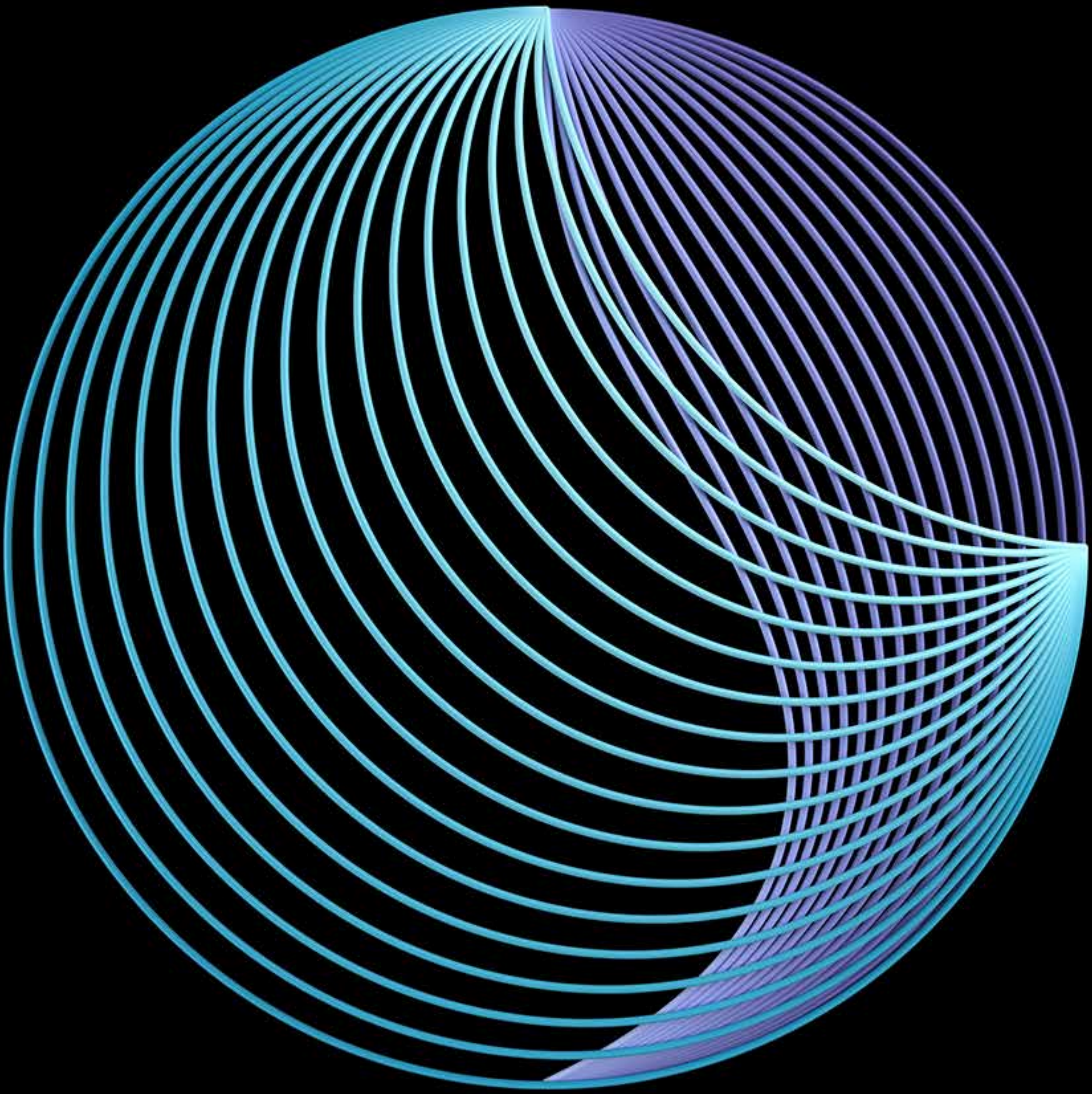


Fueling the Future of Mobility

Hydrogen and fuel cell solutions for transportation

Volume 1
Deloitte China

Financial Advisory

Executive summary

Jointly written and published by Deloitte and Ballard, this white paper seeks to introduce the wondrous technology of fuel cell vehicles, as well as their commercial applications. Through in depth research and analysis, this paper provides answers to the most pertinent questions from industry executives and laypeople alike - how economically viable are fuel cell vehicles, and what is their impact on the environment?

Hydrogen is the single most abundant substance in the universe. Perhaps due to this abundance, we sometimes forget how useful hydrogen is. From being used in the very first internal combustion engines as an inflammable fuel, to powering flight by airships, hydrogen has once again taken center stage in mankind's quest for energy sources, in the form of fuel cell applications.

In this three-part series, we take a comprehensive look at hydrogen and its role to power the future of mobility. This first paper focuses on an introduction of hydrogen and fuel cell technology, as well as a deep dive into a total cost of ownership view of fuel cell, battery-electric, and traditional internal combustion engine vehicles. We took a bottom-up approach of a Total Cost of Ownership ("TCO") analysis across the regions of US, China, and Europe, across a 13-year timespan. Our approach looks not only at detailed build costs for a Fuel Cell ("FC") vehicle, down to the nuts and bolts of drivetrain, fuel system, and others, but also at operational costs such as fuel, infrastructure, maintenance, and so forth. We believe that this approach is not only unique in the marketplace, but also offers our readers a perspective that can be applied to almost any operational business model. Indeed, we applied our model to 3 specific case scenarios of Fuel Cell Electric Vehicle ("FCEV") use today – focusing on an logistics operator in Shanghai, a drayage truck operator in California, and a bus operator in London.

Our TCO analysis shows consistent and highly encouraging results. Even when ignoring qualitative benefits of hydrogen (i.e. zero-emission at the use end, among others), FCEVs are forecasted to become cheaper from a TCO perspective compared to Battery Electric Vehicles ("BEV"s) and Internal Combustion Engine ("ICE") commercial vehicles over the next 10 year period in all use cases. This is driven by a combination of vehicle build cost declines as technology matures and economies of scale improve, as well as other factors such as hydrogen fuel costs, infrastructure, and so forth. It is unsurprising, then, to also find that major governments across the world are focusing their efforts on these pieces to drive hydrogen technology and use forward into the future.
In our high-level TCO analysis, our results show that, in 2019, FCEVs are approximately 40% and 90% more expensive than BEVs and ICE vehicles, on a per 100km basis considering acquisition and operational costs together. From an acquisitions cost perspective, the higher cost is primarily due to high cost of the fuel cell system, as well as a markup on other components due to lower economies of scale. From an operational cost perspective, the higher cost is primarily driven by the cost of hydrogen fuel.

However, the TCO of FCEVs is forecasted to be less than BEVs by 2026, and less than that of ICE vehicles around 2027. Overall, we estimate that the TCO of FCEVs will decline by almost 50% in the next 10 years. This is driven by several factors. From an acquisition cost perspective, fuel cell systems are forecasted to decrease in cost by almost 50% in the next 10 years. The fuel cell system is relatively light in terms of materials cost but high in manufacturing costs, due to high technological requirements. For example, contrary to common thinking, the cost of platinum makes up less than 1% of cost of the fuel stack system. This is compared to battery vehicles, in which commodity-type raw materials, such as lithium and cobalt, makes up a significant portion of total costs. The relative raw-materials-light fuel cell system leaves significant room for cost improvements in the future, together with dramatic improvements in economies of scale. Another large factor in terms of decrease in operational cost is the cost of hydrogen, which is forecasted to decrease significantly across all geographies in the future. This is due to the increased usage of renewable energies to produce hydrogen (which is less than 5% of hydrogen production today), as well as build-out of supporting infrastructure and transport mechanisms.

Our TCO forecast is furthermore relatively conservative in several aspects. For example, as history would show with emerging technologies, production costs often decrease much more dramatically than forecasted. We have also not included any government subsidies and incentives (acquisition, infrastructure, or operational) in the TCO model. When looking at the specific case scenarios in Shanghai, California, and London, the cross-over of FCEVs with BEVs and ICE vehicles are much faster, due to a variety of subsidies on FCEVs in each geography, or additional taxes on ICE vehicles or fuel. Indeed, we have also been quite conservative on pricing pressure on ICE vehicles in the future, which could be driven up significantly from quantitative (cost of fuel, higher emission standards), or qualitative (restrictions on entering city areas, or planned banning of pure ICEs) perspectives. Therefore, it is likely that FCEVs will become cheaper than BEVs and ICE vehicles from a TCO perspective sooner than 2026.

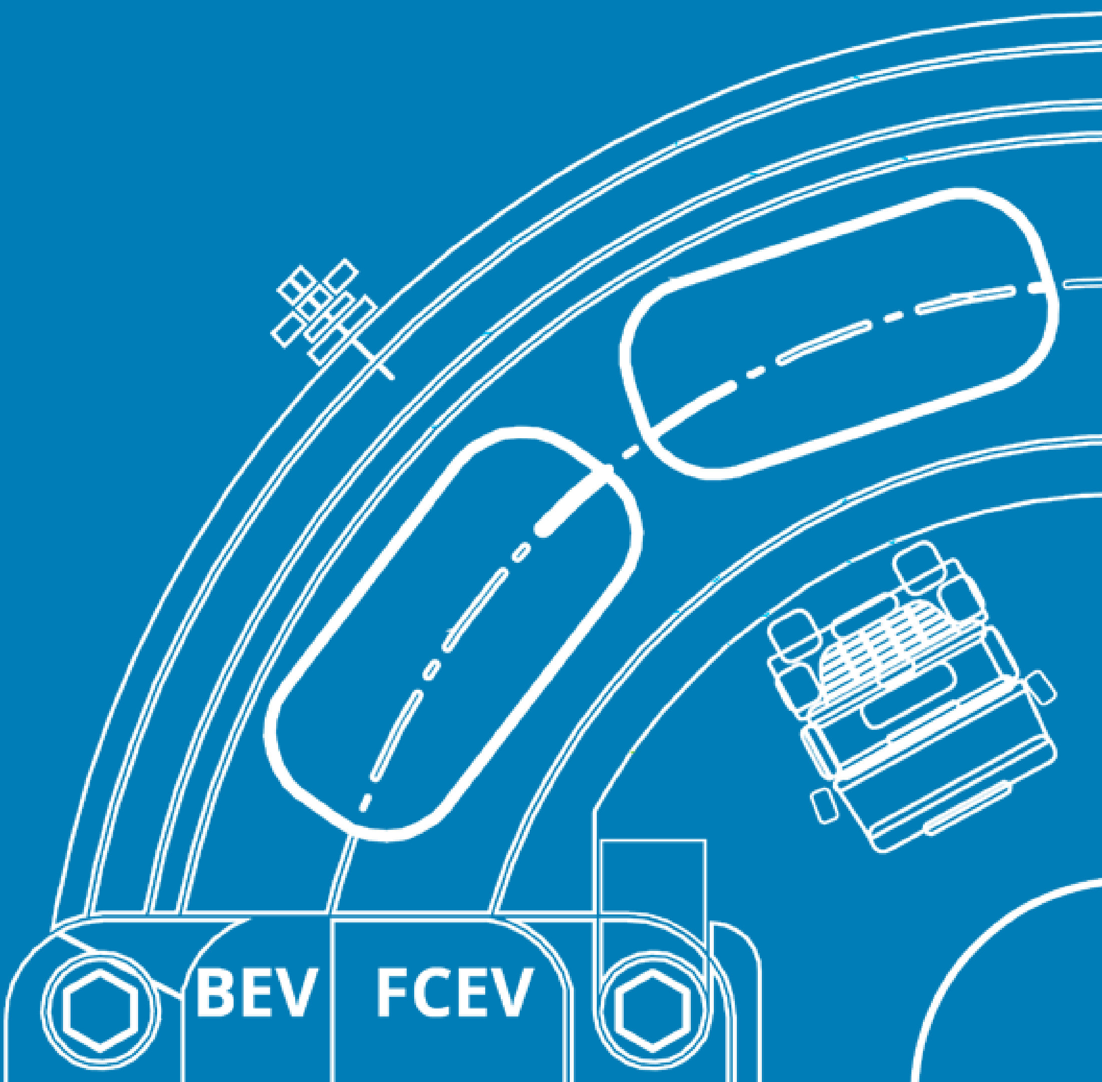
Finally, we also cover in this paper some of the energy efficiency, hydrogen production, greenhouse gas and other environmental impacts of fuel cell technology today and going forward. Although this is not a highlight of this paper, but rather Volume 3* where we shall explore the hydrogen value chain in more detail, our high level analysis in this paper can allow the reader to start garnering some insights into the incredible complexity of the hydrogen value chain and possibilities for improvements in the next years to come. For example, today, the subsidies and incentives of FCEVs are higher than ICE vehicles, but lower than BEVs today due to inefficiencies in the hydrogen production process. In the future, where renewables energies such as wind and solar play more part in the hydrogen production process, the energy efficiency of FCEVs will see dramatic improvement. For example, renewable energies (or even nuclear energy) are affected by seasonality and peak usage cycles, resulting in overcapacity of electricity production which is often wasted. The marginal cost of renewable energies is near zero, which results in their being priced below prevailing market - even negatively priced in certain countries in Europe. This wasted energy can be captured by hydrogen as a clean and efficient alternative.

From a lifetime emissions and environmental impact perspective, FCEVs are also cleaner than BEVs and ICE vehicles, with even more room for improvement as hydrogen production and delivery matures. The production or FCEVs are also significantly cleaner than BEVs due to very low requirements on raw materials, compared to the mining and heavy usage of heavy metals such as lithium and cobalt for BEVs. At the end of life process, FCEVs are also easier (and more economically attractive) to recycle than BEVs.

As Bill Gates famously said, “We always overestimate the change that will occur in the next two years and underestimate the change that will occur in the next ten. Don't let yourself be lulled into inaction.” We hope this white paper series proves useful for our readers, and that our efforts, however small, may prove as part of catalyst for change for a more economically sound business model for businesses, and a greener world for all of us.

Note: *The three volume series include: 1) Hydrogen and fuel cell solutions for transportation; 2) Hydrogen and fuel cell applications now and future; 3) Evolution and future of hydrogen supply chain

Content


BEV
FCEV

Introduction to fuel cell technology

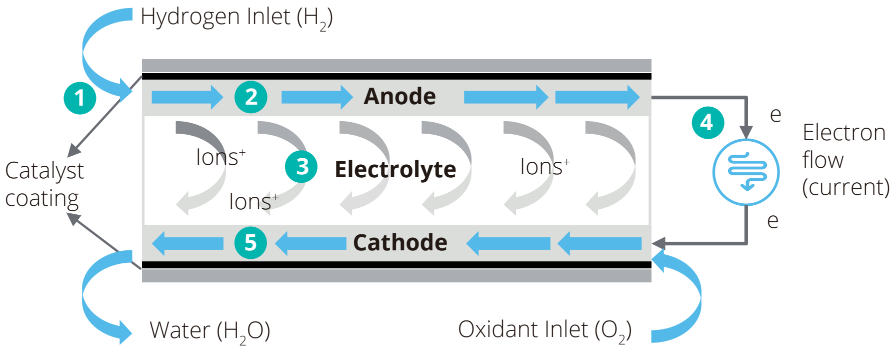
1.1 What are fuel cells?

Broadly speaking, a fuel cell is an electrochemical reactor that converts the chemical energy of a fuel and an oxidant directly to electricity [1]. More recently, the word fuel cell has been used almost exclusively to describe such a reactor using hydrogen as the primary source of energy [2].

Hydrogen has a long history of being used as fuel for mobility. More than 200 years ago, hydrogen was used in the very first internal combustion engines by burning the hydrogen itself, similar to burning gasoline today [3]. However, this did not prove to be quite successful, due to safety concerns as well as low energy density [7]. Rather, in a modern fuel cell, hydrogen is a carrier of energy, by reacting with oxygen to form electricity [4].

The reaction between hydrogen and oxygen is astoundingly simple, and can be represented by the following formula: $2H_2+O_2=2H^2O$. [5] In a fuel cell, hydrogen and oxygen are introduced separately with hydrogen supplied to one electrode of the fuel cell and oxygen to the other (Figure 1). The two electrodes are separated by a material called the electrolyte, which acts as a filter to both stop the cell reactants mixing directly with one another and to control how the charged ions created during the partial cell reactions are allowed to reach each other.

Figure 1: Operating principle of the fuel cell stack



Hydrogen molecules first enters the hydrogen electrode (called the anode) of the fuel cell (step 1). The hydrogen molecules then react with the catalyst coating the anode, releasing electrons to form a positively charged hydrogen ion (step 2). These ions cross the electrolyte and reach the oxygen at the second electrode (called the cathode) (step 3). The electrons, however, cannot pass the electrolyte. Instead, they flow into an electrical circuit, generating the power of the fuel cell system (step 4). At the cathode, the catalyst causes the hydrogen ions and electrons to bond with oxygen from the air to form water vapor, which is the only byproduct of the process (step 5) [6].

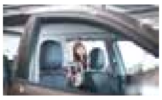
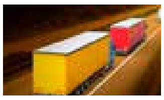
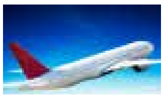
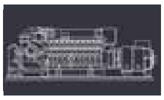
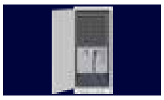
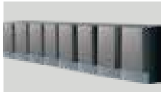
Fuel cells are typically categorized by the type of electrolyte used. Typical types of fuel cells electrolytes include Proton Exchange Membrane ("PEM"), Alkaline fuel cell ("AFC"), Phosphoric Acid Fuel cell ("PAFC"), Solid Oxide Fuel Cells ("SOFC") and Molten Carbonate Fuel cell ("MCFC"). Figure 2 below shows a high-level comparison of the different technologies, without diving into too much technical detail of how each technology works. Of these, PEM is the most commercialized type today, due to its low operating temperature (50-100°C), short start time and ease of use of its oxidant (atmospheric air) [8]. These characteristics make PEM ideal for mobility solutions, and is part of the reason for the rapid development of FCEVs starting from the 1990s [10].

Figure 2: High-level comparison of 5 typical fuel cell types[9]

Fuel cell type	Electrolyte type	Operating temperature (˚C)	Catalyst type	Key advantages	Key weaknesses	Areas of application
PEM	Proton Exchange Membrane	50-100	Platinum	• Quick start • Work at room temperature • Air as oxidant	• Sensitive to CO • Reactants need to be humidified	• Vehicle power • Portable power
AFC	Alkaline	90-100	Nickel /Silver	• Quick start • Work at room temperature	• Need pure oxygen as oxidant	• Aerospace • Military
PAFC	Phosphoric Acid	150-200	Platinum	• Insensitive to CO_2	• Sensitive to CO • Slow start	• Distributed generation[1]
SOFC	Solid Oxide	650-1,000	LaMnO3/LaCoO3	• Air as oxidant • High energy efficiency[2]	• High operating temperature	• Large distributed generation • Portable power
MCFC	Molten Carbonate	600-700	Nickel	• Air as oxidant • High energy efficiency[2]	• High operating temperature	• Large distributed generation

Note: 1. electrical generation and storage performed by a variety of small, grid-connected or distribution system connected devices referred to as distributed energy resources; 2. 85% overall with combined heat and power, or 60% pure electricity

Figure 3: Major applications & examples of hydrogen fuel cell usage

Category	Major applications	Example
Transportation	Passenger vehicles	
	Trucks	
	Forklifts	
	Buses	
	Logistic vehicles	
	Aviation	
	Marine	
	E-bikes	
Stationary power	Combined heat and power ("CHP")	
	Uninterruptible power systems ("UPS")[1]	
	Distributed Power Generation	
Other application	Portable power	
	Unmanned Aerial Vehicles ("UAVs")	

Being a carrier of energy, hydrogen fuel cells can be applied in a variety of use cases. Typical applications of fuel cell can be categorized into three major types: transportation, stationary power and other application such as portable power (Figure 3) [11]

Note: 1. An uninterruptible power supply (UPS) system provides power to a critical load when the main input power source fails

1.2 History and Evolution of Fuel cell and fuel cell vehicles

Fuel cell is not a new topic. It can be traced back to 1839 when it was firstly invented by a Welsh scientist by the name of William Grove[12]. However, the first time fuel cell vehicles were in the international spotlight was during the oil crisis in the 1970s [14]. In the next few decades, carmakers from different countries spent various degrees of efforts developing fuel cell vehicles[14]. The year 2014 was marked by the world's first commercialized fuel cell vehicle by Toyota, representing a culmination of years of R&D efforts. From then on, in the eyes of the public, fuel cell vehicles were no longer experimental, but were recognized as one of the key driving technologies of the future of mobility. In the next 5 years (till now), countries such as China, US, Japan, and various countries in Europe focused their efforts on driving this technology forward [14]. A brief history of fuel cell advancement can be seen below in Figure 4. Through a combination of governmental policy, technology advancement and industrial involvement, fuel cell applications are now entering into a golden era of advancement.

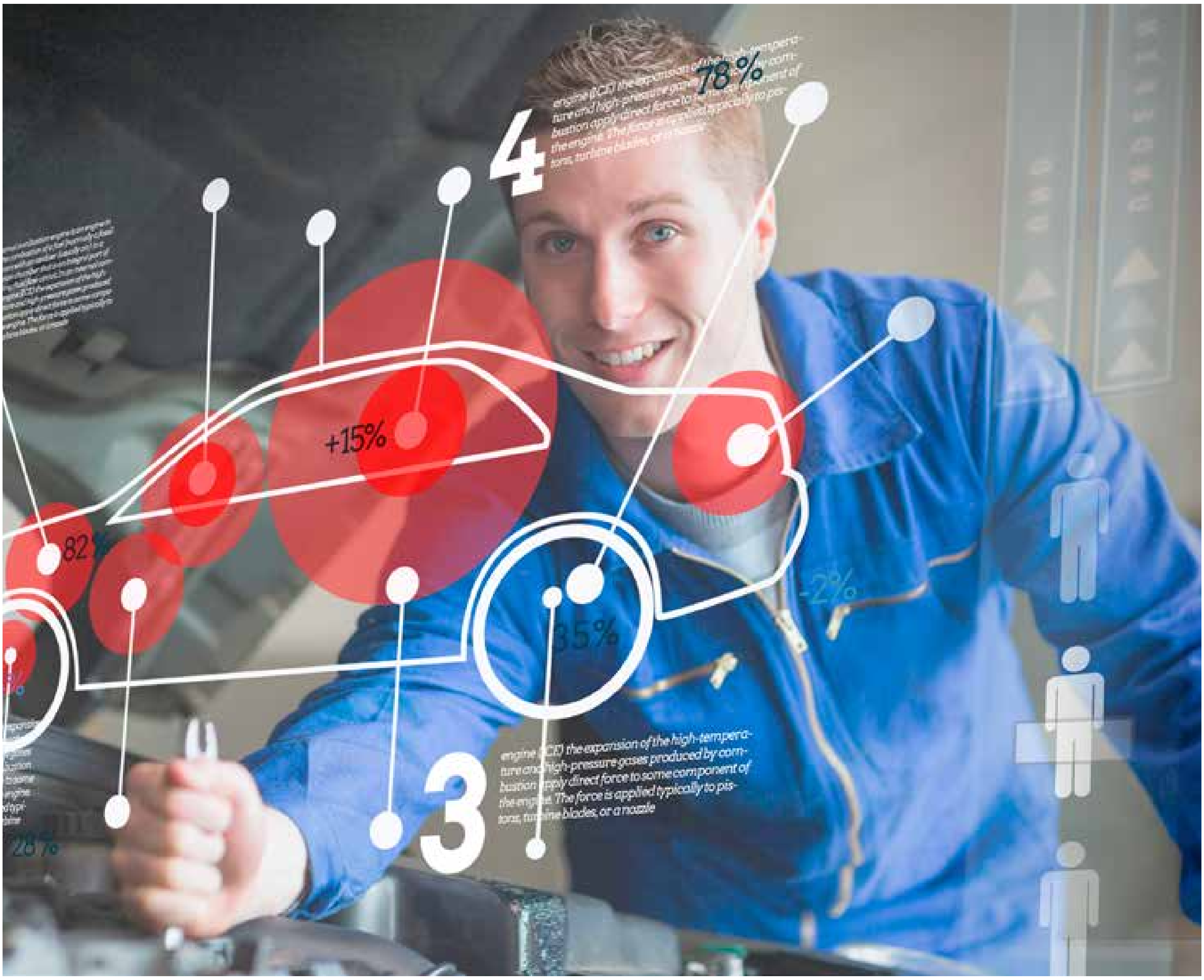
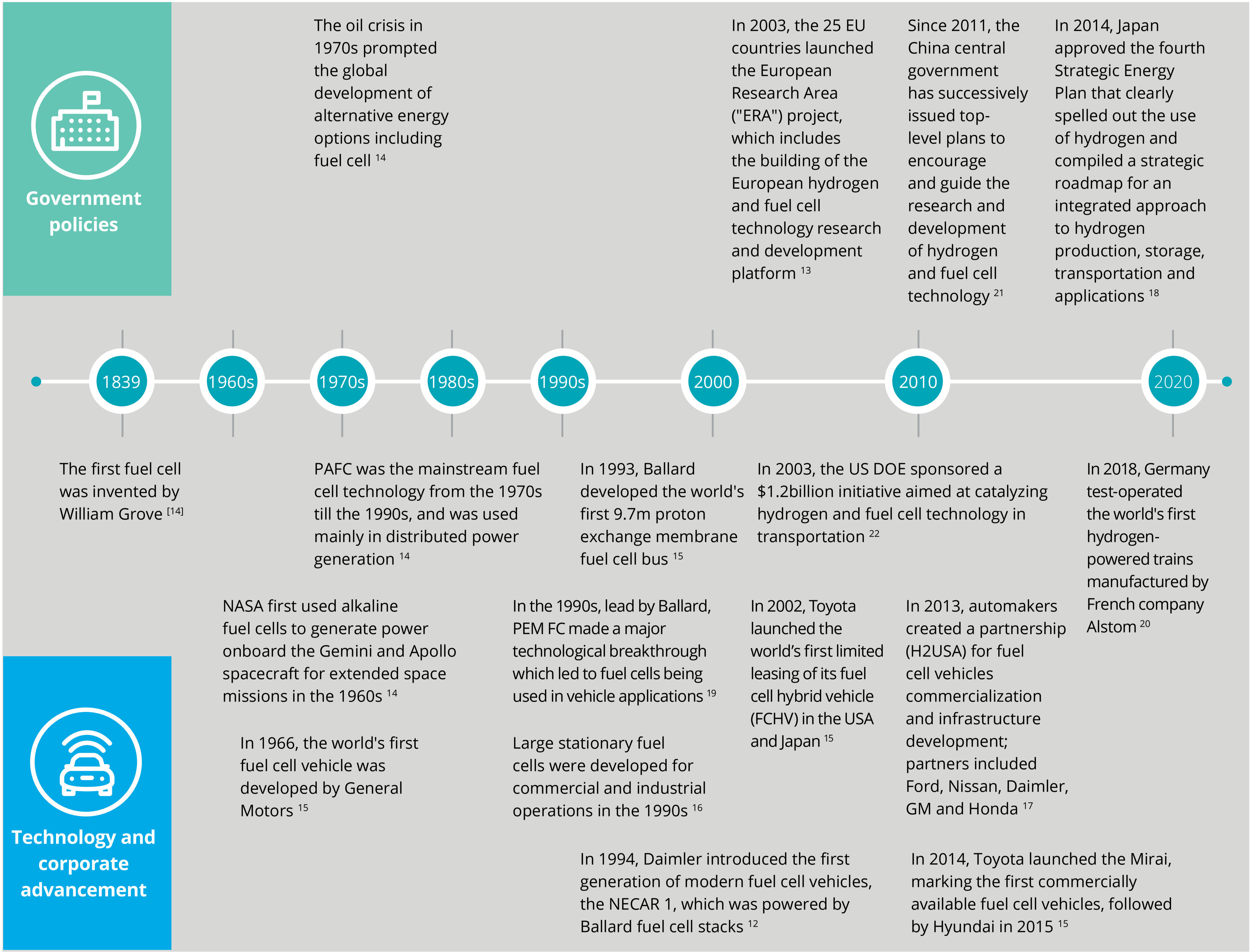


Figure 4. Brief History and Evolution of fuel cell and fuel cell vehicles



Government policies

The oil crisis in 1970s prompted the global development of alternative energy options including fuel cell [14]

In 2003, the 25 EU countries launched the European Research Area ("ERA") project, which includes the building of the European hydrogen and fuel cell technology research and development platform [13]

Since 2011, the China central government has successively issued top-level plans to encourage and guide the research and development of hydrogen and fuel cell technology [21]

In 2014, Japan approved the fourth Strategic Energy Plan that clearly spelled out the use of hydrogen and compiled a strategic roadmap for an integrated approach to hydrogen production, storage, transportation and applications [18]

Technology and corporate advancement

The first fuel cell was invented by William Grove [14]

NASA first used alkaline fuel cells to generate power onboard the Gemini and Apollo spacecraft for extended space missions in the 1960s [14]

In 1966, the world's first fuel cell vehicle was developed by General Motors [15]

PAFC was the mainstream fuel cell technology from the 1970s till the 1990s, and was used mainly in distributed power generation [14]

In 1993, Ballard developed the world's first 9.7m proton exchange membrane fuel cell bus [15]

In the 1990s, lead by Ballard, PEM FC made a major technological breakthrough which led to fuel cells being used in vehicle applications [19]

Large stationary fuel cells were developed for commercial and industrial operations in the 1990s [16]

In 1994, Daimler introduced the first generation of modern fuel cell vehicles, the NECAR 1, which was powered by Ballard fuel cell stacks [12]

In 2003, the US DOE sponsored a $1.2billion initiative aimed at catalyzing hydrogen and fuel cell technology in transportation [22]

In 2002, Toyota launched the world's first limited leasing of its fuel cell hybrid vehicle (FCHV) in the USA and Japan [15]

In 2013, automakers created a partnership (H2USA) for fuel cell vehicles commercialization and infrastructure development; partners included Ford, Nissan, Daimler, GM and Honda [17]

In 2014, Toyota launched the Mirai, marking the first commercially available fuel cell vehicles, followed by Hyundai in 2015 [15]

In 2018, Germany test-operated the world's first hydrogen-powered trains manufactured by French company Alstom [20]

1.3 Hydrogen development overview by geography

As with most technologies, the initial development and deployment phases of fuel cell technology is heavily dependent on government policies and incentives. To various extents and for various reasons, governments of China, US, European nations and Japan have promoted the development of the fuel cell industry, investing heavily in the core technology research and establishing subsidy policies and medium/long-term strategic plans. By analyzing various countries' government policies, as well as industrial development, insights can be drawn from the development of hydrogen and fuel cell in each country. Figure 5 below provides an overview of the policy focus of each country, which we will dive into in further detail in the following pages.

Figure 5. Policy overview across major markets

	US	China	Europe	Japan
National strategy	• As early as in 1990, the US government published the Hydrogen Research, Development And Demonstration Act, formulating 5-year plan for hydrogen energy R&D [13] • Due to the long period of hydrogen development, the United States has formed a systematic basket of laws, policies and scientific research plans to promote hydrogen energy [30]	• Although comparatively late in development compared to other nations, China is putting a strong focus on hydrogen • Hydrogen was listed as one of the 15 key focus areas of China's energy strategy and technology innovation plan in 2016 [25] • During the 2019 Two Sessions (a public national meeting to discuss governmental results), hydrogen was written into the government work report for the first time [26]	• In 2003, the 25 EU nations launched the European Research Area ("ERA") project, which includes the building of the European hydrogen and fuel cell technology research and development platform [13] • In 2019, Fuel Cells and Hydrogen Joint Undertaking ("FCHJU") released the Hydrogen Roadmap Europe, which proposed a roadmap for hydrogen energy development towards 2030 and 2050 [34]	• Hydrogen was established as a "national energy" of Japan, and the government has committed to make Japan a hydrogen society [30][31][32] • In 2014, Japan launched the fourth Strategic Energy Plan and published the Strategic Roadmap for Hydrogen and Fuel Cells, outlining an integrated approach to hydrogen production, storage, transportation and applications [33]
Hydrogen production & distribution	◑ • In 2019 DOE issued a funding opportunity announcement for up to $31 million in funding to advance the H2@Scale[2] concept, including innovative concepts for hydrogen production, and an integrated production, storage, and fueling H2@Scale pilot system [35]	◔ • No clear nation-wide subsidies or policies on hydrogen production & distribution [27] • The current classification of hydrogen as a Hazardous Material is one of the major policy barriers to be overcome [27]	◑ • Relative high focus on clean production of hydrogen going forward • Hydrogen Roadmap Europe: a transition to one-third ultra-low carbon hydrogen production by 2030 [34]	◕ • Strategic Road Map for Hydrogen and Fuel Cells: – Building up a commercial-based domestic system for efficiently distributing hydrogen by mid-2020s [24] – Full-fledged operation of manufacturing, transportation and storage of zero-carbon emission hydrogen by 2040 [24]

Note: 1. Harvey balls represent focus/completeness of policies in each area, and are illustrative for comparison purposes only 2. H2@Scale is a concept that explores the potential for wide-scale hydrogen production and utilization in the United States to enable resiliency of the power generation and transmission sectors, while also aligning diverse multibillion dollar domestic industries, domestic competitiveness, and job creation.

	US	China	Europe	Japan
Hydrogen Infrastructure	◑ • The DoE launched H2USA — a public-private partnership with FCEV OEMs, focusing on advancing hydrogen infrastructure [36] • The California Fuel Cell Partnership ("CaFCP") has outlined targets for 1,000 hydrogen refueling stations by 2030 [37]	◔ • No clear nation-wide subsidies or policies on hydrogen infrastructure[27] • Several city-level government like Foshan, and Zhongshan city are setting local subsidy policies [25] • However, approval procedures for hydrogen stations are still unclear [27]	◑ • In 2009, Germany established H2 Mobility, investing in world's first nationwide network of hydrogen filling stations [39] • Hydrogen Roadmap Europe: 3,700 hydrogen refueling stations are expected by 2030 [34]	◕ • From 2016-2018, the Ministry of Economy, Trade and Industry has provided ~$88million budget on R&D and ~$539million budget on construction subsidies of hydrogen fueling stations [23]
Support for passenger vehicles	◕ • The US government clarified the leading role of hydrogen energy in transportation transformation in the all-of-the-above Energy Strategy in 2014 [13] • The California Fuel Cell Partnership has outlined targets for 1,000,000 FCEVs by 2030 [37] • In 2018, the California Air Resources Board ("CARB") has preliminarily awarded $41 million for the 'shore to store' project, developing 10 FC class 8 drayage trucks [38]	◑ • Subsidies to consumers on each FCEV sold are expected to last at least until 2025 [28] • Similar to BEVs, the government is focusing first on commercial applications of FCEVs, which is easier to regulate and deploy on a large scale [28]; this is not written into policy per-se, but more from a implementation perspective [28]	◑ • Hydrogen Roadmap Europe: 3.7 million fuel cell passenger vehicles on road by 2030 [34]	◕ • Japan's hydrogen fuel cell vehicles are mainly passenger vehicles [29], starting from the R&D by OEMs which led to the release of the Toyota Mirai in 2014 [40] • Target of 800,000 FCEVs by 2030 "Hydrogen Strategy 2017" [23]
Support for commercial vehicles	◕	◕	◑ • Hydrogen Roadmap Europe: 500,000 fuel cell LCVs, 45,000 fuel cell trucks and buses on road by 2030 [34]	◑ • Target of 1,200 FC buses and 10,000 forklifts by 2030 "Hydrogen Strategy 2017" [23]

Note: 1. Harvey balls represent focus/completeness of policies in each area, and are illustrative for comparison purposes only

US

The United States is the first country to establish hydrogen and fuel cell technology as part of its national energy strategy [31]. Initiated due to the oil crisis, the US government has funded research sponsorship on hydrogen since 1970s [41]. As early as in 1990, the US government published the Hydrogen Research, Development And Demonstration Act, formulating 5-year plan for hydrogen energy R&D [13]. In 2002, the US DOE issued the National Hydrogen Energy Development Roadmap, provides a blueprint for the coordinated, long-term, public and private efforts required for hydrogen energy development. [13] In 2012, the US congress rewrote the hydrogen fuel cell policy, increasing the tax credit for hydrogen refueling properties from 30% to 50%, and creating a tiered investment tax credit to reward highly efficient fuel cells utilizing combined heat and power (CHP) systems. [51] In 2014, the US government promulgated the all-of-the-above Energy Strategy, which clarified the leading role of hydrogen energy in transportation transformation.[13] The 8th of October was chosen to be the national hydrogen and fuel cell day by the Fuel Cell and Hydrogen Energy Association in 2015, and was designated in Senate Resolution 217 in the same year, signifying increased important places by the federal government.[49] As demonstrated below in Figure 6, years of efforts by various US organizations has created policies that comprehensively cover almost all parts of the hydrogen industry.

The R&D of hydrogen and fuel cell in US was mainly led by the DOE, which has established a framework on a R&D system led by the national lab of DOE and supplemented by universities, research institutes and enterprises through allocating funds on key technical challenges. [31] Due to the long period of hydrogen development, the United States has formed a systematic basket of laws, policies and scientific research plans to promote hydrogen energy research, development and deployment. [30] A Timeline of major government policies/initiatives can be seen below in Figure 6. In March 2019, the DoE announced intentions to spend up to $31 million on H2@scale[1], focusing on economic scale hydrogen production, transportation, storage and utilization in multiple sectors in the US. [34]

To further promote wide adoption and address infrastructure challenges, the DoE launched H2USA — a public-private partnership with FCEV OEMs, focusing on advancing hydrogen infrastructure to support more transportation energy options for U.S. consumers. [36] The years of investment definitely shows in practice. In terms of commercial applications, the US has the largest number of fuel cell passenger cars in the world – number of FC cars sold and leased in US reached 7,271 by August 2019 [44]. In addition, there are over 30,000 fuel cell forklifts in US as of April 2019 [335], which are widely used in the United States by companies such as Walmart and Amazon. [50]

California represents the highest level of commercialization of hydrogen fuel cell vehicles in the United States, due to a level of government support and public support for renewable energies not found in other states.[46] There are 6,830 FCEV operating in California as of June 2019, which far outstrips that of any other state [37]. Since June 2010, when the California Energy Commission's first grant was released, 35 retail hydrogen refueling stations have opened, with another 29 stations in development. [45] The California Air Resources Board and the California Fuel Cell Partnership played a major role in advancing the commercialization process. [47] With a complete "planning-subsidiary-evaluation" system, California has become the most active and demonstrative market for hydrogen and fuel cell development and deployment in the United States. [48] Looking forward, the California Fuel Cell Partnership has outlined targets for 1,000 hydrogen refueling stations and 1,000,000 FCEVs by 2030.[37]

Note: 1. H2@Scale is a concept that explores the potential for wide-scale hydrogen production and utilization in the United States to enable resiliency of the power generation and transmission sectors, while also aligning diverse multibillion dollar domestic industries, domestic competitiveness, and job creation.

Figure 6. Timeline and coverage of major government policies/initiatives

		Hydrogen production & distribution	Hydrogen Infrastructure	Support for passenger vehicles	Support for commercial vehicles
1974	Miami University organized The Hydrogen Economy Miami Energy (THEME) Conference	✓	✓		
1990	United States Department of Energy - "Hydrogen Research, Development And Demonstration Act" [54]	✓			
1996	United States Department of Energy - "Hydrogen Future Act of 1996" [55]	✓	✓		
2002	United States Department of Energy - "National Hydrogen Energy Development Roadmap" [53]	✓	✓	✓	✓
2003	United States Department of Energy - "Hydrogen Fuel Initiative" [56]	✓	✓	✓	✓
2006	United States Department of Energy & United States Department of Transportation - "Hydrogen Posture Plan" [57]	✓	✓	✓	✓
2012	United States Congress - "The Fuel Cell and Hydrogen Infrastructure for America Act" [51]	✓	✓		
2013	The DoE launched H2USA — a public-private partnership with FCEV OEMs, focusing on advancing hydrogen infrastructure and enabling the large scale adoption of FCEVs [36]	✓	✓	✓	✓
2014	Executive Office of the President of the United States - "All-of-the-above Energy Strategy" [52]			✓	✓
2019	DOE issued a funding opportunity announcement for up to $31 million[34] The California Fuel Cell Partnership has outlined targets for 1,000 hydrogen refueling stations and 1,000,000 FCEVs by 2030 [37]	✓	✓	✓	✓

China

The first Chinese fuel cell vehicle was developed in 1999[60]. Since then, China has developed into one of the world's largest hydrogen markets – both in production and consumption. The country has the largest hydrogen production volume worldwide, with existing industrial hydrogen production capacity of 25 million tons / year [31]. On the consumption side, China sold more than 3,000 FCEVs accumulated from 2017 to 2019 (all of which were commercial vehicles), making it one of the world's largest markets for FC deployment. [64]

The achievement of developing such a huge market was the culmination of decades of government policy and initiatives. Since 2011, the central government has successively issued top-level plans to encourage and guide the research and development of hydrogen and fuel cell technology, such as the "13th Five-Year Plan for Strategic Emerging Industry Development", "Energy Technology Revolution and Innovative Action Technology (2016-2030)", "Energy Conservation and New Energy Vehicle Industry Development Plan (2012-2020)" and "Made in China 2025". [21] Also, in order to promote NEVs development, a "Dual Credit Management System", has been applied to passenger vehicles production [188]. This refers to positive credits given for NEV production and negative credits for ICE production [188]. This system may be also applied to commercial vehicles in the future [189]. Hydrogen was listed as one of the 15 key focus areas of China's energy strategy and technology innovation plan in 2016[25]. As China is in a nation-wide effort to transition to renewable energy, hydrogen is seen as an important part of this initiative. [63] Hydrogen can help alleviate many outstanding problems existing in China's energy system, such as security and sustainability concerns.[65] During the 2019 Two Sessions (a public national meeting to discuss governmental results), hydrogen was written into the government work report for the first time, signifying increasing importance placed upon by the central government [26]

In terms of FCEVs, China has devoted significant efforts in the hydrogen fuel cell vehicle industry since 2014, which drove technology maturation, decrease hydrogen cost, and drove the application of hydrogen in various areas. It is important to note that hydrogen is not the only type of renewable energy being focused on, with BEV initiatives being carried out in parallel [28]. Similar to BEVs, the government focused first on commercial applications of FCEVs, which is easier to regulate and deploy on a large scale.

Subsidies from central and local governments are key drivers of fuel cell vehicles industry, and subsidies were mainly developed covering 3 aspects:

- Subsidies to consumers on each FCEV sold. Though subsidies on battery electric vehicle are being reduced yearly, subsidies on FCEVs are expected to last at least until 2025. Based on expert interviews, it is likely that subsidies on FCEV will be gradually reduced and requirement on technical performance would be higher over time.[28]
- Subsidies on hydrogen refueling station construction. Currently, there is no clear national wide subsidies on hydrogen refueling station, while several city-level government like Foshan, and Zhongshan city are setting local subsidy policies.[25] Foshan city, one of the most active cities in hydrogen deployment announced that each newly constructed stationary hydrogen refueling station can receive a maximum subsidy of 8 million RMB. [62]
- Subsidies on hydrogen refueling cost. According to government expert interviews, the goal of these subsidies reduce hydrogen cost per 100km to be less than or on par with that of ICE vehicles. However, to whom the subsidies go to is still under discussion, which could be given to the hydrogen station operator or direct to consumers refueling their FCEVs. [28]
- Despite the advancement and political will of the government, the hydrogen industry still have much room for improvement in China. For example, there is still space for improvement of relevant policies and supporting facilities. Based on key expert interviews, improvements that are expected to have the most impact on the industry include [27]:
- Policies and infrastructure support for hydrogen production and transportation
- De-classification of hydrogen as part of the Hazardous Chemicals Category
- Approval procedures of hydrogen stations
- Increased localization and batch production capacity of core fuel cell components to drive down costs

In June 2019, NDRC[1]'s plan "Improving Circular Economy of Automobiles in China" was agreed by key agencies, introducing initiatives to remove NEV from purchase/number plate restrictions by local government, continue central government subsidies for NEV and accelerate the removal of restrictions on pickups from entering the cities. [66] NDRC's plan is expected to stimulate the consumption of NEV, including FCEVs, in the near future (Figure 7).

Figure 7: "*Improving Circular Economy of Automobiles in China*" 's impact areas for the automotive market

		Major initiatives related to NEV promotion	Possibilities of implementation and potential benefit to hydrogen industry
1	Remove Purchase Restrictions	• Continue excluding NEV from purchase restrictions by local governments • NEV number plate restrictions to be removed (e.g. Beijing)	●
2	Upgrade Rural Consumption	• Encourage rural residents to replace old cars, and provide subsidies for NEV purchase	◑
3	Remove Restriction on Pickups	• Currently, pickups are classified as light trucks in China, and are applicable for all restrictions on truck • The removal of restrictions would unleash the demand for pickups in cities below the prefectural level	◔
4	Optimize Charging Infrastructure	• Charging facilities and right-of-way policies (e.g. Allow NEVs to use bus lanes) benefit NEV usage	◕
5	Scrap Old Vehicles	• Reward and subsidize the scrappage of passenger vehicles less than 10 years of usage when replacing them with NEVs	◑
6	Encourage Auto Leasing/ Auto Finance	• Encourage long-term and short-term leasing and promote NEV rentals	◔
7	Electrify Public Vehicles (People & Goods)	• Promote public service vehicles such as bus, sanitation, postal, commuter, urban logistics, etc., to upgrade to NEV	◕

Level of Potential Impact: Low ○ ◔ ◑ ◕ ● High

Note: 1. National Development and Reform Commission

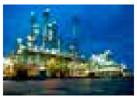
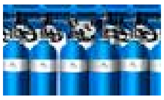
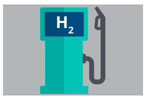
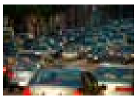
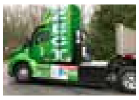
Europe

The European Union ("EU") regards hydrogen as an important part of energy security and energy transformation [31]. In 2003, the 25 EU nations launched the European Research Area ("ERA") project, which includes the building of the European hydrogen and fuel cell technology research and development platform, focusing on key technologies in the hydrogen and fuel cell industries[13]. In 2008, the EU established a public-private partnership called the Fuel Cells and Hydrogen Joint Undertaking ("FCHJU") , which played vital role in development and deployment of hydrogen and fuel cell technologies in Europe [67].

In February 2019, FCHJU released the Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, which proposed a roadmap for hydrogen energy development towards 2030 and 2050, paving the way for large-scale deployment of hydrogen power and fuel cells in Europe [34].

- The roadmap gave an overarching recommendation for all stakeholders:
  - Regulators and industry should jointly set out clear, long-term and realistic decarbonization pathways for all sectors and segments [34].
  - The European industry should invest in hydrogen and fuel cell technology to remain competitive and positioned to capture emerging opportunities [34].
- The roadmap also proposed the following concrete milestones across following sectors (Figure 8):
  - In terms of transportation, a fleet of 3.7 million fuel cell passenger vehicles, 500,000 fuel cell LCVs, 45,000 fuel cell trucks and buses are projected to be on the road by 2030. Fuel cell trains could also replace roughly 570 diesel trains by 2030 [34].
  - In terms of infrastructure for fuel cell vehicles, about 3,700 large refueling station are expected by 2030 [34].
  - In terms of heating, hydrogen could replace an estimated 7% of natural gas (by volume) by 2030, and 32% by 2040, and would cover the heating demand of about 2.5 million and more than 11.0 million households in 2030 and 2040 [34].
  - In terms of industrial applications, a transition to one-third ultra-low carbon hydrogen production by 2030 could be achieved in all applications, including refineries and ammonia production [34].
  - In terms of power generation, the at-scale conversion of "surplus" renewables into hydrogen, large-scale demonstrations of power generation from hydrogen, and renewable-hydrogen generation plants could also take place by 2030 [34].

Figure 8. Hydrogen Roadmap plan by 2030 in Europe [34]

Hydrogen Roadmap Europe	**Roadmap Plan by 2030**					
Hydrogen production & distribution		**1/3** ultra-low carbon hydrogen production in industrial applications, including refineries and ammonia production		at-scale conversion of "surplus" renewables into hydrogen large-scale demonstrations of power generation from hydrogen renewable-hydrogen generation plants		
Hydrogen Infrastructure		**~3,700** hydrogen refueling station by 2030				
Support for passenger vehicles		a fleet of **3.7 million** fuel cell passenger vehicles				
Support for commercial vehicles		**500,000** fuel cell light commercial vehicles on road		**45,000** fuel cell trucks and buses projected to be on the road		Fuel cell trains replace **570** diesel trains

Germany is one of the key leaders in hydrogen and fuel cell development in Europe. To promote the fuel cell and hydrogen energy strategy, the German federal government set up the National Organization for Hydrogen and Fuel Cell Technology ("NOW"), responsible for the coordination and management of the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP) and the Electromobility Model Regions programme of the Federal Ministry of Transport and Digital Infrastructure (BMVI). [68] In 2006, the Federal Government initiated the National Innovation Program for Hydrogen and Fuel Cell Technology ("NIP") together with representatives from research organizations as well as from various industry sectors, to advance the role of hydrogen and fuel cell technology in Germany's energy system [69]. The 2006-2016 phase of NIP funded ~EUR 1.4 bn in research, development and demonstration projects. [70] In 2009, Germany also established the H_2 Mobility initiative with Air Liquide Group, Linde Group, Shell, TOTAL and other companies, planning to invest 350 million euros in the construction of world's first nationwide network of hydrogen filling stations in German.[39] By the end of 2018, Europe has 152 hydrogen refueling stations, 41% of which are in Germany [71].

As the country where hydrogen was first discovered and fuel cell was invented, UK government' support for hydrogen and fuel cell market was less consistent and coordinated compared with other European countries such as Germany, and had no overarching strategy for the hydrogen sector until 2016. [72] In 2016, E4tech and Element Energy published a integrated Hydrogen and Fuel Cells roadmap with 11 sectoral 'mini-roadmaps', including supply chain roadmaps (e.g. H_2 production and distribution) and end-use roadmaps (e.g. road/non-road transportation), aiming to develop the hydrogen and fuel cell market as a part of the zero emissions strategy. [72] In January 2017, the JIVE project funded by European Union deployed 139 FCEBs in 5 European countries, of which 56 are in UK. [73]

Japan

Of the countries studied, Japan is perhaps the most dedicated towards becoming a "hydrogen society". Due to geographical and environmental restrictions, renewable energy is highly valued in Japan [30]. Initially, Japan was expected to achieve its renewable energy vision through nuclear energy. However, the Fukushima nuclear power plant accident forced the government to review its energy strategy [30]. Instead, hydrogen was established as a "national energy", and the government has committed to make Japan a hydrogen society [30 31 32].

In 2014, Japan launched the fourth Strategic Energy Plan that clearly spells out the use of hydrogen, and published the Strategic Roadmap for Hydrogen and Fuel Cells, outlining an integrated approach to hydrogen production, storage, transportation and applications[33]. In 2015, NEDO* issued a white paper on hydrogen energy, positioning hydrogen as the third pillar of domestic power generation[32]. In 2017, Japanese government released the "basic strategy of hydrogen energy", which aims to commercialize hydrogen fuel cell power generation by 2030 [30]. METI** has funded as much as $260 million in R&D of hydrogen and fuel cell industry in 2018 [75].

Japan is a leading player in commercial application of fuel cells, with applications such as stationary power generation for household CHP, business/industrial fuel cells and fuel cell vehicles. Fuel cell for household CHP was first applied commercially in 2009, and Japan was the first country to introduce fuel cells for home-use power generation that are capable of producing electricity and hot water[33]. To date, Japan has deployed more than 20,000 stationary combined heat and power fuel cell systems at commercial and residential spaces [78].

Fuel cell vehicles is another area of key focus for Japan. Since the 1990s, Japan automakers Toyota, Honda and Nissan has been devoted to R&D in fuel cell vehicles. By 2014, Toyota launched the first commercialized car Mirai, which was a milestone in FCEV industry, followed by Honda with Clarity [40]. Unlike some other countries, Japan's hydrogen fuel cell vehicles are mainly passenger vehicles [75]. As of June 2019, fuel cell cars sold and leased in Japan reached 3,219, according to Japan METI [44]. Besides passenger vehicles, Japan plans to have at least 100 fuel cell buses deployed by the 2020 Olympics [77].

As expected from such a wide fuel cell vehicle deployment, hydrogen infrastructure is also extremely advanced in Japan, with government funding as well as industry alliances driving hydrogen refueling station density. In 2018, a consortium of 11 companies, including Toyota and Nissan, established Japan H_2 Mobility, which aimed to build 80 hydrogen refueling station by 2021 [32]. Currently, Japan has 127 hydrogen fueling stations, which is the most of any nation in the world [42].

Note: *NEDO: The New Energy and Industrial Technology Development Organization; ** METI: the Ministry of Economy, Trade and Industry

According to the Hydrogen Council, transportation is one of the most critical applications of hydrogen and fuel cell technology [82]. From the perspective of most countries with FC initiatives, FCEVs are seen as a critical pathway to meet goals both in terms of energy strategy as well as decarbonization goals.

Using hydrogen in fuel cells in mobility have been explored since 1966. [79] Like any new technology, nascent development has been slow primarily due to a lack of existing infrastructure to support wide adoption. [80] However, the very real benefits of fuel cell technology have led governments around the world to continue exploring it as a form of green and emission-friendly energy.

Fuel cells for transportation include a wide range of use cases. Some of these applications, such as trains, unmanned aerial vehicles, and e-bikes are still quite early in development with limited deployments to date.[11]

For the purposes of this paper, most of our analysis will focus on passenger and commercial vehicle applications of fuel cell technology, which is perhaps one of the areas showing highest signs of promise for widespread adoption.[81] Some of these applications can be seen in Figure 9 below. From a policy perspective, the current and future number of FC vehicles by type can be seen below in Figure 10. We shall explore the details behind each vehicle type in Section 2.

Figure 9: Typical passenger & commercial vehicle applications of hydrogen fuel cell

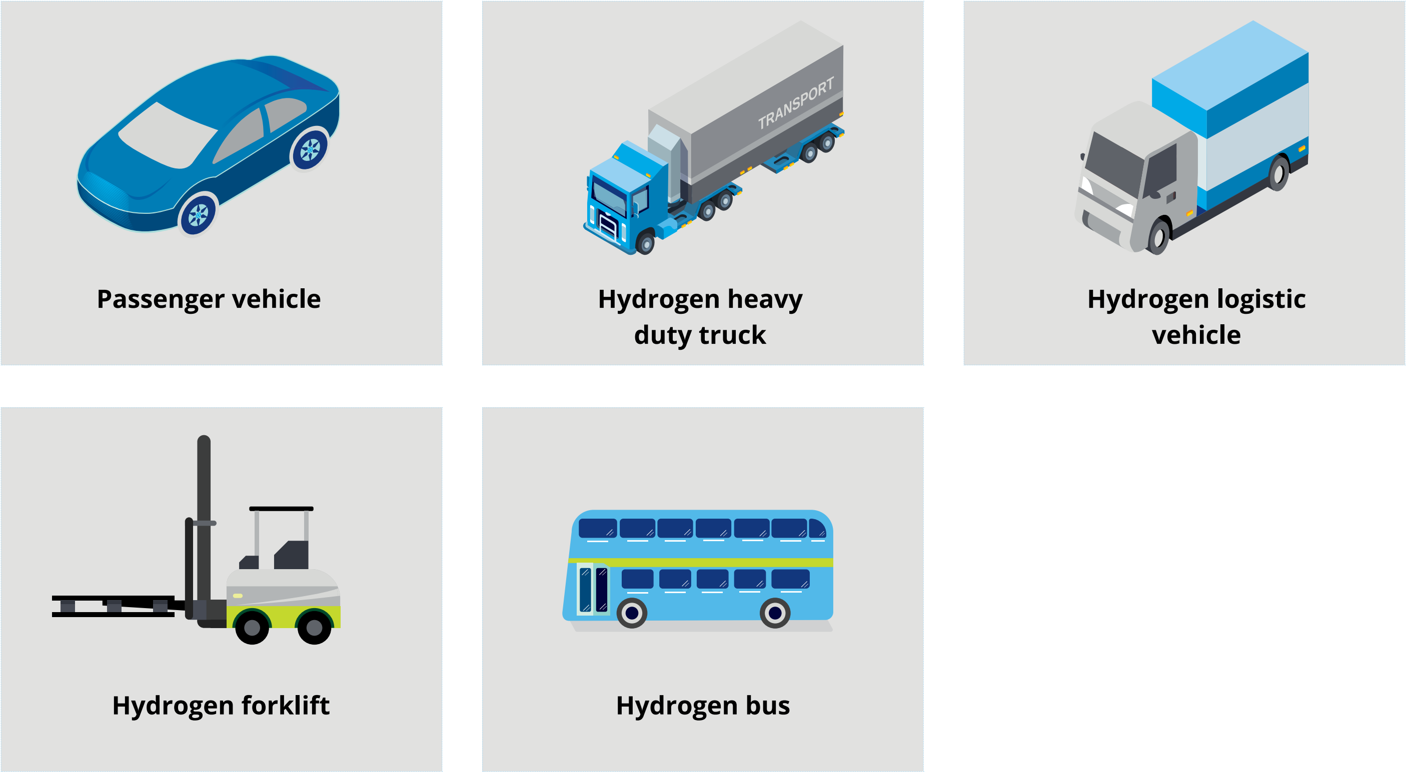
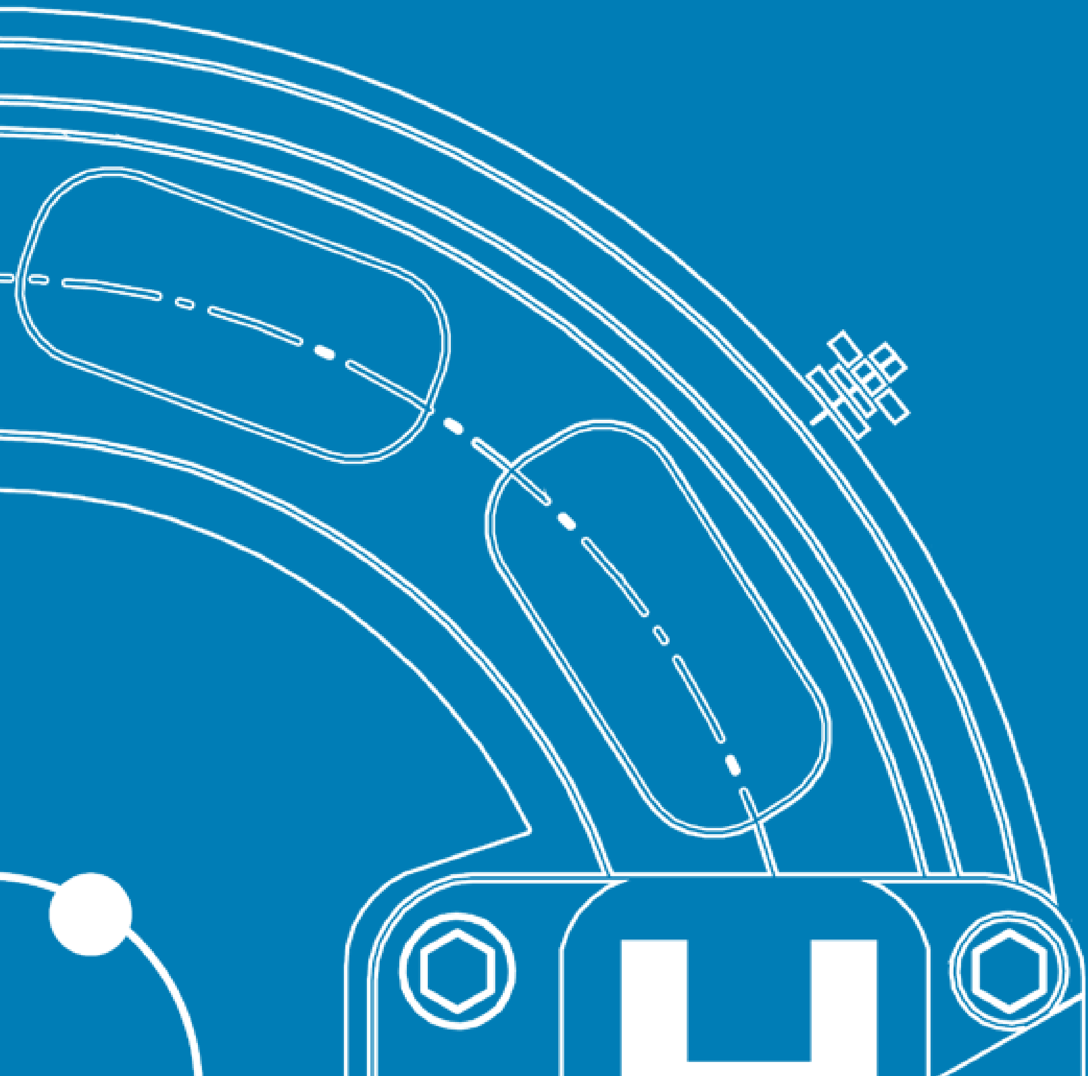


Figure 10. Current and future number of FC vehicles by type and geography*

		Passenger vehicles	**Buses and coaches**	**Trucks****	**Forklifts**	**Refueling stations**
US	Current	7,271 [44]	35 active, 39 in development	prototype test	>30,000 [335]	~42 online [37]
	Target		5,300,000 FCEVs on US roads by 2030 [337]		300,000 by 2030 [337]	7,100 by 2030 [337]
China	Current	0	2,000+ [64,83,84,85]	1,500+ [94]	2	23 [89]
	Target	3,000 by 2020 [87] 1,000,000 by 2030 [336]	11,600 commercial vehicles by 2020 [87]			100 by 2020 500 by 2030
Europe	Current	~1000+ [42]	~76 [42,73,86]	~100 [88]	~300 [42]	~152 [71]
	Target	3,700,000 by 2030 [34]	45,000 fuel cell trucks and buses by 2030 [34]			~3,700 by 2030[34]
Japan	Current	3,219 [44]	18	N/A	160	127; 10 in progress
	Target	40,000 by 2020 200,000 by 2025 800,000 by 2030 [24]	100 by 2020 1,200 by 2030 [24]		500 by 2020 10,000 by 2030 [24]	160 by 2020 900 by 2030 [24]

Note: *Japan, United States, and China data updated April 2019; Germany in Europe data updated July 2019; **Due to the different definitions of trucks by sources tabulating total number of vehicles, logistic trucks and heavy trucks are included here together; for detailed analysis and breakdown of vehicle types, kindly review to Section 2.



Overview of fuel cell vehicle applications

To most consumers, fuel cell vehicles sound incredibly complex and sophisticated. However, when broken down into pieces, fuel cell vehicles are quite simple. Partially because of this simplicity, fuel cell technology is used in a wide variety of vehicle types.

This section provides context for different types of vehicles and potential fuel cell applications. This sets the stage and provides a logical entrance for deeper analysis into certain vehicle types.

First, let us introduce basic components of fuel cell vehicles and explain their simple operation principles. We shall also compare and contrast component differences between fuel cell, battery-electric, and ICE vehicles.

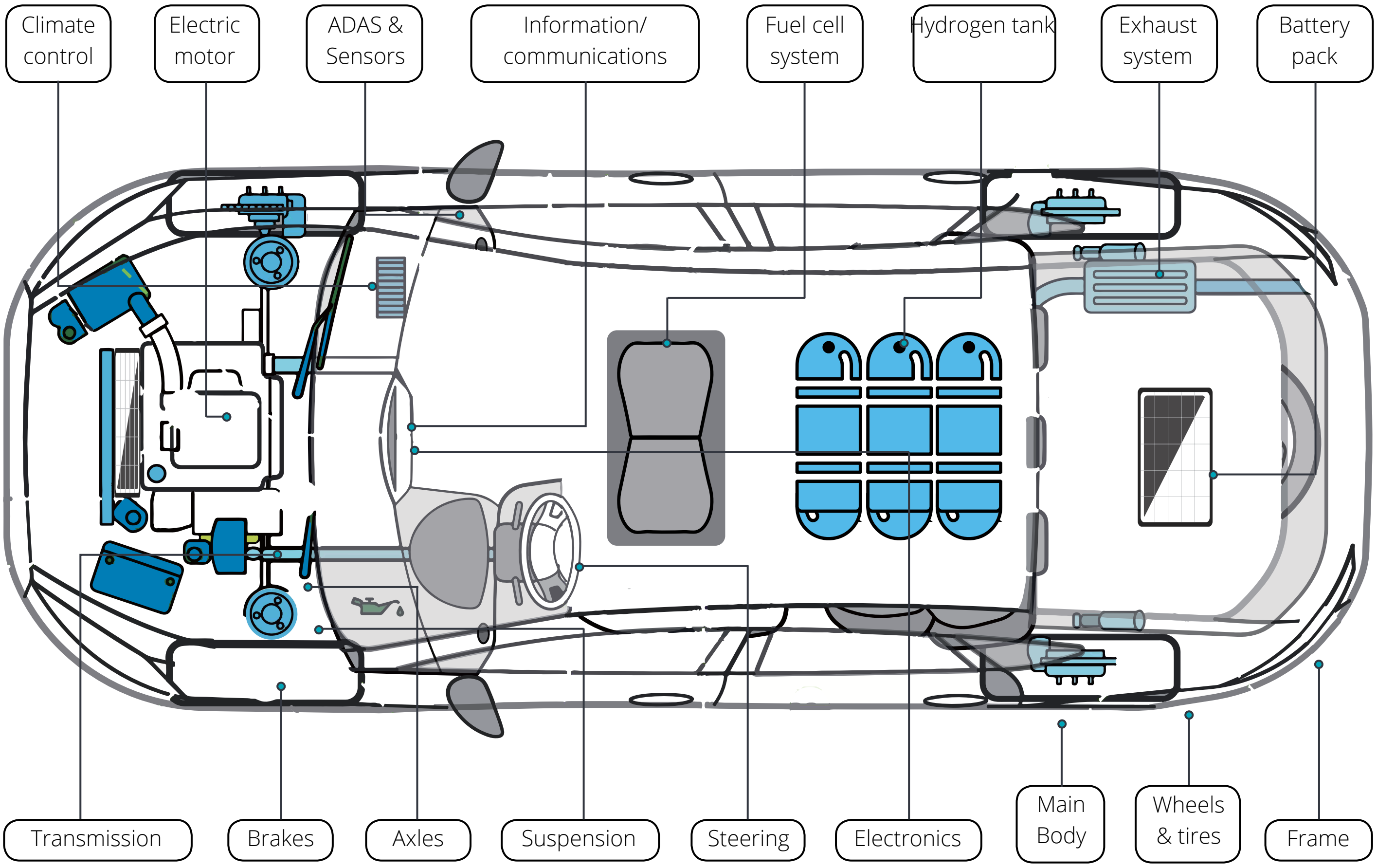
2.1 : Basic components of fuel cell vehicles

As shown in Figure 11, similar to the majority of modern day vehicles, fuel cell vehicles are comprised of four basic component categories: propulsion system, chassis, automotive electronics and body [90 96 97]. The propulsion system provides electricity to power the car through a fuel system and electric motor. This power is derived from hydrogen, which is stored in pressurized tanks in the vehicle [91]. A fuel cell stack converts this energy to electricity, which is supplemented by a battery to drive the electric motor. This is not dissimilar to BEVs, although FCEVs have batteries with much smaller battery capacity. Whereas BEV batteries are used to store the entirety of the power used to move the car, FCEVs only use batteries to smooth fuel cell power fluctuation: absorb extra electricity when power requirement is low and release more power when required [92].

Theoretically, BEVs have higher energy efficiencies, as we shall discuss in section 4, but the heavy battery weight minimizes this advantage especially for heavy duty vehicles in long distance transit. BEVs must add more battery capacity for every additional mile the vehicle should operate, which adds extra weight [94]. For example, Tesla's electric heavy truck model is estimated to reach 4.5 tons of battery weight [95]. FCEVs, on the other hand, does not suffer from the same problem, since the amount of hydrogen carried adds in comparison much less weight to the vehicle. This is due to hydrogen having much higher specific energy - about 120MJ/kg compared to 5MJ/kg for batteries [94].

Aside from the propulsion system, other components of a vehicle are essentially identical and fuel-type agnostic. The vehicle chassis includes transmission, steering, brake and running systems. Automotive electronics are compromised of electronic control system such as chassis control system, safety system and vehicle electronics products such as infotainment/communications, Advanced Driver Assist System ("ADAS") & sensors. Finally, body contains main body, seats and interior [93].

Figure 11 FCEV Components



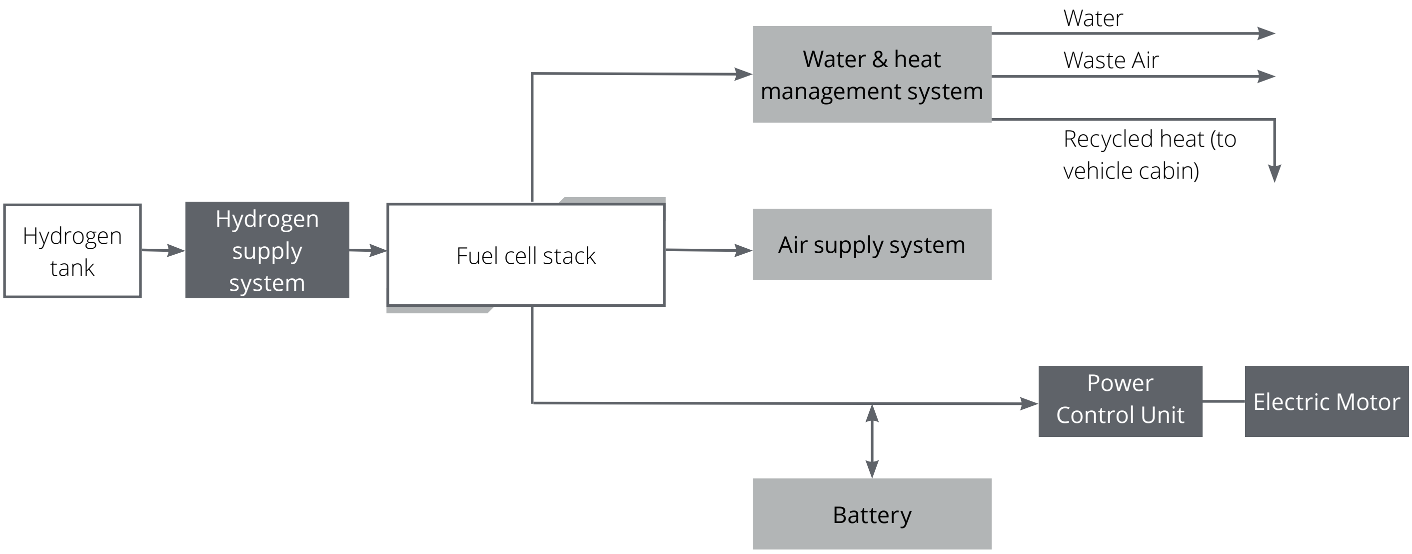
Category	Sub-category	Component
Propulsion system	Energy storage	Hydrogen tank
	Fuel system	Fuel-cell system, Battery pack
	Drive train	Electric motor
	Exhaust system	Exhaust system
Chassis	Transmission	Transmission
	Steering	Steering
	Brake	Brake
	Running system	Wheels & tires, Frame, Suspension, Axles
Automotive Electronics	Electronics control system	Electronics
	Vehicle electronics products	Infotainment/communications, ADAS & Sensors, Climate Control
Body	Body	Main body, Seats, Interior

In a hydrogen fuel cell vehicle, the fuel cell system is comprised of a fuel cell stack and assistant systems. As seen below in Figure 12, the fuel cell stack is the core component [98], which converts chemical energy to electrical energy to power the car. The detailed principles of a fuel stack has been illustrated in Section 1 and will therefore not be repeated here.

Besides the fuel stack, there are four assistant system in fuel cell: hydrogen supply system, air supply system, water management system and heat management system [99]. The hydrogen supply system transits hydrogen from tank to the stack. An air supply system, which is comprised of an air filter, air compressor and humidifiers, provides oxygen to the stack [99]. Water and heat management systems with separate water and coolant loops [99] are used to eliminate waste heat and reaction products (water) [100]. Through heat management system, heat from fuel cell could be harvested to heat vehicle cabin and improve vehicle efficiency [94 101].

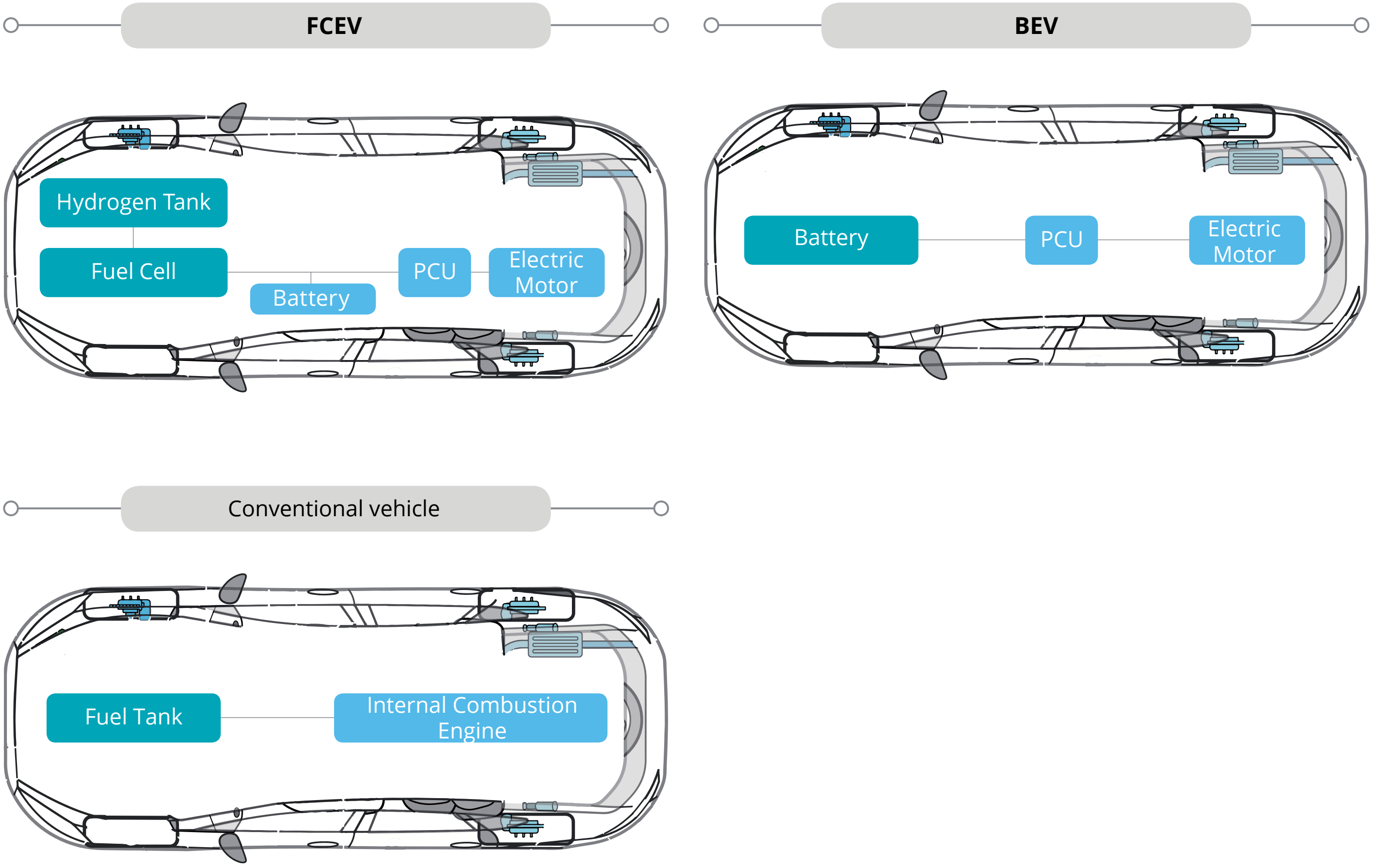
The electricity produced by the fuel cell system goes through a power control unit ("PCU") to the electric motor, with assistance from a battery to provide additional power when needed[99].

Figure 12. Fuel cell vehicle operation principle



Note: *For purposes of this paper, fuel cell system consists of the fuel cell stack, balance of plant, electronic controls for fuel cell, etc. but does not include the hydrogen tank etc.

Figure 13. Propulsion systems of FCEVs and other powertrains



As shown in Figure 13, The main difference between FCEV and other vehicles is the propulsion system. All other components are essentially similar, and are therefore not highlighted here.

FCEV and BEV transfer electric energy to kinetic energy through an electric motor, while Gasoline and Diesel vehicles ("G/D") transfer thermal energy of fuel burning to kinetic energy in an internal combustion engine [102].

The main difference between FCEV and BEV is the source of electricity. Unlike FCEVs, BEVs utilize all its energy from a battery pack which is recharged externally at charging stations [91].

2.2: FCEV, BEV and ICE applications in different vehicle types

As alluded to earlier, FCEVs have a wide range of vehicle application types due to its simplicity and flexibility. FCEVs and BEVs are both alternative solutions to replace conventional gasoline and diesel vehicles to promote zero-emission and sustainable transportation systems [103]. As shown in Figure 14, many countries have introduced policies to ban internal combustion engine vehicles [106]. Using clean vehicles such as FCEVs and BEVs is an undeniable trend for the future.

Compared to FCEVs, the development and adoption of BEVs are more mature in most applications, but suffer from limitations due to battery weight and range issues [104 105]. As shown in Figure 15, BEVs real world ranges typically have a large discount compared with its official range in lab conditions. Battery performance is also easily affected by external environment. As shown in Figure 16, low temperatures have large effects on driving ranges [106].

Additionally, fuel cell vehicles offer a refueling experience similar to a conventional IC vehicle - there is no need for battery charging infrastructure, which can be difficult to implement at multi-unit dwellings (apartment buildings) and along highways [94]. The full commercialization of the BEV and its charging infrastructure will lead to an impact on the grid system. As predicted by the UK National Grid, the power demand of BEVs will be around 45 TWh in 2050, representing around 10% of the power demand of the whole country [106].

Figure 14. Planned ban on pure internal combustion engine vehicles [106]

Country	Year to Ban Pure ICEVs
UK	2040
France	2040
Germany	2040 (tentative)
Spain	2040
Netherland	2025
Canada	2040
India	2030

Figure 15. BEVs range [106] [334]

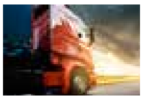
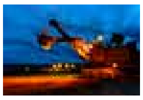
Model	Official range (km)	Real world range (km)
NISSAN Leaf 30kwh	270	199
Volkswagen e-Golf	299	232
BMW i3 120Ah	358	257
Renault Zoe Z.E. 40	402	299
Tesla Model S 75D	489	391
BYD Qin EV450	480	400

Figure 16. Temperature affects battery performance* [106]

Temperature (oC)	Distance range (km)
-15	207
-5	225
5	272
15	283**

Note: *taking Renault Zoe Z.E. 40 for experiment
**Real world range baseline

Figure 17. Summary of FCEV, BEV and ICE application status in each vehicle type

	Example Model	Features [107] [108] [109]	FCEV [108]	BEV[1]	ICE
Passenger vehicles		Designed to carry people, usually less than 7 seats	Commercially available	Accepted	Incumbent
Commercial Vehicle					
Bus		Used for urban public transportation with 30-50 seats	Commercially available	Accepted	Incumbent
Van/Light-duty vehicles		Used in inner-city logistics with Gross Vehicle Weight ("GVW") less than 4.5 metric tons (payload <3 tons, corresponding to US Classes 1 and 2)	Demonstration	Accepted	Incumbent
Medium-duty trucks		Used in inner and inter-city logistics, with GVW of 4.5-12 metric tons (payload 3-8 tons, corresponding to US Classes 3-6)	Demonstration	Demonstration[338]	Incumbent
Heavy-duty trucks		Used in long-haul transportation with GVW larger than 12 metric tons (payload >8 tons, corresponding to US Classes 7-8)	Prototype	Demonstration[339]	Incumbent
Special-use vehicles					
Forklift		An industrial truck used to lift and move materials over short distances	Commercially available	Incumbent (Indoor Warehouse)	Incumbent (Outdoor Warehouse)
Mining truck		Off-road dump trucks designed for mining operations	Prototype	Prototype	Incumbent

Application status:

- **Prototype:** no product is launched, companies are in the product development phase
- **Demonstration:** prototype or product is tested or demonstrated on a small scale
- **Commercially available:** product is launched and sold publicly. And it is proved to be commercially viable
- **Accepted:** Products are generally accepted by end customers
- **Incumbent:** Products are used in most scenarios

FCEVs have been in various stages of prototyping and production since the early 2000s. Since then, with years of efforts made by governments and industry players, almost all vehicle types have fuel cell products or prototypes, as shown below in Figure 17. For passenger vehicles, FCEVs are commercially available but have low adoption due to limited refueling infrastructure as well as high acquisition cost [110]. In the commercial vehicle sector, forklifts, buses, light and medium-sized trucks have been on the forefront of fuel cell commercial vehicle applications [111].

Notes: 1. Due to limitations on payload and range, BEVs are not "full service" vehicles yet

Figure 18. Summary of fuel cell passenger vehicle application status

	China	Japan	Europe	US
Typical products available	• SAIC launched a plug-in hybrid FC version of Roewe 950 in 2016 • Grove, a Chinese fuel-cell vehicle brand, launched China's first fuel-cell passenger vehicle in 2019	• Toyota Mirai • Honda Clarity (leased only)	• Toyota Mirai • Honda Clarity (leased only) • Hyundai Tucson • Hyundai Nexo	• Toyota Mirai • Honda Clarity (leased only) • Hyundai Tucson • Hyundai Nexo
Application status	• In 2018, no sales of fuel-cell passenger vehicles were achieved in China [114] • 50 plug-in hybrid fuel cell version of Roewe 950 were used in a demonstration operation of UN project and car-sharing services in Shanghai [119]	• 575 and 766 Toyota Mirai were sold in Japan in 2017 and 2018 respectively [114]	• 132 and 160 Toyota Mirai were sold in Europe in 2017 and 2018 [113] • Clever Shuttle and BeeZero are car sharing companies operating with 20 and 50 FCEVs [116]	• 1700 and 1838 Toyota Mirai was sold in 2017 and 2018 respectively[113]
Level of application	🚗	🚗 🚗 🚗	🚗 🚗	🚗 🚗 🚗

Level of application:

Indicated by no. of annual newly registered FC passenger vehicle, estimated via sales [113] of typical models, e.g. Mirai and Nexo

🚗 <100
🚗 🚗 100-500
🚗 🚗 🚗 >500

Fuel cell passenger vehicles (Figure 18)

The first commercially assembly-line produced hydrogen fuel cell passenger vehicle can be traced back to the Toyota Mirai in 2014 [117]. However, adoption has been limited to hundreds or low thousands of units per year in US, Europe, and Japan [113].

Fuel cell passenger vehicles offer a zero-emission solution with similar usability compared to conventional vehicles. Typical fuel-cell passenger vehicle only needs 3-5 min to refuel and can travel 250-350 miles on a single tank, which is comparable to ICE vehicles [112].

Early adopters are mainly leasing companies, fleet operators [115], government agencies and corporate customers, with few individual customers, limited mainly by a lack of widespread hydrogen infrastructure. As infrastructure increases, however, it is expected that private consumption will increase in the future [118].

Figure 19. Summary of fuel cell electric bus ("FCEB") application status

	China	Japan	Europe	US
Application status and cases	• In 2003, 3 Mercedes-Benz hydrogen fuel cell buses were first tested in Beijing[124] • In 2017, the first commercially operated fuel cell bus line in China was put into operation in Foshan Yunfu by Feichi Bus [125]. • As of 2018, there are over 200 FCEBs operating in cities including Shanghai, Foshan, Zhangjiakou and Chengdu [120]	• In 2018, Toyota launched its first FCEB, Sora, and is expected to introduce over 100 buses within the Tokyo metropolitan area, ahead of the Olympic and Paralympic Games Tokyo 2020 [123]	• The CHIC* project, regarded as the first step of FCEBs application, deployed 60 buses in 8 countries during 2010-2016 [86, 73] • The JIVE** project(Phase1) starting from 2017, will deploy 139 FCEBs in 5 countries with tech support from Ballard and other partners, of which 56 are in UK and 51 are in Germany [73] • Combing phase 2, JIVE will deploy nearly 300 FCEBs in Europe by the early 2020s [73]	• As of April 2019, there were 35 FCEBs were in active demonstrations in US [42], funded by NFCBP***, TIGGER**** and other government programs, in order to identify improvement to optimize reliability and durability of FCEBs
Major OEMs	• Foton AUV • Yutong • Yong Man • Zhongtong	• TOYOTA	• Van Hool • Solaris • Wrightbus	• New Flyer • ENC Group
Level of application	🚌 🚌 🚌	🚌	🚌 🚌 🚌	🚌

Level of application:

Indicated by estimated no. FCEB in operation. [120, 121, 42]

🚌 <50

🚌 🚌 50-200

🚌 🚌 🚌 >200

Fuel cell electric buses (Figure 19)
Currently, FCEBs are one of the most widely adopted fuel cell applications. This is due to most of them being publically operated, as well as predictable operation patterns [109]. Buses typically feature regular, predictable routes, which requires few refueling stations. Additionally, bus operators are significantly influenced by actions taken by public authorities, making it a proper choice for early application of fuel cell technology. Moreover, FCEB acts as a highly-visible, green-society initiative of public transportation. [121, 122]

However, challenges remain for widespread adoption of FCEBs. Firstly, the price of hydrogen is still expensive if compared to fossil fuels [121]. Secondly, although fuel cell system are generally reliable, technical problems may arise due to the technology being relatively new compared to ICEs, which may cause inefficiencies for operators; the same may apply to maintenance and parts replenishment, although these issues are forecasted to be alleviated as adoption matures [121].

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*CHIC: The Clean Hydrogen in European Cities project; **JIVE:Joint Initiative for hydrogen Vehicles across Europe; ***NFCBP: National Fuel Cell Bus Program; ****TIGGER: Transit Investments for Greenhouse Gas and Energy Reduction

Figure 20. Summary of fuel cell light and medium-duty truck application status

	China	Japan	Europe	US
Application status and cases	• STNE, the largest fuel cell vehicle operator in China, now operates ~500 FCEVs to serve logistics and e-commerce companies like JD and STO Express in Shanghai [126] • 500 fuel cell trucks with 3.5 ton payload and a range ~330 km were deployed in Shanghai in 2018. The truck was produced by Dongfeng with Ballard fuel cell stack technology. Shanghai Sinotran operates the fleet for intra-city deliveries. [136] Another 600 fuel cell trucks were announced to be deployed on April 2019. [140]	• In 2017, Toyota and 7-Eleven convenience stores reached an agreement to test and deploy fuel cell mid-size delivery trucks starting from 2019 [137].	• DHL is expected to deploy 100 "H2 Panel Vans" in Germany in 2020; the van is a 4.25-ton commercial fuel cell vehicles with a range of up to 500 km, manufactured by truck maker StreetScooter [127] • H2ME* is the major efforts to support the application of FC vehicle in EU that ~900 of Renault Kangoo FC vans will be deployed by 2021 and 170 have been deployed [88] for fleet and business operation	• Fuel Cell Hybrid Electric Delivery Van Project is a demonstration project led by DOE to increase commercial viability of electric drive medium-duty trucks. Currently 17 fuel-cell vans are in collaboration with UPS [128] • FedEx started to test 20 fuel cell extended-range battery electric delivery van in California and Tennessee in 2014 [138] and launched another test project with Workhorse and Plug Power for fuel cell delivery van in 2018 [139]
Major OEMs	• Saic Maxus • Feichi Bus • Dongfeng Trucks • Zhongtong Bus • Foton • Aoxin	• Toyota	• Renault • StreetScooter • Mercedes-Benz	• Workhorse • UPS • FEDEX
Level of application	🚚 🚚 🚚	🚚	🚚 🚚	🚚

Level of application:

Indicated by estimated no. fuel cell light and medium-duty truck in operation

🚚 <100 🚚 🚚 100-500 🚚 🚚 🚚 >500

Fuel cell light and medium-duty trucks (Figure 20)

There are a variety of activities surrounding deployment of fuel cell light and medium-duty trucks among major markets studied, which offers an interesting comparison to buses, as most of these deployments are privately operated (albeit with government support) [130].

Fuel cell technology is regarded as a strong contender for inner and inter-city logistics for several reasons. From a technology standpoint, fuel cell trucks typically exceed 150 km in range, enabling them to accomplish most of the inner- and inter-city deliveries of goods [131]. Secondly, fuel cell trucks can meet stricter environmental requirement and noise regulations in urban areas, which encourages the government and fleet operators to accelerate its adoption [132]. Thirdly, compared with BEVs, FCEV have very short refueling times, which greatly improves the operational efficiency of a logistics fleet [133].

Freight transport accounts for large portion of total traffic flow in urban areas (e.g., 8-15% [129] in Europe), making fuel cell technology a promising way to reduce emissions. It is expected that in the near future, the application of fuel cell light and medium truck in inner- and inter-city logistics will continue to grow, especially in China where development of commercial infrastructure is proceeding at a rapid pace [134] [135].

*H2ME: Hydrogen Mobility Europe

Figure 21. Summary of fuel cell heavy duty truck application status

	China	Japan	Europe	US
Products available and in pipeline	• In 2017, Sinotruk announced the first heavy-duty truck in China, a fuel cell port tractor[141] • Foton Motor Group is developing a prototype of a fuel cell heavy duty truck[145]	• Toyota launched a Class 8 drayage truck in 2017[151] • No public deployment is observed	• ESORO launched world's first FC truck in the 34t category in 2017 [153]. • The H2-Share* project, starting from 2017 to 2020, will build and test a 27 ton rigid truck developed by VDL in Europe [149]; • In 2018, Hyundai announced plans to provide 1,000 FC heavy trucks to H2 Energy, a Swiss company, from 2019 to 2023[150].	• Fast Track Fuel Cell Truck project and Port of Los Angeles Shore-to-Store project were two representative projects in US to promote the application of fuel cell heavy duty truck, deploying 10 and 5 units respectively [144]. • Nikola Motor, a startup truck company in US, is planning to launch a Hydrogen fuel semi truck, Nikola Tre, which is expected to entry mass production in 2023. Anheuser-Busch has ordered 800 units[142].
Major OEMs	• SINOTRUK • Foton	• TOYOTA	• E-Truck • ESORO • VDL • Hyundai	• KENWORTH • Nikola • TOYOTA
Level of application	⚫	⚫	🔵	🔵

Level of application:

Indicated by stages of fuel cell heavy duty truck application

⚫ Prototype

🔵 Demonstration

Fuel cell heavy duty truck (Figure 21)

Considering the high pollution and greenhouse gas emissions[154], heavy-duty trucks are regarded as a promising segment to develop zero-emission vehicles. The development of fuel cell heavy duty trucks are relatively lagging behind other applications. Most major OEMs are in the R&D stage, and only limited products are launched or being tested [152].

The relatively slow development of fuel cell heavy duty truck can be attributed to a combination of high vehicle cost, high hydrogen cost (to carry heavy loads over long distances) and limited refueling infrastructure [146] [148].

On the positive side, fuel cell heavy duty truck could offer faster refueling times compared with battery electric trucks, which is essential for fleets to reduce the downtime in their daily operations. FC heavy duty trucks are also able to travel longer distances than battery electric trucks with similar specifications [148]. Fuel cell technology is becoming increasingly mature and optimized for heavy duty applications. Ultimately, fuel cell heavy duty truck could provide range and refueling time closed to conventional vehicles, while also benefiting from zero-emissions [147]. This provides fuel cell heavy duty vehicle a great potential to displace diesel and battery electric heavy duty truck in the long term.

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*H2-Share:Hydrogen Solutions for Heavy-duty transport Aimed at Reduction of Emissions in North West Europe

Figure 22. Summary of fuel-cell forklift application status

	China	Japan	Europe	US
Application cases	• The Foshan government in the Guangdong province plans to introduce 5,000 FC forklifts by 2025, although this is still at an early planning stage[155]; • Weichai has established a JV with Ballard Power Systems to develop fuel cells being utilized in forklift applications [160].	• In 2018, Toyota adopted 20 FC forklift trucks in its Motomachi factory, where it is also constructing a hydrogenation station[156].	• Viessmann, a leading manufacturers of heating systems, announced that it had adopted a hydrogen forklift truck to undertake every day warehouse operations in 2013[157]; • Carrefour in Vendin-Le-Vieil, France, has purchased 137 forklifts from Still to operate in Carrefour's logistics base [159].	• In 2014, Walmart began to cooperate with Plug Power to invest in forklifts. From 2014 to 2018, FC forklifts in Walmart warehouses has increased from 1,700 to 8,000 [50]; • In April 2017, Amazon announced partnership with Plug Power planning to deploy fuel cell forklift in its 11 warehouses [50].
Major OEMs	• N/A	• TOYOTA	• STILL • Linde	• Hyster • Linde
Application status	●	● ●	● ●	● ● ●

Level of application:

Indicated by estimated no. fuel cell forklifts in operation[42].

● <100 ● ● 100-1000 ● ● ● >1000

Fuel cell forklifts (Figure 22)

Forklifts are a frontier application of fuel cell technology. Firstly, forklifts have advantages over other vehicles types in terms of lower technology requirement and infrastructures. The required maximum output power of forklift is only one tenth of passenger vehicles [50]. In addition, since forklifts primarily operate in small areas such as warehouses, only limited hydrogen refueling stations are required. Thirdly, FC forklifts have advantages over other types of forklift. Traditional electric batteries' voltage drops as they discharge, slowing forklifts over time and causing a productivity decline in the process. Electric forklifts' speed drops an average 14% in the second half of an eight-hour shift [158], while fuel-cell forklifts can achieve a steady "pick rate". Finally, since FC vehicles have no polluting emissions, forklifts are suitable in enclosed warehouses for industry applications such as food and beverage [50].

FC forklifts are in a commercial stage, especially in the US, where FC forklift ownership is over 25,000[42]. In China, usage of FC forklifts is relatively limited now, but a variety of companies have begun to conduct related development of such vehicles, which has been supported by regulations from district governments [161 162].

Fuel cell application status in mining trucks

Mining companies facing significant decarbonization challenges are gradually gaining awareness of fuel cell mining trucks as an alternative zero-emission solution. Compared to conventional diesel unit and battery electric vehicle, fuel cell mining equipment have advantages in the following aspects:

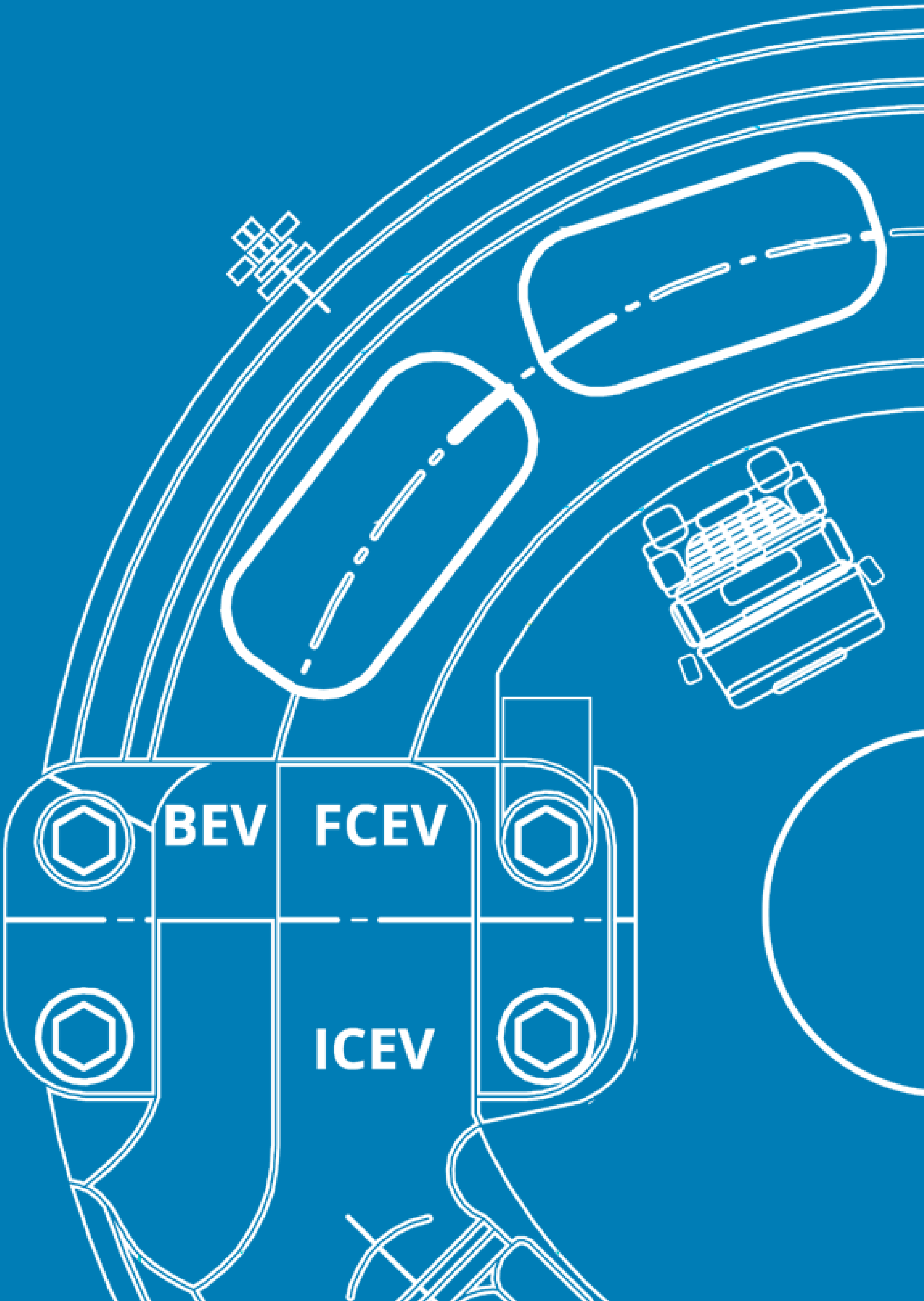
- Theoretically, it could achieve the same mobility, power and safety performance as a diesel vehicle; while it enjoys the same environmental cleanliness as a battery vehicle and can be charged in shorter time for longer distances [163]
- As opposed to diesel units, fuel cell mining equipment can avoid producing harmful emissions for miners in an underground environment [109]

However, there are limited FC mining truck products available in the market now and no wide-spread demonstration deployment, indicating the development of FC mining truck is still in an early stage. Several companies are working on the development of FC mining truck. For example, in China, Weichai Group reached a cooperation with several industry partners to develop 200 ton FC mining trucks in 2018 [164]. In US, Anglo American is also working on new mining technologies including FC mining truck [165]. Further technical research and government support are required to develop the application of FC mining truck [109].

2.3 Conclusion

As seen in this section, FCEVs have a wide range of vehicle application types due to its simplicity and flexibility. We have highlighted a variety of vehicle types – from passenger cars to forklifts – in this section, and have shown how each vehicle type is gaining adoption in various markets around the globe.

So how are fuel cell vehicles actually being used by public and private companies? What are the actual and total costs associated with running such operations? How will this change in the future as technology continue to mature? Let us explore these pertinent questions in the next section.


BEV
FCEV
ICEV

Total cost of ownership analysis

3.1: High level TCO framework - introduction

No discussion of new and emerging technologies can be complete without deep analysis of its commercial viability. To compare and contrast the economic efficiency of fuel cell vehicles, we built a Total-Cost-of-Ownership model that examines FCEVs in detail, in relation to BEVs and ICE vehicles. We took a highly-granular bottom-up approach of building a vehicle by analyzing the cost of each of its components, down to minute detailed components as showcased in Section 2.1. Furthermore, we analyzed operational considerations and costs, such as fuel, maintenance, infrastructure, etc. This framework is illustrated in Figure 23 below.

This TCO analysis is from the perspective of the operator. The operator may not care about detailed component prices, but rather a retail cost of the entire vehicle. However, this would present a rather limited view of the whole picture. The reason for such a deep level TCO analysis is to understand exactly what components are driving current and future costs, both from a vehicle-build and operational perspective. Once this is understood, we can then apply nuances of different operators and business models, such as a logistics fleet operator (case study 1), drayage truck operator (case study 2), and intra-city bus operator (case study 3). But the overall framework on the cost components and future trends would be similar across case studies. To provide a broad yet fair comparison, our TCO framework:

- Presents 3 scenarios, situated in the geographical regions of US, China, and Europe*
- Presents historical (past 3 years) and forward-looking (future 10 years) forecasts
- Does not take into consideration subsidies (whether on vehicle purchase, infrastructure, or fuel) for each region analyzed; however, subsidies are applied for specific case studies in the later sections of this paper
- Assumes a constant gross-margin from an OEM perspective from the components build-costs, including added on a component mark-up due to economies of scale. This assumption is based on in-depth expert interviews with vehicle and component manufacturers. Even though many propulsion-system agnostic components are similar across vehicles (such as chassis, seats, body, etc.), there are minor variations in dimensions, which may require different molds to build, which can lead to differences in price on an individual component level of hundreds-fold. Since a vehicle is made up of thousands of different components, it is extremely hard to determine which components are identical, and which are similar but require tiny modifications, which may also be up to individual OEMs and customer-requirements to decide. However, when rolled up into an overall build cost and compared to retail prices, a surprisingly consistent overall component mark-up due to this economy of scale is observed. This is observed in both FCEVs and BEVs, with an assumption that ICE components are at a "baseline" level due to full economy of scale. We have also assumed that FCEV propulsion-system-agnostic components will reach full economy of scale within the next 10 years.

Note: *since each region is extremely large with inter-country, inter-state(provincial), and inter-city differences, we have tried as much as possible to use average values in each country/region; European values are averaged across Western-Europe; unfortunately, it is the limit of this exercise that we are not able to drill-down to the level of detail of each European country, US state, Chinese province, or city level differences

Figure 23: High level TCO framework

		FCEV	BEV	ICEV
Purchase cost	Gross profits	• Incremental costs to OEM COGS	• Incremental costs to OEM COGS	• Incremental costs to OEM COGS
	Components mark up	• Mark-up on propulsion-agnostic components due to lower economies of scale of FCEV production compared to ICE vehicle	• Mark-up on propulsion-agnostic components due to lower economies of scale of BEV production compared to ICE vehicle	• N/A due to assumed full economies of scale
	Drive train	• Electric motors and other associated components	• Electric motors and other associated components	• Internal combustion engine
	Energy storage	• Hydrogen tanks • Fuel cell system • Battery (around 1/10 size of BEV battery)	• Battery • Battery management system	• Gasoline/diesel tank
	Propulsion-agnostic components	• Cost of other vehicle components including chassis, body, electronics, etc. as detailed in Section 2		
Operation cost	Fuel	• Hydrogen cost multiplied by consumption per 100km	• Electricity cost multiplied by consumption per 100km	• Diesel cost multiplied by consumption per 100km
	Charging station	• Hydrogen fueling station	• Dedicated onsite chargers and related infrastructure	• Assume stations cost has been include in fuel prices
	Maintenance	• Daily vehicle maintenance cost	• Daily vehicle maintenance cost	• Daily vehicle maintenance cost
	Parts replacement	• Fuel cell system replacement • Battery replacement	• Battery replacement	• ICE replacement
	Others	• Insurance and other expenses		

The above figure provides an overview of the TCO model. In this framework, we selected a 12-meter bus as our primary target for contrast, with a fleet size of 100, traveling on average 200km per day. The TCO costs are broken down into purchase cost and operation cost. In purchase cost, gross margin, energy module and other vehicle components are included. An extra component markup for FCEVs and BEVs are considered, as explained earlier. For operation, fuel cost, charging station cost, maintenance cost, parts replacement cost and insurance cost are included.

Charging station costs for hydrogen includes infrastructure costs, which we assumed to be born by the operator (which may or may not be the case in actual scenarios). Similar, we assumed that BEVs require dedicated chargers onsite, as well as station chargers for opportunity charging during operation.

3.1.1: High level TCO framework – results for US

We shall first take a look at TCO results for the US, followed by China and Europe in the later pages.

When taking a current snapshot of TCO costs based on the framework just described, it is unsurprising that FCEVs are more expensive compared to BEVs and ICE vehicles. As shown in our model in Figure 24, the TCO of FCEV is around 243 USD per 100 km, while that of BEV and ICE vehicles are 166 and 125 respectively.

A detained breakdown of 2019 vehicle purchase cost has been illustrated in Figure 25.

As can be garnered from the illustration, the biggest costs differences come from the energy module. Current fuel cell system is still expensive and costs approximately 1,500 USD per kw, which makes up around 73% of energy module cost and around 13% of total fuel cell vehicle cost. Other than the fuel cell system itself, hydrogen tanks also make up around 15% of the energy module costs. When taken together, these two components result in the majority of cost increases over the other two vehicles. However, as with any emerging technology, component costs continue to decrease in price, as we shall see in the later figures.

Figure 24: 2019 US high level TCO for a bus breakdown (unit: USD/per 100km)

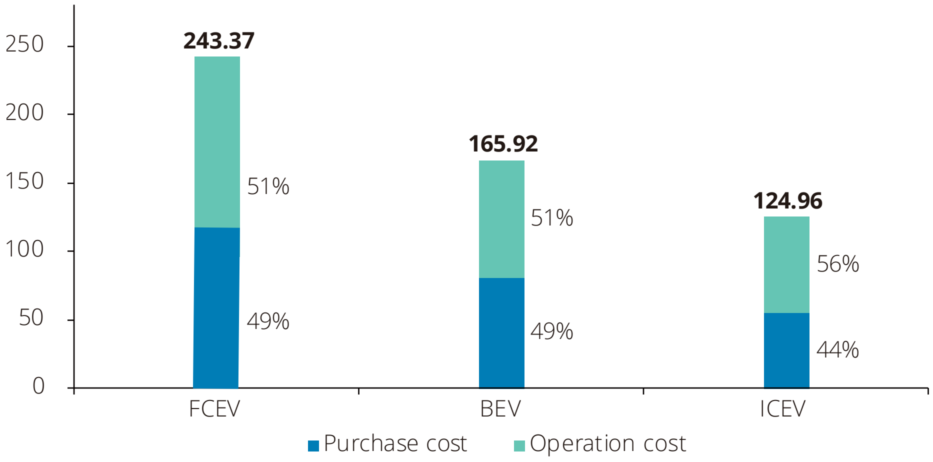
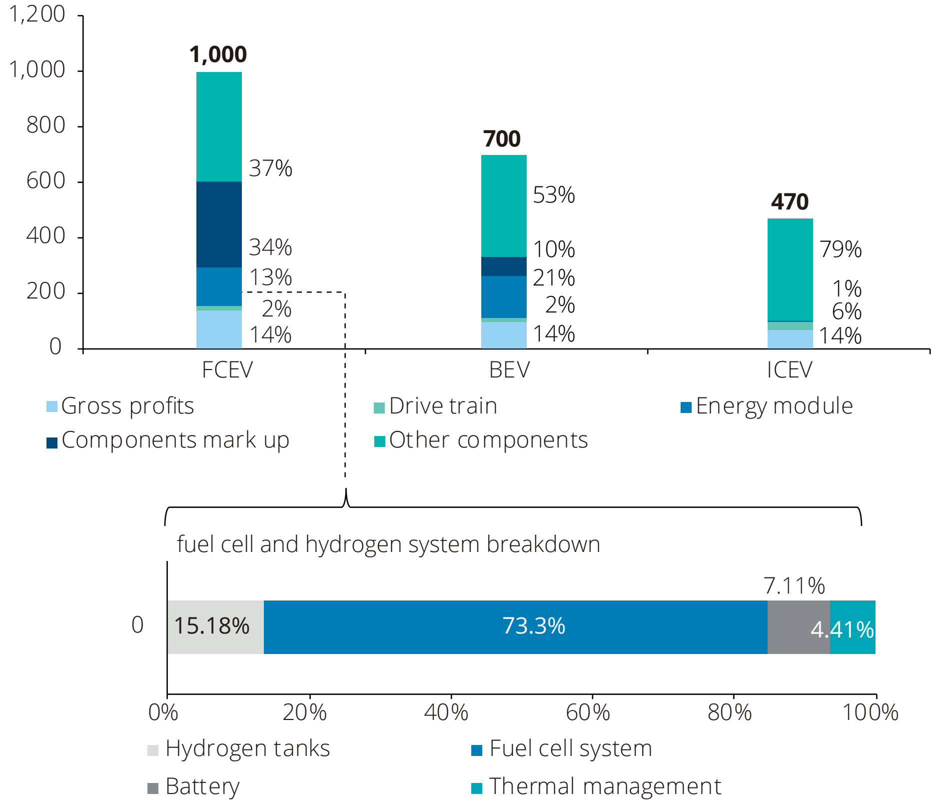


Figure 25: 2019 US purchase price for a bus breakdown (unit: thousands USD/per vehicle)

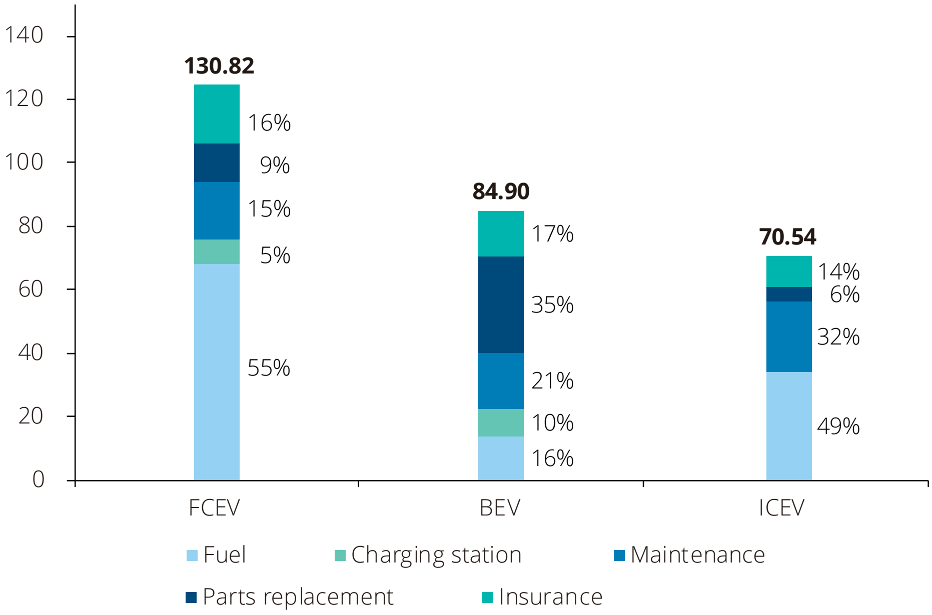


Other than the energy module, the component mark-up costs for FCEVs and BEVs also play significant roles in their overall price. However, as expected, this component cost is lower for BEVs, due to its earlier commercialization and being closer to mass-market status. The industry consensus from our interviewed experts suggest that FCEVs might reach full scales of economy within the next 10 years, which in our model would eliminate this additional component mark-up.

The operational cost breakdown in our theoretical TCO framework is demonstrated in Figure 26.

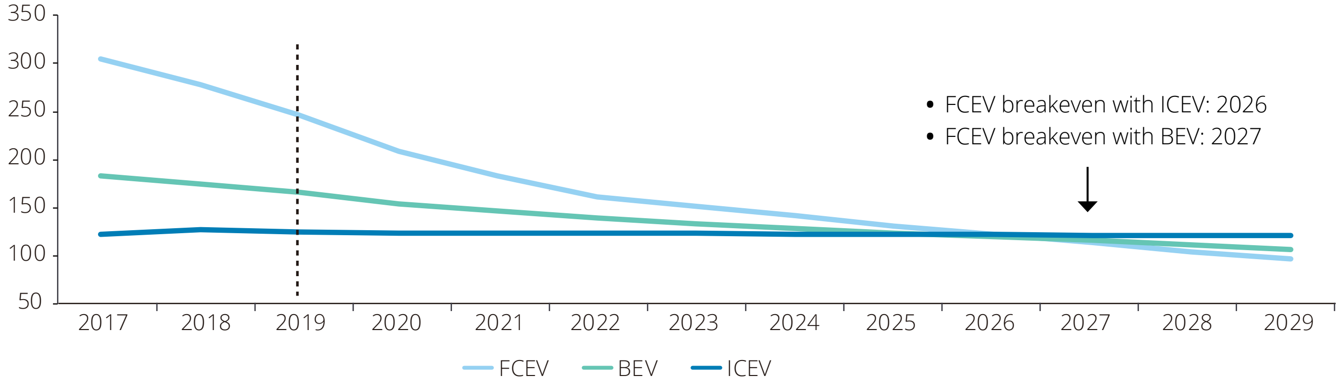
Fuel cost makes up the largest proportion of FCEVs operational costs due to high hydrogen prices, while BEVs have the cheapest fuel cost due to low electricity costs (which, coincidentally, is a major selling point for passenger BEVs). Compared to ICE vehicles, electric vehicles have less maintenance costs due to simpler mechanics of its electric motor. However, fuel cell and battery replacement costs for FCEVs and BEVs add an additional burden to the operator. This is due to capacity attenuation of the fuel cell system (which lasts approximately 25,000 hours currently), as well as for the battery pack (typically replaced every 5 years for commercial vehicles). As expected, these replacement costs are driven down rapidly as technology matures for new energy vehicles, as we shall see later in the future trends comparisons.

Figure 26: 2019 US operational cost for a bus breakdown (unit: USD/ per 100 km)



Another large component of operational cost stems from infrastructure build costs for FCEVs and BEVs. For example, a hydrogen fueling station for such a fleet in our framework costs approximately 6-7 million USD. Similarly, BEV infrastructure requires a large amount of investment; large scale operations even require grid and substation modifications, as well as opportunity charging stations. Infrastructure costs would differ quite dramatically by operating model, but this framework presents an illustrative perspective for the reader to consider. It is also worth noting that infrastructure costs are forecasted to decrease quite rapidly, as we shall soon see.

Figure 27: US TCO for a bus outlook (unit: USD/per 100 km)



- FCEV breakeven with ICEV: 2026
- FCEV breakeven with BEV: 2027

Figure 27 shows the results of our future projections for the TCO model. As with the base model, we have forecasted the cost of every component (build or operational) for the next 10 years.

For sake of completeness, we have included ICEV forecasts here as well. It is also worthwhile to note that we are quite moderate in terms of accounting for the challenges for ICE commercial vehicles in the future. Since our model is built on a component bottom-up approach, we have forecasted ICE operational costs to be relatively stable over the next 10 years. However, this may not be the case as jurisdictions across the world continue putting pressure on the use of fossil fuel vehicles. For example, ever-tightening restriction standards on emissions may cause engines and catalytic convertors to spike in costs. Other qualitative restrictions, such as bans from entering city regions, for instance, may have a pronounced impact on operators not currently reflected in this TCO analysis. Various countries have also announced plans to ban pure ICE vehicles by 2030-2050, as we had discussed in section 2.

In this theoretical model, the TCO of FCEVs is forecasted to be less than ICEVs by 2026, and less than that of BEVs around 2027. Overall, we estimate that the TCO of FCEVs will decline by almost 50% in the next 10 years.

Figure 28: US purchase cost for a FC bus outlook (unit: thousand USD)

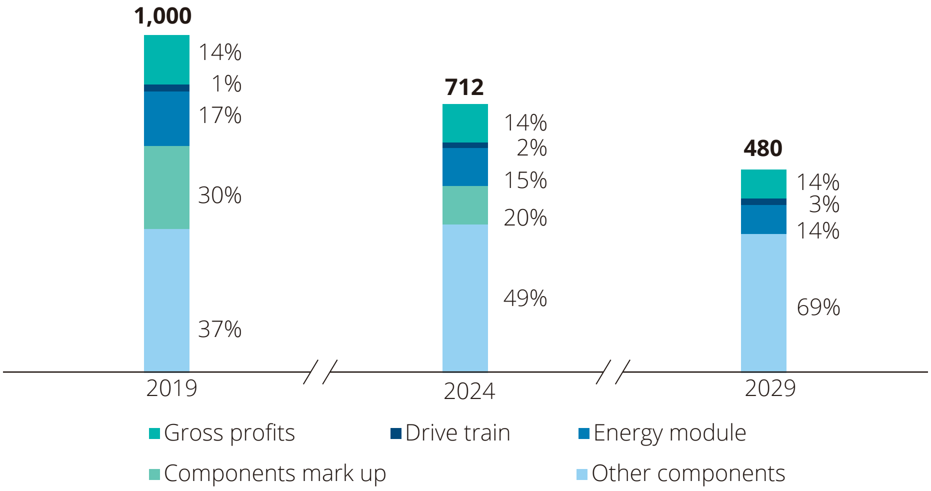
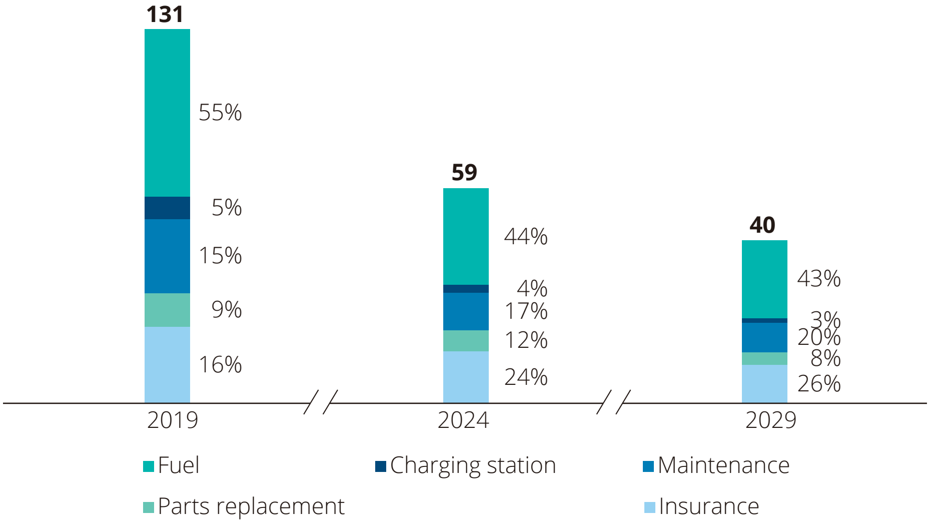


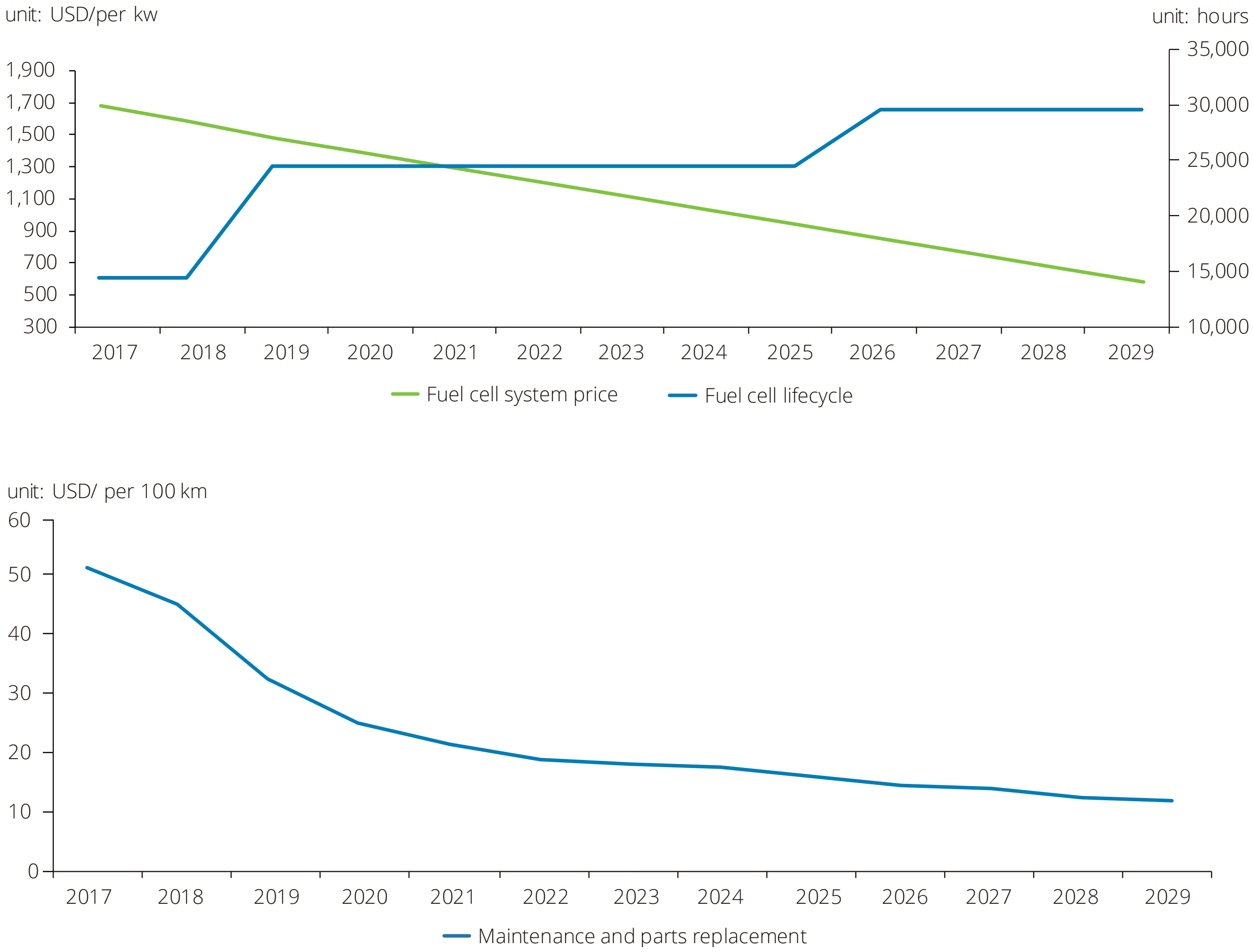
Figure 29: US operation cost for a bus outlook (unit: USD/per 100 km)



This decline is especially apparent in the first 5 years. As we shall see in Figure 28 and Figure 29, this decrease is due to a combination of:

- Decrease of fuel cell system manufacturing and replacement costs
- Decrease in hydrogen costs
- Decrease in infrastructure costs

Figure 30: Prediction of fuel cell system trends and related parts replacement cost for FC buses



Though the declines in TCO costs over the next 10 years are driven by almost every single component, we have highlighted a few notable ones here that plays a large impact on future price declines.

Fuel cell system price is highly related with purchase cost as well as parts replacement cost. From Figure 30, we forecast a continuous decline in fuel cell system pricing from 1,500 USD per kw in 2019 to 600 USD per kw in 2029 [166]. As we shall see in Section 4, the fuel cell system is relatively light in terms of materials cost but high in manufacturing costs, due to high technological requirements. This leaves significant room for cost improvements in the future, together with dramatic improvements in economies of scale.

Furthermore, the lifecycle of fuel cell systems are also expected to improve quite significantly in the future. Currently, the lifecycle of a fuel cell system is approximately 25,000 hours, but is forecasted to reach 30,000 hours by 2026 [166].

With these two factors combined together, FCEVs will be affected not only by decreases in purchase cost, but also maintenance and parts replacement cost. We estimates the total maintenance and parts replacement cost will decline over 60% in the next 10 years.

Figure 31: US hydrogen price (Unit: USD/kg)

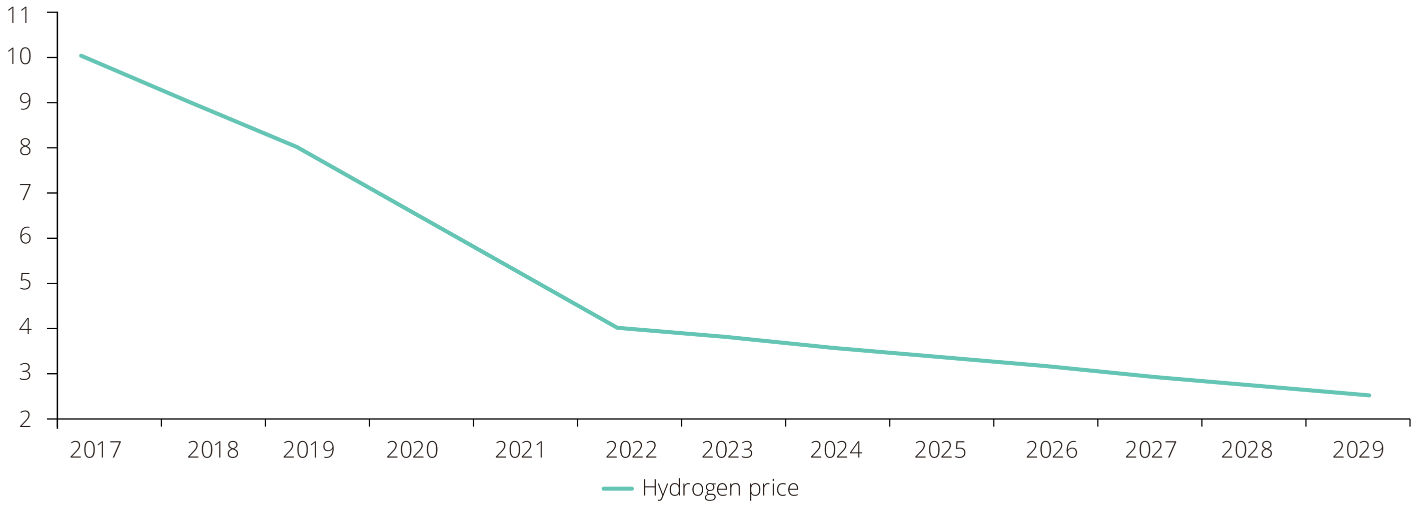
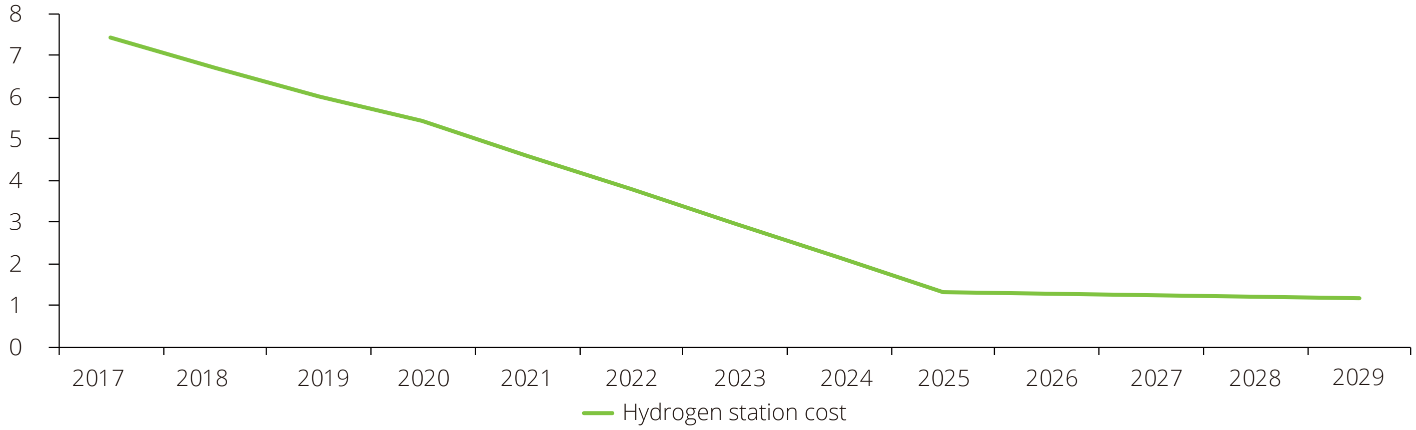


Figure 32: US hydrogen station trend (Unit: USD/per vehicle/per 100km)



Hydrogen fuel costs and infrastructure costs are two other significant components of the TCO model, accounting for over 50% of operational costs in 2019.

At the moment, hydrogen costs are at a significant premium over diesel or gasoline used by conventional ICEV and the electricity used by pure electric buses. One of the reasons for this high cost is due to the extreme low density of hydrogen gas, making it difficult to store and transport. With the development of storage and transportation technology and the economies of scale brought by large-scale applications, the price of hydrogen fuel is expected to drop to below half of the current hydrogen price by 2029 [167] (Figure 31).

Hydrogen infrastructure also poses significant costs for fuel cell buses operation no matter if this cost is born by the operator, third parties, or public agencies. The current average infrastructure cost per bus per 100 km is around 6 USD based on our assessment. With the large-scale application of hydrogen energy and the improvement of scales of economy, the hydrogen infrastructure cost is predicted to drop below 2 USD per bus per 100 km by 2029 (Figure 32).

3.1.2: High level TCO framework – results for China

Applying our framework to China (Figure 33-35), in 2019 the TCO of FCEVs is around 178 USD per 100 km, while the TCO of BEVs and ICE vehicles are 101 USD per 100 km and 74 USD per 100 km respectively. Compared with the U.S. application, buses have a much cheaper purchase prices, due to propulsion-agnostic components being significantly cheaper. This also means that the energy module has an increased proportion in the whole retail price structure. In terms of operation cost, that of FCEVs is around 123 USD per 100 km, which is a little higher that of American fuel cell bus. This is mainly due to a high hydrogen price which is higher than that in the U.S.

The TCO of FCEVs has declined 32% from 2017 to now. We estimate the TCO of FCEVs will keep declining to 55 USD per 100 km by 2029, which is lower than both TCO of BEVs and ICE vehicles. This decline is mainly due to fuel cell system and hydrogen prices decrease. We estimate fuel cell system price will decline over 70% in the next 10 years. The decline of fuel cell system not only causes purchase cost decrease, but also reduce the parts replacement cost which is closely related with fuel cell system price. Meanwhile, with hydrogen station increasing and hydrogen production technology improvement, hydrogen price is forecasted to decline 63% in the next 10 years and the hydrogen station cost will also decrease. These two fuel related cost has made up near 60% of operation cost and around 40% of TCO, so the decline of fuel and fuel station prices will significantly help the decline of FCEVs' TCO.

Overall the TCO of FCEVs is estimated to be lower than ICE vehicles around 2027, which is around one year behind the U.S. situation. Due to a relatively lower purchase cost of BEVs in China , the TCO of BEVs is close to ICE vehicles now. We estimate that the TCO of FCEVs will be lower than that of BEVs around 2028, which is also a little bit slower than in the US forecast.

Figure 33: 2019 purchase price for a bus in China breakdown (unit: thousands USD/per vehicle)

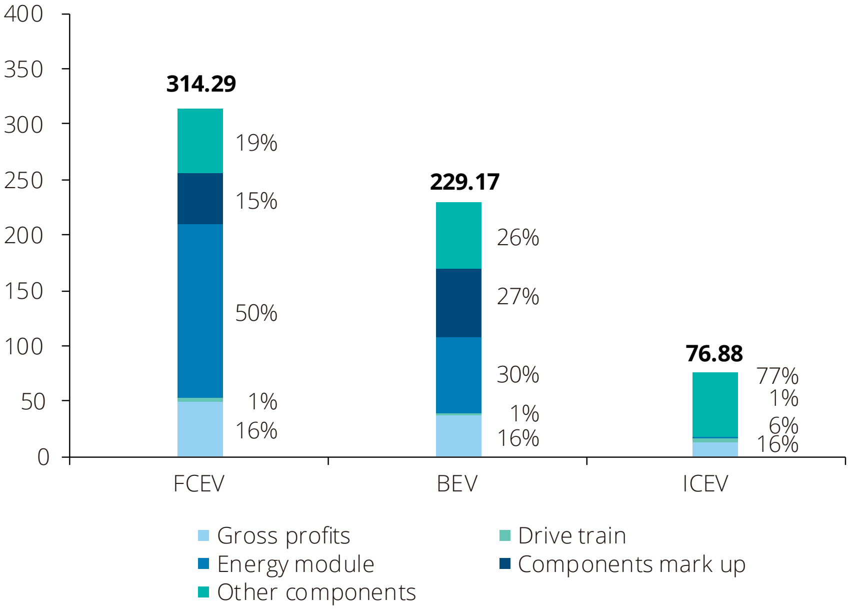


Figure 34: 2019 operation cost for a bus in China breakdown (unit: USD/ per 100 km)

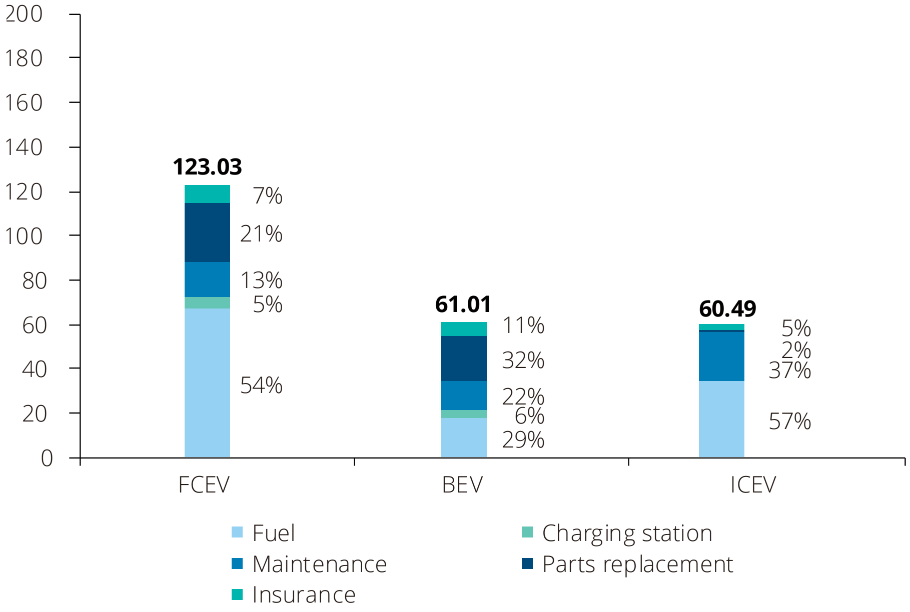
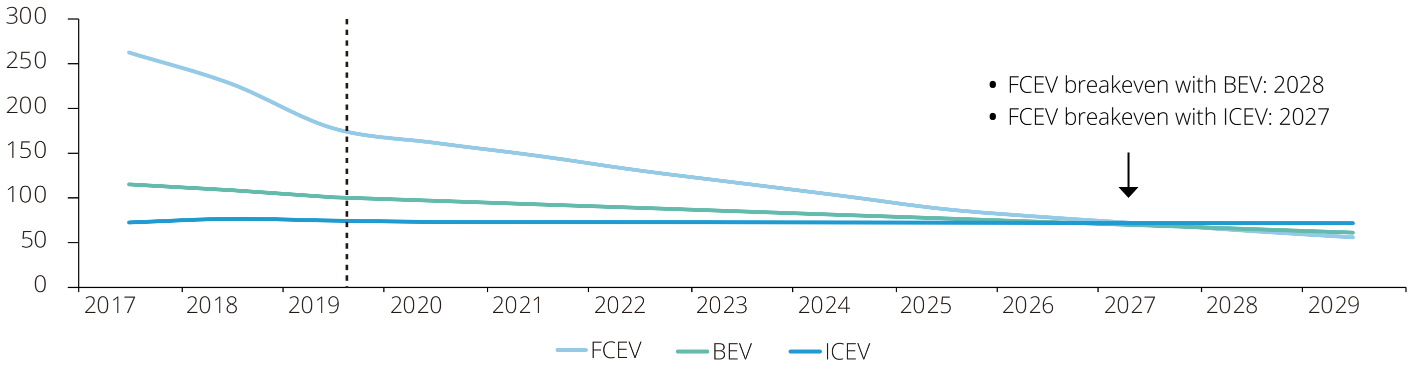


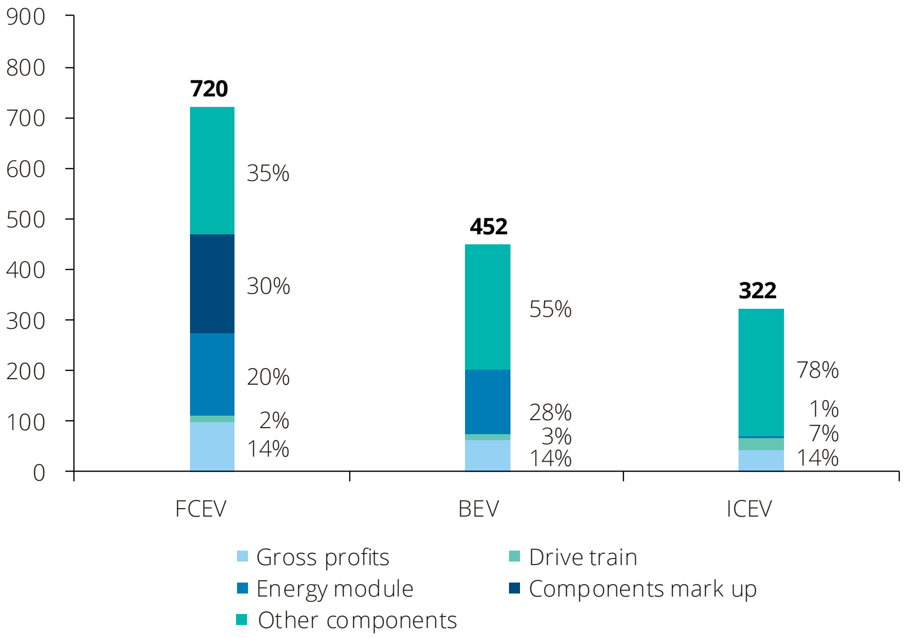
Figure 35: Bus TCO outlook in China (unit: USD/per 100 km)



3.1.3: High level TCO framework – results for Europe

In the Europe application (Figure 36-38), the TCO of FCEVs appears to have a quicker decline than the U.S. application and China applications. In 2019, the TCO of FCEVs is around 190 USD per 100 km, while that of BEVs is around 150 USD per 100 km and that of ICE vehicles is around 124 USD per 100 km. In 2023, the predicted TCO of FCEVs would be lower than that of BEVs and reaching 124 USD per 100 km. In 2024, the predicted TCO of FCEVs would be lower than that of ICE vehicles reaching 116 USD per 100 km.

Figure 36: 2019 purchase price for a bus in Europe breakdown (unit: thousands USD/per vehicle)



The overall cost of the vehicle is cheaper than the U.S. due to shorter OEM warranty periods as well as less manufacturing-location requirements. The fuel cell system price is predicted to decline around 60% in the next 10 years. Besides build costs, hydrogen prices and station costs are also predicted to decline rapidly. Hydrogen prices are predicted to decline around 44% in the next 10 years. As most European countries, such as the U.K., add significant tax rates to diesel[168], the TCO of FCEV and BEV are estimated to be lower than ICEV much sooner than in other regions.

Figure 37: 2019 operation cost for a bus in Europe breakdown (unit: USD/per 100 km)

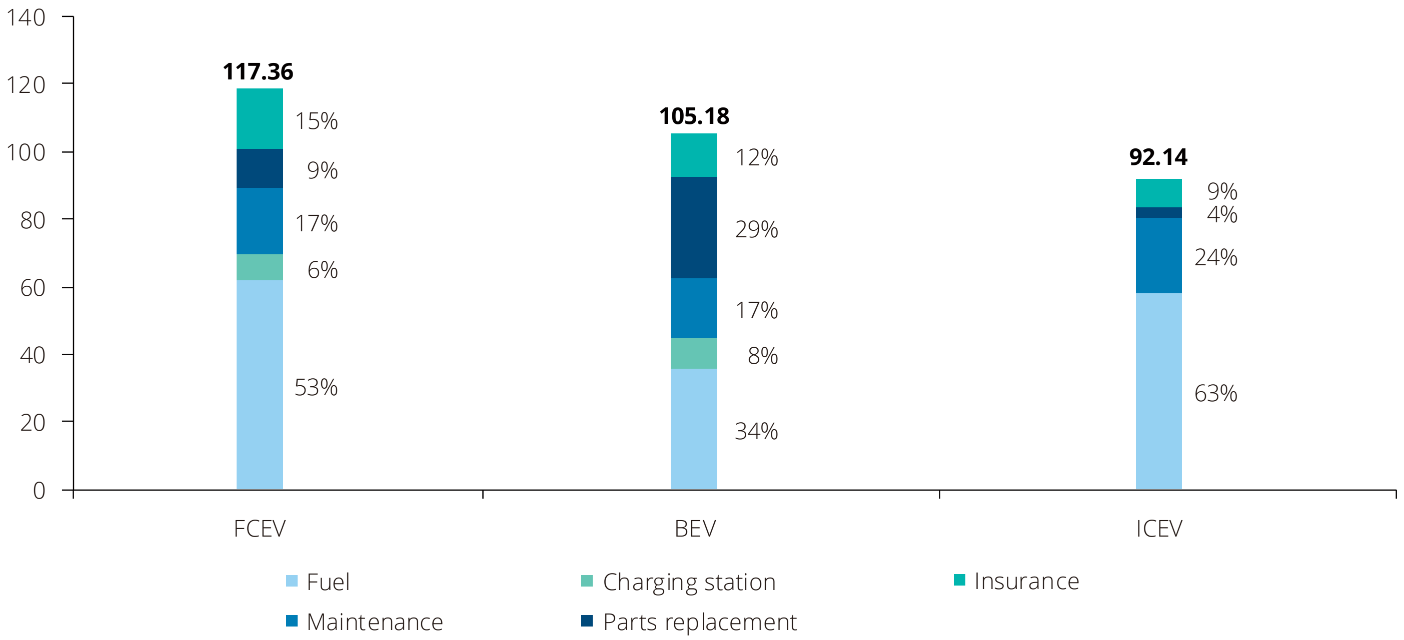
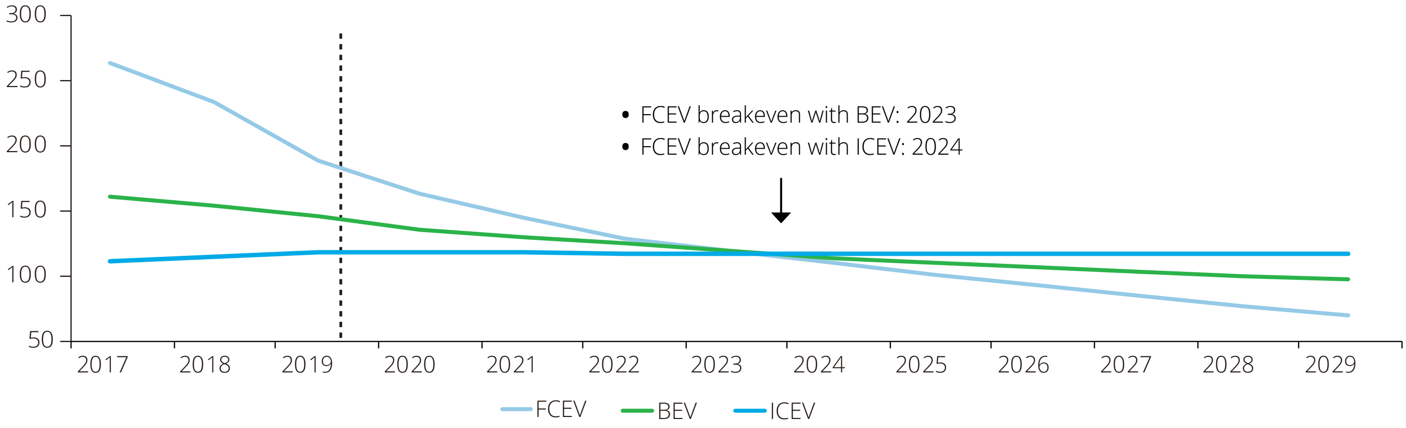


Figure 38: Bus TCO outlook in Europe (unit: USD/per 100 km)



- FCEV breakeven with BEV: 2023
- FCEV breakeven with ICEV: 2024

3.1.4: High level TCO framework —TCO contrast among different regions

Though the general decline trends are similar in the three regions, the different prices of key components in the regions leads to the different TCO models in 2019 and different decline speeds. We have illustrated the 2019 TCO in a previous paragraph, but we would like to put the 2019 FCEVs TCO together in this page to show more clear TCO differences among the three regions (Figure 39-41).

It could be seen that China has the lowest TCO due a relatively low purchase cost with significant manufacturing advantages. As for operation cost, Europe has the lowest operation cost due to relatively low fuel related cost and parts replacement cost (mainly due to fuel cell system). The 3 regions have very similar total operation cost, but the structures are a little bit different. China has higher parts replacement cost, but the relatively cheap station cost and insurance narrow down the operation cost gap with other regions.

Figure 39: 2019 FC bus TCO contrast (unit: USD/per 100 km)

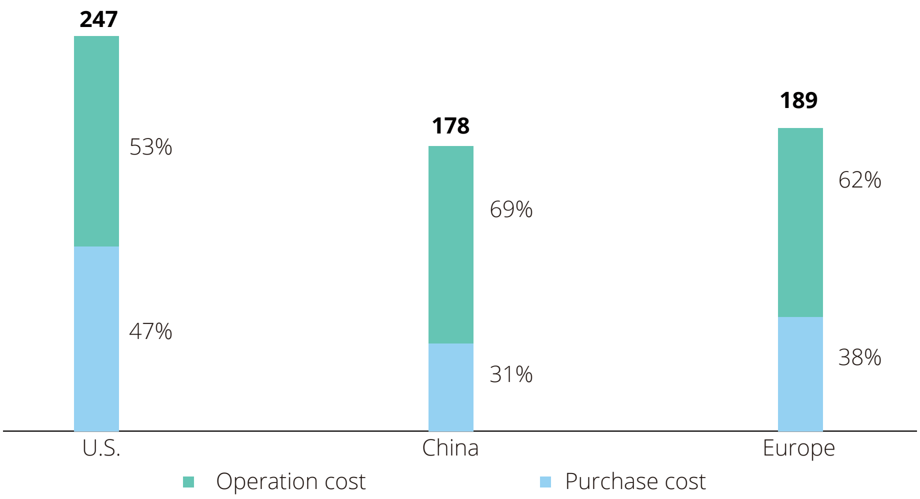


Figure 40: 2019 FC bus purchase cost contrast (unit: thousand USD)

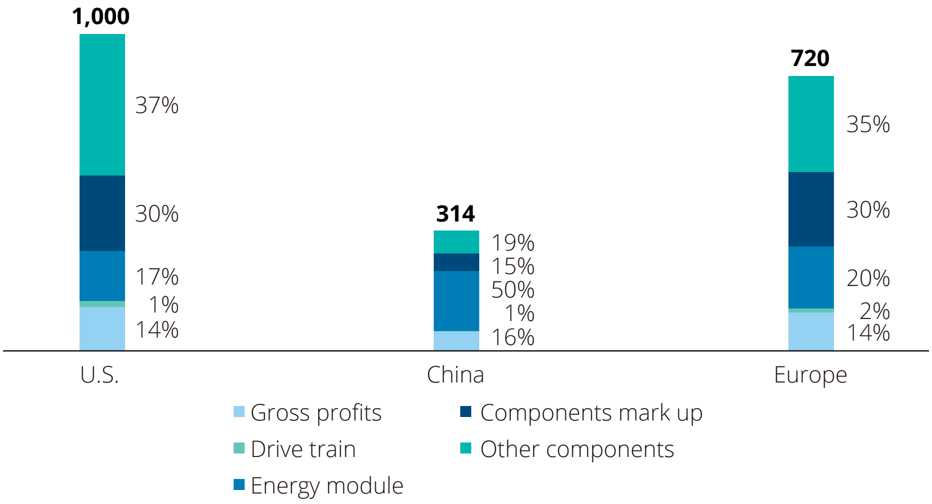
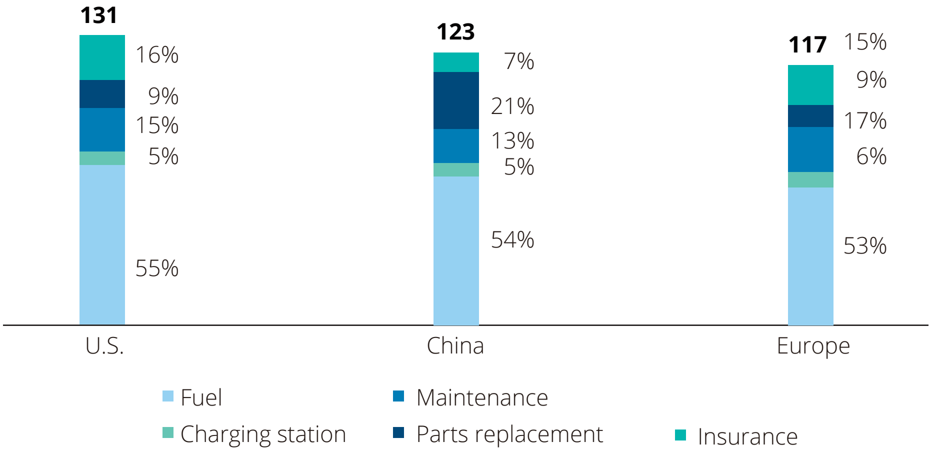


Figure 41: 2019 FC bus operation cost contrast (unit: USD/per 100 km)



Chinese vehicles have the cheapest vehicle price due to cheaper labor and parts cost, as well as the vehicles being rated for less mileage. The U.S. has the highest purchase cost, due to a combination of higher technical and "Buy-America" requirement which is a policy to encourage domestic manufacturing development, in addition to some components having higher OEM warranties.

Operationally, the differences in fuel prices across the regions also play significant roles in overall cost. Further, infrastructures costs in the three regions vary. For example, Chinese hydrogen stations have less hardware cost which cause a less hydrogen station cost.

Besides key components prices differences, vehicle lifecycles are also different in the three region. In the U.S. and Europe, typical buses are rated for 12-16 years, while in China, a bus would typically retire in 8 years. This lifecycle difference has impact on purchase cost per km as well as parts replacement cost leading to different forecast TCO curves.

The price contrast in Figure 42 is meant to provide an illustrative figure for the tremendous differences in TCO costs across different regions. Obviously, different sub-regions (such as states or cities), as well as operational business models and types of vehicles will have an even more pronounced impact. In this paper, we shall examine 3 real-life case studies involving FCEVs in more detail.

Figure 42: Key components contrast of a bus in 2019

		U.S.	China	Europe
Purchase cost (thousand USD)	FCEVs	• 1,000	• 314	• 720
	BEVs	• 700	• 229	• 452
	ICE vehicles	• 470	• 77	• 322
Fuel cell system (USD/per kw)		• 1,500	• 2,000	• 1,200
Fuel price (USD/per unit)	Hydrogen (kg)	• 8	• 8.4	• 7
	Electricity (kwh)	• 0.11	• 0.14	• 0.18
	Diesel (L)	• 0.76	• 0.96	• 1.62
Infrastructure for a bus fleet (thousand USD)	Hydrogen station	• 6,500	• 6,400	• 8,000
	Charging infrastructure (BEV)	• 12,500	• 5,200	• 12,500
Vehicle lifecycle (years)		• 12	• 8	• 14

3.2.1: Case Study 1—Logistics Vehicle

Established in July 2017, Shanghai Sinotran New Energy Automobile Operation CO., LTD. ("STNE") is a nascent start-up focused on the fuel cell logistics vehicle market. Figure 43 illustrated milestones of STNE. Despite its young age, the company is one of the largest fuel cell logistics vehicle operators in the world [169].

Figure 43. Milestones of STNE

2017.07	• Company establishment
2017.11	• Began to build the Jiangqiao Hydrogen Station in Shanghait
2017.12	• Purchased 500 fuel cell logistics vehicles from Dongfeng Motor Co., Ltd. [169] [126]
2018.05	• Introduced Air Liquide as shareholder [174]
2019	• Launched 600 fuel cell logistics vehicles in Shenzhen purchased from Zhong Tong [175]
2020	• Plan to have 2,000-3,000 various types of fuel cell logistics vehicles by 2020 [126]

When the company was founded in 2017, development of the hydrogen market in China was not yet well established, with high vehicle prices and few hydrogen fueling stations. However, STNE firmly believed that fuel cell vehicles were the future of logistics [172], especially with centralized operations driven by AI and big data. To that end, the founders of STNE ventured boldly into the market by purchasing 500 fuel cell logistics vehicles* from Dong Feng [173].

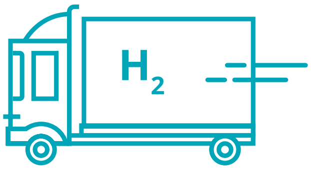
STNE focused on building an industry alliance to promote the usage of FCEV[169]. The original shareholders of STNE were leading players among FCEV industrial chains, including Re-Fire, a leading Chinese fuel cell system company [170], and Furuise, a listed company with hydrogen storage and transport technologies [171]. In 2018, STNE introduced another hydrogen industrial player – French giant Air Liquide, and PE firm CY-Capital as shareholders [174]. The company is keeping up its momentum with another 600 fuel cell vehicles launched in the Shenzhen area in 2019 [175], as well as plans for 2,000-3,000 vehicles by 2020 [126].

In the case analysis, we used logistics trucks with similar capacities. Detailed parameters contrast is illustrated in Figure 44 below.

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

*the 500 fuel cell vehicles are 6.4meters in length, with 15m3 cargo space and 3.2 metric tons of carrying capacity; each vehicle has 10kg hydrogen capacity and 400km of range [173].

Figure 44. Vehicle parameters contrast

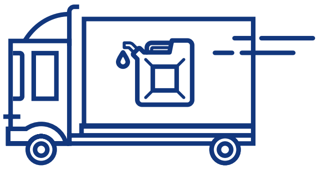


FCEV [176]

- Electric motor capacity: 55 kw (around 75 HP)
- fuel cell system capacity: 30kw
- Load capacity: 3.2 tons
- Driving distance: ≥305 km
- Vehicle length: 6.4m

BEV [177]

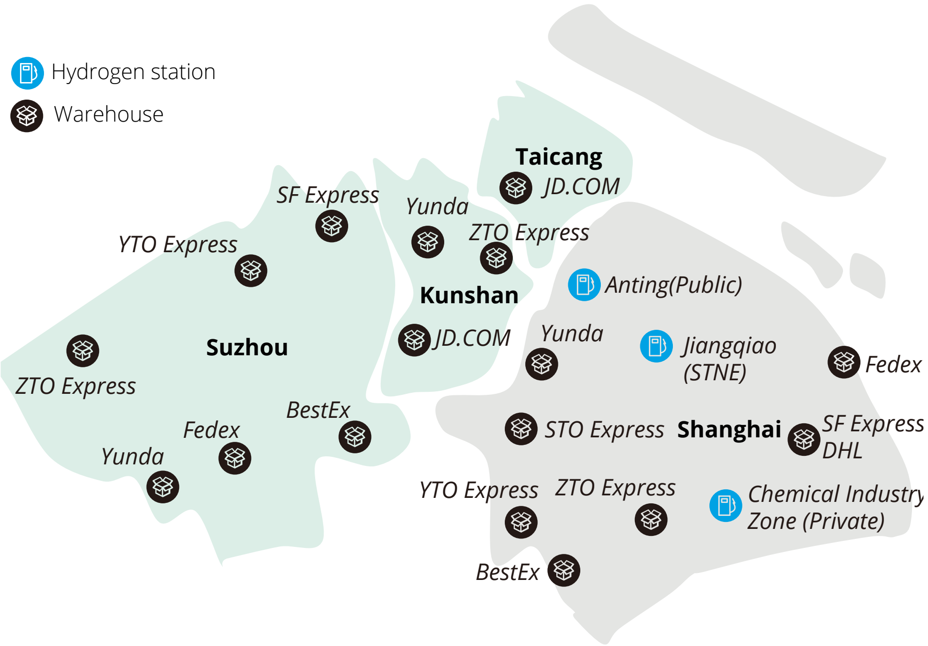
- Electric motor capacity: 120 kw (around 163 HP)
- Battery capacity: 100kwh
- Load capacity: ~3.0 tons
- Driving distance: around 200 km
- Vehicle length: 5.97m



ICEV

- ICE capacity: around 100kw [179]
- Load capacity: ~3.0 tons [178]
- Driving distance: around 400 km
- Vehicle length: 5.9m [179]

Figure 45: 2019 Shanghai operating hydrogen stations



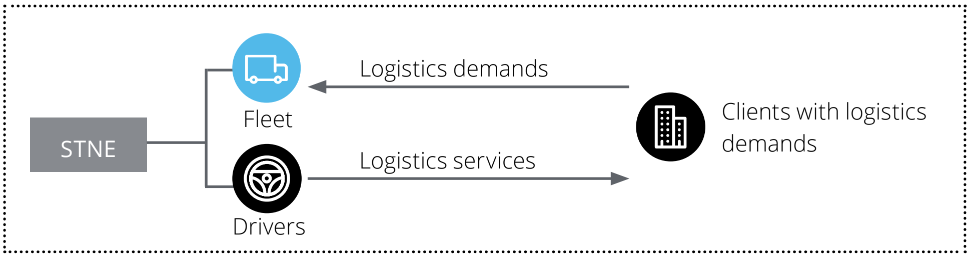
Shanghai is one of leading fuel cell application cities in China. There are currently three hydrogen stations running in Shanghai, which are located in Jiading, Fengxian and Jiangqiao respectively, as illustrated in Figure 45. Furthermore, 13 hydrogen stations are in site selection stage as Shanghai continues to expand on its hydrogen infrastructure [180]. As a major logistical focal point for surrounding regions, a large number of logistics companies have built a network of logistics centers and warehouses around the region. A network of hydrogen fueling stations will help move the city towards greener mobility solutions.

As we can see in the figure, the hydrogen station built by STNE in 2017 is strategically situated between the two other existing hydrogen stations[181].

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE; Distribution centers and warehouses are illustrative and not exhaustive; numerous smaller warehouses for all major logistics companies are spread across Shanghai, typically multiple locations in each district

Figure 46: Business models of STNE [169]

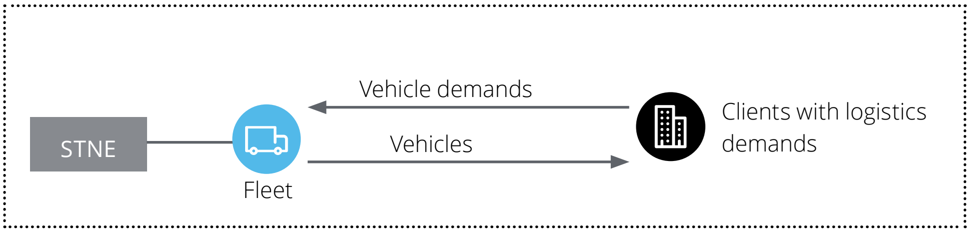
1. Self-operation



Fee rate

- Industry typically charges 300-350 RMB ($43-$50) per trip to clients, depending on distance and load.

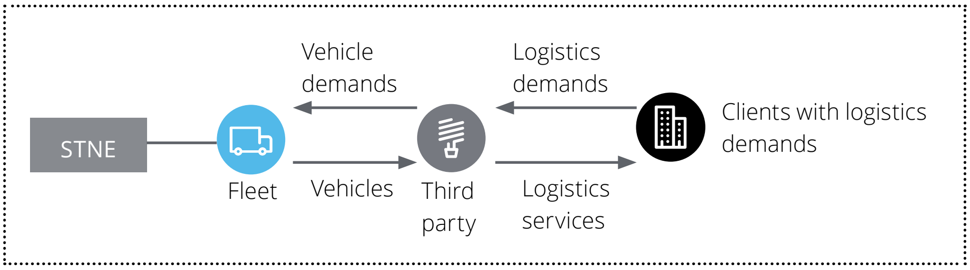
2. Direct rental



Fee rate

- Industry typically charges 5,000-6,000 RMB ($710-$860) per vehicle per month to clients with logistics demands.

3. Indirect rental



Fee rate

- Industry typically charges 5,000-6,000 RMB ($710-$860) per vehicle per month to third-party logistics providers, who then provide services to end-clients.

Due to the nascent nature of its business, STNE tries to maintain flexibility in its business models, in order to attract a wide range of clients, including JD.com, Alibaba, Shen Tong logistics, IKEA, etc. [172]. Overall, STNE business models can be categorized into three types: self-operation, direct rent, and indirect rent (Figure 46). and for each case we assume the following fee structure:

In the first case, self-operation, STNE owns all the costs associated with delivering goods for the client, including vehicles, as well as operational costs such as driver and fuel costs. Clients pay a flat fee of 300-350 RMB ($43-$50) to operator for each order, depending on travel distance and load.

In the second case, direct rental, STNE rents its FCEVs directly to clients with logistics demands. Industry typically charges 5,000-6,000 RMB ($710-$860) per vehicle per month in this model. Clients equip drivers and complete delivery of goods by themselves. Clients also bear daily operational costs (i.e. drivers and fuel), but STNE provides fuel subsidy to clients, in order to make hydrogen fuel costs be on par with diesel costs per 100km. STNE also pays maintenance and insurance costs for its vehicle fleets.

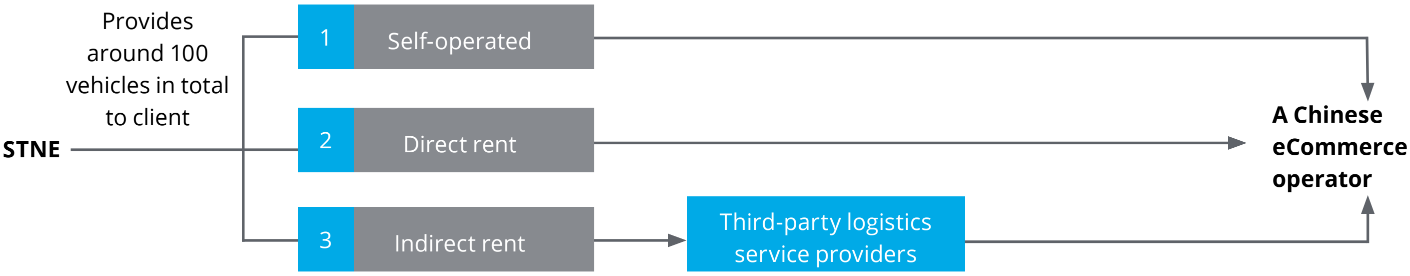
The third case, indirect rental, is essentially the same as the second case from the perspective of STNE. The only difference is that STNE rents the vehicles to a third-party logistics provider, who then provides logistics services to end clients.

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts, customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

Generally, among all these three business models, operator keeps its fee rate on par with market rates for BEV and ICE vehicles, in order to build market presence and recognition.

Clients focus on cost as a first priority, as well as service quality. Though some big clients such as JD would consider social and environmental benefits to choose FCEV, it is usually not enough to offset increases in costs. Therefore, STNE choose to bear the added costs of FCEVs themselves rather than pass them on to its clients at this stage of the company.

Figure 47: Business models assumptions of STNE servicing a Chinese eCommerce operator [169]



The three business models above can be illustrated by using a hypothetical scenario where STNE's services for a Chinese eCommerce operator (Figure 47). The eCommerce operator also has a flexible business model, acting as a platform for other sellers, as well as selling a certain portion of its goods through self-operated eCommerce stores and warehouses.

Based on current assumptions for revenue and cost components, we calculated the TCO and gross margin per 100km for STNE based on the self-operate and rent options in the above business models. Renting to the end customer or renting to a third-party logistics provider is identical from the perspective of STNE financials. It should be noted that the revenue, TCO and gross margin were estimated based on STNE business models, market benchmarking, and our high level TCO model and the results do not represent the actual operation result of STNE.

Figure 48 and Figure 49 below shows a breakdown of the revenue per km for both the self-operation model and rent-out models, as well as associated purchase cost and operation costs, adjusted for USD per 100km. Overall, the high costs of FCEVs when compared to BEVs and ICE vehicles are a combination factors such as purchase costs, fuel, maintenance, insurance and hydrogen station.

It can be seen that both using the self-operation business model is currently profitable, and using the rent-out business model is similarly unprofitable with BEVs. The profitability of the self-operation model is primarily due to higher revenues per km of operation compared to renting out logistics vehicles directly, which is not surprising. Nevertheless, the fact that FCEVs can be profitable today is an overwhelmingly positive sign for the continued development and commercialization of the fuel cell industry, as well as indication that hydrogen has indeed come a long way since it was first used in mobility.

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

Figure 48. TCO estimation- self operation (USD/100km)

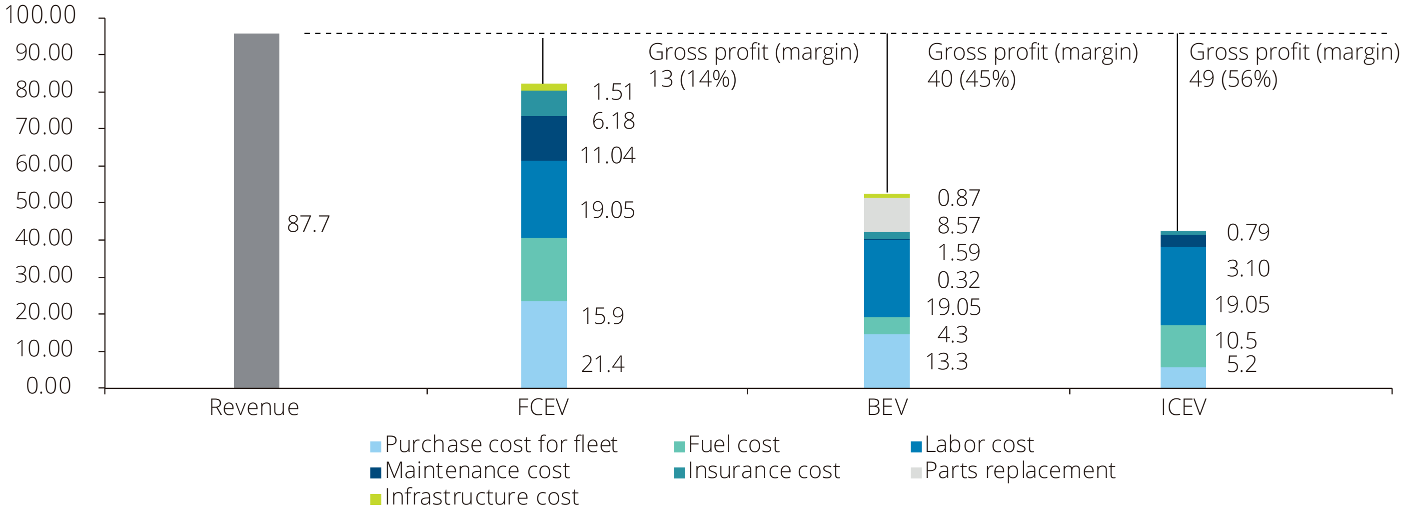
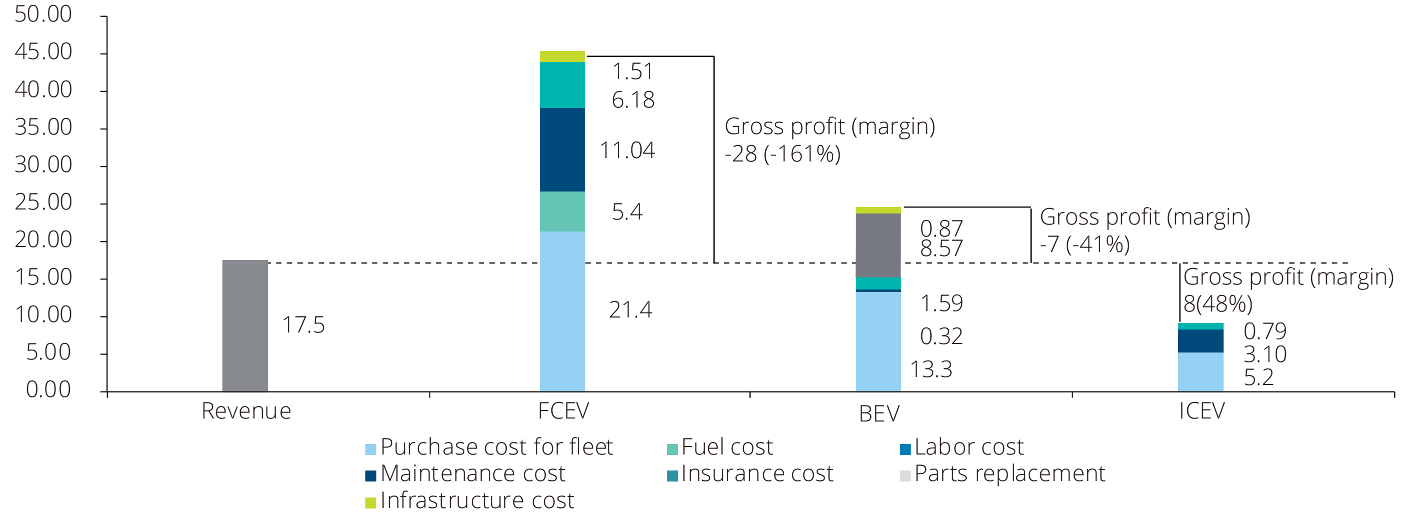


Figure 49. TCO estimation– renting out (USD/100km)



Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

Figure 50. Economies of scale comparison of logistics vehicles

	FCEV	BEV	ICEV
Number of vehicles in Shanghai	• ~500	• 5,000~20,000 [182] [183]	• >100,000 [184]
Price/thousand RMB	• 1,480 – Fuel cell system around 750 – Fuel tank around 45 – Component markup 385 – Fixed components 300	• Around 300	• 100~150
Infrastructures	• Few hydrogen stations, which limited service range of FC trucks	• Medium, number pf charging stations is increasing	• Plentiful

In our assumptions, operator price its offerings at market rates similar to ICE vehicles and undertake operation loss in order to promote the use of fuel cell logistic trucks application, but it should be noted that there is wiggle room for profits increases, due to potential cost deduction items and other unquantifiable benefits of using FC logistics trucks.

First, there is a large decline room in purchase cost. Assuming, operator would've bought the 500 trucks for 1,480 thousand RMB per vehicle in 2017, among which fuel cell system and tanks made up near 50%. We estimate with technology improvement and fuel cell vehicle production increases, there will be economies of scale in fuel cell system, the fuel cell system (including tanks) would decline 70% by 2024 compared with the initial purchase year. In fact, compared with 2017, the fuel cell system cost has decline 30% in 2019.

Furthermore, similar to reasons stated in Section 3.1, FCEV logistics trucks currently have a large propulsion-system agnostic component markup. This markup is also forecasted to decrease in the future as economies of scale improves for FCEVs (Figure 50).

There is also a decline room in infrastructures cost. As seen earlier, there are only 3 hydrogen stations in Shanghai, which limits service range of FC trucks. In our assumptions, cost related to hydrogen station make up around 3% of operation cost in self-operation model and 6% of operation cost in rental model. We estimate the infrastructure costs would also decline significantly in the future.

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

Figure 51. Qualitative contrast among logistics vehicle types in Shanghai

	FCEV	BEV	ICEV
Pollutant emission	• No emission	• No emission	• Polluting emissions in greenhouse gases and noise
Permits to enter the city area	• Around 20% trucks have permits	• Approximately 5-10% of trucks have permits [187]	• Only 5% trucks have permits, which limits the services within the city
Other right-of-way [66]	• Local gov'nt to halve tolls • Allowed to use bus lanes	• Local gov'nt to halve tolls • Allowed to use bus lanes	• None

Aside from a quantitative comparison of the vehicle types, using FCEV logistics trucks also includes other qualitative benefits, as seen in Figure 51.

First, since FCEVs and BEVs have no emissions, local governments have issued policies to encourage new energy vehicles ("NEVs") development. In fact, the proportion of NEVs in the service sector is expected to achieve >80% in key air-pollution-prevention areas [66]. This also includes other benefits such as tolls deduction and right-to-use bus lanes for FCEVs and BEVs [66]. In addition, in Shanghai, logistics trucks have a strict permit system when entering the city area, in order to reduce pollution and ease congestion [185] [186]. Only 5% of ICE trucks have such permits, while based on industry experts feedback 20% of FCEV trucks have such permits, with ongoing talks with city government to increase the permit rate of FCEVs to 100% [169]. Though it can be argued that not all trucks and not all routes require such permits, having them for a fleet is undoubtedly beneficial in terms of ease of fleet operations, planning, and travel distance (not having to go around the city for delivery from one end of the city to the other, for instance.)

For ICE vehicles, there is a replacement risk because of its high emissions. Since 2000, the national emission standard has been updated 6 times, with each becoming more strict. The draft also mentions accelerating phasing out of diesel truck that are below National 3 Emission Standards and to pilot zero-emission zones in selective cities [66]. In order to promote NEVs development, a "Dual Credit Management System", has been applied to passenger vehicles production [188]. This refers to positive credits given for NEV production and negative credits for ICE production [188]. This system may be also applied to commercial vehicles in the future [189].

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

Based on the current TCO, we conducted a series of exercises to predict the trend of each cost component over the next 10 years, based on a variety of industry and subject matter expert sources. As we mentioned before, this results were estimated based on our key assumptions and not represented the actual operation situation of STNE.

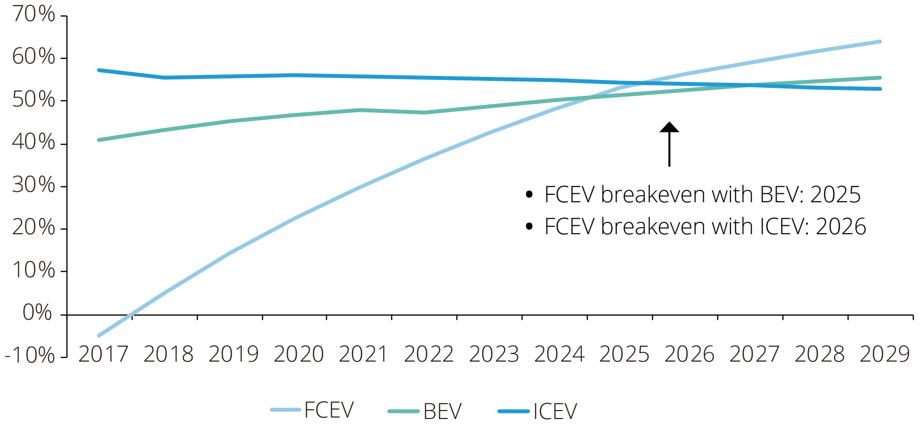
Figures 52 and 53 shows the results of these forecasts, for the self-operation model and renting model, respectively. It can be seen that the profit margin for self-operation rises rapidly to 2024, which is aided by the forecasted rapid reduction in fuel cell system prices, as well as of other components due to economies of scale in producing fuel cell trucks. Gross margin rises to a healthy 53% by 2025, which outstrips that of BEVs. Around 2026, we estimate the gross margin of fuel cell logistics vehicles would exceed of ICE logistics vehicles.

In terms of renting out, the positive trend of commercial viability over the next few years for FCEVs are even more pronounced. In fact, the gross margin of FCEVs becomes higher than that of BEVs around 2024, and also turns positive in 2024. With the purchase price declining, we estimate gross margin of FCEVs will exceed that of ICE vehicles around 2028.

It also should be noted that though we put ICE vehicles in comparison, fuel cell logistics trucks and BEVs may be the mainstream vehicles in the future based on the ICE replacement risk we have mentioned in qualitative contrast. It is highly likely that ICE vehicles be phased out by operators as pressure from multiple fronts rise.

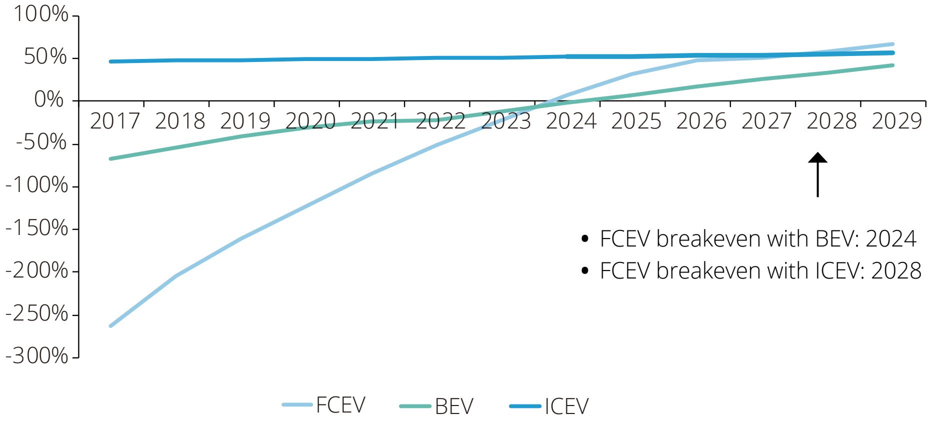
These results prove that there is significant opportunity for logistics operators using FCEVs in the Chinese market in the near future. It is unsurprising then, that STNE is investing heavily in this space despite little to negative margins on its offerings. The potential upside in commercial viability is further augmented by the qualitative benefits of FCEVs as mentioned prior.

Figure 52. Gross margin estimation of STNE– self operation (%)



- FCEV breakeven with BEV: 2025
- FCEV breakeven with ICEV: 2026

Figure 53. Gross margin estimation of STNE – renting out (%)



- FCEV breakeven with BEV: 2024
- FCEV breakeven with ICEV: 2028

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with industry experts as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

3.2.2 Case Study 2—Drayage Trucks

The Ports of Los Angeles and Long Beach both belong to Greater Los Angeles and comprise the San Pedro Bay port complex, which handles more containers per ship call than any other port complex in the world[190]. Nearly 40% of all containerized goods entering the U.S. move through the Port of Long Beach ("POLB") and/or Port of Los Angeles ("POLA") [46]. The Ports of Los Angeles and Long Beach are also pioneers in fuel cell drayage trucks applications, and act as a beacon of innovation with their various testing and demonstration projects. Figure 54 illustrated major milestones of drayage truck applications in Ports of Los Angeles and Long Beach.

In April 2017, Toyota launched "Project Portal," a test program for hydrogen fuel-cell trucks at the Port of Los Angeles and Long Beach [191]. This study was a collaboration among Toyota Motor North America, the Ports of Los Angeles and Long Beach, the California Energy Commission, and the California Air Resources Board [192]. Since 2017, Toyota has tested its first generation Class 8 fuel cell drayage trucks nearly 10,000 miles in the area of Ports of Los Angeles and Long Beach [193].

In July 2018, Toyota showcased its second generation Class 8 fuel cell drayage truck, Project Beta, and released it for use in the fall [193]. The Beta edition features added capacity for hydrogen storage to extend range by about 50 percent [194], Which extends driving range from 200 miles to 300 miles [196]. Furthermore, Beta's launch moved from proof of concept to a field test with goals for commercialization [194].

In the fourth quarter of 2019, 10 fuel cell heavy-duty trucks produced by Toyota Kenworth will begin to serve the Ports of Los Angeles and Long Beach, which is a part of the ports' Shore-to-Store project. This project is a collaboration within Toyota, Kenworth, the port of Los Angeles, Shell, UPS, South Coast Air Quality Management District [144] and also includes $41 million of funding by the California Air Resources Board. Together with the 10 trucks to be put in use, 2 hydrogen stations will be completed in 2020 [195]. Prior to 2020, the trucks will utilize a hydrogen station in long beach, which is 10 minutes away from the Port of Long Beach and 20 minutes away from the Port of Los Angeles [197].

Another project, known as ZECAP, has also launched in POLA, which is managed by GTI, a leading organization that has been addressing global energy and environmental challenges, and partially funded by the California Air Resources Board [198]. This project aims to validate the commercial viability of zero-emission fuel cell electric hybrid yard trucks operating in real world. Two fuel cell electric hybrid yard trucks will be put in use around March 2020. TraPac, a container terminal and stevedore operator at POLA, will be in charge of the operation [199].

The use of fuel cell drayage trucks in these test projects provides new possibilities in clean energy. On the one hand, it demonstrates how fuel cell drayage trucks could be utilized for future large-scale use, benefitting improvements in air quality with its zero-emissions features. On the other hand, testing fuel cell technology in port transit accumulates important operational data and would benefit applications in other commercial vehicles. This is a prime example of how fuel cell vehicles are being used now and has potential for wide adoption in the future. Detailed parameters contrast is illustrated in Figure 55 below.

Note: Business model, revenue, TCO and gross margin were estimated based on literature review, public/market information, inputs from our proprietary TCO model, anonymous interviews with company management as well as customers/business partners, etc. This case study is not meant to be an actual representation of operational results of STNE.

Figure 54. Milestones of drayage truck applications in Ports of Los Angeles and Long Beach

2017.04

Project Portal Alpha

- Tested first generation fuel cell drayage truck (Alpha) nearly 10,000 miles
- Collaborated with the Ports of Los Angeles and Long Beach, the California Energy Commission, and the California Air Resources Board

2018.03

Test project

- A fuel cell heavy-duty truck was put in use at POLA and POLB
- A proof of concept, still needs 3-4 years to develop

2018.07

Project Portal Beta

- Tested upgraded version of fuel cell drayage model Beta
- Began to move beyond proof of concept into commercialization

2019.Q4

Project Shore-to-Store

- 10 hydrogen fuel cell Class 8 trucks scheduled to be in operation
- Two large-capacity H2 refueling stations in construction process

2020.03

Project ZECAP

- Two fuel cell electric hybrid yard trucks will operate for 1 year in POLA
- Aim is to validate the commercial viability of zero-emission fuel cell electric hybrid yard trucks

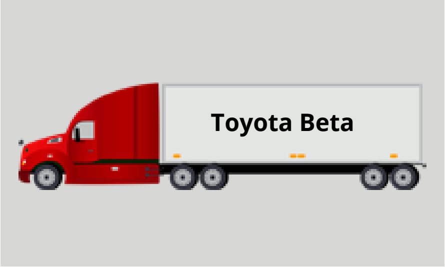
Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of drayage trucks in the Ports of Los Angeles and Long Beach

Figure 55. Parameters contrast of different drayage trucks

Kenworth T680[206]

- Prototype launch: 2018.02
- Purpose: proof of concept[207]
- Drivetrain capacity: 420 kW and 1,850 pound-feet (2,507 Nm) torque
- Fuel cell system: 85 kw
- Hydrogen tank storage capacity: 30 kg
- Battery capacity: 100 kWh
- Gross combined weight capacity: ~36.3 metric tons[201]
- Driving distance: ~209km

Toyota Beta



- Prototype launch: 2018.07 (for deployment in Q4 2019)
- Purpose: proof of commercial viability
- Drivetrain capacity: 670-plus horsepower (500 kW) and 1,325 pound-feet (1,796 Nm) of torque
- Fuel cell system: 2x Mirai fuel system[201] each rated at 114 kW[202]
- Fuel cell tank storage capacity: 60kg[200]
- Battery capacity: 12kWh
- Gross combined weight capacity: ~36.3 metric tons[201]
- Driving distance: ~480km[201]

BEV

- Drivetrain capacity: 340-740 horsepower (250-550 kW) and 2,000-4,000Nm of torque
- Battery capacity: 200-600kWh[203]
- Gross combined weight capacity: 20-47 metric tons
- Driving distance: 150-300km[203]

ICEV

- Drivetrain capacity: 400 horsepower (around 300 kW) and 1,200-1,800 pound-fee (1,600-2,500Nm) of torque[204]
- Gross combined weight capacity: ~40 metric tons[204]
- Driving distance: >1,000km[205]

Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of drayage trucks in the Ports of Los Angeles and Long Beach

Figure 56: Duty cycles of drayage trucks at the Port of Los Angeles and Long Beach [46]

	Driving distance	% of use	Covered area
Near-dock operation	• 2-6 miles	• 64%	• Cargo moves to Intermodal Container Transfer Facility
Local operation	• Within 20 miles	• 10%	• From the ports to warehouses, truck terminals, or major rail yards in downtown Los Angeles, Compton, and Rancho Dominguez
Regional operation	• 20-120 miles	• 26%	• From the ports to the Mexico border to the south, Coachella Valley to the east, and Bakersfield to the north

Figure 57: Logistics companies using fuel cell drayage trucks in Ports of Los Angeles and Long Beach

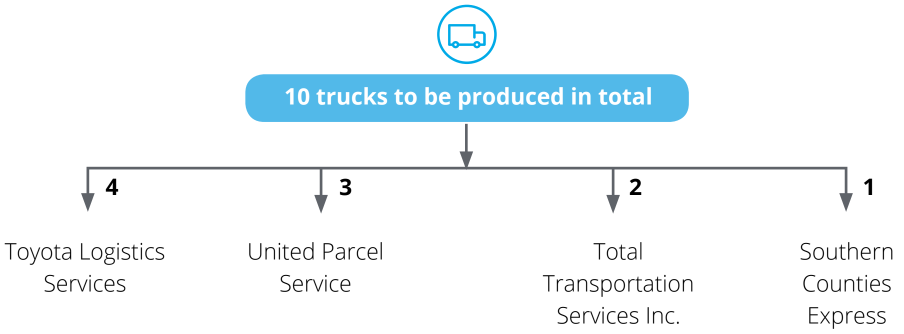
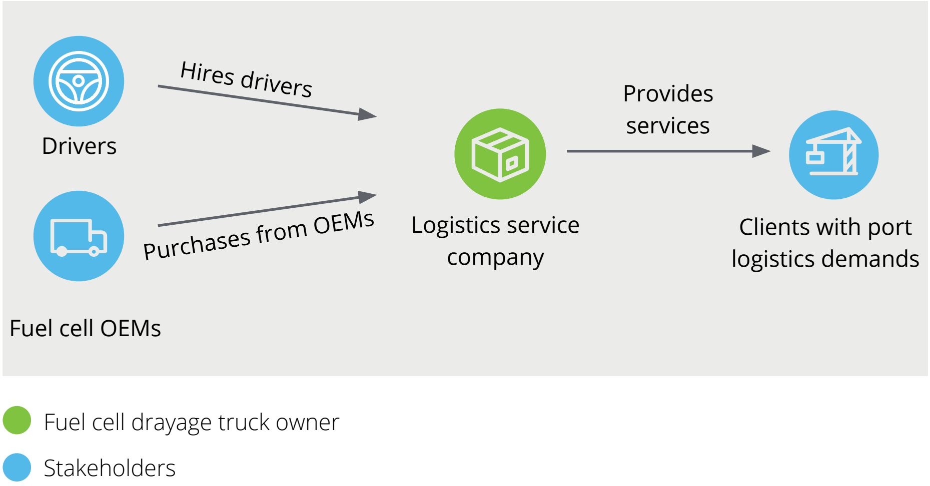


Figure 58: Business models of drayage truck operation



As shown below in Figure 56, there are three duty cycles of drayage trucks at the Ports of Los Angels and Long Beach based on driving distance: near-dock operation, local operation and regional operation [46]. Since the driving distance in all of the duty cycles are relatively short compared with distance of other heavy duty trucks, port transit is a suitable usage situation in early stage of fuel cell vehicle application. All three duty cycles are within the maximum driving distance (480km) of fuel cell drayage trucks.

Currently, the 10 fuel cell drayage truck will be owned by 4 logistics service companies. As shown in Figure 57, Toyota Logistics Services will operate four of the trucks. United Parcel Service will get three, Total Transportation Services Inc. will get two, and Southern Counties Express will get one [195]. Generally speaking, logistic service providers purchase vehicles from OEMs and hire drivers to form their own fleet, then take orders from clients with port logistics demands (Figure 58). We have assumed that the business model for these fuel cell trucks will be similar to trucks using traditional propulsion systems for the purpose of this case.

We estimated the 2019 TCO per 100km of different drayage trucks in Figure 59. The main cost components selection were based on the typical drayage trucks operation we mentioned above, including purchase cost, fuel, labor, maintenance, insurance, licensing and fuel station cost. It can be seen that purchase and fuel costs are two major incremental costs of fuel cell drayage trucks ownership.

Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of drayage trucks in the Ports of Los Angeles and Long Beach

From Figure 60, we could see a clear decline in the TCO of fuel cell drayage trucks in the next 10 years. This decline is due to the decrease of purchase cost of the truck and fuel costs, among others. With technology improvements as discussed in Section 3.1, we estimate that the fuel cell system and tanks, which are main cost components of fuel cell drayage trucks, would decline dramatically in price. Fuel cost per 100km of fuel cell trucks is also estimated to reach a level close to ICE trucks in the next 10 years. The TCO of FCEVs is forecasted to be lower than BEVs around 2024, and lower than that of ICE trucks around early 2028.

The benefits of application of fuel cell technology in portal transit also have other qualitative aspects (Figure 61). Fuel cell drayage trucks not only are zero-emissions vehicles, but also have the potential to showcase similar performance with diesel trucks. The paired ports of Long Beach and Los Angeles are serviced by 16,000 heavy trucks today and have become a hotspot for poor air quality as a consequence. Thus the area has become the focus of efforts by the South Coast Air Quality Management District (SCAQMD) to improve air quality, especially as the number of trucks servicing the ports is expected to double to more than 32,000 trucks per day in 2030 [201]. Though FCEV and BEV are both clean vehicles with no emission, battery drayage trucks have relatively short driving distance for one charging and hours charging time, which limits the use of battery drayage truck in regional operation and multiple shifts.

Figure 59. TCO break down (USD/100km)

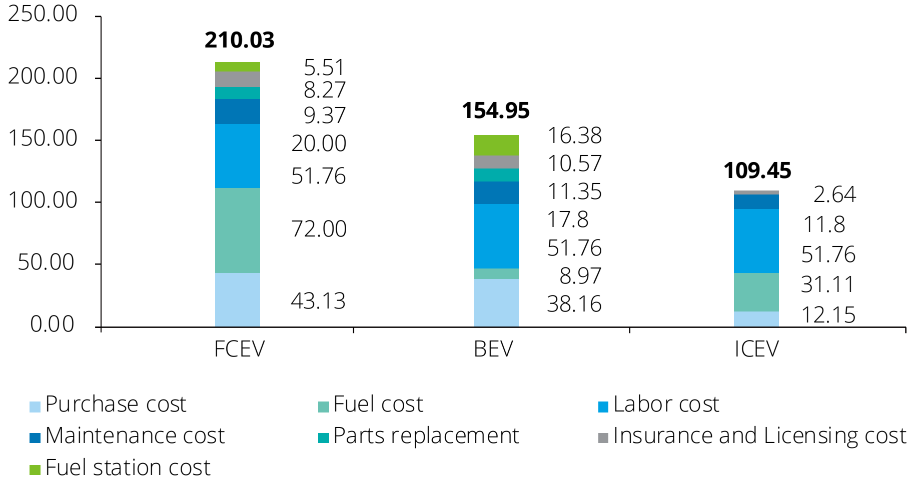
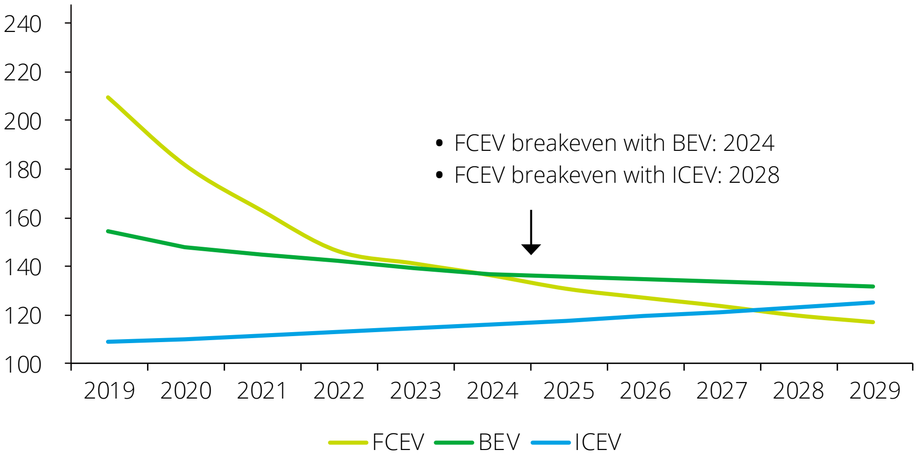


Figure 60. Total cost of ownership/ USD per 100km



Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of drayage trucks in the Ports of Los Angeles and Long Beach

Figure 61. Qualitative contrast among drayage truck types in the Port of Los Angeles and Long Beach

	FCEV	BEV	ICEV
Pollutant emission	• No emission	• No emission	• Lots of pollutant emissions
Vehicles lifecycle	• Still in test	• Need to replace battery after several years use	• Around 10 years
Charging time	• 5-10 minutes	• Around 3-5 hours	• 5-10 minutes
Infrastructures	• Limited, but the number of hydrogen stations is increasing. There are currently 40 stations in California [197] • A few strategically located refueling stations (e.g., at the ports and along the freight corridors) can satisfy most of the fuel cell truck refueling needs	• Limited high power stations (350kw) for heavy duty vehicles • 120kw and under charging stations plentiful along west coast	• Plentiful
Types of operations	• Near-dock operation • Local operation • Regional operation	• Battery weight and range become significant concerns for regional and longer operations	• Near-dock operation • Local operation • Regional operation

3.2.3 Case Study 3—Transit Buses

Transport for London ("TfL") is the integrated transport authority responsible for the day-to-day operation of the city's public transport network including buses, the undergrounds, light railways, taxis, etc. [208] Figure 62 illustrates the milestones of hydrogen fuel cell buses applications by TfL.

In December 2003, TfL started its trial of the first generation of fuel cell buses in London to reduce air pollution in the city [209]. This trial was also part of HyFleet: CUTE project, which brought together 31 partners from industry and government from across Europe aiming to push the development of hydrogen-based transport systems in Europe, and was funded by the European Union and the UK government [210].

After the successful trial, in 2010, as part of the Clean Hydrogen Cities project ("CHIC"), TfL purchased 5 next-generation hydrogen fuel cell buses[211] and put them into formal operation serving London citizens on the popular tourist route RV1 between Covent Garden and Tower Gateway. This is the first time a whole route has been fully operated by hydrogen powered buses in the UK [211].

In 2013, TfL purchased three more hydrogen fuel cell buses and expanded the size of the fleet to eight buses [211]. Then in 2015, TfL again added 2 more fuel cell buses to the fleet. [212] At present, the ten zero-emission fuel cell buses are serving London citizens on route RV1 in the city center of London.

In May 2019, Transport for London ordered another 20 hydrogen fuel cell double-decker buses to expand its zero-emission bus fleet. The 20 hydrogen fuel cell buses will be put into operation in 2020 on routes 245, 7 and N7 [213].

In Figure 63, we contrast the major parameters of three types buses.

Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of drayage trucks in the Ports of Los Angeles and Long Beach

Figure 62. Milestones of hydrogen fuel cell buses applications by TfL

2003-2017

Trial Run

- Started a trial of the first generation of zero emission fuel cell buses in city of London
- Purchased 3 fuel cell buses run on Route RV1[209]

2010

Formal operation stage

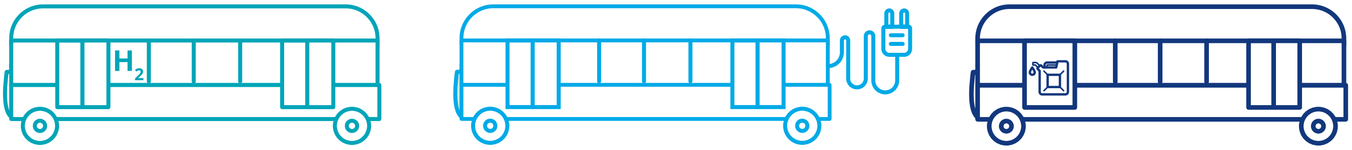
- Following the successful trial, 5 next generation hydrogen fuel cell buses were purchased and put into formal operation on route RV1[210]

2013 **2015** **2019**

Capacity Upgrade

- In 2013, 3 additional hydrogen fuel cell buses joined the fleet [210]
- In December 2015, purchased 2 hydrogen fuel cell buses from Van Hool in December 2015 [211], the size of the fuel cell fleet reached 10
- Ordered another 20 fuel cell double-decker buses from Wrightbus in May 2019 [212]
- The 20 buses will be put into operation starting 2020 on routes 245, 7 and N7 [212]

Figure 63. Parameters contrast of different types of buses



FCEV [214]

- Electric motor capacity: 200 kw (around 270 HP)
- Fuel cell system capacity: 30-100 kw
- Load capacity: 85 passengers
- Driving distance: Avg. 350 km, up to 500 km

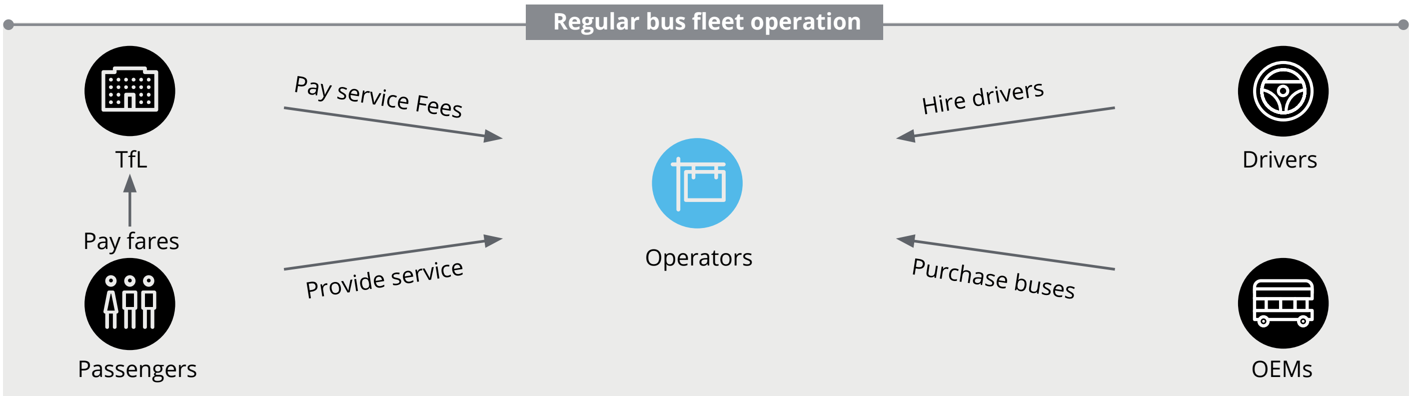
BEV [215]

- Electric motor capacity: 200 kw (around 270 HP)
- Battery capacity: 382 kwh [216]
- Load capacity: 84 passengers
- Driving distance: ~250 km [215]

ICEV

- ICE capacity: 310 HP [217]
- Load capacity: ~120 passengers
- Driving distance: >300 km

Figure 64. Business model of London buses operation



Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of London fuel cell buses of TFL

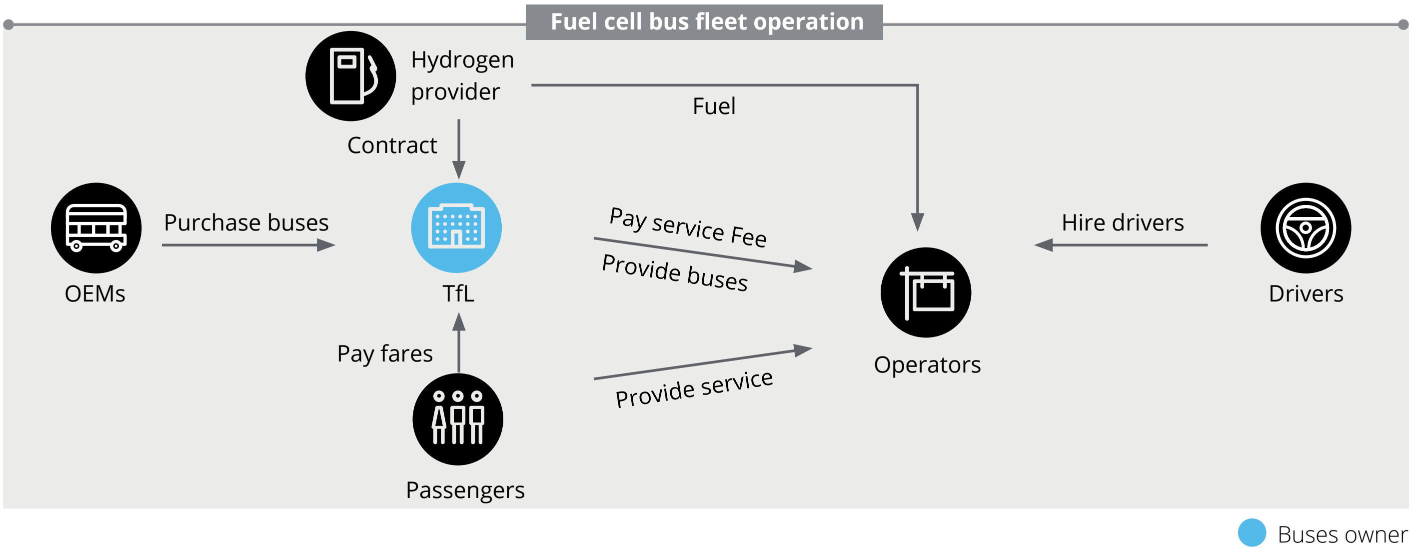


Figure 65. Fuel cell buses operation routine in London [221]

Route	Terminals	# of Stops	Length	Transit Agency	Garage Code
RV1*	• Tower Gateway • Covent Garden	10	9.7 km	Tower Transit	LI
7	• East Acton • Oxford Circus	7	10.6 km	Metroline	PV
N7	• Northolt • Oxford Circus	12	24.6 km	Metroline	PV
245	• Alperton • Golders Green	6	15.4 km	Metroline	PV

▨ Not in operation 🟦 Fuel cell buses will be in operation next year

Figure 64 illustrated two business model of bus operation by Tfl.

In regular bus routes operation, TfL launches competitive tenders to qualified privately owned operators. Then the operator who wins the bid would provide service in this bidding route. Generally, the operators should form their own fleet by purchasing vehicles and hiring drivers. The contracts are normally for 5 years and based on the best value of money taking into account quality and safety. The contract would set the service fee related to the mileage operated and overall reliability of the service.[218] The fare income generated from passengers in day-to-day operation are collected by TfL.

However, because fuel cell buses are still in early stage (Figure 65) and London government would like to promote the use of fuel cell buses, the routes with fuel cell buses running took a different operation model. TfL purchased fuel cell buses from VanHool and Wrightbus with financial support from the UK government and EU [213]. TfL franchised the operation of the fuel cell buses to operators, who then hire drivers to provide services in the routes [218].

Most of the hydrogen fuel used in transit bus applications is generated at large scale production facilities, delivered to bus garages and stored as a liquid or compressed gas [219]. In this case, Air Product is the partner of TfL to provide hydrogen fuel to the city's planned fleet of hydrogen buses and to build and maintain the hydrogen refueling infrastructure [220].

Note: RV1 has been permanently withdrawn in 14 June 2019; Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of London fuel cell buses of TFL

Figure 66. TCO of transit buses in London break down (USD/100km)

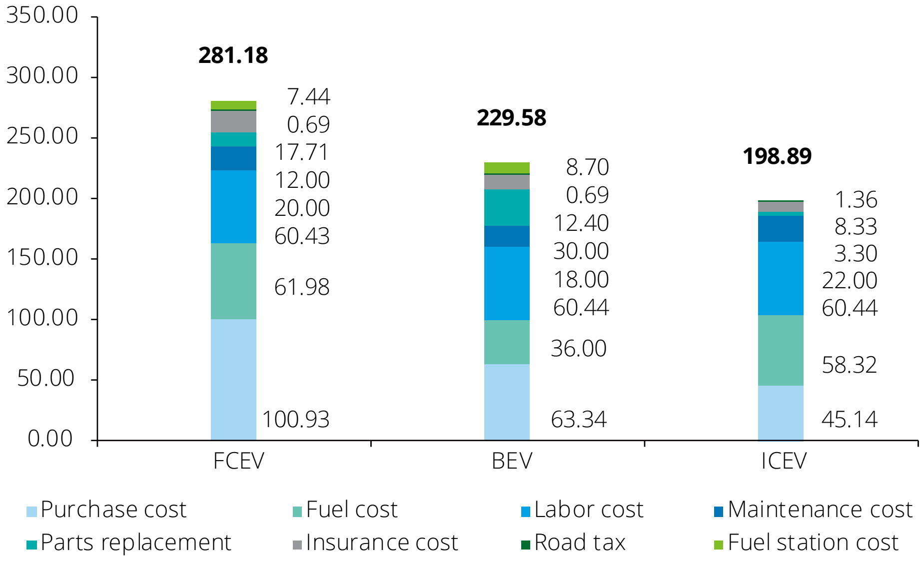
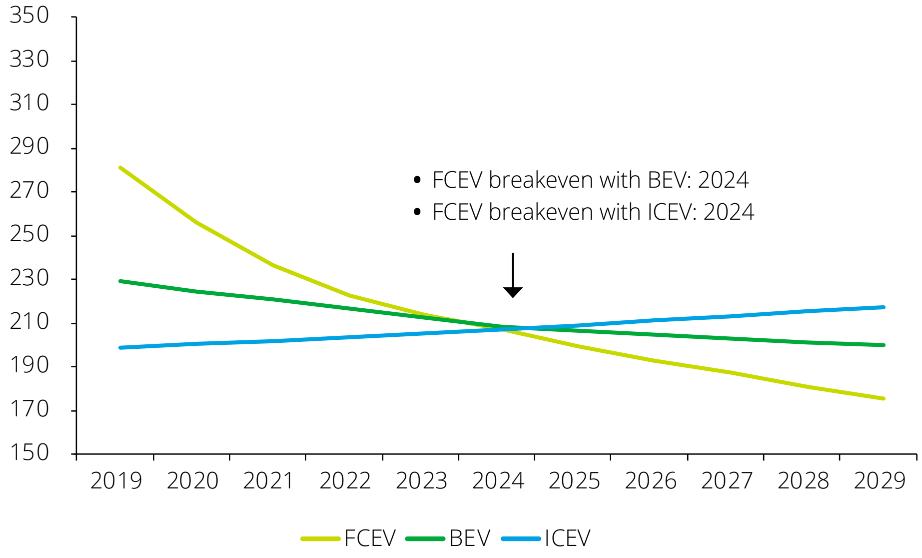


Figure 67. Total cost of ownership of transit buses in London / USD per 100km



In this case study, we assumed that fuel cell buses operate as any other normal bus operation models (i.e. operator purchases the fleet), and placed our perspective from the operator's view, in order to compare and contrast with BEVs and ICEs.

Figure 66 shows our TCO calculation result. Purchase cost and operational cost are included. Just as the other two application cases, purchases cost and fuel cost make up the main incremental costs of fuel cell buses. Associated with high purchase prices, insurance cost of fuel cell buses are also high. But we estimate these costs will decrease soon with fuel cell system and hydrogen prices decreasing. An added component compared to the other two case studies is road tax, which is an extra tax implements on vehicles with high emissions in the UK [222]. All three bus types pay road taxes, but that for ICE vehicles are significantly higher due to high polluting emission. Though the overall amount of road tax is small when taking the entire TCO in perspective, this is a positive signal for clean energy vehicle promotion.

In Figure 67, we estimated the TCO of fuel cell buses in the next 10 years. We estimate that the TCO of fuel cell buses would be lower than that of battery buses and ICE buses around 2024.

Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of London fuel cell buses of TFL

Figure 68. Qualitative contrast among transit bus types in London

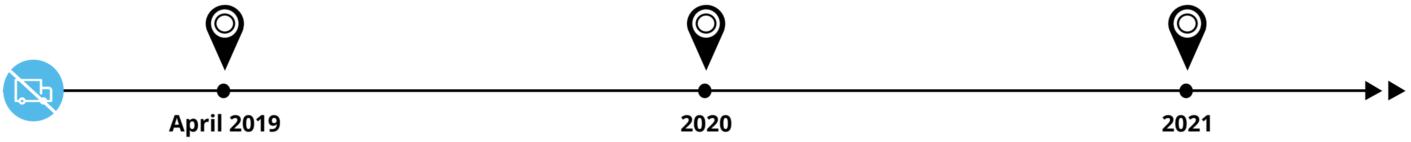
	FCEV	**BEV**	**ICEV**
Pollutant emission	No emission	No emission	Pollutant emissions
Charging time (to full)	5-10 mins	4-5h [223]	5-10 mins
Infrastructures	Limited, only 17 in the UK* [224]	Medium	Plentiful

Though the TCO of fuel cell buses is higher than battery buses and ICE buses, the benefits of application of fuel cell technology in city transit appear in other aspects as shown in Figure 68.

Firstly, fuel cell buses meet the emission standards of London government and have potentials to be widely used. In April 2019, London began to introduce an “ultra-low emission zone“ (“ULEZ”) (Figure 69). Vehicles exceeding the emission standard that drives into this area will be charged 12.5 pounds per car per day for cars, motorcycles and vans. Heavier vehicles, including lorries (over 3.5 t) and buses or coaches over 5 t, will be charged 100 pounds per vehicle per day. [223] According to the city government, only the cleanest cars and vans are exempt from the "ultra-low emission zone" fee. Diesel cars that fail to meet the EU's “Euro VI" emission standard and most petrol cars over 14 years old are required to pay the fee[224]. The scope of the ultra-low emission zone is expected to be expanded for larger vehicles like buses, coaches and lorries first in 2020, and then expand to all inner London boroughs a year later on 25 October 2021[225].

The introduction of ULEZ is one of the steps to meet the mayor’s ambition of reducing London’s carbon dioxide emissions by 60% of their 1990 level by 2025. [226] In the foreseeable future, the city government would be increasingly harsh on vehicle emissions, which makes the cost of driving conventional ICE vehicles much higher and green vehicles like BEVs and FCEVs a better choice for either commercial or civil use. In fact, the trend of employing green vehicles is unstoppable as TfL mentioned in annual report that only hybrid or zero-emission buses would be purchased from 2018.

Figure 69. Countdown to Ultra Low Emission Zone



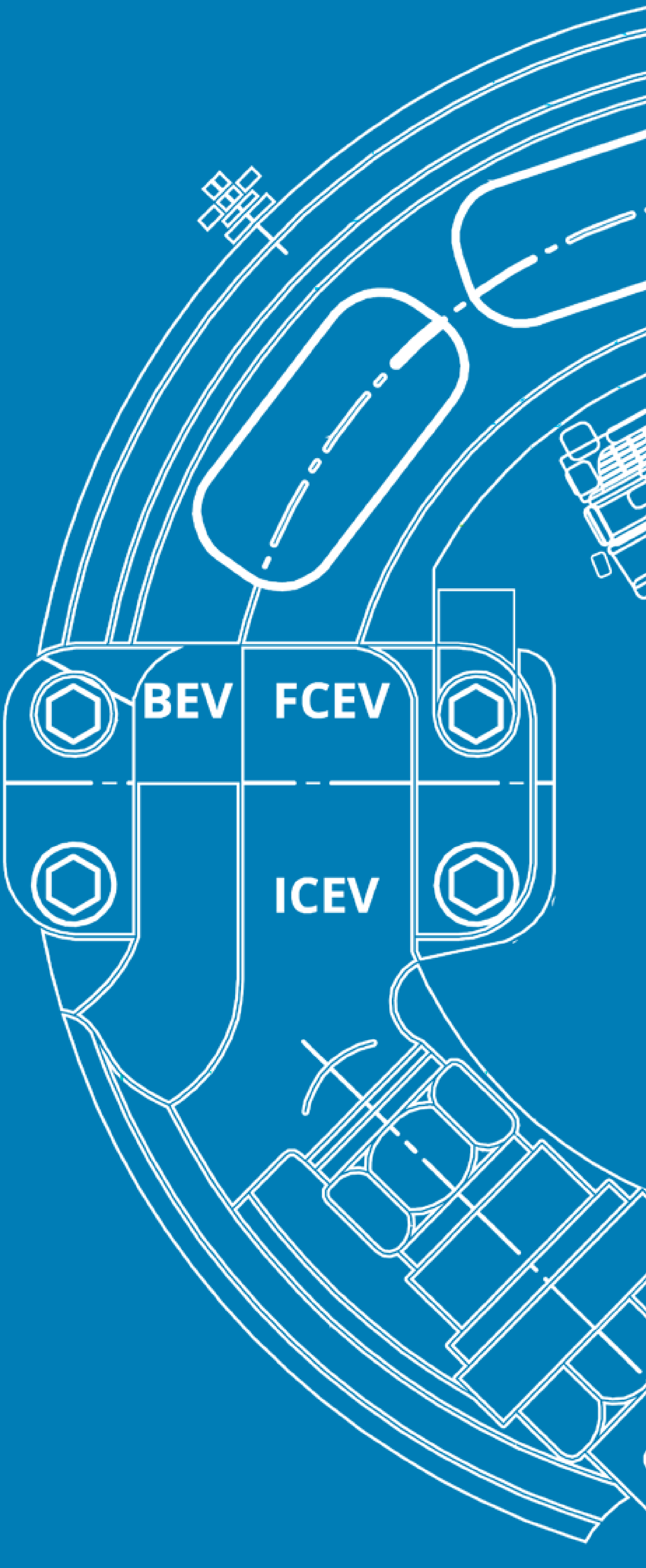
- Ultra Low Emission Zone was first introduced in the city center of London

- Expand the Ultra Low Emission Zone for larger vehicles like buses, coaches and lorries

- Expand the Ultra Low Emission Zone to the North and South Circulars for cars, vans, minibuses and motorbikes

*Note: Stationary hydrogen stations

Note: Business model and TCO were estimated based on literature review, public/market information, inputs from our proprietary TCO model, etc. and is not representative of the actual operation results of London fuel cell buses of TFL


BEV
FCEV
ICEV

Section 4 Comparison of energy efficiency and environmental impacts

4.1 Energy efficiency framework

In the previous section, we covered in depth the practical applications of FCEVs, and compared their total cost of ownership in real-life case studies to BEVs and ICE vehicles. We showed that FCEVs are starting to match (and in some cases outstrip) the economic viability of BEVs, while providing benefits of zero-emissions, green mobility that are widely lauded by governments and private companies around the globe. The future indeed looks bright for FCEVs from this perspective.

However, from a macroeconomic and overall societal impact perspective, it is important to consider many other factors. For example, how is hydrogen produced? How is it transported from the production site to the vehicle? What is the energy efficiency at each step along the process? Similarly, how are fuel cells produced, and what are the environmental impacts of such production processes? Can they be recycled? All the above questions deserve deeper analysis and pondering. It is also important to understand current technological advancements, and their associated impact on all of the above points in the future.

In this section, we cover:

- Well-to-wheel energy efficiency of FCEVs vs. other vehicle types (energy conversion efficiency, energy consumption, and Greenhouse Gas ("GHG") emission during whole fuel cell lifecycle)
- Production of hydrogen and associated impacts on efficiency
- Cradle-to-grave energy and materials efficiency of FCEVs vs. other vehicle types (such as vehicle and fuel cell/ battery manufacturing, component disposal/recycling/refurbishment, etc.)
- Environmental impact and considerations, including materials security
- Recent and future technology development and associated impacts

4.1.1 Considerations of well-to-wheel ratio

When considering the efficiency of an overall vehicle, a well-to-wheel ("WTW") analysis is typically used. This can be divided into 2 stages, typically known as well-to-tank, and tank-to-wheel. The former usually refers to fuel production from feedstock to its delivery to the vehicle's energy carrier, while the latter refers to energy consumption during vehicle operation phase [227]. When considering different vehicle types, this analysis more specifically refers to:

- In the case of FCEVs: hydrogen production, delivery & storage to the vehicle hydrogen tank, as well as the fuel cell use during FCEV operation
- In the case of BEVs: electricity generation, transmission in the grid, charging the BEV battery, and use during BEV operation
- In the case of ICE vehicles: gasoline/ diesel mining, refining, transportation to gas stations, and fuel consumption during vehicle operation

The following Figure 70 shows common ranges in terms of energy efficiency at each step of the process for each type of drivetrain technology.

Figure 70: Well-to-wheel analysis framework of vehicles by propulsion type

Energy Efficiency	Well → Tank		Tank → Wheels	Overall WTW Energy Efficiency
	4.1.2 Production	4.1.3 Delivery	4.1.4 Use	
FCEV	**23~69%** [228 233 234 235 236227] • Range is due to differences in hydrogen production pathways • Production efficiency = Feedstock extraction efficiency X fuel to hydrogen efficiency • See details in following pages	**54~80%** [230 231 232] • Energy loss during compressing, transportation (pipeline/truck) and storage (gaseous/liquid hydrogen)	**36~45%** [230 232] • Conversion of hydrogen to electricity, and electricity to mechanical energy • The additional energy loss compared with BEV operation, is due to added step of hydrogen to electricity	**4~25%**
BEV	**35~60%** [234 235 236] • Range varies depending on different methods of electricity production, as well as grid-mix which varies dramatically between different countries	**81~84.6%** [235 236 240] • Average conversion rate during electricity transmission is about 90%-94% • 90% energy efficiency during charging process	**65~82%** [229 230] • Energy loss during electricity conversion to move vehicle, including loss in motor, AC conversion, auxiliary parts and transmission system, excluding the charging process	**18~42%**
ICE Vehicle	**82%~87%** [234 238 239] • 13~18% energy loss during fossil fuel mining, refining processes	**~99%** [237] • Small amount of energy loss during transportation process, due to evaporation, spilling or adhesion to containers	**17~21%** [229] • Majority of energy lost as heat • Current efficiency is near the limit of ICEs after years of improvements as the incumbent vehicle type	**14~18%**

As shown in Figure 70, the impact on overall energy efficiency of FCEVs is heavily dependent on hydrogen production and transportation, as well as the fuel cell technology in the vehicle converting the energy stored in hydrogen to drive the vehicle. Opponents against FCEVs will argue that hydrogen is by nature inferior to battery vehicles, by the simple fact that hydrogen has to be produced from electricity (by electrolysis), and then back to electricity (which must have some loss of energy). However, this is not the case as we examine the hydrogen value chain in more detail. For example, hydrogen can also be produced from natural gas and the associated carbon could be captured and recycled.

So how is hydrogen produced and transported today? What are their implications on energy efficiency? How will future trends in production and transportation change? These are complex questions that deserve deep analysis which we will cover in the next part of this white paper series. However, for the purposes of this current paper, we will cover each part of the well-to-wheel ratio at a high level, focusing on current and future trends.

Energy efficiency comparison of fuel production among FCEV, BEV & ICEV

For FCEV, the energy conversion of hydrogen production phases ranges from 23%~69%. The variety in efficiency is due to the different hydrogen production pathways, which we will illustrate with a bit more details later in this section, with different types of fuel or feedstock and different processing technologies.

The energy efficiency of hydrogen production process is comprised of two parts: 1) the efficiency of feedstock extraction and recovery; 2) the efficiency of converting the fuel into hydrogen. USDOE has complied energy efficiency of different types of fuel into hydrogen, which we will explore in the next section. [233]

Taking electrolysis as an example – for hydrogen produced from central water electrolysis, the energy conversion rate from electricity to hydrogen is 66.8% [235,233]. However, the energy efficiency of the electricity itself is around 35%-60%. This wide range is dependent on different raw materials and countries – coal-fired electricity and natural gas combined cycle production results in quite different efficiencies and greenhouse gas emissions.[228,233] [234,235,236] In electrolysis, it is obvious that the core reason for difference in energy efficiency in fuel production stage between FCEV and BEV is the secondary energy conversion from electricity to hydrogen for FCEV with electrolysis hydrogen production pathway. The broad efficiency range for FCEV is mainly due to production efficiency differences. [240,235,236,241,228,233]

For conventional ICEs using diesel or gasoline, the energy efficiency on production stage is more standardized at about 82%-87%, with 13~18% energy loss during fossil fuel mining, refining and recovery processes.[234,238,239]

Hydrogen production

Electricity production

Fossil fuel production

Energy efficiency comparison of energy transportation among FCEV, BEV & ICEV

For hydrogen delivery and storage efficiency of FCEVs, hydrogen can be stored and delivered as compressed gas, liquid, or solid, the former two being the most common methods. Compressing hydrogen into a liquid for transport and storage causes 40%~46% efficiency loss mainly due to the energy required to cryogenically compress the hydrogen. [231 230]. While compressing hydrogen as a gas form is more efficient, but still incurs a total system efficiency loss. The overall energy efficiency of gaseous hydrogen is approximately 72%~80%. [230 231 232]

Energy transmission for BEVs is relatively simple; the average loss rate during electricity transmission is about 7%-10% and is predicted to decrease to 6.00% by 2020 [235 236 240]. There is also a 10% energy loss during the charging process. It also should be noted that batteries can self-discharge, although we did not include these losses in this analysis due to difficulties on quantification [94].

For ICEs, the overall loss rate during loading, unloading, transportation and retail is less than 0.4% for gasoline and 0.28% for diesel, mainly due to evaporation, spilling or adhesion to containers [241]

Hydrogen delivery

Electricity transmission

Fossil fuel delivery

Energy efficiency comparison of TTW stage among FCEV, BEV & ICEV

As we can see from Figure 70, the energy efficiency of tank to wheel stage of fuel cells is 36%~45%, converting hydrogen first into electricity and then into kinetic energy [230 232 243]. The electric energy efficiency of fuel cell system is around 55% with the current industry standard, which is the efficiency from pure hydrogen to electricity of fuel cell system. [94 242] For BEVs, the energy efficiency of tank to wheel is around 65%–82% [229 230 234].

Though ICEs have high energy efficiency from well to tank, conventional gasoline vehicles only convert about 17%–21% of the energy stored in gasoline to power at the wheels, with majority of energy being lost as heat. This is an inherent weakness of ICEs, even after decades of improvement [229 234]. Overall, the WTW energy conversion of conventional gasoline ICEV is 14~18%, which is less than the maximum efficiency of BEVs and FCEVs.

FCEV

BEV

ICEV

4.1.2 Hydrogen production and energy efficiency

The production of hydrogen, as we have seen from the previous section, plays a dominant role in the energy efficiency of the FCEV lifecycle [247].

In this section, we will first get to know a bit about hydrogen production pathways, and will continue exploring this fascinating subject and the technological breakthroughs in recent years in a following white paper of this series.

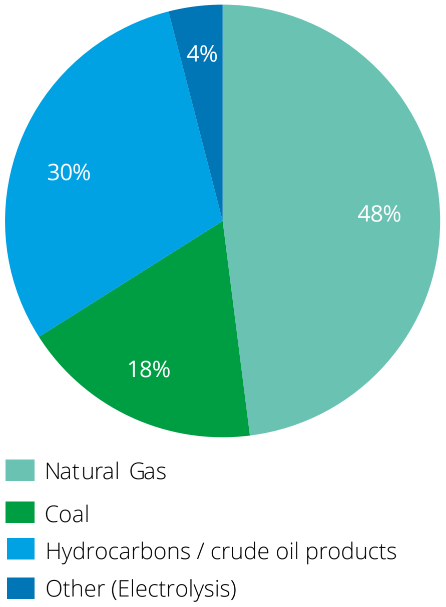
Today, hydrogen can be produced using a range of energy sources and technologies. [245] As we can see from Figure 71, global hydrogen production today is dominated by the use of fossil fuels, accounting for 96% of hydrogen produced globally. [245] 48% of hydrogen comes from natural gas; 30% from hydrocarbons/crude oil products, 18% from coal, and only 4% from electrolysis of water.

Globally today, annual production of pure hydrogen is around 70 million tonnes ("Mt"), most of which is used for oil refining and industry production (of ammonia, for instance). Only <0.01 Mt of hydrogen is now used in FCEVs. [245]

The reason that the majority of hydrogen is produced using "unclean" methods can be attributed to several reasons:

1. Traditionally, hydrogen is mainly used in industrial processes, with transportation and fuel cells accounting for a very minor portion of usage [245 248].
2. Due partially to point 1, there was not an overwhelming focus on clean energy involving hydrogen, which is rapidly changing around the globe [227]
3. Electrolysis of water, although very simple in principle, is currently expensive compared to other production methods, since the electricity has to be generated in the first place, which results in overall lower efficiency of hydrogen production [249]. However, this case is quite different when considering renewable energies (such a solar and wind), which are affected by seasonality and peak usage cycles; resulting in overcapacity of electricity production which is often wasted [31 250 251] . The marginal cost of renewable energies is near zero, which results in their being priced below prevailing market - even negatively priced [252]. For example, negatively priced electricity has occurred in Germany, Belgium, U.K., France, the Netherlands and Switzerland due to overcapacity of electricity production [253].

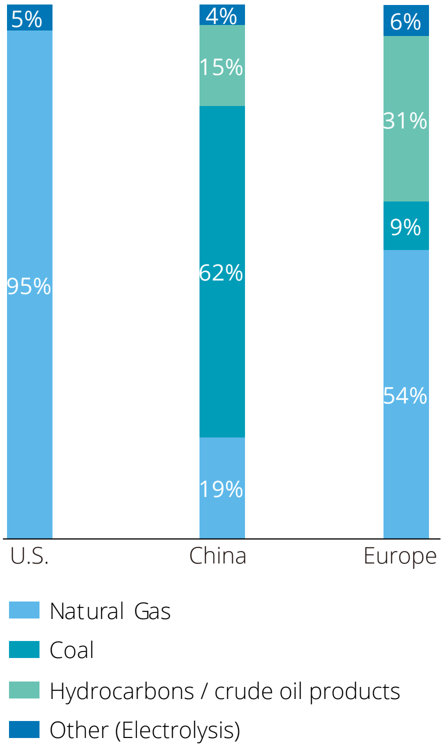
Figure 71. Global Energy source of pure hydrogen production (2018) [244 245]



The source of hydrogen production also varies greatly by geography (Figure 72). In the US, 95% of the hydrogen produced is made by natural gas reforming in large central plants, which is an important technology pathway for US as a near-term hydrogen production [254]. The reason why natural gas accounts for such a major portion of production is due to it being the most economic production method currently in the US [255].

China has been the largest hydrogen production country with ~19 Mt hydrogen produced in 2017, [261] around 62% of hydrogen production comes from using coal/coke oven [31] [256]. This is unsurprising, since China has traditionally been extremely reliant on coal for energy production [31] [256] . However, this is changing as China is overall shifting to green, renewable energy on a country-wide scale [31].In the mid and long term plan, renewable resources would play more and more important role as source of hydrogen. According to China hydrogen alliance, by 2050 around 70% of hydrogen would be produced by renewable resources.[31]

Figure 72. Energy source proportion of hydrogen production by geography [31 257 261]



As an island nation focused on renewable resources, Japan relies on both import and domestic production in terms of hydrogen production. For domestic need, it is mainly derived from industrial by-products and natural gas reforming [23]. In the longer term, Japan aims to develop international hydrogen supply chains with other countries, to produce hydrogen from a combination of low cost unused energy from overseas and carbon capture and storage ("CCS"), as well as cheap renewable energy sources [23 257].

In Europe, which accounts for ~21% of global hydrogen produced, production is currently dominated by fossil fuels. 94% of hydrogen production is from fossil fuels, of which 54% comes from natural gas, 31% from petroleum and 9% from coal [258] . However, Europe is making efforts towards more "clean" source for hydrogen production. Water electrolysis would play an important role in hydrogen production according to Hydrogen Roadmap Europe [260]. For instance, Germany is actively pursing hydrogen production from electrolysis from renewable resources, especially from wind energy [259 260] .

There are variety of process technologies for the hydrogen production, which can be classified into 5 typical processes [255 263]:

- Chemical process, including steam reforming, partial oxidation, gasification, and cracking
- Biological process
- Electrolytic process
- Photolytic process
- Thermochemical process

A detailed hydrogen production pathway has been illustrated in Figure 73 below. Globally, the current most mature and common production method (and also most economic) is via natural gas SMR. [254] However, the unsustainability of the natural gas does not align with the positioning of hydrogen as "clean" and "sustainable" energy for future. On the other hand, electrolysis has been regarded as a more sustainable way to produce hydrogen. However, the source of electricity used has large impact on energy consumption and GHG emission from a lifecycle perspective. In addition, the current production cost is relatively high using electrolysis, in addition to the issue that the source of electricity has a large impact on the "cleanliness" of the energy. [262]

Figure 73. Hydrogen Production Pathways [245 246 254 255 261 263 264 265 266]

Type	Pathway		Principal	Benefits	Challenges
Fossil fuel	Natural gas steam reforming		By reacting natural gas with high-temperature steam, synthesis gas, a mixture of hydrogen, carbon monoxide was created. The carbon monoxide is reacted with water to produce additional hydrogen	• Most mature and available technology globally in short term • Existing feedstock infrastructure in many countries • Low operation cost to produce hydrogen due to cheap raw material	• Has GHG emission, but using carbon capture and storage technology (CCS) could help reduce carbon emissions
	Coal gasification		Synthesis gas is produced by reacting coal with high-temperature steam and oxygen in a pressurized gasifier, which is converted into gaseous components	• Coal as feedstock is abundant and affordable • Provide low cost synthetic fuel in addition to hydrogen • Low operation cost to produce hydrogen due to cheap raw material	• High GHG emission, but CCS could help reduce carbon emission • Rich in impurities and needs to be purified • More complex and need high initial capex
	Hydrocarbons/ crude oil products Pyrolysis	Methanol pyrolysis/ cracking	hydrogen production by high-temperature pyrolysis of compounds containing hydrogen	• Lower initial capex • Lower energy consumption	• High GHG emission, but CCS could help reduce carbon emission
		Liquid Ammonia pyrolysis			
Biomass	Biomass gasification/ pyrolysis		Similar as coal gasification to convert biomass to a mix of carbon monoxide, CO2, hydrogen and methane	• Environment friendly and sustainable • Can potentially convert all organic matter	• Produced gas needs further processes to extract hydrogen • Complexity in processing • Expensive in production
Electrolysis	Electrolysis with grid mix electricity		Electrolysis is the process of using electricity to split water into hydrogen and oxygen	• Mature technology • No pollutants if electrolysis by renewable power • High purity and low impurity content of obtained hydrogen • Suitable for diverse conditions	• High energy consumption • Operation cost depends on source of electricity • GHG emission related to the source of electricity
	Electrolysis with wind/solar		Electrolysis is the process of using electricity to split water into hydrogen and oxygen	• Off-peak wind/solar can be collected • Renewable, environment friendly and sustainable • Cheap energy source to produce hydrogen	• Wider adoption of this method to produce hydrogen required in the future
	Photo electrolysis/photolysis		Use solar power to produce hydrogen directly through photolysis of water with certain catalyst	• Clean and sustainable • Abundant of feedstock	• Still in laboratory phase • Low conversion efficiency
	Bio electrolysis		Hydrogenase is produced by microorganisms that catalyze the decomposition of water to produce hydrogen	• Clean and self-sustainable • Tolerant of diverse water conditions	• Sustainable production of efficient microorganisms • Technology expected to be available in mid-long term

Figure 74. Hydrogen production efficiency and current production method deployed by major countries [245 246 254 255 261 263 264 265 266]

Hydrogen Production Pathways	Energy Efficiency	Hydrogen production source			Hydrogen production cost (USD/kgH_2)		
		US	China	Europe	US	China	Europe
Fossil Fuel -Natural gas (SMR)	68.0%-69.1%	● ↓	◔ ↓	◑ ↓	1.3-2 ↑	1.8-2.6 ↑	1.9-2.7 ↑
Fossil Fuel -Coal (Gasification)	53.8%-55.9%	○ →	◕ ↓	◔ ↓	2.3-2.8 ↑	1.5-3.1 ↑	2.3-2.8 ↑
Electrolysis	23.4%-40.0% (with grid mix) (theoretically 100% if wasted wind/solar applied)	○ ↑	○ ↑	○ ↑	2.2-3.6 ↓	1.6-2.2 ↓	3.1-4.1 ↓

↑↓→ Future development trend, in terms of increase, decrease, or stable proportion of total hydrogen produced

Level of application:
Harvey ball refers to current deployment level of major hydrogen production source

○	◔	◑	◕	●
<5%	5%~20%	20%~50%	50%-95%	>=95%

Note: for hydrogen production cost, the direction of arrow means the long term cost. For hydrogen produced from natural gas and coal, the long term cost will increase due to increasing CO2 prices. For hydrogen from electrolysis from renewables, the long term cost will decrease.

Across the world, countries are devoting significant efforts in developing more sustainable technologies to produce hydrogen (Figure 74). For example, the US DOE Fuel Cell Technologies Office developed a pathway of hydrogen production in near, mid and long term. [255] This pathway involves biomass gasification and coal gasification with CCS in middle term and solar pathways in long term. As costs for renewable power continues to decline, electrolysis using renewable powers such as wind and solar seems to be a promising pathway for the future. [264] In addition, new and emerging technologies such as photo electrolysis and bio electrolysis are under R&D in various stages, and are showing promise for the longer term production of hydrogen.

4.1.3 Hydrogen delivery & storage

Figure 75 below shows a highlight of the production, delivery, and storage pathway of hydrogen; this section will focus on the delivery and storage portions.

The method and cost of hydrogen delivery is highly related to where hydrogen is produced, which can be classified into centralized, semi-centralized or distributed ways. [267] Centralized production refers to large central hydrogen facilities, which requires transportation to the final refueling station, while distributed pathway refers to production near the refueling facility. [268 273] Semi-centralized production refers to intermediate-sized hydrogen production facilities (5,000–50,000 kg/day) located in close proximity (40-161 km) to the point of use. These facilities can provide not only a level of economy of scale but also minimize hydrogen transport costs and infrastructure. [268] As hydrogen is still classified as part of Hazardous Chemicals Category in China, there are currently no distributed hydrogen production in China currently.[31]

Hydrogen delivery pathways are typically developed based on the various physical states in which hydrogen can be delivered. [267] Correspondingly, compressed gaseous hydrogen is usually delivered through truck/tube trail or pipeline; liquid hydrogen is often transported by truck and by other ways of transport, such as by rail or barge, which is often used in long distance transportation occasion as it is more cost-effective than gaseous hydrogen delivery method. [272] Solid hydrogen is mainly delivered within highly specific tanks, but is currently at various developmental phases and require more technological improvements for mass adoption [278 279]. Today, liquid or gaseous hydrogen via tube trailers and gaseous hydrogen via pipelines are the three primary methods of delivering hydrogen. [267]

In US and Japan, liquid hydrogen delivery is treated as an important way for transportation. [31] It is suitable for medium and long distance transportation, as its costs drop dramatically after 500km; however, liquid hydrogen suffers from high energy consumption (and therefore low energy efficiency) [274] In China, hydrogen is mainly delivered as compressed gas. [31] It has a higher energy efficiency compared to liquid truck, but still lower than pipeline delivery. [274] Delivering hydrogen through pipeline has the highest energy efficiency and cost advantage, but requires up-front investments. [275] With the development of the hydrogen energy industry, pipeline is expected to have the highest adoption rate for large-scale hydrogen transportation in the future. [274] Current deployment status and future deployment forecast of the three primary hydrogen delivery methods can be seen in Figure 76.

Hydrogen can be stored in three primary ways: compressed gaseous hydrogen, liquid hydrogen, and solid hydrogen by either absorbing or reacting with metals or chemical compounds or storing in an alternative chemical form. [271] However, the amount of energy required to compress hydrogen into liquid by super-cooling it down to -250°C results in ~40% efficiency loss with current technologies. [230] Gaseous hydrogen storage is the most matured storage technology today, and has the advantage of quick charge/discharge and low energy loss. [274] Solid hydrogen, with a theoretical energy efficiency higher than liquid hydrogen but lower than gaseous hydrogen, requires a higher technology complexity and is still at the test stage. [274]

Figure 75. current deployment status and future deployment forecast of the three primary hydrogen delivery methods [276]

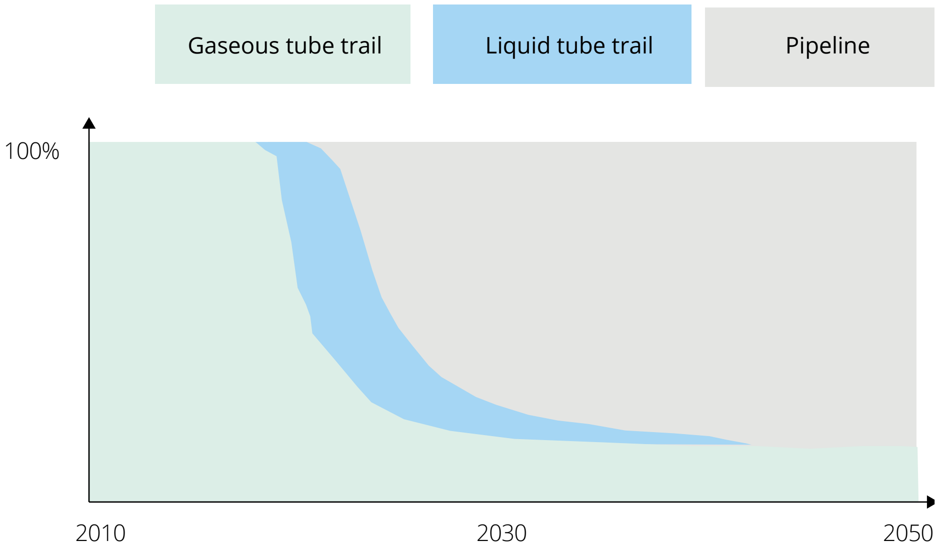
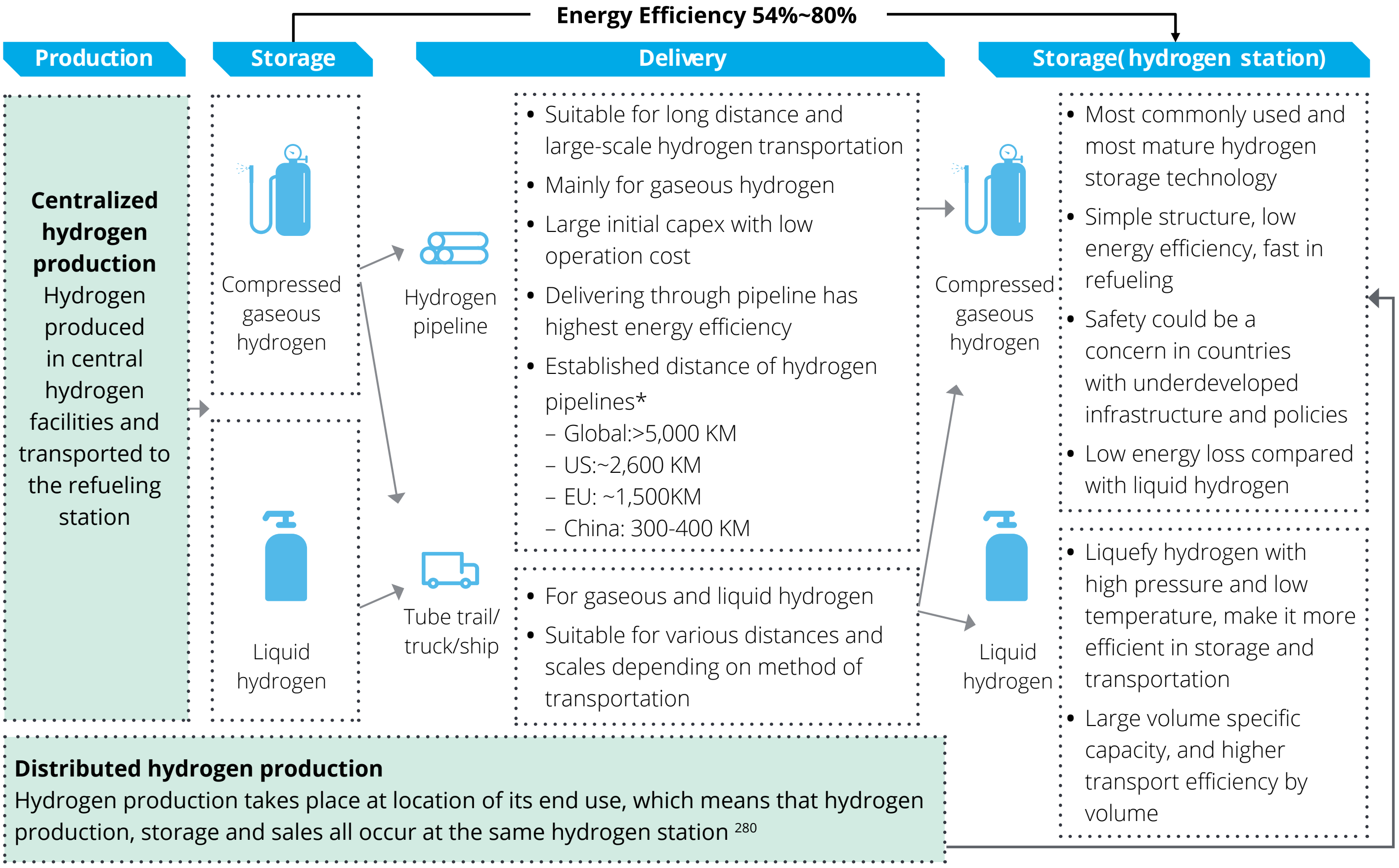


Figure 76. Hydrogen production, delivery & storage pathways



Centralized hydrogen production
Hydrogen produced in central hydrogen facilities and transported to the refueling station

- Suitable for long distance and large-scale hydrogen transportation
- Mainly for gaseous hydrogen
- Large initial capex with low operation cost
- Delivering through pipeline has highest energy efficiency
- Established distance of hydrogen pipelines*
  - – Global:>5,000 KM
  - – US:~2,600 KM
  - – EU: ~1,500KM
  - – China: 300-400 KM

- For gaseous and liquid hydrogen
- Suitable for various distances and scales depending on method of transportation

- Most commonly used and most mature hydrogen storage technology
- Simple structure, low energy efficiency, fast in refueling
- Safety could be a concern in countries with underdeveloped infrastructure and policies
- Low energy loss compared with liquid hydrogen

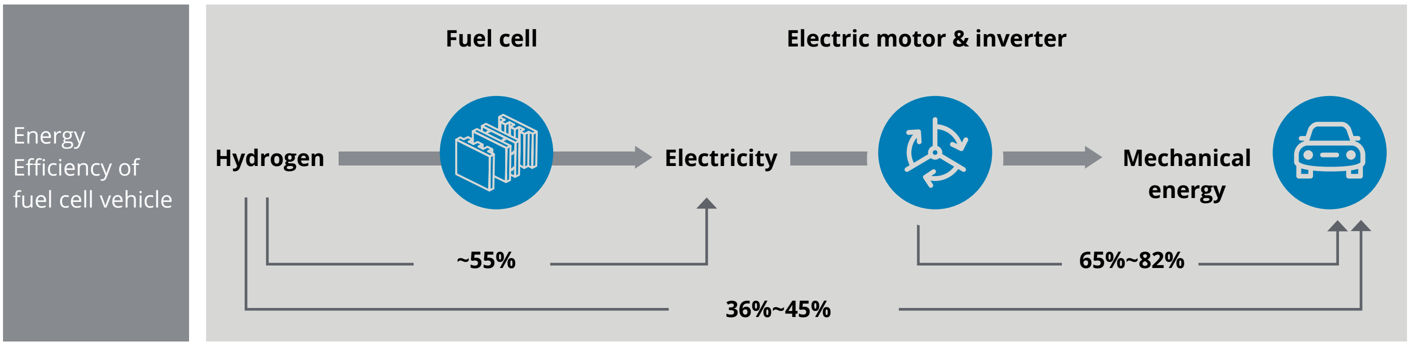
- Liquefy hydrogen with high pressure and low temperature, make it more efficient in storage and transportation
- Large volume specific capacity, and higher transport efficiency by volume

Distributed hydrogen production
Hydrogen production takes place at location of its end use, which means that hydrogen production, storage and sales all occur at the same hydrogen station [280]

4.1.4 Fuel cell operation

During fuel cell operation, FCEV turns hydrogen into electricity within the fuel cell stack, and then convert electricity into mechanical work, as shown in Figure 77. The latter part is accomplished by electric motor and inverter, which has the same energy efficiency between FCEV and BEVs. The gap in terms of energy efficiency between FCEV and BEV is mainly caused by the energy loss during hydrogen conversion into electricity, which is around 45%-55%.[229 230 232 277] [242 94] However, as technology advances, more heat can be harvested from fuel cell and provided to the vehicle, potentially increasing efficiency by 5% from 55% to 60%. [94 242]

Figure 77 Energy efficiency of tank to wheels stage of FCEV



Note:* we didn’ t consider natural gas pipeline here

4.2 Environmental impact framework

In the previous section, we covered the production, transport, and use of hydrogen, and the energy efficiency of each step. Another dimension that deserves exploration is the environmental impact of FCEVs, which is a highly complicated topic. Not only does this encompass every step of the hydrogen supply chain, we must also consider the manufacturing and disposal of the vehicle itself. These analyses are critical to understand the overall impact of FCEVs, which are hailed as a green renewable mobility solution of the future. This entire lifecycle is illustrated in Figure 78 below, which we will break down in the following pages in more detail.

Figure 78. Lifecycle analysis framework of vehicles

	Overall GHG emission (g CO_2-eq/KM) 4.2.1	**Production, delivery & use of energy (WTW)** 4.2.2	**Energy carrier production (Fuel cell/battery)** 4.2.3	**End of life**
FCEV	• The range is largely depending on hydrogen production and transportation • The low end of the GHG emissions range is electrolysis from wind/solar, while the high end is H2 from natural gas SMR	• Hydrogen production, delivery and storage account for the most part of GHG emission over FCEVs' lifetime • GHG emission result varies by different hydrogen production pathways	• FCEV has less GHG emission in energy carrier production stage than BEV • During the fuel cell systems production, majority of GHG emissions come from carbon fiber used in various components such as in the hydrogen tank	• Stilly in early stages since number of current vehicles reaching end-of-life is comparatively low • Leading fuel cell manufacturers have begun to recycle used fuel cell stacks • Recycling of platinum can be economically attractive as well as reducing environment impact • Carbon fiber in hydrogen tank has little recycle value
	FCEV 🟩▨ 130-230	**FCEV** ▨ 20~120	**FCEV** 🟦 ~110	
BEV	• GMG emissions range is due to differences in electricity sources for BEVs • BEVs also have higher emissions than FCEVs from a manufacturing perspective	• GHG emission mainly comes from production of electricity • Compared with FCEV, BEV has less energy conversion loss during fuel production, thus less GHG emissions	• Battery production accounts for largest proportion (>50%) of GHG emission during BEV lifetime, and releases 1.3-2 times higher GHG than ICEVs in this stage. • Core emission is from battery cell production and energy intensive due to high heat and sterile conditions involved	• As battery use increases in volume due to passenger Evs on the road, recycling is becoming a cause for concern • Recycling of lithium is not economically practical; recycling of aluminum and copper can significantly reduce GHG, but also have no economic incentives • Currently, second-life application is not economically attractive and still has safety concerns
	BEV 🟩▨ 160-250	**BEV** ▨ 10~100	**BEV** 🟦 ~150	
ICEV	• The range is due to the difference in gasoline and diesel	• Most of lifecycle GHG emission is the tailpipe during vehicle operation	• Manufacturing of powertrains and related components	• Recycling of vehicles consists of preparing the materials for treatment by dismounting, shredding and separation and preparing the components and materials for reuse, recycling or disposal
	ICEV 🟩▨ 180-270	**ICEV** ⬜▨ 140~210	**ICEV** 🟦▨ 40~60	

🟩▨ Overall lifecycle GHG emission (g CO2-eq/KM)

⬜▨ GHG emission of production and use of energy(g CO2-eq/KM)

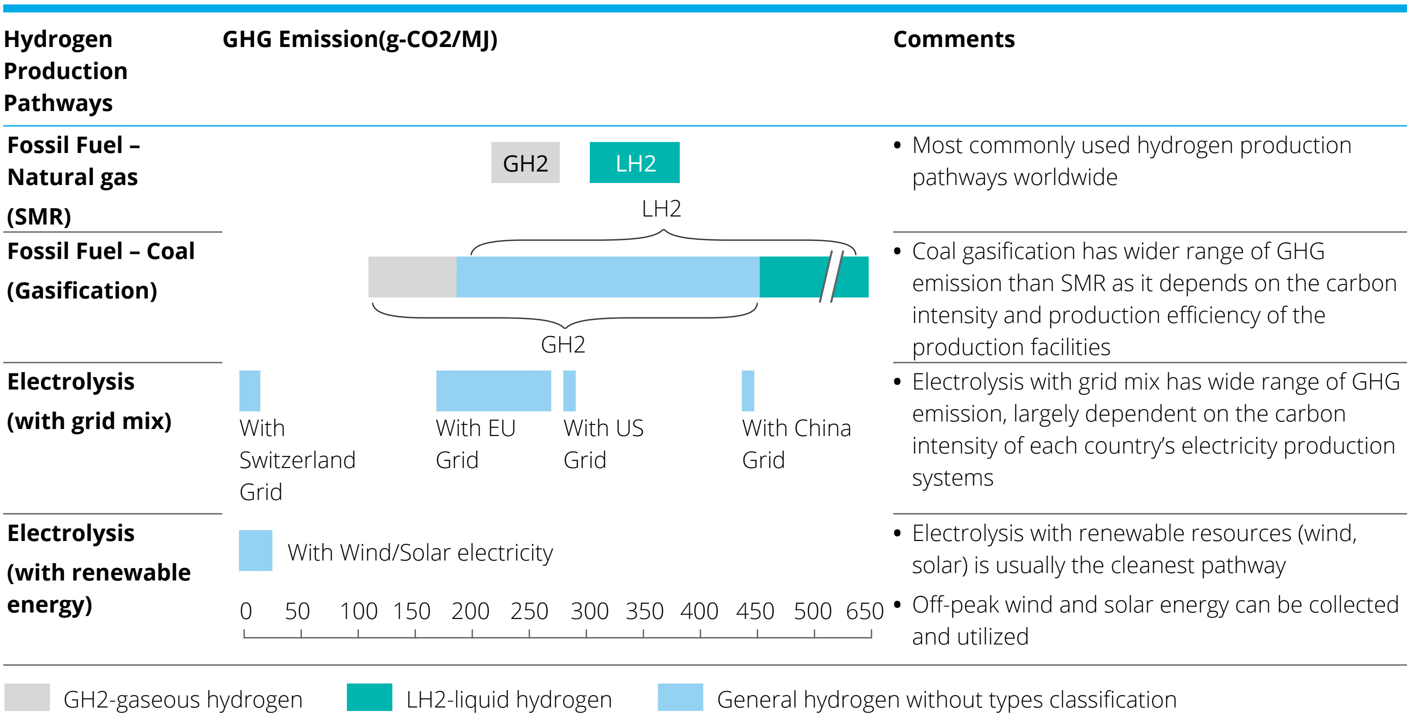
🟦 GHG emission of energy carrier production and end of life (g CO2-eq/KM)

4.2.1 Environmental impact of well-to-wheel stage

Although hydrogen fuel cell vehicle has been regarded as a green new energy vehicle that only produces water during its operation, the process of how hydrogen is produced, stored, delivered and refueled produces greenhouse gas and causes environmental impacts. According to the Hydrogen Council, the CO2 emission of hydrogen pathways (well to tank period) from natural gas via SMR was ~75 g/km, accounting for ~60% of total CO2 emission of a FCEV from lifecycle perspective. [82] Therefore, hydrogen production is a key part to ensure low-carbon performance of FCEVs [262 227]. Largely due to energy efficiency and GHG emission of feedstock conversion, the total energy consumption and GHG emission varies among different hydrogen pathways. [262 273 281] As shown in Figure 79 below, the lifecycle GHG emission of different hydrogen production pathways varies; water electrolysis with grid releases the widest range of GHG emission, while electrolysis with renewable energy is the most environmentally friendly. [282 284]

Hydrogen produced from electrolysis from US grid electricity uses relatively high amounts of total and fossil energy and results in significantly higher GHG emissions. It is largely due to the relatively low efficiency and high emissions associated with the coal-based power plants that dominate electricity generation in US. [273 283] The similar result was also found in China. Water electrolysis with China grid mix of electricity requires highest energy consumption and produces GHG emissions, as electricity generated in China is currently dominated by coal-fired energy [262 266].

Figure 79 GHG emission varies by different hydrogen production pathways



Hydrogen Production Pathways	GHG Emission(g-CO2/MJ)	Comments
Fossil Fuel – Natural gas (SMR)		Most commonly used hydrogen production pathways worldwide
Fossil Fuel – Coal (Gasification)		Coal gasification has wider range of GHG emission than SMR as it depends on the carbon intensity and production efficiency of the production facilities
Electrolysis (with grid mix)		Electrolysis with grid mix has wide range of GHG emission, largely dependent on the carbon intensity of each country's electricity production systems
Electrolysis (with renewable energy)		Electrolysis with renewable resources (wind, solar) is usually the cleanest pathway Off-peak wind and solar energy can be collected and utilized

FCEVs and BEVs do not emit GHG through the exhaust during vehicle operation. However, emissions occur instead from electricity generation. [287] As we have shown in the above figure, the GHG emission varies depending on the source of electricity or hydrogen. [228] [286 287 288 31]

Many researchers conclude FCEV produce fewer emissions than conventional vehicles, while others have argued that when viewed across their total lifecycle, FCEV are not that green after all. [285] This depends on perspective of the researcher, and how holistically the whole hydrogen lifecycle is considered. For example, using electrolysis-produced hydrogen with current grid mix of electricity in China, there is no advantage for fuel cell vehicle compared with BEV or ICE, in either energy consumption or GHG emission. [262] However, future outlook for hydrogen production is much brighter, due to the following factors:

- Renewable energy based electricity would result in dramatically lower WTW GHG emissions as we have just seen.
- Hydrogen can act as an energy-capture carrier in instances where electricity would be otherwise wasted; for example, solar and wind electricity production are affected by seasonality and peak usage cycles, resulting in overcapacity of electricity production; hydrogen captures and stores this wasted electricity, and therefore can be considered to be negative in terms of GHG production. [250 251 252]
- Though current grid mix around the world leaves much room for improvement, countries are investing significant efforts to improve electricity production; for example, according to China hydrogen alliance, by 2050 around 70% of hydrogen would be produced by renewable resources.[31]
- Finally, as we have seen in the previous section, electrolysis-based production of hydrogen only accounts for 4% of hydrogen production; this combined with the above points show a path for dramatic improvements of hydrogen production from a GHG perspective in the future.

Diesel tailpipe emissions

Power plant operations

Renewable energy outlook

4.2.2 Environment impact of manufacturing

For conventional petroleum-powered ICEVs, approximately 80% of the lifecycle GHG emissions and energy use are associated with the combustion of the fuel during vehicle operation. [227 291] However, BEVs and FCEVs have higher percentages of their overall lifetime emissions coming from its manufacturing and end-of-life processes. [227] Materials used in the energy systems of BEVs and FCEVs, as well as their associated assembling processes are two major incremental GHG emissions of BEVs and FCEVs compared with GHG emissions of ICEVs during manufacturing [326].

Though hydrogen production plays the key role in terms of energy consumption and GHG emission of FCEVs, the manufacturing process of the fuel cell system cannot be neglected. The GHG emissions of fuel cell system manufacturing make up around half of the GHG emissions of the FCEV manufacturing and disposal process [326].

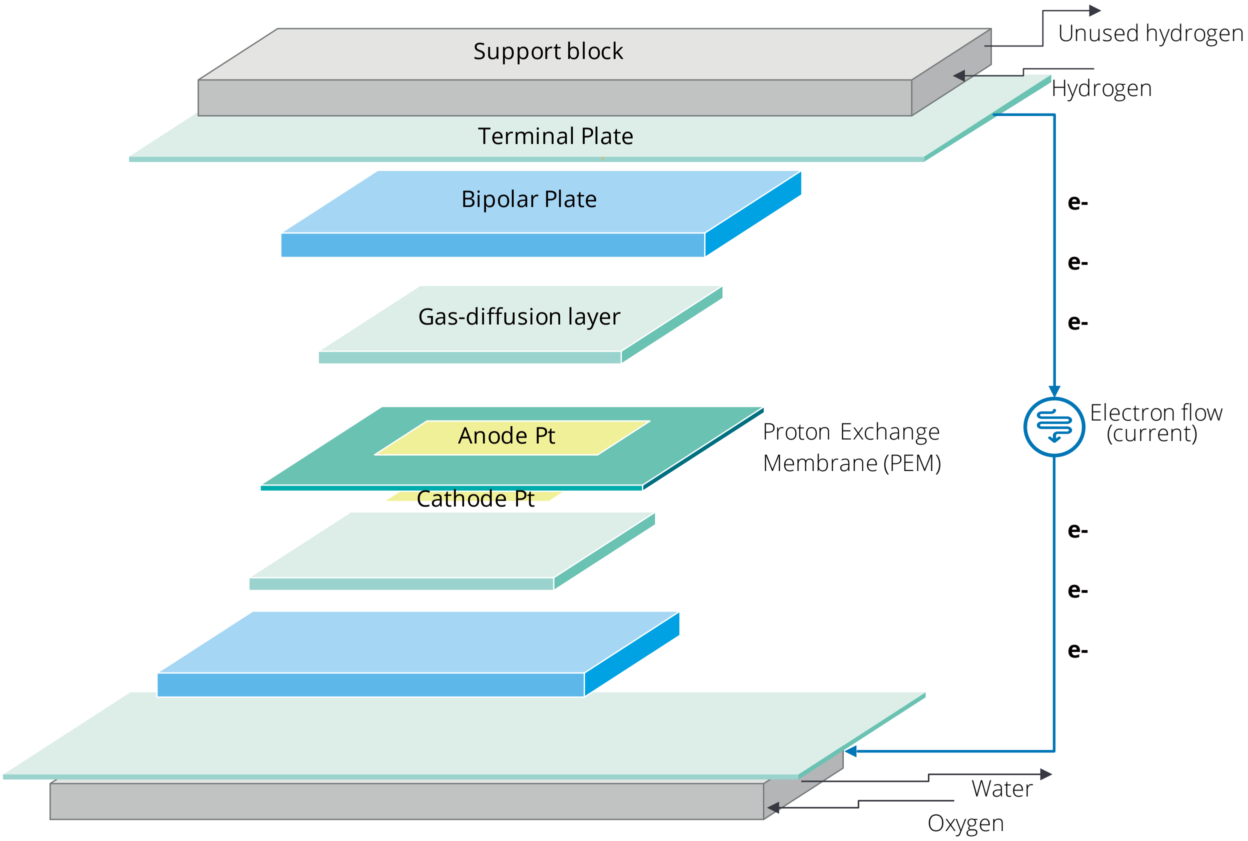
As we have shown earlier, the fuel cell system is comprised of a fuel cell stack and other supporting components. The fuel cell stack, where the actual electrochemical reaction happens, consists of components such as the catalyst layer, membrane, gas diffusion layer, and bipolar plates, as shown in Figure 80 below. [248] Using PEMFC as an example, platinum is applied in the catalyst layer. To most unawares readers, the use of platinum, which is a high-cost precious metal, might be a point of criticism for FCEVs.

Furthermore, platinum causes a series of environmental impacts, such as emissions of sulphur oxides produced during the extraction of the material. [248] [289] [290]

However, the amount of platinum used is exceedingly small and decreasing. For example, the amount of platinum used in fuel cell vehicles is approximately 10-20 grams per vehicle [294]. This can be compared to ICE catalytic convertors, which require approximately 5-10 grams of platinum for a similar sized diesel vehicle [294]. In addition, platinum-free catalysts are also under various stages of development, as showcased in later pages. [246]

Overall, it is important to note that the majority of fuel cell system costs are manufacturing-cost associated, instead of materials cost. In fact, the most expensive materials-platinum, is estimated to only comprise 0.8% of total fuel system costs for a 70kw fuel cell vehicle [295]. As production ramps up to economies of scale, IEA estimates that the cost of fuel cell components can be reduced by 65% by increasing plant scale from 1,000 to 100,000 units per year. [246]

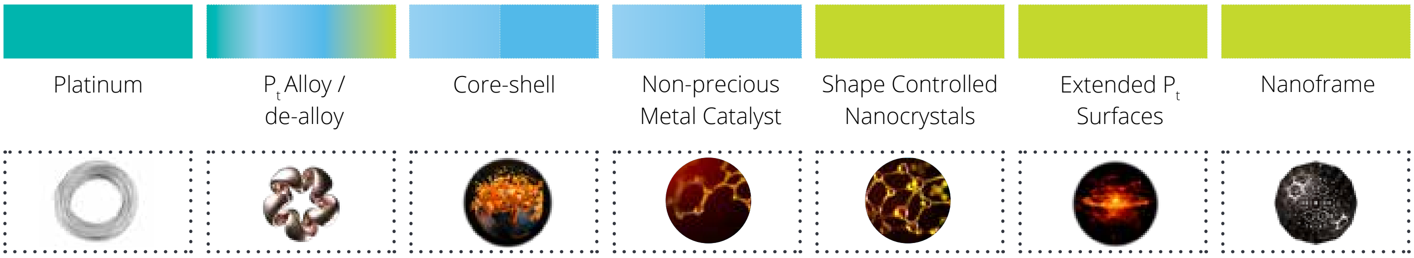
Figure 80: Fuel cell stack components and typical materials



Component	Typical Materials
Catalyst layer	Platinum (0.2~0.4 g/KW)
Membrane	Sulfonated tetrafluoroethylene-based fluoropolymer–copolymer
Gas diffusion layer	Carbon
Bipolar plates	Carbon/Metal
Terminal Plate [292] [293]	Plated-metal

It is expected that, with continued advancement of R&D for fuel cell system, the use of platinum on the catalyst will continue to decrease. A wide variety of promising catalysts have been developed, as shown in Figure 81. Those catalysts demonstrate exceptional activity based on lab testing, and are in various stages of demonstration/R&D. [296]

Figure 81: Potential Catalyst for fuel cell and the application status



P_t Alloy / de-alloy:
- Alloy P_t with other catalysts or chemically de-alloy catalyst

Core-shell:
- Combine reactive elements in a unique core-shell structure

Shape Controlled Nanocrystals:
- Nanocrystals with controlled shape (e.g. rectangular bar)

Extended P_t Surfaces:
- Increase the surface area of P_t to increases the heat transfer

Catalyst application status (catalyst production required):

🟩 **Mass Production**—Use in products (kg to tons)
🟦 **Electrode integration**—technology challenges remaining (g)
🟦 **Scale-up**—process optimization and validation (g to kg)
🟨 **R&D**—ex-situ benchmarking (mg)

Manufacturing of fuel cell stack

Manufacturing of hydrogen tank

When considering BEVs, it can often be misunderstood that BEVs have no GHG emissions. While this is relatively true during the operation phase, the manufacturing of the BEV itself leaves considerable carbon footprint [327]. In fact, BEVs leave more carbon footprint than FCEVs and ICEVs during the manufacturing process [326].

Firstly, the materials usage and trend of FCEVs are quite different from BEVs. For BEVs, the cost of a battery may be 75% related to its materials (such as lithium and cobalt [298] [299], and is therefore unlikely to decrease at a rate similar to fuel cell systems in the future.

Furthermore, the manufacturing of the battery accounts for the largest GHG emission of BEV's lifecycle. [228] [297] This is mainly due to the energy-intensive process of lithium-ion battery manufacturing. [297] [286] Battery manufacturing requires extracting and refining rare earth metals, and is energy intensive because of the high heat and sterile conditions involved. [297] [288] In the process of battery production, nearly 50% of GHG emission are from the assembly and manufacturing of battery, while the rest half mainly comes from raw materials mining, refining and processing process. [228]

Besides, mining and recycling of related metals also add pollution. For example, lithium mining consumes lots of water. Besides, toxic chemicals from lithium mining are likely to leak from the evaporation tank of lithium ores to water supply systems [300]. As for recycling, since the materials could not been fully recycled, the unrecycled lithium and cobalt would cause heavy metal pollution and increasing environment PH [301].

Lithium mining

Battery vehicle production

supply security of metals—Platinum

As outlined in previous sections, FCEVs (platinum) and BEVs (lithium and cobalt) require the use of metals in their production. In order to estimate future price trends and future large-scale production possibilities, we have provided a high-level analysis of the supply security of these metals.

Firstly, we evaluated the metal demand and supply situation for FCEVs. As shown in Figure 82, the growth of supply of platinum has outstripped demand for the past few years. From the supply perspective, global platinum reserves are estimated to be 14,000 tons (494 million oz) [302]. Mining volume of platinum is expected to remain stable over the foreseeable future [294] . In term of platinum recycling, as automotive companies are required to take responsibility for end-of-life vehicles in many countries, an increasing proportion of platinum supply are sourced "above ground", coming from recycled auto-exhaust catalysts rather than mining. The production capacity of platinum is forecasted to increase over the coming years and recycling will become a significant supplier.

From a demand perspective, overall demand for platinum has been decreasing due to investment and jewelry demands decline [303]. As shown in figure 83, platinum is mainly used in jewelry, automotive, industrial applications and investment. [303] With the decline usage in jewelry and investment, extra room has been provided for fuel cell usage. The demand in jewelry has declined 20% from 2014 to 2018, and the demand in investment has declined from 150 koz to 15 koz in 2018 [303].

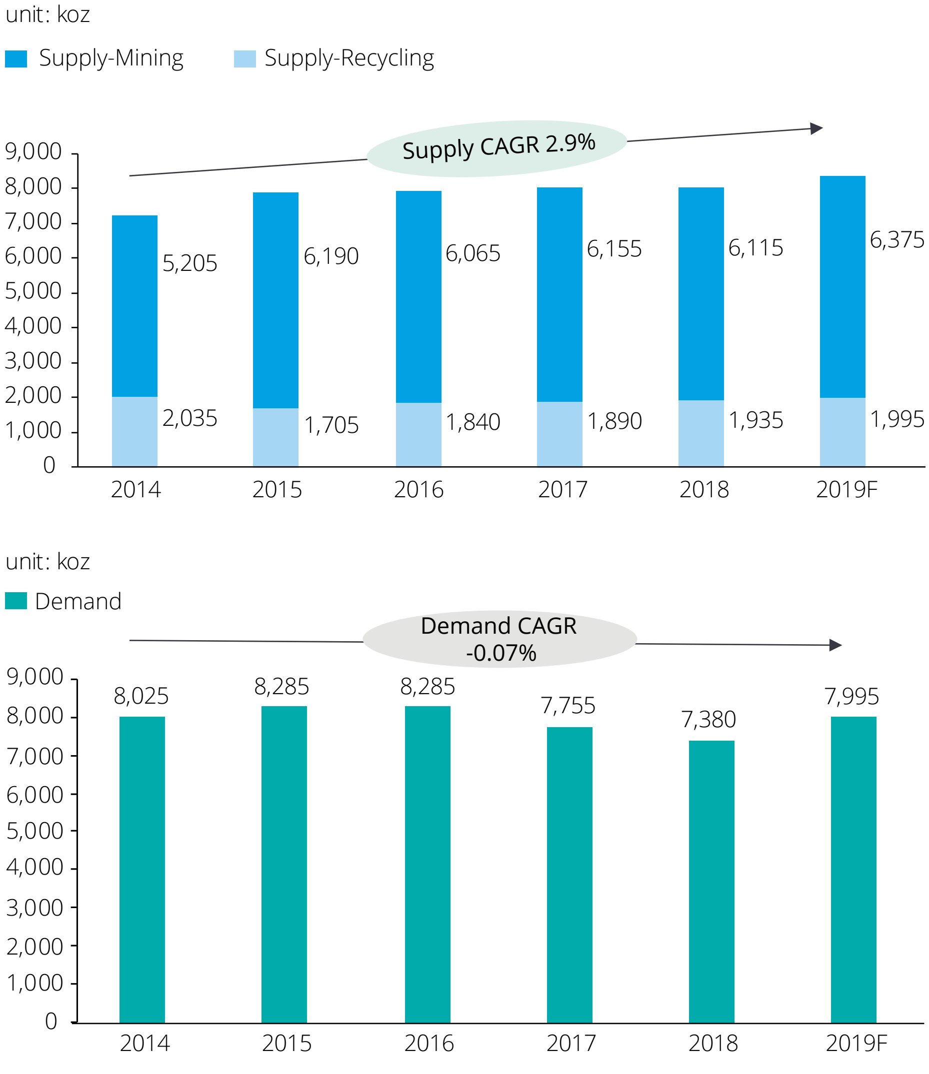
The amount of platinum used in vehicles has stabilized between 3,100 and 3,500 koz in recent years, mainly in ICE catalytic convertors, and a small proportion being used for fuel cells. [304]

According to industry forecasts, if the penetration rate of fuel cell vehicles reaches 4.5% in the short to medium term, the global demand of platinum as fuel cell catalyst will increase from 88 koz at present to around 2,280 and 2,660 koz in the future, assuming 12.5 and 17.5 g platinum per vehicle, respectively [303] [306] . Without significant demand increase from other sectors such as jewelry, there is no forecast for shortage of platinum for fuel cell vehicles.

Furthermore, the use of platinum as been continuously decreasing as fuel cell technology evolves. Currently, the platinum content in fuel cell catalyst has decreased to 0.12g/kw for Honda Clarity and 0.175g/kw for Toyota Mirai. [304] The average amount of platinum catalyst needed per fuel cell vehicle in China is about 0.4g/kw in 2015, and are forecasted to decrease to 0.3g/kw in 2020, 0.2g/kw in 2025 and 0.125g/kw in 2030. [305]

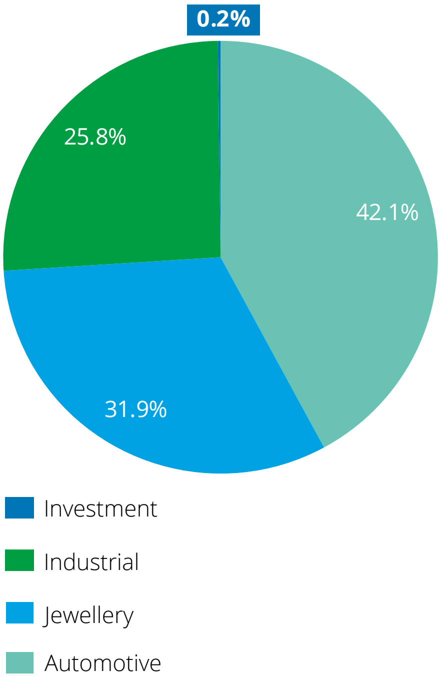
In conclusion, considering the development of the hydrogen fuel cell vehicle market, the supply of platinum are forecasted to be secure to meet the demand growth in the short and medium term. [304]

Figure 82. Global Supply and Demand of Platinum



Source: World Platinum Investment Council

Figure 83. Demand of Platinum by usage in 2018



Lithium

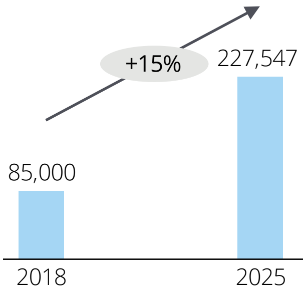
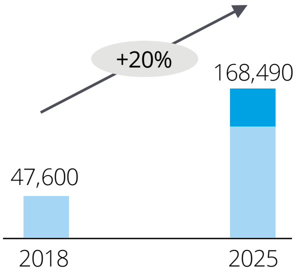
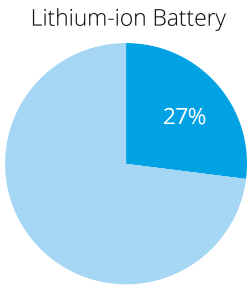
Lithium is an integral ingredient when building a battery electric vehicle. [307] From a supply perspective, current total reserves stand at 14,000,000 tons, and can be found in large quantities in certain countries, including Chile, Australia and China. [307] [309] According to mineral commodity summaries 2019, worldwide lithium production is about 85,000 tons in 2018 [309]. Meanwhile, with expansion announcements for lithium over the next several years, total lithium supply is forecasted to reach 227,547 tons by 2025, suggesting ample supply capacity to meet the expected growth in demand. [308]

Meanwhile, the demand of lithium is increasing quickly. According to mineral commodity summaries 2019, worldwide lithium consumption is about 47,600 tons in 2018, [309] and is forecasted to increase to around 126,226-168,490 tons by 2025. [308]

Lithium is mainly used in batteries, greases, heat-resistant glass and ceramics. BEV accounts for about 27% of the total lithium demand. [310]

A detailed supply and demand of lithium is shown in Figure 84. Overall, the supply of lithium can be satisfied in the short to medium term. However, as demand is projected to outstrip supply, price increases or shortage could be a concern in the future.

Figure 84. Total Supply and Demand of Lithium

Metals	Supply (tons)	Demand (tons)	Lithium-ion battery Demand as of total %	Comments
Lithium				• Supply – Lithium reserves are unlikely to be exhausted soon; – Major mining companies have expansion plans – May come under pressure, as extracting lithium from brines (accounting for half of the annual production of lithium) is a slow process that cannot respond quickly to steep rises in demand [286][287] • Demand – Increase quickly driven by BEVs number increase

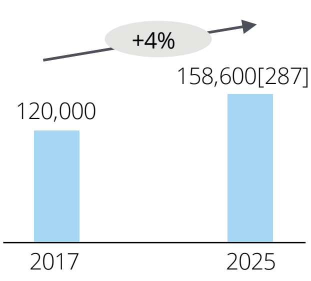
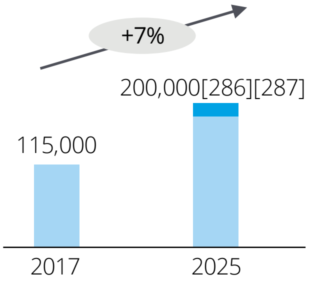
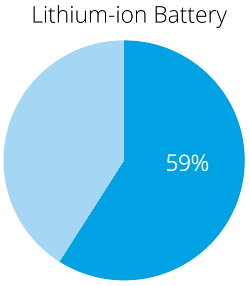
Cobalt

Cobalt is a relatively scarce metal in the earth's crust [228]. As shown in Figure 85, worldwide cobalt production is about 120,000 tons in 2017, while consumption is around 115,000. [309 310] However, cobalt presents a particular challenge in the future, given the high uncertainty of supply. [311]

Cobalt supply is heavily relied on supply from Congo, which has a high level of geopolitical risk. The world's total cobalt reserves stand at 6,900,000 tons, 49% of which is in Congo [309], which supplies more than 60% of world cobalt mine production. [309 311] Due to this geopolitical risk, cobalt is considered a "conflict metal", due to it being mined in places controlled by armed groups. [228] This is unlikely to change in the near future, and may lead to a cobalt supply crisis. [311 312] Furthermore, cobalt typically occurs at a low concentrations, which means it is mainly mined as by-product of other metals, such as copper and nickel. [309] Thus, the price of copper or nickel typically determines the economics of operations, resulting an inelasticity of cobalt supply and the inability of mined cobalt to respond to potential increasing demand. [311]

However, cobalt is an important material in BEVs. Lithium batteries account for about 59% of the total cobalt demand. [310] The uncertainty of supply will be a big challenge for battery producers. In order to solve this problem, most automobile manufacturers and battery companies are developing new formulations of lithium-ion batteries with reduced proportion of cobalt. Some companies have even begun to develop cobalt-free batteries. [313] However, to reduce cobalt usage, battery manufacturers tend to increase the amount of nickel used to maintain the energy density of the battery, which lower the structural stability of the electrode material, and in turns affects battery lifecycle and safety. [311 313]

Figure 85. Total Supply and Demand of Cobalt

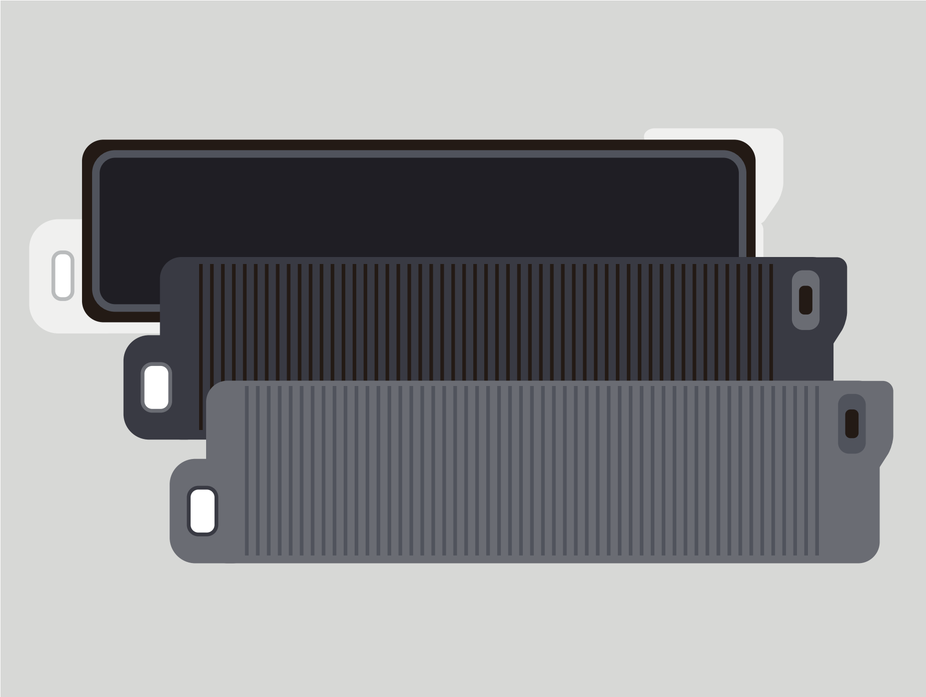
Metals	Supply (tons)	Demand (tons)	Lithium-ion battery Demand as of total %	Comments
Cobalt				• Supply – Reserve is concentrated within Congo with a high level of geopolitical risk – Produced though by-products method may result in an inelasticity of supply to respond to potential increasing demand • Demand – Increase quickly driven by BEVs number increase – Trend will be less cobalt or cobalt-free in lithium-ion battery to response to the supply risk

4.2.3 Environment impact of end-of-life

Recycling is one of the most important topics for the end-of-life environmental impact analysis. Negative environment impacts during disposal process mainly come from metal materials pollution and recycling energy consumption. This section would focus on evaluating the recycling of fuel cell system in FCEVs and battery in BEVs. It should be noted that FCEVs and BEVs have the possibility to reduce carbon footprint and decease negative impacts on environment if the materials used in fuel cell and battery are well recycled [325]. Typically, FCEVs have less GHG emissions than BEVs during the disposal process [326].

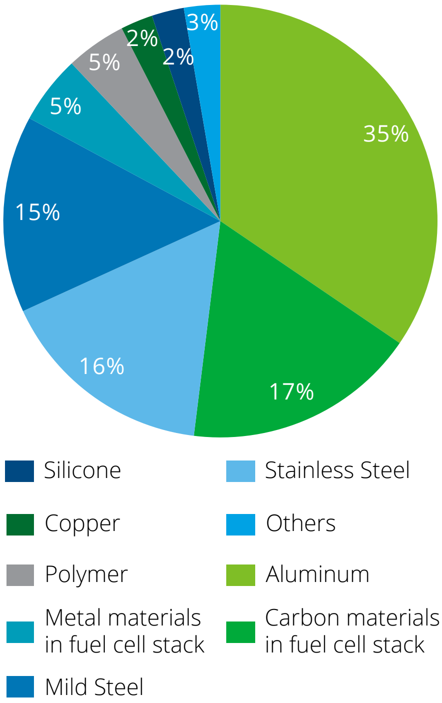
Currently, recycling technologies involved in fuel cell systems are still in early stages. Figure 86 shows the major materials breakdown used in fuel cell systems [94], among which platinum was included in metal materials in fuel cell stack, which compromised of relatively very small percentage. Today, materials in fuel cell systems are typically not being recycled on a large scale [314] [316]. Instead, traditional methods tend to involve the burning or burying of obsolete components, which causes environmental damage and wasting of resources. [314] Therefore, in order to reduce negative environmental impact in a FCEV lifecycle, apart from cutting down GHG emissions from FCEV manufacturing by adopting more advanced manufacturing technologies and processes, it is important to decrease potential environmental pollution of FCEV's disposal and reduce key material consumption through recycling. [315]

However, it should be noted that there is an existing mature supply chain to recycle platinum in traditional ICEV catalytic convertors. Therefore, the technology exists to do so for fuel cell stacks as well. Current technology by Ballard using proper recycling processes achieves more than 95% of the precious metals being reclaimed during fuel cell recycling [94]. Furthermore, the carbon bi-polar plates in the fuel cell stack can be reused when the stack are being refurbished. This not only cuts down on environmental impact, but also helps alleviate concerns of metal supply security. Ballard currently refurbishes thousands of FC stacks every year with residual value given back to customer [94].



Refurbishing, Reusing, and Reclaiming fuel cell components

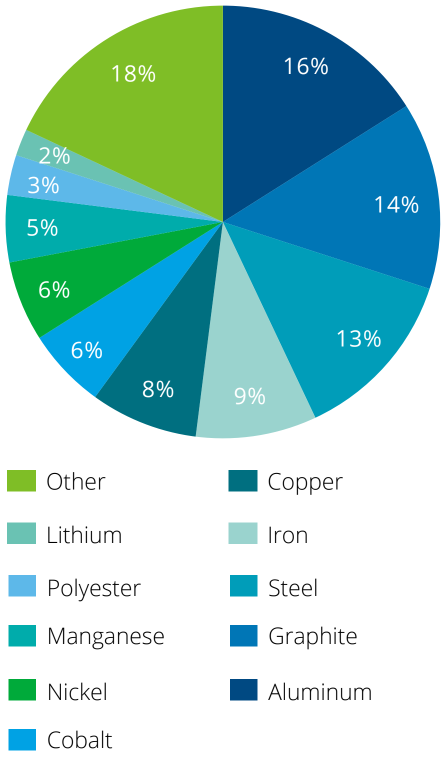
Figure 86: Materials breakdown of a typical fuel cell system (85kw) (by weight) [94]



BEV end-of-life is an important and complex topic, which we will only cover at a high level here. There are 3 main methods, which are reuse, recycling and disposal. Reuse and recycling can have significant benefits in terms of other lifecycle stages, in particular the sourcing of raw materials. [286] For example, improved waste management and higher efficiencies through increased levels of reuse and recycling could reduce the high toxicological impacts associated with the intensive use of base metals such as copper and nickel in electric vehicles. [286, 318, 319]

Reuse, or second life application, can be applied for lithium-ion battery, which retains a portion of its original capacity after being removed from the vehicle. This battery can then be used in stationary storage applications, but eventually the battery will still reach end of life and require recycling or disposal [286, 297, 320, 94]. Concerns of battery expected lifetime and safety is hindering wide adoption. [320] In addition, as the price of new battery packs continues to fall, second life batteries are having a hard time finding economic attractiveness.[320]

Figure 87: Materials breakdown of a typical BEV battery (by weight) [297] **[328, 329, 330, 331, 332, 333]**



As the electric vehicle industry grows, battery recycling may also become more feasible. [297] Using recycled materials to produce a new battery could result in reductions in GHG emissions of up to 50 % across the battery production process. [286, 297, 317] Figure 87 below shows the typical breakdown of a BEV battery by material. Recycling of rare metals such as cobalt, nickel, and lithium currently present the greatest economic incentives. However, key components such as aluminum, copper, and graphite are currently rarely recycled due to low economic inventive. [286, 297]

Disposal by landfilling of electric vehicle batteries is then the least desirable option for end-of-life treatment. [286] Unfortunately, this ends up being the most widely used method causing environmental damage due to reuse and recycling being rarely used currently, as we have just shown [321, 322, 323].

4.2.4 Environmental impact conclusions

Overall speaking, as we have shown in section 4.2, a typical FCEV offers the lowest environmental impact and GHG emission across its lifecycle compared with BEVs and ICEs, which can be summarized due to:

- Lower lifetime emissions during the energy production, delivery & use cycle compared with ICE vehicles
- Lower lifetime emissions and less hazardous materials usage/disposal during the manufacturing and end-of-life processes compared to BEVs

This reduction in emissions can be quite dramatic in real-world applications. For example, by comparing diesel trucks with gaseous hydrogen fuel cell trucks with fuel cell produced from centralized SMR, the latter can reduce 5%-26% fossil fuel consumption, and 20 to 45% of GHG emissions. [324]

As we have also shown, the range of emissions reduction depends on various factors, but is perhaps most reliant on differences in hydrogen production pathways. In the future, we anticipate that the environmental impact of FCEVs will further improve, driven by:

- Improvements in hydrogen production pathways as demonstrated in section 4.1
- Improvements to fuel cell system technology and improved optimization of platinum usage in fuel cell stack and other materials in fuel cell balance of plant, compared with BEVs that suffer inherently from large amounts of heavy metal usage
- Improvements in recycling processes at end-of-life, compared with BEVs which have much to overcome in this regard, both in terms of second-use and recycling economic viability [228, 286, 297].

Conclusion and looking ahead

Hydrogen is not only the most abundant element in the universe, it is the input for nuclear fusion that powers our sun and supports all life on this planet. It is also a key element in the fossil fuels that have powered the advancement of commerce, industry, and standards of living since the first industrial revolution. In addition, hydrogen as an energy carrier has two major advantages over fossil fuels for mobility applications. Its energy release through oxidation produces only water as an output, and it is infinitely renewable, as long as the sun shines.

It is useful to remember that all energy on our planet comes from the sun's hydrogen fusion processes. But whereas fossil fuels are the result of the sun's energy stored through the life and death cycles of plant and animal life over the history of this planet, in generous but finite supply; hydrogen is the current and infinitely sustainable result of the sun's current light and other radiation that energizes solar, wind, and hydro electricity generation. Movement towards hydrogen use on the Earth is simply a shift away from withdrawing energy deposited in finite energy banks underground to solar energy that arrives here in real time all the time, at the rate of 430 quintillion joules of energy per per hour. This is more than the entire Planet Earth uses in a year. That difference is the essence of sustainability.

There is little doubt that hydrogen will fuel the future of our planet, as it has through the Earth's entire history. The focus of this research work is to identify the optimal mechanisms to extract the maximum energy to power applications in mobility and beyond incl. production and usage of hydrogen. Over time hydrogen uses have and will include simple conversion through burning, internal combustion systems, direct electricity production through fuel cells, and eventually controlled fusion.

This three volume study has been planned to explore hydrogen in an expanding context. This volume has focused on the immediate future, as hydrogen already plays an increasing role in powering the mobility needs of the Earth's growing population. As such, we have analyzed the viability of current technologies and future trends as well as existing applications and their implications for the future, all with a total cost of ownership approach that compares direct-to-electricity hydrogen options to other systems of portable energy to power mobility, including internal combustion engines fueled by fossil fuel products and electric systems based on battery storage, primarily lithium. We have explored many aspects of current energy eco-systems, basic efficiencies and life-cycles of competing options, development status of critical technologies, and projected cost curves in a near and mid-term time frame as developments proceed.

In conclusion, based on our volume 1 analysis, fuel cell and hydrogen have great potential to drive the Future of Mobility. Regions including the U.S., China, Europe, and Japan, among others are recognizing this trend and focusing policy efforts on developing fuel cell technology, supply chain, and infrastructure on multiple fronts. Due to characteristics such as fast re-fueling (similar to ICEVs), high energy density (i.e. lower weight than BEVs), FCEVs is an extremely attractive solution for heavy duty and commercial vehicles. We have also demonstrated that the economics of FCEVs are forecasted outperform BEVs and ICEVs for specific applications. Overall, we estimate that the TCO of FCEVs will decline by almost 50% in the next 10 years, driven by several factors such as fuel cell system price decrease, economies of scale, usage of renewable energies to produce hydrogen, as well as maturation of hydrogen infrastructures. Lastly, FCEVs demonstrate the lowest lifecycle greenhouse emissions compared with BEVs and ICEVs and showcase the highest potential room for improvement room, due to increased use of renewable energies in hydrogen production.

As government leaders, business leaders, academia and technology thought leaders ponder with the climate and pollution challenges mankind faces, demand arises for productive analysis in a highly integrated ecosystem approach that that recognizes the energy needs of mobility as they fit into a broader and more comprehensive energy landscape.

Population growth, the dynamics of urbanization, improving lifestyles and rapidly growing consumption of large populations emerging in modernizing economies contribute to a highly-geared increase in energy needs. The undeniable climate impact of existing fossil fuel usage becomes more severe and unbearable. In the two forthcoming volumes of this series, we will explore hydrogen in this expanded energy landscape. Volume 2 will look more broadly at applications that will impact not only mobility but every energy need of modern life. The future role of hydrogen-based storage and management of non-mobile, renewable systems, for example, will be a synergistic counterpart of its expanding role in mobility.

The final volume will explore the hydrogen supply chain, essentially the commercial aspects and technology developments that will enable production, storage, transport, and distribution to the complex array of end-users explored in the previous two volumes. Here again the analysis will focus on costs, incentives, and risks that will shape the broad deployment of hydrogen in the future. Commercial viability of hydrogen across a range of subsystems will depend on a calculus encompassing cost, incentives, and risks. Although we are at a very early stage of consideration, much less deployment, in many subsystems where we believe hydrogen will be prominent, there is sufficient qualitative and quantitative information available to make this not only a possible but an essential undertaking.

Hydrogen sits high on the agenda of energy policy makers, energy suppliers, and technology companies in relevant sectors. In countries like China that make long range and explicit plans for future development, hydrogen is already a featured topic. Emerging global technology and economic competition is of high importance to drive the creation and deployment of efficient energy solutions. This progress will become a critical competitive advantage for major economies in the fray. But perhaps more important is the fight against Climate Change, clearly one of the most important endeavors of our generation. Even at first glance, hydrogen deployment in mobility is undeniably part of the solution. However, no reflections on the fight against climate change are useful and realistic without a solid understanding of potential economic incentives for both government and enterprises to adopt and pursue the new technology. It is also important to note, that hydrogen is not a sole solution in converting to green energy to power mobility around the world. Rather, it is part of the solution, together with BEVs and other emerging technologies. Sophisticated readers might note that all governments mentioned in this paper provide policy incentives towards many different types of green energy solutions – the future mobility ecosystem may very well be powered by different technologies depending on use cases, consumer needs, and level of infrastructure development.

We have demonstrated in this volume, that fuel cell mobility can be at least on par with or even more cost-effective than BEV or ICE competitors in the near- to mid-term, when considering a variety of commercial applications. This claim is well supported in multiple use case scenarios, across a variety of geographies. All three of these power approaches have significant room for improvement from a TCO perspective. But the improvement curve from a TCO perspective of FCEVs is demonstrably superior in the near and mid-term future. Operators of key subsystems across the world are already enjoying the benefits of FCEV, which is at a relatively younger stage of development than battery-powered BEVs and certainly ICEs. Furthermore, we have demonstrated that FCEVs are cleaner and more environmentally friendly across their entire lifecycle than BEVs and ICEVs, with more improvements to come as hydrogen production shifts toward a broader role in renewable energy development.

We look forward to our continued exploration of this fascinating topic with our readers in the next volume of this series.

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