Hydrogen Powered Cars and Trucks: Is there a role for them in the electrified U.S. future?

by

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Submitted to the System Design and Management Program in Partial
Fulfilment of the Requirements for the Degree of

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Abstract

Climate change is a systemic risk to the world's economy. Significant and rapid cuts in carbon emissions are needed to limit global warming. Fuel Cell Electric Vehicles (FCEV) offer an attractive alternative for decarbonizing the transportation sector for both Light Duty and Heavy Duty categories. The cost of hydrogen fuel cell-related technologies are decreasing rapidly and FCEVs may provide an alternative to electric vehicles in decarbonization.

This thesis provides a fresh look at economics of FCEVs and competing alternatives for decarbonizing transportation and their long-term trends in the US. Based on the recent data, the total cost of ownership (TCO) models are developed for three types of drive train Internal Combustion Engine Vehicles (ICEV), Battery Electric Vehicles (BEV) and FCEV for both Light Duty Vehicle (LDV) and Heavy Duty Vehicle (HDV) categories. A hydrogen retail cost model is developed to provide a detailed understanding of the cost components. The fleet dynamics of Light Duty vehicles (LDV), including ICEV, BEV and FCEV, are modeled using MIT Economic Projection and Policy Analysis (EPPA) model to understand the characteristics of long-term trajectories for the LDV fleet growth in the US.

The TCO for BEV and FCEV are higher than ICEV in the LDV sector in the absence of carbon abatement credits or other government support. This implies that FCEVs are about 10% more expensive than BEVs on a cost-per-mile basis. However, there are cost reduction pathways that might make FCEVs competitive in the next 10 years and in the scenarios of accelerated actions. The percentage of FCEVs in total vehicle stock in the US might grow to more than 14% by 2050. The growth is contingent upon the TCO reduction pathways. The TCO of BEV and FCEV Class 8 type trucks are 24% and 40% higher than ICEV trucks, respectively. The fuel cost for FCEV is 2.4 times of BEV's fuel cost and the retail price of FCEV Class 8 type truck is 1.5 times that of BEV truck. A 40% reduction in hydrogen retail price or a 70% reduction in FCEV truck retail price would make FCEV trucks cheaper than BEV trucks. In all scenarios, substantial government support is needed in the forms of R&D, infrastructure development and financial incentives to realize the potential of hydrogen based transportation.

Keywords: Fuel Cell Electric Vehicles (FCEV); Battery Electric Vehicles (BEV); Total Cost of Ownership (TCO); Emissions Prediction and Policy Analysis (EPPA) Modeling; Decarbonization; Climate Change; Economic Analysis, Transportation; Hydrogen

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Dedication

To my daughter, Samriddhi. I hope, one day, this work will inspire you to make a positive impact on this world. I believe in you and in your incredible potential, which is yet to reveal itself. Thanks for the unlimited happiness and love you have given to me.

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I want to give special thanks to Dr. Bruce Cameroon for his unique EM lectures and guidance- I enjoyed his lectures the most. I am grateful to MIT's System Design and Management Program for its rigorous and concept-building course work that equips students with exceptional skills and shapes them to be future technology leaders. It was fortunate to meet the talented colleagues and friends in the SDM program - they all helped in my experiential learning at MIT.

Most importantly, my wife, parents and siblings have been a special pillar of support that has shaped this achievement. During these tough pandemic times, the unconditional support of family has never felt more important than before. The

cushion of love and emotional support of my parents, wife and daughter helped me steer through these difficult times with as little stress and friction as possible.

August 31st 2021
Cambridge, MA

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Chapter 1. Motivation and Background

Human influences have warmed the atmosphere, ocean, and land, leading to unprecedented rapid changes in the Earth's climate that our planet has not seen in the previous thousands of years. The consequences of these changes are faced by every region across the globe in the form of extreme events such as heatwaves, heavy precipitation, droughts, and tropical cyclones. Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered by IPCC (Intergovernmental Panel on Climate Change 2021). Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades (Paltsev and Schlosser 2021). If the world continues to emit CO_2 at current levels, we have only about ten years remaining before breaching the 1.5-degree Celsius threshold. Continued global warming is projected to intensify further the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events. This would eventually negatively impact global food production, leading to food shortages to an ever-increasing global population. Therefore, timely science-based actions are needed to address climate change. The world is facing a more challenging situation to mitigate climate-related risks, as many of our actions and preparations must be made far in advance and the benefits are slow to evolve and materialize (Paltsev and Schlosser 2021).

Climate change is a systemic risk to the world's economy. It could erode up to 18% of GDP of the worldwide economy by 2050 if global temperatures rise by 3.2°C (World Economic Forum 2021). It is to be noted that there is no consensus among experts about the extent of monetary damages. Climate scientists have proposed a gamut of pathways to reduce the pace of climate change. Their solutions include eliminating the processes which have high carbon intensity. However, if the elimination is not possible, reducing the carbon intensity of other processes or products should be considered. Developing a globally sustainable energy portfolio that could help us reduce the human-related carbon footprint is required.

The global transportation sector contributes about 1/4th of the total CO_2 emissions from fuel combustion. Road vehicles – cars, trucks, buses and two- and three-wheelers – account for nearly 3/4th of transport CO_2 emissions (International Energy Agency 2020a).

Therefore, it is crucial to explore technologies such as Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) as alternatives that can help reducing CO_2 emissions from the transportation sector, particularly the mobility segment. It is essential to evaluate the economic competitiveness of such technologies and their impact on the global economy if widespread adoption is anticipated. It is desirable for economists to model the impact of the global energy transition of the transportation sector from fossil fuel to renewables. Economy-wide models may be used to develop policy actions and set cost reduction targets that can successfully push less carbon-intensive technologies into the market. On the other hand, the policymakers require guidance from the scientific community to design policies to enable the transition.

Hence, there is a need for a systems based analysis that can evaluate the relative merits of Fuel Cell Electric Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs) with respect to BEVs and Internal Combustion Engine Vehicles (ICEVs).

Chapter 2. Literature Review

The 2021 IPCC climate change report emphasized the need for quick and aggressive actions to curb carbon emissions to limit global warming to 2°C. The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years (Intergovernmental Panel on Climate Change 2021). Therefore, a multidimensional strategy is required to expedite global decarbonization efforts. This has spurred an interest in promoting hydrogen (H_2) as a sustained alternative for decarbonization by the policymakers. Multiple techno-economic studies have attempted to evaluate hydrogen's ability to decarbonize sectors that are otherwise impossible or difficult to abate – such as intensive personal or public transport, freight, industrial heating and industry feedstock – and its role in energy security (Hydrogen Council 2020). The industries such as automotive, chemicals, oil and gas and OEM are exploring hydrogen as an alternative for carbon-intensive processes. Notably, the automotive industry has got a renewed attention towards understanding the impact of alternatives to Internal Combustion Engine-based LDVs and HDVs.

Two major engine drive train types have emerged and continue to progress in order to be competitive with light duty ICEV. They are BEVs and hydrogen-based FCEVs. However, a comprehensive system-wide evaluation is required to gauge the relative merits of these alternatives on various metrics, especially considering recent changes in costs of different technological pathways. These metrics include Total Cost of Ownership, Technology Learning Rate, Decarbonizing Potential, Levelized Cost of Energy, Lifecycle Emissions, Recycle & Reuse Close Loop Value Chains and Cost Barriers. Broadly, there is a trade-off between the cost of mitigation and the proportion of decarbonization achieved based on the route taken, leading to an increasing marginal abatement cost. The following sections provide brief background and details of the approaches used to develop the metrics mentioned above.

2.1 Learning Curve

The term ‘Learning Curve’ was first coined by Boston Consulting Group in 1968 in a white paper where the per-unit cost of a given technology reduces linearly on a semi-log plot. It is to be noted that the cost and price of technology in a marketplace could follow a different trajectory. Cost is the amount that has to be spent for making a product or service by its manufacturer or service provider. Price is the amount a customer is willing and able to pay for a product or service. The price and cost follow a similar trend for matured technologies, as shown in *Figure 2.1*. There are four distinct stages in the price-cost evolution process (BCG 1968), namely –

- Development- In this stage, the price of technology stays constant at the marketplace. However, the per-unit cost for the manufacturer decreases with increasing cumulative production experience.
- Price Umbrella- There is a slight downward trend in the prices, but the cost decreases at the development stages' rate due to the continued pace of learning with production.
- Shakeout stage- A dramatic reduction in the technology price is observed as the market competition catches up. Interestingly, the per-unit cost continues to follow the same linear trend on semi-log plots with cumulative production.
- Stability stage- In this stage, the price and cost follow parallel trends with cumulative production experience.

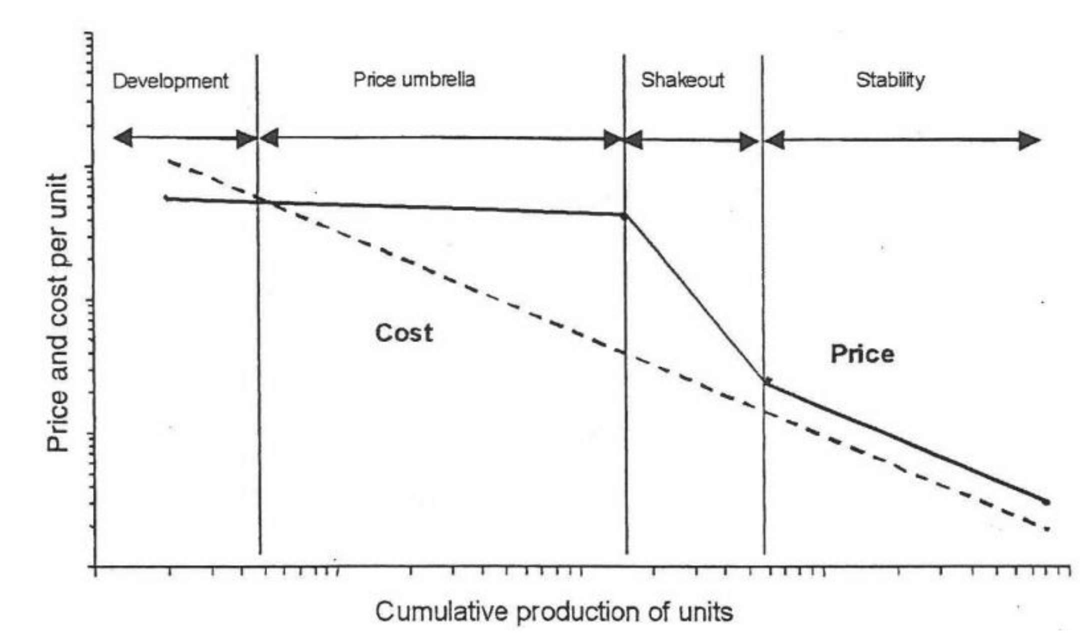

Figure 2.1: The per-unit technology cost trend with cumulative experience is often referred to as Learning Curve. Source: (BCG 1968)

2.2 Phenomenological Models for Predicting Technology Cost

A phenomenological model is a scientific model that describes the empirical relationship of phenomena occurring among various parameters without capturing the mechanism. The learning curves are based on phenomenological models that primarily follow an exponential form of representation such as $y = ax^b$, where y is the unit cost and x could be cumulative experience (Wright Curve) or economies of scale (Goddard Curve) or time (Moore Curve). The values of *a* and *b* are constant and determined empirically using historical data matching. The Wright's and Goddard's curves capture a lumped response of improvement via different terms and separating the effects in the lumped response is not trivial.

Wright's Curve (also known as an experience curve) postulates that the cost decreases linearly on a log-log plot with cumulative production (experience).

$$y_t = Bx_t^{-w}$$

Here(Hsieh et al. 2019) $w>0$ and $B>0$ are constants, y_t is the cost per unit and x_t is cumulative production at time t. The elasticity parameter (w) is the fractional reduction in cost with the doubling of experience.

Goddard's Curve predicts that the progress (an indication of cost per unit) is driven by purely economies of scale i.e. the more you produce, the cheaper a product gets.

$$y_t = Bq_t^{-s}$$

Here s and B are constants, y_t is the unit cost and q_t is the quantity produced in a batch, typically on an annual basis.

Some researchers have put together phenomenological models that are based on time rather than cumulative. One of them is Moore's Curve which postulates that the cost y of a given technology decreases exponentially with time. On a log-log plot the cost and time would be a linear plot. The formulation ignores the impact of R&D and arbitrarily connects the progress with time.

$$y_t = Be^{-mt}$$

Here m and B are constants, y_t is the unit cost of the technology and t is time since it has been used/developed.

It has been observed that some technologies improve faster than others under similar cumulative experience. It could be attributed to artifact interactions. The rate of improvement for a given technology is proportional to the inverse of its interaction parameter (Basnet and Magee 2017). Higher interaction or tighter coupling with other supporting technologies would result in slower improvements.

2.3 Learning Curve for Battery-Related Technology

The ultimate cost of battery technology is the combination of matured (material mining and synthesis) and fast-growing (battery pack production and assembly) technologies (Hsieh et al. 2019). Therefore, some researchers have proposed using a two-stage learning curve to predict per unit cost with higher accuracy for the technology that combines both matured and fast-growing technologies. In the case of batteries, the material-mining and synthesis processes have been developing for more than a century and the reduction in per-unit cost would be insignificant compared to the fast-growing new technology with cumulative production experience. It is to be noted that many factors besides costs drive the variation in prices. Therefore, energy analysts have preferred to use cost data to derive technological progress. The variation in cost for a given technology is also affected by Economies of Scale, R&D spending and learning from other associated technologies. It has been challenging for the researchers to put together a long-term forecast for fast-growing technologies as the cost may vary due to some unforeseeable factors. These factors are land costs, wages, taxes, interest payments driven by property, financial, labor markets, and government policies.

As per multiple estimates, it has been established that the cost of battery storage has to be reduced to $100/kWh or lower for wider adoption (Hydrogen Council 2020), indicating to ~70% reduction from current cost levels. A significant reduction in battery cost is unlikely to happen as part of the overall cost comes from the Mining & Synthesis phase of battery production (a matured industry. It is not reasonable to assume that the cost will scale down exponentially with cumulative experience for a matured industry like Mining. Therefore, a major cost reduction in battery technology is desired to come from Production and Assembly. Few researchers have attempted to divide the learning rate for battery technology into two parts learning rate 1) matured technology (Mining & Synthesis) 2) emerging technology (Production & Assembly), as represented in *Figure 2.2*. This would allow a better estimation of the resultant learning rate for the battery technology.   A report by the Hydrogen Council indicated that the learning rate for battery technology was among the highest from the year 2010- 2020 (Hydrogen Council 2020). Based on the limited opportunities to improve the per-unit cost, it appears challenging to meet the cost reduction targets <\$100/kWh in the battery technology.

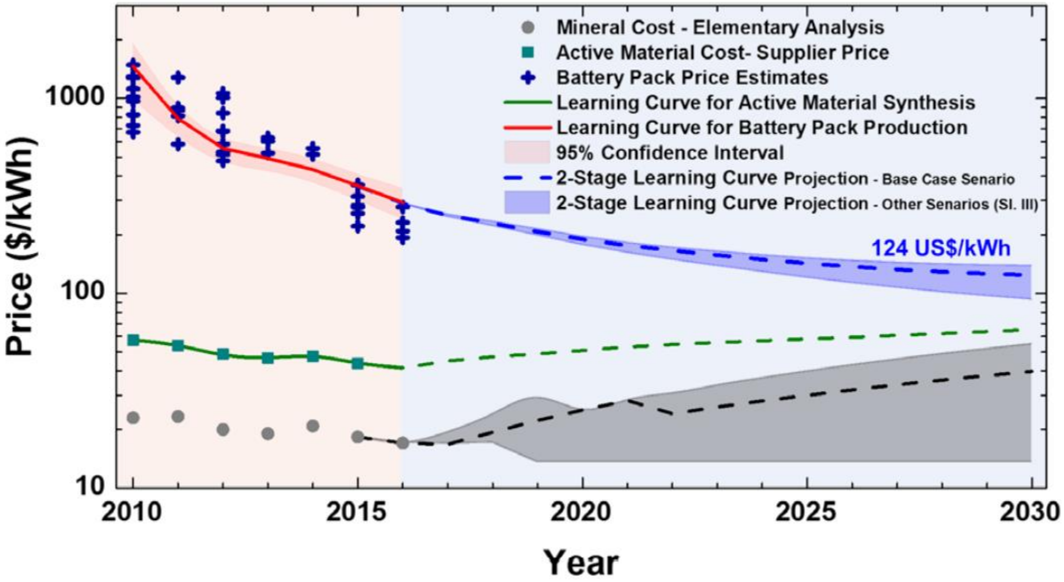

Figure 2.2: Past and projected price trajectory for lithium-ion NMC battery packs. The blue dash line represents cost projections using a two-stage learning curve model. Source: (Hsieh et al. 2019)

Unlike battery-based BEVs, the technologies related to FCVs are relatively new and have more potential to reduce the cost by demonstrating a steep learning curve. A report from the Hydrogen Council indicated three main technological components that require significant cost- reduction to make hydrogen-powered fuel cell vehicles affordable (Hydrogen Council 2020). They are –

Electrolyzers- It is the instrumental setup to generate hydrogen using electricity. There are multiple electrolyzer technologies. However, two electrolyzer technologies are leading in cost reduction:

a. *Polymer Electrolyte Membrane (PEM) electrolyzers* where the electrolyte is a solid specialty plastic material.

b. *Alkaline electrolyzers* where a liquid alkaline solution acts as an electrolyte.

Fuel Cell Stacks- The development of fuel cell stack is a relatively new technology and the cost reduction will occur as the cumulative experience of fuel cell stack production accumulates.

Refueling Infrastructure: Hydrogen is an emerging fuel source and refueling infrastructure is to be developed to make faster adoption of hydrogen. It is expected that economies of scale and cumulative experience would help in reducing the per-unit cost of the infrastructure. A more detailed discussion is available in the following sections about the cost of infrastructure development for hydrogen refueling.

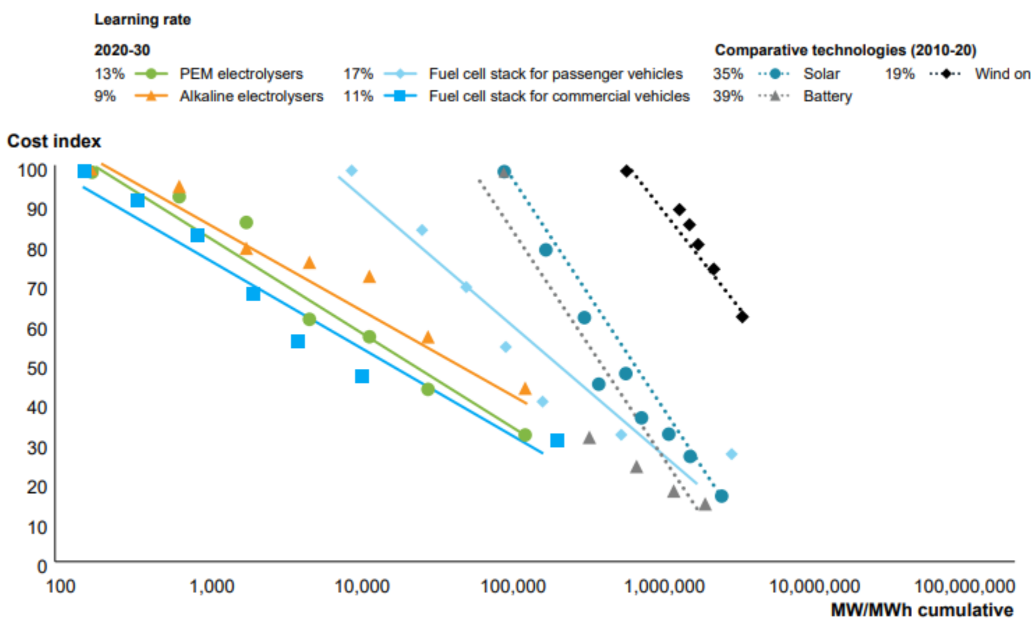

Figure 2.3: Learning rates for emerging technology PEM or Alkaline for hydrogen applications. Source: (Hydrogen Council 2020)

2.4 Lifecycle Emissions for Vehicles

The system boundaries to conduct life cycle emissions are often determined by the researchers based on their objectives. Wells-to-wheels studies are not comprehensive and often keep ICEVs at a disadvantageous position from a carbon-emission perspective. A better approach has been cradle-to-grave (C2G) Life Cycle Analysis which includes the emissions from fuel and vehicle life cycles. Elgowainy et al. conducted a thorough C2G LCA of energy consumption, GHG emissions, vehicle and fuel costs, carbon abatement costs and technological readiness for various LDV technologies (ICEV, BEV, HEV, FCEV) (Elgowainy et al. 2018). A typical LDV's emission LCA includes all emissions related to manufacturing & assembly of all parts, delivery to the end-user, operation and recycling at the end of useful life (*Figure 2.4*).

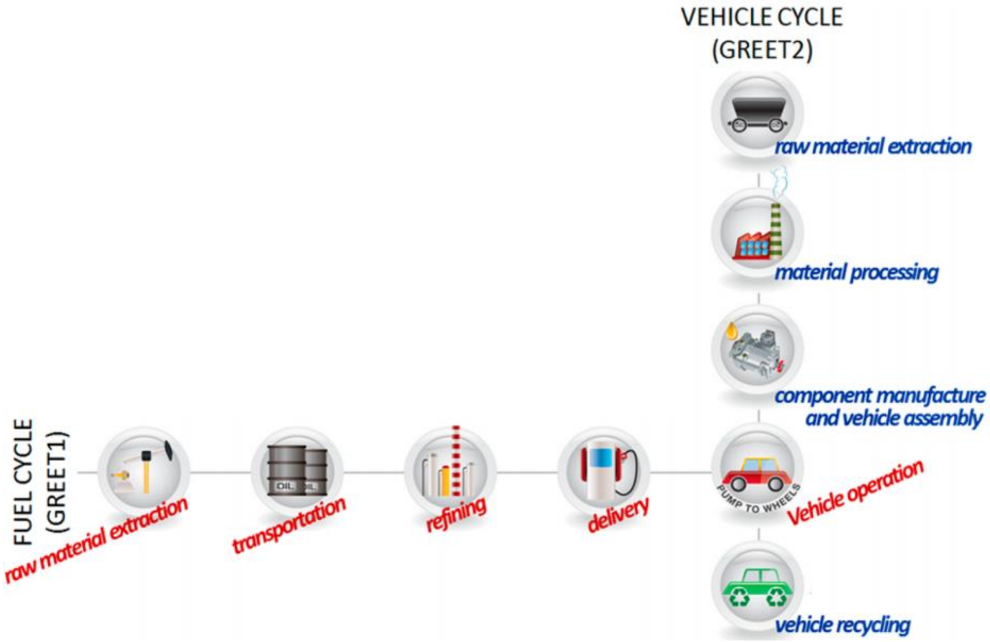

Figure 2.4: System boundaries for calculating Life cycle emissions for a vehicle. Horizontal and vertical chains, respectively, represent the Fuel and Vehicle cycles. Source: (Elgowainy et al. 2018)

The emissions may be estimated using GREET model developed by Argonne National Laboratory (Argonne National Lab 2021). Typically, the manufacturing and fuel cycle emissions for ICEVs are 50% lower and 25% higher than BEVs, respectively. Similar trends are observed for FCEVs. It is estimated that the total vehicle manufacturing life cycle emissions are expected to drop by 30% by the year 2025, attributing to the cleaner electricity mix in the future.

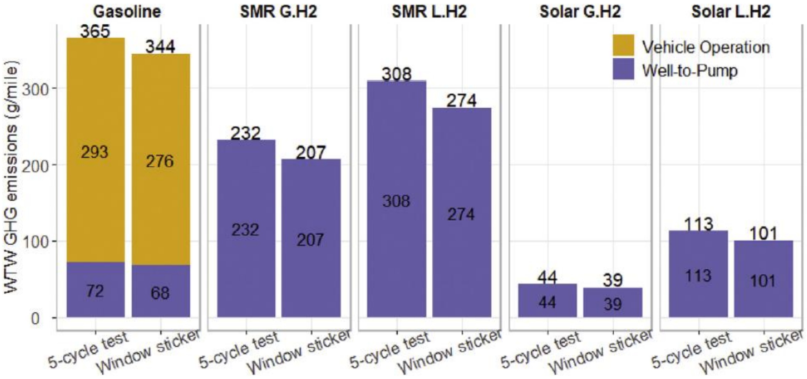

Figure 2.5: Emissions for Well to Wheel for ICEV (Mazda 3) and FCEV (Toyota Mirai). Note that the emissions related to vehicle manufacturing are not included. Source: (Liu et al. 2020)

The other major part of emissions comes from fuel usage and its associated value chain. It may vary in wide ranges depending on technology. A typical well-to-wheel value chain is presented for gasoline-ICEV by (Liu et al. 2020). Liu et al. 2020 argued that the emissions from tailpipe are practically zero for hydrogen FCEVs and BEVs.

The main source of emissions has been the fuel cycle for an ICEV. Crude oil is extracted from an oil field, transported/hauled to refineries, followed by gasoline dispatch to filling stations to be delivered to the vehicle's fuel tank. A vehicle under its operational life would indirectly contribute to the emissions caused by this whole value chain. As a common observation, the emissions from vehicle manufacturing are an order of magnitude lower than the total emissions from vehicle operations for ICEV. However, the emissions from vehicle manufacturing might be considerably higher than the emissions from operations for BEVs and FCEVs. It could be attributed to a relatively cleaner energy mix for electricity and hydrogen generation. As per the estimates published in 2018, the total LCA GHG emissions for gasoline-based ICEVs are expected to drop from the current levels at ~450 g CO_{2e}/mile to 150 g CO_{2e}/mile by 2025 (Elgowainy et al. 2018). However, LCA GHG emissions is likely to drop to 50-100 g CO_{2e}/mile by 2025 for hydrogen based FCEVs and BEVs, which are already lower than the ICEVs (Elgowainy et al. 2018).

The WTW emission results from (Liu et al. 2020) study indicate that FCEV has 15-45% lower greenhouse gas emissions than a conventional gasoline ICEV even when the hydrogen is produced using fossil-fuel-based processes such as SMR. To the contrary, some researchers in China established that Fuel-cell vehicles fueled by current grid power-based hydrogen in China have two to three times the lifecycle greenhouse gas emissions of internal combustion engine vehicles (Ren, Zhou, and Ou 2020). This highlights that the electricity mix plays a vital role in determining lifecycle emissions of FCEV or BEV (MIT Energy Initiative 2019). A recent life cycle assessment on comparing the product carbon footprint of EV (Tesla Model 3) and FCEV (Toyota Mirai) concluded that the fuel cycle (electricity generation in the case of EV and hydrogen generation in the case of FCEV) might have significant carbon footprint based on the electricity mix. The study revealed the need for greater transparency in disclosing relevant information on the PCF methodology adopted by vehicle manufacturers to enable a fair comparison of vehicle's emissions (Wong et al. 2021).

2.4.1 Life Cycle Emissions for LDVs

Light Duty Vehicles account for 17% of the total GHG emission in the USA (US EPA 2015a). Generally, the vehicles registered as Class 1 type fall under this category. The emissions are expected to reduce across the board in the future for all vehicle technologies (Elgowainy et al. 2018). However, BEVs are expected to have the highest reduction due to a cleaner electricity mix in the future. The current level of lifecycle emissions for BEVs are marginally lower than the ICEVs. However, it is expected that BEVs would eventually have lower life cycle emissions ~1/4th of the ICEV, as shown in *Table 2.1*(Elgowainy et al. 2018). The manufacturing of BEV's batteries is a carbon-intensive process. The battery causes over 40% of CO_2 emissions in the manufacturing of an EV (Hall and Lutsey 2018). The emissions related to battery manufacturing are equivalent to ICEV manufacturing (Wilmot 2021), as shown in *Figure 2.6*. The MIT Future Mobility study has reported similar numbers (MIT Energy Initiative 2019). The study concluded that the emissions for BEV manufacturing based on the 2018 electricity-grid mix in the US is ~14 tonne CO_2-eq. The current C2G studies do not include emissions related to battery recycling. A typical EV goes through at least one battery replacement in its lifetime; therefore emissions related to battery recycling must be considered in C2G studies.

Table 2.1: Combined lifecycle emissions from Fuel and Vehicle cycles LDVs (ICEV, BEV, FCEV) (Elgowainy et al. 2018). The BEVs emissions are based on state-of-the-art carbon reduction technologies such as ACC and CCS. TLE= Total Lifecycle Emissions, EI= Energy Intensity, ACC = Advanced Combined Cycle, CCS= Carbon Capture and Storage. *The MIT Future Mobility study has reported emissions based on the 2019 US electricity grid mix (MIT Energy Initiative 2019).

Year 2025+ TLE (tons CO_2-eq) EI (g CO_2-eq/mile)	**Total Emissions**	**TLE Fuel Cycle**	**TLE Vehicle Cycle**	**Ratio (Fuel /Vehicle)**	**Emission Intensity**
ICEV	63	56	7	8.1	352
BEV 210+ miles range (ACC + CCS)	14	7	7	1.0	81
FCEV (SMR+CCS)	24	14	10	1.5	132
BEV* (2019 US electricity grid mix)	50	36	14	2.6	278

In the case of FCEV, if hydrogen is produced using electrolysis with renewable electricity, then the carbon emissions are lowest for HFCEV as demonstrated by MIT Future Mobility Study (MIT Energy Initiative 2019). As the carbon footprint of the electricity mix reduces, the overall WTW emissions from FCEV and BEV would shrink (Cox et al. 2020). If the carbon intensity of the present electricity grid in the EU drops by 70%, then FCEV lifecycle emissions are expected to be lower than ICEVs. FCEV emissions may be at par with BEVs if the grid carbon intensity drops by 90% (Cox et al. 2020). The emissions related to the vehicle cycle for FCEV are lower than BEVs, but the BEVs demonstrate lower emissions under the fuel cycle (*Table 2.1*). It is to be noted that the total emissions from FCEVs are marginally higher than BEVs.

Researchers have no consensus about the system boundaries for calculating the life cycle emissions; therefore, the reported emissions should be treated with caution if assumptions and boundaries are not stated explicitly.

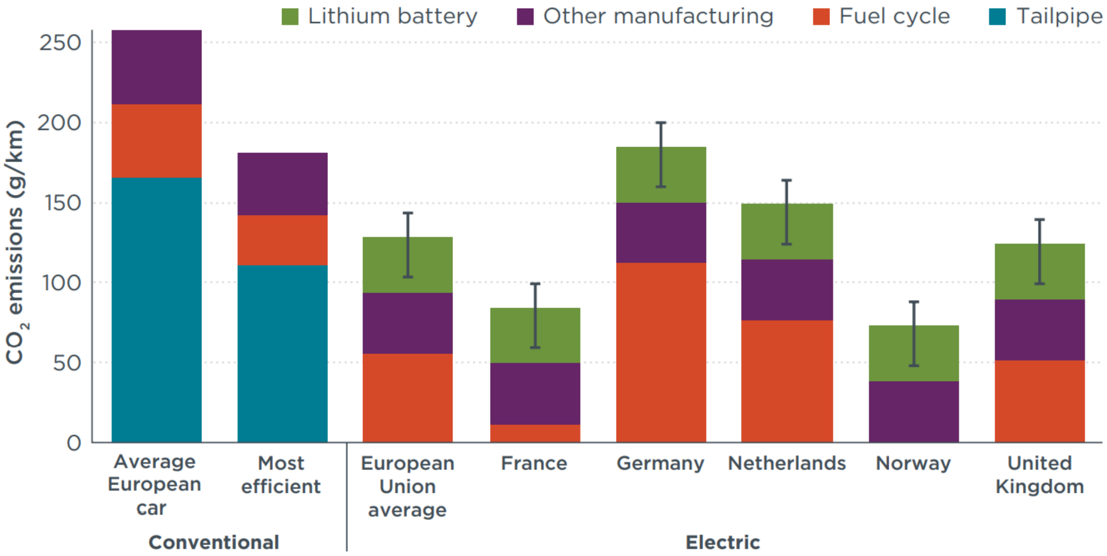

Figure 2.6: Lifecycle emissions of electric and conventional vehicles in Europe in 2015. Source: (Hall and Lutsey 2018).

2.4.2 Life Cycle Emissions for HDVs

Heavy Duty Vehicles account for 20-30% of the total GHG emission in the United States (US EPA 2015b). On-road HDVs serve 70% of all freight transportation needs in the United States (Quiros et al. 2017). Generally, the vehicles registered as Class 8 type have Gross Vehicle Weight Ratings (GVWR) exceeds 33,000 lbs weight and typically include 5 axle tractor-trailer combination. They are used for long-distance freight hauling trucks. The HDVs related CO_2 emissions in EU-28 regions were 27% of road transport CO_2 emissions. A significant growth ~46% is expected in the EU trucking industry in the next 10 years (Anon 2020). Therefore, it is important to understand lifecycle emissions for HDVs.

In this work, The emissions from HDVs are primarily divided in two categories: Manufacturing Phase and Use Phase. It was found that the emission accounting methods for HDVs are not consistent and I find no consensus among experts on data aggregation workflows (Morrison and Burnham 2019; Wolff et al. 2020). The emission data for the manufacturing phase is controlled by manufacturers and is often unavailable to the public. However, some studies on N3 type trucks in Europe (equivalent to class 8 in North America) have published data recently (Wolff et al. 2020). They compared emissions from N3 trucks with ICEV and BEV2 (Range 375+ miles). It is evident from *Figure 2.7* that the manufacturing phase emissions for BEV (160 t CO_2-eq) are 5 times higher than the ICEV (30 t CO_2-eq) trucks and the majority of BEV emissions come from battery pack manufacturing. There are 2000+ BEV N3 type registered trucks in EU (European Alternative Fuels Observatory 2021).

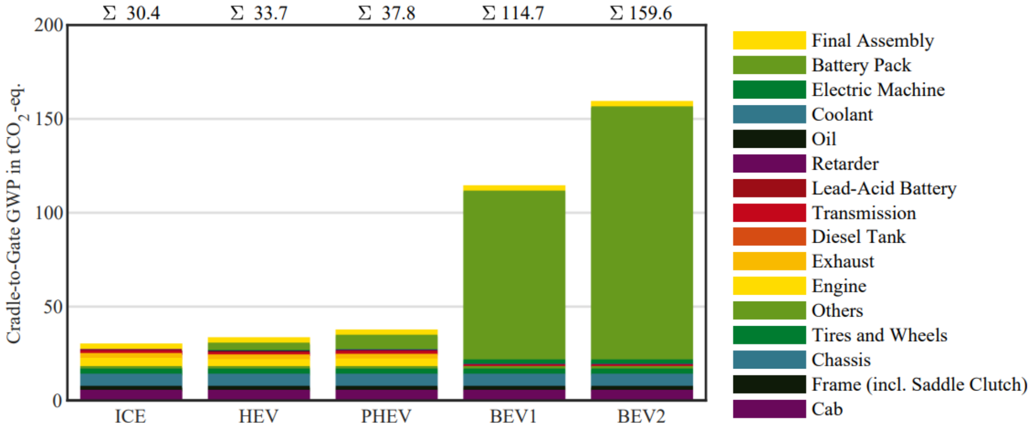

Figure 2.7: The lifecycle emissions from the manufacturing phase of N3 trucks in Europe for ICEV and BEV trucks. Source: (Wolff et al. 2020)

There is limited data available on estimating emissions from Class 8 type trucks. The primary reason is that the Use Phase emissions may vary in wide ranges and it is non-trivial to run a controlled study on a sufficiently large fleet.

The Use Phase emissions for a given truck depend on:

1. *Truck Usage*- A long-haul freight truck would have significantly different emissions compared to a city dump truck.
2. *Truck's age in operation*- The older trucks tend to have higher emissions than the newer trucks due to decreasing efficiencies with time. Also, the newer trucks are equipped with better emission reduction technologies.
3. *Maintenance frequency*- Better maintained trucks are expected to have lower emissions compared to their poorly maintained counterparts.
4. *Operating environment*- The trucks servicing in harsh climates and rough road conditions would have higher emissions.
5. *Drive train type*- The emissions may vary with drive train type ICEV, BEV or FCEV

(Morrison and Burnham 2019) compared BEV and FCEV trucks' emissions for the Use Phase with '*equivalent diesel trucks'.* While the modeling is based on a limited dataset, it provides a good starting point for analysis. The study used Argonne National Lab's AFLEET Model to estimate emissions and the Use Phase lifetime emissions for ICEV, BEV and FCEV are estimated to be 2900, 1100 and 2300 t CO_2-eq, respectively, for Class 8 type trucks.

2.5 Total Cost of Ownership for Vehicles

Total Cost of Ownership (TCO) is an estimate of the total cost to own and operate a vehicle for a defined period. It includes all the expenses such as fuel, maintenance, repairs, service, interest on loan payments, insurance and depreciation related to the vehicle at the end of the same period. Here are some main components-

1. *Fuel Cost* is calculated based on the average annual mileage and miles per gallon reported for the given vehicle.
2. *Maintenance & Repairs (M&R) Cost* is calculated based on aggregated data reported for the given type of vehicle class. One-time high overhauling costs such as EV's battery replacement are itemized as separate items in TCO sheet.
3. *Tires Cost* is directly proportional to the average annual mileage and the replacement frequency for the given type of vehicle.
4. *Principal and Interest Payments* are derived based on the interest rate, the purchase price of a new vehicle and the total period for the ownership.
5. *Insurance* expenses are the cost to maintain standard comprehensive and 3rd party coverages for the given vehicle during the ownership period.
6. *Registration & Permits* cost is related to government fees to maintain registration and road taxes.
7. *Dwell Cost* is the cost associated with the time when the vehicle is idle for refueling. The increase in non-operational time incurs a cost.
8. *Payload Cost* is the cost related to the lost hauling capacity of an EV truck due to its dead weight. Typically, EV trucks have ~10% less hauling capacity compared to ICEV or FCEV trucks.

The market analysts have utilized TCO models for Light-Duty Vehicles (LDVs)(Frost and Sullivan 2017) and Heavy-Duty Vehicles (HDVs) such as Class 8 Type hauling trucks (Frost & Sullivan 2021) to compare various ownership models (Lau 2019). The analysts have also used TCO model to calibrate economic models to understand the macroeconomic trends from comparing different drive trains (Internal Combustion Engine, Battery Electric Vehicles, Hydrogen Fuel Cell Vehicles)(Ghandi and Paltsev 2020).

2.6 Recycle and Reuse of Components from BEVs and FCEVs

The system approach indicates that the vehicles and their components should be either disposed of or recycled at the end of their useful life to support close-loop consumption. The components such as batteries and fuel cells have received much interest from researchers that study the end-life of products. Some researchers have established that repurposing EV batteries to stationary power back-ups reduces the demand for mining virgin metals and delays the environmental footprint of close-loop consumption. Interestingly, the market reports available in the public domain usually do not consider the recycling cost in TCO calculations (Frost and Sullivan 2017).

The primary benefits of battery recycling are reduced environmental footprint, energy savings and less material handling. Direct recycling is often used to recondition old cells to recover pure cathode and anode powders which need minimum processing before putting them back in the cells. These processes could result in less energy and emissions compared to metallurgical processes. It is to be noted that the battery recycling business may generate substantial returns (Niese et al. 2020). However, it would require optimized value chains for collection, transportation, repurposing and recycling processes (Jacoby 2019). There are few challenges in establishing such optimized value chains. For example, there are difficulties in processing a wide range of battery formats, designs, compositions and chemistries.

There is no established collection infrastructure for EV batteries in the US at this time. A viable business model would require conducting a full Life Cycle Analysis on comparing the cost, environmental and energy impacts of the new, recycled and reused EV batteries to rationalize the future path for end-of-life EV batteries (Steward, Mayyas, and Mann 2019). Currently, it seems reasonable to assume that recycling EV batteries would incur a cost as high as 20% of the original battery cost (Kelleher Environmental 2020). The recycling cost may rise in the future as the future batteries would be more compact, complex, variety in assembly and built-to-last designs rather than built-to-recycle (Jacoby 2019). The lithium-ion batteries use anode made of graphite and a cathode made of varying combinations of cobalt, nickel, manganese, and several other alternatives. Nickel-manganese-cobalt batteries dominate the market at present and the global supply of these metals depends on few countries (Argentina, Bolivia, Chile, DRC) and a handful of Mining & Processing companies (Picarsic 2020). This makes batteries a potential target of global supply chain risk failure.

Similarly, there are not sufficient studies available on the environmental impact of end-of-life (EOL) fuel cells. Companies have developed recycling processes that can recover 95+% of valuable metals from Membrane Electrode Assembly from a Fuel Cell Stack (Ballard Systems 2017). As per estimates, the customers may get a new replacement at 30% less cost than the original purchase price suggesting an economically viable recycling model (Ballard Systems 2017). As per some estimates, a typical fuel cell may serve from 15-30 years, while BEV battery's life may range from 7-15 years (Steward et al. 2009), indicating that a typical FCEV would not need a fuel cell replacement based on 11 years of the expected lifespan of LDVs in the US (United States Department Of Transportation, Bureau Of Transportation Statistics 2019). Also, the infrastructure needed to process EOL fuel cells would be significantly less than the EOL BEV's batteries.

2.7 Hydrogen Value Chain

The hydrogen value chain is divided into three major segments: Production, Handling & Delivery, and Refueling. Here refueling indicates the process of refilling a vehicle's tank with fuel throughout its operational life.

2.7.1 Production

The earlier techno-economic literature in hydrogen production indicated that producing hydrogen at a central location at a large scale demonstrates better economics due to Economies of Scale, better energy prices and less infrastructure cost per kg of hydrogen produced. Some of these studies focused on hydrogen pathways based on conventional technology and infrastructure deployment (Simbeck and Chang 2002). However, new technologies and novel operating options have the potential to reduce the retail cost of hydrogen.

2.7.2 Handling and Delivery

Hydrogen Handling & Delivery is defined as the entire process of moving hydrogen from the gate of a central production plant into a vehicle. Thus, Handling & Delivery includes all transport, storage and conditioning activities from the outlet of a central hydrogen-production facility to a fueling station. The conditioning required to transport hydrogen depends on the mode of transportation and phase of hydrogen. *Figure 2.8* shows five Handling and Delivery pathways. The optimum pathways for a given city would depend on city's size and hydrogen demand. There are mainly two phases (gas, liquid), three transportation methods (pipelines, tube trailers and trucks) and two storage types (geological, artificial) that are considered in optimizing Handling & Delivery pathways.

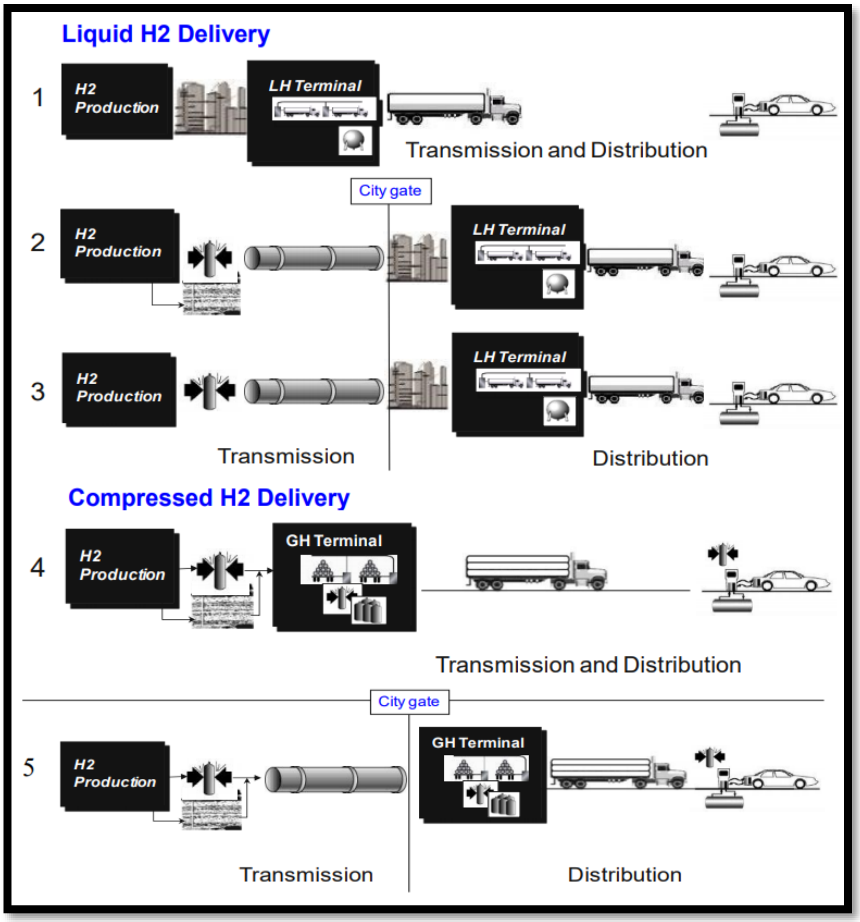

Figure 2.8: Hydrogen delivery pathways from Production, Transformation, Transportation, Storage and Refueling for Liquid and Compressed hydrogen. Source: (Elgowainy et al. 2015)

2.7.3 Refueling

Hydrogen refueling process includes a fueling station that stores, dispenses and in some cases, further conditions the hydrogen. Hydrogen delivery could also include compression, storage and dispensing of hydrogen produced on-site at a fueling station (i.e., distributed production). Hydrogen Delivery Scenario Analysis Model (HDSAM) is developed by NREL to estimate the total cost for Handling & Delivery and Refueling (Elgowainy et al. 2015). HDSAM calculates the cost of hydrogen refueling for various station capacities, utilization scenarios and design configurations. The dispensing cost depends on the hydrogen phase (Gas, Liquid), pressure rating (350, 700 bar), type of dispensing (Cascade, 700 bar Compressor Dispensing, 350 or 700 bar pump vaporization or vaporization/compression) and dispensing station capacity. The refueling cost in the future could go down based on the technology learning rate and production volume. Pipelines are usually capital intensive, but they may serve a bigger concentrated demand cost-effectively. In general, gas has a higher cost for refueling than liquid. It was observed that low-pressure refueling costs less than higher pressure delivery.

2.8 Hydrogen Production Technologies

Three promising hydrogen production technologies are being considered in my thesis. These technologies have different production costs, required feedstock, energy requirements and life cycle carbon emissions. Below is a brief description of several technologies for producing hydrogen.

2.8.1 Electrolysis

Producing hydrogen by splitting water using renewable electricity is labeled as "green hydrogen". The electrolysis of water to dissociate water molecules into hydrogen and oxygen is a commercially mature process. Few methodologies are commonly used to disintegrate water molecules via electrolysis. They are alkaline, polymer electrolyte membrane (PEM) and solid-oxide electrolysis cells (SOEC) electrolyzers. The primary source of energy for electrolysis to produce hydrogen is electricity. In the case of PEM, water reacts at the anode (positive terminal) to form oxygen and positively charged hydrogen ions (protons). The electrons are allowed to flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode (negative terminal). At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas (Department of Energy, US 2021). Electrolysis could be an alternative to store surplus renewable electricity in the form of hydrogen. Hydrogen produced via electrolysis can result in zero greenhouse gas emissions if the electricity used is carbon-free. The power grid in US in many regions is not suitable for electrolysis because of the greenhouse gases released in electricity generation and the amount of fuel required due to the low efficiency of the electricity generation process (Department of Energy, US 2021).

Storing surplus electricity in the form of hydrogen can likely be cheaper than the renewable electricity and battery combination (Pacific Northwest National Laboratory 2021). Therefore, electrolysis has got renewed attention for upscaling and US DOE has set goal of reducing the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade (Department of Energy, US 2021).

SOEC are the most electrically efficient of the three technologies but it demonstrates poor economics. PEM electrolysis is currently relatively expensive but an attractive technology due to higher current densities, efficiencies, dynamic operation and compact system design (Bhandari, Trudewind, and Zapp 2014). Alkaline electrolysis is the cheapest and commercially viable alternative for electrolysis. PEM electrolyzers use pure water and their size might be customized based on a need basis. They are found suitable for dense urban areas where highly compressed hydrogen for decentralized production and storage at refueling stations is required with flexibility in operations. Their operating range can go from zero load to 160% of design capacity, indicating that it is possible to overload the electrolyzer for 10-20% of its operation time (IEA 2019). PEM electrolyzers need expensive electrode catalysts (platinum, iridium) and membrane materials and their lifetime is currently shorter than that of alkaline electrolyzers. Therefore, PEM electrolyzers are expensive and further cost reductions are required to be a competitive alternative to alkaline electrolyzers.

As the carbon footprint of the electricity mix reduces, the overall emissions from electrolysis reduce (Cox et al. 2020). However, the cost of expensive electrode catalysts (titanium, platinum, iridium, scandium, yttrium) and membrane materials and their limited lifetime of 10 years poses a challenge for commercialization. A recent study concluded that except for titanium, all other critical materials are under moderate to high risk (platinum) or mostly high (iridium, scandium and yttrium) of supply chain disruptions (Kiemel et al. 2021). The risk was assessed based on six major indexes: country risk, country concentration, by-product dependency, company concentration in mining operations, demand growth, and recycling trends. The availability of these materials for scale-up of electrolysis capacity has an inherent risk of supply disruptions if it is ranked high. The study indicated that conventional recycling pathways for platinum, iridium and titanium from end-of-life electrolyzers would not significantly reduce the dependence on primary resources until 2050 (Kiemel et al. 2021).

There have been multiple methodologies in reporting the capital cost of an electrolyzer (or more precisely, a cost of an electrolyzer system that includes other parts) on $/kW basis. Some researchers use electrolyzer output-based methodology (i.e., $\$/kW_{H2\ HHV}$ or $\$/kW_{H2\ LHV}$), which considers electrolysis efficiency to report the electrolyzer's capital cost per unit of output capacity. The hydrogen output can be reported in Lower Heating Value (LHV) or Higher Heating Value (HHV). The LHV (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered. The HHV (also known gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products. The ratio of HHV to LHV for hydrogen is 1.183. However, more often the capital cost of electrolyzers are reported in terms of its electrical input (i.e., $\$/kW_e$ or simply $/kW). The relationship between the energy in electricity input and in hydrogen output of electrolyzer is determined by the electrolyzer system efficiency, with a current typical value of 60%.

The hydrogen cost model presented in the later sections of this manuscript has used an input-based methodology to report the electrolyzer's capital cost per unit of input capacity. A summary of conversions among various units (kWe, $kW_{H2\ LHV}$, $kW_{H2\ HHV}$) for a typical electrolyzer efficiency (60%) is presented in *Table 2.2*. If an electrolyzer capital cost is $1000/kWe in terms of electricity input, the equivalent cost in terms of hydrogen output units will be $1667/$kW_{H2\ LHV}$ and $1409/$kW_{H2\ HHV}$, respectively. With this electrolyzer system capital cost, electrolyzer capacity factor of 90%, and electricity cost of 7 cents/kWh, the cost of hydrogen production will be around $5.50/kg H_2.

Table 2.2: Electrolyzer's capital cost per unit of capacity in various units.

Electrolyzer's capital cost		
$/kWe	**$/$kW_{H2\ LHV}$**	**$/$kW_{H2\ HHV}$**
1000	1667	1409

2.8.2 Steam Methane Reforming (SMR)

Steam methane reforming (SMR) is a conventional method to produce hydrogen from natural gas (this process is often labeled as "brown hydrogen"). In this process, methane is reacted with steam (water) using a catalyst at a relatively high temperature, 650–1000 °C and 5–40 bar pressure to produce carbon monoxide and hydrogen. Additional hydrogen is produced by reacting carbon monoxide with steam in the water–gas shift reaction (Parkinson et al. 2019). The process may require additional separation to produce hydrogen from the reaction. Typically, the efficiency of the process varies between 70-80% (National Research Council and National Academy of Engineering 2004). Since the feed for SMR process is natural gas, the hydrogen costs in his option are most sensitive to natural gas prices.

2.8.3 SMR+CCS

The SMR process may be coupled with Carbon Capture and Storage (CCS) process to reduce its carbon footprint. Hydrogen produced from SMR with CCS is referred to as "blue hydrogen". Typically, SMR equipped with CCS may achieve 90% capture rates. Some researchers have noted that net LCA emission reduction with 90% capture rates is only 38-76% depending on the supply chain emissions (Parkinson et al. 2019). As demonstrated in the later sections, the cost of carbon capture from SMR process on per kg of H_2 produced adds 25% additional cost to hydrogen production with SMR without CCS. However, significant upfront investments are needed for infrastructure development that may discourage private parties from making investments. In the absence of carbon taxation, there is no economic incentive for decarbonizing hydrogen supply from SMR operations.

Chapter 3. Cost Modeling

3.1 Total Cost of Ownership Modeling

Economy-wide models often require information on expenditures related to owning a typical LDV or HDV. The cost can be aggregated based on the vehicle cost data, fuel expenditures, maintenance & repair expenses, insurance and tax and licensing expenses for a typical vehicle for an individual owner. This aggregated cost is often referred to as Total Cost of Ownership (TCO). I develop TCO models for both Light-Duty Vehicles (Class 1 type) and Heavy-Duty Vehicles (Class 8 type) to compare total life cycle costs and cost per mile values among different types of drive trains. The units used in this analysis are presented in *Table 3.1*.

Table 3.1: The cost components considered for this study for a bottom-up Total Cost of Ownership (TCO) analysis

Type	**Units**
Fuel	$/year
Annual O&M Costs	
Maintenance, repair	$/year
Tires	$/year
Full-coverage insurance	$/year
License, registration, taxes	$/year
Finance charge	$/year
Total Operation & Maintenance	$/year
Dwell (Charging Related Waiting period) Cost	$/year
General and Administrative Cost	$/year
Payload (Lost Hauling Capacity) Cost	$/year
Manufacturer Suggested Retail Price (MSRP)	$
One Time Major Cost (Battery Replacement@15 years)	$
Recycle Cost (Battery/FC)	$
Total Cost of Ownership, TCO (for 15 years)	$
Annual cost (Life Time Cost/Life Time)	$
Cost Per Mile, CPM($/mile)	$/mile

3.1.1 TCO Modeling for Light Duty Vehicles (Class 1 Type)

The analysis for LDVs has assumed that the total cost of ownership for this category could be represented by a mid-sized sedan car (Chevrolet Malibu, Tesla Model 3, Toyota Mirai) for the US market. The other significant assumptions used in the TCO model are listed below in *Table 3.2*. below.

Table 3.2: List of assumptions to derive Total Cost of Ownership for LDVs in the US

Vehicle Type	Class 1	**Source**
Annual miles	15,000	AAA Your Driving Cost (2020)
Life Time(yrs)	11	Gandhi et al. 2020
Discount Rate	5%	AAA (2020)
Fuel Price		
Gasoline Price ($/gal)	2.46	AAA (2020)
Electricity Price ($/kWh)	0.13	AAA (2020)
Hydrogen Price ($/kg)	10	NREL (Electrolysis Process) *Table 3.9*
Fuel Economy		
ICEV (miles/gallon)	30	fueleconomy.gov (Midsize sedan)
BEVs (miles/kWh)	4	fueleconomy.gov (Tesla)
FCEVs (miles/kg)~ (mpg)	72	fueleconomy.gov (Mirai)
Typical Driving Range (miles)	400+	Tesla, Mirai

The total cost of ownership can be derived from a detailed bottom-up cost analysis. The model has three major cost components, namely Fuel Cost, Services Cost and one-time capital cost. In this case, the cost of the services includes insurance, interest, taxes, licenses & permits and maintenance and repair costs. The data was collected for three drive train types, namely, Internal Combustion Engine Vehicle (ICEV), Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV). In the mid-size category for ICEV, BEV and FCEV cars are represented by Chevrolet Malibu, Tesla Model 3 and Toyota Mirai. These cars are rated for 5 passengers and have similar luggage capacities. The summary of the TCO analysis is presented below.

Table 3.3: Total Cost of Ownership (TCO) model for three drive train types LDV namely ICEV, BEV and FCEV

	Units	ICEV	BEV	FCEV
Annual Operating Costs				
Estimated Fuel (based on mpg)	$/year	1,231	491	2,083
Maintenance, repair and tires	$/year	1,434	1,119	1,119
Full-coverage insurance	$/year	1,245	1227	2,076
License, registration, taxes	$/year	730	74	74
Finance Charge	$/year	684	826	826
Total Services	$/year	4,093	3246	4,095
Annual Costs				
Fuel	$/year	1,231	491	2,083
Services	$/year	4,093	3,246	4,095
Total Cost of Ownership (TCO)				
Vehicle Manufacturer Suggested Retail Price (MSRP)	$	25,000	49,000	49,500
One Time Repair (Battery Replacement)	$	0	13500	0
Recycle Cost (Battery, Fuel Cell)	$	0	13,50	0
Fuel	$	13,541	5,404	22917
Services	$	45,023	35,706	45,045
Total Cost of Ownership $, TCO (for 11 years)	$	83,564	104,960	117,462
CPM $/mile	$/mile	0.51	0.64	0.71
Markup above ICEV		1	1.26	1.41

It is to be noted that the Maintenance & Repair costs for ICEVs are ~30% higher than FCEV or BEV as ICEV are complex machines with ~30,000 parts in a typical ICEV. On the other hand, BEV's drive train is simple and a typical BEV has ~10,000 parts making it cheaper for maintenance. The cost estimate obtained to insure Toyota Mirai in a large metropolitan city in the US is about ~70% higher than a typical ICEV or BEV. The majority of the battery recycling cost, particularly in LDV sector, is incurred in collecting and transporting the batteries to the recycling centers (Jacoby 2019). The value chain for battery recycling is not established in the US as the recycling needs are not concentrated in a region or area. Therefore, a 10% battery is added to the TCO model for LDVs.

Hydrogen has a higher energy density than gasoline; therefore, a smaller volume fuel tank is needed for FCEV compared to ICEV to travel the same distance. The FCEV fuel tanks are made heavier due to safety requirements for hydrogen handling in vehicles. The deadweight added to the fuel tank to make safer operation with hydrogen compensates for the advantage of a smaller fuel tank requirement offered by its high energy density. Therefore, the resultant weight of the full fuel tank of an FCEV is similar to ICEV's full fuel tank. A BEV car with 250-300 miles range would require batteries with a volume of 100 to 160 gallons. While for the same range, ICEVs would require only 15-20 gallon tanks (Thomas 2009). The fuel cell plus hydrogen storage tanks would take 26 gallons volume for 300 miles range as per the DOE targets (Thomas 2009). Thus BEV LDV requires more stored energy per mile than the FCEV. It has been observed that the weight advantage has a compounding effect on the curbside weight of a vehicle as a heavy car needs heavy brake assembly, larger fuel tanks and all other accessories. I believe that vehicle's weight effects are somehow lumped in fuel economy values presented in *Table 3.2*. Therefore, it has not been captured as a separate line item in the TCO model.

The analysis indicated that a typical ICEV's costs ~$84,000 to its owner for a typical ownership period of 11 years in the US. The calculations are based on an average annual mileage of 15,000 miles and fuel economy of 30 miles per gallon, as reported in *Table 3.2*. The TCO for electric vehicles for the same ownership period and mileage is ~26% higher than the ICEV and it is ~ $105,000. The hydrogen-powered fuel cell vehicle's TCO is ~41% higher than the ICEVs and it is around ~$117,000. Interestingly, the reduction in TCO has been significant for fuel cell vehicles (~17%) while the TCO for battery-based electric vehicles increased by ~8% based on the values reported in the year 2020 (Ghandi and Paltsev 2020). They reported TCO $86,000 for battery electric vehicles and $141,000 for FCEV.

A cost sensitivity analysis is presented in section 5.5 to understand the cost components and the main drivers towards the total TCO for these three engine drive train types.

3.1.2 Validation for LDVs

The TCO model that I have developed is validated by modeling the same scenario presented in the recent AAA report (AAA 2020). The cost per mile (CPM) derived from my model is close to the values published by the AAA report. The CPM for ICEVs is $0.58, while the CPM for BEVs is $0.61. It is to be noted that the AAA TCO model assumes that a car is used only for 5 years by the first-time owner and it can be sold in the retail market to capture its remaining market value. This item is not included in the TCO model developed in this work. Therefore, it was added to the TCO model to make a reasonable comparison. The results from the validation are presented in *Table 3.4*. The CPM values reported by AAA for medium ICEV sedan and BEV vehicles are the same as obtained from the TCO model. It is to be noted that the AAA analysis indicates that the CPM value for BEVs and ICEVs are the same.

Contrary to this, the TCO model in this work indicates that the CPM value for BEVs is 25% higher than the ICEV CPM on a levelized basis. The CPM assessment presented by AAA ignores the cost associated with battery replacement that typically occurs in the 7th or 8th year of ownership. The cost of replacing the battery is ~$13,500 for a battery electric vehicle, which is ~13% of lifetime TCO. Also, the battery recycling cost, which is often passed onto the customer, has been ignored in AAA. As per some estimates, the recycling of EV batteries may cost as high as 20% of the original battery cost in the US (Kelleher Environmental, Millette Environmental, and Gracestone Inc.

2019; Steward et al. 2019). My TCO model has assumed a moderate cost for battery recycling i.e., 10% of the original cost of the battery.

Table 3.4: Comparison of Cost Per Mile (CPM) values derived from the TCO model and the values reported by AAA (AAA 2020)

	Units	**Medium ICEV Sedan**	**Battery Electric Vehicle**
Estimated (based on mpg)	**$/year**	1,231	491
Annual Ownership Costs			
Maintenance, repair and tires	**$/year**	1,434	1,119
Full-coverage insurance	**$/year**	1,245	1,227
License, registration, taxes	**$/year**	730	74
Finance Charge	**$/year**	684	826
Total Services	**$/year**	4,093	3,246
Annual Costs			
Fuel	**$/year**	1,231	491
Services	**$/year**	4,093	3,246
Vehicle Manufacturer Suggested Retail Price (MSRP)	**$**	25,000	49,000
One Time Repair (Battery Replacement)	**$**	0	0
Recycle Cost (Battery, Fuel Cell)	**$**	0	0
Fuel	**$**	6,155	2,456
Services	**$**	20,465	16,230
Adding Back Residual Value		8,030	22,385
Total Cost of Ownership $, TCO (for 5 yrs)	**$**	43,590	45,301
Cost Per Mile, CPM $/mile (Lifetime cost / Lifetime miles)	**$/mile**	0.58	0.60
2020 AAA Reported CPM	**$/mile**	**0.58**	**0.61**

3.2 TCO Modeling for Heavy Duty Vehicles (Class 8 type)

The HDV transportation industry continues to rely primarily on diesel for its needs. Low-carbon fuels will be needed to decouple energy use from emissions for this section. Therefore, the HDV sector is currently being explored to evaluate GHG reduction potential without compromising the sector's growth. BEV and FCEV trucks are evaluated based on the TCO matrix to understand their competitiveness against ICEV trucks.

The TCO analysis presented in the later section is based on certain assumptions for the US market. The analysis derives the total cost of ownership for HDVs for various drive train types. These assumptions are stated in *Table 3.5*.

Table 3.5: List of assumptions to derive Total Cost of Ownership for HDVs in the US

Vehicle Type	Class 8	**Data Source**
Annual miles	65,000	afdc.energy.gov/data
Life Time(year)	15	Frost & Sullivan(2020)
Discount Rate	7%	Frost & Sullivan(2020)
Fuel Price		
Gasoline Price ($/gal)	3	statista.com Database
Electricity Price ($/kWh)	0.15	AAA , Frost & Sullivan(2020)
Hydrogen Price ($/kg)	10	Electrolysis, see *Table 3.9*
Fuel Economy		
ICEV (miles/gallon)	7.5	afdc.energy.gov/data
BEVs Trucks, Tesla Semi (miles/kWh)	0.5	Tesla, Frost & Sullivan(2020)
FCEVs Nikola Two (miles/kg)~ (mpg)	14	Nikola,(Marcinkoski 2019)
Typical Driving Range (miles)	400	Tesla

The TCO model that I have developed for HDVs also includes costs that were not part of the analysis for LDVs. These costs are related to Tires, Dwelling, Administrative, including G&A and Maintenance & Repair. A detailed cost sensitivity analysis is presented in sections 5.6 and 5.7.

It is worth noting that the assumptions for HDVs (*Table 3.5*) are significantly different than the assumptions made for LDVs (*Table 3.2*). The Levelized TCO are derived for ICEV, BEV and FCEV based on the same period of ownership, annual mileage and capital cost. The data sources corresponding to each parameter are presented in *Table 3.5*. Here 15 years period is considered a lifetime for a Class 8 type truck. As per some estimates, the Maintenance & Repair costs for trucks older than 15 years rise exponentially and may not be economical for the business (Frost & Sullivan 2021). At the end of this period, these trucks are often repurposed for short-distance hauling or other light duty activities. This work ignores the activities and costs corresponding to 2nd life of HDV trucks.

The HDV's TCO analysis indicated that a typical ICEV truck costs ~$2.1 million in its entire lifetime to its owner. The calculations are based on an average annual mileage of 65,000 miles and fuel economy of 7 miles per gallon, as reported in *Table 3.5*. The TCO for electric trucks for the same ownership period and mileage is $3.27 million that is ~24% higher than the TCO ICEV trucks.

The hydrogen-powered fuel cell truck's TCO is ~39% higher than the ICEVs and it is ~$ 3.03 million. Unfortunately, the published data for HDV's TCO is limited and often lacks clearly stated assumptions. Therefore, it is non-trivial to estimate the reduction in CPM values with time for ICEV, BEV and FCEV trucks. Interestingly, the markups for BEVs and FCEVs above ICEVs in HDVs are approximately the same as observed for LDVs in earlier sections. It is well understood that the CPMs for LDVs and HDVs are largely independent as the factors driving the total costs are different.

It is to be noted that the BEV trucks have an additional cost when Levelized CPM is computed. The cost associated with Dwelling and Lost Hauling Capacity is added. Typically, the refueling time for ICEVs and FCEVs is within 10 minutes and does not add significant idle time for HDV trucks. However, a class 8 type BEV truck may take

1-2 hours for a full recharge for a 400+ miles trip. The HDV TCO model includes cost associated with 45 mins idle time related to battery recharging. It has been assumed that the trucks are charged only when the battery is zero and a moderate 10% overhead related to charging is added to the cost. NREL has estimated a flat cost of $75/hour that is incurred when an HDV is idle (Hunter, Penev, and Reznicek 2020).

The battery for a typical BEV truck may add 4000-6000 lbs of additional dead weight, leading to ~10% reduction in hauling capacity. Therefore, a 10% additional fleet must be added to haul the same freight if BEVs are used instead of ICEV trucks as per a study conducted by NREL (Hunter et al. 2020). The HDV TCO model includes a 10% additional cost for reduced hauling capacity. The increased dead weight of the vehicle would require extra structural weight, heavier brakes, a larger traction motor and, in turn, more batteries to carry around this extra mass (Thomas 2009). These 2nd order effects are not considered in this study.

It is expected that the cost of collecting and transporting the used HDV batteries to recycling centers would be offset by the value of the precious metals recovered from recycling. Therefore, it would not cost additional expenses to the owner. The TCO model for HDV has ignored the cost of battery recycling. In few countries (e.g. China) where the battery-recycling value chains are established, battery recycling may generate up to 15% return on investment (Niese et al. 2020; Steward et al. 2009). These returns may vary based on the market price of precious metals used in battery manufacturing.

A cost sensitivity analysis is presented in section 3.2.1 to understand the cost components and the main drivers of total TCO for these three drive train types.

Table 3.6: Total Cost of Ownership (TCO) model for three engine drive train types HDVs, namely Internal Combustion Engine (ICEV), Battery Electric (BEV) and hydrogen powered Fuel Cell Electric (FCEV) trucks

Type	**Units**	**ICEV Truck**	**BEV Truck**	**FCEV Truck**
Fuel	$/year	26,000	19,500	46,429
Annual O&M Costs				
Maintenance, repair	$/year	11,050	7,800	7,800
Tires	$/year	3,120	3,120	3,120
Full-coverage insurance	$/year	10,000	10,000	17,500
License, registration, taxes	$/year	1,000	1,000	1,000
Finance charge	$/year	6,469	12,938	19,408
Total Operation & Maintenance	$/year	31,639	34,858	48,828
Dwell (Charging Related Waiting period) Cost	$/year	-	9,141	-
General and Administrative Cost	$/year	78,000	78,000	78,000
Payload (Lost Hauling Capacity) Cost	$/year	-	12,870	-
Manufacturer Suggested Retail Price (MSRP)	$	150,000	300,000	450,000
One Time Major Cost (Battery Replacement@8 years)	$	-	98,200	-
Recycle Cost (Battery/FC)	$	-	-	-
Total Cost of Ownership, TCO (for 15 years)	$	2,184,588	2,713,735	3,048,842
Annual cost (Life Time Cost/Life Time)	$	145,639	180,916	203,256
Cost Per Mile, CPM($/mile)	**$/mile**	**2.24**	**2.78**	**3.13**
Markup above ICEV			**1.24**	**1.39**

3.2.1 Validation for HDVs

The TCO model that I have developed for HDVs for three drive train types is compared with published market reports for North American and European markets for validation (Frost & Sullivan 2021; Frost and Sullivan 2017). The CPM values reported for ICEV and BEV vehicles are used for validation in this work. It was noted that the published market reports (Frost & Sullivan 2021; Frost and Sullivan 2017) have made assumptions based on the markets they were focused on. The different markets may differ in wages, interest rates, energy prices and economic predictions. For example, wages for truck drivers in EU markets are 30% lower than the North American market. The assumptions for the HDV TCO model were changed to the values reported by market reports to enable a fair comparison.

The CPM for ICEV trucks for the North American market was reported by $1.53/mile. The HDV TCO model yields the same CPM value for ICEV trucks in the North American market as shown below.

Table 3.7: Cost Per Mile (CPM) value derived from HDV TCO model based on the assumptions reported by (Frost & Sullivan 2021) for ICEV trucks in the North American market. The calculations assume 7 years lifetime with a 5% discount rate and an average gasoline price of $3.18/gal as stated in Frost & Sullivan, 2020 Report for North American Markets.

North American Market, 2020	**Units**	**ICEV Truck**
Fuel	$/year	40,101
Annual O&M Costs		
Maintenance, repair	$/year	11,000
Tires	$/year	3,000
Full-coverage insurance	$/year	7,000
License, registration, taxes	$/year	4,000
Finance Charge	$/year	3,596
Total Operation & Maintenance	$/year	28,596
Dwell (Charging Related Waiting period) Cost	$/year	-
General and Administrative Cost	$/year	67,000
Payload (Lost Hauling Capacity) Cost	$/year	-
Manufacturer Suggested Retail Price (MSRP)	$	120,000
One Time Major Cost (Battery Replacement@7 yrs)	$	-
Total Cost of Ownership, TCO (for 7 yrs)	$	1,069,875
Annual cost (Life Time Cost/Life Time)	$	152,839
Cost Per Mile, CPM($/mile)	$/mile	**1.53**
CPM (North American Market)	$/mile	**1.53**

To the best of my knowledge, there are no public reports available for EV trucks for North American markets. Therefore, the TCO model was validated with using a market report on EV trucks in EU markets. The results are presented in *Table 3.8*. The CPM value for EV trucks is reported as $1.44/mile by (Frost & Sullivan 2021; Frost and

Sullivan 2019). The HDV TCO model yields a $1.45/mile value for CPM for the EU markets, as presented below.

Table 3.8: Cost Per Mile (CPM) value derived from HDV TCO model based on the assumptions reported by (Frost & Sullivan 2021) for EV trucks in the EU markets. The calculations assume 15 years lifetime with 3% discount rate and an average electricity price of $0.20/kWh as stated in Frost & Sullivan, 2018 Report for European Markets.

European Market on BEV Trucks, 2018	**Units**	**BEV Truck**
Fuel	$/year	40,000
Annual O&M Costs		
Maintenance, repair	$/year	12,000
Tires	$/year	3,000
Full-coverage insurance	$/year	7,000
License, registration, taxes	$/year	4,000
Finance Charge	$/year	5,617
Total Operation & Maintenance	$/year	31,617
Dwell (Charging Related Waiting period) Cost	$/year	-
General and Administrative Cost	$/year	45,000
Payload (Lost Hauling Capacity) Cost	$/year	-
Manufacturer Suggested Retail Price (MSRP)	$	328,500
One Time Major Cost (Battery Replacement@15 yrs)	$	95,000
Total Cost of Ownership, TCO (for 15 yrs)	$	2,172,760
Annual cost (Life Time Cost/Life Time)	$	144,851
Cost Per Mile, CPM($/mile)	$/mile	**1.45**
CPM (European Market, Year 2020)	$/mile	**1.44**

3.3 Hydrogen Retail Cost Modeling

Several researchers have explored the techno-economical aspect of the hydrogen production-transportation- storage- refueling value chain (Blazquez-Diaz 2019; Gökçek and Kale 2018; Sun et al. 2017). As mentioned in earlier sections, three distinguished processes are involved in the hydrogen value chain- Production, Handling & Delivery, and Refueling. This section focuses on developing a cost model that can calculate the cost of the whole value chain, starting from hydrogen generation to delivery to the end-user. As discussed in earlier sections, hydrogen handling and delivery costs largely depend on the hydrogen phase, pressure ratings, transportation mode, storage type, and configuration of refueling stations (Christensen 2020).

3.3.1 Cost Components of Hydrogen Retail Price

Here are few major components of the total retail cost of hydrogen. These components are reported in $/kg of hydrogen-produced in the hydrogen Cost model presented in later sections.

- **Energy Cost-** The cost of energy required (electricity or natural gas) to complete the process of hydrogen production. The cost varies based on load factor and process efficiencies.
- **Feed Cost-** The cost of natural gas, methanol, or water needed for the chemical processes to generate hydrogen.
- **Capital Cost-** There is significant investment needed to build facilities to manufacture hydrogen. This cost is often reported in $/kg of hydrogen produced per day by a given facility. The cost further is adjusted to estimate the payments based on the interest rate or WACC. This cost is referred to as capital cost in the cost model presented here. For example, electrolyzer's cost is reported in $/kWe, i.e., the total cost in $ per unit of H2 LHV kW output.
- **Handling and Storage Cost-** The cost in $/kg to transform and store hydrogen for transportation and refueling. The transformation may include converting

liquid hydrogen to vapor form or vice-versa depending on the mode of transportation and storage.

- **Transportation Cost-** The cost of transporting hydrogen from a given central manufacturing location to Hydrogen Refueling Systems (HRS). The cost varies with location, phase, source and demand.
- **Refueling Cost-** The cost of refueling infrastructure in $/kg H2 delivered in its entire lifetime.
- **O&M Cost-** The cost to operate and maintain a hydrogen generation plant for its normal operations.
- **Carbon Mitigation Cost-** The cost associated with carbon emissions during hydrogen manufacturing under the carbon tax regime. This has not been included in the hydrogen cost model.

3.3.2 HDSAM Model

This work utilizes Hydrogen Delivery Scenario Analysis Model (HDSAM) developed by NREL to estimate the total cost for Handling & Delivery and Refueling(Elgowainy et al. 2015). HDSAM calculates the cost contribution of each component in a delivery chain that extends from the outlet of a centralized hydrogen production facility to a refueling station where hydrogen is dispensed onto vehicles *Figure 3.1*. It allows accounting for the cost of hydrogen delivery via a single or mixed mode such as cryogenic tank truck, compressed gas truck or pipeline. The model allows defining a delivery scenario by type and size of market, penetration rate, type of delivery mode and refueling station capacity. HDSAM accounts for discounted cash flow to calculate the cost contribution of each component in a delivery chain that extends from the outlet of a centralized hydrogen production facility to a refueling station where hydrogen is dispensed onto vehicles. The HDSAM models the delivery mode and refueling station components, so HDSAM estimates the delivery and refueling costs. Adding hydrogen production cost to the HDSAM cost estimate would provide the retail cost of hydrogen. HDSAM coupled with GREET models may allow analyzing the economics, primary energy-source requirements and emissions of hydrogen production and delivery pathways.

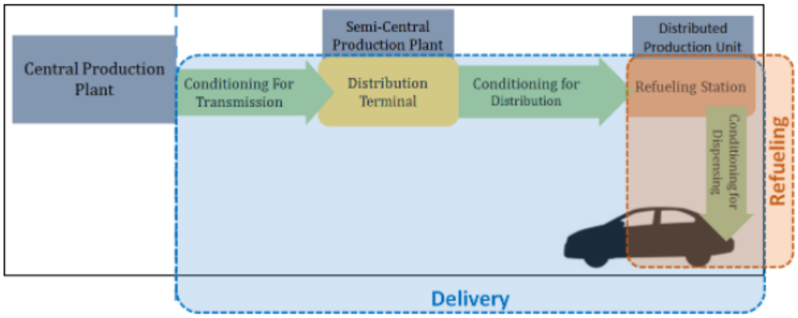

Figure 3.1: Schematic of the system boundary for modeling hydrogen delivery and refueling cost. Credit: Argonne National Laboratory Website (Elgowainy et al. 2015).

The production cost varies based on Centralized vs. Distributed production facility and the manufacturing process (Electrolysis, SMR, SMR+CCS). The Handling and delivery costs change based on transportation mode (Liquid H_2 transported using trucks, Gaseous hydrogen via tube trailers, Pipeline transportation). The refueling cost varies in wide ranges due to multiple configurations that may deliver on customer needs. Typical options may include Gas- 350/700 bar Cascade or 700 bar compressor Dispensing, Liquid- 350/700 bar pump/vaporization or vaporization/compression and Discharging Capacity (300, 600, 900, 1500 kg/day). The Handling & Delivery and Refueling costs may vary in a wide range. The author has presented the costs calculated by HDSAM for various infrastructural configurations (Appendix I). In the cost model, the HDSAM costs are calculated for the following configuration.

- Centralized production facility
- Transportation of liquid hydrogen using trucks
- Gaseous Storage in natural caverns
- Dispensing through HRS operating at 350 bar cascade with 600kg/day of discharging capacity

The production cost of hydrogen via three-generation processes is calculated in the following sub-sections. The cost presented below in the model is derived for Low

Heating Value (LHV) hydrogen i.e. the electrical equivalent value of the produced hydrogen in kWh/kg H_2 is 33.30.

3.3.3 Electrolysis

The cost model for hydrogen retail price via electrolysis process is presented in *Table 3.9*. The cost and efficiency of the electrolyzer are assumed \$1000/kWe and 75%, respectively. Electrolysis requires water as well as electricity. The electricity price is assumed \$0.10/kWh. The process consumes ~ 9 liters of water to produce 1 kgH2 (LHV) and 8 kg of oxygen is produced as a by-product. The model does not add credits earned from the sale of oxygen. All other assumptions are presented in Appendix II.

Table 3.9: Retail cost of hydrogen with hydrogen generation via electrolysis based on assumptions presented in Appendix II.

	Unit	**Cost**	**Comment**	**Year Accessed**
Electricity for Electrolysis	$/kg	4.76	Calculated (Appendix II)	
Water for Electrolysis	$/kg	0.01	Engineering Handbook	2021
Other O&M related (Grid)	$/kg	0.05	5% based on Howe's model	
Capital cost	$/kg	0.97	Assuming Electrolyzer Capital Cost in $/kWe @1000	
Delivery and Handling	$/kg	3.53	HDSAM NREL Model (Capital + O&M + Energy)	2021
Refueling	$/kg	1.05	HDSAM NREL Model (Capital + O&M + Energy)	2021
Decommissioning	$/kg	0.01	NREL Published Models	2021
Total	$/kg	**10.37**		

The retail cost of hydrogen is \$10.4/kg in this case- ~55% of this cost comes from Production, 34% cost comes from Handling & Delivery and ~10% cost is incurred from

Refueling. It is to be noted that 45% of the total cost is from electricity consumption. The 2nd largest contributor is the cost of the electrolyzer, which incurs ~10% of the total cost.

3.3.4 SMR

The cost model for hydrogen retail price via SMR process is presented in *Table 3.9*. The cost and efficiency of the SMR process are assumed $ 300/kWe and 75%, respectively. The operating load has been assumed 75% of the total capacity. Since SMR uses natural gas as feed to produce hydrogen, natural gas price mainly influences the total cost. Other technical and economic factors such as capital expenditure (CAPEX) influence the total cost significantly. All other assumptions related to the cost model are presented in Appendix III.

The model does not add credits earned from the sale of oxygen. All other assumptions are presented in Appendix II.

Table 3.10: Retail cost of hydrogen with hydrogen generation via SMR process based on assumptions presented in Appendix II.

	Unit	Cost	Source	Year Accessed
Electricity for SMR Process	$/kg	0.10	NREL Published Models	2021
Natural Gas for SMR (Feedstock)	$/kg	0.84	Engineering Handbook	2020
Other O&M related	$/kg	0.064	Assumption based on literature	
Capital cost	$/kg	0.13	NREL Published Models	
Delivery and Handling	$/kg	3.53	HDSAM NREL Model(Capital + O&M + Energy)	2021
Refueling	$/kg	1.05	HDSAM NREL Model(Capital + O&M + Energy)	2021
Decommissioning	$/kg	0.003	NREL Published Models	2021
Total	$/kg	**5.72**		

The retail cost of hydrogen with SME process is $5.7/kg in this case- ~60% of this cost comes from Handling & Delivery whereas production and refueling claim 20% each of the total cost. It is to be noted that the production cost is low as the natural gas prices are assumed to be $4/MMBTU.

3.3.5 SMR & CCS

The author has used GREET model to estimate the cost of CCS with SMR process (Sun and Elgowainy 2019). The retail cost of hydrogen with SMR+ CCS is $6.0/kg if CCS is added to the SMR process. It leads, on average, to a doubling of CAPEX as a result of CCS-related infrastructure. In this case, Delivery & Handling incurs 60% of the total cost, whereas production and refueling hold an equal share in the remainder of the cost. SMR+CCS is one of the lowest cost low-carbon hydrogen production routes.

Augmenting SMR plants with CCS adds ~ 25% cost to the hydrogen production process. The retail cost of hydrogen increases merely by 5% if CCS is added to the SMR process. It leads, on average, to a doubling of CAPEX as a result of CCS-related infrastructure. In this case, delivery & Handling incur 60% of the total cost, whereas production and refueling hold an equal share in the remainder of the cost.

Table 3.11: Retail cost of hydrogen with hydrogen generation via SMR process and CCS technology. The assumptions are presented in Appendix III.

	Unit	Cost	Source	Year Accessed
Electricity for SMR Process	$/kg	0.10	NREL Published Models	2021
Natural Gas for SMR (Feedstock)	$/kg	0.84	Engineering Hand book	2020
O&M related	$/kg	0.064	Assumption based on literature	
Capital cost	$/kg	0.13	NREL Published Models	
CCS Capital Cost	$/kg	0.19	NREL Published Models	Base Cost 2005, scaled @2% per year to 2021
CCS Energy Cost	$/kg	0.06	NREL Published Models	Base Cost 2005, scaled @2% per year to 2021
CCS O&M cost	$/kg	0.03	NREL Published Models	Base Cost 2005, scaled @2% per year to 2021
Delivery and Handling	$/kg	3.53	HDSAM NREL Model(Capital +O&M + Energy)	2021
Refueling	$/kg	1.05	HRSAM NREL Model(Capital +O&M + Energy)	2021
Decommissioning	$/kg	0.00	NREL Published Models	2021
Total	$/kg	**5.99**		

3.3.6 Model Validation

The retail cost of hydrogen derived from the cost model is presented in *Figure 3.2*. The results are validated with an earlier techno-economic study by (Simbeck and Chang 2002) on cost estimates for hydrogen production, Handling & Delivery and Refueling for Electrolysis and SMR processes. The cost estimates from the model are closely aligned (± 15%) with the values reported by Simbeck and Chang (*Figure 3.3*). The values for the retail cost of hydrogen tally closely with other market reports (Citi Research 2020; Hydrogen Council 2020). These cost values are used in the development of a macroeconomic model to predict a long-term forecast. On a separate note, the author noticed some differences as well. For example, the cost of transporting hydrogen via liquid tankers is an expensive option as per the HDSAM model but (Simbeck and Chang 2002) work indicated that it is the cheapest option. It is to be noted that the work by Simbeck and Chang was done about 20 years ago; therefore, some differences in values are expected due to inflation, altered infrastructure cost and technological improvements.

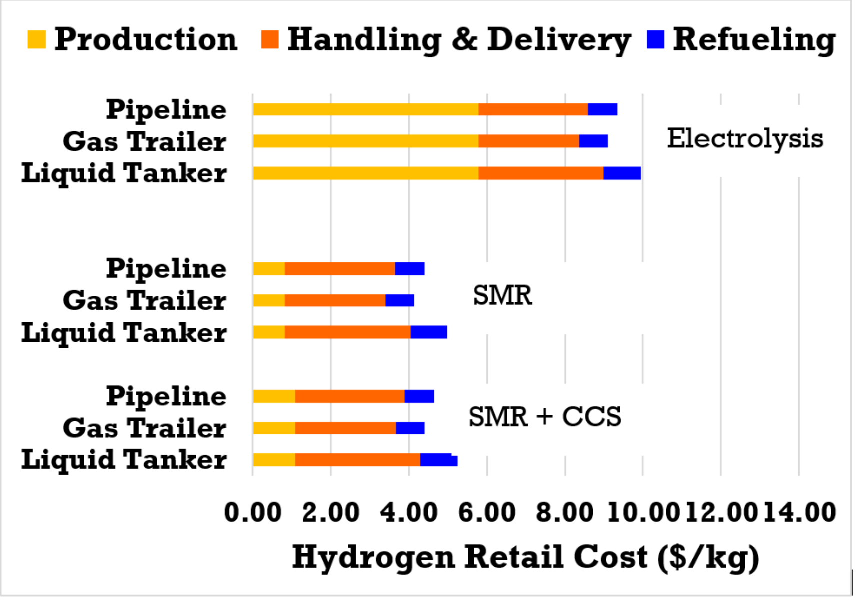

Figure 3.2: Hydrogen retail cost breakup among production, handling & delivery and refueling processes for three by production technology types.

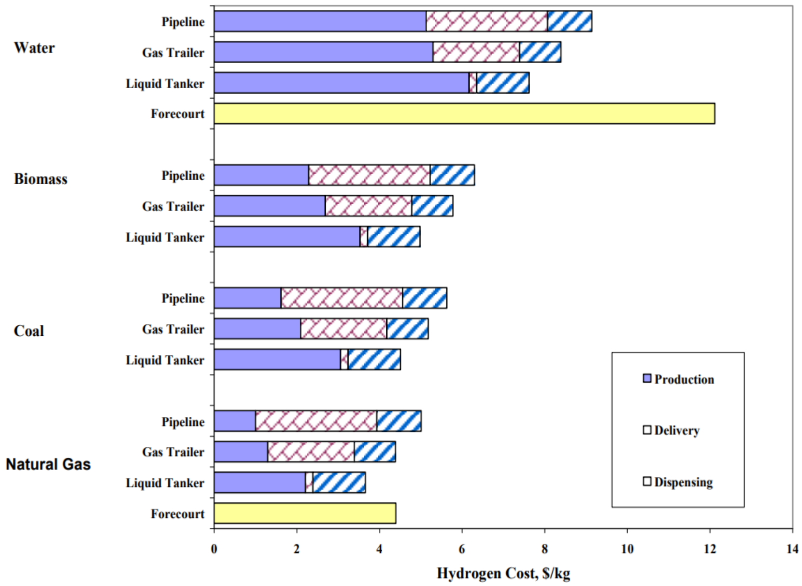

Figure 3.3: Hydrogen retail cost split for Electrolysis of water and SMR of natural gas processes (Simbeck and Chang 2002). Credit: (Simbeck and Chang 2002)

Chapter 4. EPPA Model and Scenarios

The MIT Economic Projection and Policy Analysis (EPPA) model (Chen et al. 2016; Paltsev et al. 2004, 2005) is a dynamic multi-region multi-sector computable general equilibrium (CGE) model. The model captures exchanges between all sectors of the economy, accounting for changes in international trade. The tool offers analytical abilities with a technology-rich representation of the household transport sector and its substitution with purchased modes, as presented in (Karplus, Kishimoto and Paltsev 2015). Data on production, consumption, intermediate inputs, international trade, energy and taxes for the base year are from the Global Trade Analysis Project (GTAP) dataset (Aguiar, Narayanan and McDougall 2016). The GTAP dataset is aggregated into 18 regions, as shown in *Figure 4.1*.

The EPPA model has 34 sectors (*Table 4.1*), including several advanced technology sectors parameterized with supplementary engineering cost data (Morris et al. 2019). The regional economic growth for all 18 regions for 2010-2020 is calibrated to historical data and short-term projections from the International Monetary Fund (IMF 2019). Energy use on a regional basis for 2010-2015 is calibrated to data published by International Energy Agency (International Energy Agency 2018). The model takes 5-years time steps to solve CGE for the whole world economy starting from 2020. The model includes a representation of the household transport sector and its substitution with purchased modes of public transportation, including aviation, rail and marine transport (Paltsev et al. 2004). The model includes several new features to explicitly represent the household transport sector(Ghandi and Paltsev 2019; Karplus et al. 2013). These features include an empirically-based parameterization of the relationship between income growth and demand for vehicle miles traveled (VMT), a representation of fleet turnover and opportunities for fuel use and emissions abatement, including representation of electric vehicles.

The GTAP data, which is the source for the underlying data for the EPPA model in a base year, does not provide the details on household transportation. To calibrate the EPPA model, additional data on the stocks of private light-duty vehicles, expenditures on fuel, vehicle and services, cost of alternative vehicles are used as described in (Ghandi and Paltsev 2020). The electric vehicle (EV) category in this analysis includes plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEV).

The MIT Joint Program in its 2021 Global Change Outlook has developed three policy scenarios to carve out plans to achieve the climate goals (Paltsev and Schlosser 2021). These scenarios are based on global GHG emissions cut aspirations, GDP growth expectations and climate heating-cap targets. To assess trends in the light-duty vehicle (LDV) fleet over the 2020–2050 timeframe, a *Reference* scenario and three policy scenarios are evaluated:

(1) a *Paris Forever* scenario, which assumes implementation of commitments under the Paris Agreement by 2030 and continuation of those policies thereafter, but no additional policy action; and

(2) a *Paris to 2°C* scenario, which assumes policy action beyond current Paris commitments to ensure that the increase in Earth's average surface temperature (relative to pre-industrial levels) does not exceed 2°C.

(3) an *Accelerated Actions* scenario, which targets 70% reduction in global CO_2 emissions by 2050 relative to 2015 levels. Developed countries have more stringent targets, with USA reducing by about 80% in 2050 relative to 2015 (for details, see Section 4.1.4 and the MIT 2021 Global Change Outlook).

Later sections describe the key results of the modeling analysis for each scenario.

4.1.1 Reference Case

The Reference scenario is based on the assumption that there is continued strengthening of fuel efficiency standards for LDVs and expanded use of renewables for power generation (International Energy Agency 2020b). It does not include mitigation pledges made by countries in their submissions for the Paris Agreement (United Nations 2015). Growth in population and economic activity (as measured by gross domestic product or GDP) are the key drivers of future demand for mobility changes. For population growth, a central estimate is adopted from the United Nations (Christensen, Gillingham and Nordhaus 2018; United Nations 2019), which projects that the world population will increase from 7.8 billion in 2020 to 9.8 billion in 2050. The fastest growth is expected to occur in Africa, the Middle East and Australia/New Zealand, where the model assumes average annual population growth rates of 2.1 %, 1.2 % and 1 %, respectively, over the 2020–2050 timeframe. Some countries, such as Japan, Russia, China and South Korea, are projected to experience negative population growth over this period.

For near-term GDP growth, forecasts from the International Monetary Fund are adopted. The assumptions about long-term productivity growth are taken from the MIT Joint Program Outlook (Paltsev and Schlosser 2021). This results in an assumed world GDP average annual growth rate of about 2.6 % for the 2020–2050 study period. It has been assumed that the advanced economies grow slower than the developing economies. For example, average annual GDP growth between 2020 and 2050 is modeled at 1.7 % in Europe and Japan and about 2 % in the U.S., while GDP for China, India, Africa and East Asia is assumed to grow at an average annual rate of about 4.0–4.5 % during that period. Global economic growth slows from about 2.9 % in 2020 to about 2.35 % in 2050.

The average fuel efficiency of the LDV fleet varies by region, with Europe, Japan and the U.S. having the most fuel-efficient ICEV fleets—averaging 24–26 miles per gallon (MPG)—in 2015. To model future gains in LDV fuel efficiency, we assume that fuel efficiency standards increase in all regions by 1–2 % per year. In the U.S. and Europe, standards are assumed to increase by 1.4 % per year, in China by 1.3 % per year and in India by 1.1 % per year. In most developing economies, the assumed increase is faster (close to 2 % per year), bringing fleet efficiency in these countries closer to that of advanced economies. The model has made assumptions on LDV fuel efficiency for the U.S. market based on the assessments put together by the U.S. Energy Information Administration (US EIA 2018).

4.1.2 Paris Forever

The Paris Forever scenario assumes that the country-level commitments pledged under the Paris Agreement are met by 2030 and retained after that. It has been assumed that the population growth in all scenarios is not coupled with climate change policy. However, GDP growth is affected by economic and climate policies and is different in different policy scenarios. The Paris Forever scenario assumes no emissions trading, which means that each region has its own carbon price. The model works on roughly stable carbon prices in these regions from 2030 to 2050 at about \$70–\$80 per tonne of CO_2 (t CO_2) in the U.S., \$90–\$100/t CO_2 in Europe and about \$20–\$35/t CO_2 in China. All monetary values are reported in real terms in 2015 U.S. dollars.

4.1.3 Paris 2°C

This scenario assumes the same mitigation efforts as the Paris Forever scenario up to 2030, but more aggressive policy action thereafter to reach the global emissions trajectory needed to limit global average surface temperature warming to 2°C. It is assumed that mitigation is achieved through global economy-wide carbon pricing after 2030 that is based on the MIT Integrated Global System model results. In this scenario, after achieving their NDC targets for 2030, all countries impose carbon prices that are rising to about \$140/t CO_2 in 2040 and to about \$200/t CO_2 in 2050. For this scenario, additional cases that assume lower EV costs and higher levels of support for the deployment of renewable energy are considered.

The Paris to 2°C scenario assumes that countries intensify their climate-change mitigation efforts after meeting their pledged "nationally determined contributions" or NDC commitments under the Paris Agreement through 2030. Specifically, countries implement the additional emissions reductions needed to achieve the overarching goal of the Paris Agreement, which is to limit the increase in global average temperature to less than 2°C.

4.1.4 Accelerated Actions

While many countries are progressing in fulfilling their Paris pledges for 2030, even more aggressive global emission reductions are needed for reaching the long-term goal of the Paris Agreement related to "pursuing efforts to limit the temperature increase to 1.5°C (United Nations 2015)". The accelerated actions scenario evaluates the impacts of increased ambitions. For this scenario, I rely on the scenario developed by the MIT Joint Program(Paltsev and Schlosser 2021), where advanced economies (USA, Europe, Canada, Japan, Australia and New Zealand) reduce their 2050 GHG emissions by 80% relative to their 2005 levels. Most other G20 countries reduce their 2050 GHG emissions by 50% with respect to 2005 levels (except for India and Indonesia (30%) and Russia (40%)). Africa and the Rest of East Asia end up in 2050 at their 2015 GHG levels, while other countries reduce their GHGs in 2050 by 50% relative to 2015 levels. These efforts by different countries result in global CO_2 emission reduction of about 70% in 2050 relative to 2015 levels.

The US has the highest carbon emissions on a per capita basis 15.2 metric tons – it is ~4 times the world average per capita emissions(The World Bank 2018). Therefore, the US may contribute more to achieve global emission cut targets. This work evaluates a version of the Accelerated Actions scenario where the US targets to reduce its 2050 GHG emissions by 80% relative to their 2005 levels.

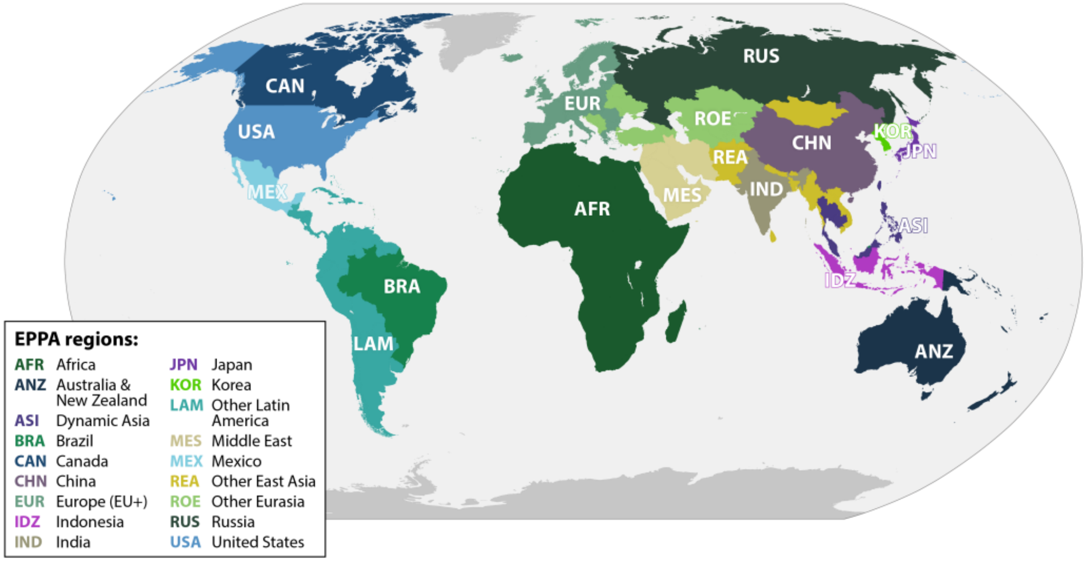

Figure 4.1: EPPA Model Regional Coverage (Ghandi and Paltsev 2019). Source: (Ghandi and Paltsev 2019)

Table 4.1: The sectors represented in the EPPA model (MIT Joint Program 2016). Source: (MIT Joint Program 2016)

Sectors	Abbreviation	Sectors	Abbreviation
Energy-Intensive Industries	EINT	Coal Electricity	ELEC: coal
Other Industries	OTHR	Natural Gas Electricity	ELEC: gas
Services	SERV	Petroleum Electricity	ELEC: oil
Crops	CROP	Nuclear electricity	ELEC: nucl
Livestock	LIVE	Hydro Electricity	ELEC: hydro
Forestry	FORS	Wind Electricity	ELEC: wind
Food Processing	FOOD	Solar Electricity	ELEC: solar
Coal Production	COAL	Biomass Electricity	ELEC: bele
Oil Production	OIL	Wind combined with gas backup	ELEC: windgas
Refining	ROIL	Wind combined with biofuel backup	ELEC: windbio
Natural Gas Production	GAS	Coal with CCS	ELEC: igcap
Synthetic Gas from Coal	SGAS	Natural Gas with CCS	ELEC: ngcap
Commercial Transportation	TRAN	Advanced Nuclear Electricity	ELEC: anuc
Private Transportation: Gasoline & Diesel Vehicles	HTRN: ice	Advanced Natural Gas	ELEC: ngcc
Private Transportation: Plug-in Hybrid Vehicles	HTRN: phev	First-Generation Biofuels	BIOF
Private Transportation: Battery Electric Vehicles	HTRN: bev	Advanced Biofuels	ABIO
Private Transportation: Hydrogen Vehicles	HTRN: fcev	Oil Shale	SOIL

Chapter 5. Results and Discussion

First, I provide several results from the developed TCO model (*sections 5.1 - 5.3*), then I apply some of my TCO calculations for LDVs to the EPPA model (in *sections 5.4 - 5.7*) to assess FCEV LDVs fleet dynamics under different assumptions.

5.1 EPPA Modeling Results

I have applied my TCO calculations to the EPPA model to assess FCEV LDVs fleet dynamic under different scenarios. The three basic policy scenarios studied for the US market demonstrated significant growth in economic activity. The increase in population drove the LDV stocks from ~250 million in 2021 to ~300 million in 2050. In the Reference scenario, the LDV stock is close to 269 million in 2030 and rises to 300 million LDVs in 2050. The implementation of climate change mitigation policies in the Paris Forever and Paris to 2°C scenarios affects fuel prices, vehicle efficiency, income levels of consumers and consumers' demand for transportation. As a result, the US stock of LDVs in 2030 is about 7 million fewer vehicles in Paris 2°C and Pairs Forever scenarios compared to the Reference scenario. After 2030, the more aggressive carbon constraints in the Paris 2°C scenario negatively impact LDV fleet growth in the US. LDV size forecast for 2050 from EPPA model shows that there would be 9 million fewer vehicles in the US under Paris 2°C scenario compared to the Reference scenario (*Figure 5.1*). Under the reference TCO assumptions, FCEV LDVs do not penetrate the U.S. market. Therefore, I have tested different conditions for their penetration.

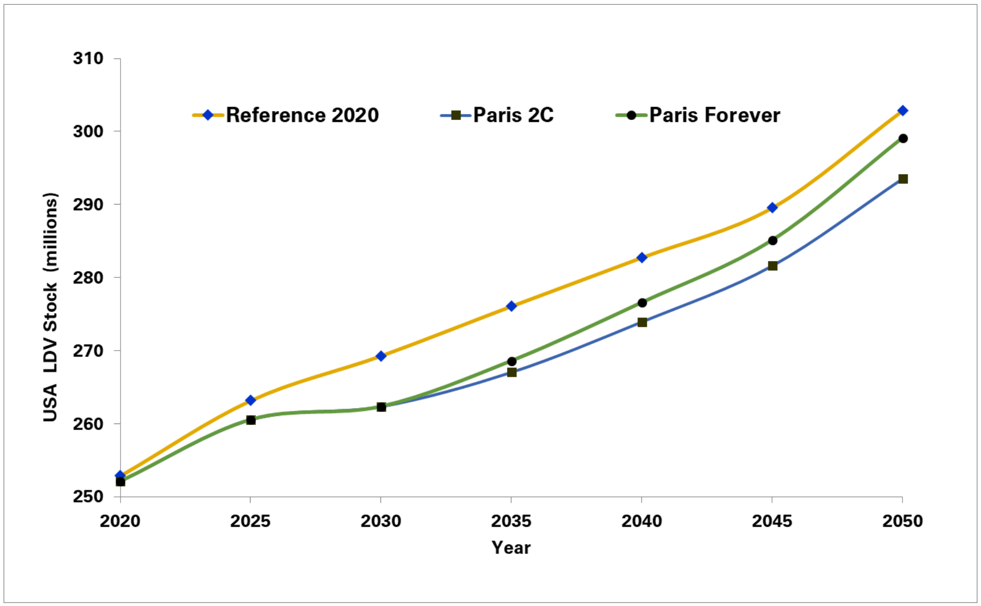

Figure 5.1: LDV stock in the US under three policy scenarios Reference, Paris 2°C and Paris Forever

5.2 Accelerated Actions

As described in section 4.1.4, the *Accelerated Actions* scenario assumes that the US would reduce its 2050 CO_2 emissions by about 80% relative to their 2015 levels. Informed by a potential for cost reduction discussed in Section 2, I have evaluated different profiles for TCO reduction over time.

5.2.1 Moderate TCO Reduction

The moderate TCO reduction scenario assumes that the total cost of ownership for fuel cell electric LDVs would become at par with ICEVs by 2050, which means the FCEV TCO relative to ICEV TCO reduces from 1.4 in 2021 to 1.0 in 2050 for FCEV (as represented by red dashed line in *Figure 5.2*). Under this assumption, the results from the EPPA model indicate that the fleet of the FCEV LDVs grows to a market share of 1% in 2030 and reaches ~14% market share by 2050 (as represented by the red solid line in *Figure 5.2*). The market share of 14% in 2050 corresponds to ~41 million vehicles.

5.2.2 Low TCO Reduction

The low TCO reduction scenario assumes that the total cost of ownership for fuel cell electric LDVs reaches 15% above ICEVs by 2050 (*Figure 5.2*). Currently, FCEVs TCO is 1.4 times of ICEVs. The results from EPPA model indicate that the growth of the FCEVs in this scenario is lowest compared to the other two scenarios, as expected. FCEVs hits a market share of ~10.7% by 2050 (*Figure 5.2*). The FCEVs in the Low TCO reduction scenario are ~8 million fewer in 2050 than the Moderate TCO reduction scenario. This difference in the number of FCEVs under these two scenarios is ~0.3 million in 2030. A slower pace of cost reduction results in a lower share of FCEVs in the total fleet.

5.2.3 High TCO Reduction

Under this scenario, it has been assumed that the reduction in TCO of FCEV is steep and the total cost of ownership for fuel cell electric LDVs would become at par with ICEVs by 2035, which means FCEV TCO relative to ICEV TCO reduces from 1.4 in 2021 to 1.0 in 2035 for FCEV (*Figure 5.2*). Thereafter, the TCO for both ICEVs and FCEVs would go hand in hand until 2050 in all scenarios. This strategy would not give any additional advantage to a relatively new emerging technology FCEV which may have a higher cost reduction potential (see Appendix IV for an extremely fast cost reduction scenario).

In this scenario, the FCEV LDV market share is 1.2% in 2030 and about 14% market share by 2050, which means there would be ~14.5 million FCEVs out of ~285 million total vehicle stock in the US (*Figure 5.2*). The number of FCEV in the High TCO reduction scenario is ~2.5 million larger in 2050 than the Moderate TCO reduction scenario.

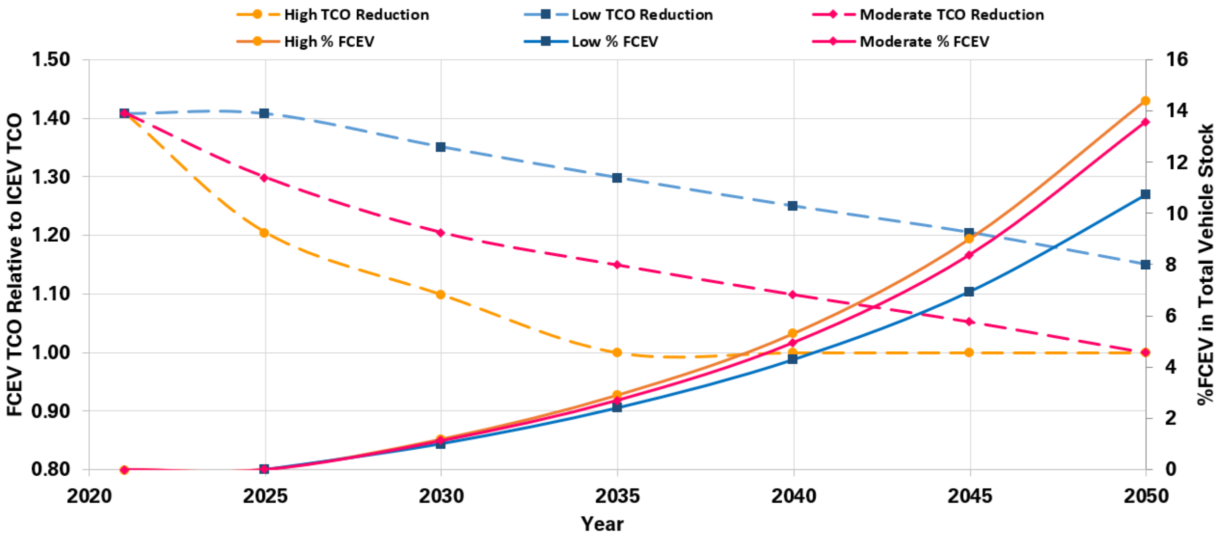

Figure 5.2: Total Cost of Ownership of FCEV relative to ICEV (y-axis on the left) are shown by dashed lines for three High, Moderate and Low TCO reduction scenarios. The corresponding percentages of FCEV in total vehicle stock (y-axis on the right) are shown by solid lines from 2021 to 2050.

5.3 Policy Actions & Technology Milestones

The TCO and EPPA modeling results suggest several policy and technology milestones that could help realize the cost reduction targets presented in *Figure 5.2*. Particularly the moderate case of TCO reduction multiple.

1. Policy Actions: The lifetime carbon emissions from a typical FCEV are ~ 50 tonnes or 60% less than ICEVs and ~10 tonnes higher than BEVs as presented in *Table 2.1*. Therefore, depending on the situation with BEV deployment, FCEV technology offers a viable alternative to ICEVs for emission reduction. With critical materials and battery supply chains currently located outside of the U.S., FCEVs may offer an option that relies on domestic resources, thereby enhancing domestic energy security. The exact competition between BEVs and FCEVs will be shaped by numerous factors (cost of batteries, availability of materials for batteries, grid decarbonization, etc.), but my analysis shows that with cost reductions, FCEV will take a sizeable share of the fleet. Supporting R&D into FCEV provides wider optionality for future policy actions.

2. Technology Milestones: The reduction in technology cost would decrease the TCO of FCEVs. The components where most of the cost reductions are expected are: vehicle cost, retail price of hydrogen and the cost of services such as insurance (because a matured technology that demonstrates safe and consistent operations, if deployed widely, would eventually be cheaper to insure).

There might be multiple cost components in LDV's TCO model presented in section 3.1.1 or their combinations that can be changed to match the TCO reduction targets used in *Figure 5.2*. In *Figure 5.3*, I show a combination of policy actions and technology milestones that can match the TCO reduction trends. I provide this discussion for illustrative purposes as numerous combinations could deliver similar reductions in TCO for FCEVs.

The retail price of FCEV (Toyota Mirai) has been reduced by ~25% from 2019 to 2021. While MSRP may or may not fully represent the cost of the vehicle (e.g., Toyota may decide to subsidize the cost of a particular vehicle), it is plausible to assume that the MSRP may reduce by 10% by 2025. The current US administration has set targets to produce green hydrogen at $2/kg by 2030, which leads to a retail price of $6/kg for hydrogen as mentioned in the proposed strategy discussed above for the FCEV path to be competitive with ICEV (*Figure 5.3*). The strategy has assumed that FCEVs' insurance costs would be at par with ICEVs or BEVs by 2035. The author has proposed allowing FCEV to have carbon abatement credits by 2040 at $60/tonne - a fair value of carbon credits assessed by multiple reports (Asen 2020; Chemnick 2021). It is expected from the FCEV manufacturers that they should be able to reduce the retail cost of vehicles by another 10% by 2045. It is desired that the hydrogen retail cost should drop to $4/kg by 2050 to attain a value of 1 or less for FCEV TCO relative to ICEV TCO. *Figure 5.3* presents one of the pathways to reduce the ratio of FCEV TCO to ICEV TCO from 1.41 to a value less than 1.0 (*Figure 5.3*).

It is to be noted that FCEV TCO would be at par with BEV TCO by 2030 if the proposed strategy is followed. A 10% reduction in FCEV MSRP and 40% reduction ($6/kg) in hydrogen retail price would make FCEV TCO equal to BEV TCO. It is based on the assumption that there will be no reduction in BEV TCO in the next 10 years.

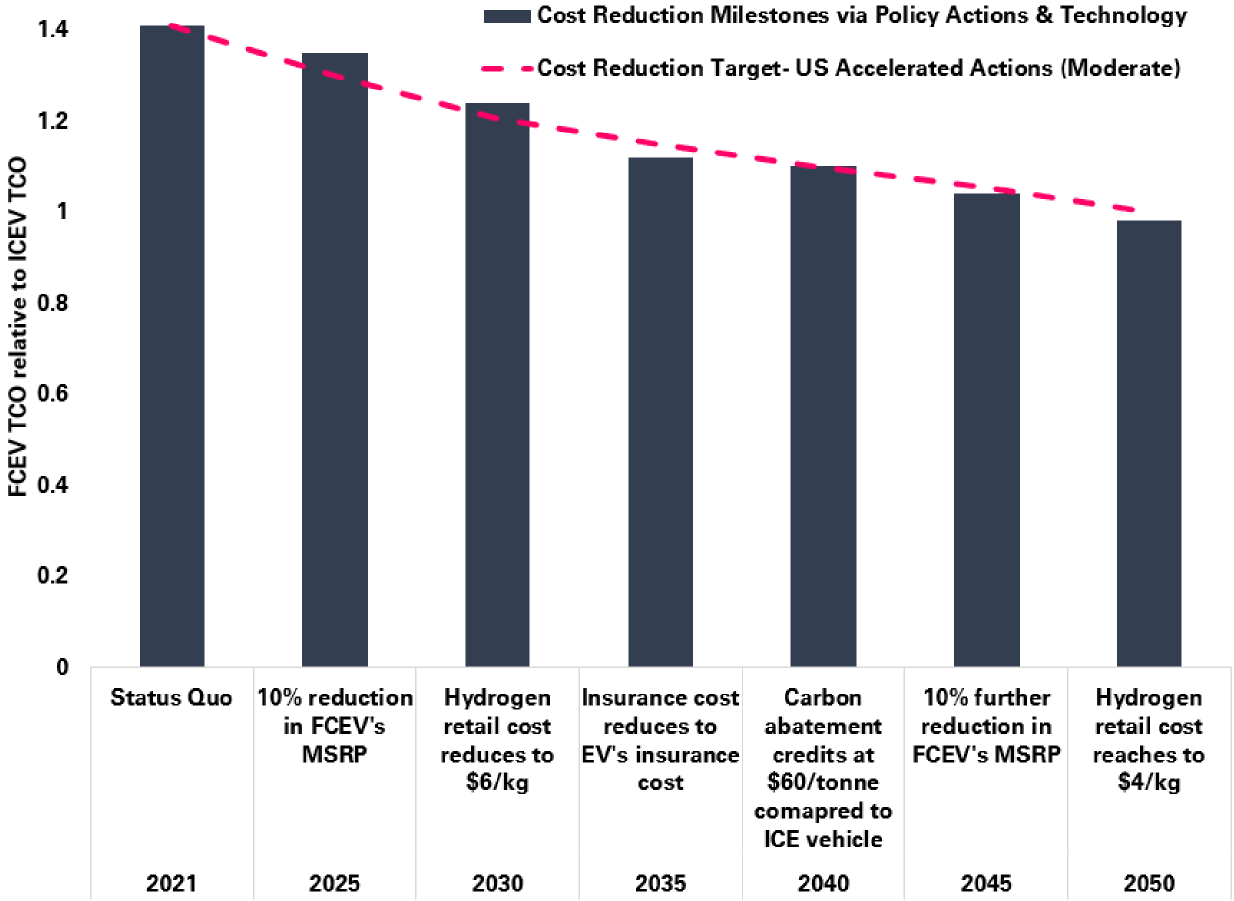

Figure 5.3: TCO reduction multiple targets (red dashed line) for US Accelerated Action (Moderate) scenario. The solid bars represent TCO reduction multiple as a result of policy actions & technology milestones mentioned at the bottom of those solid grey bars.

5.4 Total Cost of Ownership for LDVs

In the absence of carbon tax, the TCO and CPM values indicate that ICEVs are the cheapest for consumers on a lifetime basis. The CPM is higher for BEVs and FCEVs by 25% and 40%, respectively. On comparing the TCO values with earlier published work (Ghandi and Paltsev 2020), it was noted that Total Cost of Ownership (TCO) has changed by +5%, +10% and -17% for ICEV, BEV and FCEV, respectively, from 2019 to 2021. The BEVs and FCEVs would not be preferred based on pure economics unless some mechanism exists to offset the higher TCO. These mechanisms may include a carbon tax on ICEVs, carbon reduction incentives for BEVs and FCEVs, subsidies on BEV or FCEV purchase and providing fuel subsidies for FCEV.

The sensitivity analysis indicates that the fractional cost contribution (aka shares) from Vehicle's Maximum Suggested Retail Price (MSRP), Fuel and Services vary with drive train type. The fuel-related expenses for BEVs have the smallest share ~6% of the TCO, while ICEV and FCEV's fuel-related expenses are 16% and 27%, respectively. It indicates that the reduction in fuel price would have a more significant impact on reducing the TCO of FCEV compared to BEV. The vehicle's retail price is a significant TCO contributor (~60%) for FCEVs and BEVs. In contrast, ICEV's MSRP contributes only ~30% towards the TCO. The lower share of the vehicle's MSRP could be attributed to the matured technology of ICEV. The technology has been benefitted from 100+ years of learnings. The technology-related learnings could help bring down the cost of BEVs and FCEV. The continued learning curve may not achieve the cost floor until these technologies are at par with or cheaper than ICEV. Earlier work based on the EPPA model captured the LDV stock in an aggressive scenario (Ghandi and Paltsev 2020). Based on this, future technologies related to BEVs and FCEVs should target reducing the vehicle's cost to reduce TCO significantly.

5.5 Implication for FCEV in LDVs

Figure 5.4 presents a sensitivity analysis for four major contributors towards TCO for FCEV. The impacts of change in each parameter from its anticipated low to high boundary values on CPM are evaluated. The implications are discussed below.

1. FCEV MSRP: The retail price of the FCEV vehicle is one of the most significant contributors to TCO. The current MSRP is reduced by ~50% to make FCEV MSRP at par with an ICEV. In that case, CPM would reduce to $0.56/mile, i.e., lower than the current BEV CPM. However, if the MSRP increases by 20%, CPM would increase to $0.78/mile, ~10% higher than the current CPM.

2. Hydrogen Retail Price: Hydrogen retail price is another significant cost contributor as 60% of the TCO comes from FCEV's fuel-related expenses. On changing the hydrogen price from the current level $10/kg to $6/kg reduces the CPM to $0.66/mile from the current value of $0.71/mile. The lower hydrogen cost is based on $1/kg for green hydrogen generation and ~$5/kg for Delivery and Refueling as anticipated by the current US administration by 2030 (Liguori 2021). The CPM increases to $0.74/mile if the hydrogen retail cost increases to $12/kg.

3. Insurance Cost: The current insurance cost for FCEV is almost two times the insurance cost for a typical ICEV or BEV. Reducing the cost of insurance by 50% would reduce the CPM to $0.64/mile. This cost level is equivalent to the current CPM for BEVs, indicating that FCEVs are almost at par with BEVs if the insurance cost for FCEV and BEV are the same. Increasing the insurance cost by 20% from current levels would increase CPM to 0.74/mile.

4. Fuel Economy: Generally, fuel economy for LDVs is expected to get better with time. It is expected that the economy of FCEV may increase by 10%, which would decrease the CPM value to $0.68/mile. It is slightly above BEV's CPM, indicating that increasing the FCEV's fuel economy would not be sufficient to make FCEV competitive against BEV.

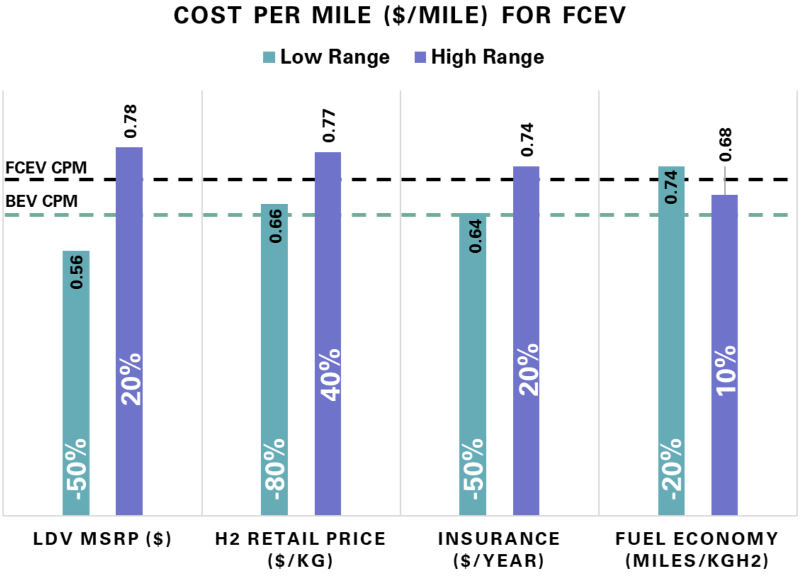

Figure 5.4: The low and high ranges of CPM for FCEV for variation in four major contributors of TCO. The dashed green and black lines indicate current BEV and FCEV levels. The bar represents the resultant CPM on changing the parameters presented on X-axis by a pre-defined percentage (indicated in white ink) in the green and purple bars.

The energy prices for gasoline, electricity and hydrogen are varied from their current level to understand the evolution of LCPM *Figure 5.5*. It is clear from *Figure 5.5*, that the Levelized CPM for ICEVs remains lowest compared to BEV and FCEV if the energy prices are varied within ±50%. However, few scenarios may be derived to recognize the price variation required to make BEV or FCEV competitive with ICEV.

1. FCEV with BEV: FCEV may have CPM at par with BEV if the hydrogen price reduces to $2.75/kg- it is unlikely that the hydrogen retail cost would drop to those levels by 2030. It is to be noted that MSRP for FCEV and BEV are similar in the market in 2021.

2. FCEV with ICEV: FCEVs and ICEVs may have comparable CPM if FCEV's retail price reduces to ICEV levels along with a reduction in hydrogen retail price to

$5.75/kg. It is expected that FCEV retail prices would continue to fall as FCEV captures a higher market share. However, it is unlikely that FCEV's MSRP would drop to ICEV's MSRP.

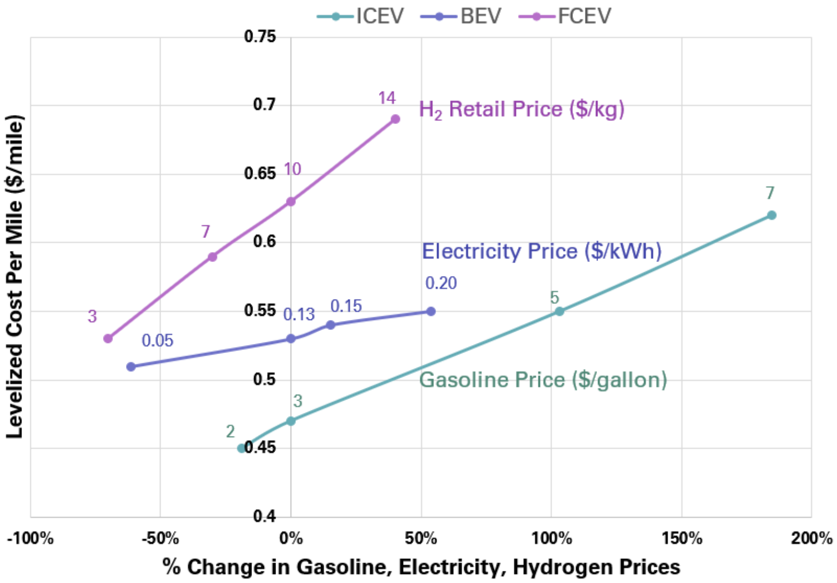

Figure 5.5: Levelized cost per mile for ICEV, BEV and FCEV with change in gasoline, electricity and hydrogen prices

3. BEV with ICEV: BEV may demonstrate CPM similar to ICEV if the battery cost falls by 75% from current levels of $400/kWh to $100/kWh (*Figure 5.6*). It has been assumed that the electricity price ~15₵ per kWh would remain at the same level. Alternatively, a scenario may be derived where electricity price falls to $0.05/kWh from $0.15/kWh and the battery cost falls by ~50% from current levels of $400/kWh to $175/kWh. It is to be noted that the battery contributes ~40% to the total cost of a typical BEV (König et al. 2021).

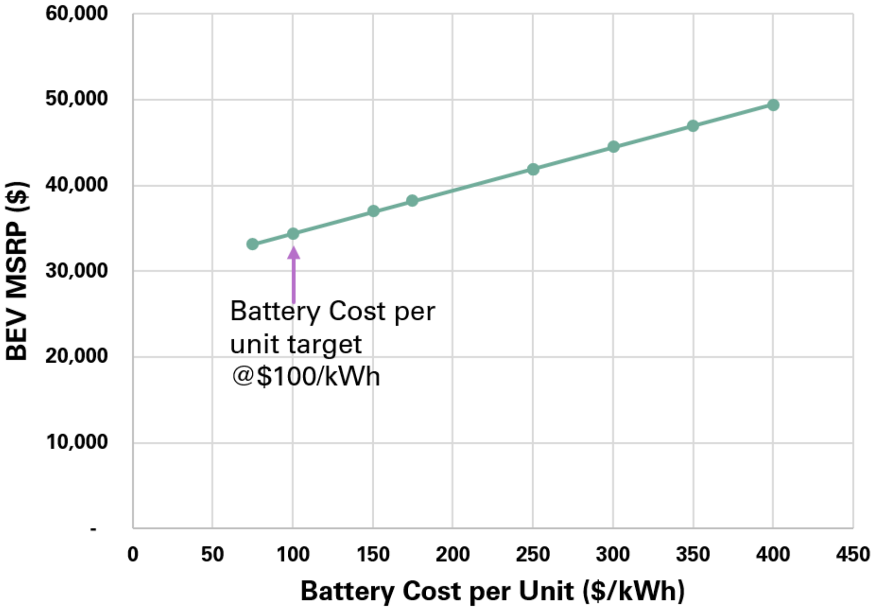

Figure 5.6: BEV retail price as a function of battery cost per unit capacity ($/kWh). It has been assumed that the overall vehicle cost varies linearly with battery cost.

5.6 Total Cost of Ownership for HDVs

In the absence of carbon tax, the TCO and CPM values indicated that ICEV (HDV) are the cheapest for the end-consumers for their lifetime. The CPM for BEV and FCEV HDVs is higher than ICEV by 25% and 40%, respectively. As discussed in the earlier section, that BEV or FCEV truck would only be preferred if some mechanism offsets the cost to the end-user. These mechanisms may include a carbon tax on ICEVs, carbon reduction incentives for BEVs and FCEVs, subsidies on BEV or FCEV purchase and providing fuel subsidies for FCEV.

The sensitivity analysis indicated that the fractional cost contribution (aka shares) from Vehicle's Maximum Suggested Retail Price (MSRP), Fuel and Services vary with drive train type. The fuel-related expenses for BEV trucks have the smallest share ~11% of the TCO, while ICEV and FCEV's fuel-related expenses are 15% and 23%, respectively. The fuel expenses for ICEV, BEV and FCEV trucks are $26,000, $20,000 and $46,000. The lifetime services cost for BEV trucks is the highest $2.1M followed by FCEV trucks $1.9M and ICEV trucks $1.6M. Here the category services include costs related to G&A, M&R, Dwell & Lost Hauling, Battery replacement, Insurance, Tires, Tax and Permits. The services cost for BEV trucks is higher due to the high cost of battery replacement, dwell and payload reduction capacity. Services hold the largest share of cost in TCO for all drive train types- FCEV(60%), ICEV (75%) and BEV (80%).

The retail prices of FCEV and BEV trucks are considered 3 and 2 times of ICEV truck MSRP (Munshi et al. 2021). A typical ICEV truck may cost $120,00 - $220,000- however, a cost of $150,000 is a reasonable market value for an average ICEV truck. The large variation in cost may be attributed to the safety features, cabin type & options and Make of the trucks (Burnham et al. 2021). It is to be noted that the cost of class 8 type BEV trucks in North America is quoted as $200,000 by some manufacturers (Tesla 2021). However, these cost levels are unlikely to sustain; therefore, this study has considered a consensus-based retail price for the BEV trucks i.e., $300,000. Similarly, some emerging FCEV truck manufacturers like Nikola have promised a price of $280,000 and $2/kg hydrogen refueling for three years for their class 8 type FCEV trucks (Field 2020; Nikola 2021). These cost levels are not deemed realistic therefore, the study has assumed the retail price for FCEV trucks as $450,000 to be conservative for TCO estimates.

5.7 Implication for FCEV in HDVs

Figure 5.7 presents a sensitivity analysis for four major contributors towards TCO for fuel cell electric Class 8 type truck. The impacts of change in each parameter from its anticipated low to high boundary values on CPM are evaluated. The implications are discussed below.

1. Fuel Economy: The technology of fuel cell electric trucks is relatively new to the market. It is expected that the fuel economy might improve as the technology matures.

The CPM may reduce to $2.64/mile if the fuel economy is improved by 50% from current levels.

2. Truck MSRP: The FCEV truck's retail price is one of the top contributors to TCO. If the current MSRP is reduced by ~70% to make FCEV truck's MSRP at par with an ICEV truck. Then, CPM would reduce to $2.62/mile, i.e., lower than the current BEV CPM ($2.78/mile). However, if the MSRP increases by 20%, CPM would increase to $3.25/mile.

3. Hydrogen Retail Price: Hydrogen retail price is another significant cost contributor in the case of FCEV trucks. If the Hydrogen retail price drops from the current level $10/kg to $6/kg, then the CPM reduces to $2.56/mile from the current value of $3.13/mile. This significant reduction in CPM makes FCEV trucks cheaper than BEV trucks on CPM basis. The CPM increases to $3.41/mile if the Hydrogen retail cost increases to $14/kg.

4. Insurance Cost: The insurance cost does not change the CPM significantly as the insurance cost is relatively smaller compared to G&A and M&R costs.

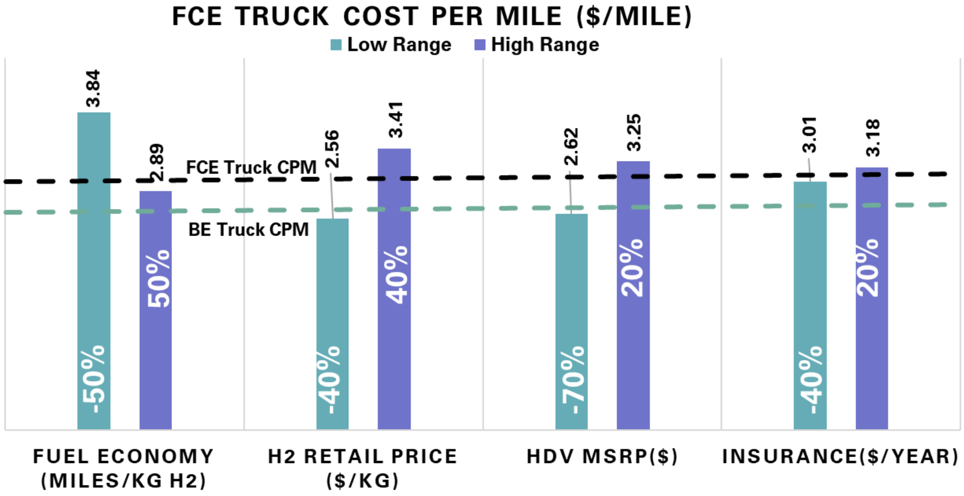

Figure 5.7: The low and high ranges of CPM for FCEV trucks for variation in four significant contributors of TCO. The dashed green and black lines indicate the current battery-electric and fuel cell electric truck's CPM levels. The solid bars represent

CPM on changing the parameters presented on X-axis by a pre-defined percentage (indicated in white ink) in the green and purple bars.

The energy prices for gasoline, electricity and Hydrogen are changed from their current levels to understand the evolution of LCPM; refer to *Figure 5.8*. The Levelized CPM for ICEV trucks remains lowest compared to BEV and FCEV if the energy prices are varied within ±50%. Based on the current situation, it is highly unlikely that BEV or FCEV trucks would have CPM at par with ICEV trucks even if the Hydrogen retail price or electricity price drops to zero. The section below explores scenarios where FCEV trucks might demonstrate competitive CPM compared to BEV or ICEV trucks.

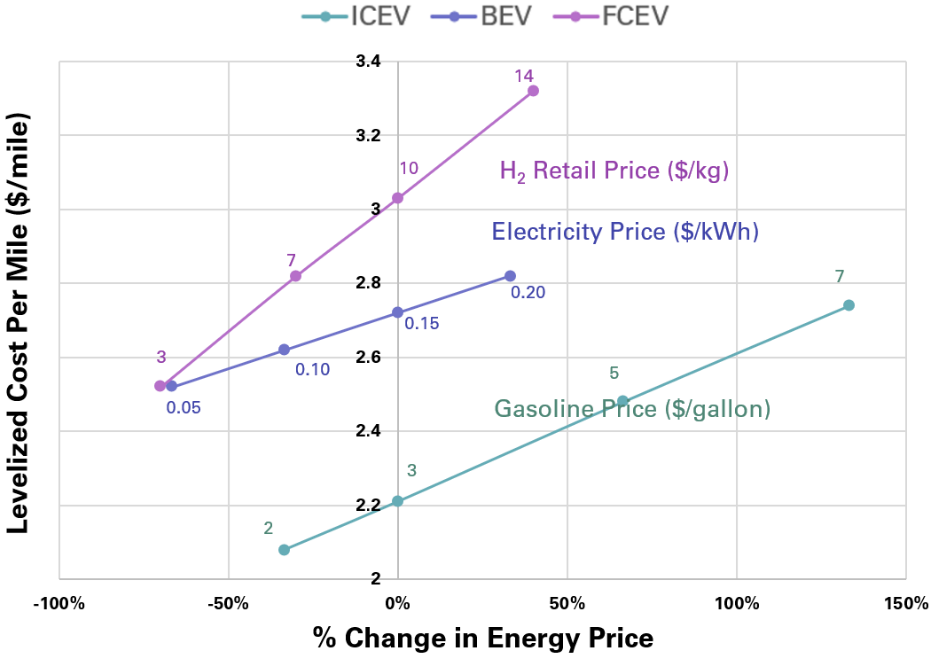

Figure 5.8: Levelized cost per mile for ICEV, BEV and FCEV class 8 type trucks with change in diesel, electricity and hydrogen prices.

1. FCEV with BEV trucks: The electricity prices are expected to stay relatively flat and the retail price for Hydrogen may go down in the future. A scenario under which Hydrogen cost may occur when the FCEV truck's CPM would be at par with BEV truck. For example: The CPM for FCEV truck at $6/kg H_2 would be at par with the CPM of BEV truck at $0.15/kWh electricity. Similarly, $3/kg H_2 would demonstrate cost parity with $0.05/kWh electricity. The cost parity might occur if FCEV truck's MSRP is slashed by ~45% to $240k from the current level of $450k. It is to be noted that BEV truck's MSRP is expected to go down in the future as well. However, a relatively higher cost reduction is anticipated for FCEV trucks. A smaller reduction in FCEV truck MSRP (~50%) is needed for cost parity if the hydrogen retail price is dropped by ~25%.

2. FCEV with ICEV trucks: Dramatic reductions are needed in cost for FCEV trucks to make FCEV truck's CPM at par with ICEV trucks. If the FCEV truck's MSRP drops by 70% and the hydrogen retail cost reduces to $5/kg then the FCEV truck would achieve cost parity with ICEV trucks. It is unlikely that the MSRP of FCEV trucks would drop by 70% in the next 5-10 years. Also, the retail price of hydrogen would reach ~$6/kg by 2030 as per US DOE ambitions. Therefore, it is expected that the FCEV trucks would not be able to compete with ICEV trucks on TCO basis for another decade.

3. BEV with ICEV trucks: BEV trucks could demonstrate at par LCPM with ICEV if the battery cost drops to $75/kWh from the current levels of $260/kWh along with 1cent/kWh electricity *Figure 5.9*. As per the current trends, both of these targets are unlikely to be met in the next 5-10 years. There are other levers in the case of BEV trucks that can be pulled to make BEV competitive with ICEV 1)Per unit battery cost and 2) A significant reduction in the cost associated with Dwelling and Lost Hauling Capacity.

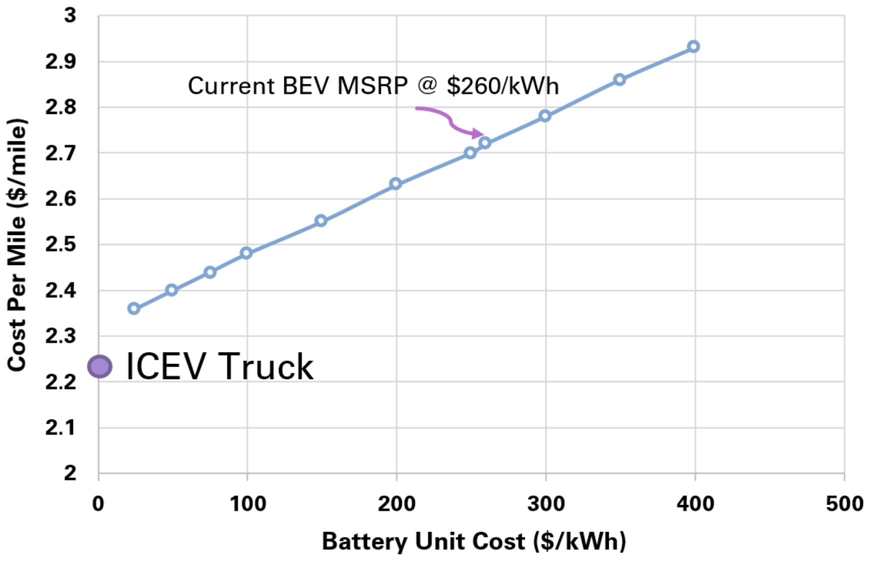

Figure 5.9: BEV truck's CPM as a function of battery unit cost($/kWh). It has been assumed that the overall vehicle cost varies linearly with battery cost.

Chapter 6. Recommendations and Conclusions

The Battery Electric Vehicle (BEVs) and Fuel Cell Electric Vehicles (FCEVs) are less carbon-intensive alternatives to Internal Combustion Engine Vehicles (ICEVs). However, these alternative technologies are emerging and yet to demonstrate their cost competitiveness against ICEVs. In this work, I have compared the overall cost of vehicle ownership based on Levelized Cost Per Mile (CPM). Total Cost of Ownership (TCO) models are developed for Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs) for three types of vehicle drive train namely ICEV, BEV and FCEV. The cost components are studied to explore the conditions under which FCEVs would have lifetime Cost Per Mile (CPM) equal or lower than BEVs or ICEVs. Fuel-related cost is the topmost contributor towards TCO of FCEV. Therefore, an attempt is made to understand hydrogen retail cost by using a cost model that calculated the total cost for the whole value chain Production – Handling & Delivery and Refueling. The growth of hydrogen-powered FCEV in the US market by 2050 is modeled using MIT's EPPA model under different climate scenarios. The TCO reduction targets used for predicting the FCEVs growth are further explored to formulate a strategy that can help achieve the targeted cost reductions. The main conclusions from this work are presented below.

6.1 Conclusions

1. The TCO for BEV (+26%) and FCEV (+41%) are higher than ICEV in the LDV sector in the absence of carbon abatement credits.
2. Currently, FCEVs are ~10% more expensive than BEVs on a CPM basis. However, there are cost reduction pathways that might make FCEVs competitive in the next 10 years.
3. The fuel-related expenses for BEVs have the smallest share ~6% of the TCO, while ICEVs and FCEVs fuel-related expenses are 16% and 27%, respectively.

Hence, there is a need to reduce the retail cost of hydrogen significantly to make FCEV competitive.

4. The cost of battery replacement and recycling is a significant expenditure for BEVs, and it represents ~14% of TCO in the LDV category. Therefore, it should be included in the TCO studies.
5. Total Cost of Ownership (TCO) for LDVs is changing rapidly. It has changed by +5%, +10% and -17% for ICEV, BEV and FCEV, respectively, from 2019 to 2021.
6. Vehicle's retail price is a significant TCO contributor (~60%) for FCEVs and BEVs. In contrast, ICEV's MSRP contributes only ~30% towards the TCO.
7. The current retail cost of hydrogen is estimated to be ~\$10.5/kg H_2 with electrolysis and \$6.0/kg H_2 with SMR+CCS. Handling & Delivery and Refueling costs are substantial (\$4.5/kg H_2) due to infrastructure-related expenses. There is an opportunity to reduce the cost of Hydrogen Refueling Stations (HRS). The hydrogen production cost is expected to drop if surplus renewable electricity is available.
8. The percentage of FCEVs in total vehicle stock in the US is expected to be more than 14% by 2050 under the Accelerated Actions scenario. The growth is contingent upon the TCO reduction pathways. I have presented a combination of policy action and technology milestones that allows meeting the cost reduction targets.
9. Unless hydrogen retail cost, FCEV retail price, and hydrogen infrastructure cost are reduced substantially, the market penetration for light-duty FCEVs is quite limited. Carbon abatement credits may be leveraged to provide additional support to grow FCEV usage.
10. The TCO of BEV and FCEV Class 8 type trucks are 24% and 40% higher than ICEV trucks, respectively. The fuel cost for FCEV is 2.4 times of BEV's fuel cost and the retail price of FCEV Class 8 type truck is 1.5 times that of BEV truck. A 40% reduction in hydrogen retail price or a 70% reduction in FCEV truck retail price would make FCEV trucks cheaper than BEV trucks.

11. All critical metals required for hydrogen economy are under moderate to high risk of supply chain disruptions. Similar vulnerabilities are observed for the metals used in battery manufacturing. Therefore, coexistence of hydrogen and battery electric economies is recommended for the US energy security.

In the title of my thesis, I have posed a question about the role of hydrogen-powered cars and trucks. While currently electric LDVs and HDVs have some cost advantages that are especially pronounced in electric cars, the expected reductions in the costs of hydrogen vehicles, hydrogen production, and hydrogen infrastructure bring them closer to being competitive. It is especially true for electric HDVs, where uncertainty about battery performance and business models are still quite large. Another consideration for hydrogen might be in accessing critical materials needed for batteries and hydrogen supply chains. Currently, supply chains are dominated by China and reliance on one decarbonization pathway might bring some risks. Diversification policy might provide an added resiliency for the U.S. economy. Based on my study, I conclude that hydrogen options in transportation deserve a strong support from the government and private sector in terms of continuing R&D and infrastructure development. With proper financial incentives, it will create a viable option for decarbonization together with increased electrification.

6.2 Recommendations for future work

The author would like to recommend the following for future work.

1. There is very limited information available for comparing the lifecycle emission of Class 8 type ICEV, BEV and FCEV trucks in the North American context and for other regions. Additional research is needed to provide regional variation of costs. There is a need for a better evaluation of GHG emissions from both manufacturing and operation cycles.

2. Estimates for hydrogen infrastructure costs are limited. Synergies and the role of government support for hydrogen infrastructure need to be assessed.
3. In my study, I have looked at several scenarios and provided a sensitivity analysis to some parameters. A more formal uncertainty analysis is warranted to evaluate the likely pathways.
4. I have assumed that the cost reductions in different cost components of the TCO model are mutually exclusive and time-independent. Future work may attempt to understand the interdependencies of cost reduction measures.
5. EPPA model can further be extended to include hydrogen-based HDVs.

Appendix I. Total cost for hydrogen Handling & Delivery and Refueling for various infrastructural configurations as predicted by HDSAM.

Drive train Mode	Distribution Mode	Dispensing Options to Vehicle Tank	Storage for Peak Loads	Production Volumes	$/kg
Liquid H2 Truck	Liquid H2 Truck	350 bar gas via pump	Liquefier and Liquid	Mid	4.15
Pipeline	Pipeline	350 bar cascade dispensing	Geologic/Gaseous	Mid	3.32
Tube Trailer	Tube Trailer	350 bar cascade dispensing	Geologic/Gaseous	Mid	3.57
Liquid H2 Truck	Liquid H2 Truck	350 bar gas via pump	Liquefier and Liquid	Low	4.83
Liquid H2 Truck	Liquid H2 Truck	350 bar gas via compressor	Liquefier and Liquid	Mid	5.10
Liquid H2 Truck	Liquid H2 Truck	350 bar gas via pump	Liquefier and Liquid	High	4.03
Liquid H2 Truck	Liquid H2 Truck	350 bar gas via pump	Liquefier and Liquid	Mid	4.14
Liquid H2 Truck	Liquid H2 Truck	350 bar gas via compressor	Liquefier and Liquid	Mid	5.1
Liquid H2 Truck	Liquid H2 Truck	350 bar Cryo pump dispensing	Liquefier and Liquid	Mid	4.37
Liquid H2 Truck	Liquid H2 Truck	700 bar gas via compressor	Liquefier and Liquid	Mid	6.13
Liquid H2 Truck	Liquid H2 Truck	700 bar gas via compressor	Liquefier and Liquid	High	5.84
Liquid H2 Truck	Liquid H2 Truck	700 bar gas via compressor	Liquefier and Liquid	Low	8.26
Pipeline	Pipeline	700 bar cascade dispensing	Geologic/Gaseous	Mid	4.3
Pipeline	Pipeline	700 bar booster compression	Geologic/Gaseous	Mid	5.24

Appendix II. List of parameters to calculate hydrogen Production Cost through SMR

Parameters	**Value**	**Units Conversion**	**Reference**
Life of Electrolyzer (years)	10.00	Yeas	NREL - future-central-pem-electrolysis-2019-v3-2018.20201209 Model
Electricity required in kWh to produce 1 kg H_2	**47.57**	LHV Electrical Equivalence Value/Electrolysis Efficiency= (kWh/kg H2)//(1)	Hydrogen Basics - Production (ucf.edu)
Electrolysis Efficiency	70%	%	2020 Citi Research Equities- Energy Transition
Electrolyzer Utilization	90%	%	
Electrolyzer Capital Cost	1000	$/kWe	
Electricity Price ($/kWh)	0.10	($/kWh)	Market Reports
Kg of water required to produce per kg of H_2	**9.02**	(gallon water/kg H_2)*(kg water/ gallon water)	First Analysis of the Water Requirements of a Hydrogen Economy (phys.org)
Water cost ($/gallon)	0.004	($/gallon)	https://www.energy.gov/sites/prod/files/2017/10/f38/water_wastewater_escalation_rate_study.pdf
Discount rate (%), monthly	1%		
Life Time (months)	120		

Appendix III. List of parameters to calculate hydrogen Production Cost through SMR and SMR + CCS

Parameters	Value	Units Conversion	Reference
Life of SMR Plant (years)	40.00	Years	NREL Model, Year 2005
Electricity required for SMR in kWh to produce 1 kg H2	1.01		GREET® & Ruhtagi et al. 2018, also calculated in box J31 in this sheet
SMR Efficiency Percentage	75%	%	2020 Citi Research Equities- Energy Transition
Electricity Price ($/kWh)	0.10	($/kWh)	Market Price
SMR Operating Capacity Percentage	75%	%	NREL Model, Year 2005
Other O&M related (50% capital cost)	50%	%	
Natural gas Price ($/MMBTU)	4.00	($/MMBTU)	Basic Solar H2 System (hionsolar.com)
Kg of water required to produce per kg of H2	9.02	(gallon water/kg H2)*(kg water/ gallong water)	First Analysis of the Water Requirements of a Hydrogen Economy (phys.org)
Water cost ($/gallon)	0.004	($/gallon)	https://www.energy.gov/sites/prod/files/2017/10/f38/water_wastewater_escalation_rate_study.pdf
SMR Capital Cost in $/kw	326		
Input natural gas needed in MMBTU per MMBTU H2	1.388	MMBTU natural gas/MMBTU H2	
Input natural gas needed in MMBTU per kg H_2	0.158	MMBTU natural gas/kg H2	
Total electricity needed for SMR	0.017	MMBTU/MMBTU H2	GREET® 2019
Total electricity needed for SMR	1.009	kWh/kg H2	GREET® 2019
Discount rate (%), months	1%		

kg H2 (LHV)	0.11	MMBTU H2/ kg H2	GREET® 2019
Tonne CO_2 released per kg H2 production	0.009	tonne CO_2/kg H2	GREET® 2019 and https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/?sh=70efcf8f24bd
Input natural gas needed in MMBTU per MMBTU H2	1.388	MMBTU natural gas/MMBTU H2	GREET® 2019
Total electricity needed for SMR	0.017	MMBTU/MMBTU H2	GREET® 2019
CCS Capital Cost	15.1	$/tonne CO_2	GREET® 2019, Cost in year 2005, 80% capture efficiency
CCS Energy Cost	4.7	$/tonne CO_2	GREET® 2019, Cost in year 2005, 80% capture efficiency
CCS O&M Cost	2.8	$/tonne CO_2	GREET® 2019, Cost in year 2005, 80% capture efficiency
Life Time (months)	480		

Appendix IV. The number of FCEVs in the US under an extremely fast cost reduction scenarios.

Three policy scenarios (Reference, Paris 2C and Paris Forever) are modeled based on an extremely fast cost reduction TCO profile presented in *Figure 1*. A multiple of more than 1 indicates that the FCEV TCO is higher than the ICEV. In these cases, the EPPA model allows applying vehicle subsidy or carbon tax on emissions to make the alternatives (BEV, FCEV) more lucrative and economically competitive. If the TCO reduction multiple is less than 1, it signifies that TCO for FCEV is smaller than the ICEV and it is economically advantageous to introduce fuel cell vehicles to cater to growing demand. The figure below assumes that the TCO of FCEV would be at par with ICEVs by 2025. Indeed, the scenario presented here assumes that the TCO would be only 30% of the ICEV by 2050. Although the projections about TCO reduction seem over-ambitious, they provide valuable insights about the aspects evaluated through the EPPA model. The EPPA model calculated global and regional carbon emissions, GDP growth, size of LDV fleet and share of each drive train type.

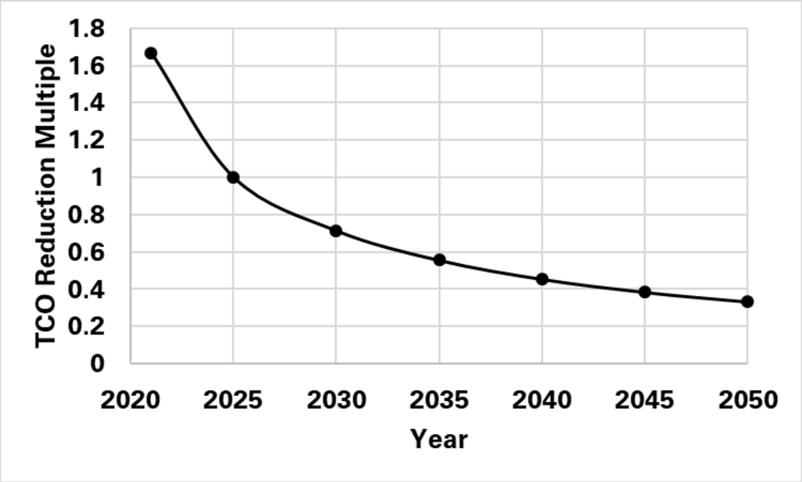

Figure 1: Total Cost of Ownership (TCO) Reduction Multiple with time.

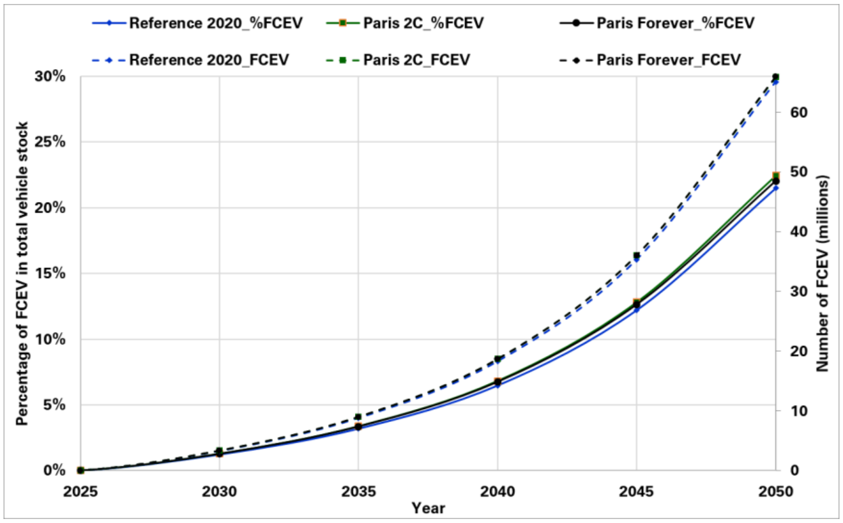

Figure 2: Percentage FCEV in total vehicle stock and number of FCEV in millions in the US from 2021 to 2050 under Reference, Paris 2C and Paris Forever policy scenarios.

The number of FCEVs increases exponentially from 2030 to 2050 in all three scenarios modeled here. It is expected that there would be ~45 million FCEVs on-road in the US by 2050, representing 1/3rd of the total vehicle stock. It should be noted that this exponential growth is contingent on the aggressive TCO reduction target presented in *Figure 2*.

The percentage of FCEV fleet grows rapidly from 2035 to 2050 in the US. FCEVs capture 1/3rd of the total vehicle stock in the US by 2050, indicating that the FCEVs could make their way into the US market. However, aggressive cost reductions as presented in *Figure 1* would be required.

Appendix V. Author's CV

HEMANT KUMAR

Digital Advisor Subsurface Workflows, Chevron Corporation
Houston-Texas

EDUCATION

Master of Science- System Design and Management, Massachusetts Institute of Technology
School of Engineering & Sloan School of Management
MS Dissertation: Hydrogen Powered Cars: Is there a role for them in the electrified U.S. future?

PhD – Petroleum and Natural Gas Engineering, The Pennsylvania State University, University Park (USA)
PhD Dissertation: Pore Mechanical Response of Naturally Fractured Sorbing Media
PhD (Minor) – Computational Science

Master of Science (MS) – Energy and Mineral Engineering, The Pennsylvania State University, University Park (USA)
MS Dissertation: Enhancing Coalbed Methane (ECBM) Extraction by Fracture Induction Using High Energy Microwave

Bachelor of Technology (B.Tech) – Mining Engineering, Indian Institute of Technology– Banaras Hindu University (IIT-BHU), Varanasi (India)

PROFESSIONAL APPOINTMENTS

2020 Chevron Corporation Pittsburgh, Pennsylvania **– *Senior Reservoir Engineer***

2019 Chevron Energy Technology Company Houston Texas **– *Senior Production Engineer***

2017 Chevron Energy Technology Company Houston Texas **– *Lead Production Engineer***

2015 Chevron Energy Technology Company Houston Texas **– *Petroleum Engineer***

2011 ExxonMobil Upstream Company Houston Texas **– *Reservoir Engineering Intern***

2008 Orica Mining Services, Kolkata (India) – ***Technical Services Engineer***

PROFESSIONAL INTERESTS

- Authored dozens of peer-reviewed journal articles and conference papers in the area of Reservoir Geomechanics, Simulation & Modeling, Production Engineering and Integrated System Design and Optimization (Google Scholar)
- Passionate and enthusiastic about training and mentoring.
- Served as a referee for many international journals and conferences. Awarded as 'Outstanding Reviewer' for few journals.

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