Alternative Powertrain Pathways for Light-Duty and Class 3 Vehicles for MYs 2024, 2027, and 2035 to Meet Future CO_2 Emission Targets

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Table of Contents

List of Figures

List of Tables

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Abbreviations and Acronyms

ADEAC	Advanced Cylinder Deactivation
AEO	Annual Energy Outlook
ASC	Ammonia slip catalyst
ASSB	All-Solid-State Battery
AT	Automatic Transmissions
AT10L3	10-Speed Automatic Transmission, Level 3
AT8L3	8-Speed Automatic Transmission, Level 3
ATK	Atkinson Cycle Engine
AWD	All Wheel Drive
BEA	Bureau Of Economic Analysis
BEV	Battery Electric Vehicle
BEV200	200-Mile Range BEV
BEV300	300-Mile Range BEV
BEV400	400-Mile Range BEV
BISG	Belt Integrated Starter Generator (48-Volt Mild Hybrid System)
BloombergNEF	Bloomberg New Energy Finance
BMS	Battery Management System
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CEGR1	Advanced Turbocharged Downsized Technology with Exhaust Gas Recirculation
CTC	Cell-To-Chassis
CVT	Continuously Variable Transmission
CVTL2	Continuous Variable Transmission Level 2HEG
DBE	Dry Battery Electrode
DCFC	Direct Current Fast Charging
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DOE	U.S. Department of Energy
DOHC	Dual Overhead Cam
DOT	U.S. Department of Transportation
eCVT	Electronic Continuously Variable Transmission
EGR	Exhaust Gas Recirculation

EIA	U.S. Energy Information Administration
EOL	End-Of-Life
EPA	U.S. Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FHWA	Federal Highway Administration
FTP	Federal Test Procedure
FWD	Front-Wheel Drive
GCTP	Gravimetric Cell-to-Pack Ratio
GHG	Green House Gas
GM	General Motors
GREET	Greenhouse Gases, Regulated Emissions, And Energy Use in Transportation
GWh	Gigawatt-Hour
GVWR	Gross Vehicle Weight Rating
HCR1	High Compression Ratio, Level 1
HE-NMC	High Energy-Nickel Manganese Cobalt
HEV	Hybrid Electric Vehicle
HP	Horsepower
HVAC	Heating Ventilation and Air-Conditioning
HV-Spinel	High Voltage-Spinel
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IM	Induction Motor
km	Kilometer
km/h	Kilometers Per Hour
kW	Kilowatt
kWh	Kilowatt-Hour
kWh	Kilowatt Hour
LAB	Lead Acid Battery
LDV	Light Duty Passenger Vehicle
LFP	Lithium Ferro (Iron) Phosphate

LIB	Lithium-Ion Battery
LMFP	Lithium Manganese Ferro phosphate
LMNO	Lithium Manganese Nickel Oxide
LTO	Lithium Titanate Oxide
LTVs	Light Trucks and Vans
MDHD	Medium-Duty and Heavy-Duty
MOVES	Motor Vehicle Emission Simulator
MPG	Miles Per Gallon
MPGe	Miles-Per-Gallon Equivalent
mph	Miles Per Hour
MSRP	Manufacturer Suggested Retail Price
MY	Model Year
NA	Naturally Aspirated
NCA	Lithium Nickel Cobalt Aluminum Oxide
NFA	Lithium -Iron and Aluminum Nickelate
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal Hydride
NMC	Nickel Manganese Cobalt
NOx	Nitrogen Oxide
NPRM	Notice Of Proposed Rulemaking
NVH	Noise Vibration Harshness
OEM	Original Equipment Manufacturer
OHV	Over-Head Valve
ORNL	Oak Ridge National Laboratory
PFI	Port Fuel Injection
PHEV	Plug-In Hybrid Electric Vehicle
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
PMSyn-RM	Permanent Magnet Synchronous Reluctance Motor
SAE	Society Of Automotive Engineers
SAFE	Safer Affordable Fuel-Efficient Vehicles Rule
SCR	Selective Catalytic Reduction
SCRF	DOC coated with SCR Catalyst
SESM	Separately Excited Synchronous Motor

SLB	Second-Life Batteries
SOC	State Of Charge
SOHC	Single Overhead Cam
SRM	Switched Reluctance Motor
SUV	Sport Utility Vehicle
TCO	Total Cost of Ownership
TM	Thermally Modulated
TURBO1	Turbocharging and Downsizing, Level 1
TWh	Terawatt-Hour
U.S.C.	United States Code
USABC	United States Advanced Battery Consortium
VCR	Variable Compression Ratio
VCTP	Volumetric Cell-to-Pack Ratio
VGP	Vehicle Glider Price
VMT	Vehicle Miles Traveled
VTG	Variable Turbo Geometry Engine
VTO	Doe Vehicle Technologies Office
VVL	Variable Valve Lift
VVT	Variable Valve Timing
WRSM	Wound Rotor Synchronous Motor

Glossary of Terms and Definitions

8-speed Automatic Transmission (AT8) with level 3 high-efficiency gearbox (HEG) technology (AT8L3) – AT is a multi-speed transmission that automatically selects and shifts between transmission gears during vehicle operation. They have been assigned from a compact car to a midsize SUV in the analysis.

10-speed Automatic Transmission (AT10) with level 3 high-efficiency gearbox (HEG) technology (AT10L3) – They have been assigned to a large SUV and pickup truck in the analysis.

Belt Integrated Starter Generator (BISG) – Also known as a mild hybrid system or a start-start system that provides the idle-stop capability and uses a higher voltage battery (48V).

Battery-Electric Vehicles (BEV) 200/300/400 – Batteries power the motors to propel the vehicle. The numbers represent the ranges of BEV in miles.

Conventional (CONV) – A vehicle that does not include any level of hybridization [1].

Cooled Exhaust Gas Recirculation (cEGR) – It is an emissions reduction technique that recirculates a portion of exhaust gas through a water-cooled heat exchanger and then mixes it with the incoming fresh air.

Dual Over-Head Camshaft (DOHC) – Enables independent phasing of intake and exhaust camshafts thus improving airflow, torque, and efficiency.

Deactivation (DEAC) – Method of selective valve deactivation thereby shutting off the cylinder. Cylinder deactivation disables intake and exhaust valves and turns off fuel injection for the deactivated cylinders during the light load operation. It reduces pumping losses and improves engine efficiency and fuel economy.

High Compression Ratio 1 (HCR1) – Enhanced Atkinson engines with variable valve timing (VVT) and stoichiometric gasoline direct-injection (SGDI) technologies. High compression ratio (HCR) engines represent a class of engines that achieve a higher level of fuel efficiency by implementing an alternate combustion cycle [1].

Strong Hybrid Electric Vehicle with P2 Parallel Drivetrain Architecture or P2 Parallel Hybrids (SHEVP2) – A strong hybrid vehicle is a vehicle that combines two or more propulsion systems, where one uses gasoline (or diesel), and the other captures energy from the vehicle during deceleration or braking, or from the engine and stores that energy for later use by the vehicle. It provides idle-stop functionality, regenerative braking, and vehicle launch assist. P2 hybrids rely on the ICE to power the vehicle with the electric mode only kicking in when the power demands are less than moderate [1].

Stoichiometric Gasoline Direct Injection (SGDI) – Sprays fuel at high pressure directly into the combustion chamber. This method cools the in-cylinder air/fuel charge which improves spark knock tolerance, higher compression ratio, and increases thermodynamic efficiency.

Turbocharging and Downsizing Level 1 (TURBO1) – It represents a basic level of forced air induction technology applied to a DOHC-based engine [1].

Variable Valve Timing (VVT) – A family of valve-train designs that alters the timing of the engine valves individually or together with respect to the piston position. VVT can reduce pumping losses and provide increased engine torque over a broad operating range.

Key Highlights

On-road vehicles account for more than 80% of the carbon dioxide emissions from the transportation sector. This study looks at the technology, cost, and efficiency of alternative powertrains for light-duty and Class 3 vehicles. Given the level of maturity of alternative powertrain technologies, their cost, and incentives such as the purchase credit offered by the IRA, a significant portion of the light-duty and Class 3 vehicle fleet is primed for transition to alternatives with a significantly lower carbon footprint.

Following are the high-level conclusion of our analysis:

a) In the light-duty segment, BEV200 is at cost parity with an ICE vehicle in the compact, midsize, and small SUV segments in 2023. BEV300 reaches cost parity with conventional ICE powertrain across all segments by 2027 (without IRA)

b) PHEV 50 architecture (minimum range mandated by The Advanced Clean Cars II rule") will be more expensive than BEV 300 in all segments by 2027. PHEV 50 is attractive for segments like medium SUVs and Pickup trucks, where most of the daily miles driven can be covered in electric mode, but the vehicle is also used for towing heavy trailers for long distances.

c) Fuel cells will be more expensive than hydrogen combustion engines in 2023. But with higher volumes, they can reach cost parity with Hydrogen ICE by 2027 and be cheaper in 2035. H2 ICE vehicles need expensive NOx aftertreatment systems. FCEVs are also significantly more efficient than H2 ICE vehicles.

d) Fuel cells are cheaper than BEV 300 and BEV 400 for large vehicles (Class 3 vehicles) that need a long-range (towing), Compressed hydrogen tanks can be refilled in under 10 minutes, and larger vehicles have more space for packaging the tank.

e) Factoring in the 2035 battery and fuel cell cost and the $7,500 IRA tax credit lasting from 2023 to 2032, the cost of a BEV and FCEV powertrain will be lower in 2027 compared to 2035.

Figure 1 shows the different vehicle segments and the powertrain pathways explored in this study. For 2024, 2027, and 2035, we estimate the direct manufacturing cost and the energy consumption for the different powertrains.

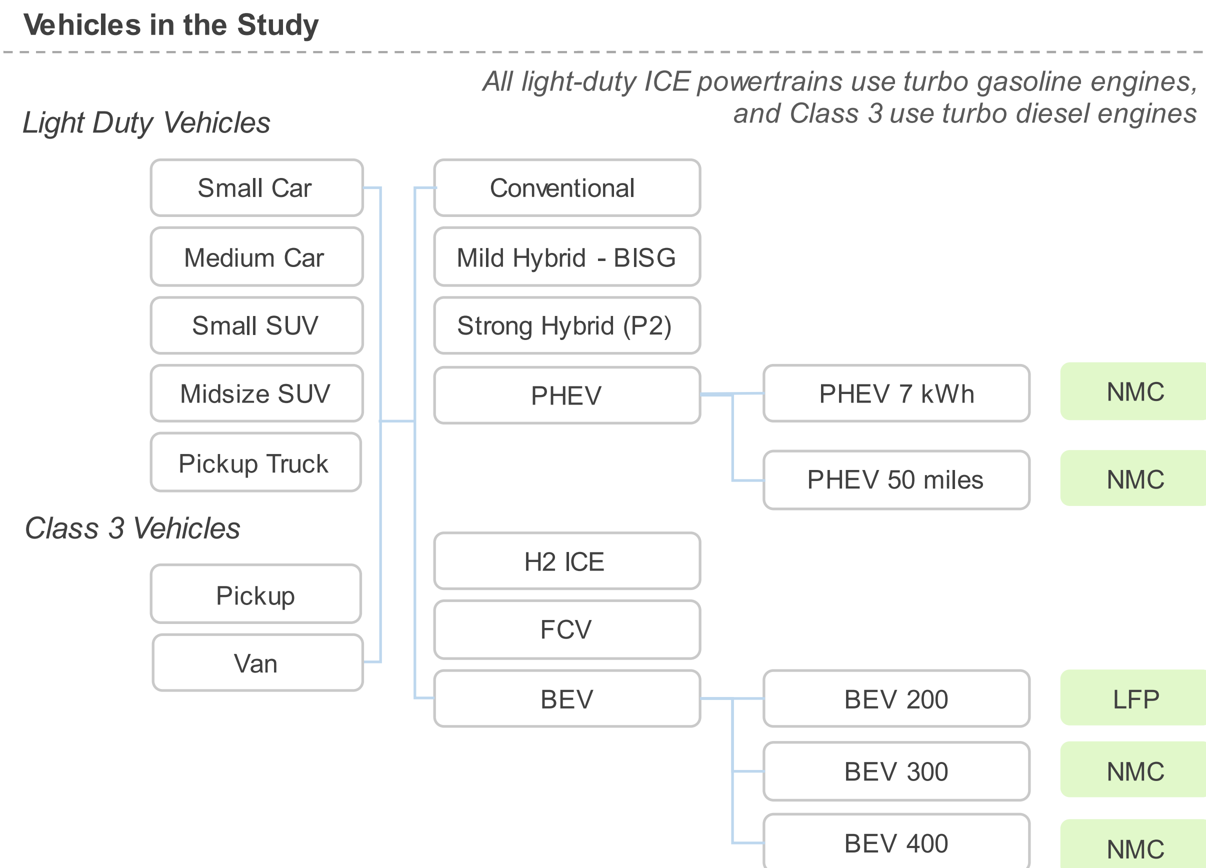

Figure 1: Light-duty vehicle powertrains in this study

Main assumptions

a) The study assumes all light-duty vehicles with an internal combustion engine run on gasoline and Class 3 vehicles run on diesel (except Hydrogen ICE). The diesel market share in the light-duty segment peaked at 6% in 1981 and declined to less than 1% in 2022 [2]. Furthermore, future emission regulations will further increase the cost and decrease diesel engines' fuel economy, reducing their competitiveness.

b) This study considers two plug-in hybrid electric vehicles to provide a lower and upper bound to the PHEV costs.

   a. *PHEVs with 7kW of usable battery capacity* "low all-electric range PHEV"- 7kWh is the minimum battery size required to qualify for the full $7,500 tax credit under the IRA if it meets the sourcing requirements for the battery and other powertrain components.

b. *PHEVs with a 50-mile real-world range* “high all-electric range PHEV” - “The Advanced Clean Cars II rule” [3] adopted by California lets automakers up to 20% of their ZEV credits with PHEVs with a real-world range of 50 miles (PHEV50).

c) We use the 2022 ANL Modeling Study [4] to estimate the size of the powertrain components (battery and motor size for BEVs, HEVs, and PHEVs; fuel cell power output, battery and motor size for FCEVs, etc.) and real-world energy consumption of different combinations of vehicle and powertrain technologies. ANL is the only study with powertrain sizing and efficiency for all the vehicle and powertrain combinations in this study. Since a ground-up modeling effort to size different powertrains to simulate efficiencies was outside the scope of this study, we went with values from the ANL study.

d) We assume the BEV 200 battery pack will use LFP chemistry in 2023 for light-duty vehicles, while the longer-range vehicles (BEV 300 and BEV 4000) use NMC chemistry.

e) The Clean Vehicle Credit (26 U.S.C. §30D) of $7,500 is used here to demonstrate the impact of the IRA of 2022 on the purchase price of vehicles. We assume that the glider is the same between all different powertrain vehicles in a segment, and any difference in vehicle price is purely attributable to the powertrain direct manufacturing costs (multiplied by the retail price equivalent).

Figure 2 illustrates the various components whose costs are summed up to determine the total powertrain cost. We looked at multiple sources of costs of different powertrain components before choosing one for this study.

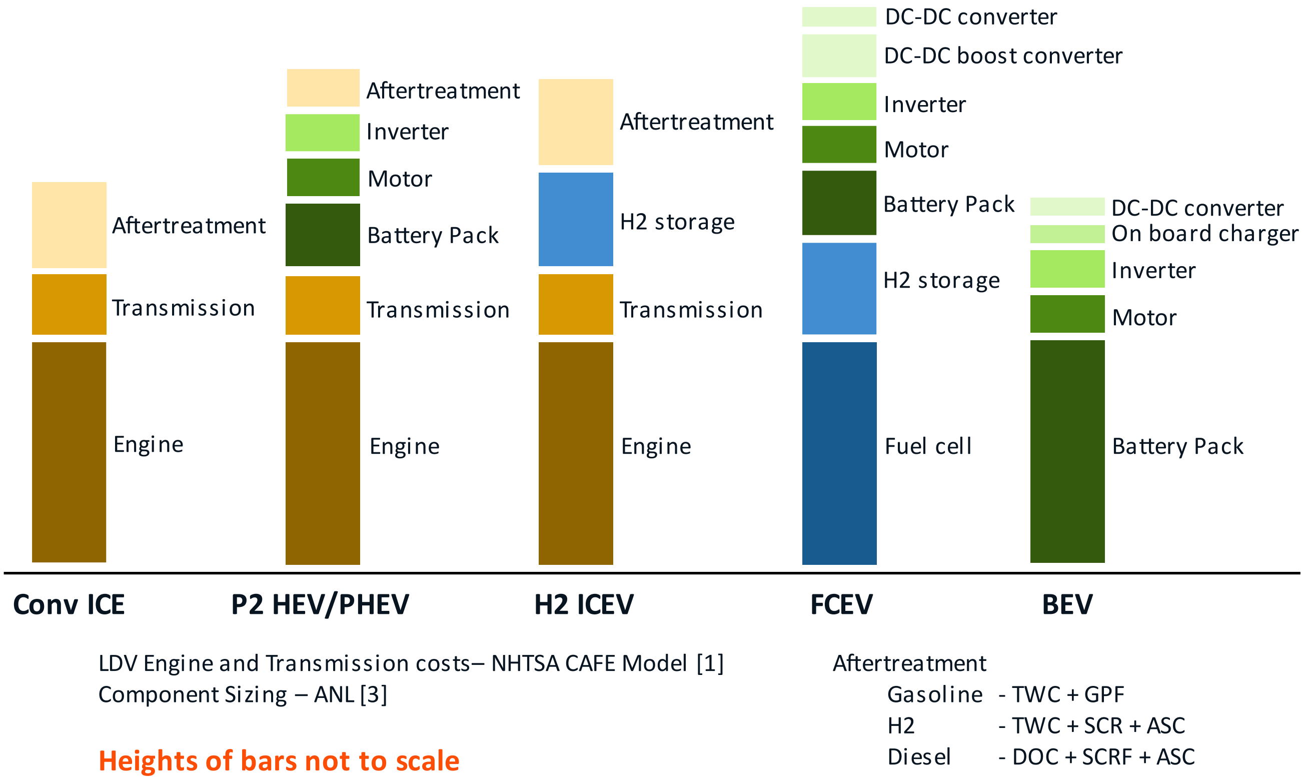

Figure 2: Components factored in for costing different powertrains.

Results

The powertrain direct manufacturing costs for 2024, 2027, and 2035 for light-duty and Class 3 vehicles are shown in Figure 3 and Figure 4, respectively. There is very little change in the cost of conventional and mild hybrid powertrains from 2023 to 2035. P2 strong hybrid powertrains provide a significant leap in fuel economy (30%) compared to conventional ICE powertrains for an additional $1,000-1,500 in powertrain costs. Given the smaller motor and battery pack, they see a relatively small impact on motor and battery cost reduction compared to BEVs. PHEVs are well suited for applications where the vehicle is occasionally used for driving long distances or towing. In such instances, most of the daily driving can be completed in EV mode (charge-depleting mode), while the hybrid mode provides the necessary range and quick fill-up during long-distance driving or towing.

Battery electric vehicles see the most significant relative drop in powertrain costs from 2024 to 2035. This is primarily due to the drop in battery costs. A BEV200 is cheaper than an ICE vehicle in the compact, midsize, and small SUV segment in MY 2024 for light-duty vehicles. BEV300 will reach purchase price parity with conventional ICE powertrain across all segments before 2027. For Class 3 vehicles, a BEV 200 will reach purchase price parity with a conventional diesel engine after 2027. BEV 300 and BEV 400 will take longer to reach cost parity with conventional diesel powertrains.

Hydrogen is a promising low-carbon fuel source. Fuel cells become attractive as the size of the vehicle increases. Large BEVs (medium SUVs, pickup trucks, and Class 3 vehicles) with long-range (BEV 300, BEV 400) need significantly larger batteries, resulting in an expensive powertrain. Even with a steep decline in battery prices, for half-ton and Class 3 pickup trucks, BEV 300 powertrain is projected to be more costly than FCEV in 2027 and almost reach price parity by 2035. Hydrogen ICE vehicles have a similar efficiency (MPG equivalent) to a conventional diesel-engine powertrain. However, hydrogen engines have a lower efficiency when compared to fuel cells (40% compared to 60% of fuel cells). This will result in hydrogen ICE vehicles having a lower range than an equivalent fuel cell vehicle. H2 ICE vehicles will also need a “diesel-like” after-treatment system for controlling NOx emissions.

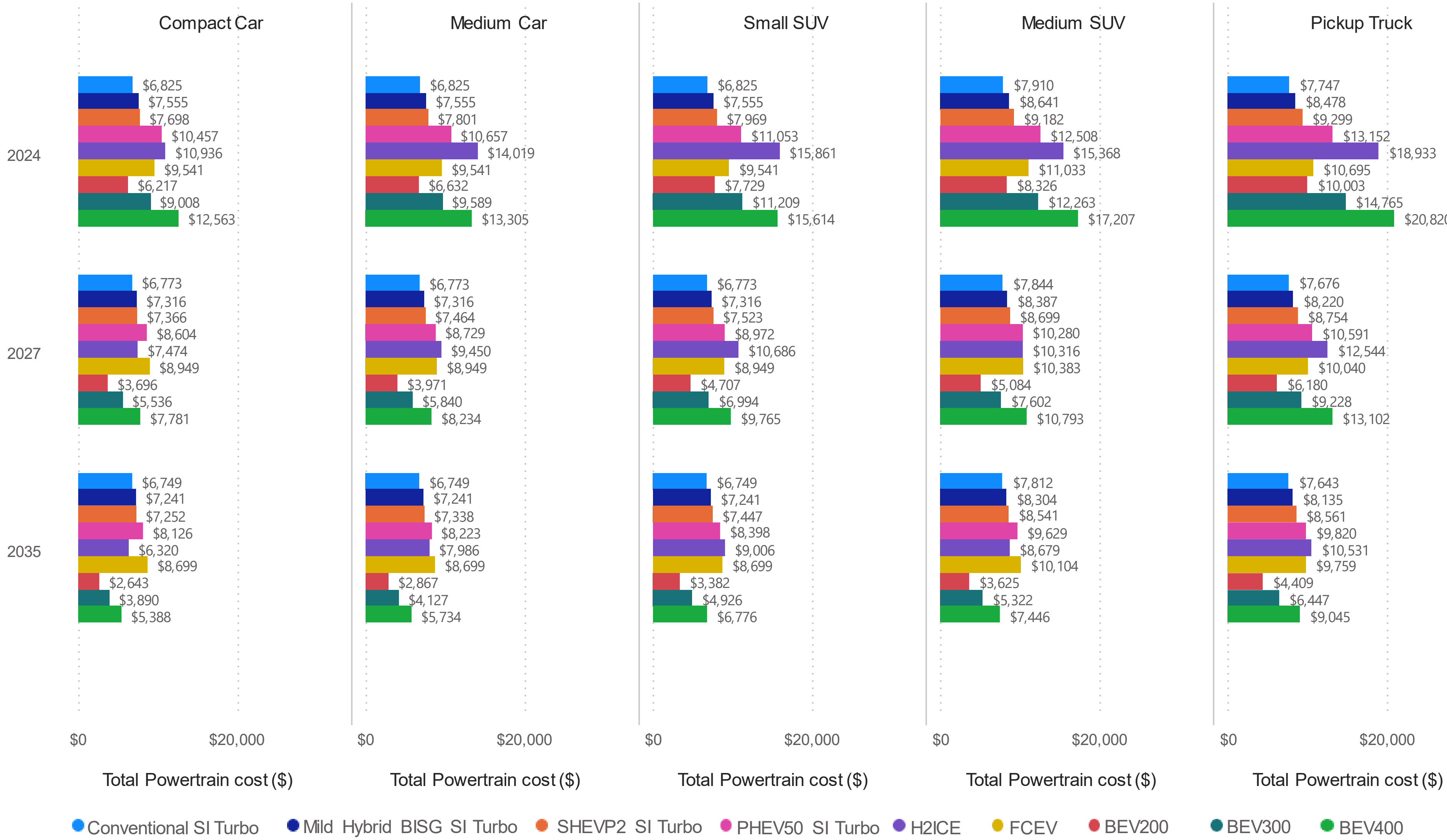

Figure 3: Projected powertrain costs of LDVs of MYs 2024, 2027, and 2035

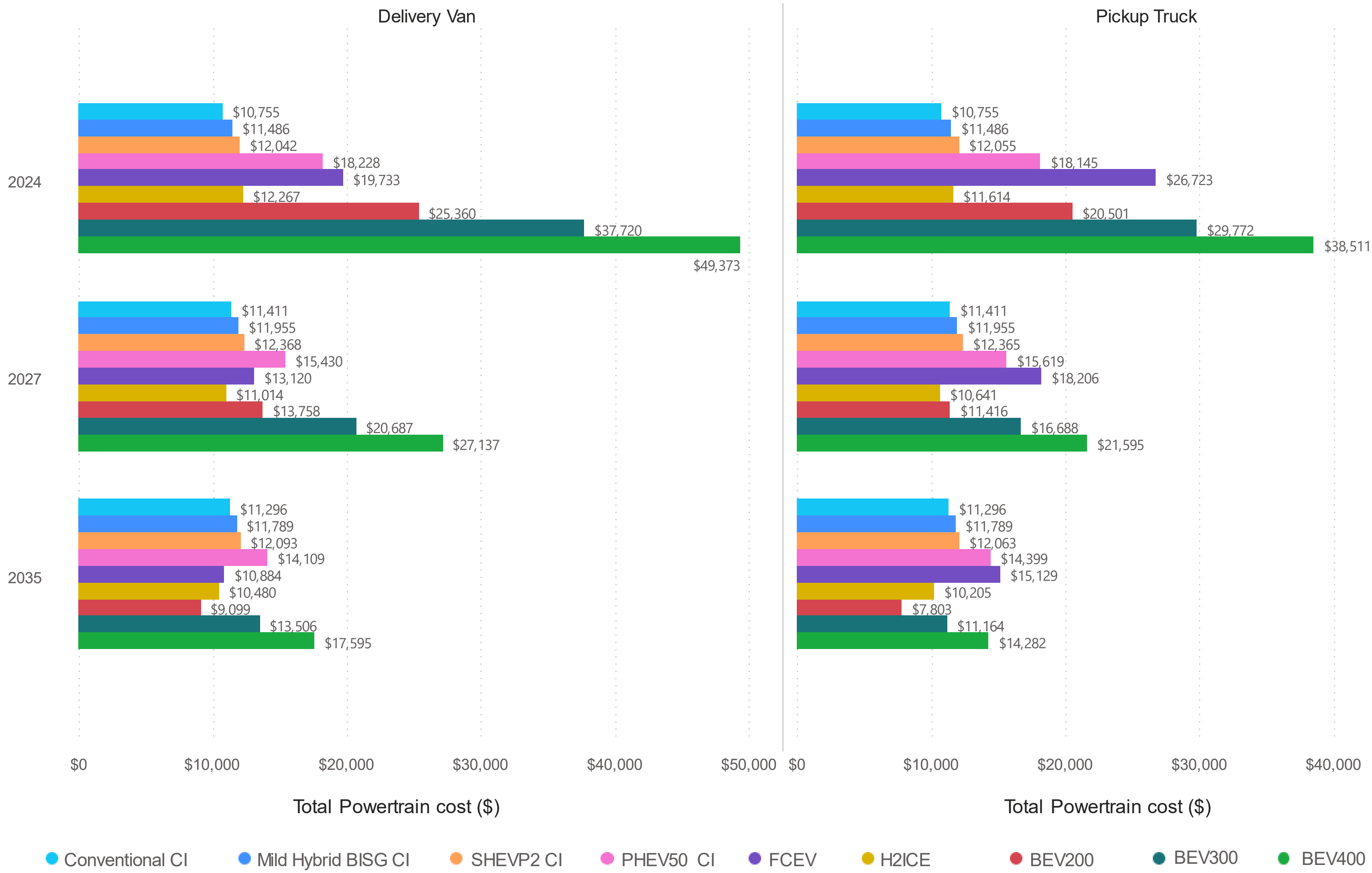

Figure 4: Projected powertrain costs of Class 3 vehicles of MYs 2024, 2027, and 2035

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Effects of the Inflation Reduction Act of 2022

This study also examined the potential impacts of the "Clean Vehicle" credit of the Inflation Reduction Act of 2022 (IRA) on the DMCs of the chosen powertrain technologies. The credit made available by the IRA will have a profound positive impact on the economic viability of MY 2024 and 2027 PHEVs, FCEVs, and BEVs. H2ICE is the only ZEV that does not benefit from this credit. We found that these credits would help absorb higher purchase prices of BEVs without penalizing end consumers. Furthermore, since the credits expire on 31 December 2032, the analysis is limited MYs 2024 and 2027. Generally, the results of this IRA impact analysis demonstrate that the purchase price parity is accelerated in the case of BEVs, FCEVs, and PHEVs, as shown in Figure 5. Figure 6 depicts the impact of clean vehicle credits on Class 3 cars, demonstrating that the effect is significant in MY 2027.

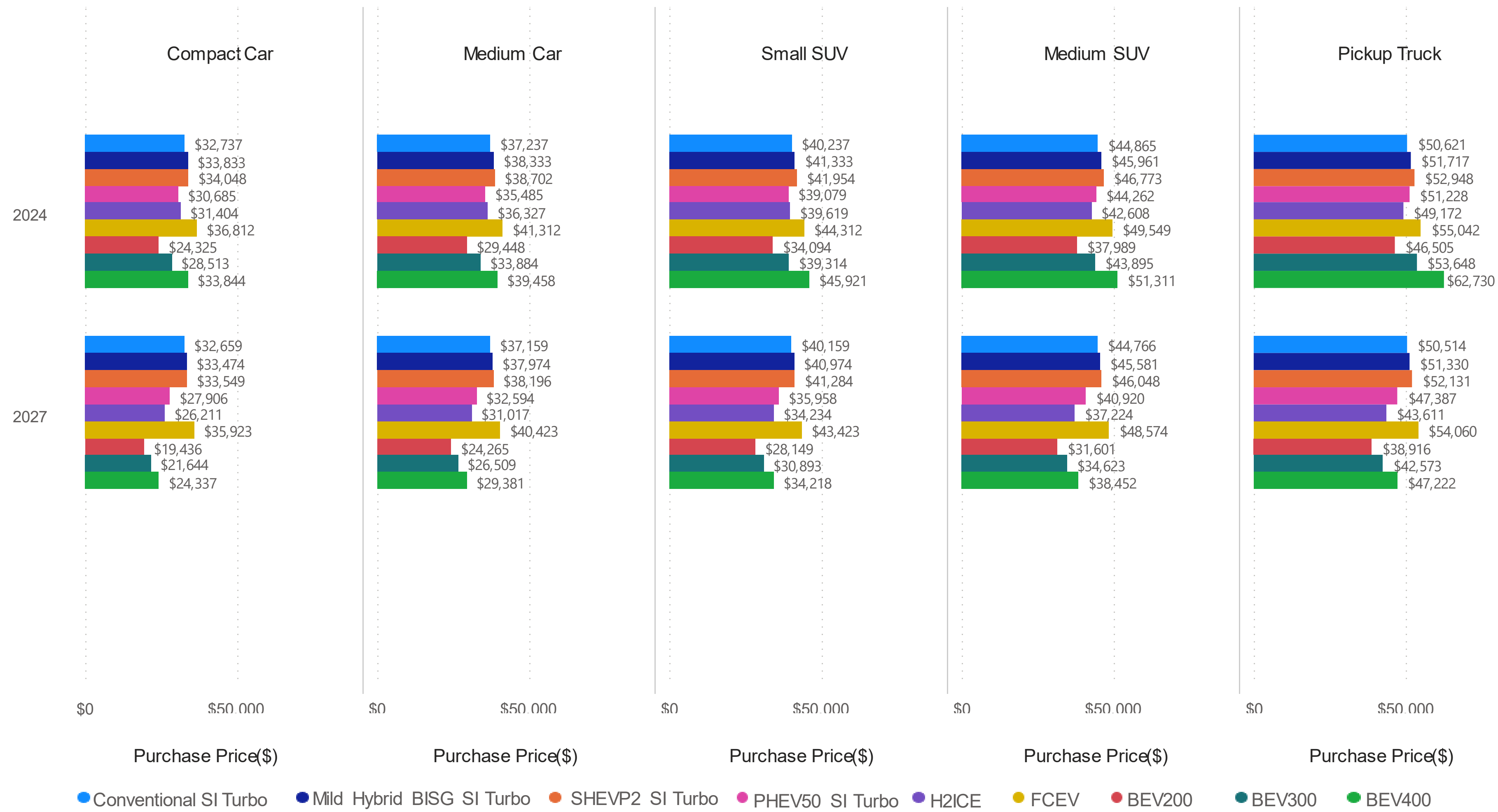

Figure 5: Impact of the Clean Vehicle Credits on LDVs in MYs 2024 and 2027

Figure 6: Impact of the Clean Vehicle Credits on Class 3 vehicles in MYs 2024 and 2027

Technological Advancements and the Way Ahead

Battery cost is the leading indicator that determines the economic viability of manufacturing and the adoption of EVs. Due to the high fluctuation of raw material costs and engineering challenges, the battery constitutes anywhere from 25%–40% of the vehicle's cost, depending on its chemistry and configuration [5]–[7]. The battery cost projections in this study are based on economies of scale. Disruptions or shortages in the supply chain could increase the powertrain costs presented in this report. However, the IRA provisions are expected to significantly reduce the powertrain cost of BEVs, as well as accelerate parity timeframes. Another factor that could lower the cost of battery packs is that the OEMs are shifting their focus to the midstream and potentially upstream (mining and refining) of the battery value chain, as well as vertical integration of cell manufacturing. This would allow them to tightly control and manage the battery value chain and the battery cost. After accounting for all the engineering and technological advancements currently being pursued, there exist clear pathways for cost-competitive, sustainable, reliable, and environmentally friendly BEVs as a replacement option for fossil fuel-powered ICEVs. Advancements in battery technology, as discussed in detail in our other studies [8], [9], are expected to further reduce battery costs, thereby impacting PHEVs, FCEVs, and BEVs.

There is also a significant effort at all levels to improve or replace current technologies, giving confidence in a more sustainable and viable supply chain and technology pool to support future rapid growth in EVs. OEMs have several alternative technologies to choose from, which reduce costs while improving efficiency and performance. Rapid advancements in the fields of motors, power electronics, and battery management systems will provide sustainable and economically viable powertrain solutions for the ZEV industry.

Major commitments by the automakers and manufacturers, in step with government policy initiatives, are driving investments toward electrification of the light-duty vehicle segment. Recently approved Advanced Clean Cars II (ACC II) standards by CARB in August 2022 will accelerate the transition to EVs. Furthermore, other states may also follow suit and implement the ACC II standards. Federal agencies are in the process of developing and deploying a national EV charging network to meet the growing demand for robust charging infrastructure. Several programs under the Infrastructure Investment and Jobs Act and the Inflation Reduction Act drive huge investments into the EV ecosystem, benefiting all stakeholders.

There are many external benefits to ZEV adoption, including environmental benefits through the reduction of PM and NOx emissions as well as the reduction in noise in congested environments. While these benefits are not included in this analysis, they may improve the case for ZEV adoption. Also not considered in this analysis are government-based incentives, subsidies, or policies that can offset or outright reduce the costs of BEV adoption. These policies will further drive investment in ZEV adoption, increasing the overall market penetration and economies of scale for ZEV components.

1. Introduction

The transportation sector is the largest producer of greenhouse gas (GHG) emissions in the United States, as illustrated in Figure 7. In 2021, light-duty vehicles (passenger cars and light-duty trucks) and medium- and heavy-duty vehicles (vehicles with a gross vehicle weight rating (GVWR) of more than 8,500 pounds) accounted for nearly 80% of GHG emissions in the transportation sector [10]. GHG emissions include carbon dioxide, methane, nitrous oxide emitted by fuel combustion, and additional air pollutants such as ozone precursors, sulfur oxides, and particulate matter. These constituents of emissions, as well as other pollutants, contribute to climate change and air pollution.

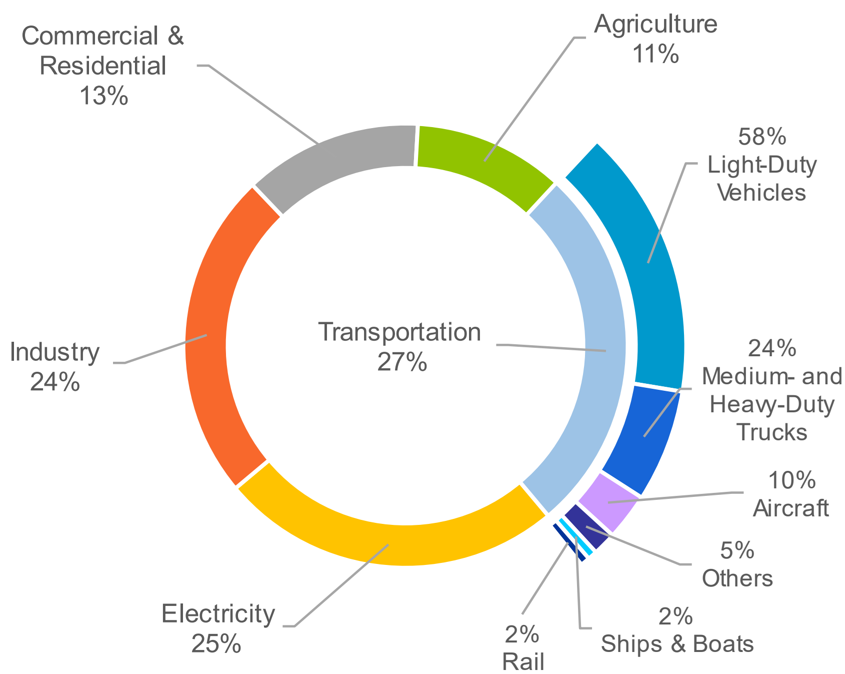

Figure 7: Distribution of U.S. greenhouse gas (GHG) emissions by sector [10]

For Model Years (MY) 2023 through 2026, the Environmental Protection Agency (EPA) promulgated new Federal GHG emissions limits for passenger automobiles and light trucks. These are the most stringent vehicle emissions regulations ever set for the light-duty vehicle sector, and they are based on a thorough examination of present and future technologies. NHTSA's Corporate Average Fuel Economy (CAFE) standards require an estimated industry-wide fleet average of 49 mpg (unadjusted mpg. The fleet-averaged sticker mpg number will be lower) for passenger cars and light trucks in 2026, increasing fuel efficiency by 8% annually for the MYs 2024 and 2025 and 10% for the MY 2026. In addition, several state administrations are introducing more stringent regulations to address the emissions from passenger cars and light trucks. To help California achieve its carbon neutrality goals and the federal ambient air quality ozone criteria, the Advanced Clean Vehicles II (ACC II) regulations, which were established in 2022, mandate the next level of low-emission and zero-emission vehicle standards for model years 2026–2035 [11]. It requires 35% of all new LDVs sold in California to be ZEVs starting in 2026, rising to 100% by 2035. Automakers can meet no more than 20% of their ZEV credits with PHEVs with a real-world range of 50 miles (PHEV50). By 2035, all new passenger cars, trucks, and SUVs sold in California will have zero emissions. The ACC II regulations supplement the state's already expanding ZEV market and rigorous motor vehicle emission control policies to achieve increasingly stringent tailpipe emissions standards and eventually transition to 100% ZEVs. California and seventeen other states have enacted ACC I standards, accounting for 36% of US LDV sales [12]. Adoption of the ACC II regulation by other states will further accelerate the transition to ZEVs. New York, Washington, Oregon, Massachusetts, and Vermont adopted the ACC II regulations in December 2022, with more states indicating they plan to adopt them in 2023. [13].

The year-on-year market share of electric vehicles (EVs) continues to increase, with sales accounting for about 6% of all LDVs sold in 2022, as shown in Figure 8. In 2022 there were 43 BEVs, 39 PHEVs, and 2 FCEVs on sale in the US [14]. According to the EPA Trends 2022 report [2], diesel engines held less than 1% market share.

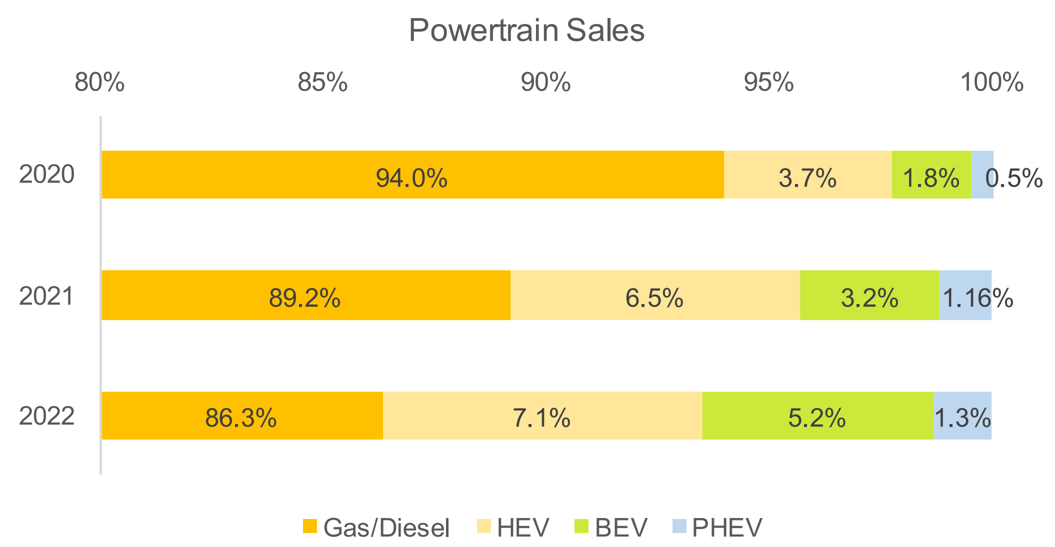

Figure 8: Powertrain sales from 2020 through the first three quarters of 2022 [14]

With EV production ramp and a $210 billion investment in the EV sector [15], the United States is positioned to become a worldwide powerhouse for EV and battery manufacturing. Furthermore, the federal government has made a historic commitment to this global EV race through supportive policies such as the Inflation Reduction Act and the Bipartisan Infrastructure Acts. The two measures provide nearly $245 billion in federal investments for electric cars, batteries, and charging stations [15]. Figure 9 shows the large-scale facilities being built or expanded upon to produce EVs and their batteries, based on the most recent data in 2022.

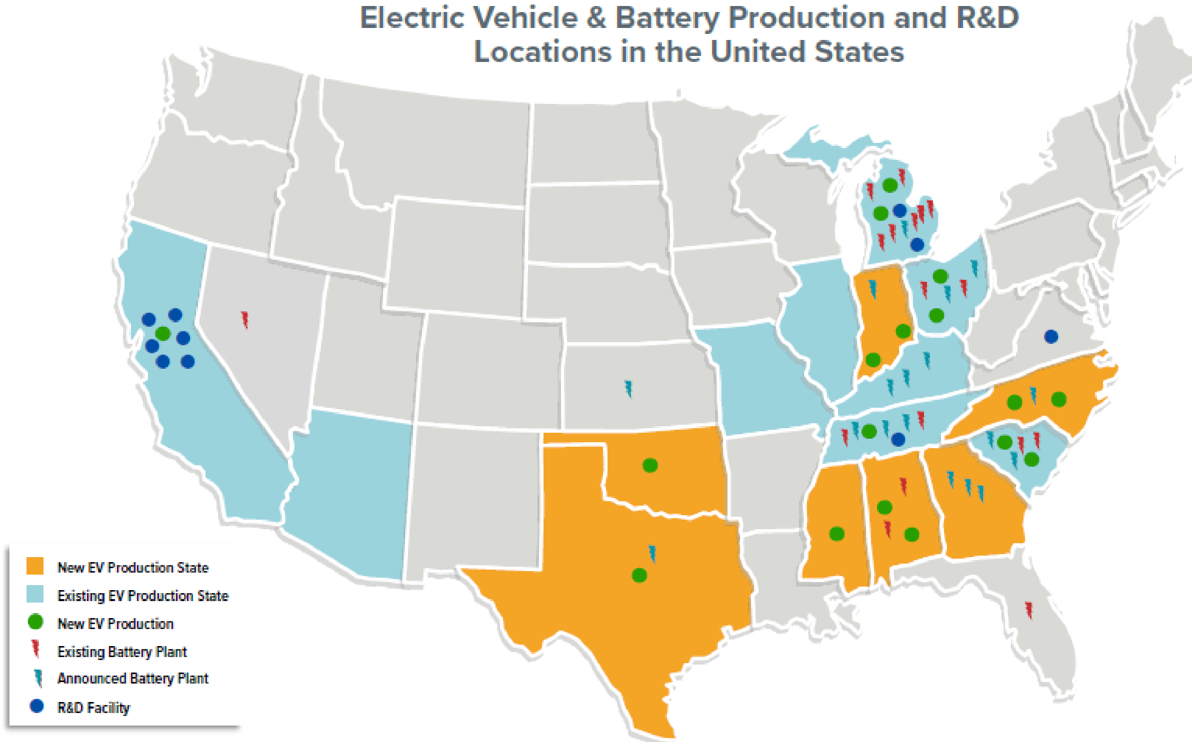

Figure 9: Overview of EV and battery production and R&D sites in the U.S. [14]

Manufacturers possess a range of technologies, including hybrid-electric, plug-in hybrid, battery electric, fuel cell electric powertrains, and hydrogen internal combustion engines, which effectively mitigate GHG emissions compared to conventional gasoline or diesel engines.

This study examines the powertrain costs and fuel economy of different powertrain technologies, as depicted in Figure 10, across various LDV segments and Class 3 pickups and vans with a GVWR of less than 14,000 lbs. Projections for the chosen powertrains are provided for 2024, 2027, and 2035. The analysis encompasses LDVs such as small cars, medium cars, small SUVs, midsize SUVs, large SUVs, and pickup trucks, investigating a range of powertrain combinations. Additionally, the subsequent sections meticulously explore the powertrain costs and ranges associated with different powertrain combinations for Class 3 pickups and vans.

Vehicles in the Study

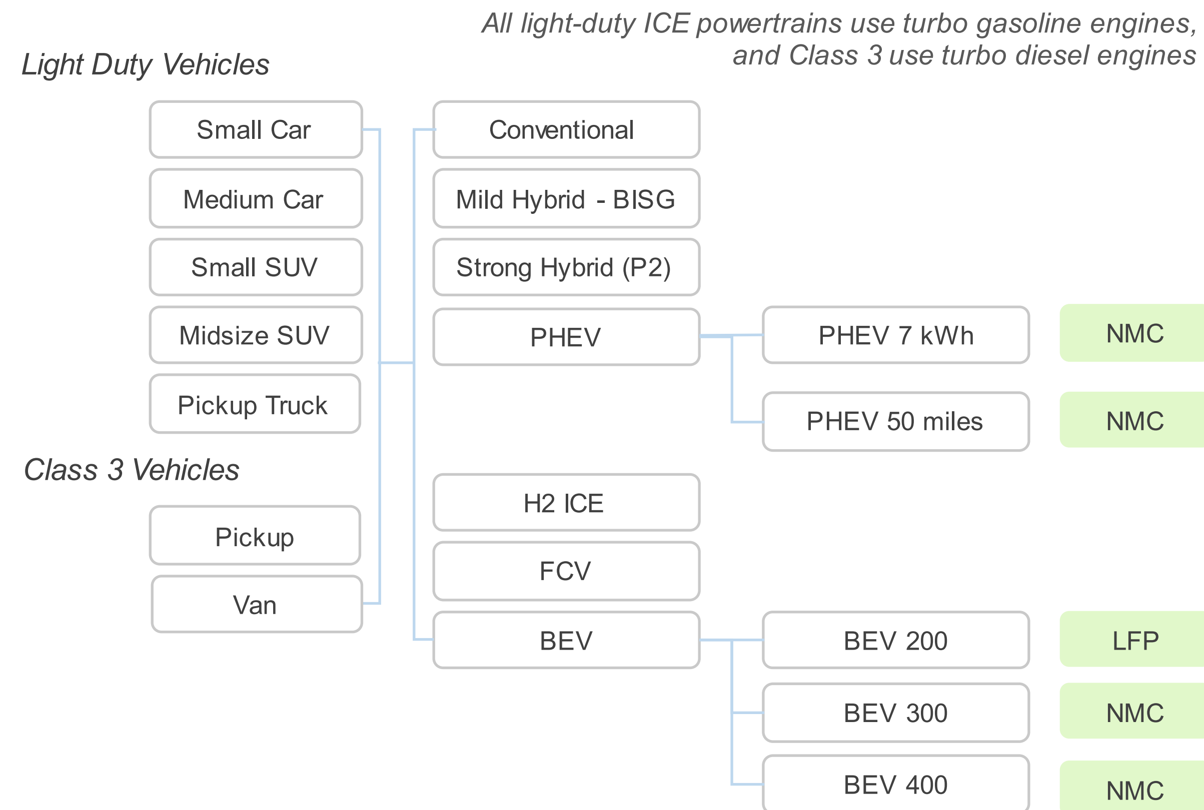

Figure 10: Technology pathways for light-duty and Class 3 vehicle powertrains

The study also looks into the clean vehicle credits (or purchase credits) under the Inflation Reduction Act (IRA) of 2022 and its impact on the powertrain costs in MYs 2024 and 2027. However, since the IRA expires on 31 December 2032, we have not considered any consumer credits for 2035.

A ground-up modeling effort for sizing the various powertrain components and estimating the vehicle's energy consumption per mile is beyond the study's scope. Instead, we use the 2022 ANL modeling study [4] to estimate fuel consumption (gasoline, diesel, hydrogen, and/or electricity) for all considered vehicles. We also use the ANL study to estimate the battery and motor sizing for BEVs, HEVs, and PHEVs, and fuel cell and hydrogen storage sizing for FCEVs. ANL is the only study with powertrain sizing and energy efficiency for all the vehicle and powertrain combinations presented in this report. Every study has different underlying assumptions for powertrain sizing and efficiency that affect the final values. Hence, combining different power trains and vehicles from different studies is impossible.

2. Technology Overview

The technology review covers those technologies that can significantly reduce the DMC of light-duty vehicles and Class 3 pickup trucks from 2024 to 2035. Sections 2.1 (Battery Technology), 2.2 (Traction Motors), and 2.3 (Power Electronics) provide a brief overview of key technologies that are vital to the electrification of powertrains, as they have been covered in detail in our previous reports [8], [9], [16]. In addition, technological evolution in H2 ICE (Section 2.4.1) and FCEVs (Section 2.4.2) is covered extensively in the following sections.

Though most of the technologies discussed in this section have not been considered in the costing exercise undertaken in this study, they demonstrate that the analysis in the 2027 and 2035 timeframes is conservative because future developments will likely further reduce BEV costs.

2.1 Battery Technology

Lithium-ion batteries of various cathode chemistries are nearly universally deployed in EVs. Each chemistry has its own set of performance characteristics and tradeoffs, resulting in a diverse class of chemistries produced globally. The EV space is currently dominated by nickel-based chemistries like the NMC (nickel-manganese-cobalt) and the NCA (nickel-cobalt-aluminum), followed by the non-cobalt, iron-based chemistry, LFP (lithium iron phosphate). These chemistries are used in various combinations of minerals, and the appended numbers represent the ratios of minerals used in the cathode. The family of lithium-ion chemistries, as shown in Figure 11, is usually identified by the compounds used to form their cathodes. NMC chemistries include NMC111/NMC333, NMC442, NMC532/NCM523, NMC622, NMC721, NMC811, and NMC9.5.5/NMC90, which have largely dominated the LIBs used in the EV space. NMC 5- and NMC 6-series chemistries were the most widely used in 2021/2022, followed by NCA+ and LFP chemistries [70].

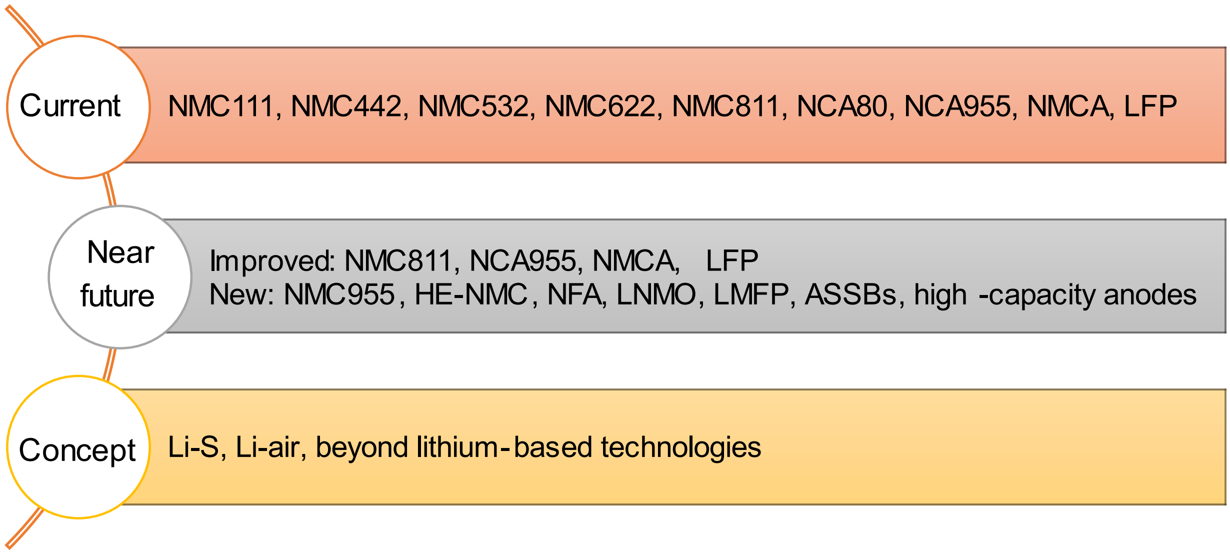

Figure 11: Snapshot of current and expected EV battery chemistries. Numbers represent the ratios of nickel-manganese-cobalt or nickel-cobalt-aluminum in the cathode [8], [16]**.**

In 2021, the average battery capacity was 55 kWh, with a volume-weighted average battery pack price of $118/kWh for BEVs [17], [18]. The global demand is projected to climb from 700 GWh in 2022 to nearly 4.7 TWh by 2030 [19]. Tesla is currently the leading EV producer in North America and is believed to use NCA955 with 3% cobalt (an advanced version of NCA80, which uses 9% cobalt) in its cars [20]. However, since 2021, Tesla has pivoted to LFP in their standard-range vehicles since it reduces dependence on critical elements like cobalt and nickel, in addition to being more environmentally sustainable, cheaper, and safer. Price volatility in the commodity market has led to the resurgence of LFP. Other automakers, like Volkswagen and Rivian, are also in favor of LFP over nickel-based cells for their entry-level, high-volume EVs. It is expected that due to the expiration of LFP patents at the end of April 2022, OEMs across North America will be able to mass-produce LFP battery-based vehicles [17].

Lithium-ion chemistries like NMC955, NMC9525, HE-NMC (high-energy NMC), and high-manganese NMC combinations are in various stages of development. They are expected to replace the currently popular NMC 5- and 6- series chemistries because they have the potential to reduce cobalt while maintaining safety and offering higher energy density. Furthermore, cobalt-free chemistries like NFA (lithium-iron and aluminum nickelate), NMA (lithium nickel manganese aluminum oxide), LMFP (lithium manganese iron phosphate), LNMO (lithium nickel manganese oxide, also known as high-voltage spinel), Li-S (lithium-sulfur), Li-air, Na-ion (sodium-ion), other metal-air batteries (metals like sodium, aluminum, and zinc), and all-solid-state batteries (ASSB) are in the pipeline. Besides the advancements made in the field of cathode chemistries, high-density anodes are also under development, which will boost the energy density of the battery chemistries. These technological advancements offer superior performance and safety while reducing the dependence on resource-constrained critical elements. However, only some of them may be commercially available by 2030, and those would have to be cost-competitive to overcome the fundamental barrier to adoption.

2.2 Traction Motors

Traction motors propel EVs by providing instant torque allowing the vehicle to accelerate quickly and smoothly. Figure 12 depicts the different types of traction motors used on BEVs. Our previous publications [8], [9], [16] go into great detail about the advantages and disadvantages of each of these motors and technical advancements.

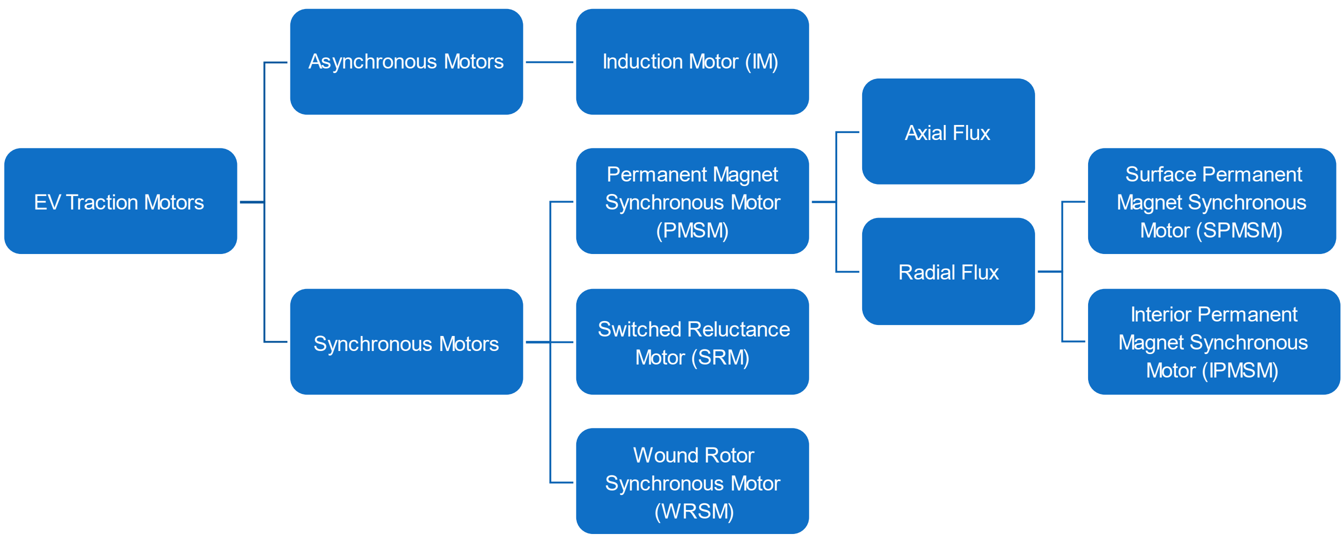

Figure 12: Different types of traction motors for BEVs.

Permanent magnet synchronous motor (PMSM) is widely used capturing more than 90% of the EV market [21] followed by induction motor (IM) and wound rotor synchronous motor (WRSM). PMSM motors use permanent magnets such as neodymium iron boron (NdFeB) magnets to generate the magnetic field needed for the motor to operate. Some of these magnets also contain heavy rare earth metals such as dysprosium and terbium. PMSMs are highly efficient, compact, and lightweight, making them ideal for use in EVs.Rare earths are a group of 17 chemical elements and are so-called as their supply is not concentrated in one location. These elements are expensive, difficult to mine, and pose environmental and health risks. Per USGS, China has the world's largest reserve of rare earth materials and is the world's main supplier.

Tesla uses both IM and PMSM in their offerings; however, during the recently held 2024 Investor Day, they announced that they will be transitioning to PMSM without the rare earth magnets. This is likely possible by using a combination of ferrite-based magnets or other alloys but it is difficult to speculate as these motors typically have a weaker magnetic field, thereby a low power-to-weight ratio. BMW's "5th generation E-drive technology" family of motors uses WRSM in all of its EVs [22]. WRSMs have better controllability and are highly efficient, as the winding coils in the rotor can be cooled more effectively than permanent magnets. This allows for higher power density and increased performance.

2.3 Power Electronics

The three major components of power electronics are the traction inverter, the DC-to-DC converter, and the onboard charger. The cost of these components has decreased significantly over the past five years due to improved manufacturing processes and economies of scale [23].

a) **Traction Inverter**: A traction converts the direct current (DC) from the high voltage (HV) battery into a variable frequency alternating current (AC) to power the traction motor that drives the wheels.

   Traditionally inverters used silicon IGBT inverters are a common type of traction inverter used in EVs. Many popular BEVs use Si IGBT inverters in their powertrain systems. Some examples of BEVs that use Si IGBT inverters include Tesla Model S and Model X (early models), Nissan Leaf (2010-2017 models), BMW i3, Volkswagen e-Golf, Ford Focus Electric, Chevrolet Spark EV, Kia Soul EV, and Hyundai Ioniq Electric. It's worth mentioning that the use of Si IGBTs in BEV inverters is dwindling as newer, more efficient power electronics technologies like Silicon Carbide (SiC) and wide-bandgap (WBG) materials like Gallium Nitride (GaN) (shown in Figure 13) become more widely available and cost-effective. These newer technologies outperform traditional Si IGBTs in terms of power density, switching speed, and loss, making them appealing to electric car makers [8], [9], [23], [24]. SiC traction inverters are used in the Tesla Model 3 and Model Y, as well as the Porsche Taycan, Lucid Air, and Chevrolet Bolt EUV. According to reports, the usage of SiC technology allows for quicker charging and increased efficiency [8], [9], [23]. SiC technology is projected to play an increasingly crucial role in the development of high-performance, efficient electric cars as it advances and becomes more generally available. In 2020, Toyota announced that it had developed a prototype electric vehicle powertrain system that uses a GaN inverter [25]. Other companies, such as Infineon and Panasonic, are also working on GaN-based power electronics for electric vehicles. These variants were not factored in this study.

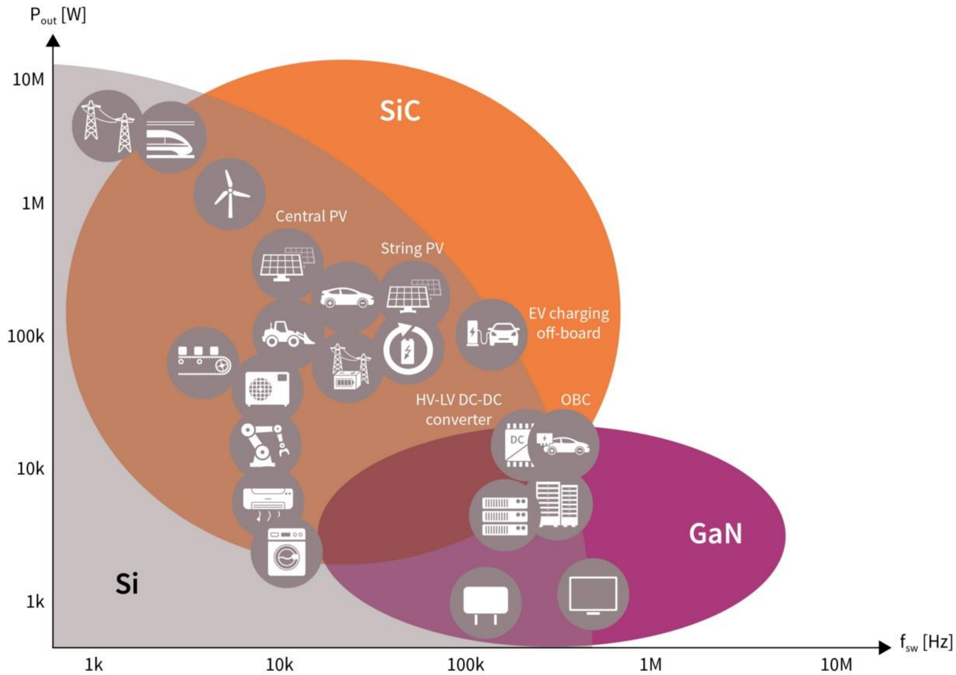

Figure 13: Wide-bandgap semiconductor applications. Source: Infineon [26]

b) **DC-to-DC converter**: DC-DC converters are an essential component of EV power electronics systems. The high-voltage DC output (400–750 V) from the EV's battery pack (250–360 V) must be converted to the lower-voltage DC required to power the auxiliary systems and subsystems such as lights, infotainment systems, steering, advanced driver assistance systems (ADAS), and air conditioning, which is typically 12–48 V. DC-DC converters are typically non-isolated or isolated and come in various configurations [27].

DC-DC converters can significantly impact the efficiency and performance of an EV, as they must convert DC output voltages to appropriate levels while minimizing energy losses. As the industry transitions to higher voltage specs 800 V and beyond to achieve more efficient motor operation and extreme fast charging technology, WBG-based architecture would be prevalent. Higher-efficiency converters can reduce the amount of energy wasted as heat and improve the overall range of the vehicle. DC-DC converters are advancing to high switching speeds to reduce power losses in passive components, and hence the SiC (in use) and GaN (not mature) are explored as possible solutions to overcome the limitations of Si-based devices [23], [27].

c) **An onboard charger (OBC)** converts the input AC power from an external source, such as a charging station or wall outlet, into DC power. This DC power is required to charge the EV battery. It can be integrated into the traction motor housing, thereby reducing costs. OBCs typically range from 3.7 kW to 22 kW [28]. With the advent of fast charging technology, some electric vehicles can charge from empty to 80% in under an hour. Figure 14 provides an overview of trends in OBC design and the solutions they offer.

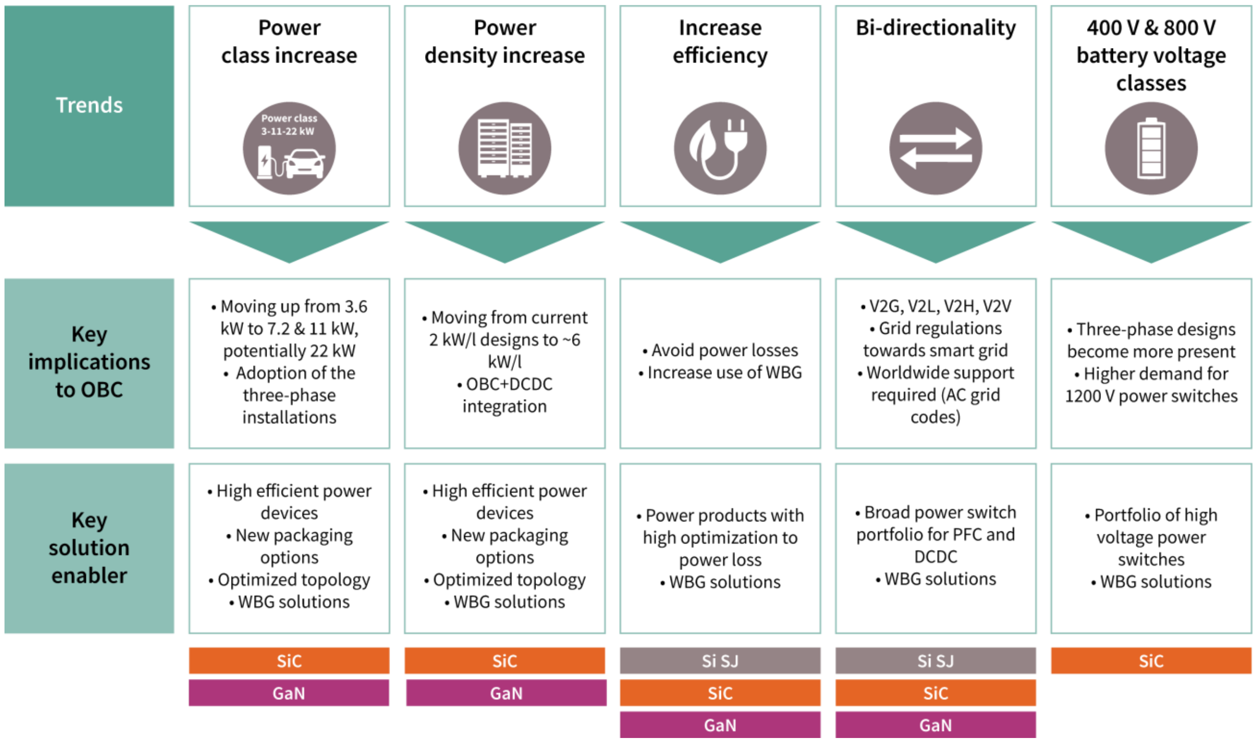

Figure 14: Developments in On-board charger (OBC) design. Source: Power Electronics News [28]

2.4 Hydrogen as Fuel for Vehicles

Hydrogen is an attractive fuel to power light, medium, and heavy-duty vehicles with the potential to reduce carbon dioxide emissions significantly. However, the carbon footprint of hydrogen fuel varied considerably depending on its production method. Figure 15 shows the different ways of producing hydrogen at an industrial scale. Green hydrogen produced by the electrolysis of water using renewable energy has the smallest carbon footprint. With increased renewable energy production, there are times when solar or wind generation exceeds demand, and the marginal cost of energy is low (or sometimes even zero). Therefore, green hydrogen is a very attractive way to turn excess renewable energy into a zero-carbon fuel for transportation. This makes renewables and hydrogen-fueled transportation complementary technologies.

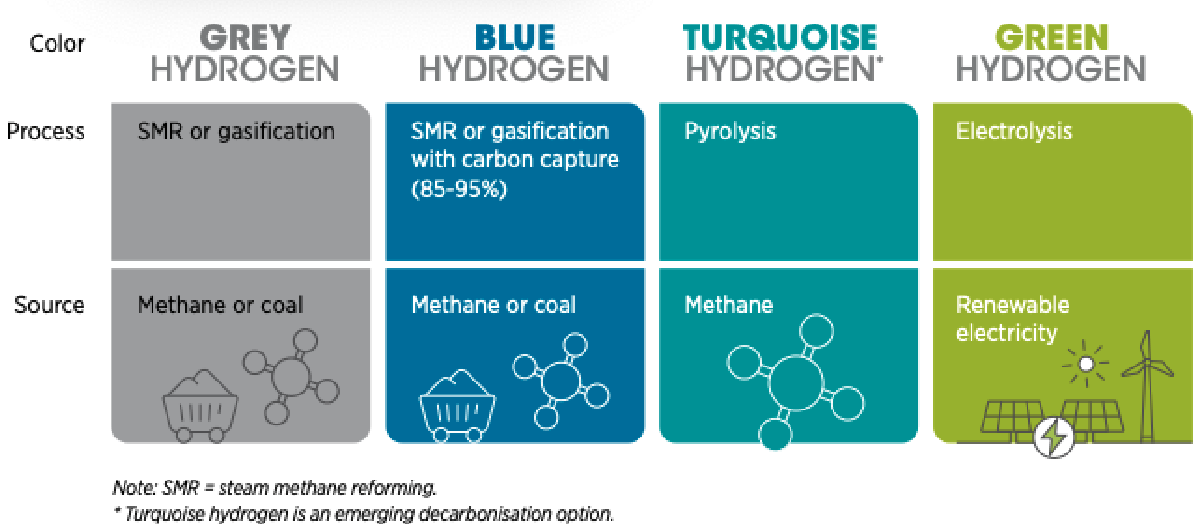

Figure 15: Different colors of hydrogen. Image: International Renewable Energy Agency

Today most of the hydrogen used in industrial processes and transportation is produced through the steam reformation of natural gas. However, only about 1% of hydrogen is currently produced from renewable sources [29]. Also, using hydrogen as a fuel for transportation will require significant investment to build out a large number of hydrogen fueling stations.

The two methods of using Hydrogen as fuel for transportation are a) to use it in a hydrogen-burning internal combustion engine or b) in a hydrogen fuel cell to produce electricity and power an electric motor to drive the wheels (fuel cell electric vehicle, FCEV). Currently, all production vehicles that use hydrogen as a fuel are FCEVs.

2.4.1 Vehicle on-board hydrogen storage

Hydrogen can be stored onboard a vehicle as a compressed gas or cryogenic liquid.

The BMW Hydrogen 7, the only production hydrogen ICE vehicle (in limited production from 2005 to 2007), used a vacuum-insulated cryogenic tank behind the rear seats to store liquid hydrogen at extremely low temperatures (Figure 16). With a volume of six cubic feet (170 liters), the tank stored 8 kg of liquid hydrogen when full (an energy equivalent of 8 gallons of gasoline). Unfortunately, the cryogenic tank had a boil-off rate of approximately 16 g/hr., emptying a full tank in less than 20 days. In addition, the boil-off presented a fire risk when parking the car in enclosed spaces.

Because of these disadvantages, most hydrogen-powered production (FCEVs) and research vehicles today use high-pressure tanks to store compressed hydrogen gas. These avoid the boil-off issue faced by liquid hydrogen. All compressed tanks used in production vehicles are “type IV” (composite fiber-wrapped tanks) with a non-metallic (polymer) lining. These tanks store hydrogen at a pressure of 10,000 psi (700 bar). This report calculates all costs based on Type IV compressed hydrogen tanks.

Figure 16: BMW Hydrogen 7 with a cryogenic tank (left) and the 2022 Toyota Mirai with Type IV compressed hydrogen tank (right)

As shown in Figure 16, both hydrogen storage methods occupy a significant volume making packaging in light-duty vehicles challenging.

2.4.2 Hydrogen Internal Combustion Engine (H2ICE)

In the early 2000s, automakers such as BMW and Ford began researching H2ICE engine cars as part of their attempts to produce hydrogen-fueled automobiles. BMW had a limited production gasoline-hydrogen bi-fuel 7 Series car in the early 2000s [30], while Ford created an H2ICE-powered shuttle bus in 2005 [31]. Ford developed a demonstration fleet of 30 E-450 shuttle buses equipped with a hydrogen-powered 6.8L Triton engine [31]. Recently, in 2021, China-based GAC Motor announced it successfully developed a dedicated H2ICE with a thermal efficiency of 44% [32]. However, efficient carbon-neutral production of hydrogen and the associated vehicle fueling infrastructure are some challenges facing the adoption of H2ICE vehicles. Furthermore, hydrogen ICE vehicles that use hydrogen produced from renewable resources may not contribute to CO2 emissions, but they still produce NOx and particulate emissions (from the combustion of engine oil).

The BMW Hydrogen 7 was the only on-road production vehicle with a hydrogen combustion engine. In limited production from 2005 to 2007, it was based on a BMW 7 series. Its 260 BHP 6.0-liter naturally aspirated V12 engine (based on the production gasoline engine) could run on either hydrogen or gasoline [30], [33]. To prevent knocking, BMW lowered the engine's compression ratio to 9.3 from the gasoline engine’s 11.3 [30]. While operating on hydrogen, the engine produced 260 bhp compared to the gasoline version’s 438 bhp [33]. In a PFI hydrogen engine, the low density of hydrogen results in an in-cylinder charge with a much lower energy content (lower heating value for the same volume) than a gasoline-air mixture.

Figure 17 illustrates the aftertreatment system and the engine operating strategy of BMW Hydrogen 7 from an ANL study [3] of the test results of a dedicated hydrogen version of the Hydrogen 7. In the upper load range, the engine is operated at λ = 0.97. Exhaust after-treatment is performed by the three-way catalytic converter, which uses unburned hydrogen to reduce NOX raw emissions. [30]. At low loads, the engine is operated at λ > 1.8. The extremely low NOX raw emissions do not require exhaust after treatment. Operation at the λ range between 0.97 and 1.8 in a hydrogen internal combustion engine is excluded, as no effective exhaust after-treatment is possible due to the high NOx emissions. With today's emission standards, the engine will require a NOx aftertreatment system if operating lean. With the EPA's refusal to recognize the BMW Hydrogen 7 as a ZEV, BMW and other automakers did not pursue H2ICE technology further [34], [35].

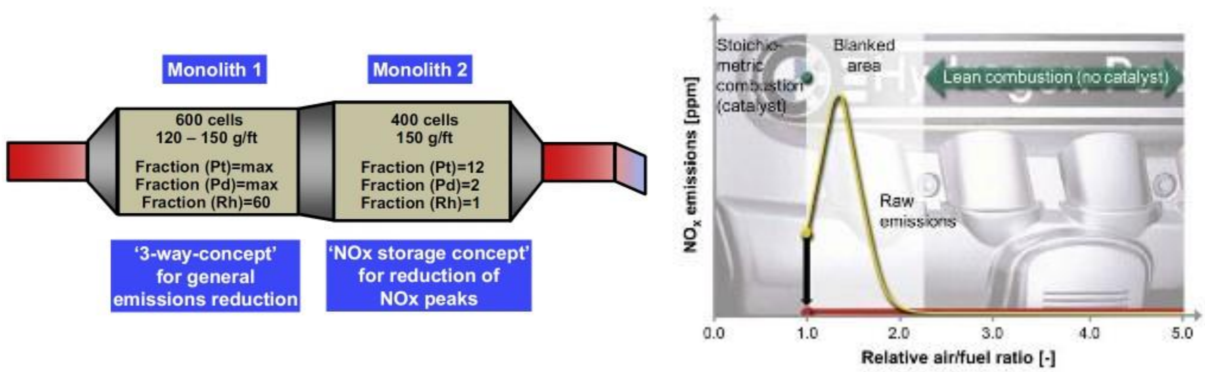

Figure 17: Schematic of the catalyst setup of the BMW Hydrogen 7 (left) BMW Hydrogen 7 relative air-fuel ratio operating strategy [3]

For costing the hydrogen engine and after-treatment system in this study, we have assumed a spark-ignited engine with a turbocharging system capable of providing higher boost pressures (when compared to a gasoline SI engine) necessary to maintain a power density (power per unit displacement – for packaging) comparable to that of an SI engine. [36] [37].

The engine will operate stoichiometric with EGR dilution at high loads. A TWC that uses unburned hydrogen as the reductant will be used for NOx aftertreatment. At low loads, the engine will operate lean (λ>1.8) and use a diesel-like SCR system for NOx aftertreatment. Furthermore, some applications may need a GPF to control particulate emissions created due to the combustion of engine oil [36], [37]. For this study, it is assumed that the hydrogen engine will not need a GPF to meet emission standards.

2.4.3 Fuel Cell Electric Vehicle (FCEV)

Fuel Cell Electric Vehicles (FCEVs), like BEVs, offer high efficiency, fossil-fuel-free transportation, and zero exhaust emissions. They have a longer driving range than BEVs and, like fossil-fuel-powered vehicles, can be refueled in minutes. Nevertheless, there are significant barriers to FCEV adoption, including a lack of hydrogen refueling infrastructure, higher production costs compared to gasoline-powered vehicles, and a need for increased hydrogen production capacity. But, as technology advances and infrastructure improves, FCEVs may become a more viable option for reducing GHG emissions from transportation. Some automakers plan to sell FCEVs alongside BEVs to fulfill varying consumer requirements and emission standards. Though the current market offerings in this segment are limited, as shown in Table 1, it is anticipated to increase in the future with the maturation of technology, decarbonization of transportation, and market demand.

Table 1: FCEVs in the United States. Source: EPA (fueleconomy.gov)

Specs	2022 Toyota Mirai LE			2022 Toyota Mirai Limited			2022 Toyota Mirai XLE			2022 Hyundai Nexo			2022 Hyundai Nexo Blue		
Fuel Economy															
Mi/Kg	72	74	70	64	65	63	72	74	70	56	58	53	60	64	56
Mi/Kg	comb	city	hwy	comb	city	hwy	comb	city	hwy	comb	city	hwy	comb	city	hwy
MPGE	74	76	71	65	67	64	74	76	71	57	59	54	61	65	58
MPGE	comb	city	hwy	comb	city	hwy	comb	city	hwy	comb	city	hwy	comb	city	hwy
Other Estimates															
Range (miles)	330	330	330	357	357	357	402	402	402	354	354	354	380	380	380
Vehicle Characteristics															
Class	Compact Car									Small SUV - 2WD					
Motor	AC Synchronous (134 kW)									Interior Permanent Magnet Synchronous (120 kW)					
Battery	311 V Lithium Ion									240 V Lithium Ion					
Availability	Dealers in California & Hawaii									California only					

An FCEV is a type of EV that generates electricity using a fuel cell as its primary power source. It generates electricity through an electrochemical reaction in the fuel cell rather than utilizing a battery to store energy. It generates energy by mixing hydrogen with oxygen from the air and producing electricity, with heat and water vapor as its byproducts. The fuel cell's electricity is utilized to power an electric motor, which propels the vehicle. It does use a battery to either store excess energy produced by the fuel cell or as a result of regenerative braking, or to augment the power by using battery power during the acceleration phase of a vehicle.

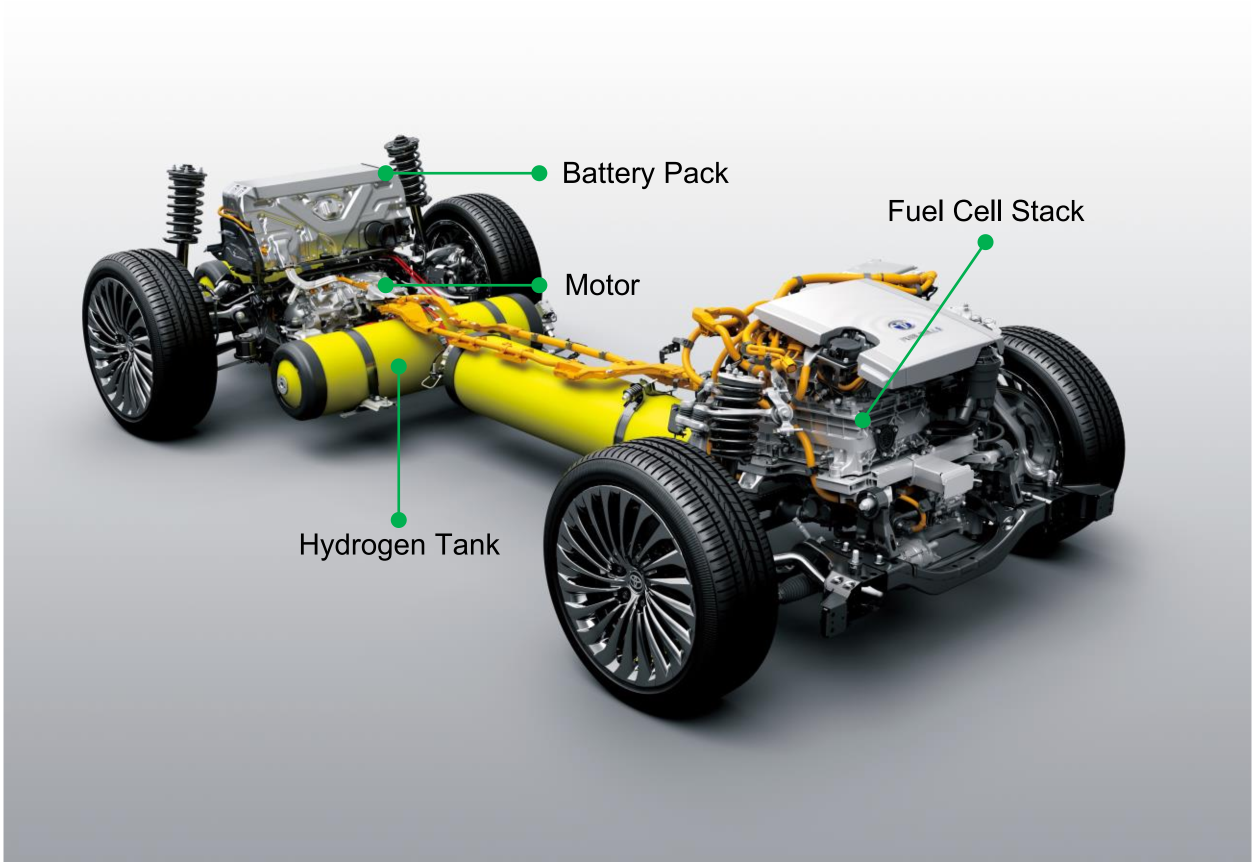

Figure 18: Schematic of Toyota Mirai FCEV. The fuel-cell stack in the second-generation Mirai contains 330 fuel cells. Source: Toyota

A fuel cell, as shown in Figure 20, is a form of a galvanic element that directly converts the chemical reaction energy of a fuel with an oxidant into electrical energy. The reactants are not contained within the fuel cell, unlike a battery. Fuel acts as a reducing agent and initiates a redox reaction which allows a flow of electrons through the circuit while the hydrogen ions pass through a membrane. Typically, the oxidant is oxygen from the surrounding air. Several fuels are employed depending on the kind of fuel cell, such as hydrogen, methanol, or natural gas.

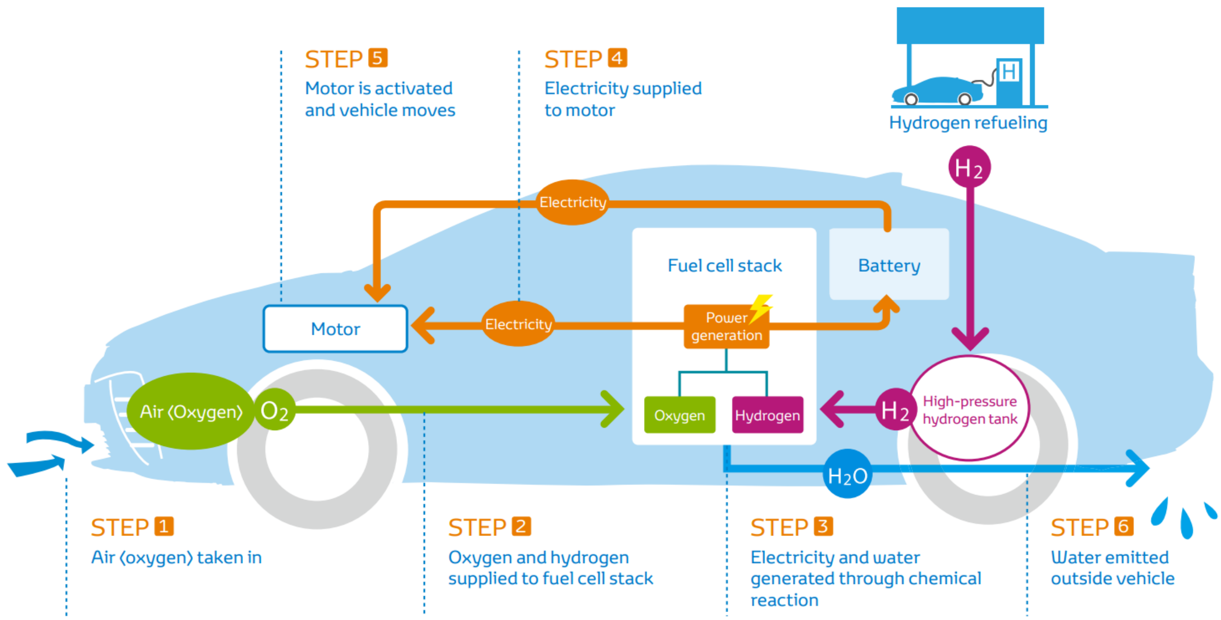

Figure 19: Schematic of Toyota Mirai's propulsion system [38]

Hydrogen nuclei (pairs of red spheres) are separated from their electrons (yellow spheres). The flow of electrons generates an electric current, which powers the car. The hydrogen nuclei pass through a membrane (center) and then combine with the electrons and oxygen (blue) from the air to form steam. Water is the only waste product, as shown in Figure 20. Hydrogen-powered fuel cells are drawing interest from automakers as a possible viable alternative or a supplement to their electrified vehicles portfolio.

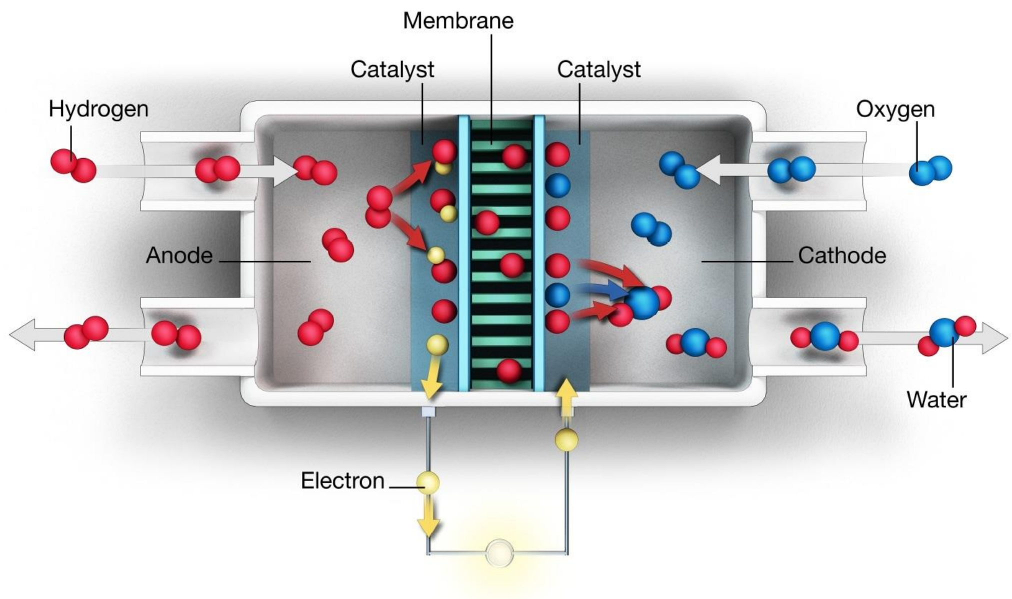

Figure 20: Hydrogen fuel cell [39]

Hydrogen fuel cell vehicles are powered by electrochemical reactions that involve oxidation-reduction (redox) reactions [23]. The following electrochemical reactions occur:

a) **Hydrogen Oxidation Reaction (HOR)**: it occurs at the anode, which is typically made of a platinum-based catalyst to facilitate the oxidation of hydrogen. The hydrogen dissociates into 2 hydrogen ions by releasing 2 electrons that flow through an external circuit to generate electrical power.
b) The protons are then transported through a proton exchange membrane (PEM), also referred to as a polymer electrolyte membrane, which can be a polymer membrane or a liquid electrolyte, to the cathode. The membrane acts as an electrolyte, allowing positively charged protons to pass through it while blocking the flow of electrons.
c) **Oxygen Reduction Reaction (ORR)**: At the cathode, oxygen gas combines with the protons and electrons to form water (H_2O). The cathode is typically made of a combination of platinum and other materials, such as carbon or nickel, which act as catalysts to facilitate the reduction of oxygen.

A comparison of a LIB against a hydrogen fuel cell is shown in Figure 21.

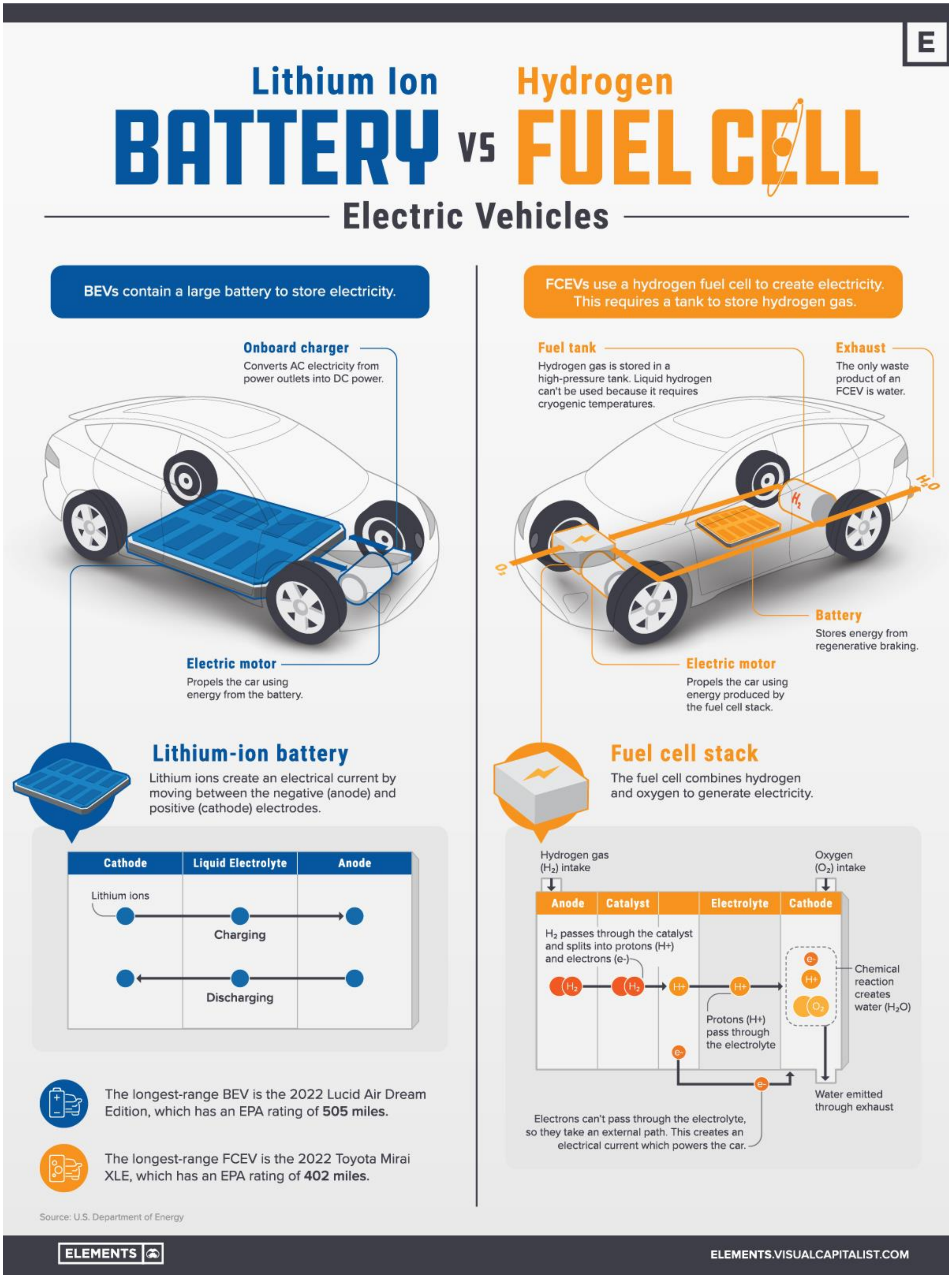

Figure 21: Lithium-ion battery vs. hydrogen fuel cell. Source: Visual Capitalist [40]

The direct conversion of material-bound chemical energy into electrical energy is a substantial benefit of the fuel cell over an ICE. In an internal combustion engine, additional conversions take place to produce chemical energy for its use as mechanical energy. Furthermore, the efficiencies achieved using an ICE and a fuel cell are dictated by Carnot's cycle and Gibbs's free energy principle, respectively. Gibbs free energy is the thermodynamic potential that quantifies the reversible work done by a thermodynamic system at constant pressure and temperature. The fuel cell's efficiency and performance depend on the properties of the catalysts, the electrolyte, and the operating conditions, such as temperature and pressure. The adoption of FCEVs is still limited due to the high cost of producing hydrogen and the limited availability of hydrogen fueling stations.

A fuel cell stack, as shown in Figure 22, is an electrochemical device that converts chemical energy from a fuel (such as hydrogen) and an oxidant (such as oxygen) into electrical energy. The key components of a fuel cell stack include:

a) Membrane Electrode Assembly (MEA): The MEA is the heart of the fuel cell stack and consists of a thin polymer membrane coated on both sides with a catalyst. The catalysts facilitate the electrochemical reaction that occurs within the fuel cell to produce electricity.
b) Bipolar plates: Bipolar plates are conductive plates that act as current collectors, distributing electrical power throughout the fuel cell stack. They also provide a path for the fuel and oxidant to flow through the fuel cell.
c) Gas diffusion layers: Gas diffusion layers are porous layers that allow the fuel and oxidant to diffuse through the MEA, ensuring an efficient electrochemical reaction. They also act as a barrier, preventing the mixing of fuel and oxidant gases.
d) End plates: End plates are used to seal the fuel cell stack and hold the MEA, bipolar plates, and gas diffusion layers in place. They also act as current collectors, connecting the fuel cell to an external circuit.
e) Cooling plates: Cooling plates are used to remove excess heat generated during the electrochemical reaction. They are typically made of a highly conductive material and are placed between the bipolar plates to help dissipate the heat.
f) Humidifiers: Humidifiers are used to maintain the proper moisture content within the fuel cell stack, which is critical for the efficient operation of the MEA. They typically contain a water reservoir and a humidification chamber.

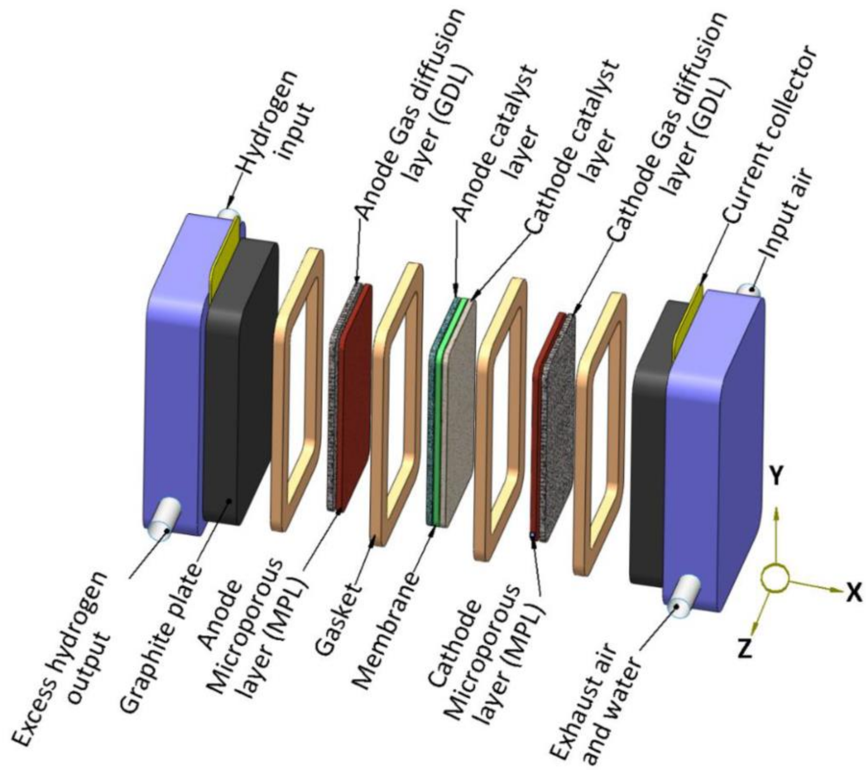

Figure 22: Schematic of PEM fuel cell stack [41]

Together, these components work to create an efficient and reliable fuel cell stack that can generate electrical power from a variety of fuels. Further cost reductions in fuel cell and hydrogen storage systems are required for broad FCEV deployment while enhancing fuel cell longevity and maintaining or improving system performance. With an annual manufacturing capacity of 500,000 units, the DOE's cost objective for vehicle fuel cell systems is \$30 per kW_{net}. The use of platinum-cobalt catalysts to increase power density, reduction in platinum loading, and improved the BP stamping process has led to cost reductions. Efforts to develop improved electrodes, membranes, gas diffusion layers, bipolar plates, and balance of plant (BOP) system components such as air loops, humidifier and water recovery loops, coolant loops, fuel loops, system controllers, and sensors are ongoing which may result in further cost reductions [23], [42]. It is estimated that the BOP system accounts for more than 60% of the cost of a 2025 automobile fuel cell system at a manufacturing rate of 500,000 systems per year, with the air loop accounting for 50% of the BOP cost [42].

3. Methodology

To meet future legislative requirements and market demand for fuel-efficient vehicles, automakers can choose from a wide range of alternative powertrain technologies to fossil-fuel-powered ICEVs. In this section, we explore the alternative powertrains that can be used by automakers to supplement their electrification efforts in MYs 2024, 2027, and 2035. It does not consider consumer preference or project penetration based on rapid technological evolution in this field. Vehicle attributes such as direct manufacturing cost (DMC) and energy consumption are used to compare these vehicles and to develop their powertrain costs. Furthermore, we also look at the impact of the IRA of 2022 on all chosen powertrains.

For 2024, 2027, and 2035, we estimate the direct manufacturing cost (DMC) and efficiency of various powertrains (ICE, hybrid, PHEV, BEV, H_2 ICE and FCV). We use the 2022 ANL modeling study to estimate the size of the powertrain components (battery and motor size for BEVs, HEVs, and PHEVs; fuel cell power output, battery size, and motor size for FCEVs, etc.), and real-world energy consumption of different combinations of vehicle classes and powertrain technologies (MPG for ICE vehicles, Wh/mile for PHEVs and BEVs and gram per mile hydrogen FCEVs) [4]. ANL is the only study that has powertrain sizing and efficiency for all the vehicle and powertrain combinations we are studying in this report. Since every study has different underlying assumptions, their powertrain sizing and efficiency will be different. Therefore it is not possible to compare different powertrains of the same vehicle from different modeling studies. For this reason, we chose the ANL Study for powertrain sizing and efficiency. We chose the "high technology case" from the ANL study that assumes aggressive technology advancements based on research and development (R&D) targets developed through support by the Department of Energy (DOE) Vehicle Technologies Office (VTO) and the Hydrogen and Fuel Cell Technologies Office (HFTO).

Figure 23 illustrates the various components whose costs are summed up to determine the total powertrain cost. We looked at multiple sources of costs of different powertrain components before choosing one for this study. We will discuss this in detail in he reminder of this section.

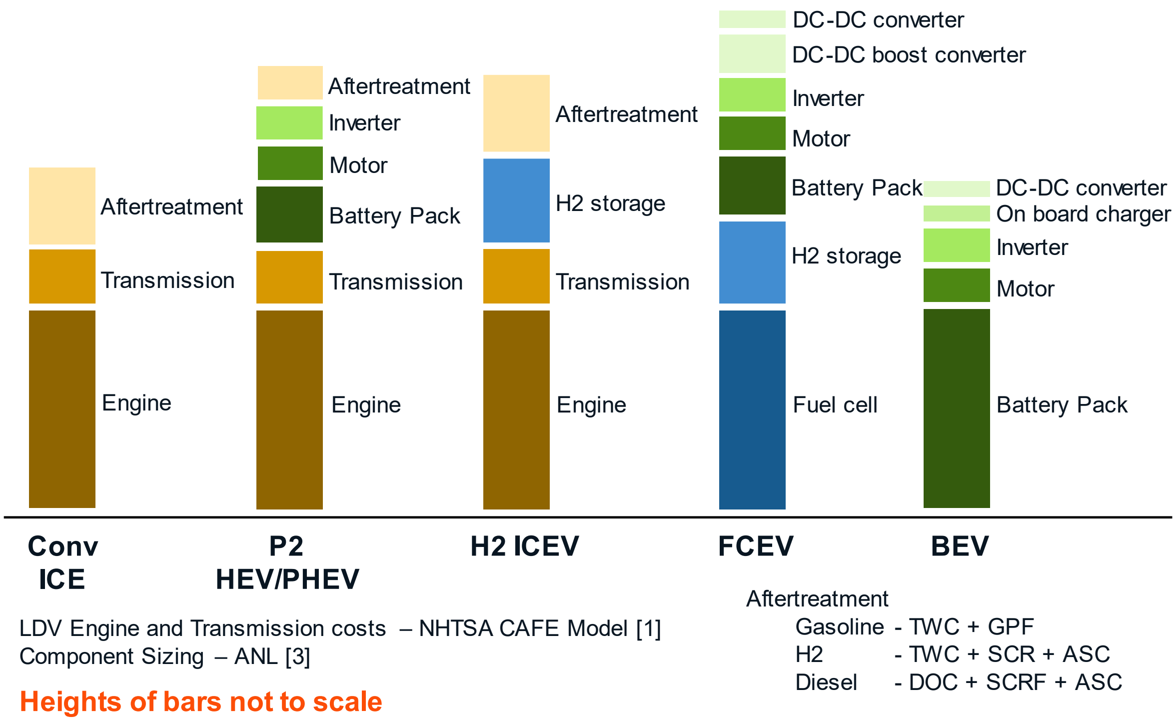

Figure 23: Components factored in computing powertrain direct manufacturing costs

3.1 Conventional Vehicle Powertrain

3.1.1 Engine technology

This study assumes that all light-duty ICEVs are gasoline-powered and Class 3 ICEVs are diesel-powered. The market share of diesel in the light-duty segment peaked at 6% in 1981 and declined to less than 1% in 2022 [2]. Future emission regulations will further increase the cost and decrease the fuel economy of diesel engines making them less attractive when compared to HEVs in the LD segment. Hence the omission of diesel engines from the light duty segment is reasonable.

Table 2 and Table 3 summarize the engine configurations of light-duty and Class 3 vehicles assumed in this study. The descriptors used to discuss engine technology packages are chosen from the 2022 EPA/NHTSA CAFE analysis [6] [7]. We assume that within a given vehicle segment, engine cost is equal between conventional, mild hybrid (BISG), HEV, and PHEV. We assume a turbocharged gasoline engine with direct injection and dual variable valve timing for the light-duty segment (technology descriptor "Turbo 1" as per NHTSA CAFE analysis documentation [6] [7]). For the light-duty pickup truck, we assume the addition of cooled EGR (cEGR) to aid extended engine operation at high loads ([6] [7]). For Class 3 vehicles, we assume a V8 turbodiesel engine with cooled EGR and closed-loop combustion control. In addition, starting in 2027, we assume that manufacturers will add an advanced cylinder deactivation system to their diesel engines to maintain high exhaust temperatures at low loads to improve the NOx conversion efficiency in the SCR catalyst.

Table 2: Technology content in various gasoline ICEV powertrains (SI, BISG, SHEVP2, and PHEV) in 2024, 2027 and 2035

Vehicle Subclass	Engine Configuration	Engine Technology*	Transmission
Compact car	4-cyl turbo gasoline	Turbo 1	8-speed
Medium car	4-cyl turbo gasoline	Turbo 1	8-speed
Small SUV	4-cyl turbo gasoline	Turbo 1	8-speed
Medium SUV	6-cyl turbo gasoline	Turbo 1	10-speed
Pickup Truck	6-cyl turbo gasoline	Turbo 1 + cEGR	10-speed
* Engine technology descriptors are taken from NHTSA-promulgated CAFE standards			

Table 3: Assumption of technology content in Class 3 Diesel ICE pickup and delivery van (Diesel, BISG, P2HEV, and PHEV)

Year	Engine	Descriptor	Engine Technology	Transmission
2023	V8 diesel	DLSI	Turbodiesel	10-speed
2027	V8 diesel	DLSIAD	Turbodiesel + ADEAC	10-speed
2035	V8 diesel	DLSIAD	Turbodiesel + ADEAC	10-speed

3.1.2 Engine and Transmission Cost

We have taken the engine and transmission costs used by NHTSA and EPA CAFE analysis [48] for this report. We choose a representative engine and transmission technology for each vehicle segment (Table 2 and Table 3) based on the vehicles currently on the market, OEM engine programs, and technology trends. Table 4 gives the engine and transmission costs used by LDVs in this study.

Figure 24 compares LDV engine costs from NHTSA (used in this report) and ICCT [43]. The cost estimated by ICCT is a weighted average engine cost for a segment based on the assumed market share of various engines and their technology content.

Table 4: Engine cost (without aftertreatment) for LDVs [44]

Vehicles	Technology	Num cylinders	Model Year		
			2024	2027	2035
Cars and small SUV	Turbo 1	4	$4,698	$4,671	$4,657
Medium SUV and pickup	Turbo 1	6	$5,555	$5,514	$5,491

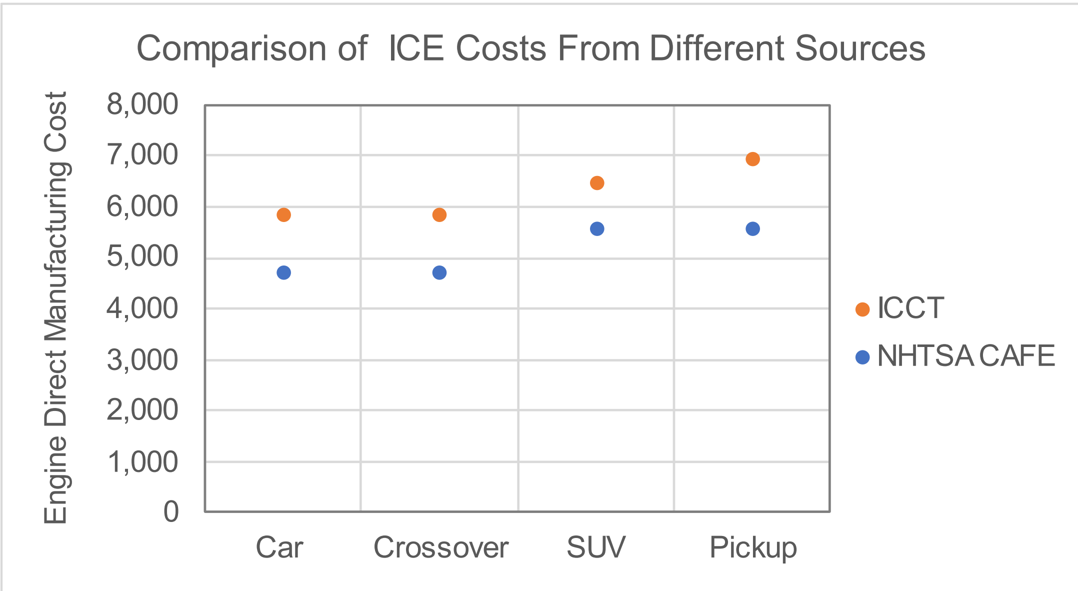

Figure 24: Engine cost comparison between NHTSA [44] **and ICCT** [43]**. Car - ICCT, Midsize Car – NHTSA. Crossover – ICCT, small SUV – NHTSA. SUV – ICCT, NHTSA**

3.1.3 Engine Aftertreatment System

The aftertreatment system is a mature technology with no future cost reductions due to “technology learning” [45]. Furthermore, the impact of potential global supply chain disruptions and price volatility of platinum group metals on after-treatment system costs between 2022 and 2035 is ignored.

All SI engines are assumed to use a three-way catalyst (TWC) and a particulate gasoline filter (GPF). In addition, diesel engines used in Class 3 vehicles are assumed to have an after-treatment system consisting of DOC, SCRF, and ASC. Table 5 lists the aftertreatment system cost (without RPE) used in this study, as presented in the Euro 7 impact assessment published in 2022 [46].

Table 5: Gasoline three-way catalyst (TWC) after-treatment system cost (expressed in €$_{2021}$). (In 2022, €1 = $1.02). *Cost source: Euro 7 Impact Assessment Study [46].

Aftertreatment system configuration and cost for LD and Class 3 vehicles			
Engine configuration	4C1B	6C2B	8C2B
Representative engine displacement (liters)	2.3	3.5	6.3
Aftertreatment system Component	**Unit cost (USD per unit)**		
Three-way Catalyst (TWC	$269	$366	$595
TWC + Coated Gasoline Particulate Filter (cGPF)	$284	$381	$610
Diesel Oxidation Catalyst (DOC)	$114	$174	$313
Selective Catalyst Reduction (SCR)	$82	$124	$224
SCR catalyst-coated DPF (SCRF)	$150	$228	$410
Ammonia Slip Catalyst (ASC)	$63	$95	$171
Aftertreatment system configuration			
Gasoline SI (Stoichiometric) - TWC+cGPF	$284	$381	$610
Hydrogen ICE (Gasoline SI based) - TWC+SCR+ASC	$413	$586	$990
Class 3 Diesel (CI) - DOC+SCRF+ASC	-	-	$894

3.2 Battery Electric Vehicle (BEV) Powertrain

3.2.1 Battery Cost

3.2.1.1 Forecasting Methods

Battery cost is the critical factor determining the economic viability of manufacturing and the adoption of EVs. Due to the high raw material costs, engineering, and manufacturing challenges, the battery constitutes 25%–40% of the vehicle's cost, depending on its chemistry and configuration [5]–[7]. Therefore, for BEVs to be cost-competitive with the ICEVs, BloombergNEF has estimated that the battery pack prices must drop below $100/kWh. In contrast, the Vehicle Technologies Office of the U.S. Department of Energy has set the federal target of reducing the cost of EV batteries to $80/kWh by 2025 [6], [18], [47]. Roush also uses the methodology for forecasting battery costs in this report in previous reports [8], [16] that deal with it in detail. This section provides a summary of the process.

Various scientific literature articles and market reports published since 2017 on battery costs were reviewed and evaluated. After thoroughly reviewing various chemistries deployed in EVs, their raw material costs, and manufacturing practices [48] and "*BatPaC V5.0*" [49], we have used the process detailed below to project battery costs in the 2027–

2035 timeframe. The field of EV batteries is continuously and rapidly evolving, and forecasting battery costs that represent all chemistries without accounting for various market forces, future volumes of production, technological and manufacturing advancements, and more, will be conjecture.

In general, the following methods [48] can be used to estimate battery costs:

a) Technological learning, also known as a learning curve or experience curve analysis, uses historical costs and a learning rate to arrive at a prediction. BloombergNEF used an 18% learning rate to estimate that the pack prices will drop below $100/kWh in 2024 and will reach $58/kWh in 2030 [6].
b) Literature-based projections use battery price and cost data aggregated from previously published literature forecasts.
c) The expert elicitations approach uses a structured interview method to gain insights and make predictions where data is uncertain and/or not easily available.
d) Bottom-up modeling uses cost estimation via first principles at the part or item level to "build up" the manufacturing cost of the battery.

Due to a fragmented, nascent, and volatile EV battery market, chemistry-dependent battery forecasting to 2027–2035 using any of those mentioned methods is a challenging exercise. Each method has its advantages and drawbacks based on the assumptions made and inherent biases. There is no single method that captures all the elements of uncertainty surrounding battery cost forecasting. Hence, a hybrid approach to arriving at battery costs in 2027–2035 is adopted that uses a combination of literature articles and BatPaC.

3.2.1.2 Roush Approach

3.2.1.2.1 BEVs and PHEVs

Using BatPaC 5.0 [49], the cost to build a cell ($/kWh) of LFP-G (Energy) and NMC811-G (Energy) for 2024 was estimated by indexing it to a plant size of 20 GWh (250,000 LDVs assuming 80 kWh packs). This approach allows the costs to be only influenced by the size of the plant and remains agnostic to the battery system parameters such as the system capacity (Ah), rated power (kW), and total energy (kWh). It can be noted that the BatPaC tool offers the user a choice between power and energy applications for a given cell chemistry. The 'Energy' option (high energy cells – lowest weight for a given energy storage capacity for a BEV) is relevant to this analysis of BEVs and was therefore chosen. The 'Power' option (high-power cells – provides the necessary power output for a hybrid powertrain with lowest battery weight) is used for modeling the cells for HEVs, as they augment and support the power requirement of a downsized gasoline engine during their drive cycle [23], [49].

For the 2027 timeframe, the plant size is assumed to be 80 GWh (a million vehilcles at 80GWh), considering the scaling of the production volumes of these cells to meet the projected US market demand of nearly 4 TWh[17]. In addition to volume scaling, a cost factor of 0.78 and 0.66 is applied to the BatPaC-derived costs in 2027 and 2030, respectively. The cost factor is derived to account for improvements in manufacturing technology and processes and is not an outcome of the BatPaC tool. It is computed from the selected publications, as shown in Table 6, from the 2021 review article, "*Battery cost forecasting: a review of methods and results with an outlook to 2050"* [48]. The review article analyzes 53 relevant peer-reviewed publications with original battery costs or price forecasts from 2361 publications. It presents the findings in a comprehensive, systematic, and transparent manner and provides supplementary information citing relevant article sources and methodologies. Roush used the detailed time-based forecasted values from the supplementary information provided by the authors. The table enumerates the peer-reviewed articles published from 2010-2020 with the forecasted technology, scenario, years forecasted, and source of the data from the cited literature. The following steps detail the methodology used to evaluate the cost factor:

a) Selection of articles published between 2018-2020. The exponential fall in battery prices since 2010 [18] has resulted in actual prices being much lower than most publicatiosn before 2018
b) Identification of articles with estimated/forecasted values in the years 2020 and 2027–2030. This resulted in the selection of 7 articles out of the 24 articles with time-based forecasted values tabulated by the authors [48].
c) Calculate the ratio of the forecasted item using the formula, (2027 value ÷ 2020 value) and (2030 value ÷ 2020 value).
d) Calculate the average cost factor from the computed ratios.

Table 6: Publications selected for determining cost factor.

Authors & year	Publication Title
Edelenbosch et al. (2018)	Transport electrification: the effect of recent battery cost reduction on future emission scenarios
Nykvist et al. (2019)	Assessing the progress toward lower-priced long-range battery electric vehicles
Schmidt et al. (2019, b)	Projecting the future levelized cost of electricity storage technologies
Hsieh et al. (2019)	Learning only buys you so much: Practical limits on battery price reduction
Penisa et al. (2020)	Projecting the price of lithium-ion NMC battery packs using a multifactor learning curve model

Authors & year	Publication Title
He et al. (2020)	Greenhouse gas consequences of the China dual credit policy
Few et al. (2018)	Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: an analysis informed by expert elicitations

The calculation of the cost factor includes a mix of approaches such as expert elicitation, technological learning, and literature-based projection. BatPaC 5.0 provides a cost using the bottom-up modeling method. This approach encompasses all the cost estimation techniques used for battery cost forecasting. However, because the literature forecast may have accounted for volume scaling in their respective projections, there is a possibility of double counting, which could affect the estimated cost. Still, this is deemed to have a minimal influence on the results as the overall approach for this study is more conservative.

The cost to build an LFP-G (Energy) and NMC811-G (Energy) cell in a 20 GWh plant is $75/kWh and $78/kWh, respectively. Table 7 details the battery cost inputs used in the analysis.

Table 7: Battery costs used for BEVs and PHEVs.

Year	Plant Size GWh	Cost to Build USD per kWh		Supplier Margin	Cell cost to OEM USD per kWh		Cell-to-Pack multip-lier	OEM cost to build pack USD per kWh	
		NMC811	LFP		NMC811	LFP		NMC811	LFP
2024	20	$78	$75	15%	$89	$87	1.25	$112	$108
2027	80	$59	$57	10%	$65	$62	1.18	$76	$74
2030	120	$50	$48	10%	$55	$52	1.18	$64	$62
2035	*10% recycling and learning rate applied on 2030 costs*							$58	$55

For the 2027 projections with a plant size of 80 GWh, the average cost factor of 0.78 is applied, and for the 2030 projections with a plant size of 120 GWh, the average cost factor of 0.66 is applied to the battery costs of $75/kWh and $72/kWh for NMC811-G (Energy) and LFP-G (Energy) cells, respectively, derived from BatPaC 5.0 [49]. The resulting cell costs of NMC811-G (Energy) and LFP-G (Energy) in 2027 are $59/kWh and $57/kWh, respectively, and in 2030, they are $50/kWh and $48/kWh, respectively.

Additionally, a supplier margin from the battery manufacturer to the automotive OEM, and the cell-to-pack multiplier are used to compute the cost incurred by an OEM for building before assembling in a vehicle. A conservative supplier margin of 15% in 2022 is assumed and will likely decrease as the automotive OEMs vertically integrate battery production within their vehicle manufacturing ecosystem. There is already a rush of joint ventures and offtake agreements that the automotive OEMs are signing with the battery producers to bring down the costs. Thus, a conservative 10% supplier margin in 2027 and 2035 is assumed in this study, though it could be much lower. Based on BloombergNEF price surveys, a cell-to-pack split of 80:20 is considered in 2024 [6], [18], and going forward to 2027 and 2035 a conservative split of 85:15 is used. Per BNEF, the cell-to-pack ratio was 70:30 in 2019 and 82:18 in 2021 [6], [18]. Historical data suggests that the cell-to-pack split would further improve as the learning efficiency and resource utilization improves (despite lower cell costs). Furthermore, as the cell-to-pack (CTP) and cell-to-chassis (CTC) or cell-to-vehicle technology improves, the cell-to-pack split may further reduce. After applying the supplier margin and cell-to-pack split, the resulting cost to build a pack of NMC811-G (Energy) and LFP-G (Energy) in 2027 is $76/kWh and $74/kWh, respectively; in 2030, it is $64/kWh and $62/kWh, respectively.

Per Benchmark Mineral Intelligence's lithium-ion battery cell assessment, the cell price of an NMC811 cell in January 2023 was $134.5/kWh in North America [50]. Based on our assessment, as shown in Table 7, the cell cost to an OEM is $89/kWh for MY 2024 vehicles. Assuming an RPE of 1.5 for MY 2024 vehicles (made in this study to estimate purchase price) brings the assumed cell price to $133.5/kWh. Thus, verifying our projections with a real-world cell price assessment by a reputable source.

For the battery cost estimation in the 2035 timeframe, a factor of 10% savings is applied to factor in recycling. Recycling is expected to play a crucial role in bringing the costs further down by 2035 and will have a far-reaching and significant contribution towards achieving a circular sustainable economy. The battery pack costs projected in 2035 for NMC811-G (Energy) and LFP-G (Energy) cells are $58/kWh and $55/kWh, respectively.

3.2.1.2.2 HEVs

In the case of HEVs, pack throughput is assumed for each of the projected years based on the estimated market volume of HEVs. The assumption for 2024 is 800,000 packs, which are expected to double to 1.6 million packs in 2027 and then to 3.2 million in 2030. As with BEVs, a 10% cost reduction is applied for 2035 costs based on recycling and learning rates. A cell-to-pack multiplier of 67:33 is assumed for HEVs. After applying the supplier margin and cell-to-pack split, the resulting cost to build a pack of NMC811-G (Power) is $393/kWh in 2024, $278/kWh in 2027, $224/kWh in 2030, and $202/kWh in 2035.

Table 8: Battery costs used for HEVs. (Number of Packs: M stands for million).

Year	Number of Packs	Cost to Build USD per kWh		Supplier Margin	Cell cost to OEM USD per kWh		Cell-to-Pack multiplier	OEM cost to build pack USD per kWh	
		NMC811	LFP		NMC811	LFP		NMC811	LFP
2024	0.8M	$229	-	15%	$263	-	1.49	$393	-
2027	1.6M	$169	-	10%	$186	-	1.49	$278	-
2030	3.2M	$137	-	10%	$150	-	1.49	$224	-
2035	*10% recycling and learning rate reduction applied on 2030 costs*							$202	-

3.2.2 Traction Motor Cost

Figure 25 summarizes the results of the motor teardown studies done by Munro & Associates, Inc. of mass-produced light-duty BEV motors [51]. Permanent magnet synchronous motors (PMSM) cost $4-$5 per kW, while induction motors (IM) with aluminum rotor conductors (Tela Model 3 - front motor) cost about $2.5 per kW. Several vehicles (such as Tesla, VW, etc.) that offer AWD BEVs use a combination of PMSM in the rear and IM in the front. The IM is common in situations with high wheel torque demand or limited traction. The front axle IM is freewheeling under normal driving conditions. This enables the rear PMSM to operate at higher average loads and efficiencies. Unlike the PMSM, the IM has no parasitic losses when freewheeling due to the absence of cogging torque. This combination of PMSM on the rear axle and IM on the front axle reduces the average cost ($/kW) of the total traction motor output and increases the efficiency (miles per kWh) of the BEV. Hence, a conservative value of $4/kW for motor costs in 2024 is considered.

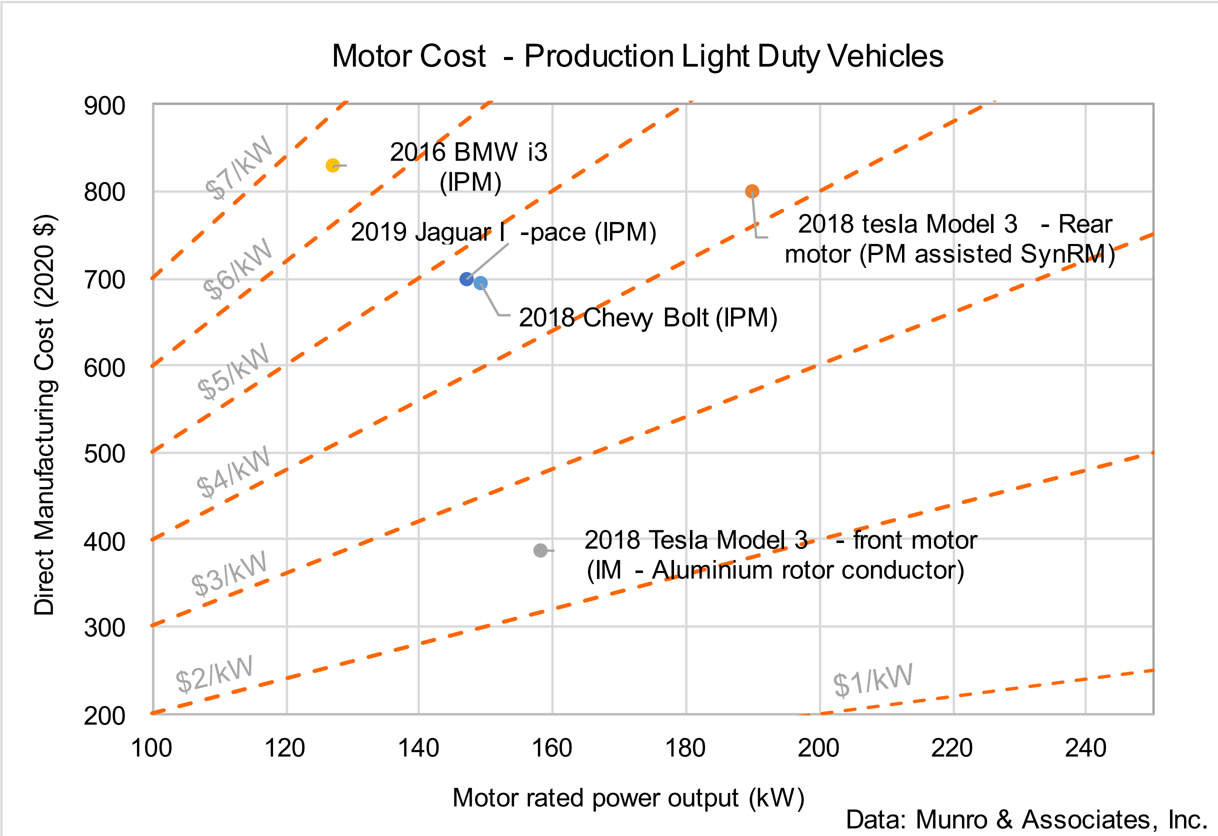

Figure 25: Production light-duty BEV motor cost [9]

As of 2022, there are several production vehicles using induction motors (Rivian, Tesla, Audi, etc.) and wound rotor synchronous motors (BMW, Renault, etc.) that use no rare earth permanent magnets. Switched-reluctance motors in limited production further simplify rotor construction and reduce costs. Pre-compressed-wound and die-cast aluminum stator windings can replace the more expensive copper stator windings while matching the performance and efficiency of copper windings. We estimate a 10% decrease in motor costs from 2024 to 2027 and 2027 to 2035, as shown in Table 9, based on future technologies and increasing economies of scale.

Table 9: Assumed traction motor costs based on peak power output

Model Year	Cost of traction motor, USD per kW
2022	$4.02
2027	$3.62
2035	$3.26

3.2.3 Power Electronics Cost

The three main power electronics components considered for costing BEV powertrains in this report are the traction inverter, the DC-DC converter, and the onboard charger.

Traction inverters convert DC power from the battery to variable frequency AC power to control the speed of the traction motor. BEVs such as the Nissan Leaf, Chevrolet Bolt, and Jaguar I-Pace use inverters that use silicon insulated-gate bipolar transistors (Si IGBTs). In 2018, the Tesla Model 3 became the first mass-produced vehicle to use silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) (sourced from ST Microelectronics in a Tesla in-house inverter design). SiC MOSFET-based inverters have higher efficiency when compared to ones using Si IGBTs. Over low speed and load points (typical light-duty city cycle), a silicon IGBT inverter has an average efficiency of 96%, while the SiC MOSFET-based inverter has an efficiency of 99% [52].

Figure 26 shows the cost of various light-duty inverters based on teardown studies by Munro & Associates, Inc. [24]. The cost includes the “housing, printed circuit board assembly (PCBA), IGBT/ MOSFET module and cooling structure, DC-link capacitor, motor-phase lead, connectors, self-contained structural and connected components”. The teardown shows that in 2018, the Tesla Model 3 inverter that used SiC MOSFETs was at price parity (≈$4/kW) with the Nissan Leaf and Chevrolet Bolt inverters that used Si IGBTs. The 2020 Tesla Model 3 and Model Y have inverters with the same performance but at a significantly lower cost (≈$2.5/kW). As for 2022, most newly introduced BEVs from manufacturers such as Hyundai-Kia, Lucid, Rivian, etc. use SiC MOSFETs in their inverters.

For this study, an inverter cost of $3.5/kW for 2022 is used, as shown in Figure 26, significantly higher than Tesla’s inverter costs in 2020, dropping to $2.4/kW in 2030 (comparable to Tesla’s cost in 2020) and remains constant from 2030 to 2035.

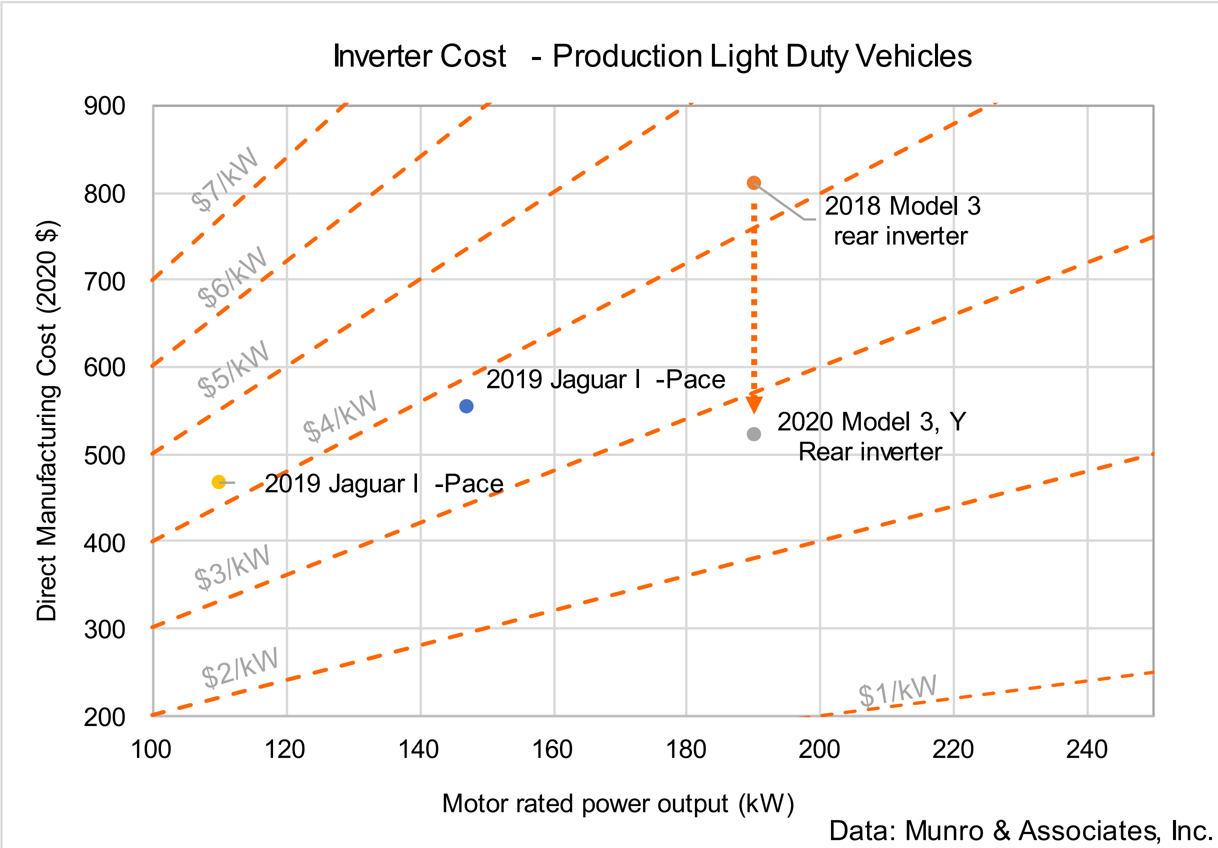

Figure 26: Production BEV inverter cost based on teardown studies. The cost includes Housing, PCBA, IGBT module and cooling structure, DC-link Capacitor, Motor phase lead, connectors, self-contained structural and connected components

The DC-DC converter steps down the high voltage of the BEV traction motor to supply all 12V loads and maintain the 12V battery charged. This report assumes a 2kW DC-DC converter size for all vehicle types. The onboard charger converts the AC supply from a level 2 charger into DC at the proper voltage to charge the traction battery. Most BEVs have a 10-12kW onboard charger, while few, such as the Lucid air, are equipped with a 19.2kW onboard charger. Therefore, we assume an onboard charger size of 11.5 kW for all vehicle subclasses and segments in the study.

Currently, many OEMs source traction inverters, DC-DC converters, and onboard chargers from tier-1 suppliers. Each component is a separate box under the hood resulting in a higher $/kW cost. It is projected that OEMs will have the traction inverter, the DC-DC converter, and the onboard charger all integrated into one package, even being part of a single PCB. In line with this observation, based on the U.S. Drive 2017 projected cost, a cost of $50/kW each for the DC-DC converter and the onboard charger is used for 2022. In 2030 it is assumed that inverters, DC-DC converters, and onboard chargers will each have the same $/kW cost of $2.4/kW.

3.3 Mild Hybrid: 48-Volt Belt Integrated Starter Generator (BISG) Powertrain

48 V mild-hybrid systems employing a belt-integrated starter generator (BISG) use a 10-15 kW e-machine connected to the crankshaft at the front of the engine through a belt drive. These systems increase powertrain efficiency by enabling enhanced start-stop, switching off the engine while coasting to reduce emissions, helping in energy recovery during braking, and using harvested energy to power accessories. BISG systems typically increase fuel economy by 5-7%, as shown by the EPA MPG numbers of the RAM 1500 E-torque at an additional cost of $700-800 [53]. For this study, we have not costed out mild hybrid systems. The BISG system cost is taken directly from the NHTSA CAFE analysis [44] for light-duty vehicles. The fuel economy of BISG systems is taken from the 2022 ANL modeling study [4]

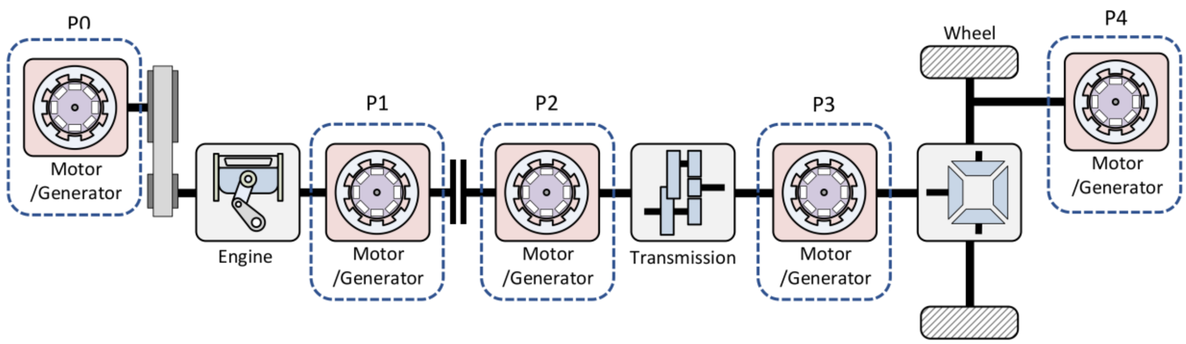

Figure 27: Different hybrid vehicle architectures. Source: Borg Warner [54]

3.4 Strong Hybrid Electric Vehicle Powertrain

Hybrid electric vehicles provide up to a 30-40% increase in fuel economy (depending on the vehicle and hybrid architecture) compared to a standard ICEV. For example, the hybrid version of the Toyota RAV4, the best-selling SUV in the US market, provides a 30% increase in fuel economy (40 vs. 30 MPG) for a $2,700 price premium. In the first half of 2022, the hybrid and plug-in hybrid versions accounted for 48% of the RAV-4 sales in the United States [55].

To simplify costing and fuel economy estimation, all hybrid vehicles in this study are assumed to have P2 architecture. In a P2 architecture, the motor is mounted to the transmission's input shaft, as shown in Figure 27. In many cases, the electric motor and the power electronics are integrated into the transmission casing by the supplier, thereby reducing cost and complexity.

For the hybrid powertrain, we have taken the motor power output (kW) and the battery size (kWh) for different vehicles from the 2022 ANL modeling study [4]. The inverter size (kW) is assumed to be the same as the motor peak power (kW). We have used the battery, traction motor, and power electronics costs presented in earlier sections.

3.5 Plug-in Hybrid Electric Vehicle (PHEV) Powertrain

Plug-in hybrid electric vehicles (PHEVs) have a battery pack large enough for pure EV driving (charge-depleting mode). The battery pack can be charged by plugging the vehicle into a compatible charger. The larger the battery pack, the higher the fraction of driving that can be done in EV mode before the battery is depleted and the vehicle switches to a less efficient hybrid mode. The utility factor (UF) quantifies the fraction of miles covered in electric mode. The larger the battery, the higher the vehicle's pure EV range, UF, and composite MPGe. Multiple analyses [56], [57] have found that in real-world usage, PHEVs are plugged in for only a fraction of the time (assumed by the UF) used by the EPA to calculate the MPGe of the vehicle.

In the case of PHEVs, we analyzed two variants: PHEVs with 7 kWh of battery capacity, and the PHEV50 which has a 50-mile range. Most of the PHEVs are already equipped with a battery pack of more than ~14 kWh (see Figure 28). Since the IRA of 2022 specifies a minimum size of 7 kWH to be eligible as a "clean vehicle", we included a PHEV with a 7 kWh battery pack for analysis.

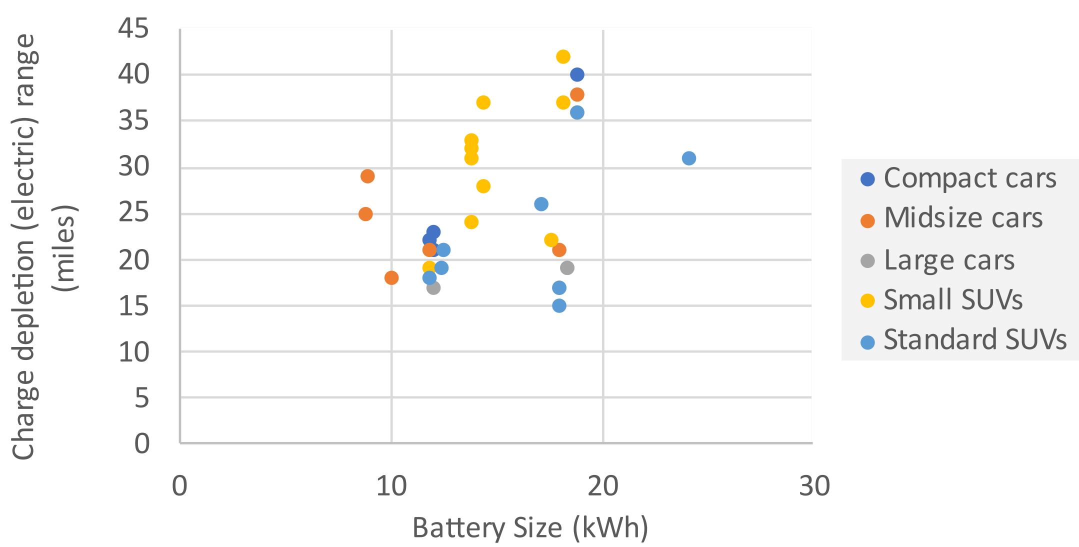

Figure 28: Battery size and all-electric range (sticker/ real world) of PHEVs on sale in the US in 2022. (fueleconomy.gov)

"The Advanced Clean Cars II rule" [3] adopted by California requires 35% of all new LDVs sold in California to be ZEVs starting in 2026, rising to 100% in 2035 (Figure 29). Automakers can meet no more than 20% of their ZEV credits with PHEVs with a real-world range of 50 miles (PHEV50). California and the other states that have adopted "The Advanced Clean Cars I rule" represent 36% of annual sales of LDVs in the United States[12]. A similar adoption of "The Advanced Clean Cars II rule" might lead to manufacturers introducing PHEV50s in more vehicle segments. Hence, a PHEV50 is used in this analysis.

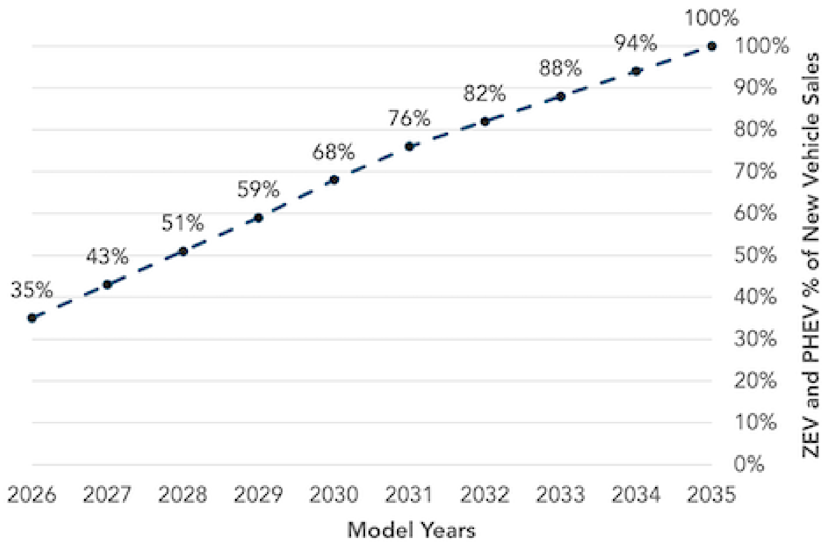

Figure 29: ZEV sales as a percentage of new vehicle sales in California

PHEVs are expensive compared to a conventional powertrain owing to having "two separate powertrains", a battery electric powertrain, and an internal combustion engine powertrain. PHEVs are an attractive powertrain for midsize SUVs and Pickup trucks with a short daily commute but are also used occasionally to tow heavy trailers over long distances. In such a case, the daily commute can be covered in the pure EV mode, while the ICE powertrain provides the driving range when towing.

3.6 Fuel Cell Electric Vehicle (FCEV) Powertrain

Figure 30 depicts a simplified schematic of an FCEV powertrain used in this study. We have taken the values of the power output of the fuel cell stack (kW), hydrogen tank size (liters), and motor power output (kW) for different vehicles from the 2022 ANL modeling study [4]. For powertrain costing, we assumed that the size of the DC-DC (boost) converter (kW) was equal to the fuel cell stack output and that the inverter size (kW) was identical to the motor power output. The cost for power electronics is the same as presented in earlier sections.

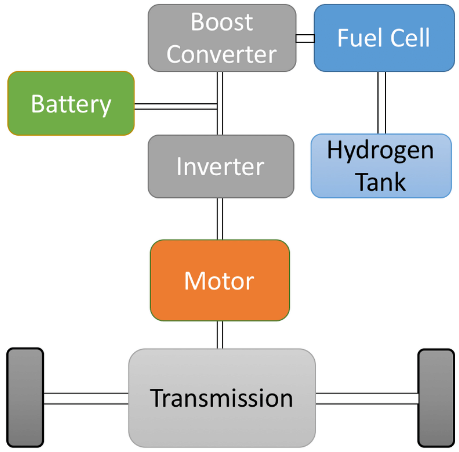

Figure 30: Simplified FCEV powertrain schematic assumed in this study [58]

We used the 2022 ANL modeling study [4] to estimate the fuel cell vehicle's efficiency (hydrogen consumption). According to the 2021 DOE report [59], the durability-adjusted (8000 hours of on-road use) fuel cell cost of an 80kW (net) polymer electrolyte membrane at an annual manufacturing volume of 100,000 units is $82/kW$_{net}$ (2020 dollars). The DOE 2025 fuel cell and ultimate target costs are $43 (2020 dollars) and $32 (2020 dollars), respectively. Figure 31 compiles fuel cell system costs from various sources, including the DOE cost mentioned above.

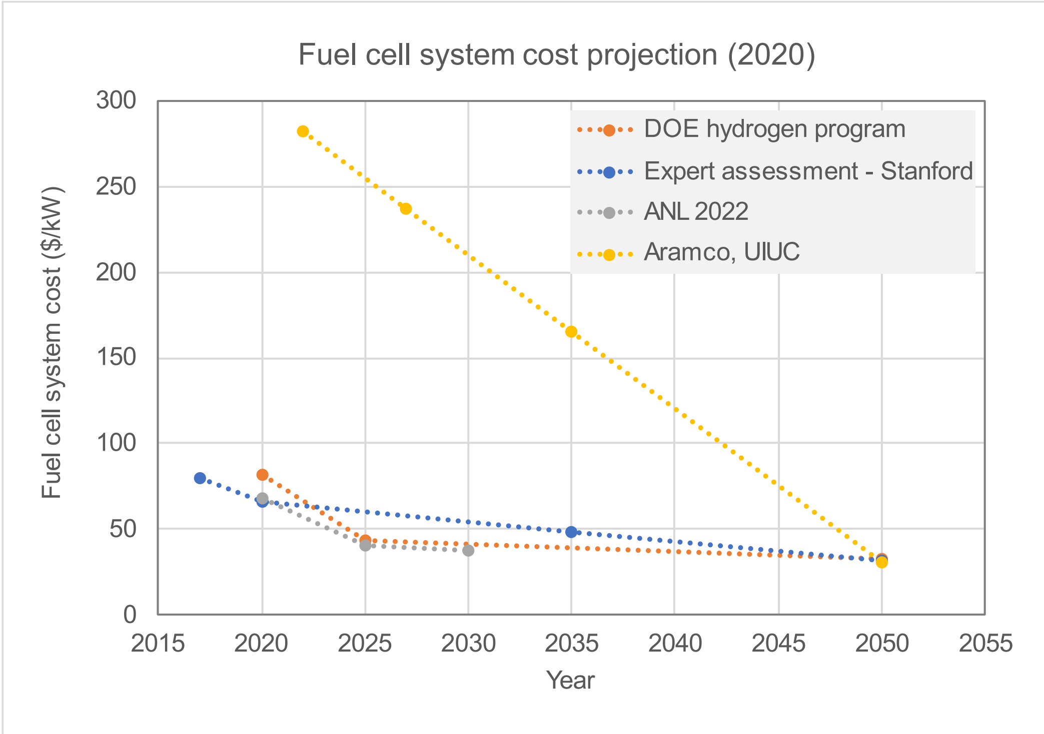

Figure 31: future cost projections of fuel cell system cost. Sources: DOE hydrogen [59], **program, expert assessment** [60], **ANL 2022** [4], **Aramco UIUC** [61]

Table 10 lists the fuel cell costs ($/kW$_{net}$) used in this study. It combines the DOE [59] durability-adjusted fuel cell cost in 2020 and expert assessments on the future performance and cost of PEM fuel cells for vehicles published in 2019 [60].

Table 10: Hydrogen storage costs used in this study

Model Year	Fuel cell cost $/kW
2022	$82
2027	$57.6
2035	$48.6

3.7 Hydrogen Internal Combustion Engine (H2ICE) Powertrain

Light-duty hydrogen ICEVs will use an architecture similar to a turbocharged gasoline engine with similar engine costs and MPGGe. However, hydrogen engines will need a turbocharging system that can deliver higher intake pressures to maintain (to compensate for the lower energy density of the hydrogen-air mixture. This is essential for a power density (power per unit displacement) similar to a gasoline engine to maintain engine size in the interest of packaging. Hence, for costing the H2ICE powertrain, a "Turbo2" engine (technology level according to NHTSA CAFE standards [44]) whose turbocharging system is capable of delivering higher intake pressures and hence break mean effective pressure (BMEP) is chosen. The engine cost for all light-duty engines is taken from the "technologies_ref" file of the NHTSA-based CAFE cost sheets [44].

The onboard hydrogen storage (Type-4 composite tanks) and diesel-like aftertreatment systems for reducing NOx emissions under lean operating conditions add significant costs to the powertrain. This makes the cost of an H2ICE powertrain significantly higher than that of a stoichiometric gasoline ICE. A spark-ignition-based hydrogen ICE has a peak efficiency of about 35%, similar to its gasoline counterpart and much lower than the 60% of the H_2 fuel cell. This would give the H2ICE an MPGGe number similar to the gasoline ICE MPG. The 2023 Toyota Mirai FCEV (a compact car by EPA classification) has a usable hydrogen storage capacity of 5.6 kg, a combined MPGE rating of 74, and a usable range of 402 miles[62]. The Toyota Corolla (also a compact car by EPA classification with an HCR engine with cooled EGR) has a gasoline MPGe rating of 40.2 MPGe. 1 kg of H_2 has the equivalent energy of one gallon of gasoline [63]. Hence, a Toyota Corolla with an H2ICE and the hydrogen storage capacity of the Mirai will have an approximate range of 225 miles. The low efficiency of the H2ICE, when compared to a fuel cell, makes it more expensive to operate and limits its range on a full tank, increasing the H_2 infrastructure requirements.

H2ICE is assumed to be based on an SI architecture and is assumed to be equipped with an aftertreatment system consisting of a TWC (for stoichiometric operation) and a combination of SCR and ACR for reducing NOx under lean operating conditions [9].

3.7.1 Hydrogen Storage Tank Size and Cost

For this study, usable H_2 storage capacity for different vehicle types (compact car to Class 3 pickup truck) is taken from a 2022 ANL modeling study [4]. In line with the Toyota Mirai and other production FCEVs, we assume that H_2 fuel is stored in type IV tanks at a maximum pressure of 700 bar in all vehicles (FCEV and hydrogen ICE). Figure 32 gives H_2 storage costs assumed by ANL in their 2022 modeling study [4]. Hydrogen storage cost assumed by ANL falls significantly from 2020 to 2050. In any given year, the storage cost per kg of H_2 also falls significantly with higher storage capacity per vehicle.

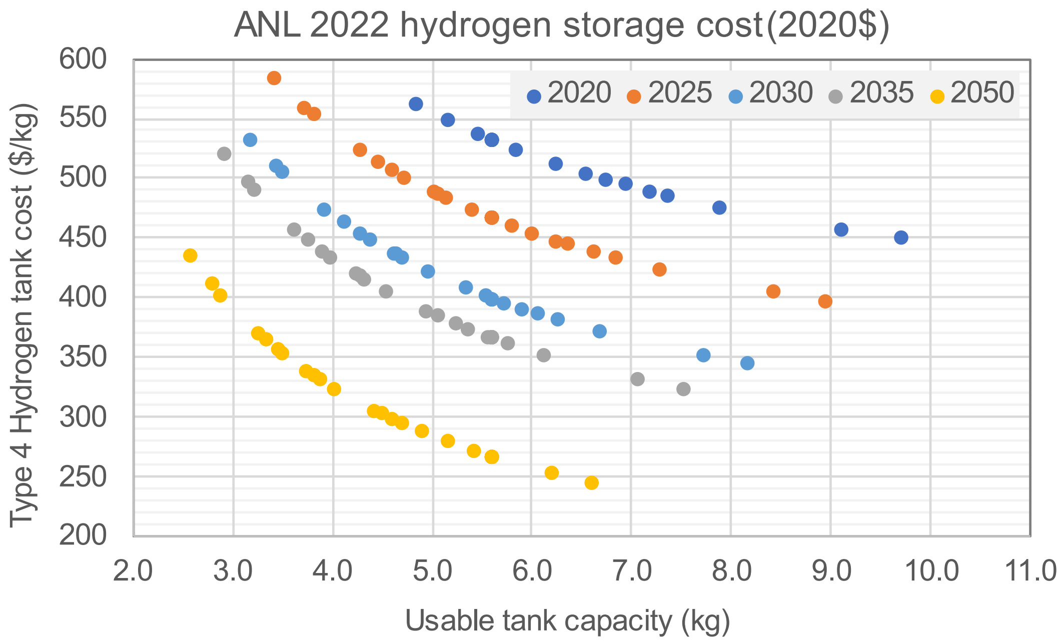

Figure 32: Vehicle on-board hydrogen storage cost, ANL 2022 [4]

Figure 33 shows the 2022 DOE [42] estimate for the cost of storing 60 kgs (usable) of H_2 in frame-mounted 700 bar Type 4 tanks for class 8 long haul trucks for an annual production volume of 100,000 units. The storage capacity required for light-duty and Class 3 vehicles is significantly lower at 6-10 kgs.

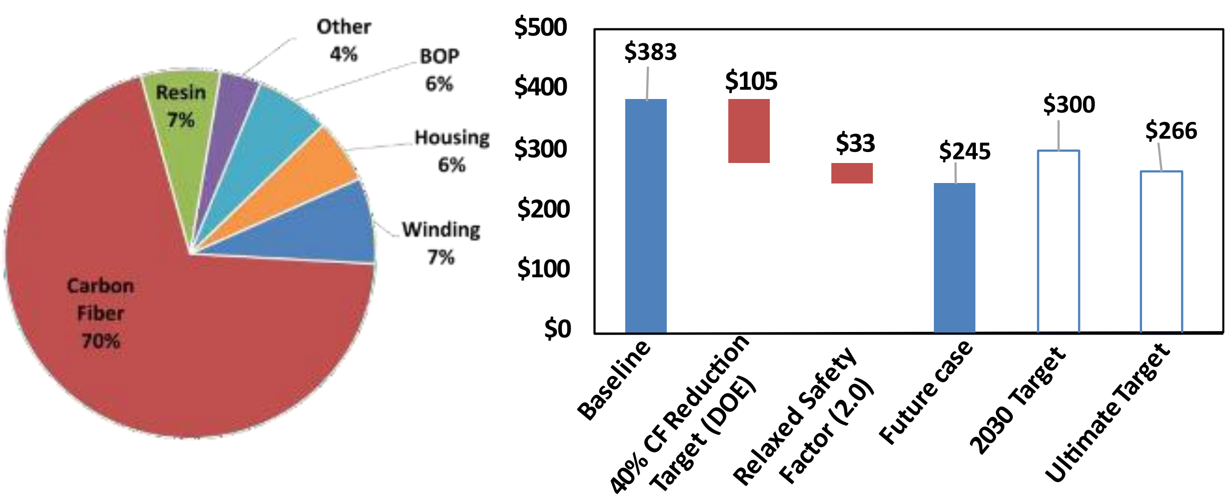

Figure 33: Storage cost of 60 kgs of H_2 in 700 bar Type 4 storage at 100k units. Source: DOE 2022 [42]

Figure 34 compares the H_2 storage costs from various publications. Based on the underlying assumptions, the storage cost per unit mass ($/kg) varies significantly between publications.

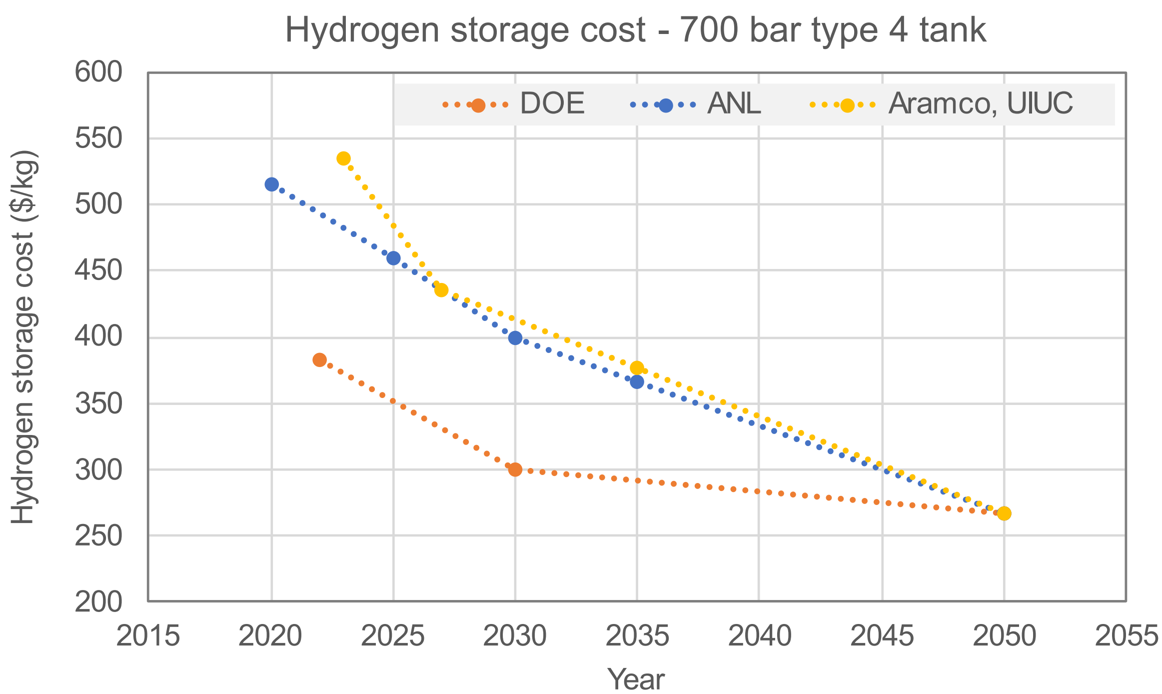

Figure 34: Comparison of hydrogen storage costs from different sources. DOE 2022 [42], **ANL 2022** [4], **Aramco UIUC** [61]

Table 11 lists the H_2 storage costs used in the study.

Table 11: Hydrogen storage cost for FCEVs and H2ICEVs used in this study [64]

Year	$/kg of usable hydrogen, 2020 USD
2022	$383
2027	$300
2035	$266

3.8 Glider Price

Table 12 lists the assumed glider price for LDVs and Class 3 vehicles. The glider price remains constant across the powertrains for each of the vehicle types since this analysis assumed that a conventional ICE platform is being retrofitted with an alternative powertrain to meet the emission standards. The estimated price is purely an assumption and is not reflective of the market offerings.

Table 12: Glider price assumed for light-duty and Class 3 vehicles

Vehicle	Glider Price ($)
LDVs	
Compact Car	$22,500
Medium Car	$27,000
Small SUV	$30,000
Medium SUV	$33,000
Pickup Truck	$39,000
Class 3	
Pickup Truck	$30,000
Delivery Van	$30,000

3.9 Retail Price Equivalent (RPE)

The DMCs do not account for the indirect costs of tools, capital equipment, financing costs, engineering, sales, administrative support, or return on investment. The agencies account for these indirect costs using a scalar markup of DMCs known as the retail price equivalent, or RPE [1]. RPE is the ratio of vehicle retail price to manufacturing cost [56], a scalar markup factor used by OEMs to earn a competitive rate of return on their production investment [57]. The RPE multiplier is applied to direct manufacturing costs to account for the difference between the cost of producing vehicle components and the price that manufacturers typically charge when selling a vehicle. The difference between these two costs is referred to as indirect costs and includes the retail price associated with the indirect costs such as production overhead, corporate overhead, selling costs, dealer costs, and net income before taxes. Our other studies [8], [16] explain in detail the determination of RPE for these powertrains. The following has been assumed in this analysis:

a) An RPE of 1.5 has been assumed for Conventional, Mild Hybrid BISG, SHEVP2, PHEV50, PHEV7kWh, FCEV, and H2ICE for MYs 2024, 2027, and 2035
b) An RPE of 1.5 for BEV200, BEV300, and BEV400 for MY2 2024; and an RPE of 1.2 has been assumed for MYs 2027 and 2035 BEVs. The reasons for lower RPE assumption for BEVs is discussed in detail in our earlier studies [8] [16].

3.10 Impact of Clean Vehicle Credits

On August 16, 2022, the Inflation Reduction Act of 2022 (IRA) was signed into law. It contains multiple provisions regarding the adoption and deployment of clean transportation technology. Many of the provisions in the act provide incentives, tax credits, and funding for various programs designed to electrify the transportation sector. This section analyzes the effect of the clean vehicle credit on light-duty and Class 3 vehicles and attempts to quantify the effects on the powertrain cost of an EV. Our other studies describe in detail the quantitative and qualitative impacts of the IRA of 2022 on the LDVs, class 2b-3 vehicles, and MD/HDVs [8], [65], [66]. This impact analysis does not factor in the geopolitical risks to the battery supply chain and associated rising raw material costs. This study assumes that the long-term raw material supply grows simultaneously with EV demand without any shortages.

The clean vehicle credit (under 26 U.S.C. §30D) of $7,500 is used here to demonstrate the impact of the IRA of 2022 on the powertrain costs of vehicles (and not the purchase price) for MYs 2024 and 2027. Since the credits expire on 31 December 2032, they do not have any effect on MY 2025 costs. This analysis assumes that an ICEV is being retrofitted with an alternative powertrain such as a plug-in hybrid powertrain, a battery electric powertrain, an H2ICE, or a hydrogen fuel cell powertrain, thus, the cost differential is attributable solely to the powertrain and not the glider. Furthermore, since it is difficult to estimate their price, which is a function of production volumes and adoption rates, the best approach would be to apply the clean vehicle credits to the powertrain costs. This would allow a reasonable comparison of these powertrains with the IRA credits.

3.11 Fuel Efficiencies

We used the 2022 ANL simulation study [4] as the basis for vehicle energy consumption since ground-up simulation for estimating vehicle efficiency was outside the scope of this study. For light-duty PHEVs with a 7 kWh battery pack, we assumed the same efficiency (electricity consumption in EV mode – Wh/mile and charge sustaining hybrid mode - mpg) as that of a PHEV with a 50-mile range in the ANL study.

For Class 3 vehicles, ANL does not simulate a PHEV. The only BEV modeled by ANL has a range of 150 miles. The test weight assumed by ANL (Table 13) is almost at the GVWR limit of Class 3 (14,000 lbs). This study assumes that PHEV7kWh, PHEV50, and all BEVs have the same test (or simulation) weight and electric energy consumption in EV mode. We assume that the cargo weight is adjusted so that the test weight is the same. For PHEVs, we assume a charge-depleting (EV mode) electricity consumption equal to BEV150, and charge-sustaining (hybrid mode) fuel consumption (mpg) equal to the SHEVP2.

Table 13: Test weight of Class 3 BEV150 in the ANL study [4]

Production Year	Vehicle	Test weight (lbs.)
2021	Pickup	13,923
2025	Pickup	12,866
2035	Pickup	11,801
2021	Van	14,018
2025	Van	12,959
2035	Van	11,683

Table 14 and Table 15 list the fuel efficiencies of the various powertrain technologies considered in this study. Though these fuel efficiencies are not a direct input to the powertrain cost calculation, they have been listed here as they are one of the key factors of powertrain sizing. A detailed breakup of powertrain costs for each component in each vehicle is given in Appendix 6.1.

Table 14: CS Real world FE (mpg on gas) of light-duty and Class 3 vehicles

Vehicle	Vehicle powertrain	2024	2027	2035
LDVs				
Compact Car	Conventional SI Turbo	39	42	48
	FCEV	72	78	85
	H2ICE	38	40	48
	Mild Hybrid BISG SI Turbo	41	44	51
	Par HEV SI Turbo	48	50	54
	PHEV50 SI Turbo	48	50	54
	PHEV7kWh SI Turbo	48	50	54
Medium Car	Conventional SI Turbo	34	37	43
	FCEV	63	69	75
	H2ICE	33	35	41
	Mild Hybrid BISG SI Turbo	36	39	46
	Par HEV SI Turbo	44	46	51
	PHEV50 SI Turbo	44	46	50
	PHEV7kWh SI Turbo	44	46	50
Small SUV	Conventional SI Turbo	32	34	39
	FCEV	54	59	64
	H2ICE	31	34	40
	Mild Hybrid BISG SI Turbo	34	36	42
	Par HEV SI Turbo	41	43	47
	PHEV50 SI Turbo	40	42	46

Vehicle	Vehicle powertrain	2024	2027	2035
	PHEV7kWh SI Turbo	40	42	46
Medium SUV	Conventional SI Turbo	31	32	37
	FCEV	51	56	61
	H2ICE	30	33	39
	Mild Hybrid BISG SI Turbo	32	34	39
	Par HEV SI Turbo	38	40	43
	PHEV50 SI Turbo	38	39	44
	PHEV7kWh SI Turbo	38	39	44
Pickup Truck	Conventional SI Turbo	26	28	31
	FCEV	42	46	50
	H2ICE	26	29	33
	Mild Hybrid BISG SI Turbo	27	29	33
	Par HEV SI Turbo	33	34	37
	PHEV50 SI Turbo	32	34	37
	PHEV7kWh SI Turbo	32	34	37
Class 3 vehicles				
Delivery Van	Conventional CI	13	15	17
	Mild Hybrid BISG CI	13	15	18
	Par HEV CI	16	20	25
	PHEV50 CI	16	20	25
	PHEV7kWh CI	16	20	25
Pickup Truck	Conventional CI	11	13	14
	Mild Hybrid BISG CI	15	16	18
	Par HEV CI	18	22	27
	PHEV50 CI	18	22	27
	PHEV7kWh CI	18	22	27

Figure 35 and Figure 36 depict the plotted representation of fuel efficiencies of LDVs and Class 3 vehicles, respectively, for MYs 2024, 2027, and 2035. It can be seen that the BEVs have the highest efficiency amongst all powertrains, followed by PHEVs, and the conventional fossil-fuel-powered vehicles have the lowest fuel efficiency as they progress to MY 2035. The fuel efficiencies of FCEVs and H2ICEVs are a function of their H_2 storage capacities, i.e., the higher the capacity to store H_2, the greater their fuel efficiencies. FCEV fuel efficiencies are similar to the real-world values seen in the models of Toyota and Hyundai. We have not assumed an H2ICE powertrain for Class 3 delivery vans.

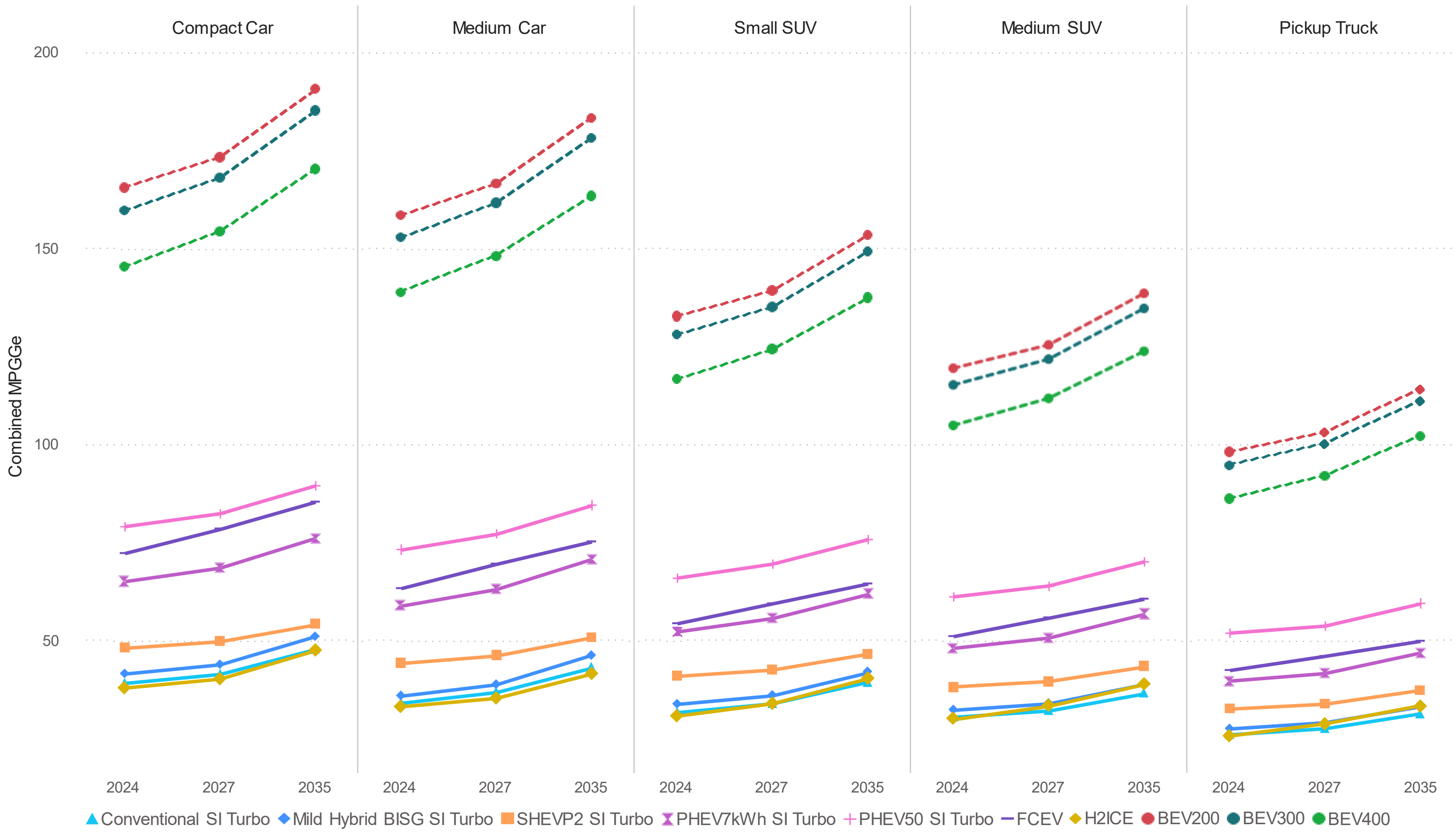

Figure 35: Fuel efficiencies of LDVs

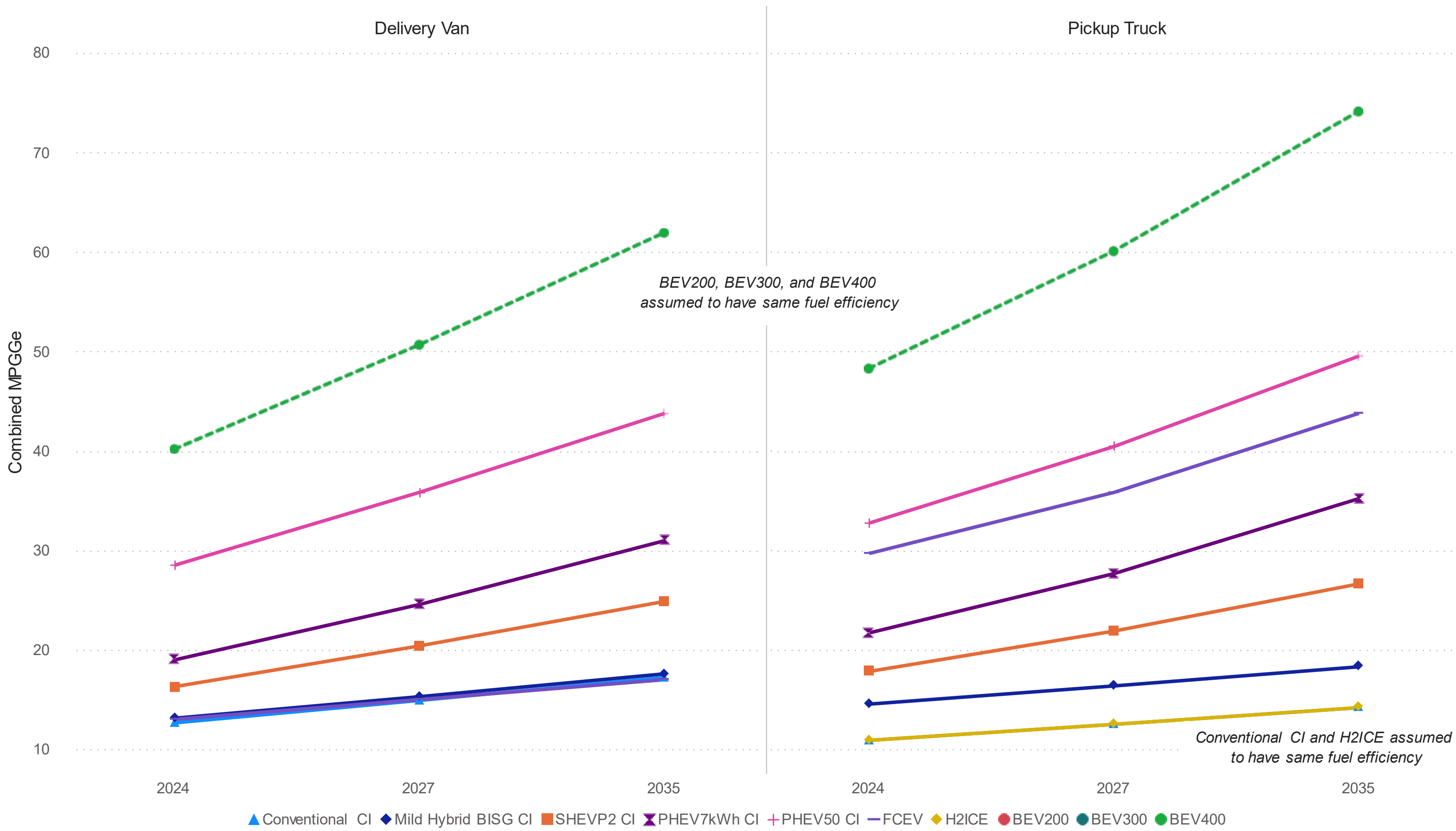

Figure 36: Fuel efficiencies of Class 3 vehicles

ANL study had only simulated a Class 3 BEV150 to estimate the energy consumption [4]. There is no simulation data on PHEVs, BEV200, BEV300, and BEV400. We assumed the same energy consumption for Class 3 vehicles such as PHEVs, BEV200, BEV300, and BEV400 as ANL calculated for the Class 3 BEV150 since estimating the energy consumption of Class 3 pickups and delivery vans without simulating or doing ground-up modeling is challenging. We assumed that the test weight of the vehicle remains the same and the cargo weight reduces from BEV200 to BEV400.

Table 15: Energy consumption (Wh per mile) of light-duty and Class 3 vehicles

Vehicle	Vehicle powertrain	2024	2027	2035
LDVs				
Compact Car	BEV200	204	194	177
	BEV300	211	201	182
	BEV400	232	218	198
	PHEV50 SI Turbo	319	306	281
	PHEV7kWh SI Turbo	319	306	281
Medium Car	BEV200	213	202	184
	BEV300	221	208	189
	BEV400	243	228	206
	PHEV50 SI Turbo	340	324	295
	PHEV7kWh SI Turbo	340	324	295
Small SUV	BEV200	254	242	220
	BEV300	263	250	226
	BEV400	289	271	245
	PHEV50 SI Turbo	382	363	335
	PHEV7kWh SI Turbo	382	363	335
Medium SUV	BEV200	282	269	244
	BEV300	293	277	251
	BEV400	322	302	273
	PHEV50 SI Turbo	420	401	367
	PHEV7kWh SI Turbo	420	401	367
Pickup Truck	BEV200	344	327	295
	BEV300	356	337	303
	BEV400	391	366	330
	PHEV50 SI Turbo	493	483	437
	PHEV7kWh SI Turbo	493	483	437
Class 3 (assumed same as BEV150 as estimated by ANL)				
Delivery Van	BEV 200	838	665	544
	BEV 300	838	665	544

Vehicle	Vehicle powertrain	2024	2027	2035
	BEV 400	838	665	544
	PHEV50 CI	838	665	544
	PHEV7kWh CI	838	665	544
Pickup Truck	BEV 200	698	561	455
	BEV 300	698	561	455
	BEV 400	698	561	455
	PHEV50 CI	698	561	455
	PHEV7kWh CI	698	561	455

Figure 37 and Figure 38 depict the plotted representation of energy consumption of PHEVs and BEVs for LDVs and Class 3 vehicles as listed in the above tables. With the progression in technology, the consequent MYs 2027 and 2035 EVs are expected to have improved energy efficiency, thereby reducing energy consumption

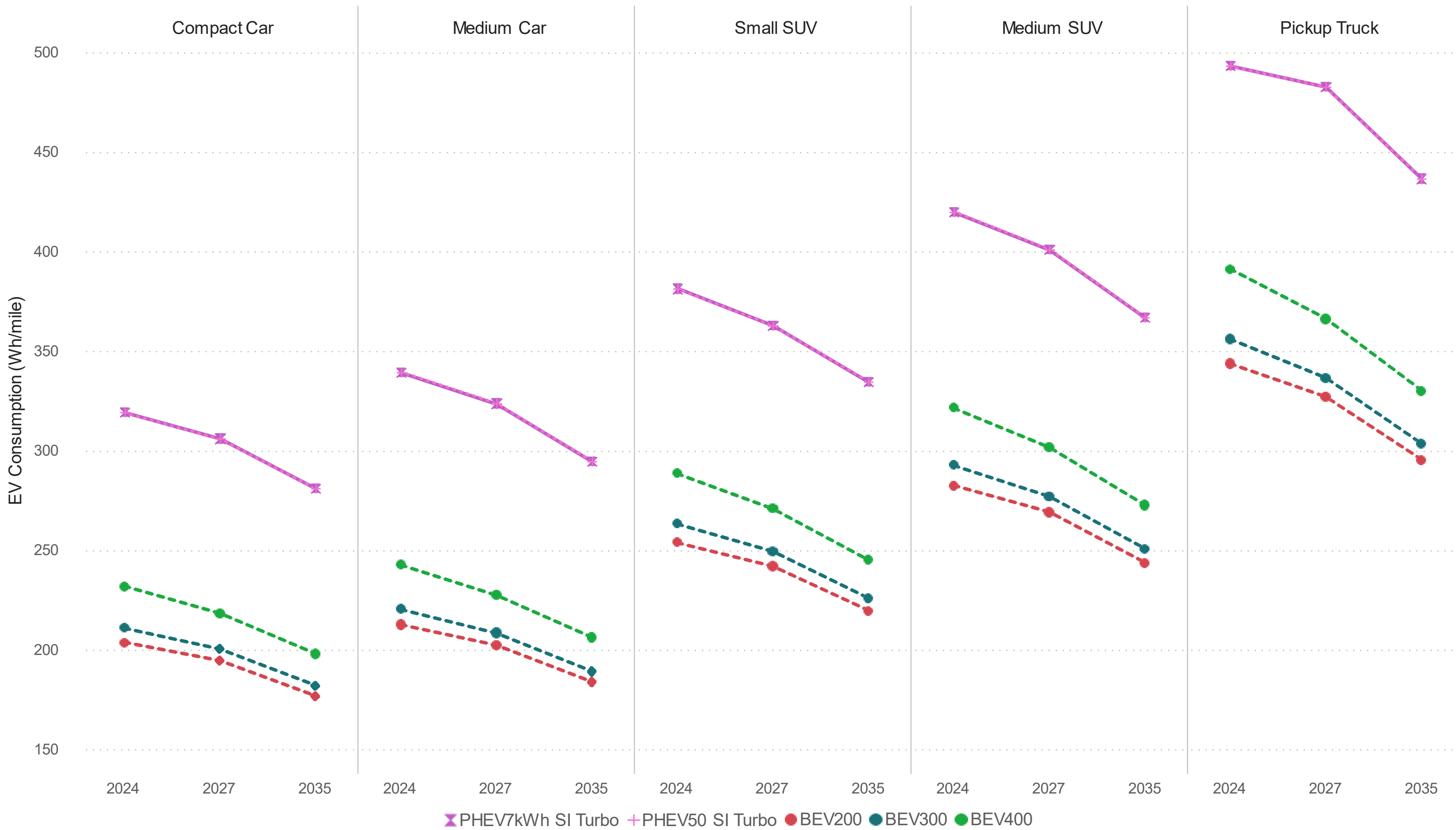

Figure 37: Energy consumption of LDVs

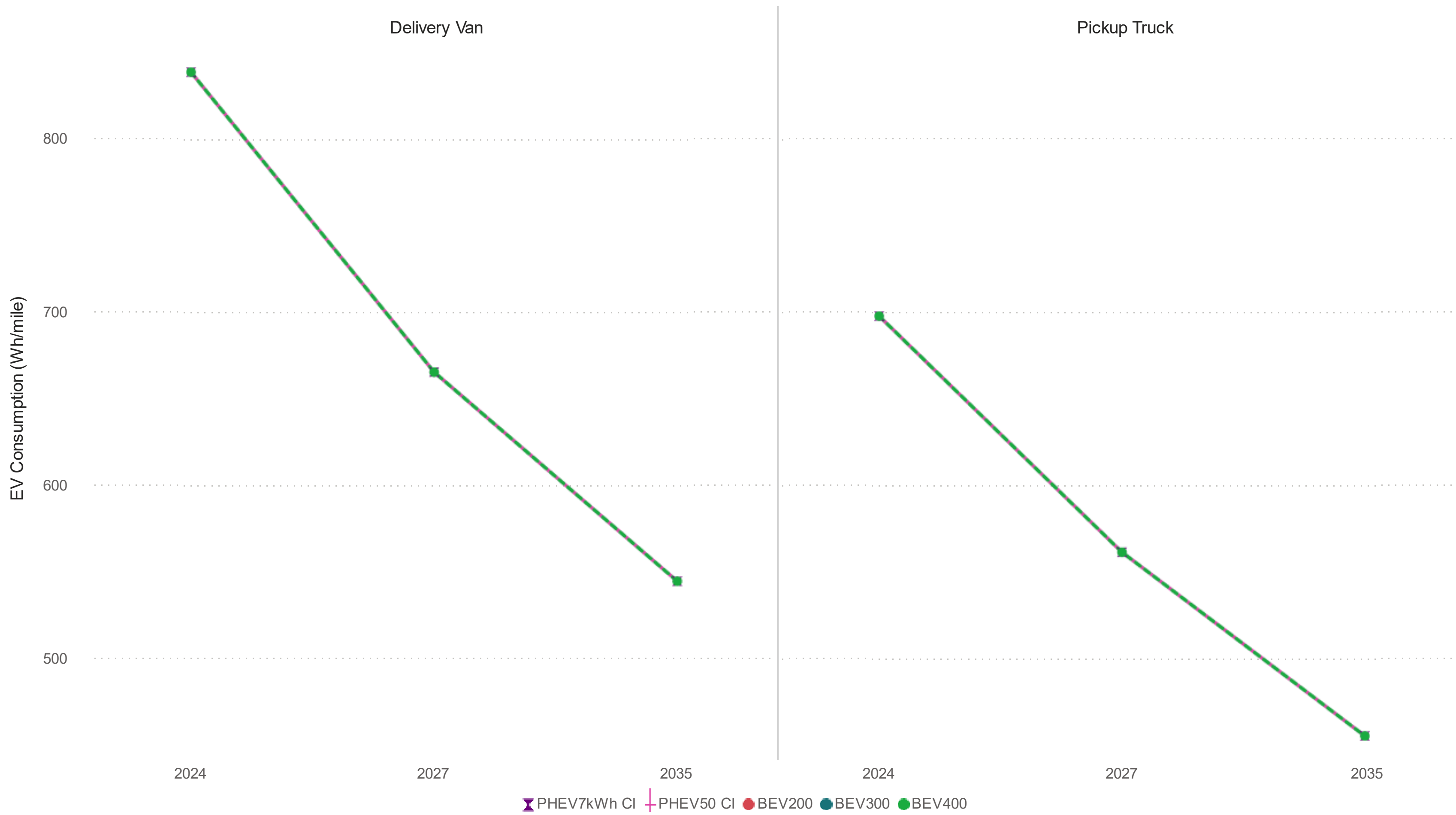

Figure 38: Energy consumption of Class 3 vehicles. The same values have been assumed for all powertrains.

4. Results

4.1 Powertrain Costs

The detailed direct manufacturing cost of different powertrain technologies for light-duty vehicles is shown in Table 18. The fuel economy assumptions of the different powertrains are shown in Table 14.

a) **Conventional ICE vehicles**: There is very little change in the DMC of ICE powertrains from 2023 to 2035. Improvements in the fuel economy of non-electrified ICE powertrains will come from refinements in the combustion systems and improvements in driveline efficiencies. Though these will take time and investments in R&D, they will only result in a small increase in the DMC of the powertrain.
b) **BISGs**: 48-volt mild hybrid systems improve fuel economy by 5-7% for an increase in powertrain cost of 600-800 USD. They enable more of the mechanical accessories (HVAC compressor etc.) to be electrically driven and improve start-stop functionality. Widespread adoption of BISG systems can significantly impact the light-duty fleet fuel economy.
c) **HEVs**: P2 hybrid powertrains assumed in this study provide a significant leap in fuel economy (30%) compared to conventional ICE powertrains for an additional $1,000-1,500 in powertrain costs. This correlates well with market offerings like the Toyota Rav4 hybrid which offers a 30% increase in efficiency (40 vs. 30 MPG) with a $2,700 price premium. The RAV4-hybrid saw close to a 50% take rate [55] in 2022.
d) **PHEVs**: Two types of PHEVs were costed for this study, (i) PHEVs with 7kW of usable battery capacity – These qualify for the full $7,500 tax credit under the IRA if they meet battery manufacture and material sourcing requirements and (ii) PHEVs with a 50-mile real-world range- as required by the “The Advanced Clean Cars II rule” adopted by California

   Table 16 and Table 17 list the energy consumption and fuel economy of MY2024 PHEVs. A compact car (base) with a 7 kWh of battery is estimated to have an electric range of about 22 miles, while a pickup truck with the same battery size has an estimated electric range of 14 miles. As the PHEV’s range increase, the fraction of miles traveled in EV mode increases, as shown by the utilization factor. PHEVs are well suited for applications where the vehicle is occasionally used for driving long distances or towing. In such instances, most of the daily driving can be completed in EV mode (charge-depleting mode), while the hybrid mode provides the necessary range and quick fill-up during long-distance driving or towing.

Table 16: PHEV7 kWh SI Turbo fuel economy for MY 2024 (CD – Charge depleting, CS – Charge sustaining)

Model Year	Vehicle	CD EV (Wh/mile)	EV range (miles)	CS (mpg on gas)	Utilization Factor	Combined MPGe
2024	Compact	319	22	48	0.48	65
2024	Medium Car	340	21	44	0.46	59
2024	Small SUV	382	18	40	0.43	52
2024	Medium SUV	420	17	38	0.40	48
2024	Pickup Truck	493	14	32	0.36	40

Table 17: PHEV 7 kWh SI Turbo fuel economy for MY 2024 (CD – Charge depleting, CS – Charge sustaining)

Model Year	Vehicle	CD EV (Wh/mile)	CD EV range (miles)	CS (mpg on gas)	Utilization Factor	Combined MPGe
2024	Compact	319	50	48	0.72	79
2024	Medium Car	340	50	44	0.72	73
2024	Small SUV	382	50	40	0.72	66
2024	Medium SUV	420	50	38	0.72	61
2024	Pickup Truck	493	50	32	0.72	52

Figure 39 shows the battery size (kWh) and range (miles) of all the light-duty PHEVs on sale in the US in 2022.

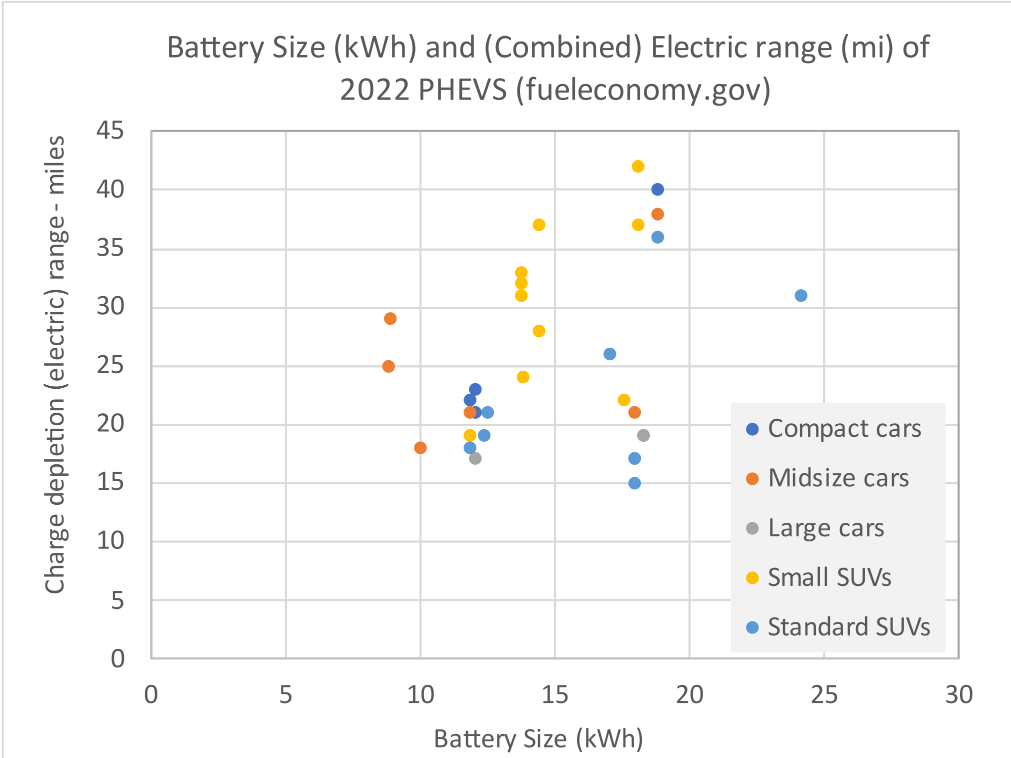

Figure 39: Battery size and all-electric range (sticker/ real world) of PHEVs on sale in the US in 2022.

a) **BEVs** – A BEV200 is cheaper than an ICE vehicle in the compact, midsize, and small SUV segment in MY 2024. BEV300 will reach cost parity with conventional ICE powertrain across all segments by 2027. This timeline for reaching cost parity is in line with the prediction by VW that EVs will reach price parity with ICE counterparts by 2025 [67]. Factoring in our 2035 battery cost projection and the $7,500 IRA tax credit lasting from 2023 to 2033, the cost of an EV powertrain will be lower in 2027 compared to 2035.
b) **FCEVs** – Fuel cells become attractive as the size of the vehicle increases. Large BEVs (medium SUVs, pickup trucks, and Class 3 vehicles) with long-range (BEV 300, BEV 400) need significantly more batteries, resulting in an expensive powertrain. Even with a steep decline in battery prices, for half-ton and Class 3 pickup trucks, BEV 300 powertrain is projected to be more costly than FCEV in 2027 and almost reach price parity by 2035. Meanwhile, for a compact car, a BEV 300 powertrain is at price parity with FCEV in 2022 and significantly cheaper than FCEV in 2027.
c) **H2 ICEVs** – Hydrogen ICE vehicles have energy consumption similar to a conventional diesel-engined powertrain (lower than HEVs and PHEVs and significantly lower than fuel cell HEV). Packaging constraints in a light-duty vehicle limit the tank size. The hydrogen storage capacity of the hydrogen ICE vehicle was assumed to be similar to that of the fuel cell HEV (about 6kgs). The low density of

hydrogen (less fuel energy per unit volume of the fuel tank) and the lower efficiency (compared to fuel cells) result in a limited driving range compared to a fuel cell. This low driving range of a hydrogen ICE will demand a higher density of hydrogen fueling stations than a fleet of fuel cells HEVs. In addition, the high cost of onboard hydrogen storage and aftertreatment system cost (TWC + SCR + ASC) puts the hydrogen ICE powertrain at a cost disadvantage compared to a fuel cell HEV.

Figure 40 and Figure 41 illustrate the powertrain costs of light-duty and Class 3 vehicles, respectively (as listed in Table 18).

Table 18: Projected direct manufacturing costs for light-duty and Class 3 powertrains

Vehicle	Vehicle powertrain	2024	2027	2035
LDVs				
Compact Car	Conventional SI Turbo	$6,825	$6,773	$6,749
	Mild Hybrid BISG SI Turbo	$7,555	$7,316	$7,241
	Par HEV SI Turbo	$7,698	$7,366	$7,252
	PHEV7kWh SI Turbo	$9,287	$8,048	$7,786
	PHEV50 SI Turbo	$10,457	$8,604	$8,126
	FCEV	$10,936	$7,474	$6,320
	H2ICE	$9,541	$8,949	$8,699
	BEV200	$6,217	$3,696	$2,643
	BEV300	$9,008	$5,536	$3,890
	BEV400	$12,563	$7,781	$5,388
Medium Car	Conventional SI Turbo	$6,825	$6,773	$6,749
	Mild Hybrid BISG SI Turbo	$7,555	$7,316	$7,241
	Par HEV SI Turbo	$7,801	$7,464	$7,338
	PHEV7kWh SI Turbo	$9,349	$8,097	$7,829
	PHEV50 SI Turbo	$10,657	$8,729	$8,223
	FCEV	$14,019	$9,450	$7,986
	H2ICE	$9,541	$8,949	$8,699
	BEV200	$6,632	$3,971	$2,867
	BEV300	$9,589	$5,840	$4,127
	BEV400	$13,305	$8,234	$5,734
Small SUV	Conventional SI Turbo	$6,825	$6,773	$6,749
	Mild Hybrid BISG SI Turbo	$7,555	$7,316	$7,241
	Par HEV SI Turbo	$7,969	$7,523	$7,447
	PHEV7kWh SI Turbo	$9,430	$8,155	$7,881
	PHEV50 SI Turbo	$11,053	$8,972	$8,398
	FCEV	$15,861	$10,686	$9,006
	H2ICE	$9,541	$8,949	$8,699

Vehicle	Vehicle powertrain	2024	2027	2035
	BEV200	$7,729	$4,707	$3,382
	BEV300	$11,209	$6,994	$4,926
	BEV400	$15,614	$9,765	$6,776
Medium SUV	Conventional SI Turbo	$7,910	$7,844	$7,812
	Mild Hybrid BISG SI Turbo	$8,641	$8,387	$8,304
	Par HEV SI Turbo	$9,182	$8,699	$8,541
	PHEV7kWh SI Turbo	$10,603	$9,296	$9,003
	PHEV50 SI Turbo	$12,508	$10,280	$9,629
	FCEV	$15,368	$10,316	$8,679
	H2ICE	$11,033	$10,383	$10,104
	BEV200	$8,326	$5,084	$3,625
	BEV300	$12,263	$7,602	$5,322
	BEV400	$17,207	$10,793	$7,446
Pickup Truck	Conventional SI Turbo	$7,747	$7,676	$7,643
	Mild Hybrid BISG SI Turbo	$8,478	$8,220	$8,135
	Par HEV SI Turbo	$9,299	$8,754	$8,561
	PHEV7kWh SI Turbo	$10,636	$9,267	$8,959
	PHEV50 SI Turbo	$13,152	$10,591	$9,820
	FCEV	$18,933	$12,544	$10,531
	H2ICE	$10,695	$10,040	$9,759
	BEV200	$10,003	$6,180	$4,409
	BEV300	$14,765	$9,228	$6,447
	BEV400	$20,820	$13,102	$9,045
Class 3 vehicles				
Delivery Van	Conventional CI	$10,755	$11,411	$11,296
	Mild Hybrid BISG CI	$11,486	$11,955	$11,789
	Par HEV CI	$12,042	$12,368	$12,093
	PHEV7kWh CI	$14,186	$13,401	$12,987
	PHEV50 CI	$18,228	$15,430	$14,109
	FCEV	$19,733	$13,120	$10,884
	H2 ICE	$12,267	$11,014	$10,480
	BEV200	$25,360	$13,758	$9,099
	BEV300	$37,720	$20,687	$13,506
	BEV400	$49,373	$27,137	$17,595
Pickup Truck	Conventional CI	$10,755	$11,411	$11,296
	Mild Hybrid BISG CI	$11,486	$11,955	$11,789
	Par HEV CI	$12,055	$12,365	$12,063
	PHEV7kWh CI	$14,976	$14,031	$13,557
	PHEV50 CI	$18,145	$15,619	$14,399

Vehicle	Vehicle powertrain	2024	2027	2035
	FCEV	$26,723	$18,206	$15,129
	H2 ICE	$11,614	$10,641	$10,205
	BEV200	$20,501	$11,416	$7,803
	BEV300	$29,772	$16,688	$11,164
	BEV400	$38,511	$21,595	$14,282

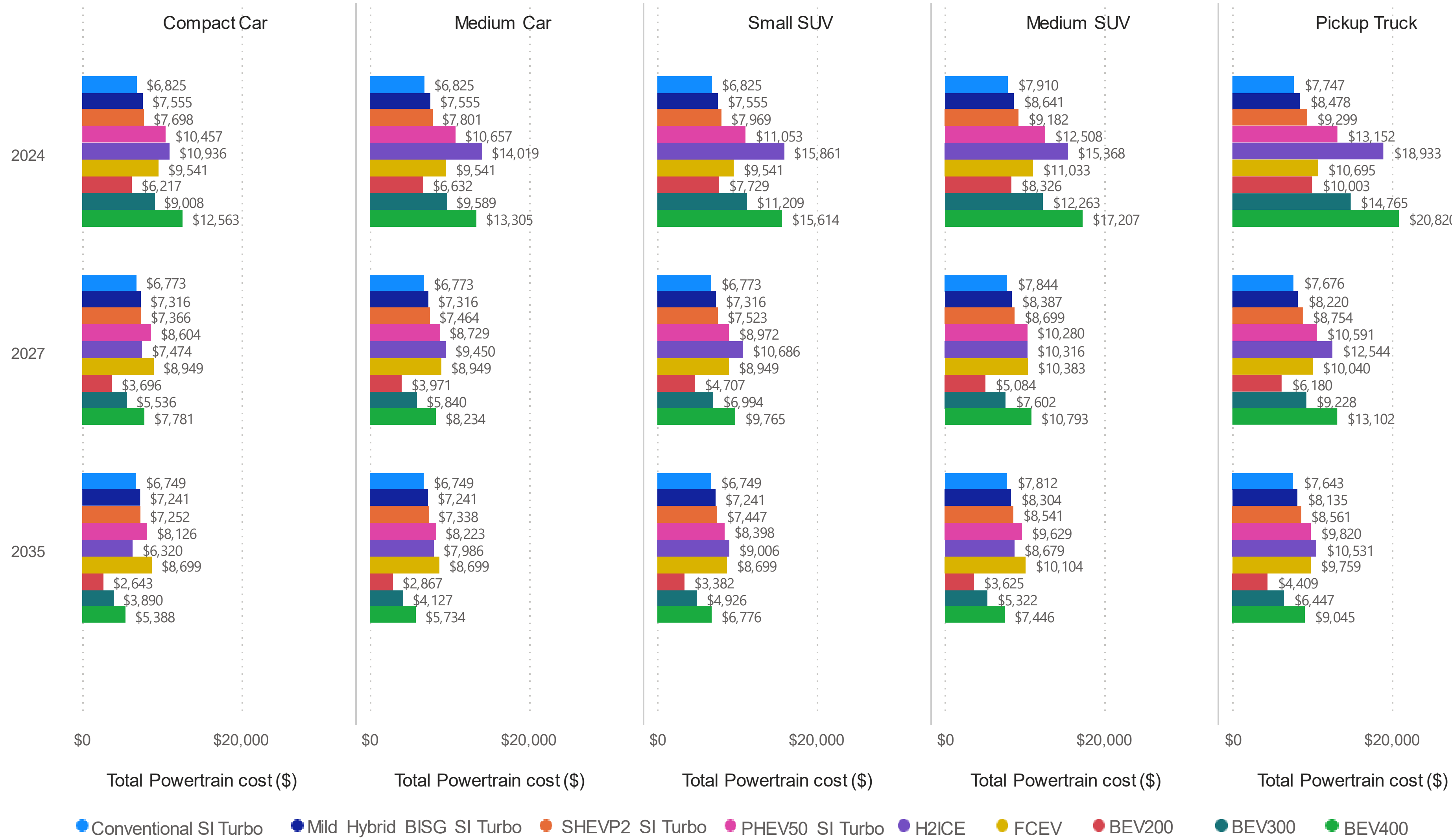

Figure 40: Powertrain costs of LDVs

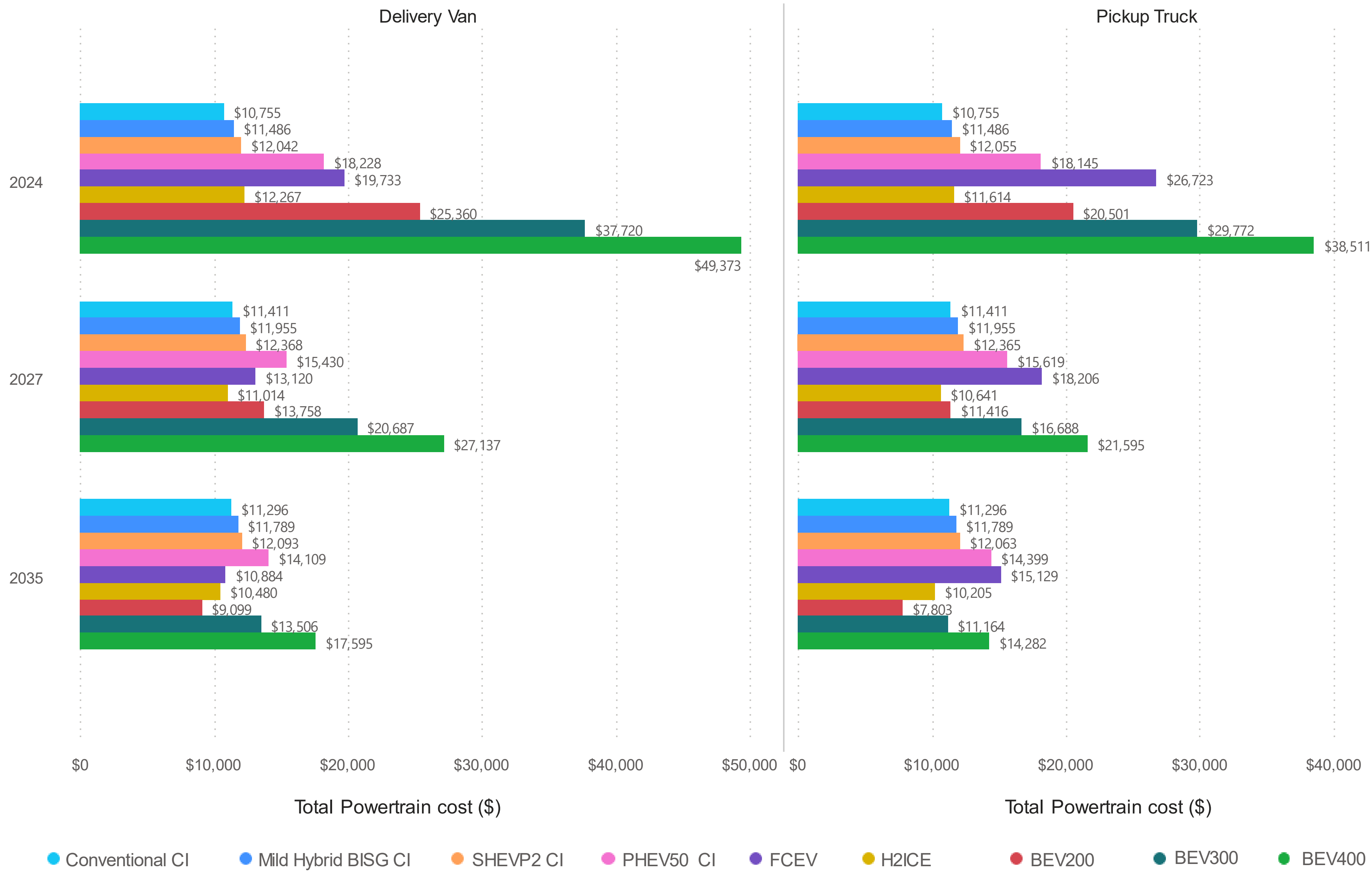

Figure 41: Powertrain costs of Class 3 vehicles

4.2 Purchase Price

The purchase price is calculated by adding the prices of the glider and powertrain. The powertrain price is calculated by multiplying the powertrain cost by the RPE based on MY under consideration. Figure 42 and Figure 43 depict the purchase prices of light-duty and Class 3 vehicles (refer to Table 28 for details).

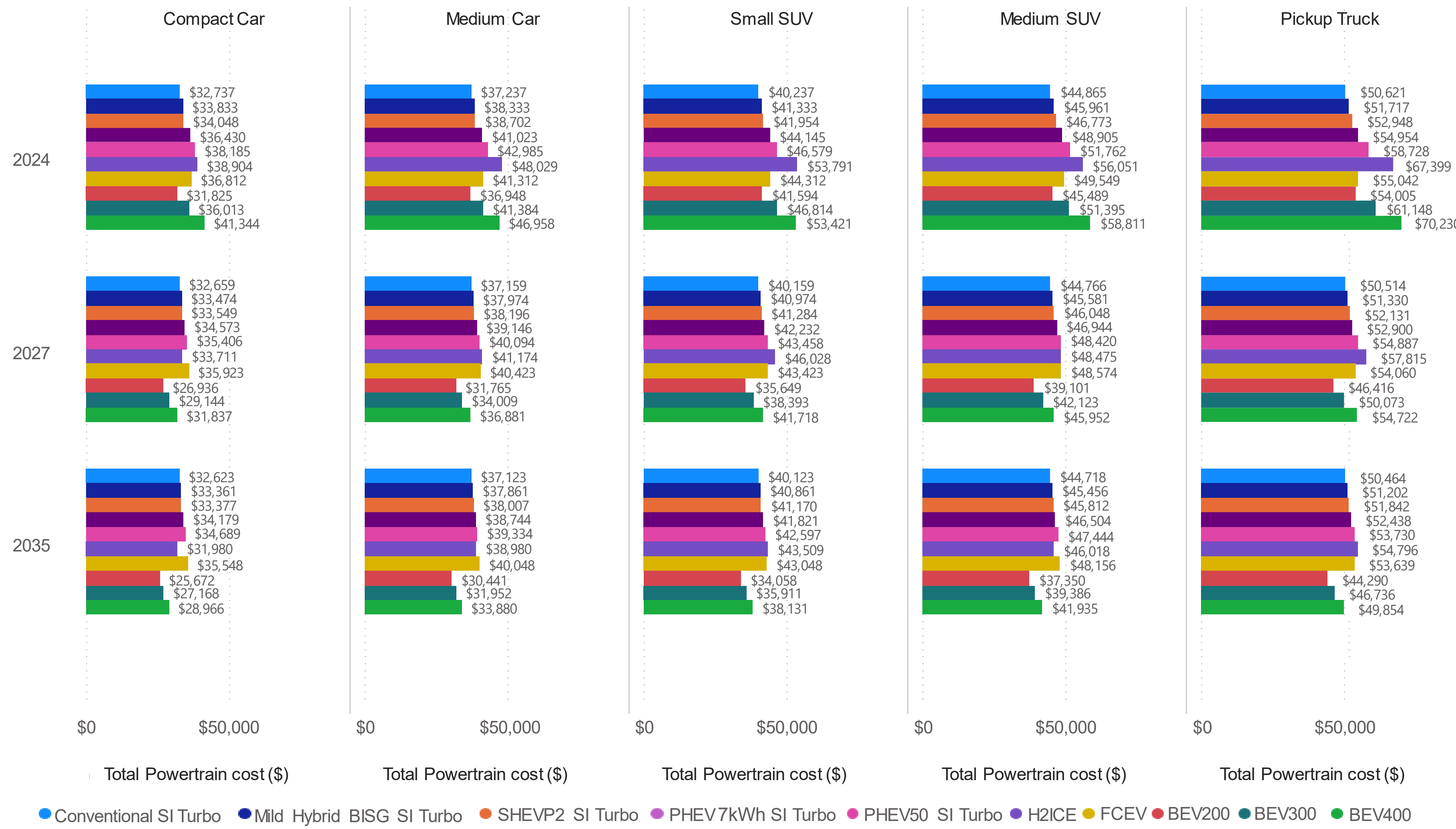

Figure 42: Projected purchase price of LDVs

Figure 43: Projected purchase price of Class 3 vehicles

4.3 Purchase Price with Clean Vehicle Credits

The provisions under the IRA were considered in this study to arrive at the quantitative effect of the IRA on powertrain costs were presented in detail in Section 3.8. Clean vehicle credits of $7,500 have an impact on the powertrain cost of vehicles with the following powertrains:

a) BEVs
b) PHEVs with battery sizes larger than 7kWh
   i) PHEV7kWh
   ii) PHEV50
c) FCEVs

The clean vehicle credits can be seen in MY 2024 and 2027 only as the credits expire on 31 December 2032. Furthermore, there is no effect on H2ICE despite it being a ZEV. Going forward, the exclusion of H2ICE from clean vehicle credit could discourage the automakers from pursuing the H2ICE ZEVs. The impact of IRA is presented as the escalation of powertrain costs that can be offset by the IRA and the powertrains still be the cost presented in this study or lower. As can be seen in Figure 44 and Figure 45, the clean vehicle credits advance the purchase price parity in MYs 2024 and 2027 vehicles. Since the analysis assumes the retrofitting of these powertrains on a conventional ICE platform, the glider price is assumed to be the same across these powertrain configurations. Therefore, the effect of the clean vehicle credit of $7,500 is shown on the powertrain costs.

Figure 44 and Figure 45 illustrate the impact of clean vehicle credits of $7,500 on the purchase price of the considered vehicles. It can be seen that a significant impact is seen in BEVs and FCEVs followed by PHEVs making them an attractive choice for consumers and an option for automakers to explore (refer to Table 29 for details).

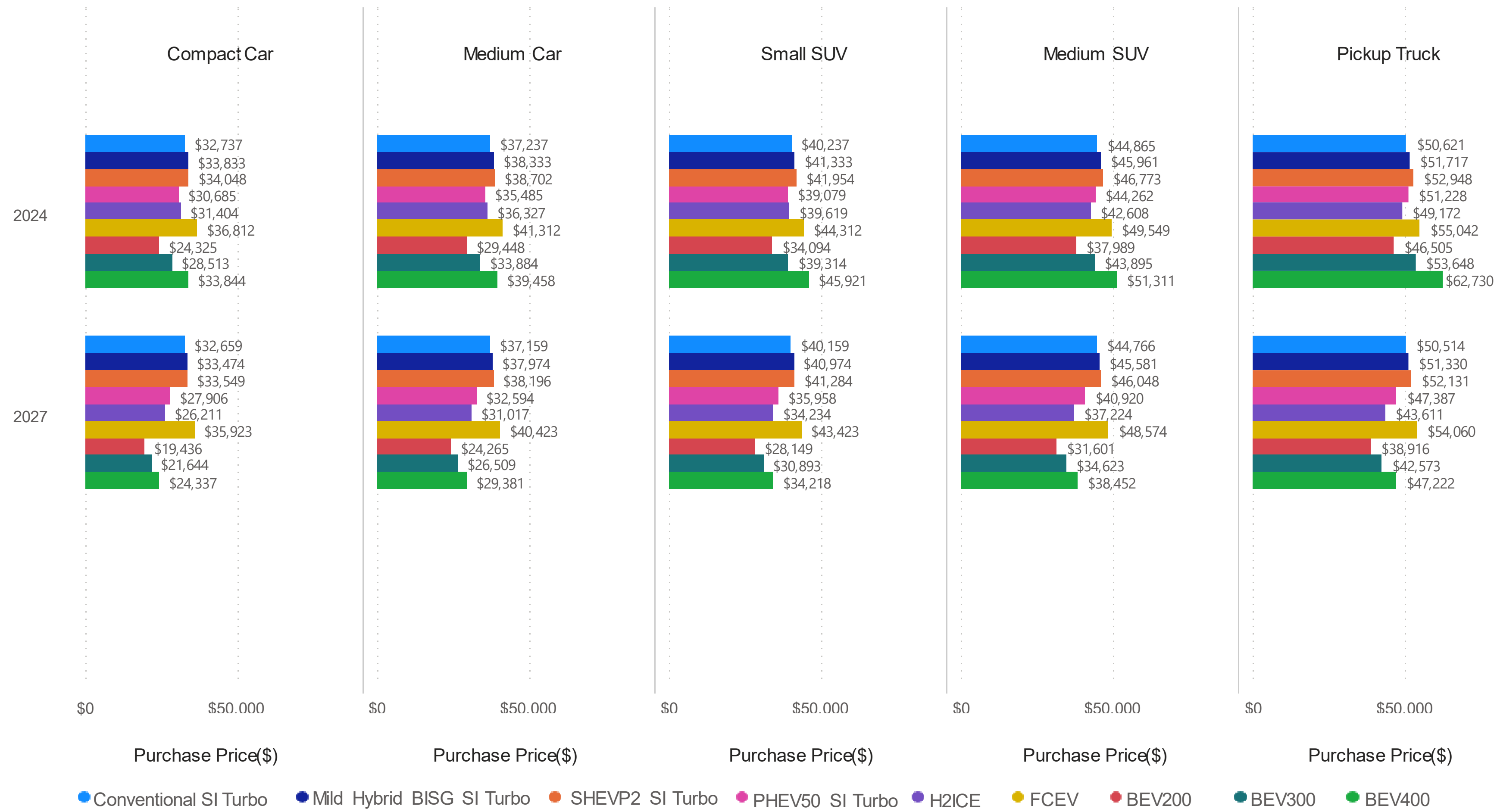

Figure 44: Purchase price of LDVs with Clean Vehicle Credits of $7,500

Figure 45: Powertrain costs of Class 3 vehicles with Clean Vehicle Credits of $7,500

4.4 Tailpipe Carbon Dioxide Emissions

Table 19 and Table 20 give the equivalent fuel economy (gas + electric combined) and the tailpipe carbon dioxide emissions for all vehicles that use gasoline/ diesel as fuel. The CO2 emissions have been calculated from MPG equivalent (gas + electric) using EPA Greenhouse Gases Equivalencies Calculator [68].

Table 19: Tailpipe CO2 emissions of light-duty vehicles (fuel – gasoline)

Vehicle	Vehicle powertrain	MPGe			CO_2 (gram/mile)		
		2024	2027	2035	2024	2027	2035
LDVs (fuel: gasoline)							
Compact Car	Conventional SI Turbo	39	42	48	226	214	186
	Mild Hybrid BISG SI Turbo	41	44	51	215	203	174
	Par HEV SI Turbo	48	50	54	185	179	164
	PHEV50 SI Turbo	79	82	90	112	108	99
	PHEV7kWh SI Turbo	65	69	76	137	130	117
Medium Car	Conventional SI Turbo	34	37	43	261	242	206
	Mild Hybrid BISG SI Turbo	36	39	46	247	229	193
	Par HEV SI Turbo	44	46	51	200	192	175
	PHEV50 SI Turbo	73	77	85	121	115	105
	PHEV7kWh SI Turbo	59	63	71	151	141	126
Small SUV	Conventional SI Turbo	32	34	39	280	262	226
	Mild Hybrid BISG SI Turbo	34	36	42	264	247	212
	Par HEV SI Turbo	41	43	47	217	209	190
	PHEV50 SI Turbo	66	70	76	135	128	117
	PHEV7kWh SI Turbo	52	56	62	170	160	144
Medium SUV	Conventional SI Turbo	31	32	37	291	277	243
	Mild Hybrid BISG SI Turbo	32	34	39	275	262	228
	Par HEV SI Turbo	38	40	43	233	225	205
	PHEV50 SI Turbo	38	39	44	236	225	204
	PHEV7kWh SI Turbo	38	39	44	236	225	204
Pickup Truck	Conventional SI Turbo	26	28	31	341	322	284
	FCEV	42	46	50	210	193	179
	H2ICE	26	29	33	346	309	267
	Mild Hybrid BISG SI Turbo	27	29	33	324	306	268
	Par HEV SI Turbo	33	34	37	273	263	238
	PHEV50 SI Turbo	61	64	70	145	139	127
	PHEV7kWh SI Turbo	48	51	57	185	176	157

Table 20: Tailpipe CO2 emissions of Class 3 vehicles (fuel – diesel)

Vehicle	Vehicle powertrain	MPGe			CO2 (gram/mile)		
		2024	2027	2035	2024	2027	2035
Class 3							
Delivery Van	Conventional CI	13	15	17	802	680	588
	Mild Hybrid BISG CI	13	15	18	769	663	578
	Par HEV SI	16	20	25	625	499	409
	PHEV50 CI	29	36	44	356	284	232
	PHEV7kWh CI	19	25	31	533	413	328
Pickup Truck	Conventional CI	11	13	14	932	810	713
	Mild Hybrid BISG CI	15	16	18	695	618	554
	Par HEV SI	18	22	27	569	464	382
	PHEV50 CI	33	41	50	310	251	205
	PHEV7kWh CI	22	28	35	469	368	289

The tables above do not account for the CO2 equivalent of criteria pollutants (carbon monoxide, nitrogen oxides, particulate matter, sulfur dioxide, etc.) emitted by the vehicle. Also, the CO2 emission in the table ignores any CO2 generated in fuel production. The tables do not show BEVs, H2 ICEs, and FCEVs since their tailpipe emissions are zero.

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6. Appendix

6.1 Detailed Breakup of Powertrain Costs

6.1.1 Small Car

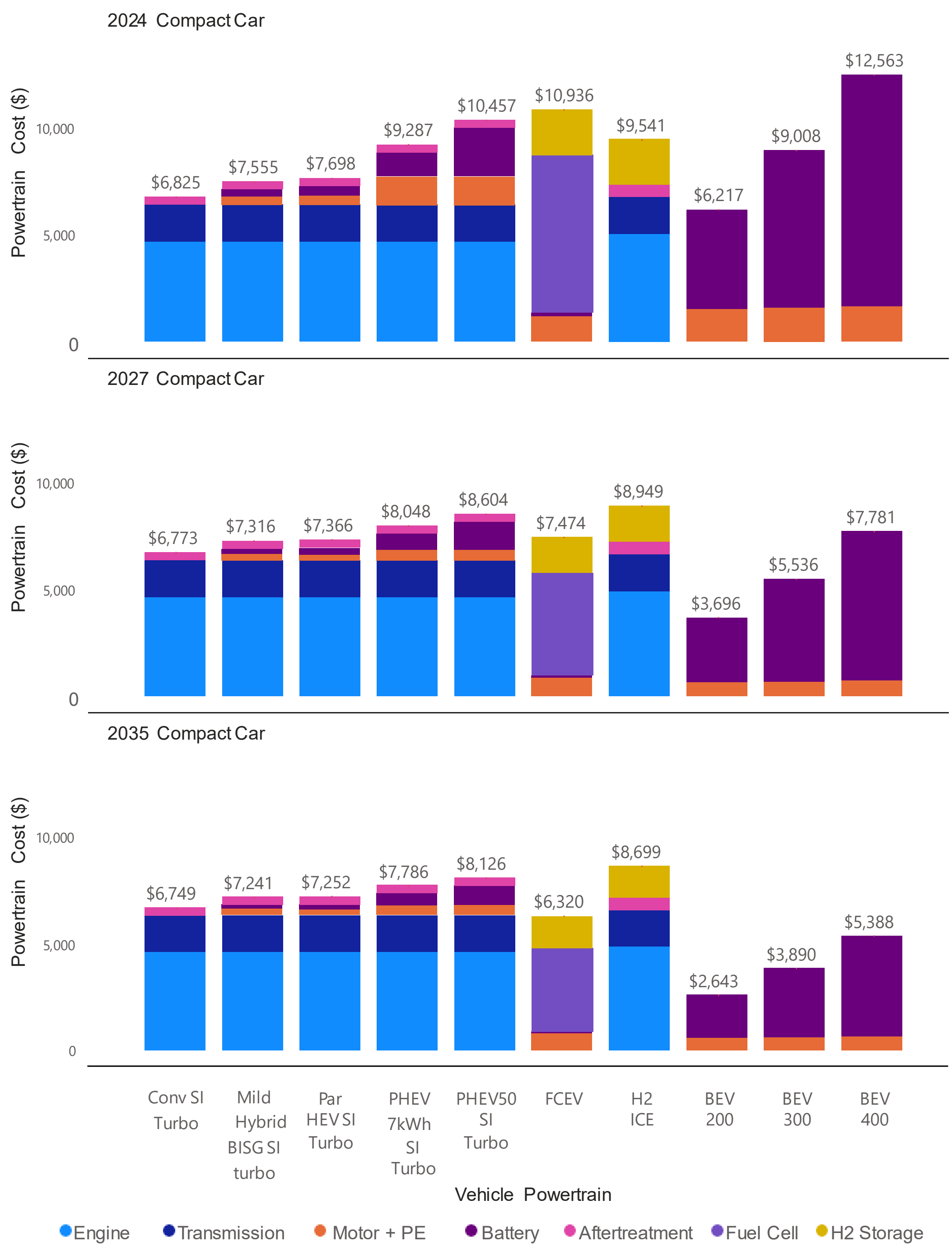

Figure 46: Costs of small car powertrain components

Table 21: Costs of small car powertrain components

Small Car Powertrain	Component	2024	2027	2035
Conventional SI Turbo	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$381	$381	$381
Mild Hybrid BISG SI Turbo	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$342	$216	$197
	Aftertreatment	$381	$381	$381
Par HEV SI Turbo	Motor	$137	$114	$102
	Inverter	$195	$162	$145
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$441	$312	$252
	Aftertreatment	$381	$381	$381
PHEV7kWh SI Turbo	Motor	$345	$286	$243
	Inverter	$300	$193	$182
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$1,117	$764	$577
	Aftertreatment	$381	$381	$381
PHEV50 SI Turbo	Motor	$345	$286	$243
	Inverter	$300	$193	$182
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$2,287	$1,319	$918
	Aftertreatment	$381	$381	$381
FCEV	Motor	$483	$402	$353
	Inverter	$421	$271	$265
	DC-DC Converter	$100	$5	$5
	DC-Boost Converter	$221	$204	$198
	Battery	$157	$96	$73
	Fuel Cell	$7,410	$4,816	$3,936

Small Car Powertrain	Component	2024	2027	2035
	Hydrogen Storage	$2,145	$1,680	$1,490
H2ICE	Engine	$5,065	$4,963	$4,913
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$586	$586	$586
	Hydrogen Storage	$2,145	$1,680	$1,490
BEV200	Inverter	$405	$255	$246
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$4,647	$3,029	$2,034
	Motor	$465	$378	$329
BEV300	Motor	$493	$398	$344
	Inverter	$429	$268	$258
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$7,387	$4,836	$3,254
BEV400	Motor	$531	$425	$364
	Inverter	$462	$286	$273
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$10,869	$7,036	$4,717

6.1.2 Medium Car

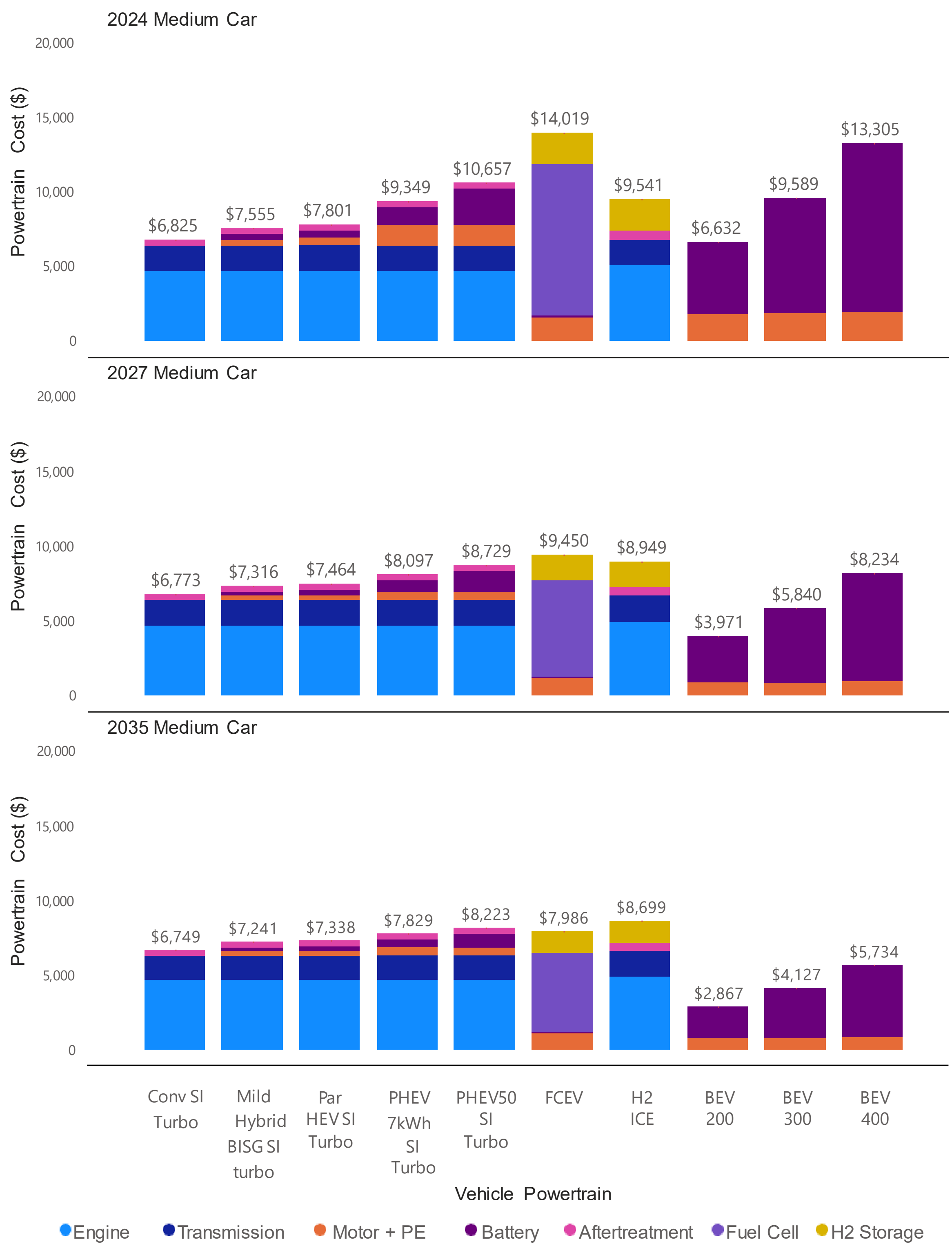

Figure 47: Costs of medium car powertrain components

Table 22: Costs of medium car powertrain components

Medium Car Powertrain	Component	2024	2027	2035
Conventional SI Turbo	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$381	$381	$381
Mild Hybrid BISG SI Turbo	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$342	$216	$197
	Aftertreatment	$381	$381	$381
Par HEV SI Turbo	Motor	$157	$139	$124
	Inverter	$223	$197	$177
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$497	$351	$283
	Aftertreatment	$381	$381	$381
PHEV7kWh SI Turbo	Motor	$378	$315	$268
	Inverter	$329	$212	$201
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$1,117	$764	$577
	Aftertreatment	$381	$381	$381
PHEV50 SI Turbo	Motor	$378	$315	$268
	Inverter	$329	$212	$201
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$2,425	$1,396	$971
	Aftertreatment	$381	$381	$381
FCEV	Motor	$625	$517	$456
	Inverter	$545	$349	$342
	DC-DC Converter	$100	$5	$5
	DC-Boost Converter	$302	$276	$269
	Battery	$172	$107	$81
	Fuel Cell	$10,130	$6,515	$5,345
	Hydrogen Storage	$2,145	$1,680	$1,490
H2ICE	Engine	$5,065	$4,963	$4,913

Medium Car Powertrain	Component	2024	2027	2035
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$586	$586	$586
	Hydrogen Storage	$2,145	$1,680	$1,490
BEV200	Motor	$587	$477	$414
	Inverter	$511	$321	$311
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$4,834	$3,139	$2,108
BEV300	Motor	$621	$499	$432
	Inverter	$541	$337	$324
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$7,727	$4,970	$3,336
BEV400	Motor	$668	$532	$457
	Inverter	$581	$359	$343
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$11,356	$7,309	$4,900

6.1.3 Small SUV

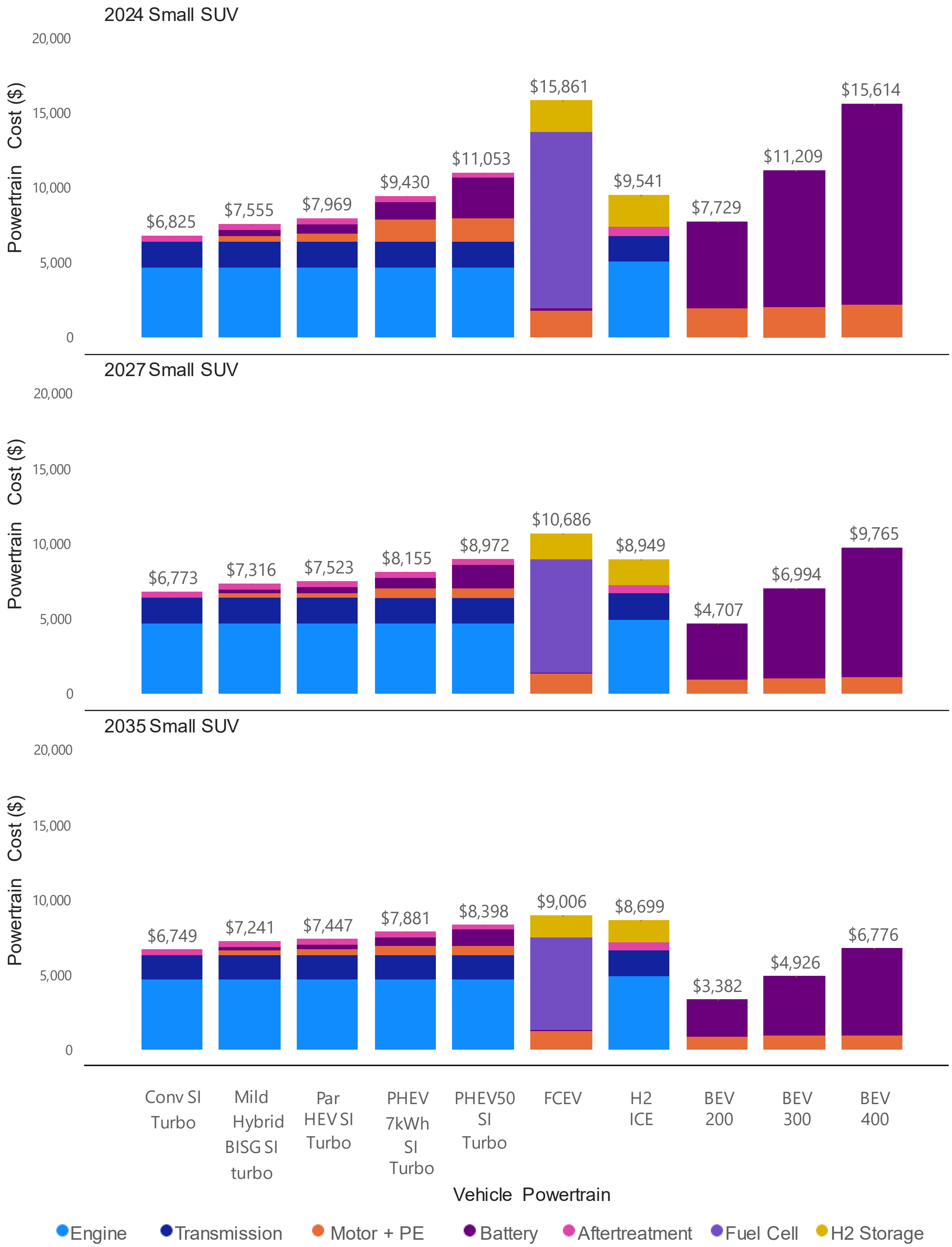

Figure 48: Costs of small SUV powertrain components

Table 23: Costs of small SUV powertrain components

Small SUV Powertrain	Component	2024	2027	2035
Conventional SI Turbo	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$381	$381	$381
Mild Hybrid BISG SI Turbo	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$342	$216	$197
	Aftertreatment	$381	$381	$381
Par HEV SI Turbo	Motor	$181	$147	$143
	Inverter	$257	$208	$204
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$607	$390	$346
	Aftertreatment	$381	$381	$381
PHEV7kWh SI Turbo	Motor	$422	$349	$298
	Inverter	$367	$235	$223
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$1,117	$764	$577
	Aftertreatment	$381	$381	$381
PHEV50 SI Turbo	Motor	$422	$349	$298
	Inverter	$367	$235	$223
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$4,698	$4,671	$4,657
	Transmission	$1,745	$1,720	$1,711
	Battery	$2,739	$1,581	$1,095
	Aftertreatment	$381	$381	$381
FCEV	Motor	$721	$597	$525
	Inverter	$628	$403	$393
	DC-DC Converter	$100	$5	$5
	DC-Boost Converter	$349	$320	$311
	Battery	$188	$118	$89
	Fuel Cell	$11,729	$7,562	$6,193
	Hydrogen Storage	$2,145	$1,680	$1,490
H2ICE	Engine	$5,065	$4,963	$4,913

Small SUV Powertrain	Component	2024	2027	2035
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$586	$586	$586
	Hydrogen Storage	$2,145	$1,680	$1,490
BEV200	Motor	$684	$556	$481
	Inverter	$596	$375	$361
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$5,749	$3,743	$2,506
BEV300	Motor	$733	$590	$508
	Inverter	$639	$398	$381
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$9,137	$5,973	$4,002
BEV400	Motor	$790	$628	$539
	Inverter	$688	$424	$404
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$13,436	$8,679	$5,798

6.1.4 Medium SUV

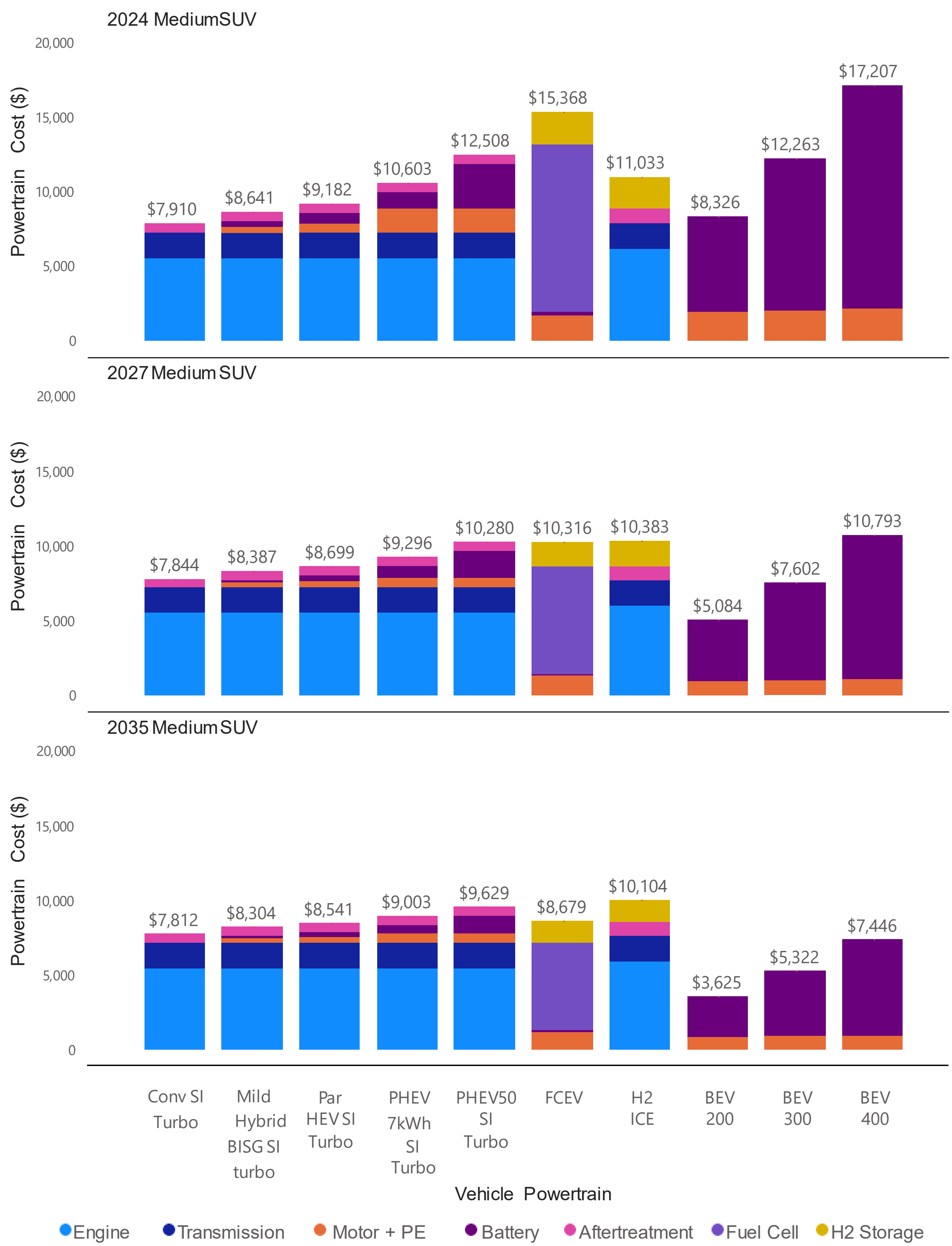

Figure 49: Costs of medium SUV powertrain components

Table 24: Costs of medium SUV powertrain components

Medium SUV Powertrain	Component	2024	2027	2035
Conventional SI Turbo	Engine	$5,555	$5,514	$5,491
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$610	$610	$610
Mild Hybrid BISG SI Turbo	Engine	$5,555	$5,514	$5,491
	Transmission	$1,745	$1,720	$1,711
	Battery	$342	$216	$197
	Aftertreatment	$610	$610	$610
Par HEV SI Turbo	Motor	$210	$174	$156
	Inverter	$299	$247	$222
	DC-DC Converter	$100	$5	$5
	Engine	$5,555	$5,514	$5,491
	Transmission	$1,745	$1,720	$1,711
	Battery	$662	$429	$346
	Aftertreatment	$610	$610	$610
PHEV7kWh SI Turbo	Motor	$468	$391	$331
	Inverter	$408	$264	$248
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$5,555	$5,514	$5,491
	Transmission	$1,745	$1,720	$1,711
	Battery	$1,117	$764	$577
	Aftertreatment	$610	$610	$610
PHEV50 SI Turbo	Motor	$468	$391	$331
	Inverter	$408	$264	$248
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$5,555	$5,514	$5,491
	Transmission	$1,745	$1,720	$1,711
	Battery	$3,021	$1,747	$1,204
	Aftertreatment	$610	$610	$610
FCEV	Motor	$709	$587	$515
	Inverter	$617	$396	$386
	DC-DC Converter	$100	$5	$5
	DC-Boost Converter	$335	$306	$296
	Battery	$204	$129	$97
	Fuel Cell	$11,258	$7,214	$5,889
	Hydrogen Storage	$2,145	$1,680	$1,490
H2ICE	Engine	$6,153	$5,993	$5,914

Medium SUV Powertrain	Component	2024	2027	2035
	Transmission	$1,745	$1,720	$1,711
	Aftertreatment	$990	$990	$990
	Hydrogen Storage	$2,145	$1,680	$1,490
BEV200	Motor	$682	$553	$477
	Inverter	$593	$373	$357
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$6,351	$4,124	$2,757
BEV300	Motor	$724	$582	$503
	Inverter	$630	$393	$377
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$10,209	$6,594	$4,408
BEV400	Motor	$782	$623	$533
	Inverter	$681	$420	$399
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$15,045	$9,715	$6,480

6.1.5 Pickup Truck

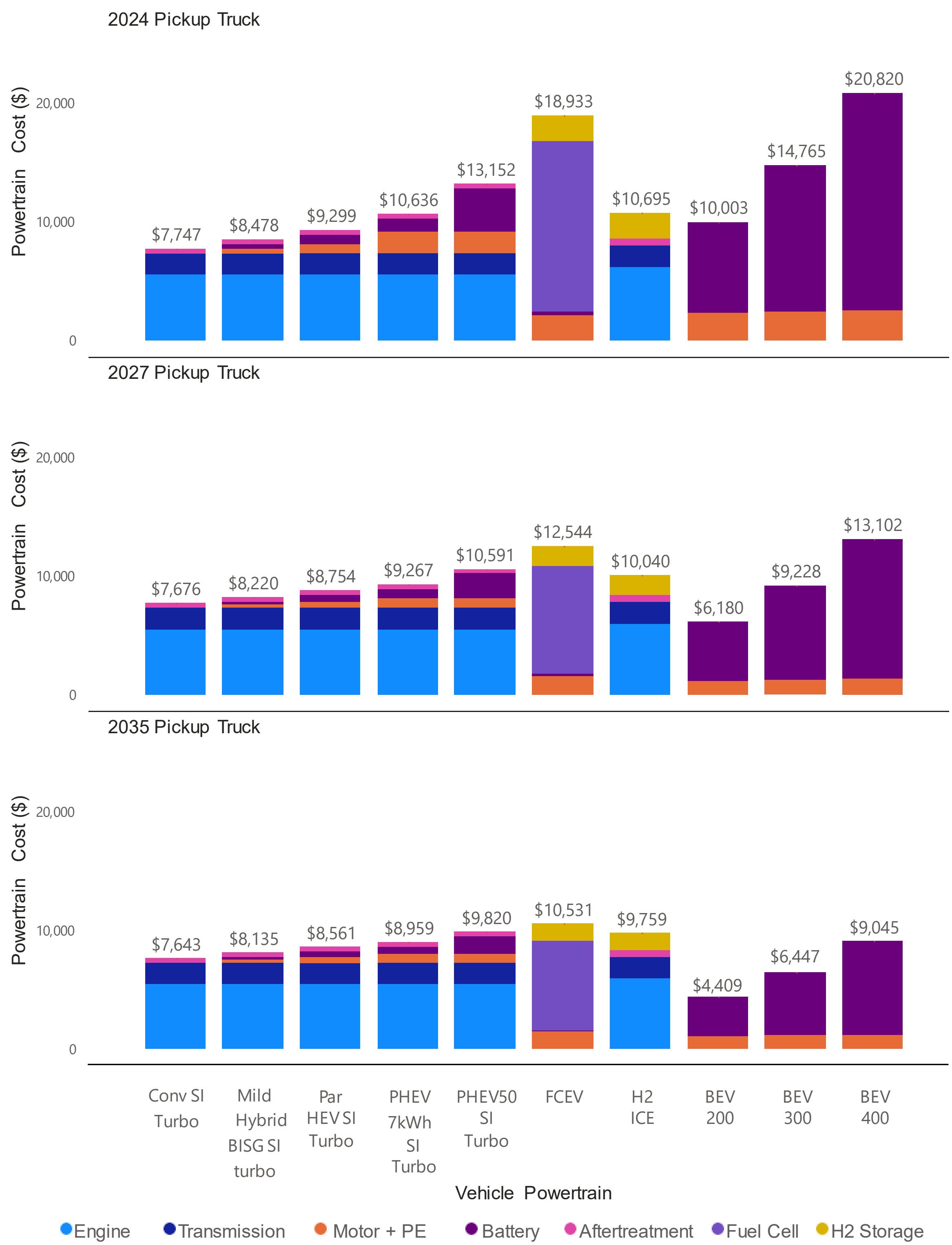

Figure 50: Costs of pickup truck powertrain components

Table 25: Costs of pickup truck powertrain components

Pickup Truck Powertrain	Component	2024	2027	2035
Conventional SI Turbo	Engine	$5,555	$5,514	$5,491
	Transmission	$1,811	$1,781	$1,770
	Aftertreatment	$381	$381	$381
Mild Hybrid BISG SI Turbo	Engine	$5,555	$5,514	$5,491
	Transmission	$1,811	$1,781	$1,770
	Battery	$342	$216	$197
	Aftertreatment	$381	$381	$381
Par HEV SI Turbo	Motor	$258	$217	$195
	Inverter	$366	$309	$278
	DC-DC Converter	$100	$5	$5
	Engine	$5,555	$5,514	$5,491
	Transmission	$1,811	$1,781	$1,770
	Battery	$828	$546	$441
	Aftertreatment	$381	$381	$381
PHEV7kWh SI Turbo	Motor	$573	$473	$403
	Inverter	$499	$319	$302
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$5,555	$5,514	$5,491
	Transmission	$1,811	$1,781	$1,770
	Battery	$1,117	$764	$577
	Aftertreatment	$381	$381	$381
PHEV50 SI Turbo	Motor	$573	$473	$403
	Inverter	$499	$319	$302
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$5,555	$5,514	$5,491
	Transmission	$1,811	$1,781	$1,770
	Battery	$3,633	$2,088	$1,438
	Aftertreatment	$381	$381	$381
FCEV	Motor	$885	$728	$639
	Inverter	$770	$491	$479
	DC-DC Converter	$100	$5	$5
	DC-Boost Converter	$427	$386	$373
	Battery	$251	$150	$114
	Fuel Cell	$14,355	$9,104	$7,432
	Hydrogen Storage	$2,145	$1,680	$1,490
H2ICE	Engine	$6,153	$5,993	$5,914

Pickup Truck Powertrain	Component	2024	2027	2035
	Transmission	$1,811	$1,781	$1,770
	Aftertreatment	$586	$586	$586
	Hydrogen Storage	$2,145	$1,680	$1,490
BEV200	Motor	$856	$690	$599
	Inverter	$745	$465	$449
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$7,702	$4,991	$3,327
BEV300	Motor	$907	$727	$627
	Inverter	$790	$490	$470
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$12,369	$7,976	$5,315
BEV400	Motor	$980	$778	$664
	Inverter	$853	$525	$498
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Battery	$18,286	$11,765	$7,849

6.1.6 Class 3 Delivery Van

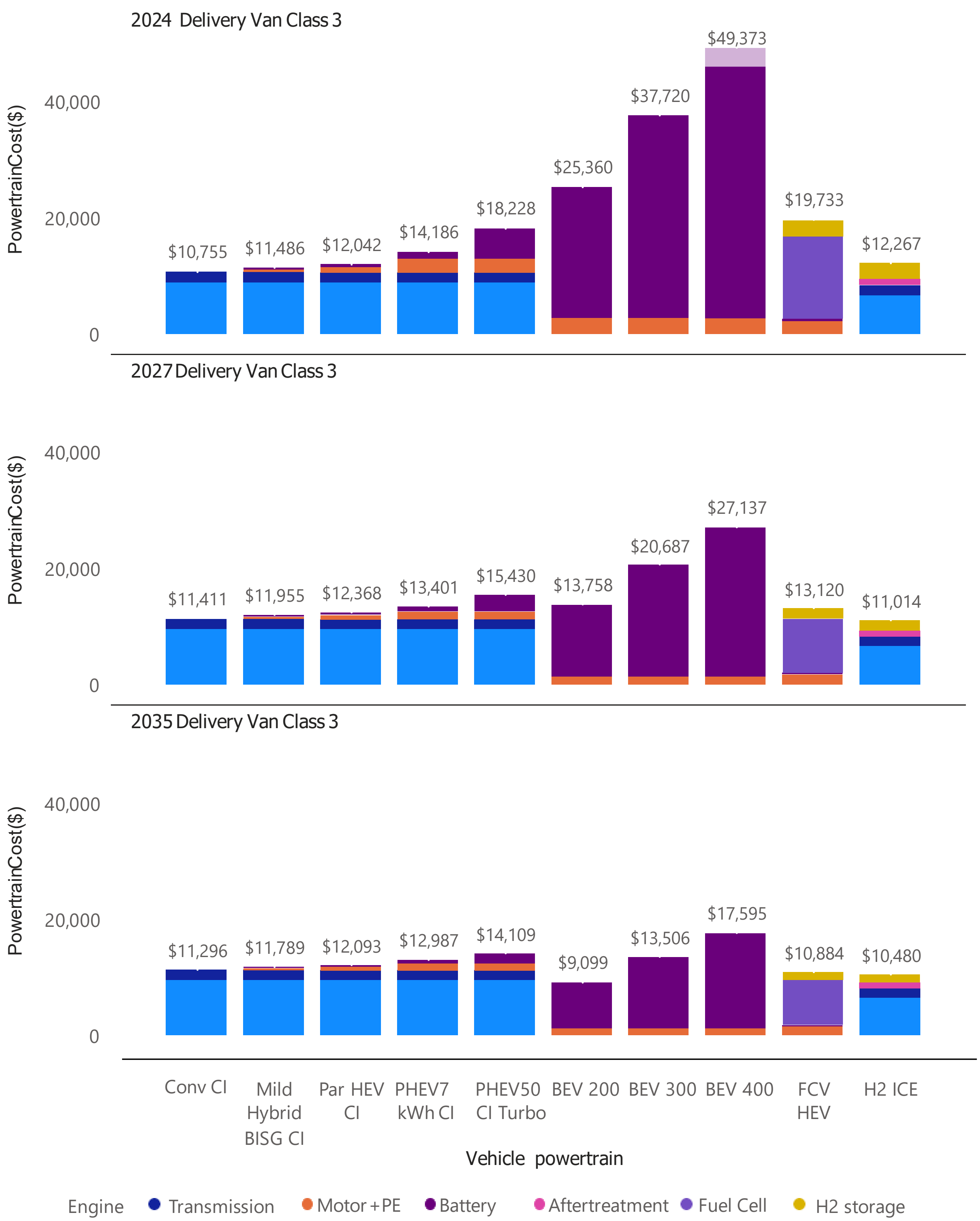

Figure 51: Costs of delivery van powertrain components

Table 26: Costs of delivery van powertrain components

Delivery Van Powertrain	Component	2024	2027	2035
Conventional CI	Engine	$8,944	$9,630	$9,527
	Transmission	$1,811	$1,781	$1,770
Mild Hybrid BISG CI	Engine	$8,944	$9,630	$9,527
	Transmission	$1,811	$1,781	$1,770
	Battery	$342	$216	$197
Par HEV CI	Motor	$341	$305	$264
	Inverter	$485	$433	$375
	DC-DC Converter	$100	$5	$5
	Engine	$8,944	$9,630	$9,527
	Transmission	$1,680	$1,660	$1,652
	Battery	$492	$335	$271
PHEV7kWh CI	Motor	$910	$767	$679
	Inverter	$792	$517	$509
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$8,944	$9,630	$9,527
	Transmission	$1,680	$1,660	$1,652
	Battery	$1,159	$793	$586
PHEV50 CI	Motor	$910	$767	$679
	Inverter	$792	$517	$509
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$8,944	$9,630	$9,527
	Transmission	$1,680	$1,660	$1,652
	Battery	$5,201	$2,822	$1,709
FCEV	Motor	$911	$779	$678
	Inverter	$794	$526	$508
	DC-DC Converter	$100	$5	$5
	DC-Boost Converter	$425	$398	$392
	Battery	$1,192	$900	$695
	Fuel Cell	$14,281	$9,400	$7,797
	Hydrogen Storage	$3,051	$1,948	$1,480
H2ICE	Engine	$6,786	$6,607	$6,519
	Transmission	$1,680	$1,660	$1,652
	Aftertreatment	$990	$990	$990
	Hydrogen Storage	$3,051	$1,948	$1,480
BEV200	Motor	$910	$767	$679
	Inverter	$792	$517	$509

Delivery Van Powertrain	Component	2024	2027	2035
	On-board Charger	$960	$47	$47
	DC-DC Converter	$100	$5	$5
	Battery	$22,598	$12,422	$7,860
BEV300	Motor	$910	$767	$679
	Inverter	$792	$517	$509
	On-board Charger	$960	$47	$47
	DC-DC Converter	$100	$5	$5
	Battery	$34,959	$19,351	$12,267
BEV400	Motor	$910	$767	$679
	Inverter	$792	$517	$509
	On-board Charger	$960	$47	$47
	DC-DC Converter	$100	$5	$5
	Battery	$46,611	$25,801	$16,356

6.1.7 Class 3 Pickup Truck

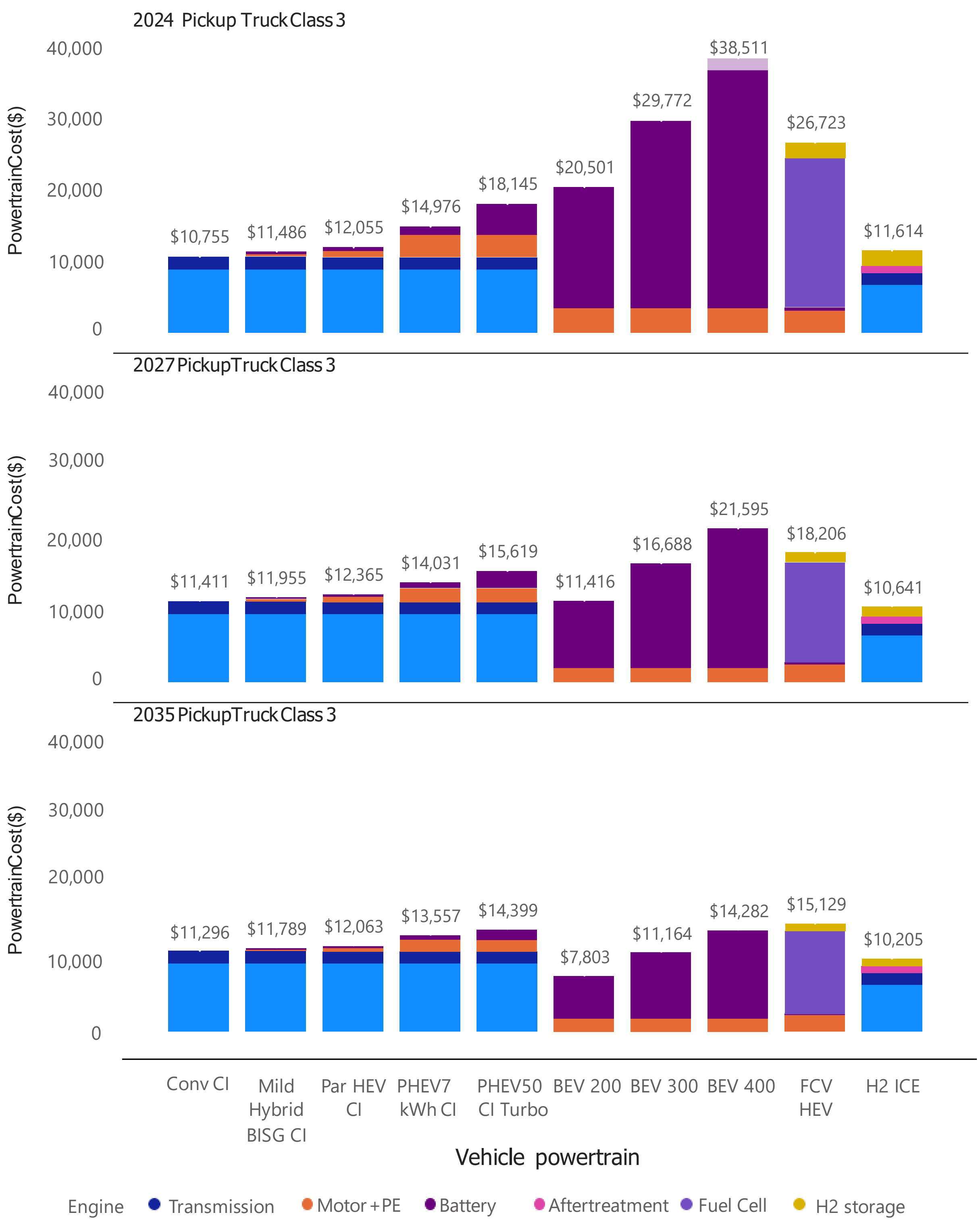

Figure 52: Costs of Class 3 pickup truck powertrain components

Table 27: Costs of Class 3 pickup truck powertrain components

Pickup Truck Powertrain	Component	2024	2027	2035
Conventional CI	Engine	$8,944	$9,630	$9,527
	Transmission	$1,811	$1,781	$1,770
Mild Hybrid BISG CI	Engine	$8,944	$9,630	$9,527
	Transmission	$1,811	$1,781	$1,770
	Battery	$342	$216	$197
Par HEV CI	Motor	$339	$304	$264
	Inverter	$483	$432	$376
	DC-DC Converter	$100	$5	$5
	Engine	$8,944	$9,630	$9,527
	Transmission	$1,680	$1,660	$1,652
	Battery	$509	$335	$239
PHEV7kWh CI	Motor	$1,332	$1,143	$1,005
	Inverter	$1,160	$771	$753
	DC-DC Converter	$100	$5	$5
	Engine	$8,944	$9,630	$9,527
	Transmission	$1,680	$1,660	$1,652
	Battery	$1,159	$793	$586
PHEV50 CI	Motor	$1,332	$1,143	$1,005
	Inverter	$1,160	$771	$753
	On-board Charger	$600	$29	$29
	DC-DC Converter	$100	$5	$5
	Engine	$8,944	$9,630	$9,527
	Transmission	$1,680	$1,660	$1,652
	Battery	$4,327	$2,380	$1,428
FCEV	Motor	$1,332	$1,143	$1,005
	Inverter	$1,160	$771	$753
	DC-DC Converter	$100	$5	$5
	DC-Boost Converter	$623	$594	$580
	Battery	$434	$300	$203
	Fuel Cell	$20,916	$14,010	$11,540
	Hydrogen Storage	$2,157	$1,384	$1,044
H2ICE	Engine	$6,786	$6,607	$6,519
	Transmission	$1,680	$1,660	$1,652
	Aftertreatment	$990	$990	$990
	Hydrogen Storage	$2,157	$1,384	$1,044
BEV200	Motor	$1,332	$1,143	$1,005
	Inverter	$1,160	$771	$753
	On-board Charger	$960	$47	$47

Pickup Truck Powertrain	Component	2024	2027	2035
	DC-DC Converter	$100	$5	$5
	Battery	$16,948	$9,450	$5,994
BEV300	Motor	$1,332	$1,143	$1,005
	Inverter	$1,160	$771	$753
	On-board Charger	$960	$47	$47
	DC-DC Converter	$100	$5	$5
	Battery	$26,219	$14,722	$9,354
BEV400	Motor	$1,332	$1,143	$1,005
	Inverter	$1,160	$771	$753
	On-board Charger	$960	$47	$47
	DC-DC Converter	$100	$5	$5
	Battery	$34,959	$19,629	$12,472

6.2 PHEV Electricity and Fuel Consumption

The ANL study [4] provides gasoline (CS MPGgas) and electricity consumption (CD Wh/mile) for a PHEV with an SI turbo engine and 50 miles of EV range (PHEV 50 SI Turbo). The following assumptions are made for the energy consumption of the following PHEVs

1. PHEV 50 SI (PHEV with a 50-mile EV range and NA SI engine)

$$(MPG_{elec})_{PHEV50\ SI} = (MPG_{elec})_{PHEV50\ SI\ Turbo}$$

$$(MPG_{gas})_{PHEV50\ SI} = (MPG_{gas})_{PHEV50\ SI\ Turbo} \times \left(\frac{(MPG)_{HEV\ SI}}{(MPG)_{HEV\ SI\ Turbo}}\right)$$

2. PHEV 7kW SI (PHEV with a 7kWh battery pack and NA SI engine)

$$(MPG_{elec})_{PHEV\ 7kWh\ SI} = (MPG_{elec})_{PHEV50\ SI}$$

$$(MPG_{gas})_{PHEV\ 7kWh\ SI} = (MPG_{gas})_{PHEV50\ SI}$$

3. PHEV 7kW SI Turbo (PHEV with a 7kWh battery pack and Turbo SI engine)

$$(MPG_{elec})_{PHEV\ 7kWh\ SI\ Turbo} = (MPG_{elec})_{PHEV50\ SI\ Turbo}$$

$$(MPG_{gas})_{PHEV\ 7kWh\ SI\ Turbo} = (MPG_{gas})_{PHEV50\ SI\ Turbo}$$

The composite fuel economy of the PHEV (MPGe) is a function of its fuel economy in charge depletion (CD) or pure electric mode (MPGelec – a function of the efficiency Wh/mile) and its fuel economy in the charge sustaining (CS) mode (MPGgas). As the pure electric range of vehicles increases, the weightage of MPGelec increases. The utility factor (UF), a function of the electric range of a PHEV describes this weightage. Figure 53 shows how the utility factor increases with an increase in the electric range. The composite fuel economy MPGe is calculated using the formula below

$$MPG_e = \frac{1}{\left(\frac{UF}{MPG_{elec}} + \frac{(1 - UF)}{MPG_{gas}}\right)}$$

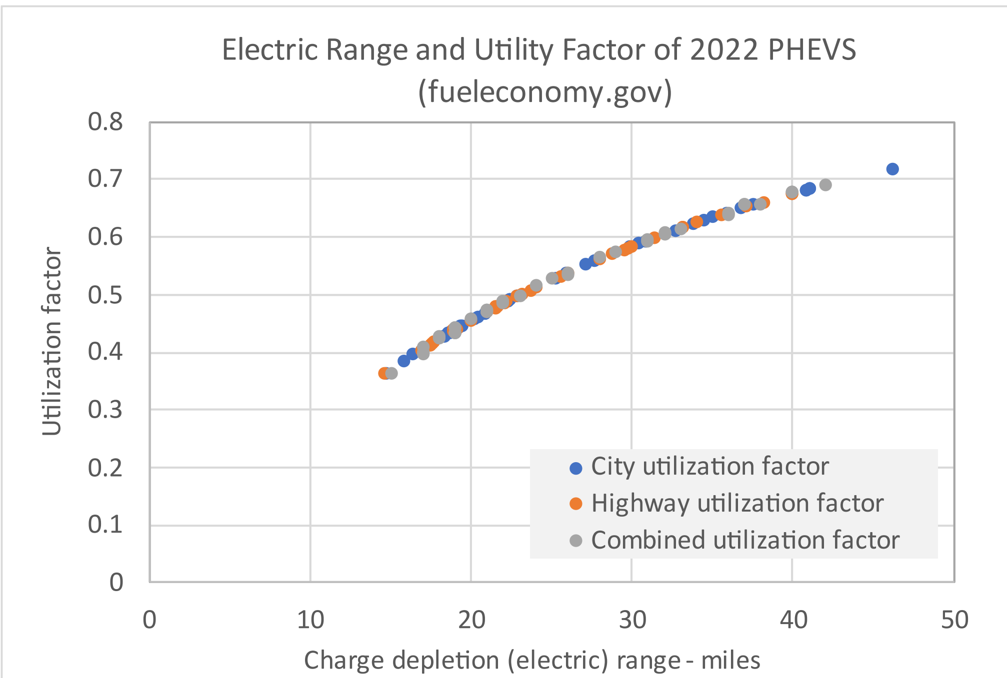

Figure 53: Variation of utility factor (UF) with the pure EV range of a PHEV [69]

6.3 Purchase Price

Table 28: Projected purchase prices of light-duty and Class 3 vehicles

Vehicle	Vehicle powertrain	2024	2027	2035
LDVs				
Compact Car	Conventional SI Turbo	$32,737	$32,659	$32,623
	Mild Hybrid BISG SI Turbo	$33,833	$33,474	$33,361
	SHEVP2 SI Turbo	$34,048	$33,549	$33,377
	PHEV7kWh SI Turbo	$36,430	$34,573	$34,179
	PHEV50 SI Turbo	$38,185	$35,406	$34,689
	FCEV	$38,904	$33,711	$31,980
	H2ICE	$36,812	$35,923	$35,548
	BEV200	$31,825	$26,936	$25,672
	BEV300	$36,013	$29,144	$27,168
	BEV400	$41,344	$31,837	$28,966
Medium Car	Conventional SI Turbo	$37,237	$37,159	$37,123
	Mild Hybrid BISG SI Turbo	$38,333	$37,974	$37,861
	SHEVP2 SI Turbo	$38,702	$38,196	$38,007
	PHEV7kWh SI Turbo	$41,023	$39,146	$38,744
	PHEV50 SI Turbo	$42,985	$40,094	$39,334
	FCEV	$48,029	$41,174	$38,980
	H2ICE	$41,312	$40,423	$40,048
	BEV200	$36,948	$31,765	$30,441
	BEV300	$41,384	$34,009	$31,952
	BEV400	$46,958	$36,881	$33,880
Small SUV	Conventional SI Turbo	$40,237	$40,159	$40,123
	Mild Hybrid BISG SI Turbo	$41,333	$40,974	$40,861
	SHEVP2 SI Turbo	$41,954	$41,284	$41,170
	PHEV7kWh SI Turbo	$44,145	$42,232	$41,821
	PHEV50 SI Turbo	$46,579	$43,458	$42,597
	FCEV	$53,791	$46,028	$43,509
	H2ICE	$44,312	$43,423	$43,048
	BEV200	$41,594	$35,649	$34,058
	BEV300	$46,814	$38,393	$35,911
	BEV400	$53,421	$41,718	$38,131
Medium SUV	Conventional SI Turbo	$44,865	$44,766	$44,718
	Mild Hybrid BISG SI Turbo	$45,961	$45,581	$45,456
	SHEVP2 SI Turbo	$46,773	$46,048	$45,812
	PHEV7kWh SI Turbo	$48,905	$46,944	$46,504
	PHEV50 SI Turbo	$51,762	$48,420	$47,444

Vehicle	Vehicle powertrain	2024	2027	2035
	$56,051	$48,475	$46,018	$56,051
	H2ICE	$49,549	$48,574	$48,156
	BEV200	$45,489	$39,101	$37,350
	BEV300	$51,395	$42,123	$39,386
	BEV400	$58,811	$45,952	$41,935
Pickup Truck	Conventional SI Turbo	$50,621	$50,514	$50,464
	Mild Hybrid BISG SI Turbo	$51,717	$51,330	$51,202
	SHEVP2 SI Turbo	$52,948	$52,131	$51,842
	PHEV7kWh SI Turbo	$54,954	$52,900	$52,438
	PHEV50 SI Turbo	$58,728	$54,887	$53,730
	FCEV	$67,399	$57,815	$54,796
	H2ICE	$55,042	$54,060	$53,639
	BEV200	$54,005	$46,416	$44,290
	BEV300	$61,148	$50,073	$46,736
	BEV400	$70,230	$54,722	$49,854
Class 3 vehicles				
Delivery Van	Conventional CI	$46,133	$47,117	$46,945
	Mild Hybrid BISG CI	$47,229	$47,932	$47,683
	SHEVP2 CI	$48,063	$48,551	$48,140
	PHEV7kWh CI	$51,278	$50,101	$49,480
	PHEV50 CI	$57,342	$53,145	$51,163
	FCEV	$59,599	$49,680	$46,326
	H2ICE	$48,762	$46,808	$45,962
	BEV200	$68,040	$46,509	$40,919
	BEV300	$86,581	$54,824	$46,207
	BEV400	$104,060	$62,565	$51,114
Pickup Truck	Conventional CI	$46,133	$47,117	$46,945
	Mild Hybrid BISG CI	$47,229	$47,932	$47,683
	SHEVP2 CI	$48,083	$48,548	$48,094
	PHEV7kWh CI	$52,464	$51,046	$50,335
	PHEV50 CI	$57,217	$53,428	$51,598
	FCEV	$70,084	$57,309	$52,693
	H2ICE	$47,421	$45,962	$45,307
	BEV200	$60,752	$43,699	$39,364
	BEV300	$74,657	$50,025	$43,396
	BEV400	$87,767	$55,914	$47,138

6.4 Purchase price with §30D credits

Table 29: Projected purchase price with $7,500 credit

Vehicle	Vehicle powertrain	Model Year	Purchase Price without IRA ($)	Purchase Price with IRA ($)
LDVs				
Compact	Conventional SI Turbo	2024	$32,737	$32,737
		2027	$32,659	$32,659
	Mild Hybrid BISG SI Turbo	2024	$33,833	$33,833
		2027	$33,474	$33,474
	Par HEV SI Turbo	2024	$34,048	$34,048
		2027	$33,549	$33,549
	PHEV7kWh SI Turbo	2024	$36,430	$28,930
		2027	$34,573	$27,073
	PHEV50 SI Turbo	2024	$38,185	$30,685
		2027	$35,406	$27,906
	FCEV	2024	$38,904	$31,404
		2027	$33,711	$26,211
	H2ICE	2024	$36,812	$36,812
		2027	$35,923	$35,923
	BEV200	2024	$31,825	$24,325
		2027	$26,936	$19,436
	BEV300	2024	$36,013	$28,513
		2027	$29,144	$21,644
	BEV400	2024	$41,344	$33,844
		2027	$31,837	$24,337
Medium Car	Conventional SI Turbo	2024	$37,237	$37,237
		2027	$37,159	$37,159
	Mild Hybrid BISG SI Turbo	2024	$38,333	$38,333
		2027	$37,974	$37,974
	Par HEV SI Turbo	2024	$38,702	$38,702
		2027	$38,196	$38,196
	PHEV7kWh SI Turbo	2024	$41,023	$33,523
		2027	$39,146	$31,646
	PHEV50 SI Turbo	2024	$42,985	$35,485
		2027	$40,094	$32,594
	FCEV	2024	$48,029	$40,529
		2027	$41,174	$33,674
	H2ICE	2024	$41,312	$41,312

Vehicle	Vehicle powertrain	Model Year	Purchase Price without IRA ($)	Purchase Price with IRA ($)
		2027	$40,423	$40,423
	BEV200	2024	$36,948	$29,448
		2027	$31,765	$24,265
	BEV300	2024	$41,384	$33,884
		2027	$34,009	$26,509
	BEV400	2024	$46,958	$39,458
		2027	$36,881	$29,381
Small SUV	Conventional SI Turbo	2024	$40,237	$40,237
		2027	$40,159	$40,159
	Mild Hybrid BISG SI Turbo	2024	$41,333	$41,333
		2027	$40,974	$40,974
	Par HEV SI Turbo	2024	$41,954	$41,954
		2027	$41,284	$41,284
	PHEV7kWh SI Turbo	2024	$44,145	$36,645
		2027	$42,232	$34,732
	PHEV50 SI Turbo	2024	$46,579	$39,079
		2027	$43,458	$35,958
	FCEV	2024	$53,791	$46,291
		2027	$46,028	$38,528
	H2ICE	2024	$44,312	$44,312
		2027	$43,423	$43,423
	BEV200	2024	$41,594	$34,094
		2027	$35,649	$28,149
	BEV300	2024	$46,814	$39,314
		2027	$38,393	$30,893
	BEV400	2024	$53,421	$45,921
		2027	$41,718	$34,218
Medium SUV	Conventional SI Turbo	2024	$44,865	$44,865
		2027	$44,766	$44,766
	Mild Hybrid BISG SI Turbo	2024	$45,961	$45,961
		2027	$45,581	$45,581
	Par HEV SI Turbo	2024	$46,773	$46,773
		2027	$46,048	$46,048
	PHEV7kWh SI Turbo	2024	$48,905	$41,405
		2027	$46,944	$39,444
	PHEV50 SI Turbo	2024	$51,762	$44,262
		2027	$48,420	$40,920
	FCEV	2024	$56,051	$48,551

Environmental Defense Fund

ROUSH

Vehicle	Vehicle powertrain	Model Year	Purchase Price without IRA ($)	Purchase Price with IRA ($)
		2027	$48,475	$40,975
	H2ICE	2024	$49,549	$49,549
		2027	$48,574	$48,574
	BEV200	2024	$45,489	$37,989
		2027	$39,101	$31,601
	BEV300	2024	$51,395	$43,895
		2027	$42,123	$34,623
	BEV400	2024	$58,811	$51,311
		2027	$45,952	$38,452
Pickup Truck	Conventional SI Turbo	2024	$50,621	$50,621
		2027	$50,514	$50,514
	Mild Hybrid BISG SI Turbo	2024	$51,717	$51,717
		2027	$51,330	$51,330
	Par HEV SI Turbo	2024	$52,948	$52,948
		2027	$52,131	$52,131
	PHEV7kWh SI Turbo	2024	$54,954	$47,454
		2027	$52,900	$45,400
	PHEV50 SI Turbo	2024	$58,728	$51,228
		2027	$54,887	$47,387
	FCEV	2024	$67,399	$59,899
		2027	$57,815	$50,315
	H2ICE	2024	$55,042	$55,042
		2027	$54,060	$54,060
	BEV200	2024	$54,005	$46,505
		2027	$46,416	$38,916
	BEV300	2024	$61,148	$53,648
		2027	$50,073	$42,573
	BEV400	2024	$70,230	$62,730
		2027	$54,722	$47,222
Class 3 vehicles				
Delivery Van	Conventional CI	2024	$46,133	$46,133
		2027	$47,117	$47,117
	Mild Hybrid BISG CI	2024	$47,229	$47,229
		2027	$47,932	$47,932
	Par HEV CI	2024	$48,063	$48,063
		2027	$48,551	$48,551
	PHEV7kWh CI	2024	$51,278	$51,278
		2027	$50,101	$50,101

Vehicle	Vehicle powertrain	Model Year	Purchase Price without IRA ($)	Purchase Price with IRA ($)
	PHEV50 CI	2024	$57,342	$57,342
		2027	$53,145	$53,145
	BEV 200	2024	$68,040	$60,540
		2027	$46,509	$39,009
	BEV 300	2024	$86,581	$79,081
		2027	$54,824	$47,324
	BEV 400	2024	$104,060	$96,560
		2027	$62,565	$55,065
	FCEV	2024	$59,599	$52,099
		2027	$49,680	$42,180
	H2ICE	2024	$48,762	$48,762
		2027	$46,808	$46,808
Pickup Truck	Conventional CI	2024	$46,133	$46,133
		2027	$47,117	$47,117
	Mild Hybrid BISG CI	2024	$47,229	$47,229
		2027	$47,932	$47,932
	Par HEV CI	2024	$48,083	$48,083
		2027	$48,548	$48,548
	PHEV7kWh CI	2024	$52,464	$52,464
		2027	$51,046	$51,046
	PHEV50 CI	2024	$57,217	$57,217
		2027	$53,428	$53,428
	BEV 200	2024	$60,752	$53,252
		2027	$43,699	$36,199
	BEV 300	2024	$74,657	$67,157
		2027	$50,025	$42,525
	BEV 400	2024	$87,767	$80,267
		2027	$55,914	$48,414
	FCEV	2024	$70,084	$62,584
		2027	$57,309	$49,809
	H2ICE	2024	$47,421	$47,421
		2027	$45,962	$45,962