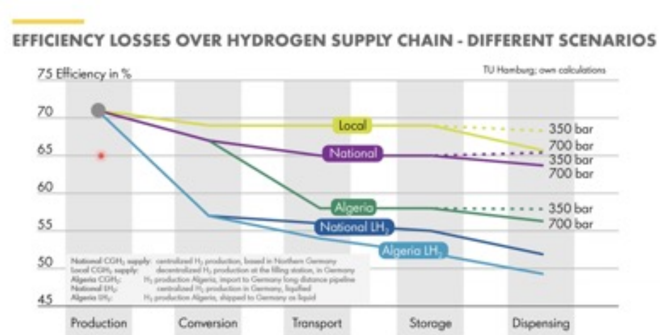
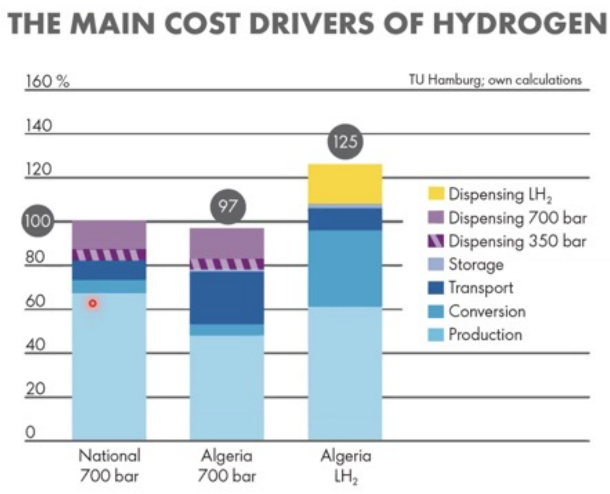


Figure 21: Economic Analysis of 3 Most Promising Supply Chain Scenarios

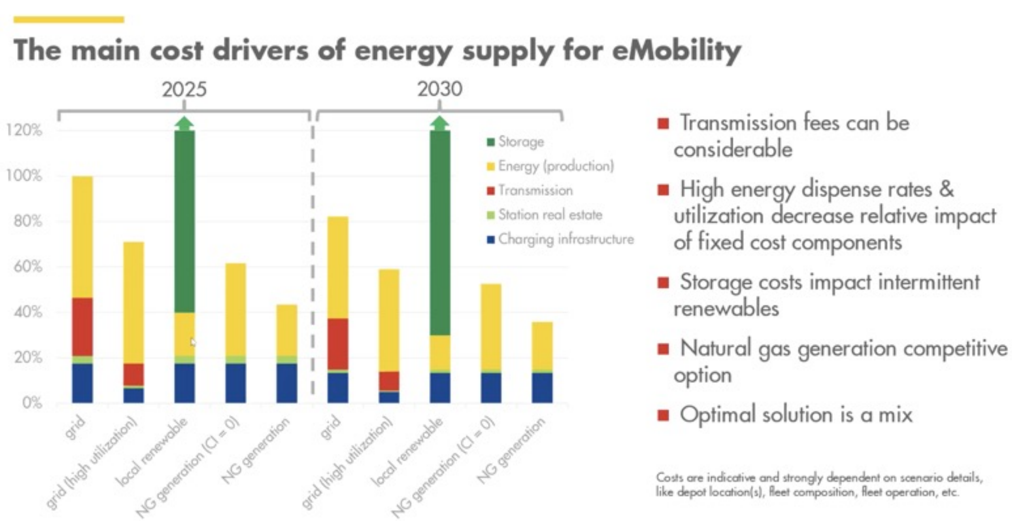


The costs are further broken down in Figure 21 focusing on the three of the more viable options: National compressed gas hydrogen pipeline (purple in figures above), Algeria compressed gas pipeline (green), or Algeria liquid hydrogen supply chain (light blue). Ideally, hydrogen could be dispensed at about $5 per kilogram of hydrogen, however cost depends on a number of drivers. Production through electrolysis is consistently the largest cost (based on cost for renewable power from wind/solar and electrolyser capex), however transportation from Algeria and liquefaction also cause the overall cost to increase significantly. Lower production costs in Algeria are compensated by higher transport cost in comparison with national production in Europe. Liquid hydrogen can be dispensed more rapidly at larger on-board capacities.

To focus more on the broader ZEV space, Shell is currently looking at ways to scale up electric charging systems for heavy-duty fleets. Recent technological advances have pushed charging power to around 250kW, but Shell wants to go further and develop an automated megawatt charging system. This system will have V2X capabilities, allowing a power exchange between the grid and heavy-duty vehicles. Thus heavy-duty vehicles can act as energy storage systems, taking large amounts of the electricity from the grid with the ability to give it back, effectively recharging the grid when electricity supply is low.

A charging site for heavy-duty vehicles can be supplied through local electricity generation from natural gas, local electricity generation from renewable sources, or directly from the grid. The latter is very cost effective, especially when there is high utilization. Local renewable energy generation is also very competitive on its own, however energy storage is needed to offset the intermittent nature of renewables, driving up the cost (See Figure 22).

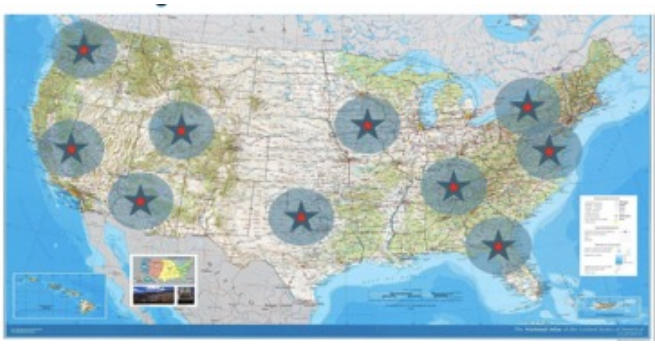
Figure 22: Economic Analysis of Electric Refueling Station Options



Plug Power represents a successful business that operates in the heavy-duty FCEV market. Plug power controls >90% of the hydrogen fuel cell market specific to material handling (e.g. machines such as forklifts used in warehouses). They have over 40,000 units in operation, and currently buy and resell 40 tons of liquid hydrogen a day. They design their fuel cells for vehicles that work in extreme warehouse conditions, including lack of shock absorbers, frequent start-stop action, and exposure to extreme temperatures as well as a range of airborne contaminants. Despite these design challenges, Plug Power has produced fuel cells that easily replace battery modules, and consistently perform better than their battery electric counterparts. Specifically, fuel cells outperform batteries with respect to performance drop-off with temperature and time, capacity loss with age, and long recharge times. Consequently Plug Power has shown that zero emission fuel cells are economically competitive with zero emission batteries.

Plug power has also constructed 140 hydrogen refueling stations to support its fleet of FCEVs. All of those stations use delivered liquid hydrogen as the primary source as this is currently the most cost effective and reliable option. Eventually, Plug Power aims to produce a network of fueling stations entirely with green hydrogen.

Figure 23: Plug Power's Network of Hydrogen Refueling Stations



For larger use vehicles, the advantages of BEVs over internal combustion engines are purely with respect to emissions, but FCEVs can come closer to matching internal combustion engines in other areas as well (see Figure 24). Consequently, for high capacity, high utility vehicles, Plug Power believes that this space will be dominated by FCEVs rather than BEVs.

Figure 24: A Comparison of ICE, Battery, and Fuel Cell Vehicles (X Advantage – Disadvantage)

Commercial Motive Power

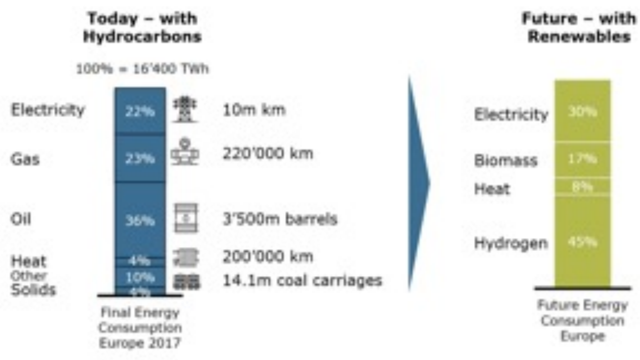
Operational Criteria	ICE	Battery	Fuel Cell
Refuel/Recharge Time	X	---	X
Vehicle Cycle Performance	X	---	X
Work Force Productivity	X	---	X
Asset & Space Utilization	X	---	X
Emissions	---	X	X
All Weather Operation	X	---	X
Vehicle Dispatch	X	---	X

Applies to ALL Commercial Vehicles operating in high capacity and high daily utilization

H2energy is another company that is focused solely on the Hydrogen space, particularly in Europe. H2energy has also demonstrated the viability of heavy-duty FCEVs in European markets, and the importance of completing the supply chain for these vehicles. Their goal is to establish hydrogen in the energy system, focusing on general hydrogen strategy and ecosystems, hydrogen refueling stations, and hydrogen infrastructure. Governments across the world want to decarbonize their transport sectors by replacing natural gas and oil. When we take into account fossil fuels and how they will be replaced by different renewables, the total amount of energy generated by fossil fuels cannot be accounted for by current renewable capacity without hydrogen or e-fuels.

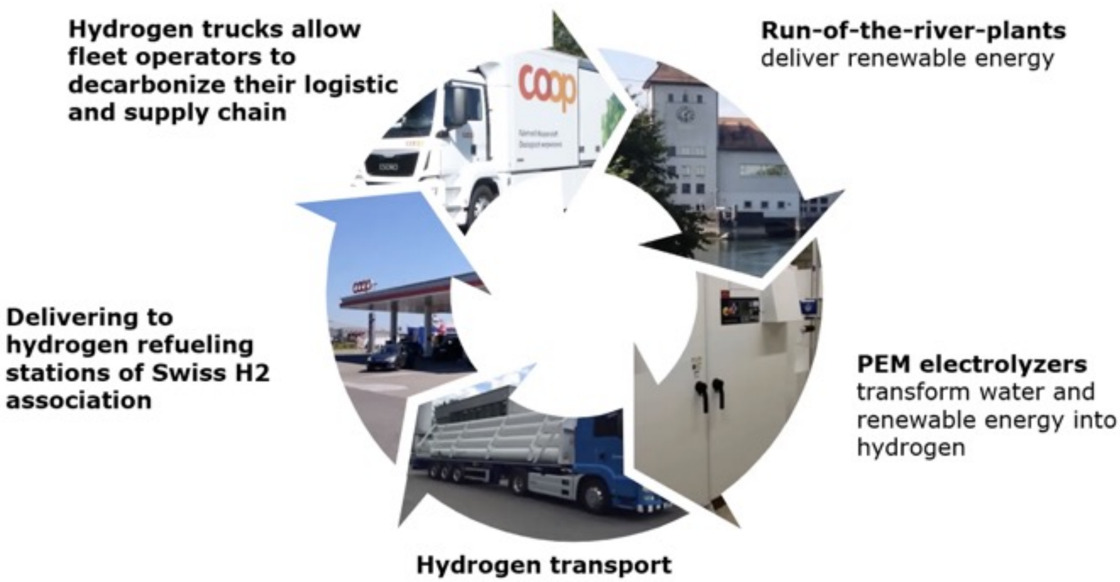
One of H2energy's flagship projects was in collaboration with the chain supermarket Coop to convert their truck fleet to a zero emissions fleet in Switzerland. BEVs don't have the payload or the charge-rate that Coop required, so H2energy built Coop a FCEV truck with support from the Department of Energy in Switzerland. Following this, H2energy proceeded to build a hydrogen refueling station in Switzerland, and then expanded the scope to provide Coop with a green hydrogen production system, completing a small H2 eco-system in less than a year.

Figure 25: Sources of Electricity Now and in the Future



This initial project demonstrated that a truck fleet powered by hydrogen fuel cells is a viable zero emission option for companies, and what's more, that there's demand for these systems. Switzerland has a punitive emissions tax for heavy-duty vehicles that can be avoided with FCEVs, allowing H2energy to offset the price of the vehicle as well as necessary fuel. H2energy decided to expand on their initial project with Coop by creating a pay-per-use business model: clients pay to use trucks in H2Energy's fleet, using fuel and stations provided by H2energy's hydrogen ecosystem. H2Energy partnered with Hyundai, Linde, and Alpiq to scale-up the venture. Hyundai produced 46 FCEV trucks that as of October 2020 are available to clients, and have committed to a full scale production starting later in 2021 with the potential to produce 2000 trucks per year across Europe.

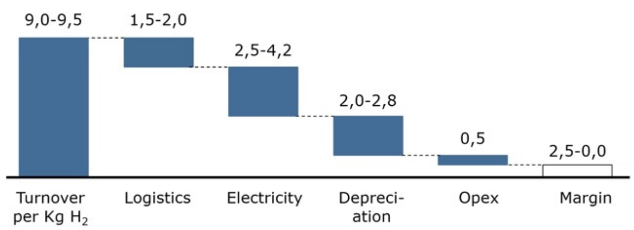
Figure 26: H2energy's Ecosystem



Figures 27 & 28: H2energy's Hydrogen Containers and Fuel Cell Truck Fleet

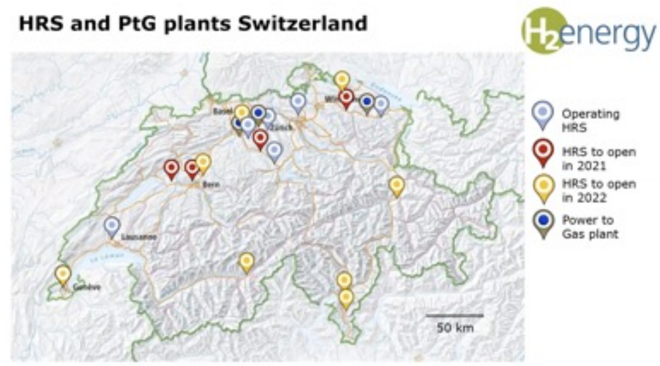
H2energy also partnered with Alpiq and Linde to create Hydrospider, a company that produces and sources low cost green hydrogen. Specifically, Hydrospider produces electricity and uses it to drive a Proton Exchange Membrane electrolyzer to produce hydrogen. This hydrogen is then transported in containers to refueling sites where it is swapped with an empty container. For this to be a profitable business, H2Energy estimates that they need to achieve roughly 9.5 CHF (Swiss francs) per km travelled (See Figure 29).

Figure 29: Financial Breakdown of Profit Margins per Refueling Station



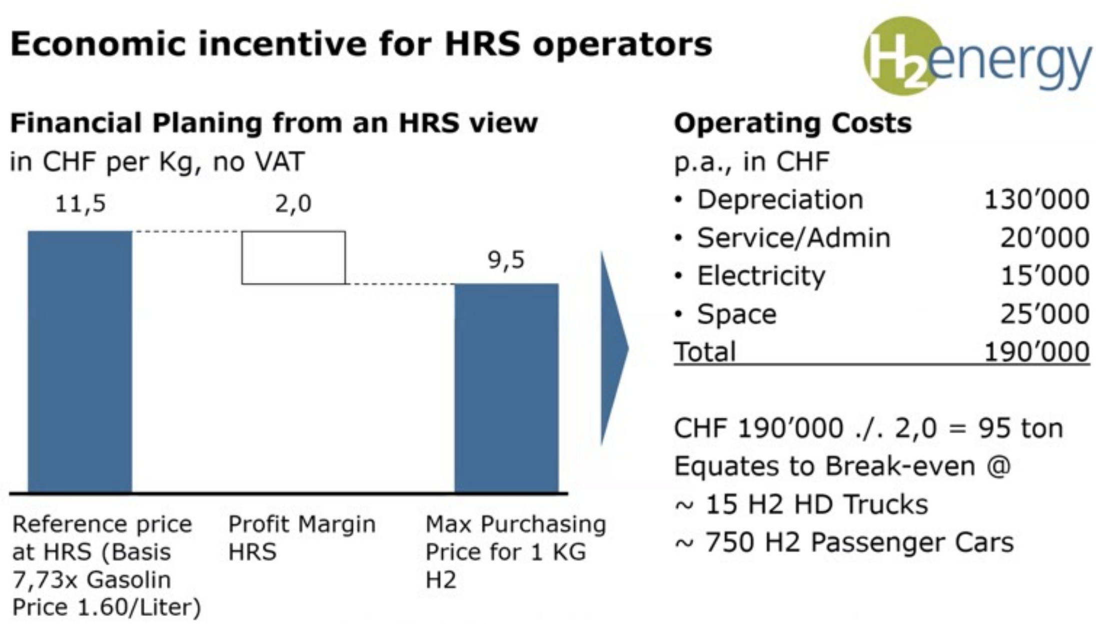
H2energy's most recent partner is the Hydrogen Mobility Association of Switzerland, which was founded with seven petrol companies that cover 80% of petrol stations in Switzerland, including Shell, and 14 of the largest transportation and logistics companies. With this support, H2energy has privately financed 6 hydrogen refueling stations across Switzerland, and has another 4 stations opening soon with 8 more planned to open in 2022.

Figure 30: H2energy Proposed Hydrogen Network



In order to break even and remain competitive, the hydrogen price at the pump has to be less than or equal to roughly 7.7 times the cost per liter of diesel: for example, if gasoline in Switzerland costs 1.60 CHF, then the cost per liter of hydrogen cannot cost more than 11.50 CHF. If the profit margin for the hydrogen refueling station is 2 CHF, and the annual operating cost for the station is $200,000, then 95 tons of hydrogen need to be sold in a year to break even. To achieve these numbers, over 700 passenger cars would need to regularly use the refueling stations, however only 15 trucks are required to match these same numbers.

Figure 31: Break Even Analysis for H2energy Refueling Station



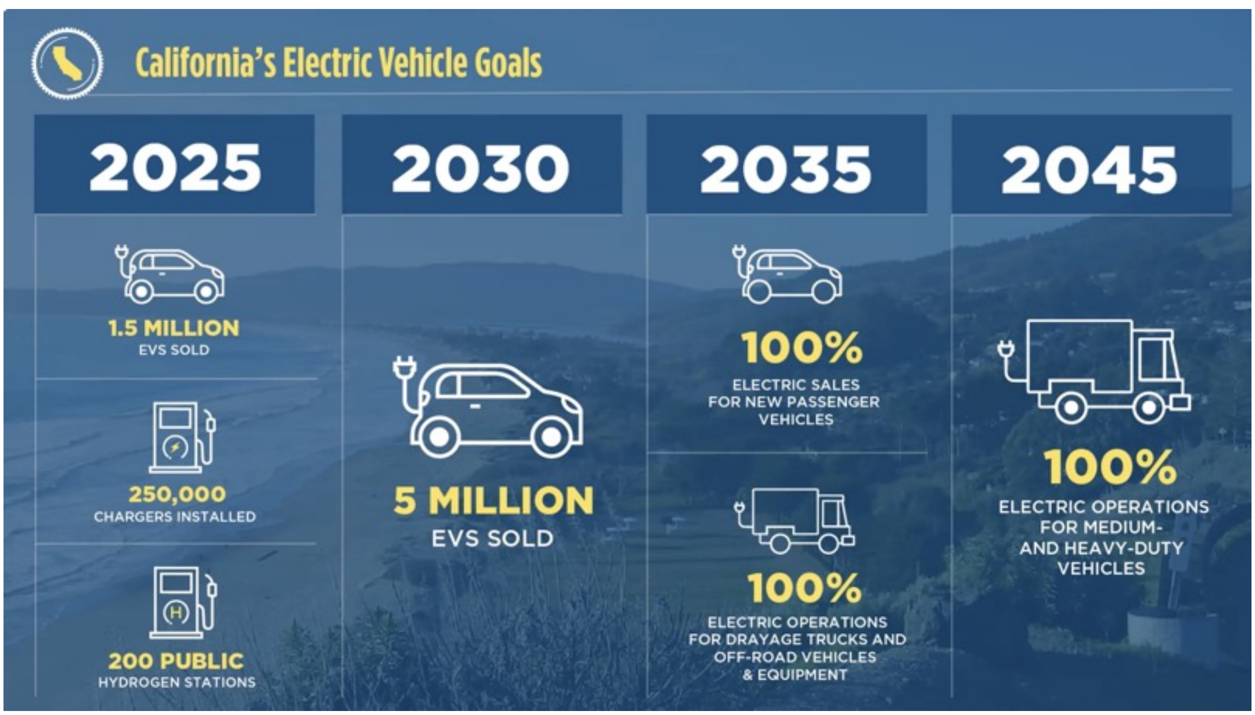
As part of a belief in a free market economy, both Plug Power and H2energy share the understanding that this infrastructure should be privately funded. It is the job of the suppliers and businesses to make this economically viable. This can be done by approaching hydrogen vehicles and infrastructure as an entire ecosystem to be developed at the same time, as seen through H2energy and Plug Power's work. Treating infrastructure and demand as separate problems that need to eventually be matched does not appear to be a fruitful view. Government incentives can play a crucial role in encouraging early adoption of ZEV and associated infrastructure, but private markets should decide which technology is best to ensure that solutions will remain economic in the long term. H2energy suggests that in order for markets to make rational decisions on the technology, external costs must be considered. Consequently, governments must correct for the effect of external costs. This can be done most effectively by allocating external costs to its originators. If said allocation is being implemented properly, H2energy is convinced that solutions based on green hydrogen and fuel cell technologies offer a commercially superior solution for a wide range of applications.

GOVERNMENT INVOLVEMENT

California has a problem, specifically caused by the transportation sector. Transportation is the greatest cause of greenhouse gas emissions in California, accounting for half of the states' emissions, with 40% from the vehicles and 10% from the production of the fuel to power the vehicles.[1] Furthermore, these numbers continue to rise as more people are driving longer distances. At the same time significant advances in technology and the renewable sector are causing overall reductions in greenhouse gas emissions.[2] But we're seeing reductions in GHGs overall due to advances in renewable energy in the power sector. The solution has to be zero emissions in the transportation sector. California has a suite of targets (See Figure 32):

The ZEV market share of passenger vehicles is growing, mainly between hybrids and plug-in BEVs, as well as roughly 10,000 FCEVs as of 2020.

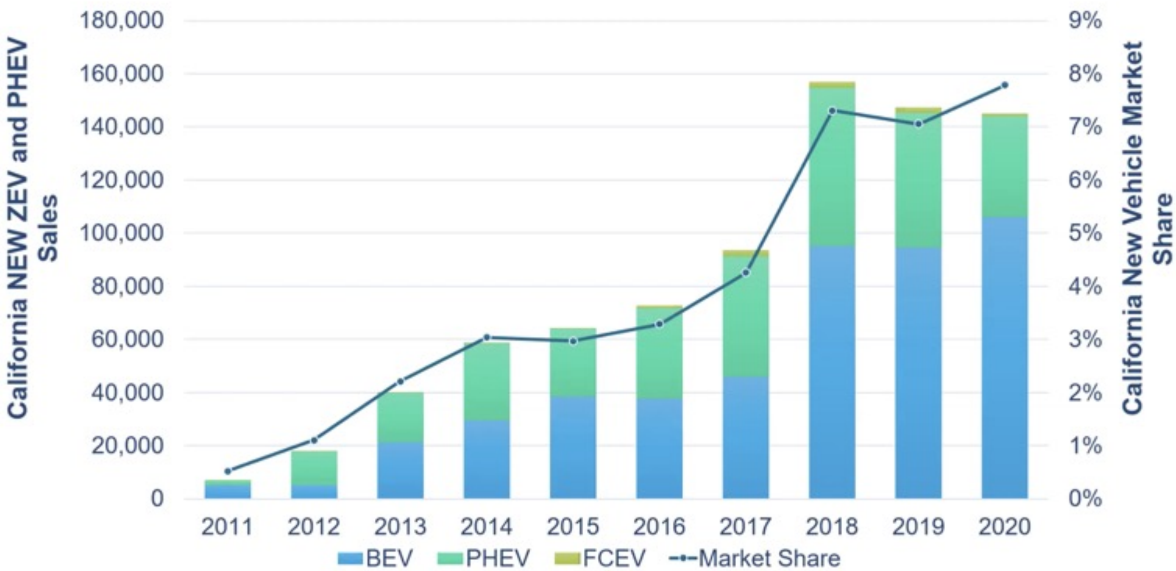
Figure 32: California Electric Vehicle Targets



1 Source: 2020 Integrated Energy Policy Report Update Volume 1

2 Source: Ibid

Figure 33: Projected Growth of PHEV and ZEV Vehicle Sales in California



California has been a leading proponent of low carbon vehicles, markedly since 2009 with the creation and implementation of CARB's Low Carbon Fuel Standard Regulation that provided national incentives for producers and users of vehicles to use low carbon fuels. More recently, in 2018 the Innovative Clean Transit Regulation was implemented to encourage transit operators to move towards zero emission fleets, and in 2020 the Advanced Clean Trucks Regulation that requires truck manufacturers to have a percentage of zero emission vehicles. To do this the government has invested about $100 million a year into the **California Energy Commission**'s Clean Transportation Program to advance zero emission technology and fueling infrastructure for zero-emission vehicles.

Figure 34: Growth of Hydrogen Infrastructure in CA, CEC

Light-Duty Network Growth

Year-to-Year Growth	2016	2017	2018	2019	2020
Open retail stations	25	31	39	43	45
Average daily hydrogen dispensed (fueling demand)	340 kg	1,400 kg	2,700 kg	3,400 kg	2,800 kg
Cumulative light-duty FCEV sales or leases in California	1,148	3,271	5,667	7,751	8,751
Percentage of disadvantaged community population that live within 15 minutes of an open retail station	12.8%	18.6%	23.0%	23.3%	23.5%

Note: The average daily hydrogen dispensed is the average for Quarter 3 of each year.

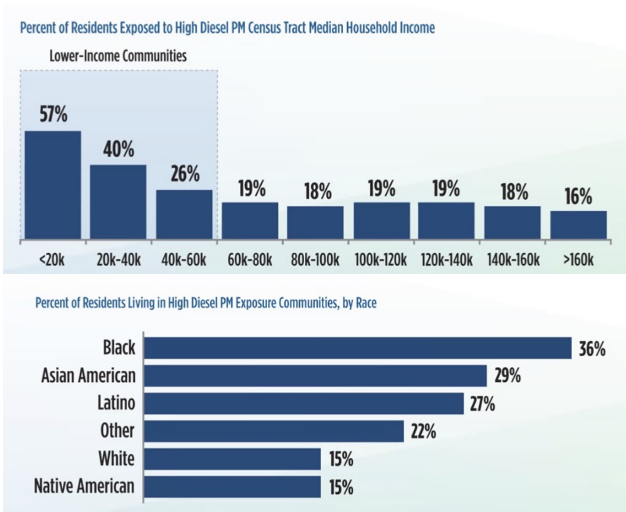
In California there is a distinct increase in demand for hydrogen and FCEVs. There are 47 open hydrogen refueling stations; this number is projected to increase to 179 stations by the end of 2030.

In particular, the California Energy Commission (CEC) recognizes the advantages FCEVs have over BEVs in the heavy-duty transport sector, including shorter refueling times, longer ranges, and lighter weights. The CEC is planning to fund 13 dual purpose (heavy, mid and light-duty) refueling stations, and are also partnering with Shell, Toyota, and the Port of Long Beach to operate a hydrogen fueling station for mid- and heavy-duty vehicles .

In California the state government is mandated to provide funding for at least 100 light-duty hydrogen refueling stations. However there is no such requirement for heavy-duty infrastructure, leaving the market open to private industries. However the CEC believes for hydrogen to fully succeed in the heavy-duty transport sector, California does need to provide some support for the infrastructure required. This would involve carefully structuring investment programs to both support this sector and ensure that it is sustainable without the state's continuous support.

It is important to recognize that there is a disparity in the populations that are affected by transportation emissions: low income communities and people of color are at a greater risk of diesel particulate pollution due to where these communities are located (See Figures 35 & 36).[3]

Figures 35 & 36: Graphs Demonstrating the Disproportionate Impact of Diesel Emissions



To address this, the world's first ZEV truck requirement comes into effect in 2045, stipulating that all truck sales are zero emission vehicles by this time. To support this regulation, the CEC is working to deploy fueling infrastructure to support this increase in ZEVs with programs such as its a partnership with CALSTART to administer EnergIIZE, a developing incentive program for fleet operators to obtain funding for initial infrastructure to support their zero emissions fleet. Other programs include the Carl Moyer Program, California Core, California HVIP, and the Clean Transportation Program.

The CEC has several project demonstrations planned to display fuel cell vehicles in the marine and rail sectors. The first demonstration with GTI Energy is switching a locomotive engine to be entirely fuel cell powered. The second is with Calstart who will lead the design of a hydrogen fuel cell powered tug-boat. Third, Golden Gate zero is producing a hydrogen powered passenger and patrol vessel in Northern California. Further advances in the fuel cell sector include Sunline Transit agency adding 17 fuel cell electric buses to their fleet, and North County Transit San Diego will add 25 buses to their fleet by 2025. The CEC are also funding a project that will provide funding for 100 BEV drayage trucks, and a project that will demonstrate up to 30 FCEV drayage trucks.

Moving to the federal level, the Department of Energy supports the ZEV space through grants, research, and development. At the DoE, the transportation offices are divided into vehicle technology, hydrogen fuel cell technology, and biofuel technology offices. They work with stakeholders across the government to advance the DoE's strategy to decarbonize the transport sector. Their current focus is 'demonstration and deployment'. The most recent government plan to this effect includes:

- $600 billion to modernize infrastructure with priorities for electrification for transportation, including funding for BEVs and FCEVs.
- $174 billion for the electric vehicle (EV) supply chain, including EV chargers, and transitioning buses and federal fleet.
- $17 billion for investments in ports, especially for ports in areas surrounded by disadvantaged communities.
- $100 billion in renewable power and grid investments.
- $15 billion in climate research, including hydrogen market research.

3 Source: 2020 Integrated Energy Policy Report Update Volume 1

With respect to the transportation sector, the DoE expects to see hydrogen FCEVs primarily in the MDV and HDV sectors, with some light-duty FCEVs in pockets across the country, such as in port cities with a surplus hydrogen infrastructure. Interestingly the DoE does not believe that there is one 'silver bullet' solution, but rather there should be a mix of FCEVs, biofuel vehicles, and BEVs in the medium- and heavy-duty vehicle industry. The DoE recently announced a new initiative called H2@Scale which aims to accelerate research in hydrogen production, transportation, storage and end use activities. This initiative has found the hydrogen costs will be crucial in determining the market share of FCEVs in the transportation sector. Consequently the DoE is looking at strategies to drive hydrogen costs down to leverage hydrogen technology as much as possible. The biggest challenges facing hydrogen adoption as well as zero emission vehicles in general are:

1. Reducing costs.
2. Manufacturing needed to produce ZEVs at scale.
3. Supply chain requirements: including where materials are sourced from, and ensuring that the supply chain benefits first and foremost the American job market.
4. Inclusivity: ensuring that a diversity of voices are heard from communities that would be affected by any resulting policies.
5. Infrastructure: The government currently has intentions to fund a national EV network for light-duty vehicles under the assumption that BEV sales will increase over the next decade. This same question exists for FCEVs and the infrastructure required to support a fuel cell powered heavy-duty fleet. However the DoE also questions to what extent a heavy-duty fleet is required, and if there are alternative methods of transportation that could be used to phase out HDVs.

INFRASTRUCTURE SUMMARY

Key messages are:

- Infrastructure is a key consideration for the rollout of low carbon solutions for the transport sector;
- OEM (Original Equipment Manufacturer) investment in heavy-duty vehicles and cost reduction via manufacture at scale must be staged with investment in infrastructure for recharging or refuelling (hydrogen). This is particularly important for hydrogen, where cost sharing of transport, storage and dispensing infrastructure across applications can enable lower unit costs when deployed at a large scale;
- Pipelines, as well as gaseous or liquid transport infrastructure and costs must be considered along with distributed generation of hydrogen in optimizing supply chain roll out;
- Policy support for infrastructure investment is needed to enable the initial deployment of low-carbon transportation options.

Trains

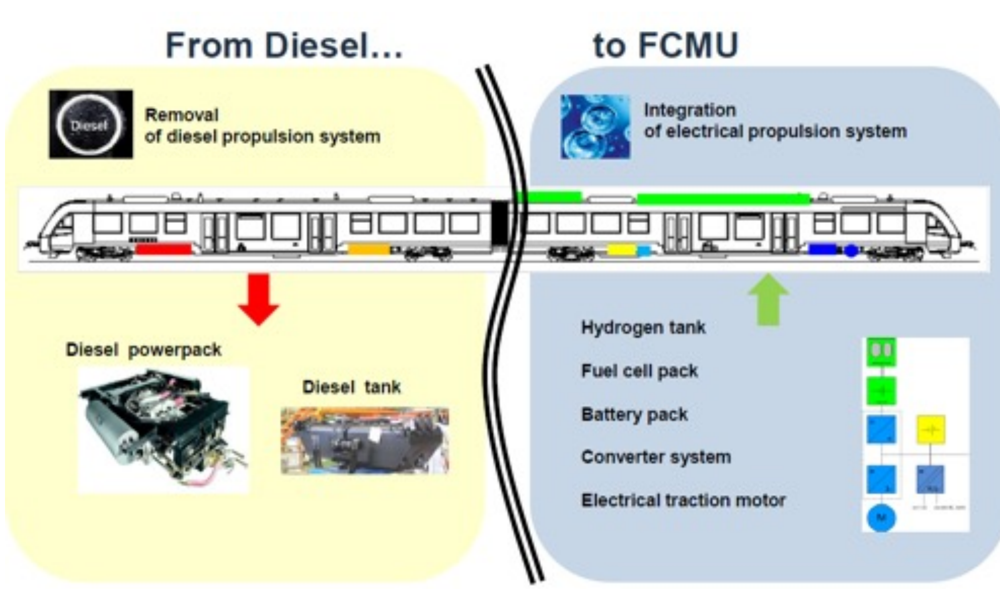
Alstom "Coradia iLint" hydrogen fuel cell electric multiple unit (FCMU) zero-emission trains have been demonstrated for regional transit in the **Deutsche Bahn** railway in Germany, the largest revenue global rail line (Figure 37). Demos have been ongoing since 2018 including routes with daily revenue service, and have now totaled more than 180,000 km of use. The prototype trains are being redeployed for new test routes across Germany including the Black Forest, Franken, Oldenburg, Ludwigshafen, Rottenbach, Berlin, Kiel, and Mainz. The demonstrations deploy mobile refueling and allow continuous improvement of hydrogen tanks, fuel cell composition and energy management systems. One train removes 700t CO_2/year, the equivalent of emissions from 400 cars.

Figure 37: Coradia iLint H_2-powered Train

FCMUs have a range of up to 1000 km, versus only 80-120 km for a battery electric multiple unit train (BEMU). The use of battery electric with diesel in hybrid configurations is also plausible for some routes, especially where catenary electric lines are available. However, fuel cell hydrogen trains are the emission-free answer where hydrogen can be considered a direct replacement for diesel service, which is dominant for many regional and longer distance routes in Germany and North America. North America has 30,000 trains, most operating off of diesel mobile units (DMU), and hence hydrogen is an attractive option for decarbonization. Scalable, fast fueling is a big advantage vs. grid charging for electric trains. The same track can be used so no catenary or third rail is needed, which is a great savings in capital costs. However, trains must be retrofitted to electric direct drive. Ultimately, as the cost of hydrogen decreases with production scale and technology advances, it is anticipated that hydrogen trains will have a lower total cost of operation compared with diesel. Improved operational performance of fuel cells and optimization of refueling infrastructure is also part of ongoing cost reduction. To this end **Sandia** is focusing on materials for production, storage, and use of hydrogen, as well as hydrogen safety including risk analysis and modeling to help establish codes and standards, offset distances for refueling and other system safeguards.

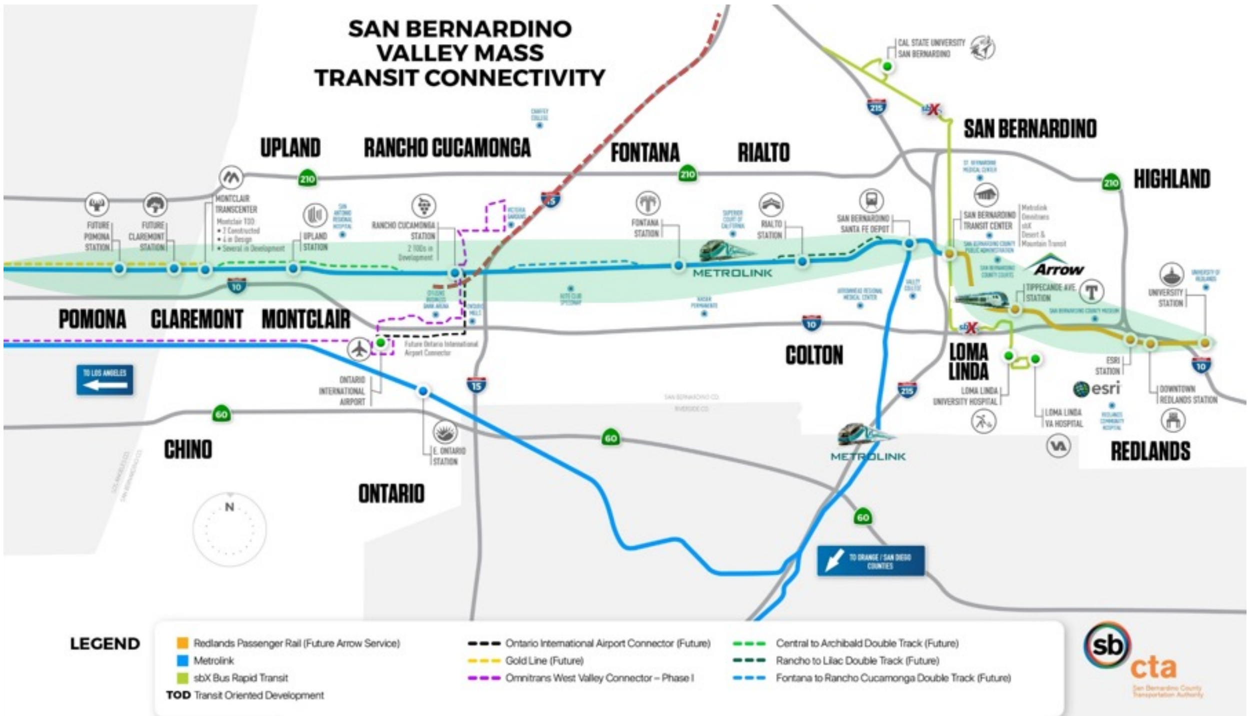
Figure 38 shows the transition from diesel "Lint" to fuel-cell "iLint" multiple units in the Alstom Coradia series, including a move to direct drive motors augmented by battery storage.

Figure 38: Adapting From Diesel to Hydrogen Fuel Cell and Direct Drive



San Bernardino County Transit Authority (SBCTA) will demonstrate the first North America hydrogen-powered train via transitioning Diesel Multiple Units (DMU) to hydrogen-powered Zero Emission Multiple Units (ZEMU) for testing 2023 – 2024 via a Redlands to San Bernadino 9- mile corridor demo (Figure 39).

Figure 39: 9-mile "Arrow" Corridor Will Provide First North American Hydrogen-powered ZEMU Train



Ultimately this will be expanded via service to Los Angeles. Installing catenary lines is expensive and has low public acceptance, such that hydrogen with fast refueling makes the best use of existing infrastructure for diesel lines where electric infrastructure is not already present. A detailed study was conducted to compare electric trains using wayside power, battery, supercapacitor, biofuel, natural gas, and hydrogen options. Factors considered included:

- Cost (20%): capital, operations and maintenance;
- Infrastructure (10%): right-of-way, charging and fueling, utilities;
- Environmental (15%): land use, GHG, aesthetics, noise, socio-economic factors;
- Operations (25%): range, scalability, reliability, operations, life span;
- Regulatory compliance and stewardship (10%): railroad administration, fire safety codes, non-governmental organization involvement;
- Implementation schedule (10%): timeline for planning, design, construction;
- Risk analysis (10%): identify and document risks for further analysis.

Detailed performance and energy usage modeling was conducted to assess options. Primary inputs were vehicle characteristics (mass, loading condition, tractive & braking curves, rotating inertia, electrical efficiencies and auxiliary loads) as well as track characteristics (distances, grades, curves, speed limits and restrictions). Key requirements for the specific applications were quantified, including power charge/discharge rates and required energy storage capacity. These criteria were used to assess technology feasibility. Scenarios included 2-car and 4-car hydrogen fuel cell (FLIRT), and combinations of 2-car hydrogen and 2-car diesel. The energy required between existing terminals for these scenarios was assessed, both with and without regenerative braking to improve energy efficiency.

Table 2 shows the preliminary screening results. On-board battery was thought to be the optimal solution prior to analysis, given the cost of electrifying track for wayside power. Surprisingly, hydrogen fuel cell options scored higher, with relative capital costs the only significant issue. Only hydrogen was deemed plausible for meeting California 2035 zero-emission targets.

Table 2: Screening of Emission-reduction Options for San Bernardino

Category	Baseline – Arrow DMU	Wayside Power Supply		On-Board Energy Storage System					Hybrid System			
Rail Technology	Diesel	Overhead Contact System (OCS)	Ground Level Power Supply – Third Rail	Battery	Supercapacitor	Hydrogen Fuel Cell	Biofuel	Natural Gas	Hydrogen Fuel Cell + Battery	Diesel + Battery	Biofuel + Battery	Natural Gas + Battery
Relative Capital Costs	Good	Poor	Poor	Moderate	Moderate	Moderate/ Poor	Good	Good/ Moderate	Moderate/ Poor	Good	Good/ Moderate	Moderate
Relation Life Cycle Cost	Moderate/ Poor	Good/ Moderate	Good/ Moderate	Moderate	Good/ Moderate	Moderate	Moderate/ Poor	Good/ Moderate	Moderate	Moderate	Moderate	Moderate
GHG Emissions	Poor	Good	Good	Good	Good	Good	Moderate/ Poor	Moderate	Good	Poor	Moderate	Good/ Moderate
Aesthetics	Good	Poor	Moderate	Good	Good	Good	Good	Good	Good	Good	Good	Good
Range	Good	Good	Good	Moderate	Poor	Good	Good	Good	Good	Good	Good	Good
Scalability	Good	Poor	Poor	Moderate	Moderate	Good	Good	Good	Good	Good	Good	Good
Life Span	Good	Good	Good	Poor	Moderate	Moderate	Good	Good	Moderate	Moderate	Moderate	Moderate
Regulatory Compliance	Good	Moderate	Poor	Moderate	Moderate	Moderate	Good	Moderate	Moderate	Moderate/ Good	Moderate/ Good	Moderate
Result	Baseline	Incompatible	Incompatible	Compatible	Compatible	Compatible	Incompatible	Incompatible	Compatible	Incompatible	Incompatible	Incompatible

Powertrain configurations are shown in Table 3 for what is actually a hydrogen fuel cell / battery electric hybrid system. Cost details are shown in Table 4. If the California grid moves to 100% renewables, the GHG emissions are reduced 100%. This also holds true for hydrogen production. On-site steam methane reforming does not allow carbon capture and storage, and hence GHG emissions are not reduced, and the option therefore does not meet the required decarbonization targets for California.

Hydrogen remains expensive, however. Key research areas to reduce costs are:

- Life cycle costs as compared to other alternative fuels;
- Hydrogen storage – ways to increase capacity and flexibility;
- Cost reduction regarding renewable hydrogen;
- Maintenance facility design – best practices for building facilities of the future;
- Component durability and impact resistance (e.g. Federal Railroad Administration (FRA) testing of an LNG tender car).

Table 3: Powertrain Type and Configuration for Hybrid Hydrogen Fuel Cell Train

Powertrain Configuration	HFC Hybrid
Mass (tonnes)	132
Max. Power at Wheels (kW)	700
Powerplant Power (kW)	300
Average Duty Cycle Powerplant Efficiency (%)	49
Battery Power (kW)	828
Battery Capacity (kWh)	138
Battery Charging Efficiency (%)	86

Powertrain Type	HFC Hybrid
Fuel Cell System	
Power (kW)	300
Mass (kg)	825
Volume (m^3)	1.5
Hydrogen Tanks	
Pressure (bar)	350
Hydrogen stored (kg)	220
Mass of tanks and hydrogen (kg)	3,150
Volume (m^3)	16.5
Battery System	
Mass (kg)	4,000
Volume (m^3)	4
Total	
Mass (kg)	7,975
Volume (m^3)	22

Table 4: Relative Cost and Emissions Reduction Performance for Battery and Fuel Cell Options

	BATTERY		HYDROGEN FUEL CELL HYBRID			
	TRACTION POWER SUBSTATION (TPSS)	WAYSIDE ENERGY STORAGE SYSTEM (WESS)	HYDROGEN DELIVERY	ON-SITE STEAM METHANE REFORMING	ON-SITE ELECTROLYSIS	
CAPITAL COST (TO PURCHASE ONE NEW ZEMU VEHICLE)	$29 M	$31 M	$33 M	$33.8 M	$34.6 M	
ANNUAL O&M COST (TO OPERATE FULL ZEMU ARROW SERVICE 2 VEHICLES)	$769 K	$690 K	$1.2 M	$540 K	$856 K	
EMISSIONS REDUCTION (PERCENTAGE IN COMPARISON TO DMU BENCHMARK)* — Energy	60%	57%	45%	21%	-24%	55%
GHGs	75%	100%	25%	37%	25%	100%
NOx	98%	100%	96%	96%	95%	100%
PM2.5	97%	100%	93%	95%	89%	100%
PM10	93%	100%	90%	95%	79%	100%
CO	90%	100%	82%	79%	71%	100%
	CA GRID MIX	IF 100% RENEWABLE			CA GRID MIX	IF 100% RENEWABLE

*EMISSIONS LEGEND
Energy GHGs NOx PM2.5 PM10 CO

Figure 40: California Intercity Passenger Rail

The state-run Caltrans intercity rail differs from commuter rail because it essentially leases tracks owned by freight railways. Caltrans routes are shown in Figure 40. Any decarbonization pathways determined by Caltrans will be relevant and applicable in decarbonizing heavy freight rail, which accounts for the majority of rail emissions.

Caltrans has conducted a study of zero-emissions options and will have deployment goals developed in 2021. Zero-emissions targets for intercity are to be developed by 2035. The overarching targets are 15% less fuel use by 2025 and 35% less by 2030, with 100% reduction in GHG and criteria pollutants for trains by 2035 (Figure 41). The results of the study (Figure 42) indicate that hydrogen fuel cells trains are the preferred option, primarily due to similarity in operating cycles and infrastructure with the diesel units being replaced. Neither the incumbent diesel nor renewable natural gas options meet the goals for zero emission due to criteria pollutants. Electrification is not feasible due to high capital cost for catenary or third-rail line additions. Battery powered trains do not provide the power needed for longer routes, and the long charging times and cost of wayside charging are impractical.

Figure 41: Caltrans' Zero emission Goals

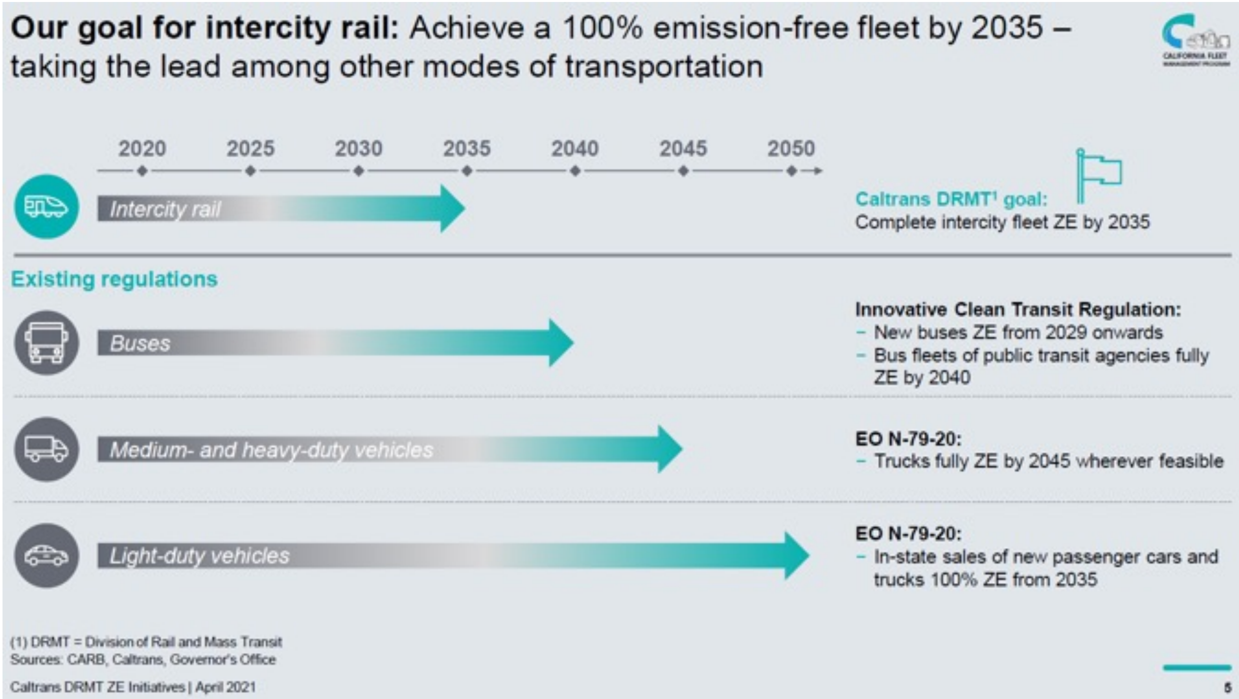
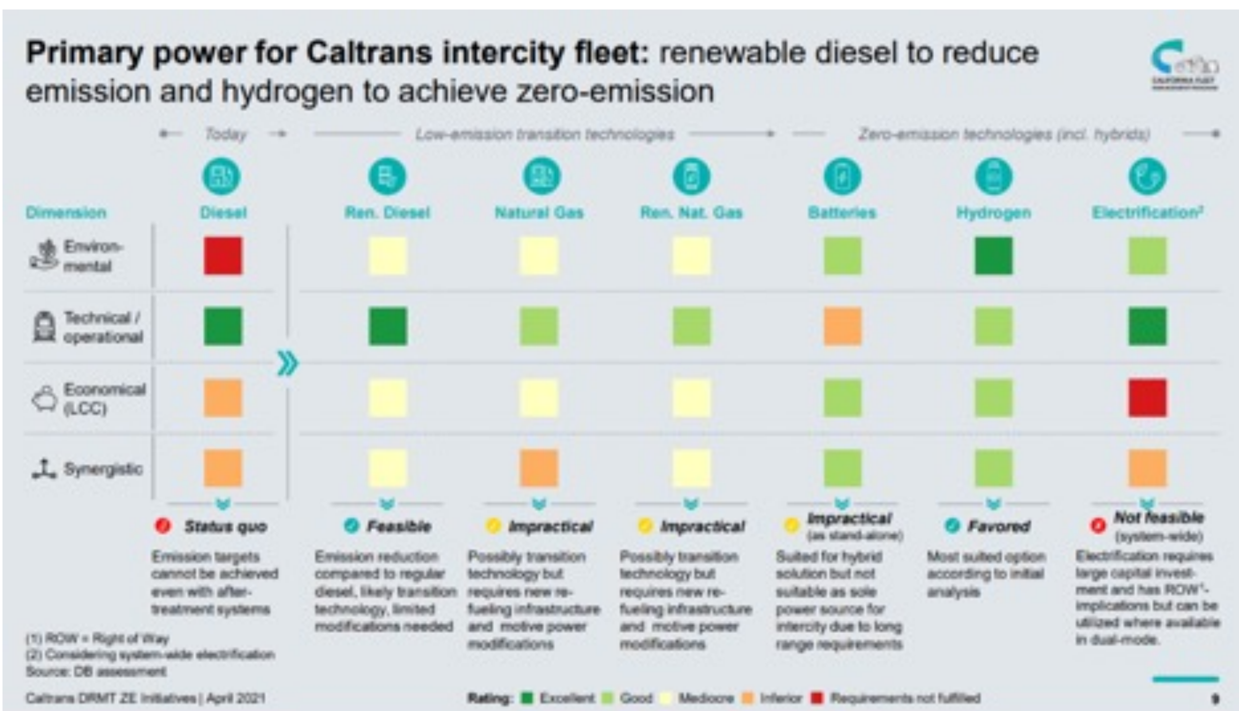


Figure 42: Caltrans Matrix for Options Selection and Results Ranking



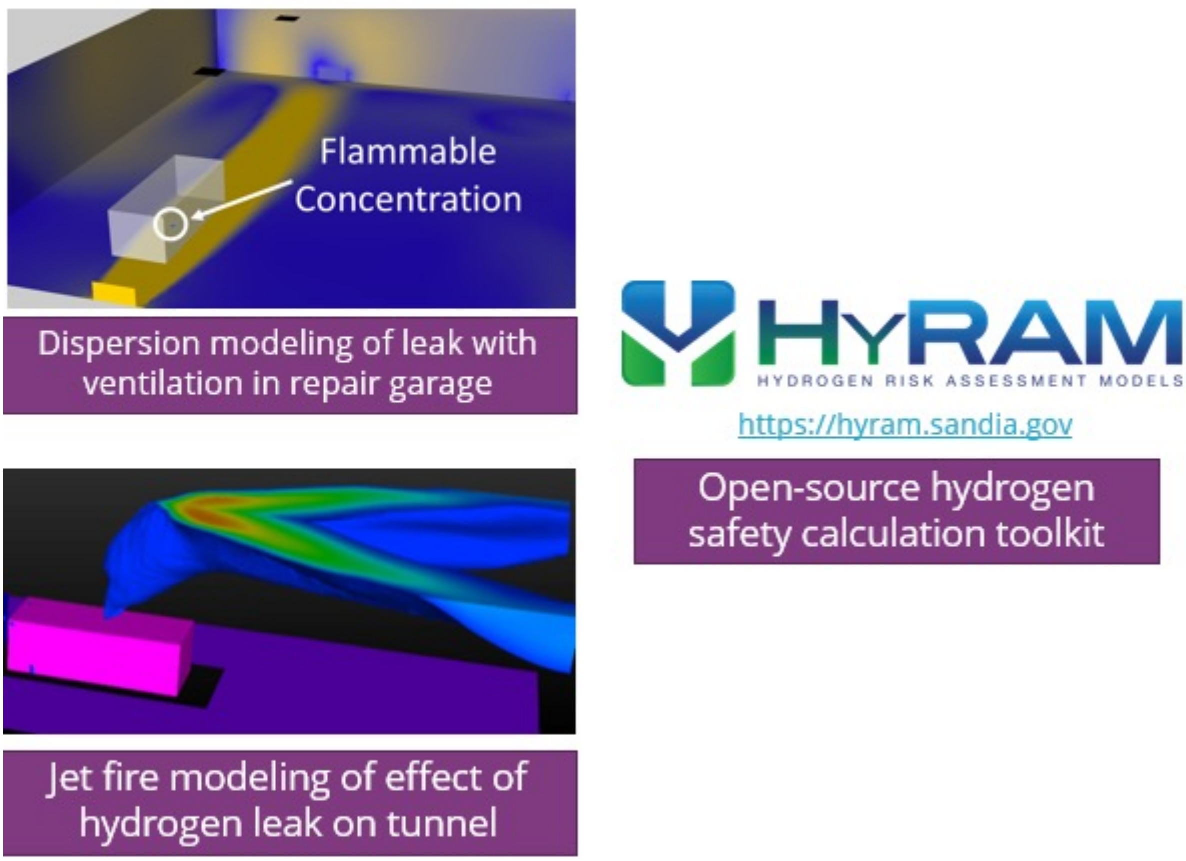
The decarbonization roadmap for Caltrans has a mix of renewable diesel as an intermediate solution, followed by full implementation of hydrogen. Reduced idling of diesel engines via the use of ground power will also curtail emissions. Full transformation to ZE by 2035 with hydrogen as focal point is an ambitious plan relative to global precedence and status.

Sandia labs provides support to Alstom iLint and similar rail programs[1,2,3] with a focus on (1) materials for production, storage, and use; and (2) safety, including codes and standards, as well as risk analysis and modeling (HYRAM).[4] For hydrogen options, scalable, fast fueling is a big advantage vs. grid charging. In rail applications, the same track can be used so no catenary or third rail is needed. For vehicles, typically one is using captive fleets and routes, so refueling infrastructure needs are less. A switch from diesel to electric requires direct drive motors.

Energy is required to store hydrogen. Regime is cryogenic if in liquid form, such that one has the risk of either high pressure (compressed gas) or very low temperature (liquid) for storage. There is no resource contamination risk if spilled. One can avoid the need for catenary or 3rd rail, improving aesthetics and delivering cost advantage. Refueling and maintenance infrastructure costs must be considered. Infrastructure for rail can support other hydrogen applications.

HYRAM (Figure 43) is an open source model for risk assessment. Train standards must be modified for hydrogen, as hydrogen standards are currently not written with trains in mind. Other risk considerations include embrittlement relative to shock impacts, offsets and layouts for refueling facilities. Both gaseous and liquid refueling options must be considered and optimized.

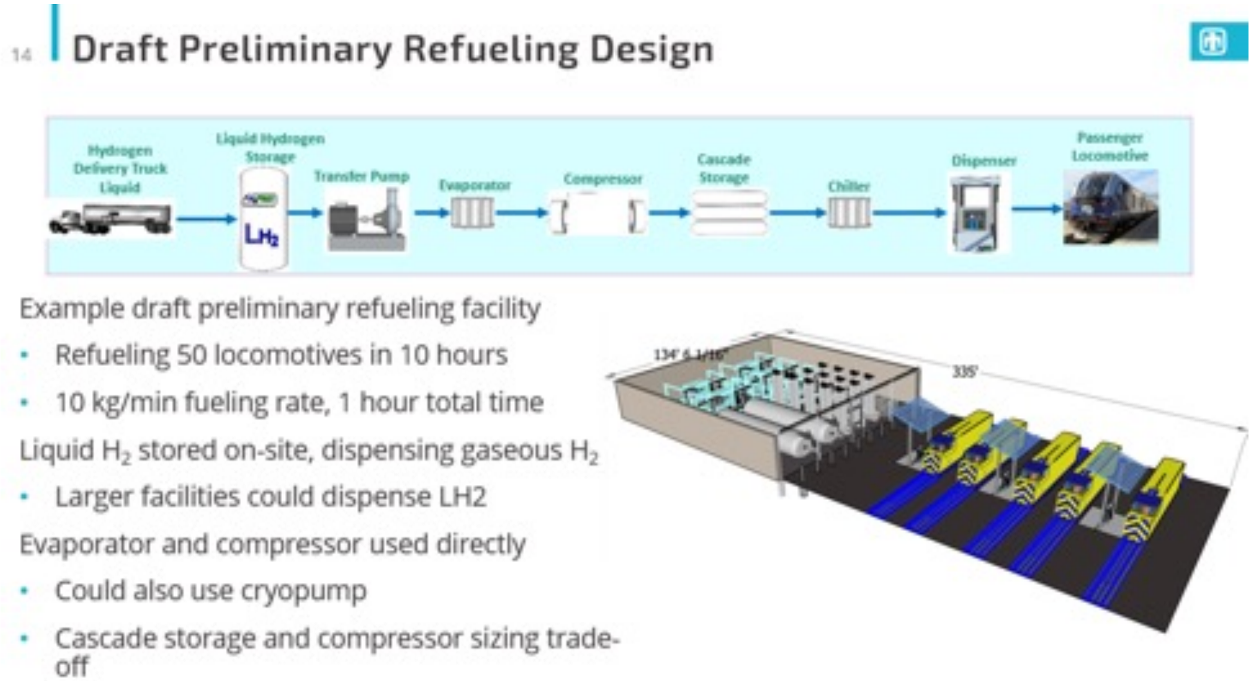
Figure 43: HYRAM Hydrogen Risk Assessment Model



1 https://www.nrel.gov/docs/fy02osti/32405a30.pdf
2 https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-hoffrichter.pdf
3 https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-cleveland.pdf
4 https://h2tools.org/hyram

Infrastructure and safety is important in addition to the trains themselves. Refueling speed is important for "tight" operations where one cannot refuel or recharge overnight. A draft refueling design for trains developed by Sandia is shown in Figure 44.

Figure 44: Draft Refueling Design for Hydrogen Trains



TRAINS DISCUSSION

What is required to move forward in decarbonization? Support at the Federal level is needed to incentivize the decarbonization of rail and bring lifecycle costs down. Safety codes and standards are difficult to develop until systems exist, and there is a need for sharing of relevant safety data and designs. A repository of information would be useful to operators as they start to deploy pilots, including details of crash testing and components and costs of retrofitting locomotives vs. buying new units. There is also an opportunity for developers to collaborate on refueling and charging infrastructure.

Is there a competition between battery and fuel cell options for electric trains? Batteries are actually included in hydrogen fuel cell trains, and hence the two are complementary. Hydrogen trains represent a direct diesel replacement, with same operations and maintenance cycles, unlike the battery-only option which allows only shorter cycles with long recharge times.

What does a change from battery-electric (only) to hydrogen fuel cell (with battery) mean? It means space savings (as seen in forklift operations) in moving from battery to hydrogen fuel cell, requiring less infrastructure for refueling. hydrogen brings flexibility in operation.

How have externalities been considered? North America is dominated by diesel, and hydrogen is a direct substitute. Ideally we would become more efficient in fuel cell power output, to directly replace diesel combustion, and a DOE modeling effort on freight will provide critical data on this. Note that the Metrolink climate action plan calls for a 2028 selection of an option for zero emission commuter trains. A very good feasibility study is needed to make a decision!

Has the direct combustion of hydrogen vs. use in fuel cells been considered? Yes it has to reduce cost of engine retrofits, but efficiency is reduced to as low as 30% relative to fuel cells at 50% efficiency.

What about the potential for increased efficiency with high-temperature solid oxide electrolyzers? This is an attractive idea, one can take advantage of temperature gradients and run a second energy cycle. But stability of operation is problematic. Lower temperature PEM electrolyzers can stabilize much faster. Optimal choice of electrolyzer depends on use cycle.

TRAINS SUMMARY

Key messages:

- Hydrogen powered trains have been successfully demonstrated in Germany.
- Unlike electrification or battery power, existing diesel train operating cycles and rail lines can be used with hydrogen, once hydrogen refueling infrastructure is provided.
- Electrification via catenary overhead lines or third rail is costly, and generally not favored by the public.
- With future drop in hydrogen price due to scale of production, total cost of ownership for hydrogen powered trains can be on par with diesel. Given similar infrastructure and use cycle, hydrogen is a natural option for replacement of diesel, which powers the majority of rail in North America.
- Further research and modeling of safety scenarios and risk to update codes and standards is required for roll out of hydrogen transport.

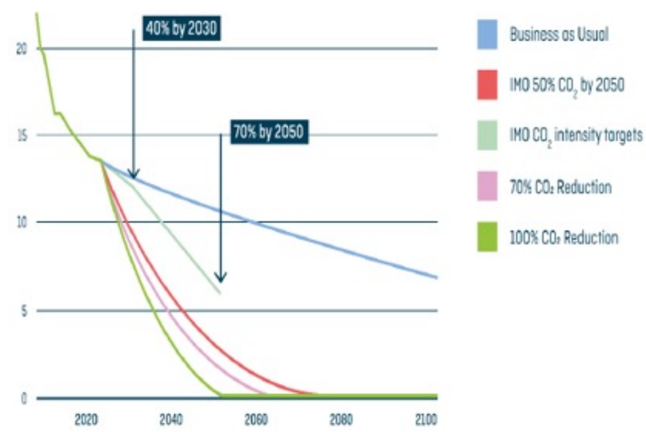
Marine and Aviation

MARINE (SHIPPING)

Shipping today accounts for about 2.5% of global GLG emissions, yet 80% of global trade[1]. Shipping has a shorter-term option to decarbonize via the use of ammonia as a preferred energy vector. This propulsion "of the future" can be ready by 2024-25, but the economics do not work, as currently green ammonia is 3 times more costly than marine bunker fuel. **Trafigura** has examined various transportation fuels and believes that the hydrogen-based fuels green methanol and green ammonia will be the transport fuels of the future to achieve zero emissions in the near term. However, there is a critical need for a global regulatory framework to neutralize costs of the low- and zero-carbon fuels, and regulations are lagging aspirations although a significant global agenda is building also on the back of Trafigura white paper launched Sept/20 – 'an IMO-led global shipping industry decarbonization programme'. The International Maritime Organization or "IMO" is the UN body which governs global shipping. The IMO's current target to reduce CO_2 by 50% by 2050 vs 2008 levels (Figure 45) is not aggressive enough. While targets can be revised, the strongest possible regulatory framework is needed to support investment. The IMO shipping proposal brought forth last year by Trafigura[2], saw inspiration drawn from the California Low Carbon Fuel Standard policy model.

A carbon levy between $250-300/mt of CO_2eq on shipping fuels is needed to make zero- and low-carbon fuels more economically viable, and close the competitiveness gap to carbon-intensive fuels. Trafigura is not alone in requesting carbon regulations for maritime vessels and global leading industry players are now following suit recommending a price on carbon within the maritime industry. A global price on carbon would be groundbreaking as less than 12 months ago this was seen as an impossible achievement.

Figure 45: IMO Shipping Targets for GHG Mitigation



AVIATION

GHG emission reduction targets for aviation are shown in Figure 46. Reductions for 2050 will occur mostly by use of sustainable aviation fuel (SAF), as well as new technology. The goal is to reduce GHG footprints to less than 50% of 2005 emissions by 2050, but there is discussion about making the goal to be zero net emissions by 2050. Airlines are buying carbon offsets today for the 13,000 airliners worldwide. Operations improvements, such as automation of routing relative to weather, traffic, wind, using big data and data analytics, could reduce emissions by about 8%. Automation inside the cockpit can also reduce fuel use. It is estimated that 40% of emission reductions will occur via new technology in next generation aircraft in service by the 2035 timeframe, which will in turn have an impact by 2050.

SAF is an intermediate carbon-reduction solution for single-aisle & regional aircraft over short to medium terms. Up to 50% SAF blend can be used to fuel single-aisle aircraft today, resulting in up to 85% CO_2 reduction across the entire lifecycle. More than 250,000 flights have been operated on SAF to date and all aircraft are approved for up to 50% blend.

Hydrogen emits no CO_2 and when used in fuel cells has the potential to reduce non-CO_2 emissions (i.e. NOx) as well as persistent contrails, enabling true zero-emission operation. Production from clean or renewable sources is needed to provide lifecycle GHG footprint reduction. The cost of

1 Fourth IMO Greenhouse Gas Study (2020); www.imo.org

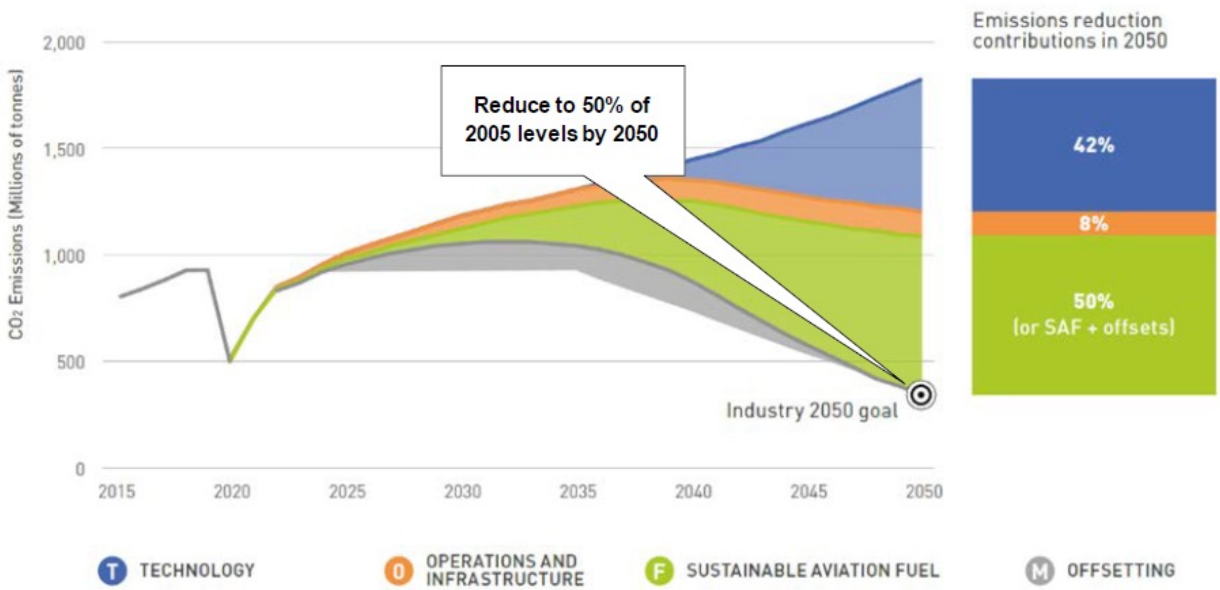
2 https://www.trafigura.com/brochure/a-proposal-for-an-imo-led-global-shipping-industry-decarbonisation-programme

producing hydrogen is likely to decline over the next decade, which will make zero-emission flying increasingly economical. Hydrogen is three times greater in specific energy (per mass) than jet fuel but has a lower volumetric density such that four-times more volume is required, thereby requiring a different approach to on-board storage.

Technologies include hydrogen combustion, which generates thrust by burning liquid hydrogen. Hydrogen fuel cells are also employed, converting energy stored in hydrogen into electrical energy to power electric motors. Synthetic fuel options use combustion for propulsion, and entail forming a net-zero carbon fuel derived from renewable hydrogen & CO_2.

Challenges include technology compatibility, bringing airplane weight and costs down by improved technology and increasing the scale of hydrogen availability. The growth of renewable electricity will increase the cost-competitiveness of hydrogen. Infrastructure for hydrogen will entail repurposing of existing fueling, as well as on-site production as an option. Regulatory acceptance will require the changing of public perceptions.

Figure 46: Aviation Emission Reduction Targets (Air Transportation Action Group (ATAG))



While technology for decarbonizing shipping will be available by 2025, hydrogen solutions for aviation will not be commercial until 2035. **Airbus** believes hydrogen is the preferred energy vector for future aviation decarbonization, and initiated a "Zeroe" concept program which uses tube-and-wing designs for (1) turboprop and (3) turbofan vs. a (2) blended-wing design (Figure 47). The Tube-and-wing aircraft back portion has no windows due to storage of cryogenic hydrogen. Tube-and-wing configurations are more aerodynamically efficient since there is no fuel storage in the wings, allowing for improved lift. Blended wing concepts allow storage in wings, increasing storage capacity but with reduced efficiency.

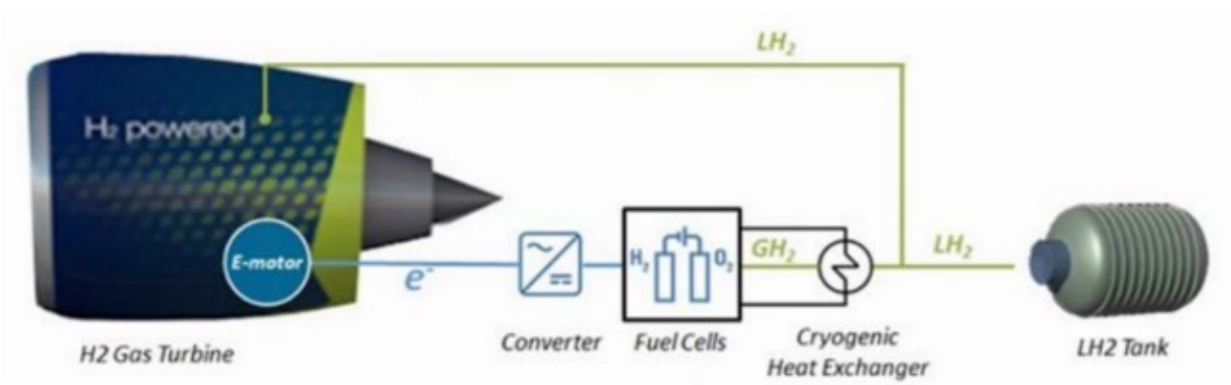
Figure 47: Future Hydrogen Plane Designs (Airbus)

Power is based on hybrid configurations with direct combustion of liquid hydrogen for cruise operation, with fuel-cell power boost for takeoff and climb. Figure 48 shows the hybrid powertrain for turbofan or prop drive.

In addition, an ASCEND Advanced Superconducting and Cryogenic Experimental powertrain Demonstrator is being developed to examine superconducting and cryogenic technologies, which take advantage of low temperature / cryogenic hydrogen storage to halve the weight of components and electrical losses, enabling a reduction in voltage from 3 kV to below 500V. Furthermore, a "POD's" configuration is being examined, each pod being complete with LH2 fuel, heat exchanger, electric motor and propeller. This latter system is fully electric, with no turbine.

The objective for Airbus is to have a technology selection by 2025, with certification and deployment in plane fleets starting 2035. Technology development is focused on bringing weight down for aircraft and hydrogen storage, as well as reduction in the cost of hydrogen and infrastructure. This approach emphasizes technology development and systems optimization, including considering airports as Hydrogen Hubs for zero-carbon non-flight operations.

Figure 48: Hybrid Power Trains for Aviation



- Combine H2 Gas Turbine and H2 Fuel Cells
- Several hybridization strategies: Boost in take-off/Climb, Assistance in transient phases, ...
- Enabler to increase Gas Turbine efficiency
- No power offtakes on gas turbines

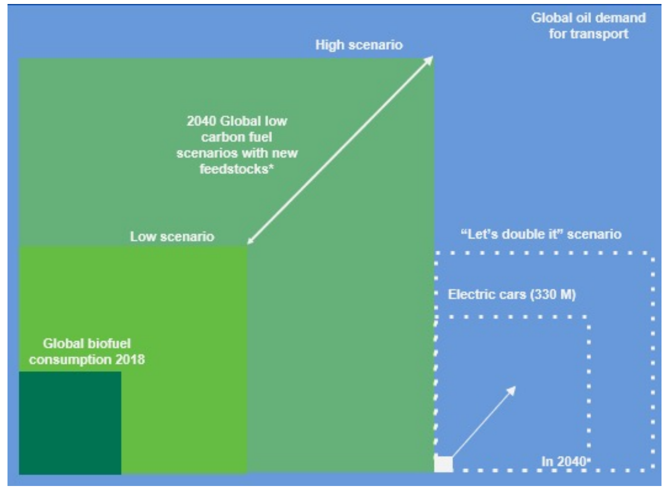
Neste is one of the largest producers of biofuels targeting carbon neutral production by 2035, and mitigation of 20 MM tons of customer emissions by 2030. Initially the focus is on reducing CO_2 emissions from production, but over time Neste plans to get closer to net zero by including the emissions associated with shipping of fuels.

Neste is decarbonizing aviation today as an interim solution via use of synthetic aviation fuel SAF made from fats, oils and greases, renewables. Waste and residues such as used cooking oil are favorites. These are efficient for production of polymers and chemicals as well as SAF, because they have the right carbon length. Existing infrastructure and planes can be used, but there is a cost premium for this decarbonized solution over fossil-derived jet fuel. Future supply can consider expanding to additional feed stocks such as forestry residues, algae, etc. Criteria pollutant emissions are an issue for SAF vs. zero emission hydrogen, but the approach does provide for partial decarbonization of aviation in the near term, and possible negative greenhouse gas emissions if combined with future production of chemicals.

Figure 49 shows low and high volume scenarios for expansion of SAF to reduce oil demand for transport, in comparison with battery electric vehicles. Phillips 66, Valero, and Marathon use the technology, while Shell and BP are also partners. American Airlines is an end-use partner, as is the San Francisco Airport (SFA). Signature flight support is provided for users of private jets. All business travel for Neste employees is compensated by SAF.

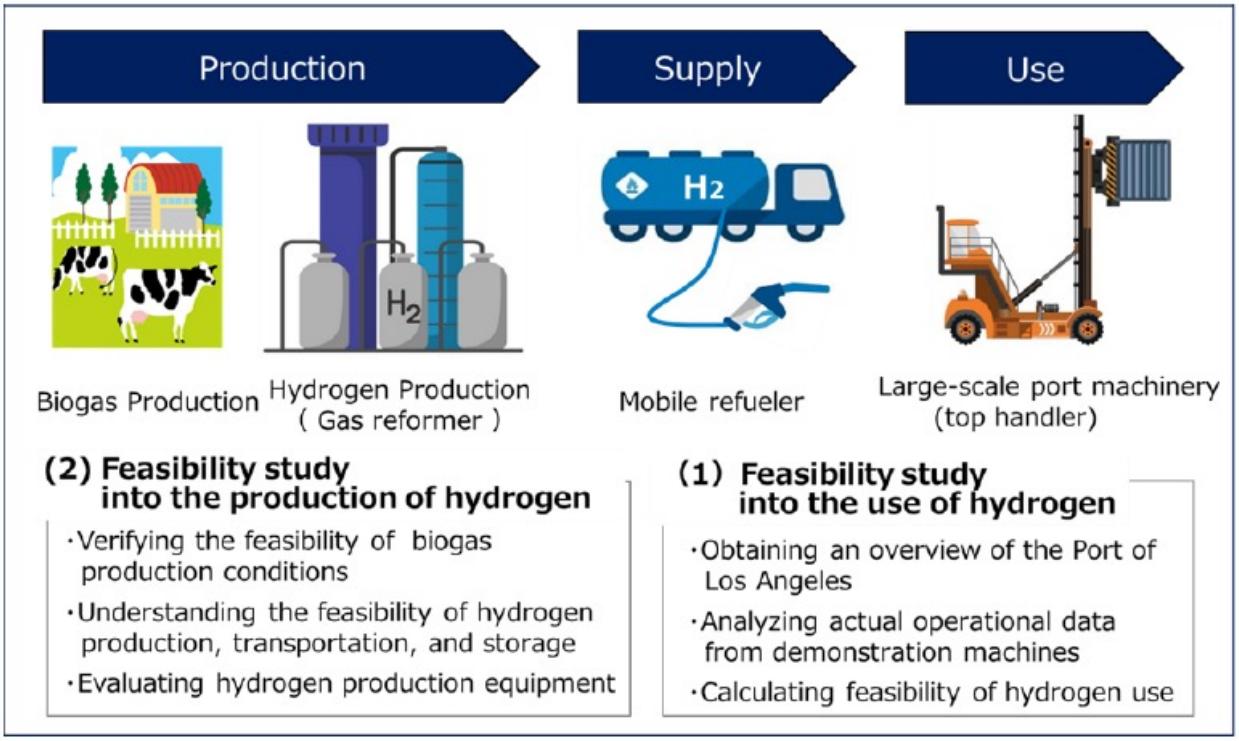
The overall approach for aviation is to halve emissions by 2030, again in 2040, and again in 2050. All solutions are needed: electrification, hydrogen, SAF. Policy is needed, as well as a market-based price per segment to decarbonize. Renewable fuels may never be cheaper but fossil fuels may no longer be acceptable. Consider an eco-plus seat next to economy plus seat, as a consumer choice!

Figure 49: Scenarios for Expansion of SAF vs. Battery Electric Vehicles for Mitigating Today's 4,500 MTa Oil Use in Transportation *(Source: Neste based on IEA World Energy Outlook 2019, Stated Policies Scenario. UNDP, ExxonMobil and others)*



For port operations, **Toyota** is examining an integrated play in port decarbonization for LA and Longbeach, where decarbonization policy is world leading. Integrated solutions combined with effective policy provide potential economic viability. OEM's have been reluctant to supply equipment due to lack of policy incentives elsewhere. Toyota is developing fuel-cell dominated overhead lift trucks for demonstration, which have the advantages of being operated on hydrogen only, and thus there is no need for battery charging which is otherwise a challenge for other options considered. BEVs require very large charging infrastructure, and potentially a small power plant if one makes all top handlers battery based. BEV's require large charging times, for proposed operations in LA and Long Beach. California has a zero emission target for 2030 in all port equipment, and for drayage trucks by 2035. Port applications are among the fastest emerging markets for hydrogen use. Toyota is doing a feasibility study for the Port of LA, where use of the newly-developed mobile refueler is a valuable tool to connect hydrogen production with end use (Figure 50).

Figure 50: Toyota Port of LA Feasibility Study



Station-only operation in Japan has not been a viable business proposition. Therefore, an integrated value chain developing demand and supply at the same time is needed, and will be examined. A biogas project in central valley CA, and a small reformer near the port of LA to avoid high transport costs over longer distances, are both considered. The mobile refueler can be used as an intermediate station application, or can be deployed in the port terminal. LA and Long Beach have more than 3000 vehicles and equipment, most operating off diesel. Most can be replaced with FCEV alternatives. Fuel consumption is 5 – 10x more than the 5 kg per day of a typical Mirai light-duty passenger vehicle. The port area can therefore come to high demand for hydrogen quite soon, given the zero-emission goal by 2030 for port equipment, and requirement for drayage trucks to be zero emission by 2035. Top handlers (huge versions of conventional forklift) have already been converted to battery (1000 kW). Also tested are hybrid 27 kg hydrogen and 500 kW battery vehicles. Toyota has a FC dominant top handler with only 85 kW battery. Figure 51 shows hydrogen requirements for port handling equipment.

Figure 51: Hydrogen Requirements for Port Handling Equipment

Type	Drayage Truck	Top Handler	RTG	Yard Truck
Image				
Units	13,000+	386	152	1,654
Diesel Usage (Average)	30〜40 gallon/day	60〜80 gallon/day	80〜100 gallon/day	30〜40 gallon/day
H2 Usage (Estimate)	20〜30 kg/day	40〜50 kg/day	50〜60 kg/day	20〜30 kg/day

As stated, CA has a zero emission mandate 2030 for all equipment, and for drayage trucks by 2035, such that port applications are the fastest emerging market for hydrogen. Given long lifetimes for trucks, with 13 – 15 year renewable cycles, action needs to be taken soon to meet these mandates. Japan has conducted several demos for wind, solar, biogas to hydrogen, and currently operates 8 hydrogen stations in Japan.

Challenges for hydrogen include hardware commercialization by OEM. The Los Angeles area is the only global location driving port equipment regulations, so port equipment OEM's are not yet driving the commercialization of new technology. hydrogen fuel and infrastructure are 2X to 3X more costly than diesel. How to reduce these costs to enable a switch to hydrogen? Beyond cost reduction, refueling protocol, fire code, and safety must also be considered. User education and training is an important need. Is hydrogen safe? Stakeholders must be convinced. Regulatory approval for operation of the mobile refueler in the port area is an example of a key coordination need.

SHIPPING AND AVIATION DISCUSSION:

How to supply and store hydrogen in Long Beach and address stakeholder concerns? Note that 4- am to 7-am is the typical time for refueling, such that infrastructure for simultaneous refueling is needed. Liquid hydrogen is therefore a good option given high energy density, but also a pipeline to the port terminal area can be considered. Otherwise, multiple mobile refuelers can be considered. These issues are currently under study.

Green ammonia is considered as an option, but what about renewable dimethyl ether (DME) or propane? Ammonia has no CO_2 content, and hence is preferable to DME (if the latter is not made from bio-based feeds or using renewable hydrogen and CO_2 from direct air capture), or propane. Note that shipping cannot compete with aviation in willingness to pay for fuel. Fuel for shipping must be lower cost.

Can invasive vegetation be used to make SAF? Harvesting invasive vegetation is not doable at scale today. 4 million metric tonnes per annum of feedstock oils and greases is required today for Neste.

Can all airplanes run on renewable fuel? There are not enough sources today, but one must consider what new sources will be discovered in future. If additional source and process discoveries are made, then yes, there may be enough to replace fuels in aviation.

Is Ammonia viable for aviation? Airbus has looked at ammonia. Toxicity is an issue, and ammonia does not quite have the energy density of hydrogen. Ammonia therefore has none of the advantages of hydrogen, and some disadvantages, when used in aviation. Ammonia is therefore not likely to find a way onto aircraft but may play a role in hydrogen transport, with "cracking" or reforming to hydrogen.

When does hydrogen become economic? Currently it is sold at \$10 - \$12/kg. Port terminal operators expect a similar price as diesel, or \$5.50 - \$6 / kg range for hydrogen for equivalent value with diesel at about \$3/gallon. How to reduce cost for hydrogen is key, but incentives, policy support, grant programs may be required to compete with current diesel. Note 1 kg hydrogen has about the energy of 1 gallon of diesel, but with a fuel cell may be up to 2X more efficient for some applications versus an internal combustion engine.

When will transportation decarbonize? Shipping will continue to produce CO_2 emissions, but hopes to peak in 2030 – 2035. Same as for aviation. Aviation is only about 3% of global emissions. Heavy-duty trucking change is needed soonest, given the larger scale, and will be more tractable than aviation for decarbonization.

MARINE (SHIPPING) AND AVIATION SUMMARY

Key messages are:

- Hydrogen is a preferred decarbonization vector for trains and aviation; green ammonia and green methanol are, as of today, the most plausible long term options as transport fuels of the future for shipping (marine);
- Green ammonia will be ready by 2025 and the global green ammonia engine is ready by Q4/24, but a global regulatory carbon price policy is required to cost neutralize the low- and zero carbon fuels;
- Aviation is not amenable for ammonia, and requires some technology development for use of hydrogen; Airbus plans selection of preferred options by 2025 for commercial implementation in 2035.
- Sustainable Aviation Fuels (SAF) are available now as a transitional mode for decarbonization using existing planes and infrastructure. Costs are higher than fossil-derived fuels, but some markets have developed to allow implementation. Overall environmental advantages are not as great as for future zero-emission hydrogen.

Conclusion

Decarbonization of heavy-duty transport encompasses a broad range of end-use scenarios where both battery electric and hydrogen fuel cell solutions will have an opportunity to co-exist as optimal deployment options. This contrasts the independently-owned light-duty vehicle sector where low usage rates per vehicle and opportunity for at-home charging create a market opportunity that may not require ongoing policy incentives as renewable energy costs continue to diminish, given lower maintenance costs for electric drive trains versus the current internal combustion engine with added emissions controls.

Battery electric transport offers some of the same advantages in the heavy-duty sector, but becomes challenged as power and energy density needs increase. Four-fold longer charging times become expensive for larger transport vehicles and vessels, and the total power density required for an ensemble of applications around an industrial area such as a commercial port may be restrictive in terms of land-use required for longer-duration electrical charging vs. refueling with hydrogen, not to mention the added power per unit of weight for a hydrogen fuel cell vs. electric vehicle.

Differences in end use application cycle will drive different choices between battery electric vs. hydrogen fuel cell options. For medium- and heavy-duty trucks, battery electric options can be optimal for smaller vehicles used for shorter duration cycles, with several options potentially replacing the normal service cycle of a current diesel unit, or future hydrogen fuel cell vehicle. Commercial vehicles requiring high "up time" or power density for longer range, will benefit from hydrogen refueling in minutes vs. multiple hours required for battery recharge, and longer range. Certainly, electrification of trucks is occurring now for some fleet operations, but range and utility advantages of hydrogen fuel cell vehicles especially in the heaviest duty sectors may be compelling if supporting hydrogen infrastructure becomes available. Hydrogen pipelines provide an efficient way to disseminate larger supplies of energy vs. grid expansion, especially in dense commercial areas.

Many bus routes and service cycles can be organized around battery electric vehicles, at lower cost than hydrogen. In moving up to trains, one finds that unless tracks are already electrified (catenary), infrastructure costs for wayside electrification are prohibitive, and battery energy density and service cycles are too poor to allow consideration for most routes. Trains provide a clear opportunity for decarbonization via hydrogen fuel cells. In many areas, local air quality, or avoidance of "criteria pollutants" including particulates and smog, are compelling reasons to switch from diesel to zero emission options, over and above concerns over climate change and greenhouse gas emissions.

Aviation will be very difficult to decarbonize via battery electric except for very small commuter traffic or futuristic on-board solar, as wayside (catenary) recharging is not plausible. Hydrogen may become an option by 2035 and beyond, with further technology development to accommodate the lower volumetric energy density for hydrogen vs. today's liquid aviation fuel. A switch to hydrogen will however require a complete redesign of all aircraft. Hydrogen in aviation can be implemented via a hybrid fuel cell plus regenerative battery approach, taking advantage of higher fuel cell efficiency relative to direct combustion. Ammonia is not a viable option for aviation, given lower gravimetric energy density.

Shipping or maritime may electrify some harbor craft, but longer routes for heavy transport will require long-duration storage options similar to that contemplated for renewable grid power. Conversion of hydrogen to ammonia provides for longer-duration storage options, and integrates with direct combustion for power applications. Currently there are more than 120 ports that can safely handle toxic ammonia. The hydrogen based fuels are likely to become the transport fuels of the future. Subject to technology developments over time, it could come in the form of fuel cells, although this is still unclear, and according to leading industry experts also unlikely. Other options including combustion of renewable fuels or renewable hydrogen could become viable alternatives.

For hydrogen deployment, ongoing research and technology development is required on all fronts, from increase in storage and power density of associated batteries, to reduction in cost of electrocatalysts and components for batteries, fuel cells, and electrolyzers used to make hydrogen from renewable energy, to systems and materials for hydrogen storage, overcoming embrittlement in pipelines and storage applications. Battery storage and hydrogen safety fundamentals, scenario modeling, and development of codes and standards for uses in multiple sectors is required.

Policy incentives are important (in the marine space ideally in the form of a global carbon levy) as continuing use of diesel can otherwise provide lowest costs in the medium term, but will not meet societal ambitions for mitigating climate change and providing cleaner, zero-emission options. In some heavy-duty applications, biofuels or synthetic fuels derived from capture of CO_2 and reaction with renewable or clean hydrogen could provide a solution. However, cycle efficiency for use of renewable energy is lower than direct use of battery electric or hydrogen fuel cells, and use of these synthetic or bio- fuels in combustion does not meet zero-emission goals (including all pollutants) for clean transport.

Infrastructure support is especially important for options where hydrogen is optimal, as costs decrease dramatically as scale-of-use is increased. Integration of sector use per DOE's "H_2@Scale"[1] initiative is an important consideration to drive down unit costs of hydrogen to enable adoption. Heavy-duty transport can thus synergize with use of hydrogen for heavy industry decarbonization, given that all-important hydrogen costs are reduced when produced at larger scale

In summary, the heavy-duty transport sector has broadly diverse needs that warrant strong consideration of both battery-electric and hydrogen for decarbonization. Robust R&D is needed to drive down costs. Strong policy support can serve to speed adoption via assistance in driving down cost curves for deployment at scale, and investment in required infrastructure.

1 https://www.energy.gov/eere/fuelcells/h2scale