

# SURVEY OF HEAVY-DUTY HYDROGEN FUEL CELL ELECTRIC VEHICLES AND THEIR FIT FOR SERVICE IN CANADA

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## About CESAR and The Transition Accelerator

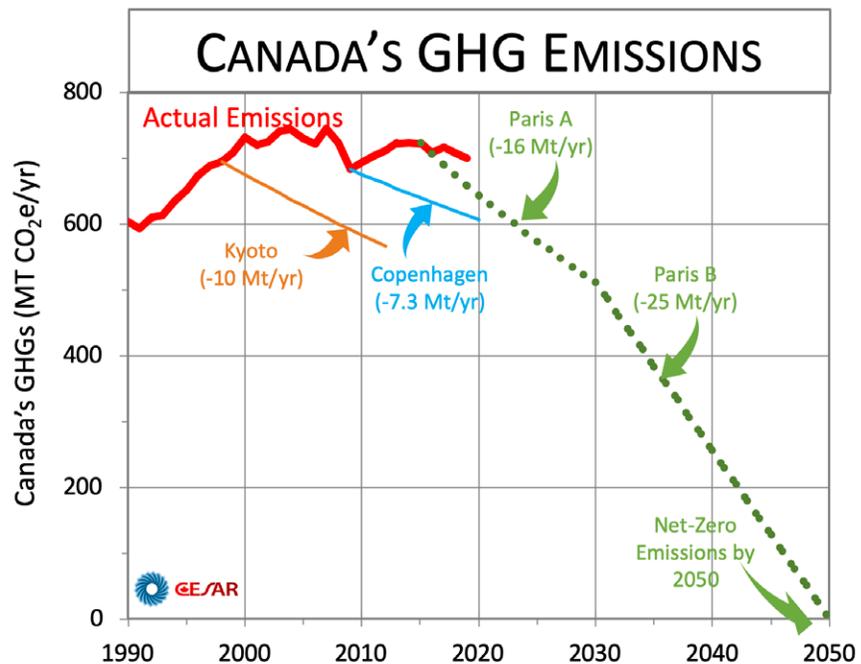
**CESAR (Canadian Energy Systems Analysis Research)** is an initiative started at the University of Calgary in 2013 to understand energy systems in Canada, and develop new analytical, modeling, and visualization tools to support the transition to a low carbon economy.

In 2017, CESAR launched its **Pathways Project** to define and characterize **credible** and **compelling** transition pathways for various sectors of the Canadian economy that would help the nation meet its 2030 and 2050 climate change commitments made in Paris in 2015 (**Figure i**).

A CESAR Scenarios publication in early 2018<sup>1</sup>, and the support and encouragement from a number of charitable foundations led to discussions among CESAR's Director, **David Layzell**, Carleton University professor **James Meadowcroft** (Canada Research Chair in Governance for Sustainable Development, School of Public Policy and Administration) and

Université de Montréal professor **Normand Mousseau** (Dept of Physics and Academic Director, Trottier Energy Institute) regarding the need for a pan-Canadian initiative to accelerate the development and deployment of Transition Pathways.

With guidance and financial support from a number of private Canadian foundations, a charitable non-profit was launched in 2019 and called The Transition Accelerator. Associated with the launch, a report was published<sup>2</sup> to articulate the philosophy and methodology that is now used by both CESAR and the Accelerator.



**Figure i.** Canada's Greenhouse Gas (GHG) Emissions (Solid Blue Line), Showing the Future Trajectory Needed to Meet Paris Commitments (Red Line). Past failed commitments are also shown. Data from the 2018 National Inventory Report for Canada for 1990-2016 (<http://www.publications.gc.ca/site/eng/9.506002/publication.html>).

<sup>1</sup> D. B. Layzell and L. Beaumier, "Change Ahead: A Case for Independent Expert Analysis and Advice in Support of Climate Policy Making in Canada," CESAR, vol. 3, no. 1, Feb. 2018 [Online]. Available: <https://www.cesarnet.ca/publications/cesar-scenarios/change-ahead-case-independent-expert-analysis-and-advice-support>

<sup>2</sup> J. Meadowcroft, D. B. Layzell, and N. Mousseau, "The Transition Accelerator: Building Pathways to a



**Figure ii.** Criteria for a Useful Transition Pathway. The two-mountain image is provided to stress the importance of pathways being capable of achieving longer term targets. Some climate change policies encourage dead end pathways to 'false' targets based only on incremental GHG reductions, but which clearly are not on a pathway to a longer-term target.

In defining and advancing transition pathways, **CESAR** and the **Accelerator** recognize that transformative systems change is needed to achieve climate change targets, especially the commitment to net-zero emissions by 2050 (**Figure i**).

However, for many, perhaps most Canadians, climate change is not a sufficiently compelling reason for large-scale systems change, especially if it has substantive costs. Nevertheless, we live in a time of disruptive systems change driven by innovations that both promise and deliver highly compelling benefits such as enhanced convenience, comfort, status, value for money and quality of life. *What if it were possible to harness these disruptive forces to also deliver societal objectives for climate change mitigation?*

The **Accelerator's** mandate is to work with key stakeholders and innovators to speed the development and deployment of credible and compelling pathways that are capable of meeting climate change targets using a 4-stage methodology:

- 1. Understand** the system that is in need of transformative change, including its strengths and weaknesses, and the technology, business model, and social

Sustainable Future," vol. 1, no. 1, p. 65, Aug. 2019. [Online]. Available: <https://www.transitionaccelerator.ca/blueprint-for-change>

innovations that are poised to disrupt the existing system by addressing one or more of its shortcomings.

2. **Codevelop** transformative visions and pathways in concert with key stakeholders and innovators drawn from industry, government, the academy, environmental organizations and other societal groups. This engagement process will be informed by the insights gained in Stage 1.
3. **Analyze** and model the candidate pathways from Stage 2 to assess costs, benefits, trade-offs, public acceptability, barriers and bottlenecks. With these insights, the researchers then re-engage the stakeholders to revise the vision and pathway(s) so they are more credible, compelling and capable of achieving societal objectives that include GHG mitigation (see **Figure ii**)
4. **Advance** the most credible, compelling and capable transition pathways by informing innovation strategies, engaging decision makers in government and industry, participating in public forums, and consolidating coalitions of parties enthusiastic about transition pathway implementation.

This study reports Stage 1 and Stage 3 results for the freight transportation sector in Canada. Specifically, it explores the current global state of the hydrogen fuel cell electric heavy-duty vehicle technology and evaluates the goodness of fit for service in Canada

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Jessica joined CESAR with more than a decade of business experience in the railway and trucking sectors. Throughout her career, she has designed transportation and logistics solutions that enable economic potential and drive operational efficiency in a vast array of industries, including wind energy, oil and gas, automotive and global trade. Jessica has a Master of Science degree in Sustainable Energy Development (SEDV), a Bachelor of Commerce degree, and a professional designation with the Canadian Institute of Traffic and Transportation.

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### **Geoff G. Martin, BSc, MIM**

Geoff Martin has 40 years of “hands-on” experience in the energy business. He obtained his earth science undergrad degree at Memorial University of Newfoundland in St. John’s where he studied geology and geophysics. That led to varied experience in North America, Latin America, the Middle East and Australasia. His exploration experience has covered specific exploration projects in teams, at times mentoring new students, to large regional basin studies for new exploration concept developments.

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**David B. Layzell, PhD, FRSC**

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## List of Abbreviations

<b>Abbreviation</b>	<b>Definition</b>
Blue Hydrogen	Hydrogen produced from natural gas
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization and storage
CESAR	Canadian Energy Systems Analysis Research Initiative, University of Calgary
Class 8 Truck	A common term for combination tractor-trailer HDVs with GVWR > = 15 tonnes
CNG	Compressed natural gas
GHG	Greenhouse gas
Green Hydrogen	Hydrogen produced by water electrolysis using zero-carbon electricity
GVWR	Gross Vehicle Weight Rating (the weight of the vehicle plus the payload)
H <sub>2</sub>	Hydrogen gas
HDV	Heavy-duty vehicle: GVWR of >= 4.5 tonnes. Includes trucks, buses, and vocational vehicles.
HFCE	Hydrogen fuel cell electric drivetrain (typically hybrid, with batteries)
ICE	Internal combustion engine
OEM	Original equipment manufacturers
SMR	Steam methane reforming
TCO	Total cost of ownership

## Executive Summary

Heavy-duty vehicles (HDVs) in Canada currently account for about 9% of Canada's total GHG emissions and HDV demand is expected to continue to grow more quickly than other economic sectors. To achieve Canada's net-zero climate change goals by 2050, while also addressing air pollution and ensuring acceptable vehicle performance, the industry sector is looking towards the electrification of the powertrain.

While plug-in, battery electric vehicles may have applications with medium duty vehicles or with HDVs running short distances, the longer distance, HDV market is looking to hydrogen fuel cell electric (HFCE) vehicles to meet their needs. With life cycle GHG emissions that are zero to 20% of the incumbent diesel internal combustion engine (ICE) HDV, HFCE vehicles convert hydrogen fuel to electricity on board the vehicles. The hydrogen can be produced by water electrolysis using zero carbon power ('green' hydrogen) or from fossil fuels coupled to carbon capture and storage ('blue' hydrogen). The production, transport and use of these zero emission fuels has broad economic, energy security, and environmental benefits that are sought after by jurisdictions around the world.

This report uses a systems level approach to explore the potential fit of HFCE HDVs to the needs of the heavy vehicle sector. It also assesses the deployment strategies and progress that has been made globally to gain insights that can be applied in a Canadian context. Given that trucks and vocational vehicles represent over 90% of Canada's HDVs, this report puts an emphasis on this fleet segment, complemented with some discussions on buses.

Diesel ICE technology has long dominated the HDV markets with engrained performance standards that the alternative technology will need to meet or outperform to gain share in a competitive market while being aligned with the disruptive forces and emerging innovations that are reshaping industry. The HFCE HDV has many performance strengths including high torque, reliability, and driver appeal advantages such as low noise and vibration. Any limitations associated with range, weight, cold weather, and fueling time are likely acceptable for most HDV duty cycle applications. This includes long-haul trucking applications with heavy payloads where battery electric options are restrictive.

Companies like Nikola Motor Company and Hyundai have recognized HFCE HDV trucks as a lucrative new market segment and existing and emerging

HDV original equipment manufacturers (OEMs) are entering this new market. These companies have been met with a positive response from fleet owners that have, on good faith, collectively pledged large orders for these trucks without having driven nor seen the proposed truck model. These companies have yet to produce trucks beyond prototype models but have production plans in America and Europe in the upcoming years. In contrast, China has deployed around 2,000 trucks as of 2019.

Ongoing demonstration projects of HFCE trucks, like the ones conducted at the Ports of Los Angeles and Long Beach, the H2Haul and H2-Share projects in Europe, as well as the Alberta AZETEC project are of critical importance in testing the performance of the HFCE technology under real world conditions for a range of different service applications.

However, despite an apparent fit for HFCE vehicles in many HDV duty cycles, the technology remains in the demonstration phase across the world. While governments are spending billions to help advance the hydrogen economy and support the adoption of HFCE vehicles, barriers such as a purchase price for HFCE HDVs that can be 2 to 3 times higher than its diesel equivalent and the lack of accessible, competitively priced fuel overshadows progress and keeps HFCE powertrain technology from gaining market share. Additional barriers also include the absence of qualified maintenance facilities and trained personnel along with gaps in standards and regulations creating uncertainty and increased operating costs.

To address these barriers, governments are introducing various incentives to encourage adoption of HFCE HDVs and put hydrogen fueling stations into operation. Research and development activities to reduce component costs such as fuel cells or onboard hydrogen storage tanks are also being explored to reduce costs. In addition, new business models that bundle fuel, maintenance, and vehicle use are being deployed by companies to help de-risk the total cost of ownership (TCO) for customers.

While these initiatives show promise in the short term, when the government incentive programs end, the value chain may cease to be economically viable and growth may halt. To avoid this scenario, the self-reinforcing 'vicious cycle' that keeps vehicle and fuel prices high must be broken by reaching a critical self-sustaining scale for both hydrogen fueled HDV production and the fuel distribution network. Along with HFCE powertrains, hydrogen-diesel dual fuel vehicles could also be part of this transition pathway. The resulting 'virtuous cycle' would achieve the TCO parity that many organizations are projecting and will require little or no additional public funding once established while contributing to the economy of the region and nation.

To achieve commercial scale, a sufficient amount of hydrogen powered HDVs will need to be strategically deployed in concentrated locations to

support hydrogen fueling stations with multiple tonnes per day of hydrogen capacity that sell hydrogen at diesel competitive prices of \$3.50–\$5.00/kg H<sub>2</sub>. These coordinated efforts should also create opportunities for high volume distribution systems (i.e. pipelines) to be built.

A common theme in most of the hydrogen strategies reviewed is that no one entity or sector can drive the energy transition alone. The successful adoption of HFCE HDVs will require extensive coordination between government, industry, and academia focused on both the energy supply and demand sides of the transportation ecosystem.

The countries that have made the most progress in the deployment of HFCE HDVs have national hydrogen strategies and/or have incorporated hydrogen into their national energy strategy for air pollution, economic development, and energy diversification reasons. This is in addition to corresponding emission reduction and transportation frameworks and often includes adoption targets and significant funding for research and development and demonstrations.

The HFCE HDV has the potential to be part of a zero-emission pathway for Canada. However, the pathway will require coordinated cross-sector visions, commercialization strategies and deployment plans that are dedicated to achieving a critical scale for HFCE fleets and hydrogen supply systems.

Recommendations from this report include:

### **Technology Fit for Service**

The successful adoption of HFCE HDVs depends on the technology's ability to perform its intended work as well as, or better than, the incumbent diesel technology. Therefore, governments (municipal, provincial, federal) should continue to work with OEM providers and end users from a wide range of sectors (including public service sectors) to deploy pilot, demonstration, and commercialization projects involving both battery electric and HFCE vehicles to understand and report on their 'technology fit-for-service' in a future, net-zero emission Canada. Also, demonstrations that integrate other emerging innovations like autonomous driving would be beneficial as the transition to autonomous and electric-drive vehicles is likely to be happening at the same time.

Universities and colleges should be encouraged and supported to take an active role in these projects to identify problem areas and conduct research to address these problems. These organizations should also consider using the demonstration projects to develop programs that can educate and train individuals in how to operate and maintain the new technologies.

Such work will inform policy and investment decisions on the optimal transition pathways to electrification of internal combustion technologies by sector and region.

## Standards and Regulations

As an emerging technology and energy system, there are still many gaps in standards and regulations. Transportation associations and governments need to work together to actively investigate the foreseen gaps in standards and regulations and advocate to the international community to address the gaps while balancing regional needs. Once gaps are identified, governments must proactively introduce and/or modify regulations to meet the unique safety and operation protocols of HFCE vehicles, fueling stations, and garage facilities.

Existing technology incentives and environmental policy also need to be reviewed to ensure compatibility with hydrogen value chains. For example, clean fuel standards will need to include acceptable carbon intensities for hydrogen.

## Total Cost of Ownership

To gain market share over the dominant diesel HDV, the zero-emission HDV must be cost competitive on a TCO basis. To encourage early adoption when cost spreads are large, governments should consider using policy incentive mechanisms that can include vehicle and infrastructure subsidies, rebates, warranty programs and capital cost allowance (CCA) benefits, along with fuel price backstops to help close the TCO gap and de-risk the hydrogen value chain.

Investment needs to continue in research and development to promote cost reductions in fuel cells and other expensive powertrain components including onboard hydrogen tanks. However, this cannot be done exclusively as the potential cost reductions are limited without scale.

## Achieving Scale

To break the 'vicious' cycle that is dependant on continuous subsidies, a critical scale of HDV production and fuel station capacity must be reached. For this to happen, the transportation community needs to demonstrate to government and investors that there is committed demand for HFCE HDVs and other hydrogen fuel technologies through pledges, demonstration projects, and order placements. With initial momentum, zero emission HDV targets to reach a net zero Canada need to be mapped out and recognized to set political and business priority.

The government can then introduce policy mechanisms, such as zero emission sales mandates (ZEV standards) and preferential treatment for permits and road access, that support the ongoing demand for zero-emission HDVs. The development of hydrogen dual fuel ICE technology should also be supported to more quickly reach minimum demand requirements for fueling stations and distribution systems.

Concurrently, implementation strategies to efficiently connect low cost hydrogen supplies into transportation corridors where there is concentrated, and assured demand need to be defined. Academia, government, and industry should jointly explore options and capabilities to economically transport and distribute hydrogen. The price advantages of blue hydrogen can like help establish these distribution systems.

### **Cross-Sector Collaboration and Commercialization Strategies**

For commercial scale to take shape, strategies need to be codeveloped by cross functional stakeholder groups and projects deployed where there is high transportation demand and access to low cost, low carbon hydrogen. Governments and funders can foster collaboration by supporting non-vested entities to coordinate and guide initiatives that are made up of groups of diverse companies that share a common vision.

### **National Hydrogen Vision**

A hydrogen vision for Canada needs to be developed and a policy framework established for the successful deployment of a hydrogen economy. The vision should leverage the potential hydrogen demand from HDVs to build a new energy system that benefits many other sectors. Visions, roadmaps, and frameworks should include targets for HFCE HDV deployments and retail hydrogen sold for transportation uses for 2030 and 2050. Provinces should also develop their own hydrogen strategies that align with a pan-Canadian strategy but address provincial situations and needs.

# 1. Introduction

By providing essential services and moving goods and people, robust fleets of trucks, buses, and vocational vehicles are vital for the well-being and prosperity of all Canadians. These heavy-duty vehicles (HDV) are predominantly fueled by diesel and contribute about 9% (65 MtCO<sub>2</sub>e/yr in 2018) of Canada's total greenhouse gas (GHG) emissions [1]. The demand for these vehicles along with the fuel consumed and emissions produced is expected to increase with population and economic growth.

Canada has identified HDV transportation as a climate change risk and has introduced several measures to mitigate HDV fuel consumption and reduce emissions (see **Box 1**). Globally, approaches to reduce transportation related GHG emissions generally include strategies that: reduce transportation demand, shift demand to low carbon intensity modes, decrease fuel consumption through fuel efficiency and load factor improvements, and/or reduce the carbon intensity of transportation fuel [2].

Bio-based diesel provides one low-carbon alternative to fossil diesel. However, the scale of diesel demand in Canada relative to the biomass resource available [3] and the cost of bio-based diesel production [4], suggests

## Box 1. Federal Programs and Policies to Reduce HDV GHG Emissions

### Directed at Fleet Owners

*SmartWay Program:* Facilitates improvements in fuel efficiency and load factor through benchmarking, best practice, and data sharing.

*Green Freight Assessment Program:* Evaluates fleet performance and provides funding support for fleet assessments and the implementation of recommended measures including fuel-switching, aerodynamic retrofits, and other fuel efficiency technologies

*Smart Driver for Highway Trucking Program:* Provides training programs to inform fuel efficient driving practices and reduce operating costs.

### Directed at Purchaser of Service & Fleet Owners

*Greenhouse Gas Pollution Pricing Act:* Uses the polluter pays principle to encourage behaviors that lead to a reduction in fuel consumption including changing operating practices, adopting fuel efficient technology, modal shifts, and/or reducing the demand for transportation.

### Directed at HDV Manufacturer

*Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations:* Sets the acceptable fleet average GHG emissions standard for new HDVs and engines to be sold in Canada, thereby directing an improvement in the technical fuel efficiency of the HDV.

### Directed at Fuel Suppliers

*Clean Fuel Standard:* Sets the acceptable carbon intensity of liquid and gaseous fuels sold in Canada.

that bio-based diesel has limited potential to reduce the carbon emissions associated with freight movement.

Another alternative is to modify diesel engines so they can accept hydrogen as a secondary fuel, and thereby reduce the use of and emissions from diesel by 30% to 50% or more [5]–[7]. As long as the hydrogen is produced with little or no GHG emissions, the well-to-wheels emissions from these vehicles would be reduced by a similar fraction. While such a technology could be on the transition pathway to emission-free heavy transport, there are major challenges with running a diesel engine on 100% hydrogen, include vehicle performance and other air emissions [7].

To achieve Canada’s net-zero climate change goals, while also addressing air pollution emissions and ensuring acceptable vehicle performance, electrification of the powertrain is necessary for HDVs [4], [8].

Canada’s HDV fleet is made up of about 1.1 million trucks plus about 90 thousand buses [9]. About 45% of these trucks have a gross vehicle weight rating (GVWR) > 15 tonnes (often referred to as Class 8 trucks), most of which are likely involved in freight transportation services. The remaining 55% of the HDV fleet is made up of both freight trucks and vocational vehicles such as refuse, construction, and government service trucks and have a GVWR between 4.5 and 15 tonnes (Figure 1.1). The adoption of electric powertrains into these market segments will require that the new powertrain technology meets the unique demands of the specific duty cycles being performed, at comparable total cost of ownership.

For electrification of HDVs to be compelling, it is also important to understand how electric powertrains align with the disruptive forces and other innovations emerging in the transportation industry. As the road freight sector explores innovations to address issues such as labour shortages, empty movements, and changing delivery expectations in a low margin environment, the electric powertrain can provide benefits to address some of these issues, including attracting a new generation of drivers. Furthermore, the electric powertrain

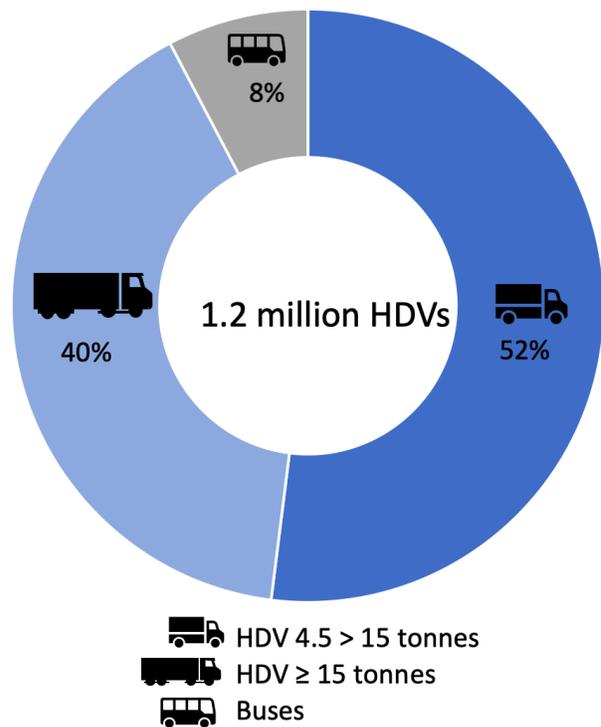


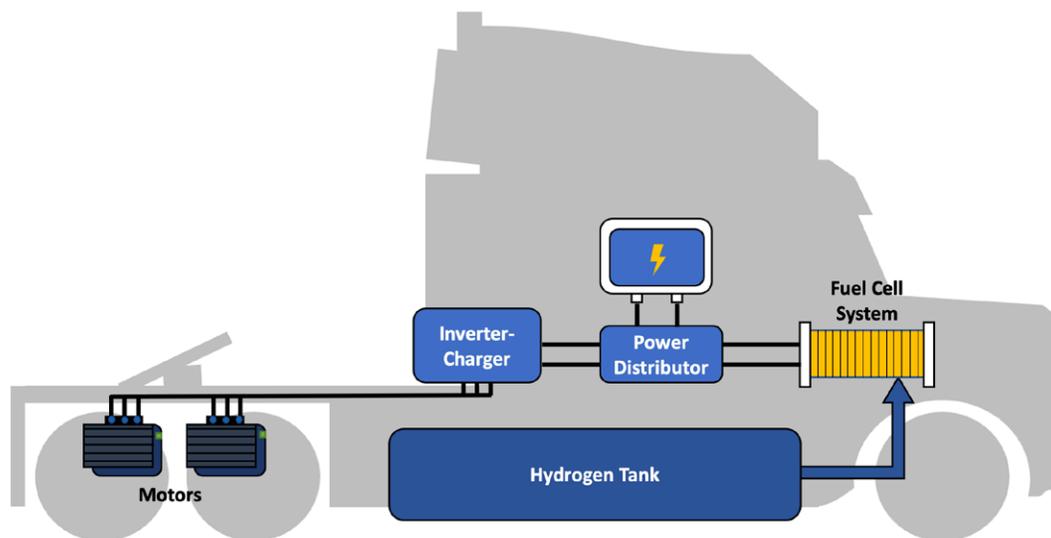
Figure 1.1. Canada’s Heavy-Duty Vehicle Stock (2018). HDV; Heavy-Duty Vehicle. CESAR figure adapted from Statistics Canada data [9].

is likely to have a symbiotic role with innovations like connected, autonomous vehicles [10] and the physical internet [11], that could define the future of the transportation sector [12].

Battery electric HDVs, which use energy supplied from the public grid to power an electric motor, are credible options to electrify HDVs for some duty cycle applications. Several original equipment manufacturers (OEM) have been developing this technology. With China leading the way, there has been some traction in global battery electric HDV sales in the last decade. Between 2015 and 2018, global annual sales ranged from 122,000 to 208,000 battery electric HDVs per year with about 82% of these HDVs being buses [13]. Bloomberg NEF projects that global sales of electric commercial trucks and vans will accelerate in the 2020s and will reach 10% to 20% of their respective market share classes by 2040 [14].

However, because of the heavy batteries and lengthy recharge times, these options are limited to duty cycles that travel shorter distances between refueling and have lighter payloads. Therefore, they are not a suitable option for a large portion of the duty cycles performed by HDV operators, particularly long-haul trucking [4], [15], [16]. In addition, the electrification of all HDVs in Canada with battery electric or even catenary line technology will have implications to the public grid load [3], [17] and depending on the region, may not be able to provide any greenhouse gas (GHG) reduction benefits [4], [15].

Many companies and jurisdictions around the world have been investigating hydrogen fuel cell electric (HFCE) technology, which generates electricity onboard the HDV using hydrogen gas and fuel cells to power an electric



**Figure 1.2.** Example Configuration for a Hydrogen Fuel Cell Electric Heavy-Duty Truck. CESAR figure adapted from Mojtaba Lajevardi et al., 2019 [18].

motor, as a low carbon electrification alternative for HDVs where battery or catenary electric options are not practical or are unable to provide GHG savings. The general design of the HFCE is presented in **Figure 1.2**. Note that the design including tank layout and battery use may vary depending on specific engineering [15], [18].

Hydrogen options are also appealing to regions with strong fossil fuel resources and/or an abundance of low cost renewable electricity that can create lucrative economic opportunities for the region to become a producer and possibly an exporter of either ‘blue’ hydrogen that is produced from fossil fuels paired with carbon capture and sequestration, and/or ‘green’ hydrogen that is produced from renewable electricity. By being capable of reducing lifecycle GHG emissions by 80–100% [4], both options can provide a credible transition to a net-zero future.

**With a focus on HDV trucks, this report characterizes the general goodness of fit for HFCE HDVs by evaluating the business/operational performance, cost, and safety considerations. The assessment is followed by a review of progress that has been made in the global deployment of the HFCE technology in HDVs and concludes with a discussion on key lessons to help overcome barriers and advance this low carbon pathway in a Canadian context.**

## 2. Goodness of Fit: Business/Operational Performance

Diesel internal combustion engine (ICE) technology dominates the HDV market. With close to a century of continuous development, the relationship between this technology and its end-users is strong with engrained performance expectations. Although, the diesel ICE has significant GHG and air pollution disadvantages, in a competitive marketplace any alternative powertrain technology, including the HFCE HDV, will need to meet or out-perform the proven performance standards.

The various HDV duty cycles operate on different service and business models and the goodness of fit expectations will differ accordingly. This section of the report discusses basic considerations that can impact the decision to adopt an HFCE HDV and identifies the strengths and weakness of the HFCE technology compared to the dominant ICE technology.

## 2.1. Operational Consideration #1: Power, Torque, and Drivability

To perform their intended duties, high amounts of power and torque are necessary for Canada's HDV fleets to gain traction, accelerate, safely maintain pace with surrounding traffic, and move heavy weights across a variety of terrain, grades and road conditions.

The HFCE HDV has the potential to out-perform the large and powerful engines of many diesel HDVs. While designed to perform work at a power rating of at least 400 to 500 HP (300–370 kW) and deliver torque 10 times that of an average American passenger car [12], the diesel HDV is still currently challenged to gain traction, accelerate and climb steep grades.

In comparison, the unique torque to power relationship of an electric motor creates conditions where the HFCE HDV is able to produce instant torque that can reduce the time required to get into motion and up to the desired speed with lower power demands [20]. The necessary power needs for a HFCE HDV are met through the integration of multiple fuel cell stacks, batteries, and electric motor systems. Some design options can include direct drive motors, commonly known as e-axles, that can direct power to the individual axles, for more dynamic performance and greater reliability [21]. In addition, vibrations traditionally associated with a diesel engine are not present with an electric truck thereby improving the driving experience [22].

Although the high power and torque of the electric motor has some superior performance qualities, there may also be some unintended consequences. Driver response and control is likely different and may require additional training and practice to safely operate the vehicle.

### Power, Torque, and Drivability Strengths (✓) and Weaknesses (X)

- ✓ Superior power and torque capabilities
- ✓ Less vibrations
- X Additional driver training may be required

## 2.2. Operational Consideration #2: Range and Fueling Needs

The daily work cycles of many HDVs include traveling long distances in continuous operation. Frequent or lengthy stops for fueling can be impractical and an unproductive use of the asset. Currently, HDV fleets can drive distances greater than 1,000 km on a single fueling and fueling takes less than 5 minutes to complete. Therefore, the productive operation of fleets

fueled by diesel is often more constrained by driver rest needs [23] and work plans than by vehicle range.

Since HFCE HDVs are equipped with fuel tanks that store gaseous hydrogen at either 350 or 700 bar pressures, the distance that can be traveled between fueling is dependent on the amount of hydrogen that can be stored onboard the HDV. Assuming a fuel efficiency of 8 kg/100km for an HFCE HDV [4], an estimated range of about 1,000 km can be reached with 80 kg of hydrogen. This range can reasonably be accommodated with either 350 bar or 700 bar storage tanks, either behind the cab or on the side rail and under the chassis [24].

While the HFCE HDV can achieve comparable ranges for most HDV duty cycles, including many long-haul trucking applications, the technology is not as flexible in scaling up range should that be desired for specific operating conditions. For example, a diesel HDV can easily increase the fuel tank size to carry additional fuel; however, because of vehicle weight and space constraints discussed in Consideration #3 below, the HFCE HDV will likely not have that same capability.

By taking less than 20 minutes to fill a 80 kg hydrogen tank at 350 bar [25], the fueling time for HFCE HDVs is likely not prohibitive to productive operations. This is contrary to similar battery electric powertrain options that can require hours of downtime for charging.

The greater concern for fuel management of the HFCE HDVs is the current unavailability of fuel cell grade hydrogen supply and the lack of supporting fueling station infrastructure. Without readily accessible fuel in locations compatible with the operations of HDV fleets, it will be challenging for fleet operators to accept the HFCE as a viable HDV option regardless of its technical goodness of fit.

#### **Range and Fueling Needs Strengths (✓) and Weaknesses (X)**

- ✓ Capable of achieving comparable range between fueling
- ✓ Fueling times are acceptable
- X Extreme ranges will be challenging
- X Current lack of fuel cell grade hydrogen and fueling infrastructure

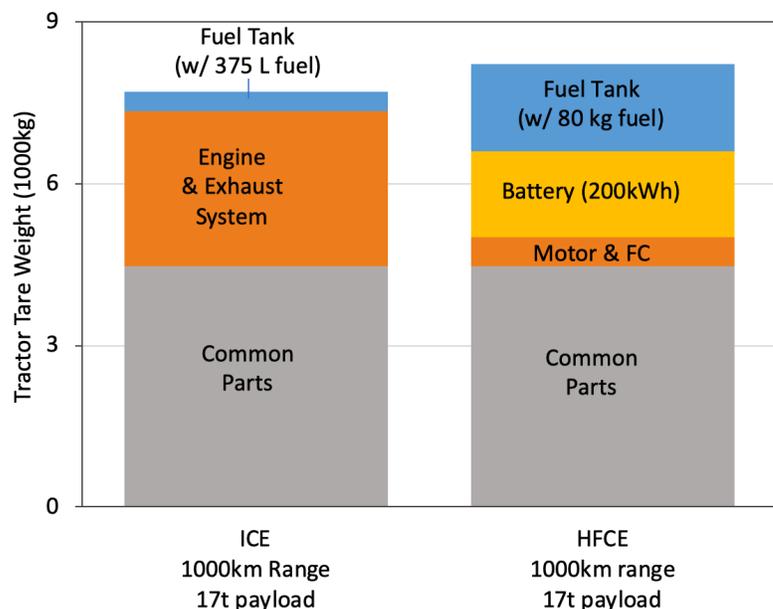
### 2.3. Operational Consideration #3: Vehicle Weight and Space

Many businesses and agencies that operate HDVs are concerned about vehicle weight. This is especially true for those that provide freight services and those that move heavy products. Provinces set and enforce gross vehicle weight allowances, the sum of the vehicle tare (unladen) and payload weight, that are permitted to travel on the roads. Any increase in tare weight will reduce allowable payload which could impact revenue and/or increase operating costs. Likewise, any increase to the space occupied by the powertrain system can have business model impacts by sacrificing potential payload.

Although there are many common components, the HFCE HDV has a different weight profile than the conventional diesel ICE. The incumbent technology has engine and exhaust systems that contribute weight that is not needed in a HFCE HDV [27]. However, the HFCE HDV adds weight from the fuel cells, the large batteries, and the motor and hydrogen tanks which are significantly heavier than diesel fuel tanks.

In the analysis shown in **Figure 2.1**, it is determined that an HFCE HDV fueled with 80 kg of hydrogen, to complete a 1000 km trip with a 17 tonne payload, would have a tare weight that is 7% (~500 kg) higher than an equivalent diesel HDV. Although, because the tank to fuel weight ratio for hydrogen is very high, at 19 kg tank to 1 kg hydrogen [28], any increase to the hydrogen tank capacity would have large impacts to the tare weight compared to the diesel alternative.

There are some space challenges with on-board hydrogen storage. Hydrogen is a low density gas and 80 kg of hydrogen would occupy around 3.5 cubic meters of space when pressurized to 350 bar, in addition to the storage tank. This tank space could negatively impact payload capacity or cab space that could



**Figure 2.1.** Estimate of Vehicle Tare Weights for Hydrogen Fuel Cell Electric and Diesel Internal Combustion Heavy Duty Vehicle travelling 1000km with a 17 tonne payload. Analysis completed by CESAR with assumptions supported by literature [16], [29]–[31]; Fuel efficiencies of 2.2 L<sub>diesel</sub>/100tkm and 8 kg<sub>H<sub>2</sub></sub>/100km assumed.

otherwise be used for sleeping quarters. Compressing the gas to 700 bar is an option to reduce the tank space required but the tanks would likely be more costly.

As the distribution of mass is different in the design of HFCE HDVs from the ICE standard, there may be negative implications to the vehicle's suspension systems which were reported in early HFCE bus trials [32]. Manufacturers and OEMs should be able to address this engineering design issue with appropriate material selection and placement of mounts and suspension bushings [33].

#### Vehicle Weight and Space Strengths (✓) and Weaknesses (X)

- ✓ Comparable tare weights are possible
- X Hydrogen tanks have both weight and space implications
- X Different weight distribution may negatively impact the suspension systems

## 2.4. Operational Consideration #4: Reliability and Life Span

It is important to HDV owners that their asset can reliably perform its intended work. Unexpected repairs or prolonged planned maintenance will negatively impact the business model of the HDV services. In addition, there is an industry expectation a HDV truck should operate reliably over a productive life span upwards of 10 years or up to 1.9 million km [34].

In Canada, cold weather operations are a reality and the alternative power-train must be able to start and operate in very low temperatures. Fuel cells are sensitive to freezing; however, the fuel cell electricity generation process generates heat which allows for operations between  $-30^{\circ}\text{C}$  to  $+45^{\circ}\text{C}$  without impacting performance [35]. This waste heat can also be used to keep the cab of the HDV warm.

In the past, for fast start-up in negative temperatures, fuel cell companies like Ballard have introduced kits, such as plug-in resistance heaters and programmed automatic start-up of the fuel cell systems, that will prevent the fuel cells from freezing and enable an immediate start in temperatures as low as  $-20^{\circ}\text{C}$  [35]. Currently, modifications to stack design have allowed for freeze starting from  $-30^{\circ}\text{C}$  and development targets are aiming for freeze starts as low as  $-40^{\circ}\text{C}$  [36]. These cold weather fuel cell systems have been demonstrated on buses in Whistler, Oslo, and Aberdeen; however, they have not been tested in truck applications or even more extreme weather that can be observed in Canada [35].

Because electric powertrains have fewer moving parts and less fluids than its ICE counterparts [37], HFCE HDVs are anticipated to be more reliable and require less regular maintenance however, this benefit still needs to be proven in real-world conditions. Literature further suggests the HFCE HDV should have a comparable life span [34], although there is a possibility that fuel cells and batteries may need to be replaced.

There is a concern of the current lack of qualified facilities and staff to perform planned and unplanned maintenance on these vehicles [38]. Drivers and maintenance staff need to be trained on safety, scheduled maintenance, diagnostics, and repair of systems. Dispatchers also need to have knowledge of these procedures so they can assist an operator that calls [39].

The OEM and the component suppliers have an important role in ensuring the necessary maintenance resources are available. For example, Nikola Motor Co. is partnering with Ryder System to be their national service provider for training technicians when the trucks begin real-world operations [40]. The electric driveline parts supplier, Dana Inc, is investing heavily in new training resources for their technologies and building a strong knowledge base across their customer base [38]. It is also the responsibility of the purchaser of new technology to engage with the OEMs to mutually establish training protocols and procedures and circulate knowledge.

#### Reliability and Life Span Strengths (✓) and Weaknesses (X)

- ✓ Electric powertrains should be more reliable
- ✓ Comparable life spans
- X Lack of qualified maintenance facilities and personnel
- X Extreme cold weather conditions (below -20°C) have not been real-world tested

## 2.5. Operational Consideration #5: Safety

Safety is of the utmost importance for the operation of any HDV and cannot be compromised in a transition to an alternative fuel and powertrain system. While hydrogen gas is flammable and has the potential to be highly explosive given the right conditions, it is often argued that it poses no greater risk than diesel or other transportation fuels, but the risks are different [41].

Just as fuel safety measures are built into fossil fuel systems, the risks associated with hydrogen fuel will need to be equally mitigated. Furthermore,

it will be important to gain public acceptance and increased familiarization of the potential risks.

Hydrogen is a nontoxic, nonpoisonous molecule that carries a lot of energy. Being 14 times lighter than air, hydrogen rises and quickly disperses when exposed to atmosphere. As shown in **Box 2**, these properties can reduce the potential damage of a leak when combined with an ignition source [38], [43].

The two main risks associated with HFCE HDVs that do not exist with conventional vehicles are the risk of electric shock due to built-in high-voltage electricity sources (the fuel cell stack and the accompanying battery pack) and the risk of ignition or explosion due to the on board high-pressure fuel storage tanks [42]

To address these risks, HFCE vehicles are designed with the below safety controls following Phase 1 of the *Global Technical Regulation No. 13* [44] developed by the United Nations:

- Hydrogen storage tanks onboard HFCE vehicles are wrapped in carbon-fiber [45] and are designed to bear twice the maximum pressure to avoid rupture. They are consequently much stronger than tanks found in conventional gasoline vehicles [42].
- Separate metal encasements seal both the battery pack and the fuel cell stack which are then electrically insulated from the metal body of the vehicle, with color coding to indicate their presence and appropriate training for first responders [42].

### Box 2. Gasoline Versus Hydrogen Fuel Leak

The 2001 fuel leak simulation at the University of Miami captured in a 3.5 minute video the comparable severities of a HFCE vehicle and conventional gasoline ICE vehicle at 1 minute after a fuel line leak and ignition [43].

The HFCE vehicle on the left shows the outcome of a pressure release activation with the hydrogen released in a standing jet flame with its flow already subsiding. The tank emptied in 100 seconds with the vehicle left undamaged and its rear window glass only reaching 47°C.

The gasoline vehicle on the right however, led to severe damage with a pool of gasoline beneath the car, flames engulfing the entire vehicle, ruptured tires and the unrestrained release of coolant.



- Hydrogen sensors are positioned throughout the vehicle to ensure safety for both the vehicle and its occupants [42], shutting off flow if a leak is detected such that delivered fuel dips by a programmed amount or conversely, flow exceeds volumes required by the fuel cell [43].
- The vehicle system and its components undergo destructive and non-destructive testing with the cylinders required to pass the same tests as compressed natural gas (CNG) tanks [45], evaluating the vehicle's safety when exposed to both unusual and severe conditions for crash safety [42], with regulations more stringent than those for CNG tanks [46].

Hydrogen fueling stations are also equipped with components that have built-in safety protection including at the customer-facing fueling dispensers, hoses and nozzles [42], each tested and certified to meet automotive and national codes and standards including the *Canadian Hydrogen Installation Code (CHIC) (CAN/BNQ 1784-000)* [47] or the more comprehensive *National Fire Protection Association Hydrogen Technologies Code (NFPA-2)* [48].

Major safety components at the fueling station [48], [49] include:

- Temperature, pressure and leak sensors
- Fire and flame detectors
- Ventilation located in key areas where leaks may occur, or hydrogen may accumulate
- Breakaway hoses, grounding cables or fueling pads installed to prevent the discharge of static electricity
- Automatic and manual emergency shut offs at the hydrogen source in the event of a leak
- Audible and visible alarms
- Safety signage, safety videos prior to refueling, and equipment interlocks limiting access to trained personnel
- Programmed safety checks to assess system integrity before fueling begins, with additional checks conducted throughout fill

Cold weather conditions that are common in Canada can present additional levels of risk that requires mitigation. These can include corrosion on storage equipment or user-interfacing dispenser units due to salt de-icing applications or the use of gravel which may trigger the production of static electricity. This necessitates the placement of equipment away from areas where corrosive materials may be present or conversely, the avoidance of salt application or gravel distribution within the vicinity of these stations [50].

Some exposure to confined spaces is likely for most HDVs as they will be required to enter tunnels during transport and remain in garages for maintenance and storage. Although further research is required, recent studies suggest hydrogen does not present additional hazards nor contribute to incident severity in tunnels [46]. For HFCE vehicle servicing, facility upgrades are likely only required for major repair garages to support hazard detection to identify leaks, gas dilution to reduce ignition risk and extraction to enable safe re-entry [51].

Though current knowledge, technological, and regulatory gaps are quite extensive relating to hydrogen safety, significant progress is being made with increasing international collaboration to conduct research to close the gap, support the dissemination of information between all relevant organizations and create harmonized global standards to reduce risk. With increased understanding and proven design of robust systems that can safely contain and reduce the risk of hydrogen leaks and ignition will come increased public acceptance of an alternative fuel.

#### Safety Strengths (✓) and Weaknesses (✗)

- ✓ With effective management, poses no greater risk than other fossil fuels
- ✓ International cooperation and standard development is ongoing
- ✗ Harmonized standards are still lacking
- ✗ Knowledge and technical gaps still exist
- ✗ General unfamiliarity with safety risks

## 2.6. Operational Consideration #6: Noise and Emissions

Noise and air pollution caused by diesel HDVs can impact the health and well-being of the driver, the general population and the environment. In fact, pollution has become a powerful force for the development of alternative powertrain technologies.

Globally, many places have taken steps to ban the use of diesel ICEs and/or introduce incentives for the adoption of electric vehicles between 2020 and 2040 (refer to **Box 3**) [52].

In contrast to the diesel ICE HDV, the HFCE HDV does not produce any nitrogen or sulphur oxide emissions; its sole tailpipe emission is water vapour and the only particulate matter emissions are from tire and road wear and tear that also occur in the incumbent diesel HDVs [4].

In addition, the operation of the electric powertrain produces less noise than its ICE equivalent which benefits the driver’s health and aids technology acceptance.

While the HFCE HDV does not produce harmful emissions from the tailpipe, the upstream production of hydrogen can generate GHG emissions depending on the production method. Although these upstream emissions are unlikely to directly impact business and operating performance of the HDV, there will likely be consequences related to sustainability reporting and branding. The upstream GHG emissions will also be subject to clean fuel standards set by the Canadian government that could impact fuel prices (refer to **Box 1**).

With blue hydrogen produced from natural gas paired with carbon capture and storage (CCS) and a low carbon grid utilized for compression activities, a HFCE HDV in long-haul operations is capable of reducing GHG emissions by 80% compared to the lifecycle emissions (well-to-wheel) of a diesel ICE HDV [4]. Without CCS, emissions can be reduced by 34% (assuming a 30% renewable grid is used for compression activities) [4].

Hydrogen produced from renewable electricity (green hydrogen) can eliminate most upstream GHG emissions; however, as discussed in the next section, it is a more costly method of producing hydrogen.

**Box 3. Nations and Cities with Actions to Phase-out Internal Combustion Engines as of September 2018**

From the Center for Climate Protection [52].

**Nations**

Austria	India	Scotland
Britain	Ireland	South Korea
China	Israel	Spain
Costa Rica	Japan	Taiwan
Denmark	Netherlands	Germany
France	Norway	Portugal

**Cities**

Athens	London	Quito
Auckland	Los Angeles	Rome
Barcelona	Madrid	Seattle
Cape Town	Milan	Vancouver
Copenhagen	Mexico City	
Heidelberg	Paris	

**Noise and Emissions Strengths (✓) and Weaknesses (X)**

- ✓ Zero tailpipe emissions
- ✓ Very little noise
- X Possible upstream GHG emissions

### 3. Goodness of Fit: Cost Performance

Regardless of the potential environmental and operational fit, the long-term sustainability of the HFCE HDV technology requires that it can be cost competitive with the dominant diesel ICE technology.

In Canada, it can cost upwards of C\$2/km to own and operate an HDV in long-haul freight service (**Figure 3.1**) [53]. Close to 50% of these operating costs are associated with asset ownership, fuel consumption, and maintenance costs. Other HDV duty cycles would have variations of this operating cost profile, but the same three factors will directly impact the total cost of ownership (TCO) for existing and alternative powertrain technology.

In addition, indirect factors such as driver attraction and retention, alignment with emerging innovations like connected autonomous vehicle technology, and changing market and regulatory drivers are also important considerations that should be accounted for [54].

#### 3.1. Cost Consideration #1: Asset Cost

The diesel HDV is a mature technology in an active market with a capital cost of around C\$165,000/HDV for a Class 8 freight tractor [53]. New technologies trying to break into the market will need to be able to compete against this relatively low-cost standard. Initially, government incentives could help in the transition to a more sustainable technology and over time, the costs for the alternative HDVs should come down.

Because HFCE HDVs are not currently available at commercial scale, asset costs are still widely unknown. Literature suggests the HFCE vehicle is expected to be around 2 to 3 times the cost of its diesel HDV equivalent, likely between C\$335,000 [55] and C\$455,000 [56]. However, the technology is advancing rapidly with falling component costs and the future price of these vehicles could even be lower [16]. In comparison, the battery electric HDV is anticipated to have a lower purchase price than the HFCE HDV but will still be higher than the diesel ICE [15], [57].

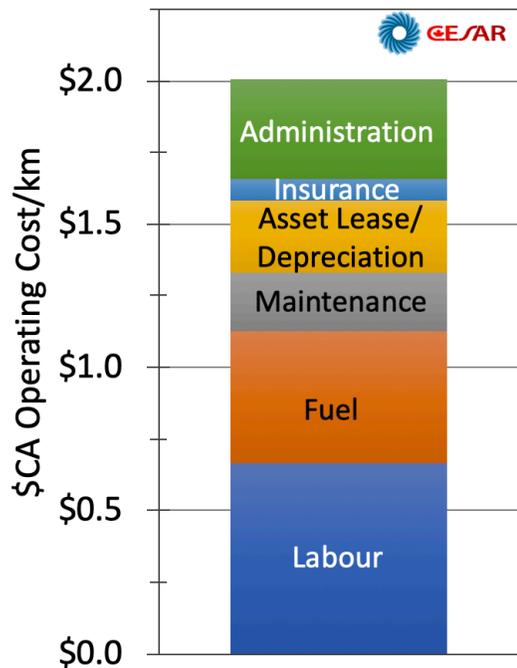


Figure 3.1. Operating Cost Profile for a Typical Class 8 Truck Operating in Freight Service in Canada. CESAR figure sourced from Statistics Canada data [53].

According to a recent study prepared by Deloitte and Ballard Power Systems [57], the cost of the energy module, which includes the fuel cell system, hydrogen tanks, battery, and thermal management systems along with the corresponding component mark-ups, accounts for most of the purchase price differential between the HFCE and the ICE HDV; the fuel cell system is the most costly component at 73% of the energy module cost and hydrogen tanks make up another 15%.

A recent report written for the Hydrogen council has projected that by 2030 the cost of fuel cells could be between 70%–80% lower by 2030 and hydrogen tank cost could be reduced by 85% [58]. These reductions are thought to be made possible by downward pressure on emerging technology costs and the benefits of manufacturing scale, assuming HFCE HDV production volumes of around 150,000 units per year can be achieved in the next 10 years [58]. In comparison, however, the US Department of Energy (DOE) is targeting cost parity to diesel ICE for long-haul Class 8 trucks by 2050 with a 100,000 unit/year commercial production volume [34].

While the long-term outlook for the capital costs of HFCE HDV appears promising, much is dependent on achieving economies of scale. At present, it is unclear if government, technology OEMs, or end-users would be willing to pay the interim price premiums [59].

#### Asset Cost Strengths (✓) and Weaknesses (✗)

- ✓ Projected to reach parity by 2050 or sooner
- ✗ Currently 2-3 times more expensive
- ✗ Cost reductions are dependent on reaching economies of scale

### 3.2. Cost Consideration #2: Maintenance Cost

Representing close to 10% of a commercial freight carrier's operating expenses in Canada [60], maintenance costs are one of the top concerns for the freight industry and are likely equally concerning for other HDV fleets. In addition to the actual costs for repair and upkeep, there are opportunity costs associated with planned and unplanned maintenance for HDVs that are unavailable for service.

The maintenance costs of electric HDVs (either HFCE or battery electric) are currently unknown but should have considerably lower maintenance costs because of the simpler design, fewer friction sensitive mechanical parts, and reduced amount of fluids. A consensus has not been found for the expected maintenance costs specific to HFCE HDVs because of lack of data

[34]. Some studies, including a recent International Energy Agency (IEA) report [41] and Deloitte/Ballard report [57], suggest maintenance costs could be between 50–65% of the cost to maintain the diesel equivalent. Whereas the DOE expects maintenance costs will be higher than the diesel equivalent and reach parity by 2050 [34]. The higher cost assumptions from the DOE are linked to the challenges of early stage deployment.

Lessons learned from HFCE bus demonstrations in California and Ohio indicate there are significant costs associated with troubleshooting and diagnostics through the early periods of the deployment of a new HFCE fleet. Such costs can be mitigated through the deployment of larger fleets to accelerate the learning curve for staff and through the incorporation of HFCE training into standard maintenance training programs [61].

Another potentially large maintenance cost element would be the replacement of the fuel cell and battery. With an expected life span of 25,000 hours, the fuel cell may last the lifespan of the HDV [34]. If it does not, the replacement cost for a 308 kW fuel cell (the size likely for a long-haul truck) at US\$190/kW would be at least C\$59,000 assuming a 1,000 fuel cell production scale [34]; this would decrease with the anticipated reductions in fuel cell cost. Similarly, the battery should outlast the HDV lifespan [54] but with replacement costs currently around US\$200/kWh [62] that cost could be significant depending on the size of the supplemental battery.

#### Maintenance Cost Strengths (✓) and Weaknesses (✗)

- ✓ Potential for low maintenance costs due to simpler design
- ✗ Increased diagnostics associated with lack of training
- ✗ Replacement fuel cells and batteries are expensive

### 3.3. Cost Consideration #3: Energy Cost

Aside from labour, energy is the largest cost driver in the operation of an HDV. In the long-haul freight example provided in **Figure 3.1**, fuel costs are currently higher than asset and maintenance costs combined. Therefore, the difference in costs for alternative energy sources like hydrogen cannot be overlooked and must be competitive with the cost of diesel.

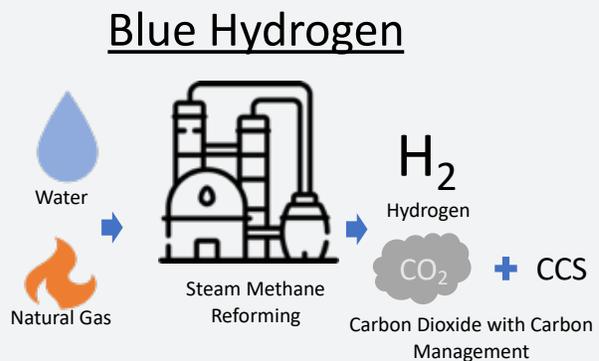
The HFCE powertrain has inherent energy efficiency advantages over the diesel ICE. Depending on the engine type and drive cycle, HFCE vehicles typically consume only 40% to 80% of the fuel consumed by an ICE vehicle to move a similar weight the same distance [4], [41].

The cost of hydrogen varies depending on how the hydrogen gas is produced, distributed and prepared for consumption through purification, storage, and compression. In addition, hydrogen prices will fluctuate with the price of its primary feedstock, either electricity for green hydrogen or natural gas for blue hydrogen. **Box 4** provides more information on the two predominant hydrogen production technologies.

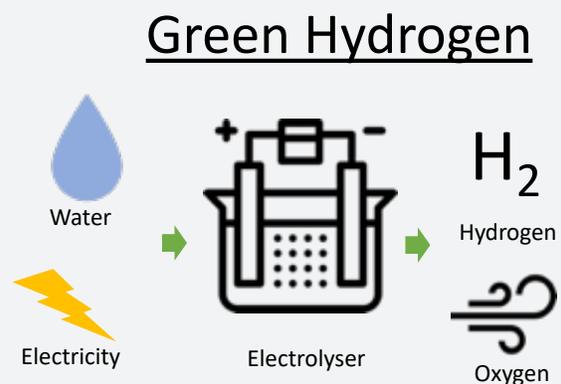
In addition to the production costs of hydrogen, a large portion of the delivered cost of hydrogen is due to distribution. This can include gaseous transportation by pipeline (lowest cost at high volume) or by tube truck. Alternatively, the hydrogen can be converted to a liquid, either cryogenically to  $-252^{\circ}\text{C}$ , reacting it with a liquid organic hydrogen carrier or converting the hydrogen to ammonia that can be liquefied at relatively low pressures. Storage and compression to 450 or 900 bar pressures are also components of the distribution system that adds cost. In a recent study, CESAR [4] estimated that a hydrogen price of between  $\$3.50$ – $\$5/\text{kg H}_2$  ( $\$25$  to  $\$35/\text{GJ}$ ) was needed to be cost competitive with a wholesale diesel price of  $\$0.75/\text{L}$  ( $\$19/\text{GJ}$ ), depending on the drivetrain and drive cycle efficiency improvements of HFCE vehicles (Figure 3.2). This assessment is consistent with the DOE's price target for delivered hydrogen of US $\$3.90/\text{kg H}_2$  (2007 dollars) by 2020 [63].

#### Box 4. Common Hydrogen Production Methods

**Steam methane reforming (SMR)** uses high temperature and steam to convert natural gas into hydrogen and carbon dioxide. This low-cost method is frequently used by the fertilizer and oil refinery industries. The carbon dioxide from this process can be captured, compressed and permanently sequestered in the sub-surface (CCS). When combined with CCS, the product is referred to as “Blue Hydrogen”.



**Electrolysis** uses electricity to split water into oxygen and hydrogen. Hydrogen produced from this process is emission free, but currently more costly than SMR unless the electricity is very low cost (less than  $\$20/\text{MWH}$ ). The product is referred to as “Green Hydrogen”.



With the low commodity price of natural gas in Canada [64], the wholesale price to produce hydrogen using SMR technology paired with CCS is projected to be under \$1.5/kg<sub>H<sub>2</sub></sub> (less than \$10/GJ<sub>HHV</sub> H<sub>2</sub>) if carried out at large, industrial scale [4], [65]. However, without hydrogen distribution systems available at scale, the retail delivered price of blue hydrogen could add \$4–\$8/kg H<sub>2</sub> (~\$28–\$57/ GJ<sub>HHV</sub> H<sub>2</sub>) [4], illustrating the importance of strategically locating fueling stations in regions where there will be high demand.

Through the introduction of distribution systems at scale (e.g. pipelines) and high capacity fueling stations, blue hydrogen should be able to provide a cost advantage over diesel fuel [3]. This advantage would be even greater when considering carbon pricing and clean fuel standards.

Green hydrogen production using water electrolysis with renewable or nuclear power has the advantage of being deployable at a smaller scale than SMR with CCS, perhaps right at each fueling station. However, to be competitive with blue hydrogen production, the price of low/zero carbon electricity must be very low (ideally less than \$20–30/MWh) (Figure 3.2). While such a price may be possible in Quebec or in other provinces during particular times of the day, Alberta is not likely to be one of those provinces in the

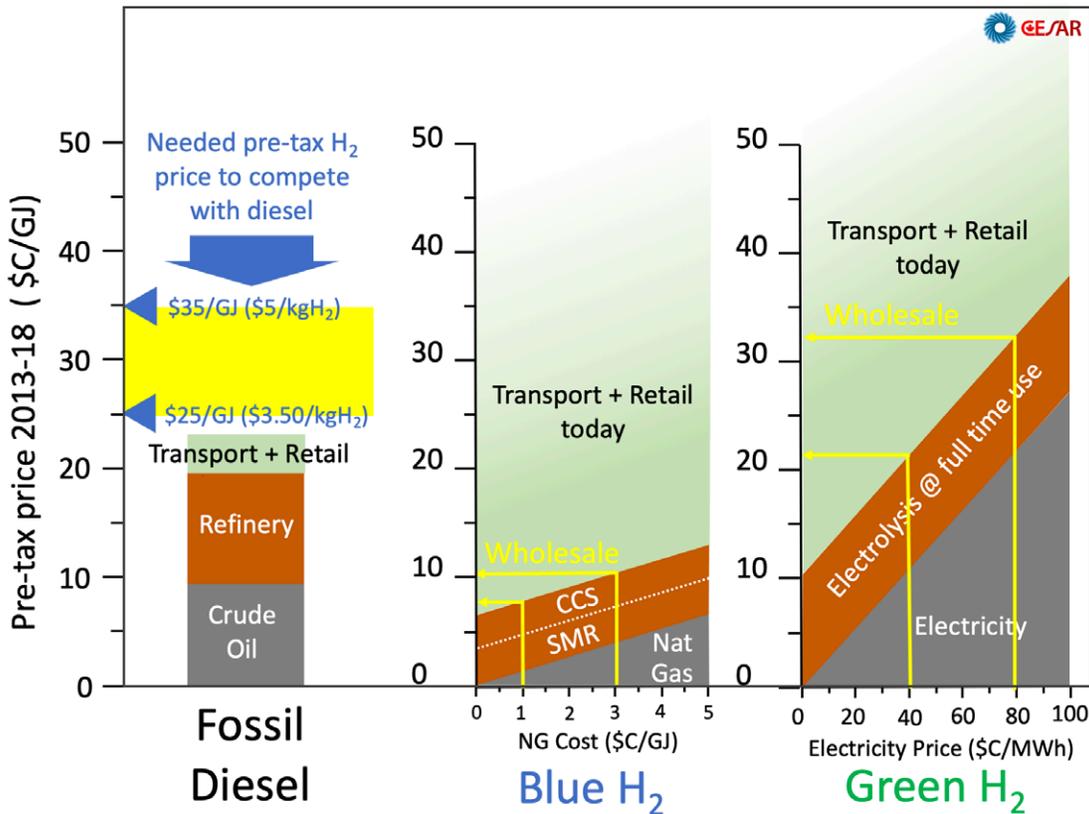


Figure 3.2. Pre-tax Price Breakdown of Delivered Diesel Compared to Blue and Green Hydrogen. CESAR Figure adapted from CESAR’s Future of Freight Part C report [3]; SMR: Steam Methane Reforming; CCS: Carbon Capture and Storage.

foreseeable future[4]. Assuming renewable electricity prices of \$40–\$80/MWh, green hydrogen prices in Alberta are likely to be between \$3–5/kg H<sub>2</sub> (~C\$21–\$35/GJ<sub>HHV</sub> H<sub>2</sub>) which leaves little margins for distribution, compression and retail (**Figure 3.2**). However, future cost reductions in electrolyzer technology paired with lower cost renewable power (<US\$30/MWh), some researchers suggest green hydrogen could be competitive with diesel as early as 2030 [66].

Policy and regulatory tools such as carbon pricing and clean fuel standards (refer to **Box 1**) can help bolster the potential price advantage, but strategic investments focused on the rapid, coordinated deployment of supply and demand at scale is essential for the creation of a vibrant hydrogen economy supporting freight transport [58].

#### Energy Cost Strengths (✓) and Weaknesses (✗)

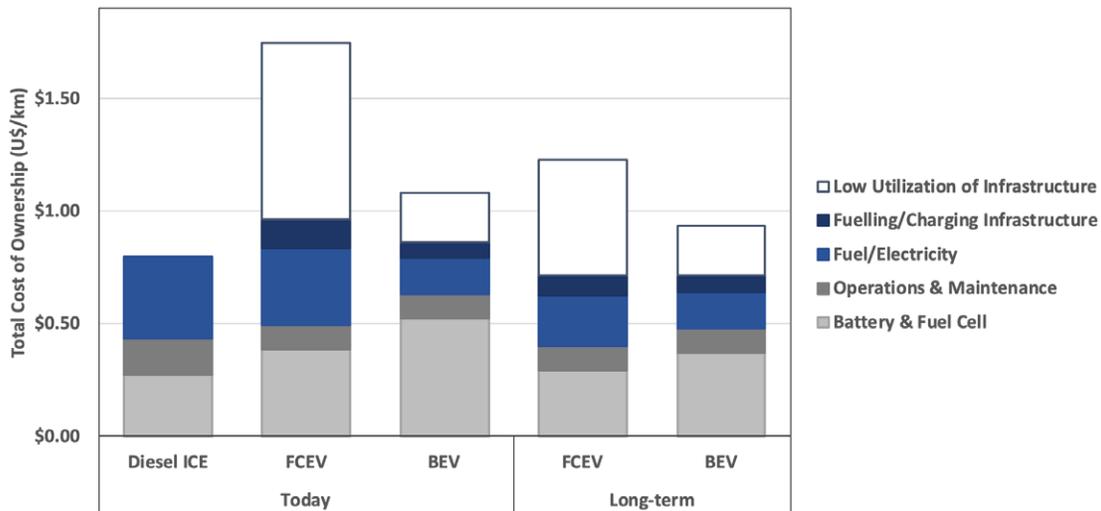
- ✓ HFCE powertrains are more energy efficient
- ✓ Blue retail hydrogen prices can provide a price advantage when deployed at scale
- ✓ Green retail hydrogen prices are higher but expected to decrease with technology cost reductions
- ✗ The lack of distribution systems adds cost and uncertainty

### 3.4. Total Cost of Ownership

The compilation of the asset, maintenance, and fuel cost considerations allow for the determination of the lifetime cost of asset ownership and a commensurable comparison between technologies can be made. In recent years, several TCO studies comparing HFCE HDV and diesel ICE HDVs have been conducted [8], [16], [41], [57], [58], with differing results depending on the assumptions and methods utilized. There is agreement that the HFCE HDV will have higher TCOs than both diesel ICE and battery electric HDVs in the near term with most suggesting that the long-term prospects for reaching parity and even lower TCOs than diesel ICE are promising.

**Figure 3.3** summarizes the results from the IEA’s Future of Hydrogen report [41] as an example of what some researchers are projecting for TCO of the HFCE HDV.

There is risk associated with using TCO as a comparison tool, particularly when variable costs such as reduced fuel or maintenance are the primary drivers for a TCO advantage with a large asset cost. The agency responsible for paying for the fixed asset cost must trust that variable cost savings are



**Figure 3.3.** Current & Future Total Cost of Ownership of Fuel/Powertrain Alternatives in Long-Haul Trucks. Adapted from IEA's Future of Hydrogen [41]. ICE; Internal Combustion Engine; FCEV; Fuel Cell Electric Vehicle; BEV; Battery Electric Vehicle.

sustainable for the lifespan of the HDV and that the expected lifespan is possible.

To help de-risk the high upfront capital costs, a large fleet operator suggested to CESAR that an adjustment to the capital cost allowance rate with full depreciation levels reached in year one could be helpful. This approach is similar to the Accelerated Investment Initiative put in place in late 2018 to encourage investment in the trucking sector [67]

In addition, new business model innovations are emerging and are being tested by companies like Nikola Motor Company. Rather than having the fleet owner purchase the HDV and source their own fuel and maintenance, Nikola uses a lease model that charges its customers a bundled rate per mile that includes the cost of the truck, fuel, and maintenance [68].

#### Total Cost of Ownership Strengths (✓) and Weaknesses (✗)

- ✓ Promising long-term outlook for TCO parity
- ✓ New business models are emerging to address the high capital cost risk
- ✗ Near term TCO is high with high fixed asset cost

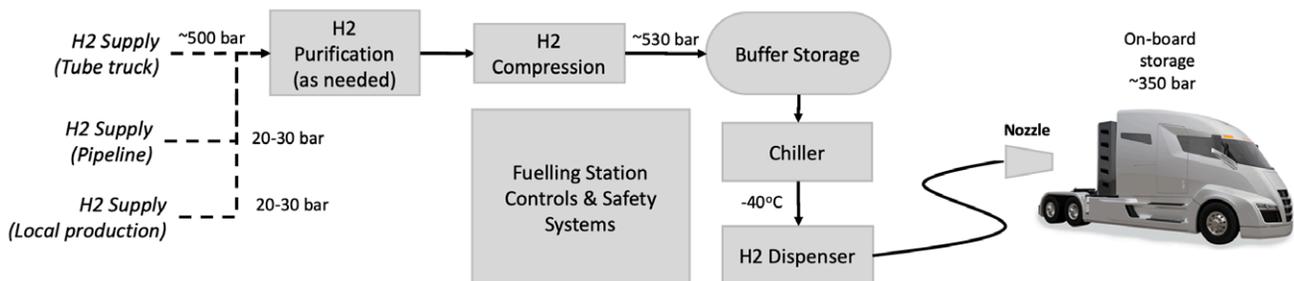
## 4. Goodness of Fit: Fueling Station Infrastructure

For the successful deployment of HFCE HDVs, a strong network of fueling stations is essential to safely, reliably, and conveniently supply fuel to support fleet operations.

**Figure 4.1** shows a general configuration of a hydrogen fueling station to fill a HFCE HDV with 350 bar pressurized hydrogen gas [69]. The main components of the fueling station include 1) purification systems to remove contaminants that could damage the fuel cell, 2) compression to suitable pre-fueling pressure, 3) intermediate storage, 4) a chiller, and 5) a hydrogen dispenser and nozzle. The stations are also equipped with the necessary controls and safety systems.

In Canada, fueling station protocols and standards are currently set by the CHIC [41] or NFPA-2 [42], along with SAE J2601-2, the latter of which was developed for HFCE buses with 350 bar hydrogen tanks [25]. However, there are concerns that standards specific to Class 8 trucks are absent along with protocols for the higher pressure of 700 bar fuel tank pressure that could be desired to increase HDV range. To address this gap, a consortium made up of Nikola Motor Company, Hyundai, Air Liquide, Shell, and Nel Hydrogen have agreed to work together to accelerate the standardization of large capacity hydrogen fueling technologies [70].

As discussed in previous sections, the costs associated with the fueling station constitute a significant portion of the retail price of hydrogen. In the Hydrogen Council's most recent report, it is estimated that fueling stations contribute around US\$5/kg to the price of hydrogen [58]. Much of this high cost can be correlated to the small scale of stations. According to this same report, a cost reduction of about 80% can be achieved through higher rates of utilization, an increase in station size, and the industrialization of equipment manufacturing.



**Figure 4.1.** Gaseous Hydrogen Fueling Station Configuration. Adapted from NREL [69].

Stations that support HDVs that each consume upwards of 100kg<sub>H<sub>2</sub></sub> per fill in captive industrial areas, may be more successful at achieving this critical scale [41].

Similarly, the benefits of scale would extend to reducing the cost to transport hydrogen from the point of production to the fueling station, through the introduction of pipelines and/or liquefaction [58]. With these potential economies of scale, an argument can be made for the strategic deployment of high capacity fueling stations along key transportation corridors in Canada that could supply fuel to HDV fleets operating on the corridor, either between two fueling stations or in return-to-base services near one of the stations.

#### Fueling Station Infrastructure Strengths (✓) and Weaknesses (✗)

- ✓ Concentrated and assured markets of HDVs can help the critical scale to reduce fueling station costs
- ✗ Insufficient fueling infrastructure currently in place
- ✗ Lack of standards for HDV trucks or 700 bar fuel tank pressures

## 5. Project and Market Status for HFCE HDVs: Trucks

The previous sections of this report demonstrate that HFCE technology has the potential to be a good fit for many HDV applications. However, there are currently very few HFCE trucks on the road anywhere in the world.

While light-duty HFCE vehicles are commercially available in places like California, Europe and Japan, as well as some Canadian provinces, with over 11,000 HFCE cars and vans currently on the road [41], the commercialization of HFCE HDV trucks is still in the early stages and remains largely in the demonstration phase.

With limited credible options available for the decarbonization of the HDV freight and service sector [71], many nations and jurisdictions have identified HFCE technology as a compelling alternative. They have been guiding the advancement of HFCE HDVs by supporting pilots and demonstrations while using policy to incentivize and remove barriers for the future adoption of the HFCE HDV technology.

Meanwhile, a few companies have similarly recognized HFCE HDV trucks as a lucrative new market segment and existing and emerging HDV OEMs are

entering this new market. These companies have been met with a positive response from fleet owners that have, on good faith, collectively pledged large orders for these trucks without having driven nor seen the proposed truck model.

In recent years, the movement towards HFCE HDV trucks has been generating excitement and gaining momentum. This section of the report reviews, by region, the progress that has been made for the deployment of both demonstration trucks and commercialization plans and identifies the corresponding policy tools that have been utilized. **Figure 5.1** summarizes the deployments (actual and planned) that are captured by this report. However, given the current momentum, it is fair to expect more developments in the near future.

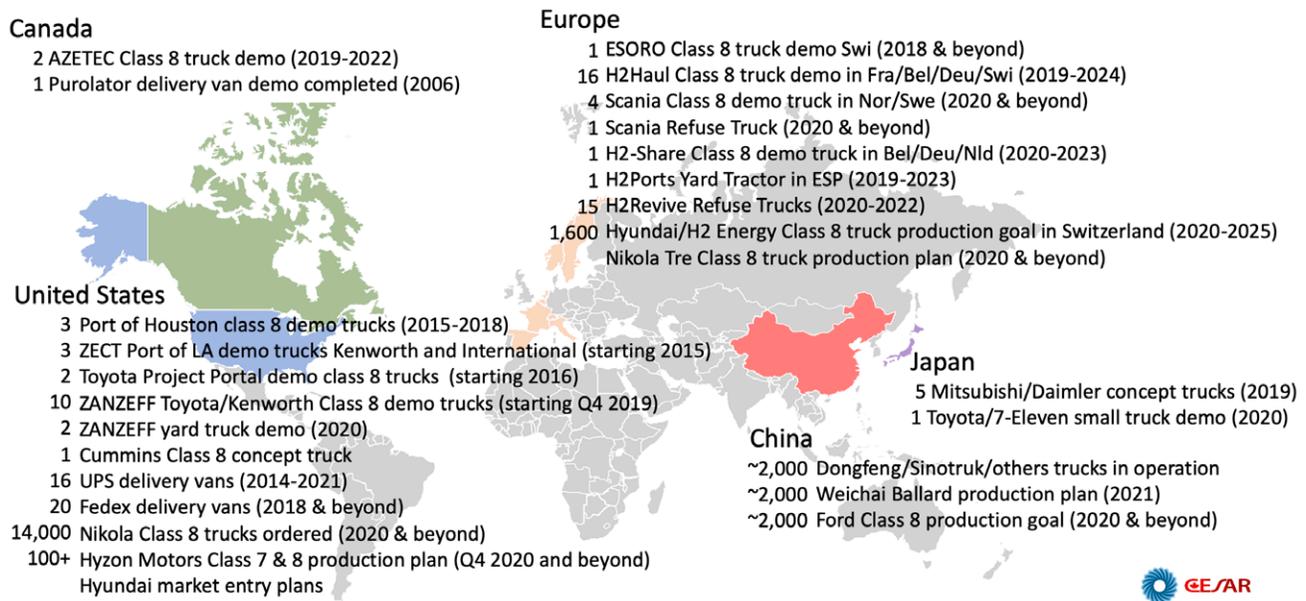


Figure 5.1. Global Deployments of HFCE HDV Trucks (Actual or Planned).

## 5.1. United States

The United States has a long history of supporting hydrogen interests dating as far back as the oil crisis of the 1970s. Legislation and policy to advance the hydrogen industry has been in place since the 1990s under the direction of the Office of Energy Efficiency and Renewable Energy within the DOE [57].

Between 2003 and 2008, the United States funded over US\$1 billion in projects that encompass most aspects of the hydrogen life cycle. These programs are believed to have [72]:

- Reduced the cost of hydrogen production from natural gas

- Developed a sophisticated model to identify and optimize major elements of projected hydrogen delivery
- Increased the storage capacity of hydrogen by 50%, thereby improving driving range
- Reduced the cost and improved durability of fuel cells

The DOE continues to support the research, development, and deployment of a hydrogen economy with investments of US\$100–\$280 million per year over the last decade [73], much of which either directly or indirectly benefits the HDV application. Some of the most recent funding announcements are summarized in **Box 5** [74–76].

Similar to Canada, OEMs would also be incentivized to develop zero-emission technology through *GHG Emission Standards for Medium and Heavy Duty Vehicles* [77] that is administered by the Environmental Protection Agency and the National Highway Traffic Safety Administration.

The State of California, motivated largely by air pollution concerns and working through the California Air Resources Board (CARB), has taken a leadership role in promoting the adoption of zero-emission vehicle technology and the use of low carbon fuels for the HDV sector.

Supported by funds enabled through its *Cap and Trade Program* and the *California Climate Investment* initiative [78] and under the vision of the *California Sustainable Freight Action Plan*, CARB has funded many *Advanced Technology Demonstration Projects* and proposed an *Advanced Clean Truck* regulation that will mandate 50% of all Class 4–8 straight trucks are zero-emission by 2030 [79].

In partnership with local agencies, CARB has leveraged its US\$1 billion *Proposition 1B: Goods Movement Emission Reduction Program* to support rapid emission reduction on transportation corridors since 2015 [80]. To provide further incentive, CARB has recently launched the *Hybrid and Zero-Emission*

#### **Box 5. Recent US Funding Announcements Covering Hydrogen and HDV Topics**

**H2@Scale (DOE) US\$31 million:** Addresses the scaling up of hydrogen production and utilization and covers topics specific to improving the fuel cell in HDV applications. Announced December 2019 [74].

**Advanced Vehicle Technologies (DOE) US\$133 million:** Not limited to hydrogen. Aims to achieve more affordable, efficient and secure transportation energy. Up to US\$36 million of funds are available for technology integration for gaseous fuels like hydrogen. Announced January 2020 [76].

**Heavy-Duty and Off-Road Truck Technology Research (DOE) US\$51 million:** With up to \$28.5 million directed towards hydrogen HDV technology and fueling systems, this funding aims to use innovation to improve energy productivity and transportation affordability. Announced March 2019 [75].

*Truck and Bus Voucher Incentive Project* that provides substantial rebates to offset the purchase price premium [81]

America's ports also have an important role in the progress towards the adoption of zero-emission HDVs, including HFCE technology. With over 17,000 HDVs registered to operate at the Ports of Los Angeles and Long Beach [82], America's two largest ports have been taking their own measures that go above and beyond the federal and state initiatives with their *Clean Air Action Plan* (CAAP), which has reduced air pollution from harbour trucks by 90% in just three years [83].

One of the main actions of the CAAP is to prohibit the entry of older HDVs to port facilities. It is anticipated that by 2020, the ports will assess gate fees to HDVs that are not near zero or zero-emission. Other ports, including the Port of Houston, also have Clean Air Strategy Plans [84].

The above federal, state, and local conditions have made it possible for port terminals to become the epicenter for the development of HFCE HDV technology through demonstration projects, including the ones listed below. Some early lessons reported from zero-emission projects at the ports are shared in **Box 6** [85].

#### **Box 6. Lessons Learned from Early Port of Los Angeles Zero-Emission HDV Demonstration Projects [85]**

- Limited demonstrations are not enough to stimulate commercialization
- Equipment must first meet minimum performance standards and then undergo long-term testing and demonstration to assure it is reliable in a maritime goods movement environment, which is more rigorous than typical goods movement distribution centers
- Small tech developers may not have the operational wherewithal to develop the technology; OEMs and component suppliers are needed
- It is advantageous for technology to match duty cycle

#### **Houston/EDF**

The Port of Houston was involved in the early development of HFCE HDVs. With project partners including the Environmental Defense Fund (EDF), US Hybrid, and GTI, the port demonstrated three (3) trucks between 2015 to 2018.

### Zero-Emission Truck Cargo Transport II (ZECT II)

The Port of Los Angeles and Long Beach began including HFCE trucks and yard tractors in its ZECT II program in 2015 with three (3) demonstration HDVs being road tested at their terminals [86].

**Kenworth** used its platform to build a Class 8 drayage model (pictured in **Box 7**) as part of ZECT II with the following specifications [86]:

- GVWR: 36 tonnes
- Drive System Provider: BAE Systems
- Fuel Cell Make: Ballard
- Fuel Cell Size: 100 kW
- Traction Motors: 2 x 180 kW (~500 HP)
- Battery Size: 100 kWh
- Hydrogen Storage: 30 kg @ 350 bar
- Range: ~240 km

**Navistar International** partnered with **US Hybrid** to build two (2) ZECT II HFCE plug-in drayage trucks with the following specifications [86]:

- GVWR: 36 tonnes
- Drive System Provider: US Hybrid
- Fuel Cell Make: US FuelCell
- Fuel Cell Size: 80 kW
- Traction Motors: 320 kW direct electric drive (~500 HP)
- Battery Size: 26 kWh
- Hydrogen Storage: 20 kg @ 350 bar
- Range: ~325 km

### Toyota Project Portal

In 2017 and 2018, **Toyota** used its experience with fuel cells from its Mirai HFCE passenger vehicles to build two consecutive versions of HFCE Class 8 HDV prototypes using a Kenworth chassis. Referred to as Project Portal Alpha (pictured in **Box 7**) and Beta, the HFCE HDVs are road tested between the two ports in southern California. The Project Portal project also includes the introduction of a 1.2 tonne/day fueling station for hydrogen produced from biowaste planned for 2020 [87]. The specification of the Project Portal HDVs are as follows [88], [89]:

- GVWR: 36 tonnes
- Fuel Cell Make: Toyota Mirai

- Fuel Cell Size: 2 x 114 kW
- Traction Motors: 500 kW (~670 HP)
- Battery Size: 6 kWh (Alpha), 12 kWh (Beta)
- Hydrogen Storage: 40 kg (Alpha), 60 kg (Beta) @ 350 bar
- Range: ~390 km (Alpha), ~480 km (Beta)

### Zero-and-Near-Zero-Emission Freight Facilities Project (ZANZEFF)

Building off the learnings from the ZECT and Project Portal trials, the Port of Los Angeles has launched the ZANZEFF project that involves the development and deployment of ten (10) HFCE Class 8 trucks under a **Toyota and Kenworth** partnership and is supported by US\$43million in funding from CARB.

It is reported that four of the HDVs have already been produced, with all ten expected to be available in 2020 for road testing by Toyota Logistics, UPS, TTSI, and Southern Counties Express [90]. In addition, the project also supports the development and testing of two (2) smaller HFCE yard tractors for the Port of Hueneme [91].

Shell is also involved in the ZANZEFF project to add two new heavy-duty fueling stations to the three existing stations at port facilities to integrate a fueling network for the Los Angeles Basin [91].

## Box 7. Photos of Demonstration HDVs

### Kenworth ZECT II



Photo : <https://www.kenworth.com/news/news-releases/2018/january/t680-zect/>

### Toyota Project Portal Alpha



Photo : <https://www.kenworth.com/news/news-releases/2018/january/t680-zect/>

### UPS Delivery Vans



Photo: [https://www.hydrogen.energy.gov/pdfs/review19/ta016\\_hanlin\\_2019\\_o.pdf](https://www.hydrogen.energy.gov/pdfs/review19/ta016_hanlin_2019_o.pdf)

### Fuel Cell Hybrid Electric Van Project

Outside of the ports, **UPS** is collaborating with the Center for Transportation and the Environment, with funding from the DOE, CARB and other agencies, to demonstrate sixteen (16) HFCE walk-in delivery vans that will operate from multiple distribution centers in California; the project end date is planned for April 2022. The first of the sixteen vans started road testing in February 2019.

Unlike the first UPS HFCE van, to extend the possible range, the design for the next fifteen vans is anticipated to accommodate 700 bar pressurized hydrogen, with the intent to utilize the new Shell fueling station that is part of the ZANZEFF project.

### FedEx Plug Power Delivery Vans

Supported by DOE funding, **FedEx** has partnered with the fuel cell company, Plug Power and the electric vehicle manufacturer, Workhorse Group, to build and road test HFCE delivery vans in their New York state operations. The first HFCE HDV was launched in early 2018 and plans to grow the HFCE fleet to twenty (20) vans in the upcoming years [92]. Details for the delivery van are as follows[93]:

- GVWR: 8.8 tonnes
- Fuel Cell Make: Plug Power
- Fuel Cell Size: 20 kW
- Traction Motors: 200kW (~268 HP)
- Battery Size: 80 kWh
- Hydrogen Storage: 11.6 kg @ 350 bar
- Range: ~250km

Beyond the demonstration environment, new and existing OEMs have announced their plans to supply HDVs to the North American market, including the ones listed below. Many of the emerging design concepts have abandoned the traditional design structure of the Class 8 freight truck and have offered different aerodynamic features. Photos of these concepts are presented in **Box 8**.

### Nikola Motor Company

Based in Arizona and founded in 2014, **Nikola Motor Company** has generated a lot of excitement from both the trucking and investment communities. The now US\$3 billion company has received over 14,000 orders for its **Nikola Two** HFCE Class 8 truck model [94]. The first test trucks are expected to start in 2021 and commercial scale production is planned to begin in 2023 [95].

### Box 8. Photos of Emerging HFCE Truck Concepts in the United States

Nikola Motors



Photo: <https://nikolamotor.com>

Hyundai Motor Co.



Photo: <http://trucknbus.hyundai.com>

Cummins Inc



Photo: <https://www.cummins.com>

Hyzon Motors



Photo: <https://www.hyzonmotors.com>

Beyond zero-emission benefits, Nikola claims it can achieve ranges greater than 800 km per fill, is lighter than the equivalent diesel truck, and can provide drivability advantages with direct to wheel torque [96]. Part of the company's strategy to achieve these performance goals is to avoid traditional thinking that seeks incremental improvements to the conventional truck architecture and has goals to 'push a revolutionary narrative' [97].

The HDV is perceived by many to be a futuristic truck with features that would be attractive to the modern truck driver. These features include large digital side mirrors, keyless entry, luxurious interiors with large digital instrumentation screens that in addition to providing standard operational information like speed and tire pressure are equipped with GPS mapping and diagnostic information. It is also anticipated that the truck platform

will be compatible with emerging innovations such as autonomous driving capabilities [40].

The specifications of the Nikola Two are as follows [96]. The Nikola One is a sleeper cab version with similar specifications.

- GVWR: 36 tonnes (8 to 9 tonne tare weight)
- Traction Motors: 735 kW (1000 HP)
- Battery Size: 250 kWh
- Hydrogen Storage: 80 kg at 700 bar
- Range: 800 km to 1200 km

Nikola Motor Company is unique in that it is internalizing and taking ownership of the challenges of having both a reliable fuel supply and qualified maintenance programs for its trucks. By partnering with Nel Hydrogen and Ryder, Nikola can offer full service packages to its customer with set fuel and maintenance rates either bundled in the HDV lease rate or paid to Nikola on a monthly basis [68].

This approach shifts the burden from the end-user or the public to the OEM. Nikola is managing this risk through plans to build a network of large (7-10 acre) truck centers that will produce fuel onsite using electrolysis technology, are equipped with fuel dispensers suitable for HDVs, and include onsite maintenance garages. Nikola is targeting the deployment of 700 of these truck centers by 2028 and expects the cost of hydrogen at these stations to be about US\$6/kg [98].

Nikola has expressed concerns that the current regulatory bureaucracy can inhibit the rapid development of these stations claiming that it takes years to obtain permits, when, in their opinion, it should take weeks [68].

### Hyundai Motor Co.

South Korea based **Hyundai Motor Co.**, announced in October 2019, its intentions to launch its HFCE HDV truck to the US market with its **HDC-6 Neptune model** as part of its FCEV 2020 vision [99]. While the Neptune truck is only a concept prototype, Hyundai has experience with HFCE vehicles in the passenger vehicle market with its Tucson and Nexo models and has HDV (with ICE powertrains) manufacturing plants in South Korea, China and Turkey with sales in 130 countries.

There are not many details currently available about the HDC-6 Neptune; however, similar to Nikola Motor Company, Hyundai is including features that are appealing to drivers and are expected to have some autonomous driving capabilities [99].

To help develop and commercialize its HFCE HDVs, Hyundai has signed an agreement with Cummins Inc. who will assist with the electric powertrain, battery, and control technologies [100].

### Cummins Inc.

In addition to supporting Hyundai and its recent acquisition of the large fuel cell company, Hydrogenics [101], **Cummins Inc.** has unveiled its own HFCE Class 8 truck, which is intended to be marketed to other OEMs as an innovative powertrain package [102].

The HFCE HDV is thought to be suitable for urban and regional haul, drayage, and container handling. It was designed with the following specifications [102]:

- Fuel Cell Make: Hydrogenics
- Fuel Cell Size: 90 kW and scalable in 30 kW or 45 kW increments
- Traction Motors: unknown
- Battery Size: 100 kWh
- Hydrogen Storage: unknown
- Range: 240 km to 400 km

### Hyzon Motors

As a subsidiary of Singapore based Horizon Fuel Cells, **Hyzon Motors** has entered into the HFCE HDV market with ambitious plans to have hundreds of trucks on the road in North America starting in November 2020 [103].

There is little official information available about Hyzon's plans, but its website has some basic design variations for trucks with GVWRs between 40 and 80 tonnes, fuel cell packages ranging between 150 to 370 kW, and hydrogen tank set ups that can accommodate 48 to 192 kg of hydrogen. Hyzon claims these designs would be able to achieve ranges between 500 and 2,000 km between fueling [103].

## 5.2. Europe

The Europe Union (EU) has recognized the need to electrify HDVs to reach its GHG emission reduction targets set by the 2015 Paris Accord and has identified hydrogen as a credible option to overcome the limitations of battery electric and catenary electrification options [104]. In a recent Hydrogen Road Map Europe report [105], it is projected that with coordinated government and industry efforts, over 1.7 million HFCE HDVs could be on the road by 2050, representing up to 25% of the segments fleet in Europe.

Furthermore, the EU is actively pursuing a hydrogen economy for its broader energy security, economic, and job creation benefits. With sector-coupling, the hydrogenation of transportation can also benefit other sectors that include, but are not limited to, power generation, the gas network, and the steel industry.

Europe uses CO<sub>2</sub> emission standards for new HDV sales [106] and Renewable Energy Directives [107] to encourage a shift toward alternative fuel power-trains for the HDV sector. In addition, the EU is also investing a considerable amount of funds into the energy transition.

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a European public private partnership, is the primary agency that supports research, technological development and demonstration activities for fuel cell and hydrogen technologies in Europe. With funds directed from the Horizon 2020, Europe's largest financial instrument for innovation, FCH JU has been backed by €1.33 billion of Europe's Horizon 2020 research and development funds between 2014–2020 [108].

The advantages of the public private structure of the FCH JU have led to the deployment of over 190 projects to advance a European hydrogen economy, including 60 projects and €926 million of investments directed to HFCE vehicle and infrastructure (refer to **Box 9**, [105], [108]). The next phase of FCH JU aims to further match industry's needs and expectations, while addressing technical, social and economic challenges, and focusing on accelerating the commercialization of fuel cell and hydrogen technologies [108].

### **Box 9. Fuel Cells and Hydrogen Joint Undertaking: Structure and Funding**

According to the FCH JU [108], the scale and scope for developing and deploying hydrogen technologies exceeds the capacity of any single company or public research institution in terms of financial commitment, resources and capability.

Therefore, the FCH JU has structured itself as a public private partnership to:

- Overcome barriers to deployment
- Pool resources
- Use market force to create impact
- Tackle market failure

Since 2014, FCH JU partnerships have participated in projects that cover most aspects of the hydrogen economy including [105]:

- 60 HFCE vehicle and fueling station projects with investments of €926 million
- 56 power generation projects with investments of €315 million
- 66 gas networks and combined heat and power projects with investments of €315 million
- 8 industrial feedstocks and heat projects with investments of €89 million

Individual nations of the EU also have their own hydrogen strategies. This includes a national hydrogen road-map in France that has a target for 200 HFCE HDVs to be on the road by 2023 supported by 100 fueling stations. These targets increase to between 800 to 2000 HDVs and 400–1000 fueling stations by 2028 [109]. To help reach these targets, France plans to establish regulatory frameworks for fueling stations, provide investment aid for fleets, and support research and development.

Germany's *National Innovation Programme for Hydrogen and Fuel Cell Technology*, which has been in place since 2006 and has endorsed 60 hydrogen fueling stations in the country as of 2018 [110]. Germany's new hydrogen strategy has been drafted and is anticipated to include €3.4 billion to promote fueling infrastructure and increase mandated renewable fuel standards, from 14% to 20% by 2030, which will include hydrogen [111].

The industry association, Hydrogen Europe, is another important player in the build-up of a future hydrogen economy and the advancement of HFCE HDVs, by representing over 100 industrial companies and 68 research organizations. Hydrogen Europe's role is to advocate, communicate, provide intelligence, and build networks.

This well-funded environment has demonstrated a few HFCE HDV trucks with several projects currently in development including the ones listed below.

### Scania

In a demonstration project supported by Enova SF that began in 2016, the Norwegian grocery wholesaler, **ASKO**, ordered four (4) HDV trucks from the Swedish truck manufacturer, **Scania** [112], with trucks delivered in January 2020. Hydrogen will be produced onsite at an ASKO facility in Trondheim, Norway. The specifications of the trucks are as follows [113]:

- GVWR: 27 tonne
- Fuel Cell Make: Hydrogenics
- Fuel Cell Size: 90 kW
- Traction Motors: 290 kW (290 HP)
- Battery Size: 56 kWh
- Hydrogen Storage: 33 kg at 350 bar
- Range: 400 km to 500 km

In addition, Scania is also developing a fuel cell refuse truck for the Swedish waste handling company, Renova, with support from Swedish government agencies. The refuse truck is also expected to be on the road in early 2020 [114].

## ESORO

In 2016, the German engineering firm ESORO prototyped a HFCE class 8 truck for the Swiss food distributor, COOP. In partnership with hydrogen producer, H2Energy, road testing of the truck began in 2017. A particularly unique aspect of this project is the additional power demands from the refrigerated food trailers that COOP is hauling. Details of this truck are as follows[115].

- GVWR: 35 tonne
- Fuel Cell Make: Powercell
- Fuel Cell Size: 100 kW
- Traction Motors: 255 kW (340 HP)
- Battery Size: 120 kWh
- Hydrogen Storage: 31kg at 350 bar
- Range: 400 km

## H2Haul (Hydrogen fuel cell trucks for heavy-duty, zero-emission logistics)

Funded from a €12 million grant from the FCH JU, the H2Haul consortium will deploy sixteen (16) HFCE trucks at four different demonstration sites. The 44 tonne trucks will be designed and built by a partnership made up of IVECO, FPT Industrial, and VDL ETS with fuel cells supplied by three different suppliers including ElringKlinger, Hydrogenics, and PowerCell [116].

The H2Haul consortium also includes: Air Liquide, Eoly, H2 Energy, Hydrogen Europe, IRU Projects, THINKSTEP, and WaterstofNe. The trucks will be road tested in Belgium, France, Germany, and Switzerland in real-world operating conditions by a German logistics company (for BMW Group logistics), Air Liquide, and the supermarket distribution channels of Coop, Colruyt Group, and Carrefour.

The H2Haul project is expected to run for five years starting in 2019 with a minimum of 2 years of road testing.

## H2Ports

Also co-funded by the FCH JU with a €4million budget, the port of Valencia in Spain has plans to test and validate one (1) HFCE yard tractor and one (1) HFCE reach stacker using Ballard fuel cells and a mobile fueling system [117]. The H2Ports project kicked off in May 2019 and is expected to run until 2023.

## H2Revive (Refuse Vehicle Innovation and Validation in Europe)

This FCH JU project will build and demonstrate fifteen (15) HFCE refuse collection vehicles that will operate in real-world conditions in Belgium, the Netherlands, and Italy. The H2Revive consortium is made up of fifteen organizations with E-Trucks Europe manufacturing the HFCE refuse vehicles [118].

The H2Revive project commenced in January 2018 and is forecast to run until December 2021, with six of the vehicles expected to be on road by February 2020; some challenges have been encountered that may have caused delay (see Box 10, [118]). The total budget for the project is €8.7 million.

### Box 10. Risks and Challenges Reported by H2Revive Project [118]

- Lack of fueling infrastructure
- European fuel cell suppliers have low technology readiness levels
- No standard truck configuration
- Lack of fueling standards for HDVs



Photo: <https://h2revive.eu>

## H2Share (Hydrogen Solutions for Heavy-duty transport Aimed at Reduction of Emissions in North-West Europe)

Targeting the northwest regions of Europe, H2Share aims to demonstrate a 27 tonne rigid truck, tested on the roads in Germany, the Netherlands, Belgium, and France [119].

The manufacturer of the truck is VDL and the project is funded by Interreg NEW and supported by a consortium of 14 partner organizations. The H2Share project started in 2016 with road trials planned for 2019. Technical details about the truck are as follows [119]:

- GVWR: 27 tonne
- Fuel Cell Make: Ballard
- Fuel Cell Size: 88 kW
- Traction Motors: 210 kW (280 HP)
- Battery Size: 82 kWh
- Hydrogen Storage: 80 kg at 700 bar
- Range: 400 km

Similar to the United States, there has been a recent surge in OEMs interested in supplying HDV trucks into the European market, including the ones listed below with photos presented in **Box 11**.

### Hyundai Hydrogen Mobility

In a joint venture with Swiss hydrogen producer, H2energy, together named Hyundai Hydrogen Mobility (HHM), **Hyundai** plans to deliver its first fifty (50) HFCE trucks in Switzerland in 2020 and ramp up to 1,600 HFCE HDVs by 2025. The HDVs will be offered to the members of H2 Mobility Switzerland Association along with other logistics companies operating in the country [120].

In coordination with the release, the HHM partnership plans to build a green hydrogen ecosystem with a network of fueling stations that supplies green hydrogen from a new 2 MW electrolysis plant using hydroelectricity.

The **Hyundai Xcient Fuel Cell** is expected to be equipped with two 95 kW fuel cells and have a range of 400km with a hydrogen storage capacity of 35 kg.

### Nikola Motor Company

Nikola is also actively pursuing the European market with the deployment of its **Nikola Tre** model, in a joint venture with **IVECO** (which is owned by CNH Industrial). Production is projected to begin in 2023 at the IVECO plant in Ulm, Germany [121].

It is reported the Nikola Tre will be based off the IVECO S-Way platform, the same as planned for the H2Haul project, instead of the Nikola One and Two platforms from North America. However, the Tre is anticipated to have similar infotainment and driver centric features as the North American models [122].

## Box 11. Photos of Emerging HFCE Truck Concepts in Europe

Hyundai Motor Co.



Photo: <https://trucks.com>

Nikola Motor



Photo: <https://nikolamotor.com>

Scania



Photo: <https://scania.com>

### 5.3. China

Although hydrogen has been on the country's agenda since the 1950s, the last decade has seen China aggressively target hydrogen alternatives to address air pollution, economic, and energy security concerns [123].

Many cities in China suffer from extremely poor air quality caused by traffic emissions from the growing number of vehicles on the road, leading to significant health consequences. Therefore, the country has championed a national strategy for the adoption of clean vehicles or New Energy Vehicles (NEVs) to provide solutions for the urban air pollution problem, beginning in the 2000's [124].

In addition to providing energy security as an energy carrier for curtailed renewable electricity, China is also motivated to advance hydrogen and the adoption of NEVs to support its economic growth ambitions. It aspires to position itself as a leader in the NEV and fuel cell manufacturing industry which is hoped to follow a similar trajectory as the photovoltaics and battery markets.

In alignment with its *Made in China 2025* plan, China aims to raise its enterprises from low cost system integrators to 'global innovation leaders that shapes the industry' and has been the largest producer of electric vehicles, since 2015 [124].

China has developed national hydrogen strategies with a series of *5 Year Plans*, and *Energy Innovation and Energy Development Action Plans*, among others, that call for research and development for the entire hydrogen value chain. China's dedication to the fuel cell industry in recent years is thought to have advanced technology maturation and adoption while reducing costs [57].

Strategies are also being deployed at a local level by setting HFCE vehicle targets [123] including in:

- Shanghai by developing short, medium, and long-term plans to build-up hydrogen value chain and promote commercialization
- Shandong by supporting industry clusters and demonstration parks
- Zhangjiagang that subsidizes research
- Wuhan that is supporting a US\$1.75 billion fuel cell industrial park
- Foshan that is providing US\$131 million to support the promotion and application of new energy buses and fueling stations
- And others.

China also relies heavily on subsidies. With an original focus on providing monetary incentives for the purchase of battery electric vehicles, the funding has now shifted to HFCE vehicles (see **Box 12**, [125], [126]). Subsidies

for HFCE trucks or buses are between US\$48,000 to 79,000 per HDV with a requirement for minimum annual kilometers driven. Some local regions are providing matching incentives as well as providing subsidies to the hydrogen fuel and fueling station infrastructure [123].

In addition, cities like Shanghai provide preferential road permit incentives for HFCE truck fleets working within city limits, restricting access of diesel ICE HDV trucks for pollution control reasons [57].

A product of China's action plans includes a *Technology Roadmap for Hydrogen Fuel Cell Vehicles* that targets the deployment of 5,000 HFCE vehicles by 2020 with 60% or 3,000 of them being commercial vehicles (trucks and buses) [123]. This commercial vehicle focus is thought to be a strategy to gain public acceptance of hydrogen as a transportation fuel, while being easier to regulate and deploy at scale [57].

Even with these rapid deployment plans, China is still challenged to ramp up HFCE HDV placements in its complex business climate with slow certification processes and subsidy approvals. In addition, China has been struggling to provide hydrogen supply and distribution systems, hindered by the lack of pipelines, restrictions of liquid hydrogen transport, and a hazardous chemical classification which confines hydrogen production to chemical parks [123].

While it is difficult to capture a complete list of HFCE HDV trucks, China is clearly the global leader in the deployment of HFCE HDV trucks, including those listed below.

### **Box 12. China's Shifting Focus from Battery Electric to Hydrogen Fuel Cell Electric Vehicles**

Wan Gang, is known as China's father of electric cars. In 2000, he promoted a new idea for transportation technology to the government. China was struggling with air pollution issues, dependent on foreign oil and its automakers could never hope to catch up with the Japanese, American or German manufacturers. He convinced China to support risky, unproven technology for electric cars. He advocated using government money, including subsidies, to help create a world class industry to surpass Western automakers. His successful efforts turned China into the largest electric vehicle market using promotion of environmental benefits as well as government subsidies to attract new customers [125].

In 2009, China launched the program, the "Ten Cities Plan". It aimed for 30 cities adding a total of 30,000 new-energy vehicles (NEVs) in three years, with the main focus on public transport. The program helped popularize electric vehicles in China, and vehicle sales grew rapidly.

Since about 2015, the Chinese government has put a great emphasis on the roll-out of fuel cell mobility in China, shifting public support slightly away from battery electric vehicles to HFCE vehicles. In December 2018, Wan is quoted saying that it's hydrogen's turn and the best option for market demands. China needs to start moving toward using fuel cells, or a hydrogen society [126].

## UNDP-GEF Most Project (United Nations Development Program, Ministry of Science and Technology)

This project supports the demonstration of 500 HFCE logistics vehicles and 28 postal trucks that were launched in 2018 in Shanghai. Another 600 trucks are expected to be on the road in Shanghai in the near future [57].

These trucks, manufactured by Dongfeng with Ballard fuel cells, have an allowable payload of 3.5 tonnes (~4.5 tonne GVWR) and an estimated range of 300 km. Several lessons were gained from the UNDP GEF Most Project (see **Box 13**, [123]).

### Ballard

The Canadian fuel cell company has dominated the HFCE vehicle market in China. As of June 2019, their fuel cells have been integrated into an additional ~1,500 HFCE 7.5 to 8.7 tonne trucks by SinoHytec, ReFire, Broad Ocean, and Synergy.

### JMC, a Ford Motor Company Venture

Partnered with Horizon Fuel Cells and Jiening New Energy, **JMC** launched its 42 tonne Class 8 truck model with the delivery of its first twenty (20) trucks in late 2019 with plans to roll-out at least 2000 more in the next few years [127]. The trucks are equipped with 150 kW Horizon fuel cells and are expected to have a range of 500 km.

### Ballard Weichai Joint Venture

With US\$33 million in funding from the *National Key Research and Development Plan*, Ballard and the powertrain manufacturer, Weichai Power Co., entered into a joint venture agreement in 2018, to demonstrate the entire value chain for the industrialization of HFCE vehicles in the Shandong province [123]. The venture is expected to produce 2,000 commercial vehicles (buses and trucks) by 2021 [128].

### Box 13. Lessons from the UNDP-GEF Most Project [123]

The United Nations Development Program implemented multiphase fuel cell bus and truck demonstrations beginning in 2012 across five cities. The local Program Management Office reported the following issues that are to be addressed in future phases:

- Insufficient standards, policies and regulations make construction of fueling systems challenging
- High HFCE vehicle prices are prohibitive without subsidies
- Lack of public awareness causes delays in gaining approvals

## 5.4. Japan

Japan has asserted itself as a leader of the world's first 'hydrogen society' with the release of its *Basic Hydrogen Strategy* at the end of 2017 to address the nation's energy insecurity and GHG emission issues [129]. It also views the significance of hydrogen as a way to contribute to the international community as an innovation leader, while creating new economic opportunities by promoting its fuel cell and hydrogen technology capabilities. It has already developed strategic relationships with Australia, Brunei, Norway, and Saudi Arabia for hydrogen supply.

One of the key objectives of the Basic Hydrogen strategy is reduce hydrogen costs available to end-users from US\$11/kg to US\$3.25/kg by 2030. To support this goal, Japan has invested about US\$1.5 billion since 2011 in research and development and subsidies [130] to:

- Achieve low-cost foreign production of blue and green hydrogen
- Develop infrastructure for distribution of hydrogen both domestically and overseas
- Scale up hydrogen consumption across a variety of applications

In addition, Japan has pledged to apply its multi-sector vision to lead international standardization of hydrogen systems and promote the understanding of hydrogen safety to citizens, while sharing the general importance of the energy carrier to the nation [131].

Japan's strategy includes ambitious targets for HFCE vehicles that aim to have 40,000 HFCE vehicles on the road by 2020, 200,000 units by 2025, and 800,000 units by 2030. This includes a target of 1,200 HFCE buses by 2030 but there is no specific target for HFCE trucks [131].

While the targets of the Basic Hydrogen Strategy are aggressive, Japan has been cautious in making long term commitments prior to the completion of its initial pilot projects [130].

Only a few plans for HFCE HDV trucks have been announced in Japan including the two listed below.

### Mitsubishi Fuso

In October 2019, **Mitsubishi Fuso Truck and Bus Corporation** presented five (5) of its Vision F-Cell concept trucks at a Tokyo Motor Show as an extended range option to its all-electric eCanter model [132]. These HFCE trucks have the below specifications:

- GVWR: 7.5 tonne
- Fuel Cell Size: 75 kW
- Traction Motors: 135 kW (180 HP)

- Battery Size: 13.8 kWh to 40 kWh
- Hydrogen Storage: 5 kg to 10 kg at 700 bar
- Range: 270 km to 300 km

### Toyota and 7-Eleven

In the launch of a next generation convenience store concept, **Toyota** and **7-Eleven** are integrating low-emission technologies into all aspects of the store's operation and distribution channels including the development of a small fuel cell truck. The project was expected to commence in late 2019 [133].

## 5.5. Canada

Currently, Canada does not have a national hydrogen strategy, nor does it have a zero-emission transportation framework for HDVs. However, Canada has a long history of leadership in the global hydrogen community that continues to be embraced by HFCE transportation initiatives around the world.

For decades, Canadian companies, like Ballard Power Systems and Hydrogenics, with government support, have been developing new fuel cell and hydrogen production technologies while building extensive expertise in systems integration and commercialization [134], [135]. In addition, these companies are involved in the development of industry standards.

Although both fuel cell giants are headquartered in Canada, most of their products and expertise is exported to other countries including China, the United States, Australia, and EU nations. However, Canada has demonstrated its innovative spirit with early experimentation with HFCE trucks and buses. In addition to the twenty (20) HFCE buses that were powered by Ballard fuel cells and trialed for the 2010 Winter Olympics [136], Canada has some experience and aspirations for HFCE HDV trucks, including the below examples.

### Purolator Greening The Fleet initiative

In 2005, **Purolator**, in partnership with Hydrogenics, Natural Resources Canada, and Industry Canada, integrated into its Toronto fleet the world's first HFCE delivery van [137]. The project included 350 bar fueling station with onsite production of hydrogen with a capacity of 70kg/day.

Following the 12-month demonstration, Purolator assembled a consortium of companies and government agencies to help advance the HFCE HDV technology, including Hydrogenics, Azure Dynamics (electric vehicle producer), Unicell Ltd (truck body manufacturer) and Natural Resources Canada, and Industry Canada. The Greening the Fleet HFCE initiative appears to have since stalled.

## The AZETEC Project (Alberta Zero Emission Truck Electrification Collaboration)

Motivated by the desire to have technology developed to meet the unique needs of Canadian freight companies while addressing climate change and creating new economic opportunities, the industry led AZETEC project was launched in 2019.

The project involves the design and build of two (2) HFCE Class 8 trucks. The trucks will be capable of hauling trailers in B-train configuration a distance of 700 km, with a GVWR of 63.5 tonnes. They will be road tested between Edmonton and Calgary, Alberta from July 2021 to December 2022 by Bison Transport and Trimac Transportation [138].

The C\$15 million project is led by the Alberta Motor Transport Association and is funded in part by the provincial agency, Emissions Reduction Alberta's BEST challenge, which supports sustainable transportation initiatives [139]. The AZETEC trucks will be built with a Freightliner glider that is integrated by Nordresa and Dana Inc.

Mobile fueling stations will be set-up in Edmonton with hydrogen produced from natural gas. The University of Calgary's CESAR initiative, the Transition Accelerator, and the Energy Future Labs are currently engaging with stakeholders to create a shared vision for the next phases of the project. It is anticipated that the vision will leverage the province's resource, built, and human capital strengths to build hydrogen corridors to service the province's captive HDV segments using blue hydrogen [140].

These HFCE trucks have the below specifications:

- GVWR: 63.5 tonnes
- Fuel Cell Make: Ballard
- Traction Motor: Supplied by Dana Spicer
- Hydrogen Storage: 100 kg at 350 bar
- Range: 700 km

## 5.6. Summary

This global scan has found that, globally, there have been modest deployments of HFCE trucks and vocational vehicles in demonstration environments with more in development for testing expected in the upcoming years alongside plans for larger commercial deployments. **Table 5.1.** below compiles the deployments documented and corresponding strategies that have been identified to support these initiatives.

**Table 5.1.** Summary of Existing, Planned HFCE Truck and Vocational Vehicle Deployments by Region. See text for details. C; Completed projects; O; In-Operation; D; In-Development; P; Commercial Plans

Region		Hydrogen Fuel Cell Electric Trucks							Examples of Strategies Used*	
		Class 3 to 8 Trucks/Yard Equipment				Delivery Vans				Refuse
		C	O	D	P	C	O	D		
North America	California		5	12			1	15		Clean Air Frameworks RD&D grants HDV Purchase Vouchers Zero-emission HDV standards (proposed) Preferential access to port terminals
	United States (other)	3			14,000		1	19		Hydrogen included in energy strategy HDV GHG emission standards RD&D grants OEM service bundling
	Canada			2		1				HDV GHG emission standards RD&D grants
Europe	EU		1	24	1,600				21	Hydrogen strategy HDV GHG emission standards RD&D grants
Asia	China		2,000	4,000						Hydrogen strategy Economic development plans RD&D grants HDV Purchase Vouchers Preferential access and permits Fuel and infrastructure subsidies
	Japan		5						1	Hydrogen Strategy RD&D grants
<b>Total</b>		<b>3</b>	<b>2,011</b>	<b>4,038</b>	<b>15,600</b>	<b>1</b>	<b>2</b>	<b>34</b>	<b>22</b>	

\*This is not a comprehensive strategy list. Intended to only highlight key instruments used to support deployments. RD&D; Research Development & Demonstration

## 6. Project and Market Status for HFCE HDVs: Buses

Much of the early development of HFCE HDV technology has focused on publicly owned bus fleets. Across the world, HFCE buses have made more progress than trucks with a far greater number of pilots and demonstration projects completed over the last few decades. The deployment of HFCE buses continues to advance rapidly with hundreds of buses on the road today and thousands on pre-order in the upcoming few years [41].

Government investment in zero-emission buses makes sense to demonstrate climate change leadership and address air quality concerns of their citizens. Given the generally centralized fueling practices of buses, the necessary fueling stations can be installed in strategic locations to support the fleets and the long distances travelled between fueling and cold weather performance capabilities [141] could be more amenable the HFCE than other zero-emission options

However, as detailed in **Figure 1.1** in the introduction, buses only represent about 8% of Canada's HDV fleet and about 12% of the global HDV fleet [41], making the growth potential of HFCE buses limited. The knowledge gained from the HFCE bus demonstrations can be leveraged to accelerate the adoption of the larger HFCE HDV truck segment, which is the focus of this report.

In contrast to trucks, HFCE bus deployments are better documented and information more readily available, as summarized in **Table 6.1**.

**Table 6.1.** Summary of Existing, Planned HFCE Bus Deployments by Region

Region	Country	HFCE Buses In Operation	HFCE Buses in Development or Planned	Ref.
North America	California	31 active 11 completed or retired	21 in development Targets for 100 in 2020 Targets for 300-400 in 2025	[143]
	United States (other)	10 active 13 completed or retired	12 in development	[143]
	Canada	20 completed	10 in development	[32], [142]
Europe	CHIC, 3Emotion, & other projects: France, Italy, Switzerland, Germany, Belgium, Netherlands	~60 ( $\pm 10$ ) active	40 in development in Germany	[145]
	JIVE/JIVE2 projects: Denmark, France, Germany, Iceland, Italy, Latvia, Norway, Sweden, The Netherlands, and UK	5 active in France	286 in development for 2020	[145]
	H2Bus Europe Consortium: UK, Denmark, Latvia, other countries in consideration		1,000 in planned for 2023	[146]
Asia	China	> 2000 active	1,200 in development in Zhangjiagang & Foshan Targets for 2,000-3,000 by 2025 in Wuhan Various targets in Shanghai	[123], [57]
	Japan	~18 active	82 planned in 2020 Target of 1,200 by 2030	[144]
	S. Korea	1 active	2,000 planned for 2022 + 800 police buses planned Target for 41,000 buses by 2040	[144]
	India	1 active		[144]
	Malaysia	3 active	4 in development	[144]
Oceania	New Zealand		1 planned	[144]

## 7. Conclusions, Key Learnings and Recommendations

Electrification of Canada's freight sector is central to the transition pathways that will move Canada to net-zero greenhouse gas emissions. While battery-electric vehicles charged with low or zero carbon power should be able to meet the needs of smaller vehicles moving shorter distances, such technologies are not well suited to the many HDV applications.

Hydrogen fuel cell electric (HFCE) vehicles are promising alternatives for many HDV duty cycles, offering benefits that extend beyond emission reductions, including fewer moving parts, lower maintenance costs, and supporting the emergence of a vibrant hydrogen economy. Given the high fuel demand of the nation's HDV fleets, and its concentration on major transportation corridors, HFCE HDV deployment could define the initial steps of a transition pathway to net-zero emissions based on hydrogen as a zero-emission fuel. As this pathway is 'built out', the supply and distribution infrastructure should also enable other markets for hydrogen including other internal combustion engine / transportation markets, or the decarbonization of power generation, industrial processes and space and water heating.

It is for these reasons that jurisdictions around the world are investing in the hydrogen economy and incorporating HFCE truck and bus technologies as part of their own regional and national hydrogen strategies. The work reported here draws on the learnings from others, and from the work of CESAR [3], [4], [12] to offer the following insights regarding how Canada could develop their own strategies to develop / build out credible, compelling transition pathways. These insights include:

### Technology Fit-for-Service

Diesel ICE technology has long dominated the HDV markets and therefore defines the performance standards that any alternative technology will need to meet or exceed in order to gain market share. Therefore, early demonstration projects like the ones conducted at the Ports of Los Angeles and Long Beach as well as the Alberta AZETEC project are of critical importance in testing the performance of the technology under real world conditions. Demonstrations that integrate other emerging innovations like autonomous driving would also be beneficial as the transition to autonomous and electric-drive vehicles is likely to be happening at the same time.

Work to date indicates that HFCE HDVs have many performance strengths including high torque, reliability, and driver appeal such as low noise and vibration. Any limitations associated with range, weight, cold weather, and fueling time are likely acceptable for most HDV duty cycle applications.

The technology also provides competitive advantages in jurisdictions that are taking actions to ban diesel ICE HDVs for air pollution reasons like in Shanghai and California.

More pilot and demonstration projects are needed to test and report on the viability / fit for service of battery electric and HFCE technologies for different market segments in different regions of Canada. These sectors should include municipal buses, heavy-duty freight vehicles, garbage trucks, airport ground vehicles, or vehicles used in mining operations, earth moving / construction, and agriculture, etc. While the pilots may only involve a few vehicles, logistical analyses must also be carried out to understand the implications for the large-scale deployment of electrification alternatives (grid, hydrogen) for the company and region, including the impact on the infrastructure needs in other sectors (e.g. electrical grid, pipelines).

Other constraints for the adoption of HFCE HDVs are related to the emerging nature of the technology and its supporting systems. For example, the absence of qualified maintenance facilities and trained personnel along with gaps in regulatory and standards creates uncertainty and increased operating costs. Standard driver training needs to be updated for the safe operation of the electric powertrain. Secondary education institutions, OEMs, and fleet operators will need to work together to grow expertise and develop programs for maintenance and training protocols.

The need for fueling infrastructure is another critical issue in the fit for service of the technology, but that will be considered in subsequent insights that focus on the need for scale in supply and demand.

### Recommendations for Canada

1. Governments (municipal, provincial, federal) should continue to work with OEM providers and end users of the diesel vehicle technologies from a wide range of sectors to deploy pilot, demonstration and commercialization projects involving battery electric and HFCE vehicles to understand and report on their 'technology fit-for-service' in a future, net-zero emission Canada. Such work will inform policy and investment decisions on the optimal transition pathways to electrification of internal combustion technologies by sector and region.
2. Where governments have their own fleets of vehicles, they should take a leadership role in piloting and demonstrating these new, electric drive technologies;
3. Universities and colleges should be encouraged and supported to take an active role in these pilots, demonstration and commercialization projects, including:
  - Assessment of and reporting on the technological fit for service for specific sectors and regions;
  - Identification of problem areas and research to address these problems;
  - Partner with OEMs and fleet operators to develop programs and train individuals in how to operate and maintain the new technologies.

## Alignment of Standards and Regulations

Establishing and implementing operational and safety protocols, standards, and regulations for HFCE HDVs and hydrogen fueling stations that are internationally harmonized and regionally accepted is an essential building block to advance the new energy system. While Canada has been able to create or adapt some standards to accommodate hydrogen systems, some gaps remain for the specific HDV truck application and in some cases specific to unique hydrogen gas properties. Clean Fuel Standards also need to be adapted to include carbon intensity limits for the various production methods of hydrogen.

Government and transportation associations, like the Canadian Truck Alliance (CTA) and their provincial counterparts, will need to work together to actively investigate the foreseen gaps in standards and regulations to be able to advocate to the international community and contribute to effective standard development. Likewise, regional governments must proactively introduce and/or modify regulations to meet the unique safety and operation protocols of HFCE vehicles, fueling stations, and garage facilities.

### Recommendations for Canada

4. Transportation associations and governments need to work together to actively investigate the foreseen gaps in standards and regulations and advocate to the international community to address the gaps while balancing regional needs.
5. Regional governments must proactively introduce and/or modify regulations to meet the unique safety and operation protocols of HFCE vehicles, fueling stations, and garage facilities.
6. Clean fuel standards need to define acceptable carbon intensities for hydrogen.

## Total Cost of Ownership

Despite the potential fit for HFCE vehicles in many HDV duty cycles and the positive long-term outlooks for TCO parity with diesel ICE, the technology remains largely the demonstration phase across the world. While governments are spending billions to help advance the hydrogen economy and support the adoption of HFCE vehicles, barriers such as the high purchase price of HFCE HDVs and the lack of accessible, competitively priced fuel continue to overshadow progress and keeps HFCE powertrain technology from gaining market share.

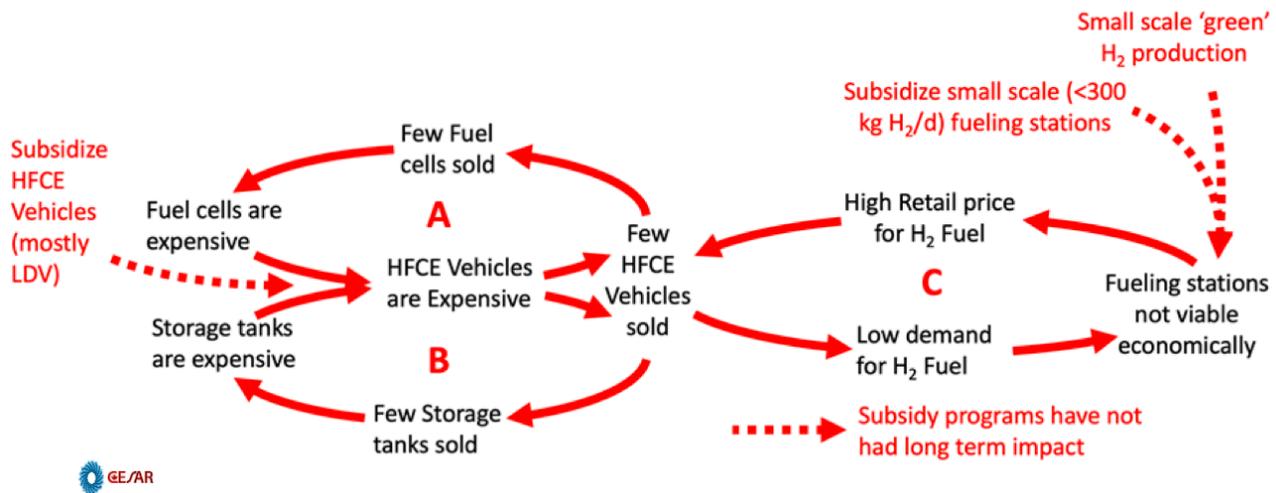
To address these barriers, governments introduce tax incentives, emission reduction policies and standards or places like China and California are using subsidies to encourage adoption of HFCE HDVs and put fueling stations into operation. Research and development activities aimed at reducing component costs such as fuels cells and onboard hydrogen storage

tanks are also being looked at to help reduce costs more rapidly. Otherwise, new business models that bundle fuel, maintenance, and vehicle use are being deployed by companies like Nikola Motor Company to help de-risk the TCO for customers.

Internationally, government funding is also used to reduce the financial risk of the HDV fueling stations, such as seen in Germany, California, and China. Setting a maximum price of hydrogen sold at fueling stations with a government backstop can provide cost assurance to the early adopters that will be the foundation for further scale-up of the fueling systems. Providing government guarantees for warranty programs would also be beneficial to manage uncertainties related to maintenance costs.

While these initiatives show promise in the short term, when the government incentive programs end, the value chain may cease to be economically viable and growth may halt. The reason for this can be attributed to three ‘vicious’ cycles that have been working in concert to hold back the emergence of HFCE HDVs (**Figure 7.1**).

### The Current ‘Vicious’ Cycles Constraining HFCE Vehicle Deployment



**Figure 7.1.** The Vicious Cycles of HFCE vehicles. Low volume sales of fuel cells (A) and hydrogen storage tanks (B) that makes the HFCE vehicles expensive compared to ICE vehicles, and the relatively high cost associated with making hydrogen fuel available to fueling stations (C). HFCE; Hydrogen fuel cell electric. CESAR figure.

The feedback chain in the vicious cycles reinforces itself to keep the price of the HFCE HDV high. There are few vehicles sold because they are 2–3 times more expensive than the incumbent ICE option. Because few vehicles are sold, the scale of fuel cell and hydrogen tank production is small. Without economy of scale, these key components remain expensive thereby reinforcing the large price gap for the HFCE HDV.

Likewise, because there are few HFCE HDVs sold, there is low demand for hydrogen which challenges the business case for the fueling station. In response, small capacity fueling stations are built using expensive hydrogen sources, such as local small-scale green hydrogen production. This creates a high retail price for hydrogen to be sold to the HDV market, thereby reinforcing a price gap in fuel costs and creates additional barriers for the adoption of the alternative powertrain which leads to low sales.

To break free of the ‘vicious cycle’ and reach a full commercialization of HFCE HDVs that is not dependent on subsidies, substantial self-sustaining scale is critical for both the manufacture of the HDV and the fuel distribution network. In this regard, supporting the ramping up of scale can have a greater impact than incremental cost reductions achieved through research and development.

### Recommendations for Canada

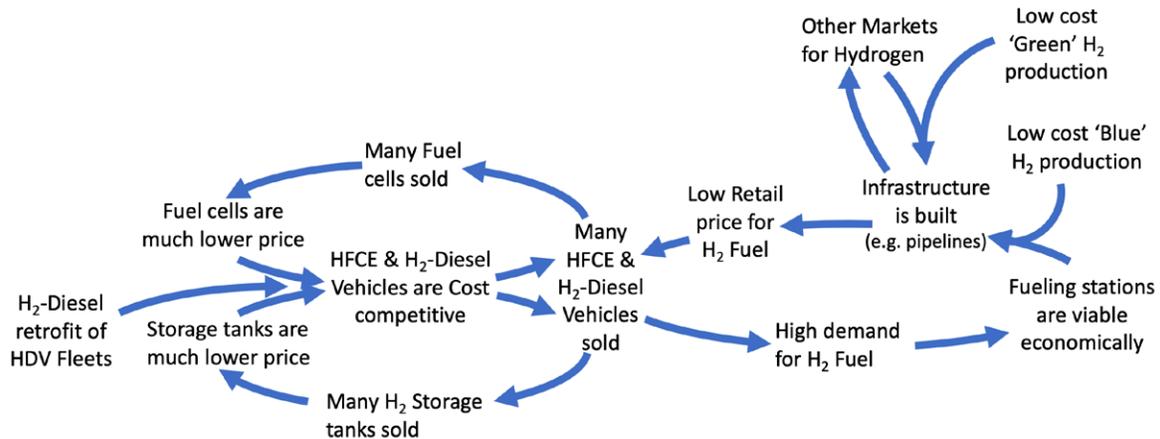
7. Governments should consider policy incentive mechanisms to encourage the early adoption of zero emission vehicles, battery electric, HFCE, and hydrogen dual fuel powertrains. This can include:
  - HDV subsidies and rebates
  - CCA Tax incentives
8. Governments should consider continued and enhanced use of policy tools that make diesel ICE powertrains less competitive. This can include:
  - Health taxes (air quality) and carbon taxes
  - Progressively stringent GHG emission standards for new HDVs sold
9. Governments need to backstop fuel prices and warranty programs to ensure competitive energy and maintenance costs for early adopters that will be the foundation for scaling-up.
10. Investment needs to continue in research and development to promote cost reductions in fuel cells and other expensive powertrain components including onboard hydrogen tanks. However, this cannot be done exclusively as the potential cost reductions are limited without scale.

### Achieving Scale

Creating scale will require the simultaneous creation of economically viable hydrogen fueling stations and the deployment of fleets of vehicles that will support these stations. The resulting ‘virtuous cycles’ (**Figure 7.2**) would require little or no additional public funding once established, and they would contribute in a positive way to the economy of the region and nation.

While the transition from vicious to virtuous cycles may take a number of years to be realized, such an objective must be the focus of a transition pathway to a low carbon economy.

## The Desired ‘Virtuous’ Cycles supporting a hydrogen Economy



**Figure 7.2.** The Virtuous Cycles of HFCE vehicles. Economically viable, high capacity fueling stations retail low priced hydrogen (A) backed by low cost hydrogen and distribution infrastructure. The high-volume sales of fuel cells (B) and hydrogen storage tanks (c) increase sales of HFCE vehicles. HFCE; Hydrogen fuel cell electric. CESAR figure.

To give confidence to the investment community and the government, it is important that the transportation industry can demonstrate that there is a committed demand for the technology. This can be done through pledges, demonstration projects, and order placements. With positive signals from the transportation industry, governments can propagate advancement by defining the scale of ambition through deployment targets.

Canada’s fleet of just over 1 million HDVs that contributes 8% of Canada’s total GHG emissions would need to transition to battery electric or HFCE powertrains by 2050 for Canada to reach its net-zero emission reduction target. Therefore, Canada should consider reasonable annual targets to reach close to 100% market share for zero-emission HDVs in the next thirty years that are inclusive of both battery electric and HFCE.

Canada and the provinces can further help support an accelerated deployment of the HFCE technology by introducing policy that requires HDV manufacturers to produce a minimum percentage of zero-emission HDVs in their fleets that are sold in the country (ZEV standards). This is a strategy that is proposed by CARB in California. Other possible options include giving preferential treatment to zero-emission HDVs to access highly visited locations or corridors such as ports and rail terminals, toll highways, or urban districts. This is a strategy taken by the port terminals in southern California and urban districts in Shanghai.

A strong industry led demonstration of demand that is backed by government, will attract existing and new OEMs, along with component suppliers, to pursue and develop the HFCE HDV market. This market will need

to rapidly reach commercial production scale in order to achieve the cost reductions that are projected by the Hydrogen Council and others.

However, to break the ‘vicious cycle’, it is equally important that a sufficient amount of HFCE HDV’s are deployed in concentrated locations to viably support hydrogen fueling stations with multiple tonnes per day of hydrogen capacity. This will help reduce the incremental hydrogen cost embedded in the station infrastructure but should also create opportunities for high volume distribution systems to be established. Examples of these distribution systems can include gaseous pipelines and/or liquid hydrogen or chemical carriers (i.e. ammonia or hydrides) moved in tank trucks.

When considering the hydrogen value chain, the cost of hydrogen transportation and distribution currently makes up a large portion of the costs and are relatively uncertain because the distribution systems are, for the most part, currently nonexistent. This is because they require scale.

Given that blue hydrogen can be produced at a comparatively low cost, there may be an opportunity to use this price advantage to build up distribution infrastructure in regions in Canada where inexpensive natural gas and CCS

### Recommendations for Canada

11. The transportation community needs to demonstrate to government and investors that there is committed demand for HFCE HDVs and other hydrogen fuel technologies through pledges, demonstration projects, and order placements.
12. Zero emission HDV targets to reach a net zero Canada need to be mapped out and recognized to set political and business priority.
13. Policy mechanisms that support the ongoing demand for zero-emission HDVs should be considered. These can include:
  - Mandates for a minimum percentage of zero-emission HDVs for new fleets sold (ZEV standards)
  - Preferential treatment should be given to zero-emission HDVs to access port and rail terminals, toll highways, and/or for other conditions that require service permits.
  - Regulations that require autonomous vehicle technology to be zero emission
14. Academia, government, and industry should jointly explore options and capabilities to economically transport hydrogen.
15. Define an implementation strategy that efficiently connects low cost hydrogen distribution systems into transportation corridors where there is concentrated and assured demand. The price advantages of blue hydrogen can help establish these distribution systems.
16. The development of hydrogen dual fuel ICE technology should be supported along with HFCE options to reach minimum demand requirements for fueling stations and distributions systems faster.

sites are available. Once distribution infrastructure is in place and transportation costs are reduced, green hydrogen may become a more viable option. Alternatively, green hydrogen produced from exceptionally low-priced electricity, may be able to achieve similar results.

Another opportunity to support the scale-up of hydrogen fueling and distribution systems could be through the introduction of hydrogen blending into diesel ICE powertrain systems with aftermarket technologies. By displacing between 30-50% of diesel fuel with hydrogen in an HDV truck, this option may help provide the necessary hydrogen demand to viably support fueling stations faster than relying only on HFCE HDV deployments.

### Cross-sector Collaboration and Commercialization Strategies

A common theme in most of the hydrogen strategies reviewed is that no one entity or sector can drive the energy transition alone. The successful adoption of HFCE HDVs will require extensive coordination between government, industry, and academia in both the supply and demand sides of the transportation ecosystem as is illustrated in **Figure 7.3**.

To reach critical scale, commercialization strategies must be developed to include the simultaneous deployment of hydrogen supply and demand. These strategies can be codeveloped with multiple stakeholder groups and include government supported projects where there is high demand for hydrogen from the heavy-duty transportation sector with the capability to supply low cost, low carbon hydrogen.

Collaboration platforms and open communications channels should help achieve the necessary scale while diminishing barriers and reducing delays caused by regulatory or technical misalignment between stakeholders.

A transition away from carbon intense fuels will require cooperation amongst industries that are not necessarily familiar with each other's businesses, such as energy producers and vehicle manufacturers, or between organizations that are traditionally competitors. However, creating shared visions to reach a common goal will benefit the entire system. To facilitate this level of collaboration, the involvement of organizations that that can

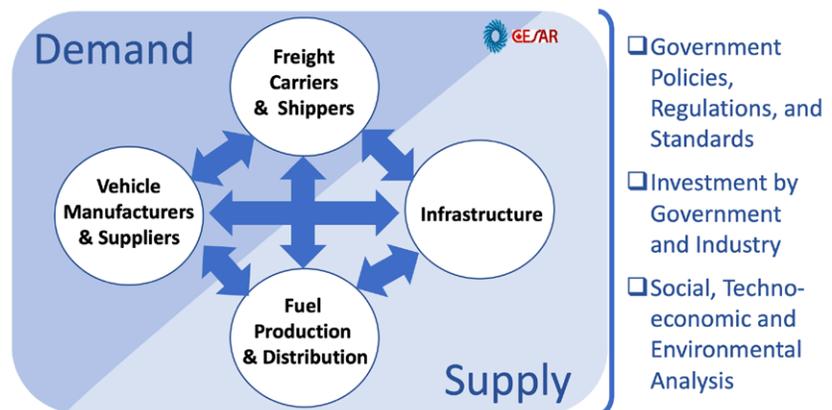


Figure 7.3. Ecosystem for Transformative Change in Road Freight Transportation

coordinate and guide the group without having a vested interest in the initiative would be beneficial.

Good examples of cross-sector collaboration that involve HFCE HDVs are seen in the industrial clusters of the Shandong province in China, the H2Share project in Europe, and the ZANZEFF projects in southern California.

### Recommendations for Canada

17. Commercialization strategies need to be codeveloped by cross functional stakeholder groups and projects deployed where there is high transportation demand and access to low cost, low carbon hydrogen. Government grants should support these projects.
18. Governments and funders can foster collaboration by supporting non-vested entities to coordinate and guide initiatives that are made up of groups of diverse companies that share a common vision.

### National Vision and Support

The jurisdictions like China, the United States and the European Unions that have made the most progress in the deployment of HFCE HDVs have national hydrogen strategies and/or have incorporated hydrogen into the national energy strategy. This is in addition to corresponding emission reduction and transportation frameworks and often includes HFCE vehicle adoption and fuel consumption targets and significant funding for research and development and demonstrations.

The hydrogen strategy is important for the advancement of HFCE HDVs because of the high level of cross-functional commitment that is required to support deployment. In addition, the strategy is important because of the immense economic, energy security, and environmental opportunities that would be a positive outcome of this transition. A national strategy can

### Recommendations for Canada

19. A hydrogen vision and road map for Canada needs to be developed and a policy framework for a hydrogen economy established. The vision should leverage the potential hydrogen demand from HDVs to build a new energy system that benefits many other sectors.
20. Hydrogen visions, roadmaps, and frameworks should include targets for HFCE HDV deployments and retail hydrogen sold for transportation uses for 2030 and 2050.
21. Provinces should develop their own hydrogen strategies that align with the national strategy but address provincial situations and needs.

help establish political priority and provide confidence to the investment community.

Provinces also need to develop hydrogen strategies that include plans and targets for HDVs. The provincial strategies should be consistent with the national strategy but differ based on the provincial resource and infrastructure capabilities along with the unique business and trade demands and priorities of the province.

**The HFCE HDV has the potential to be part of a zero-emission pathway for Canada. It is aligned with emerging innovations that are reshaping the industry, such as autonomous technology and physical internet logistics while having a goodness of fit for many duty cycles where battery electric power train options are not suitable, such as long-distance trucking. Furthermore, HFE HDVs can be a demand center for a transition to a hydrogen economy that has great economic, environmental, and energy security benefits. However, the pathway will require coordinated cross-sector visions, commercialization strategies and deployment plans that are dedicated to achieving a critical scale for HFCE fleets and hydrogen supply systems.**

# REFERENCES

- [1] Environment and Climate Change Canada, “National Inventory Report 1990-2018: Greenhouse Gas Sources and Sinks in Canada,” Apr. 2020 [Online]. Available: <https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html>
- [2] J. Eom, L. Schipper, and L. Thompson, “We Keep on Truckin’: Trends in Freight Energy Use and Carbon Emissions in 11 IEA Countries,” *Energy Policy*, vol. 45, pp. 327–341, Jun. 2012, doi: 10.1016/j.enpol.2012.02.040.
- [3] D. B. Layzell *et al.*, “The Future of Freight Part C: Implications for Alberta of Alternatives to Diesel.” Canadian Energy Systems Analysis Research, Jan-2020 [Online]. Available: <http://www.cesarnet.ca/publications/cesar-scenarios>
- [4] J. Lof *et al.*, “The Future of Freight B: Assessing Zero Emission Diesel Fuel Alternatives for Freight Transportation in Canada.” Canadian Energy Systems Analysis Research, Sep-2019 [Online]. Available: <http://www.cesarnet.ca/publications/cesar-scenarios>
- [5] “Hydra Energy.” [Online]. Available: <https://hydraenergy.com/>
- [6] “ULEMCo Ltd.” [Online]. Available: <https://ulemco.com/>
- [7] Mohamed El Hannach, et al, “Life cycle assessment of hydrogen and diesel dual-fuel class 8 heavy duty trucks,” *Int. J. Hydrog. Energy*, vol. 44, pp. 8575–8584, 2019.
- [8] L. Fulton and M. Miller, “Strategies for Transitioning to Low-Carbon Emission Trucks in the United States,” Jun. 2015 [Online]. Available: <https://escholarship.org/uc/item/93g5336t>
- [9] Statistics Canada, “Table 23-10-0067-01 Road Motor Vehicle Registrations, by Type of Vehicle,” 27-Dec-2017. [Online]. Available: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310006701>
- [10] S. Underwood, “Automated, Connected, and Electric Vehicle Systems,” Institute for Advanced Vehicle Systems, University of Michigan - Dearborn, 2014 [Online]. Available: <http://graham.umich.edu/media/files/LC-IA-ACE-Roadmap-Expert-Forecast-Underwood.pdf>
- [11] International Physical Internet Conference, “IPIC2019 - Conference Papers and Posters - Contributions,” Sep. 2019 [Online]. Available: [https://www.pi.events/IPIC2019/sites/default/files/IPIC2019%20-%20processing%20paper%20poster-%20publication\\_FL%20v190902.03.pdf](https://www.pi.events/IPIC2019/sites/default/files/IPIC2019%20-%20processing%20paper%20poster-%20publication_FL%20v190902.03.pdf)
- [12] J. Lof and D. B. Layzell, “The Future of Freight A: Trends and Disruptive Forces Impacting Goods Movement in Alberta and Canada.” Canadian Energy Systems Analysis Research, Sep-2019 [Online]. Available: <http://www.cesarnet.ca/publications/cesar-scenarios>
- [13] “EV-Volumes - The Electric Vehicle World Sales Database.” [Online]. Available: <http://www.ev-volumes.com/datacenter/>

- [14] Bloomberg NEF, “Electric Vehicle Outlook 2019,” 2019 [Online]. Available: <https://about.bnef.com/electric-vehicle-outlook/>
- [15] B. Sharpe, “Zero-Emission Tractor-Trailers in Canada,” *Int. Counc. Clean Transp.*, Mar. 2019 [Online]. Available: <https://theicct.org/publications/zero-emission-tractor-trailers-canada>
- [16] H. Zhao, Q. Wang, L. Fulton, M. Jaller, and A. Burke, “A Comparison of Zero-Emission Highway Trucking Technologies,” Institute of Transportation Studies, University of California, 2018 [Online]. Available: <https://escholarship.org/uc/item/1584b5z9>
- [17] H. Talebian, O. E. Herrera, M. Tran, and W. Mérida, “Electrification of Road Freight Transport: Policy Implications in British Columbia,” *Energy Policy*, vol. 115, pp. 109–118, Apr. 2018, doi: 10.1016/j.enpol.2018.01.004.
- [18] S. Mojtaba Lajevardi, J. Axsen, and C. Crawford, “Comparing Alternative Heavy-Duty Drivetrains Based on GHG Emissions, Ownership and Abatement Costs: Simulations of Freight Routes in British Columbia,” *Transp. Res. Part Transp. Environ.*, vol. 76, pp. 19–55, Nov. 2019, doi: 10.1016/j.trd.2019.08.031.
- [19] S. Barradas, “Facts About Trucks - Everything You Want to Know About Eighteen Wheelers,” *TruckersReport.com*, Jun-2013. [Online]. Available: <https://www.thetruckersreport.com/facts-about-trucks/>
- [20] M. Ehsani, Y. Gao, and S. Gay, “Characterization of Electric Motor Drives for Traction Applications,” in *IECON’03. 29th Annual Conference of the IEEE Industrial Electronics Society (IEEE Cat. No.03CH37468)*, 2003, vol. 1, pp. 891–896, doi: 10.1109/IECON.2003.1280101 [Online]. Available: <https://ieeexplore.ieee.org/document/1280101>
- [21] M. Howard, “Direct Drive Motors & Direct Sensors.” [Online]. Available: [https://www.zettlex.com/wp-content/uploads/Direct-Drives-and-Direct-Sensors\\_Rev\\_C.pdf](https://www.zettlex.com/wp-content/uploads/Direct-Drives-and-Direct-Sensors_Rev_C.pdf)
- [22] J. G. Smith, “Volvo Showcases an Electric Future,” *Today’s Trucking*, 20-Jun-2018. [Online]. Available: <https://www.todaystrucking.com/volvo-showcases-an-electric-future/>
- [23] Minister of Justice, *Commercial Vehicle Drivers Hours of Service Regulations SOR/2005-313*. 2009 [Online]. Available: <http://laws-lois.justice.gc.ca/eng/regulations/SOR-2005-313/>
- [24] J. Kast, G. Morrison, J. J. Gangloff, R. Vijayagopal, and J. Marcinkoski, “Designing Hydrogen Fuel Cell Electric Trucks in a Diverse Medium and Heavy Duty Market,” *Res. Transp. Econ.*, vol. 70, pp. 139–147, Oct. 2018.
- [25] N. Bouwkamp, “SAE TIR J2601/2 Hydrogen Transit Bus Fueling,” 2013 [Online]. Available: <https://www.slideshare.net/CaFCP/j2601-p-poster-fcs2013>

- [26] Kenworth Truck Company, “2013 PACCAR MX-13 Spec Sheet,” 2013. [Online]. Available: [https://www.kenworth.com/media/39986/2013\\_mx\\_spec\\_sheet\\_112912.pdf](https://www.kenworth.com/media/39986/2013_mx_spec_sheet_112912.pdf)
- [27] Transportation Research Board and National Research Council, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*. Washington, D.C.: National Academies Press, 2010 [Online]. Available: <http://www.nap.edu/catalog/12845>
- [28] Luxfer Gas Cylinders, “G-Stor H2 Technical Specifications,” *G-Stor H2 Hydrogen-Storage Cylinders*, 04-Oct-2018. [Online]. Available: <https://www.luxfercylinders.com/products/g-stor-h2#tech-spec>
- [29] U.S. Drive, “U.S. DRIVE Highlights of Technical Accomplishments,” Mar. 2018 [Online]. Available: <http://www.uscar.org/guest/teams/2/U-S-DRIVE-Electrical-Electronics-Tech-Team>
- [30] C. E. Thomas, “Fuel Cell and Battery Electric Vehicles Compared,” *Int. J. Hydrog. Energy*, vol. 34, no. 15, pp. 6005–6020, Aug. 2009, doi: 10.1016/j.ijhydene.2009.06.003.
- [31] I. Mareev, J. Becker, and D. U. Sauer, “Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation,” *Energies*, vol. 11, no. 1, p. 55, Jan. 2018.
- [32] CUTRIC, “CUTRIC-Ontario Integrated & Advanced Mobility Innovation Consultation Report 2016\_Stakeholder Version (June 2017).pdf” .
- [33] D. Winter, “Tenneco Hopes to Mainstream Intelligent Suspension Systems,” *WardsAuto*, 04-Sep-2014 [Online]. Available: <https://www.wardsauto.com/industry/tenneco-hopes-mainstream-intelligent-suspension-systems>
- [34] J. Marcinkoski, “DOE Advanced Truck Technologies,” U.S. Department of Energy, Oct. 2019 [Online]. Available: [https://www.hydrogen.energy.gov/pdfs/19006\\_hydrogen\\_class8\\_long\\_haul\\_truck\\_targets.pdf](https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf)
- [35] Ballard Power Systems, “Technical Note: Fuel Cell Buses - Cold Weather Operating Conditions.” [Online]. Available: <https://www.ballard.com/docs/default-source/motive-modules-documents/technical-note---bus-cold-weather-operation---final.pdf?sfvrsn=4&sfvrsn=4>
- [36] A. A. Amamou, S. Kelouwani, L. Boulon, and K. Agbossou, “A Comprehensive Review of Solutions and Strategies for Cold Start of Automotive Proton Exchange Membrane Fuel Cells,” *IEEE Access*, vol. 4, pp. 4989–5002, 2016, doi: 10.1109/ACCESS.2016.2597058.
- [37] California Air Resources Board, “Technology Assessment: Medium and Heavy Duty Battery Electric Trucks and Buses,” California Environmental Protection Agency, Oct. 2015 [Online]. Available: [https://ww3.arb.ca.gov/msprog/tech/techreport/bev\\_tech\\_report.pdf](https://ww3.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf)
- [38] J. Roberts, “Who’s Going to Work on Electric and Alt-Fuel Trucks?,”

- 09-Sep-2019 [Online]. Available: <https://www.truckinginfo.com/340024/finding-future-tech-truck-technicians>
- [39] L. Eudy and M. Post, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018," National Renewable Energy Laboratory, Dec. 2018 [Online]. Available: <https://www.nrel.gov/docs/fy19osti/72208.pdf>
- [40] J. O'Dell, "Inside Nikola's Truck Technology – From Fuel Cells to Lights," *Trucks.com*, 22-May-2019 [Online]. Available: <https://www.trucks.com/2019/05/22/inside-nikolas-truck-technology-fuel-cells-tail-lights/>
- [41] International Energy Agency, "The Future of Hydrogen," Jun. 2019 [Online]. Available: <https://www.iea.org/topics/hydrogen/>
- [42] California Air Resources Board, "Drive Clean Buying Guide: Hydrogen Fuel Cell," *Driveclean.ca.gov*. [Online]. Available: [https://www.driveclean.ca.gov/Search\\_and\\_Explore/Technologies\\_and\\_Fuel\\_Types/Hydrogen\\_Fuel\\_Cell.php](https://www.driveclean.ca.gov/Search_and_Explore/Technologies_and_Fuel_Types/Hydrogen_Fuel_Cell.php)
- [43] M. R. Swain, "Fuel Leak Simulation," University of Miami, Florida, NREL/CP-570-30535, 2001 [Online]. Available: <https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/30535be.pdf>
- [44] United Nations, "Revised Draft Global Technical Regulation (GTR) on Hydrogen and Fuel Cell Vehicles," United Nations, Global Technical Regulation WP.29-159-06, 2013 [Online]. Available: <https://www.unece.org/fileadmin/DAM/trans/doc/2013/wp29grsp/WP29-159-06e.pdf>. [Accessed: 10-Jan-2020]
- [45] California Fuel Cell Partnership, "Fuel Cell Electric Vehicles & Hydrogen Fuel," *Cars | California Fuel Cell Partnership*. [Online]. Available: <https://cafcp.org/cars>
- [46] C. LaFleur, G. Bran-Anleu, A. B. Muna, B. D. Ehrhart, M. Blaylock, and W. G. Houf, "Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study," Sandia National Laboratories, New Mexico / California, Unlimited Release SAND2017-11157, Oct. 2017 [Online]. Available: <https://energy.sandia.gov/wp-content/uploads/2018/05/SAND2017-11157.pdf>
- [47] Standards Council of Canada, "Canadian Hydrogen Installation Code," *Standards Council of Canada*, 09-Jan-2019. [Online]. Available: <https://www.scc.ca/en/standards/notices-of-intent/bnq/canadian-hydrogen-installation-code>
- [48] HTEC Hydrogen Technology & Energy Corp, "Feasibility Study: Zero Emissions Fleet Initiative - Infrastructure Safety Study," *Capital Regional District*, Nov-2017. [Online]. Available: [https://www.crd.bc.ca/docs/default-source/climate-action-pdf/infrastructuresafetystudy.pdf?sfvrsn=dc99f9ca\\_2](https://www.crd.bc.ca/docs/default-source/climate-action-pdf/infrastructuresafetystudy.pdf?sfvrsn=dc99f9ca_2)
- [49] California Fuel Cell Partnership, "Hydrogen Stations | H2 Station Maps," *H2 Station Maps*. [Online]. Available: <https://h2stationmaps.com/hydrogen-stations>

- [50] Pacific Northwest National Laboratory, “Cylinder Handling and Securing | Hydrogen Tools,” *Center for Hydrogen Safety*. [Online]. Available: <https://h2tools.org/bestpractices/cylinder-handling-and-securing>
- [51] Department of Energy’s Clean Cities Organization, “Hydrogen Resources,” *Alternative Fuel Vehicle Maintenance Garage Training*. [Online]. Available: <https://altfuelgarage.org/hydrogen/>
- [52] I. Burch and J. Gilchrist, “Survey of Global Activity to Phase Out Internal Combustion Engine Vehicles,” Center for Climate Protection, Sep. 2018 [Online]. Available: <https://climateprotection.org/wp-content/uploads/2018/10/Survey-on-Global-Activities-to-Phase-Out-ICE-Vehicles-FINAL-Oct-3-2018.pdf>
- [53] Statistics Canada, “Table 23-10-0219-01 Trucking Commodity Industry Activities,” 27-Dec-2017. [Online]. Available: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310021901>
- [54] North American Council for Freight Efficiency, “Medium-Duty Electric Trucks - Cost of Ownership,” Oct. 2018 [Online]. Available: <https://nacfe.org/future-technology/medium-duty-electric-trucks-cost-of-ownership/>
- [55] M. Moultak, N. Lutsey, and D. Hall, “Transitioning to Zero-Emission Heavy-Duty Freight Vehicles,” International Council on Clean Transportation, Sep. 2017 [Online]. Available: <https://www.theicct.org/publications/transitioning-zero-emission-heavy-duty-freight-vehicles>
- [56] International Renewable Energy Agency, “Electric Vehicles: Technology Brief,” Feb. 2017 [Online]. Available: <https://www.irena.org/publications/2017/Feb/Electric-vehicles-Technology-brief>
- [57] Deloitte and Ballard Power Systems, “Fueling the Future of Mobility,” Volume 1, Jan. 2020 [Online]. Available: <https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf>
- [58] Hydrogen Council, “Path to Hydrogen Competitiveness: A Cost Perspective,” Jan. 2020 [Online]. Available: <https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/>
- [59] L. Tillemann, *The Great Race: The Global Quest for the Car of the Future*. Simon and Schuster, 2016 [Online]. Available: <https://www.simonandschuster.ca/books/The-Great-Race/Levi-Tillemann/9781476773506>
- [60] Statistics Canada, “Table 23-10-0226-01 Trucking Financial Statistics, by Industry Group (x 1,000),” 19-Dec-2017. [Online]. Available: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310022601>
- [61] L. Eudy, “Technology Acceleration: Fuel Cell Bus Evaluations,” DOE Hydrogen and Fuel Cells Program, 01-May-2019 [Online]. Available: [https://www.hydrogen.energy.gov/pdfs/review19/ta013\\_eudy\\_2019\\_o.pdf](https://www.hydrogen.energy.gov/pdfs/review19/ta013_eudy_2019_o.pdf)

- [62] McKinsey & Company, “Electrifying Insights: How Automakers Can Drive Electrified Vehicle Sales and Profitability,” Jan. 2017 [Online]. Available: [https://www.mckinsey.com/~media/mckinsey/industries/automotive%20and%20assembly/our%20insights/electrifying%20insights%20how%20automakers%20can%20drive%20electrified%20vehicle%20sales%20and%20profitability/electrifying%20insights%20-%20how%20automakers%20can%20drive%20electrified%20vehicle%20sales%20and%20profitability\\_vf.ashx](https://www.mckinsey.com/~media/mckinsey/industries/automotive%20and%20assembly/our%20insights/electrifying%20insights%20how%20automakers%20can%20drive%20electrified%20vehicle%20sales%20and%20profitability/electrifying%20insights%20-%20how%20automakers%20can%20drive%20electrified%20vehicle%20sales%20and%20profitability_vf.ashx)
- [63] U.S. Department of Energy, “Multi-Year Research, Development, and Demonstration Plan,” 2015 [Online]. Available: [https://www.energy.gov/sites/prod/files/2015/08/f25/fcto\\_myRDD\\_delivery.pdf](https://www.energy.gov/sites/prod/files/2015/08/f25/fcto_myRDD_delivery.pdf)
- [64] Energy Information Administration, “Henry Hub Natural Gas Spot Price (Dollars per Million Btu),” *Natural Gas*, 24-Oct-2018. [Online]. Available: <https://www.eia.gov/dnav/ng/hist/rngwhhdA.htm>
- [65] National Renewable Energy Laboratory, “H2A: Hydrogen Analysis Production Case Studies,” *Hydrogen & Fuel Cells*, Feb-2019. [Online]. Available: <https://www.nrel.gov/hydrogen/h2a-production-case-studies.html#case-study-documentation>
- [66] Wood Mackenzie, “Green Hydrogen Production: Landscape, Projects and Costs,” Oct. 2019 [Online]. Available: <https://www.woodmac.com/news/editorial/the-future-for-green-hydrogen/>
- [67] Canadian Trucking Alliance, “CTA: Christmas Comes Early as Canadian Truckers Receives Accelerated CCA Rates for Equipment,” 21-Nov-2018 [Online]. Available: <http://cantruck.ca/cta-christmas-comes-early-as-canadian-truckers-receives-accelerated-cca-rates-for-equipment/>
- [68] J. G. Smith, “Nikola Plans a Different Truck Ownership Model for its Hydrogen-Electric Trucks,” *Today’s Trucking*, 18-Apr-2019 [Online]. Available: <https://www.truckinginfo.com/329836/nikola-plans-a-different-truck-ownership-model-for-its-hydrogen-and-electric-tru>
- [69] National Renewable Energy Laboratory and Sandia National Laboratories, “H2FIRST Reference Station Design Task: Project Deliverable 2-2,” Apr. 2015 [Online]. Available: <https://www.nrel.gov/docs/fy15osti/64107.pdf>
- [70] FuelCellsWorks, “Hyundai, Toyota Form Consortium with NEL, NIKOLA, Air Liquide and Shell to Standardize Hydrogen Fuelling Technology for Hydrogen Vehicles,” *FuelCellsWorks*, 04-Mar-2019 [Online]. Available: <https://fuelcellsworks.com/news/hyundai-toyota-form-consortium-with-nel-nikola-air-liquide-and-shell-to-standardize-hydrogen-fuelling-technology-for-hydrogen-vehicles/>
- [71] Environment and Climate Change Canada, “Canada’s Mid-Century Long-Term Low-Greenhouse Gas Development Strategy,” 2016 [Online]. Available: <https://www.canada.ca/en/environment-climate-change/news/2016/11/canada-submits-century-strategy-clean-growth-economy.html>

- [72] U.S. Government Accountability Office, “Hydrogen Fuel Initiative,” Jan. 2008 [Online]. Available: <https://www.gao.gov/assets/280/270996.pdf>
- [73] Fuel Cell & Hydrogen Energy Association, “Road Map to a US Hydrogen Economy,” Dec. 2019 [Online]. Available: [https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5dc2e7795587df7fd3d99c9a/1573054335009/Road+map+to+a+US+hydrogen+economy\\_Executive+Summary.pdf](https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5dc2e7795587df7fd3d99c9a/1573054335009/Road+map+to+a+US+hydrogen+economy_Executive+Summary.pdf)
- [74] U.S. Department of Energy, “H2@Scale: Enabling Affordable, Reliable, Clean, and Secure Energy Across Sectors,” 2019 [Online]. Available: <https://www.energy.gov/eere/fuelcells/h2scale>
- [75] U.S. Department of Energy, “Department of Energy Announces \$50 Million for Commercial Truck, Off-road Vehicle, and Gaseous Fuels Research,” *Energy.gov*, 01-Mar-2019. [Online]. Available: <https://www.energy.gov/articles/department-energy-announces-50-million-commercial-truck-road-vehicle-and-gaseous-fuels>
- [76] U.S. Department of Energy, “DOE Announces \$133 Million to Accelerate Advanced Vehicle Technologies Research,” *Energy.gov*, 23-Jan-2020. [Online]. Available: <https://www.energy.gov/eere/articles/doe-announces-133-million-accelerate-advanced-vehicle-technologies-research>
- [77] U.S. Environmental Protection Agency, “Regulations for Greenhouse Gas Emissions from Commercial Trucks & Buses,” *U.S. Environmental Protection Agency*, 09-Sep-2016. [Online]. Available: <https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-greenhouse-gas-emissions-commercial-trucks>
- [78] “Cap-and-Trade Dollars at Work,” *California Climate Investments*. [Online]. Available: <http://www.caclimateinvestments.ca.gov>
- [79] California Air Resources Board, “Public Hearing to Consider the Proposed Advanced Clean Trucks Regulation,” Oct. 2019 [Online]. Available: <https://ww3.arb.ca.gov/regact/2019/act2019/isor.pdf>
- [80] California Air Resources Board, “Proposition 1B: Goods Movement Emission Reduction Program.” [Online]. Available: <https://ww2.arb.ca.gov/our-work/programs/proposition-1b-goods-movement-emission-reduction-program/about>
- [81] California HVIP, “Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) and Low NOx Engine Incentives in 2009 to Accelerate the Purchase of Cleaner, More Efficient Trucks and Buses in California,” *California HVIP*. [Online]. Available: <https://www.californiahvip.org/>
- [82] R. Gilroy, “Nation’s Two Largest Ports Toughen Clean-Truck Standard,” *Transport Topics*, 26-Sep-2018 [Online]. Available: <https://www.ttnews.com/articles/nations-two-largest-ports-toughen-clean-truck-standard>

- [83] Port of Long Beach and Port of Los Angeles, “San Pedro Bay Ports Clean Air Action Plan. Clean Trucks Program: Overview of New Registration Requirements and FAQ,” Sep. 2018 [Online]. Available: <http://www.cleanairactionplan.org/documents/clean-trucks-program-tariff-change-fact-sheet-sept-2018.pdf/>
- [84] Port Houston, “Air & Water Quality,” *Port Houston*. [Online]. Available: <https://porthouston.com/environment/air-quality/>
- [85] Port of Los Angeles, “Zero Emission White Paper DRAFT,” Jul. 2015 [Online]. Available: [https://www.portoflosangeles.org/pola/pdf/zero\\_emissions\\_white\\_paper\\_draft.pdf](https://www.portoflosangeles.org/pola/pdf/zero_emissions_white_paper_draft.pdf)
- [86] J. Impullitti, “Zero Emission Cargo Transport II,” 11-Jun-2015 [Online]. Available: [https://www.energy.gov/sites/prod/files/2015/07/f24/vss158\\_cole\\_2015\\_o.pdf](https://www.energy.gov/sites/prod/files/2015/07/f24/vss158_cole_2015_o.pdf)
- [87] Toyota Canada, “Project Portal: Toyota’s Commitment to Reducing Transport Truck Greenhouse Gas Emissions to Zero,” *Toyota*, 01-Aug-2018. [Online]. Available: <https://www.toyota.ca/toyota/en/connect/2954/project-portal-a-more-environmentally-friendly-transport-truck>
- [88] J. O’Dell, “Secret ‘Project Portal’ Toyota Venture Launches Hydrogen Fuel Cell Heavy-Duty Truck,” *Trucks.com*, 19-Apr-2017 [Online]. Available: <https://www.trucks.com/2017/04/19/toyota-project-portal-fuel-cell-truck/>
- [89] J. O’Dell, “Toyota Unveils More Advanced Heavy-Duty Fuel Cell Truck Prototype,” *Trucks.com*, 30-Jul-2018 [Online]. Available: <https://www.trucks.com/2018/07/30/toyota-advanced-fuel-cell-truck/>
- [90] T. Berg, “Kenworth, Toyota to Build 10 Fuel Cell-Electric Tractors,” *Construction Equipment*, 28-Oct-2019 [Online]. Available: <https://www.constructionequipment.com/kenworth-toyota-build-10-fuel-cell-electric-tractors>
- [91] “Toyota and Kenworth Unveil Fuel Cell Heavy Truck at Port of LA,” *Fuel Cells Bull.*, vol. 2019, no. 5, pp. 3–4, May 2019, doi: 10.1016/S1464-2859(19)30180-4.
- [92] S. Kapadia, “FedEx tests hydrogen fuel cell van for deliveries,” *Supply Chain Dive* [Online]. Available: <https://www.supplychaindive.com/news/FedEx-hydrogen-fuel-cell-van-pilot/522449/>. [Accessed: 02-Mar-2020]
- [93] “ProGen-Powered FedEx operates more than 10,000 miles on-road,” *Plug Power*, 01-Nov-2018. [Online]. Available: <https://www.plugpower.com/2018/11/progen-powered-fedex-operates-more-than-10000-miles-on-road/>
- [94] A. Ohnsman, “Nikola CEO Trevor Milton Is Now a Billionaire Thanks to Hydrogen Truck Startup’s Fundraising Drive,” *Forbes*, 04-Sep-2019 [Online]. Available: <https://www.forbes.com/sites/alanohnsman/2019/09/04/>

nikola-ceo-trevor-milton-is-now-a-billionaire-thanks-to-hydrogen-truck-startups-fundraising-drive/

- [95] J. O’Dell, “Nikola Closes Land Deal for Arizona Truck Plant,” *Trucks.com*, 25-Mar-2019 [Online]. Available: <https://www.trucks.com/2019/03/25/nikola-land-deal-arizona-truck-plant/>
- [96] “Nikola Two,” *Nikola Motor Company*. [Online]. Available: <https://nikolamotor.com/two>
- [97] M. Geuss, “Nikola Motor Company Shows off Two Real Trucks and... a New Jet Ski?,” *Ars Technica*, 17-Apr-2019 [Online]. Available: <https://arstechnica.com/cars/2019/04/nikola-motor-company-shows-off-two-real-trucks-and-a-new-jet-ski/>
- [98] J. O’Dell, “Nikola Details Ambitious Plan for Hydrogen and Service Network,” *Trucks.com*, 22-Apr-2019 [Online]. Available: <https://www.trucks.com/2019/04/22/nikola-ambitious-plan-hydrogen-service-network/>
- [99] R. Gilroy, “Hyundai Looks to Bring Hydrogen Fuel-Cell Concept Class 8 to US,” *Transport Topics*, 29-Oct-2019 [Online]. Available: <https://www.ttnews.com/articles/hyundai-introduces-hydrogen-fuel-cell-concept-class-8-north-america>
- [100] “Hyundai Motor Company and Cummins to Collaborate on Hydrogen Fuel Cell Technology,” *Business Wire*, 26-Sep-2019 [Online]. Available: <https://www.businesswire.com/news/home/20190926005903/en/Hyundai-Motor-Company-Cummins-Collaborate-Hydrogen-Fuel>
- [101] Cummins Inc., “Cummins Closes on Its Acquisition of Hydrogenics,” *Cummins Newsroom: Electrified Power*, 09-Sep-2019. [Online]. Available: <https://www.cummins.com/news/releases/2019/09/09/cummins-closes-its-acquisition-hydrogenics>
- [102] Cummins Inc., “Making a Splash at NACV,” *Cummins Newsroom: Electrified Power*, 30-Oct-2019. [Online]. Available: <https://www.cummins.com/news/2019/10/30/making-splash-nacv>
- [103] “Heavy Trucks,” *Hyzon Motors*. [Online]. Available: <https://www.hyzonmotors.com>
- [104] European Federation for Transport and Environment, “How to Decarbonize European Transport by 2050,” Nov. 2018 [Online]. Available: [https://www.transportenvironment.org/sites/te/files/publications/2018\\_11\\_2050\\_synthesis\\_report\\_transport\\_decarbonisation.pdf](https://www.transportenvironment.org/sites/te/files/publications/2018_11_2050_synthesis_report_transport_decarbonisation.pdf)
- [105] Fuel Cells and Hydrogen Joint Undertaking, “Hydrogen Roadmap Europe Report,” Jan. 2019 [Online]. Available: <https://www.fch.europa.eu/news/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition>
- [106] European Commission, “Reducing CO2 Emissions from Heavy-Duty Vehicles,” *Climate Action - European Commission*. [Online]. Available: <https://>

ec.europa.eu/clima/policies/transport/vehicles/heavy\_en

- [107] European Commission, “Renewable Energy Directive,” *Energy - European Commission*, 16-Jul-2014. [Online]. Available: <https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive/overview>
- [108] Fuel Cells and Hydrogen Joint Undertaking, “Who We Are.” [Online]. Available: <https://www.fch.europa.eu/page/who-we-are>
- [109] Ministere de la Transition Ecologique et Solidaire, “Hydrogen Roadmap and Industrial Development in France.” [Online]. Available: <https://www.tresor.economie.gouv.fr/Articles/120903c7-34bc-49b1-a324-b1f6ba0dbf53/files/4c3ada61-fd66-479a-a683-91a63f8d6b87>
- [110] J. Carr, “Germany Fuel Cell Industry Developments,” *Fuel Cell & Hydrogen Energy Association*, 25-Mar-2019 [Online]. Available: <http://www.fchea.org/in-transition/2019/3/18/germany-fuel-cell-industry-developments>
- [111] F. Schulz, “Germany Floats Draft Hydrogen Strategy Ahead of EU Presidency,” *EURACTIV*, 03-Feb-2020 [Online]. Available: <https://www.euractiv.com/section/energy-environment/news/germany-floats-draft-hydrogen-strategy-ahead-of-eu-presidency/>
- [112] “ASKO Orders Scania Fuel Cell Trucks, Starts Hydrogen Production,” *Fuel Cells Bull.*, vol. 2018, no. 1, pp. 3–4, Jan. 2018, doi: 10.1016/S1464-2859(18)30005-1.
- [113] “Norwegian Wholesaler ASKO Puts Hydrogen Powered Fuel Cell Electric Scania Trucks on the Road,” *Scania Group*, 20-Jan-2020 [Online]. Available: <https://www.scania.com/group/en/norwegian-wholesaler-asko-puts-hydrogen-powered-fuel-cell-electric-scania-trucks-on-the-road/>
- [114] N. Manthey, “Scania Developing Fuel Cell Refuse Truck,” *electrive.com*, 11-Dec-2018. [Online]. Available: <https://www.electrive.com/2018/12/12/scania-developing-fuel-cell-refuse-truck/>
- [115] “ESORO: heavy-duty fuel cell truck,” *Fuel Cell Trucks*. [Online]. Available: <https://fuelcelltrucks.eu/project/esoro/>
- [116] H2Haul Project, “IVECO, FPT Industrial and VDL ETS to Develop Fuel Cell Electric Heavy-Duty Trucks for European Markets as Part of the H2Haul Project,” 01-Oct-2019 [Online]. Available: [https://uploads-ssl.webflow.com/5d6964b2faa2a0d27c40bff5/5d91d996d12b5b7b0aab4d16\\_PR1%20H2Haul%20Launch.pdf](https://uploads-ssl.webflow.com/5d6964b2faa2a0d27c40bff5/5d91d996d12b5b7b0aab4d16_PR1%20H2Haul%20Launch.pdf)
- [117] “H2Ports - First Application of Hydrogen Technologies in Port Handling Equipment in Europe,” *H2Ports*. [Online]. Available: <https://h2ports.eu/>
- [118] D. Van den Borre, “REVIVE: Refuse Vehicle Innovation and Validation in Europe,” Brussels, 19-Nov-2019 [Online]. Available: [https://www.fch.europa.eu/sites/default/files/04.%20REVIVE\\_Dimitri%20Van%20den%20Borre%20%28ID%207466945%29.pdf](https://www.fch.europa.eu/sites/default/files/04.%20REVIVE_Dimitri%20Van%20den%20Borre%20%28ID%207466945%29.pdf)

- [119] “VDL: 27 Ton Hydrogen Truck,” *H2-Share*. [Online]. Available: <https://fuelcelltrucks.eu/project/vdl-27-ton-hydrogen-truck/>
- [120] Hyundai Motor Company, “Green Hydrogen Allows Hyundai Hydrogen Mobility and Hydrospider to Connect Electricity with Mobility Sectors in Switzerland,” *Hyundai Motor Group Newsroom*, 26-Sep-2019 [Online]. Available: <https://news.hyundaimotorgroup.com/MediaCenter/News/Press-Releases/green-hydrogen-allows-hyundai-hydrogen-mobility-and-hydrospider-to-connect-electricity-with-mobility-sectors-in-switzerland>
- [121] C. Hampel, “Nikola Tre to Build Electric Trucks at Iveco in Germany,” *electrive.com*, 07-Feb-2020 [Online]. Available: <https://www.electrive.com/2020/02/07/nikola-tre-to-be-built-in-ulm-germany/>
- [122] R. Gilroy, “Nikola Battery-Electric Truck Slated for Europe in 2021,” *Transport Topics*, 03-Dec-2019 [Online]. Available: <https://www.ttnews.com/articles/iveco-nikola-begin-work-battery-electric-truck>
- [123] B. Verheul and Bente Verheul, “Overview of Hydrogen and Fuel Cell Developments in China,” Holland Innovation Network China, Jan. 2019 [Online]. Available: <https://www.nederlandwereldwijd.nl/binaries/nederlandwereldwijd/documenten/publicaties/2019/03/01/waterstof-in-china/Holland+Innovation+Network+in+China+-+Hydrogen+developments.+January+2019.pdf>
- [124] M. Kendall, “Fuel Cell Development for New Energy Vehicles (NEVs) and Clean Air in China,” *Prog. Nat. Sci. Mater. Int.*, vol. 28, no. 2, pp. 113–120, Apr. 2018, doi: 10.1016/j.pnsc.2018.03.001.
- [125] Bloomberg Hyperdrive, “The World’s Leading Electric-Car Visionary Isn’t Elon Musk,” *Bloomberg.com*, 26-Sep-2018 [Online]. Available: <https://www.bloomberg.com/news/features/2018-09-26/world-s-electric-car-visionary-isn-t-musk-it-s-china-s-wan-gang>
- [126] E. Huang, “The Man Who Ushered in China’s Battery Vehicle Boom Wants to Do the Same for Fuel Cells,” *Quartz*, 17-Apr-2019 [Online]. Available: <https://qz.com/1597577/architect-of-chinas-ev-boom-now-backs-hydrogen-fuel-cells/>
- [127] FuelCellsWorks, “World’s Largest Fuel Cell Heavy Truck Rollout Underway,” *FuelCellsWorks*, 25-Sep-2019 [Online]. Available: <https://fuelcellsworks.com/news/worlds-largest-fuel-cell-heavy-truck-rollout-underway/>
- [128] H. Sanderson, “Hydrogen Power: China Backs Fuel Cell Technology,” *Financial Times*, 02-Jan-2019 [Online]. Available: <https://www.ft.com/content/27ccfc90-fa49-11e8-af46-2022a0b02a6c>
- [129] Ministry of Economy, Trade and Industry (METI), “Basic Hydrogen Strategy,” Dec. 2017 [Online]. Available: [https://www.meti.go.jp/english/press/2017/pdf/1226\\_003b.pdf](https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf)

- [130] M. Nagashima and Institut français des relations internationales, “Japan’s Hydrogen Strategy and Its Economic and Geopolitical Implications,” Institut Français des Relations Internationales, Oct. 2018 [Online]. Available: [https://www.ifri.org/sites/default/files/atoms/files/nagashima\\_japan\\_hydrogen\\_2018\\_.pdf](https://www.ifri.org/sites/default/files/atoms/files/nagashima_japan_hydrogen_2018_.pdf)
- [131] Ministry of Economy, Trade and Industry (METI), “Basic Hydrogen Strategy (Key Points),” Japan, 2017 [Online]. Available: [https://www.meti.go.jp/english/press/2017/pdf/1226\\_003a.pdf](https://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf)
- [132] FuelCellsWorks, “Mitsubishi Fuso Presents its First Fuel Cell Concept Truck ‘Vision F-CELL’ at Tokyo Motor Show 2019,” *FuelCellsWorks*, 25-Oct-2019 [Online]. Available: <https://fuelcellsworks.com/news/mitsubishi-fuso-presents-its-first-fuel-cell-concept-truck-vision-f-cell-at-tokyo-motor-show-2019/>
- [133] BioAge Group, “Seven-Eleven Japan, Toyota Launching Next-Gen Convenience Store Project in 2019; Fuel Cell Trucks and Generators,” *Green Car Congress*, 06-Jun-2018 [Online]. Available: <https://www.greencarcongress.com/2018/06/20180606-toyota.html>
- [134] Zen and the Art of Clean Energy Solutions, “British Columbia Hydrogen Study,” Sep. 2019 [Online]. Available: <https://www2.gov.bc.ca/assets/gov/government/ministries-organizations/zen-bc-bn-hydrogen-study-final-v6.pdf>
- [135] Invest in Ontario, “Hydrogenics’ Ontario Technology Leads the Zero Emission Movement,” *InvestinOntario.com*, 13-Jul-2017 [Online]. Available: <http://www.investinontario.com/success-stories/hydrogenics-ontario-technology-leads-zero-emission-movement>
- [136] L. Eudy and M. Post, “BC Transit Fuel Cell Bus Project Evaluation Results: Second Report,” NREL/TP-5400-62317, 1159343, Sep. 2014 [Online]. Available: <http://www.osti.gov/servlets/purl/1159343/>
- [137] D. J. Kube, “Purolator’s ‘Greening The Fleet’ Initiative – On The Road And Reducing Greenhouse Gas Emissions” [Online]. Available: <https://ctrf.ca/wp-content/uploads/2014/07/Purolators-Greening-the-Fleet.pdf>
- [138] “AZETEC Project.” [Online]. Available: <https://azetec.ca/azetec-project/>
- [139] Emissions Reduction Alberta, “Best Challenge.” [Online]. Available: <https://www.eralberta.ca/best-challenge/>
- [140] D. Layzell and J. Lof, “Zero-emission Transportation Fuels: Alberta’s New Economic Opportunity,” *CESAR*, 05-Mar-2019. [Online]. Available: <https://www.cesarnet.ca/blog/zero-emission-transportation-fuels-alberta-s-new-economic-opportunity>
- [141] M. Henning, A. Thomas, and A. Smyth, “An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses,” *The Midwest Hydrogen*

- Center of Excellence [Online]. Available: <https://www.sartaonline.com/Content/uploads/FourSeasonFINALPDF-938.pdf>
- [142] Canadian Urban Transit Research & Innovation Consortium, “Pan-Canadian Hydrogen Fuel Cell Electric Vehicle Demonstration & Integration Trial: Phase I,” CUTRIC, 2018 [Online]. Available: <https://cutric-crituc.org/project/pan-canadian-hydrogen-fuel-cell-vehicle-demonstration-integration-trial/>
- [143] National Renewable Energy Laboratory, “U.S. Fuel Cell Bus Projects.” 12-Nov-2018 [Online]. Available: <https://www.nrel.gov/hydrogen/assets/docs/us-fcb-projects-2018.xlsx>
- [144] E4tech, “The Fuel Cell Industry Review 2019,” Dec. 2019 [Online]. Available: <http://www.fuelcellindustryreview.com/>
- [145] “Fuel Cell Electric Buses Knowledge Base,” *Fuel Cell Electric Buses*. [Online]. Available: <https://fuelcellbuses.eu/demomap>
- [146] Ballard Power Systems, “Ballard to Provide Fuel Cell Modules For Buses in Europe as a Member of New H2Bus Consortium,” 03-Jun-2019 [Online]. Available: <https://www.ballard.com/about-ballard/newsroom/news-releases/2019/06/03/ballard-to-provide-fuel-cell-modules-for-buses-in-europe-as-a-member-of-new-h2bus-consortium>

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