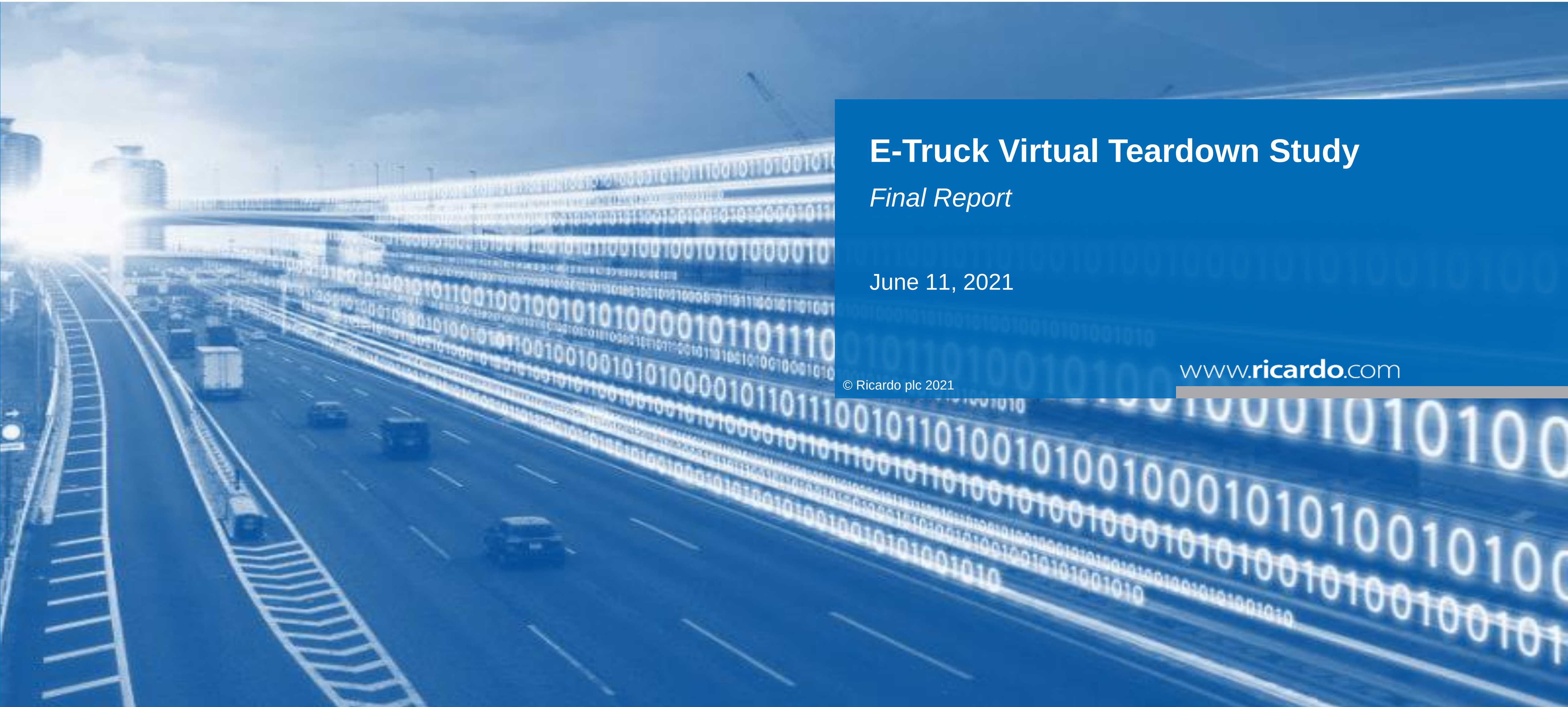
E-Truck Virtual Teardown Study

Final Report

June 11, 2021



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Ricardo has leveraged its internal cost databases, supplier quotes, industry inputs, and public domain information to provide validated data for the study

Methodology Summary

1. Task 1: Baseline diesel truck costs and weights
2. Task 2: E-truck teardown elements
3. Task 3: E-truck component costs and weights
4. Task 4: Cost reduction methodology
5. Task 5: Summary spreadsheets and slides
6. Task 6: Summary report

- The methodology includes leveraging existing Ricardo experience in cost analysis and trucking electrification to accomplish the study within accelerated timeline and reduced budget while ensuring quality and reliability of the output with validation from industry experts
- Below are the 5 key sources of data gathering in the proposed methodology:
  - **Ricardo Internal Database:** Ricardo has performed several cost studies for HD commercial vehicles and has developed a reliable database of subsystem and component level cost ranges for diesel, battery electric and hydrogen fuel cell trucks including powertrain and non-powertrain components.
  - **Ricardo Roadmaps:** Ricardo has developed cost roadmaps, technology roadmaps, volume projection and learning rates for key technology components such as battery pack, e-machine, power electronics, HV system, fuel cell system, hydrogen tanks, etc.
  - **Truck teardown:** Ricardo has performed disassembly of Class 8 trucks and can leverage available disassembled components for analysis and weight measurements as needed
  - **Supplier Interviews:** Supplier interviews will be conducted to gather and validate cost and weight information for key components and derive parametric model
  - **OEM Interviews:** Select OEM interviews will be performed to test aggregate cost and weight estimates and seek validation
  - **Public Domain:** Existing literature in the public domain will be leveraged to secure multiple data points and develop high, low and average estimates

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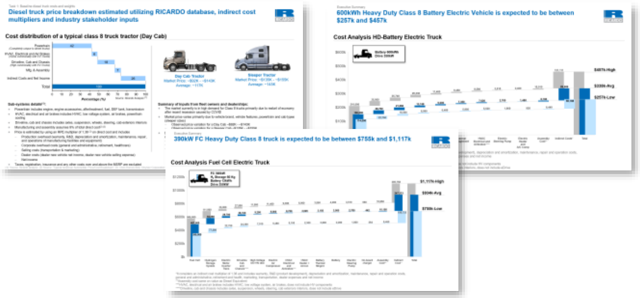
Ricardo performed cost and weight assessments of Class 8 Fuel Cell truck, Battery Electric truck, and comparable Diesel baseline

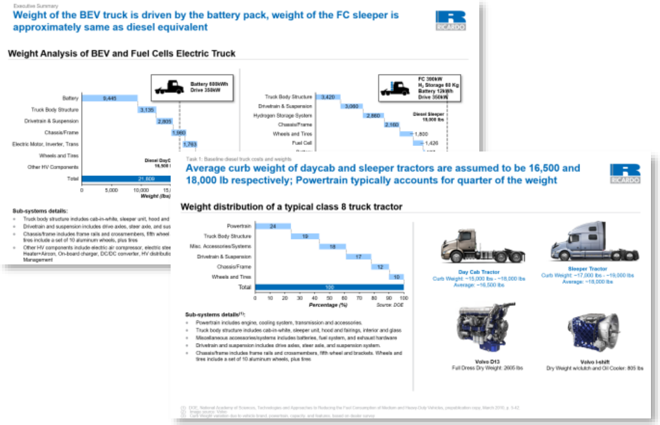
Cost Analysis

- Ricardo utilized a bottom-up cost analysis approach for Battery Electric Truck Tractors and Fuel Cell Truck Tractor in consultation with OEMs, suppliers, and other industry stakeholders
- The truck costs are estimated to be:
  - Diesel Day Cab Truck ***$92K-$143K***
  - Diesel Sleeper Truck ***$135K-$155K***
  - Battery Electric Day Cab Truck ***$257K-$457K***
  - Fuel Cell Sleeper Cab Truck ***$765K-$1,129K***
- The Battery pack and eDrive (motor, inverter, and transmission) are the main cost drivers for the Battery Electric Class 8 tractor truck
- The Battery Electric Truck has an estimated range between 200 to 300 miles
- The Fuel Cell and Hydrogen Storage Systems are the main cost drivers for the Fuel Cell Class 8 tractor truck
- The Fuel Cell Electric Truck has an estimated range between 360 to 540 miles



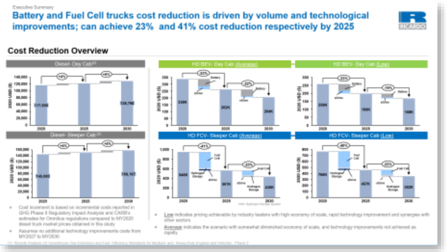
Weight Analysis

- Ricardo utilized a bottom-up weight analysis approach for the Battery Electric tractor truck and Fuel Cell tractor truck
- The truck weights are estimated to be:
  - Diesel Day Cab Truck ***~16,500 lbs***
  - Diesel Sleeper Truck ***~18,000 lbs***
  - Battery Electric Day Cab Truck ~***21,800 lbs***
  - Fuel Cell Sleeper Cab Truck ~***17,500 lbs***
- The main contributor to the Battery Electric truck weight is the battery pack and is 30%+ higher than its diesel equivalent
- The weight of the Fuel Cell sleeper truck is approximately the same as the diesel equivalent

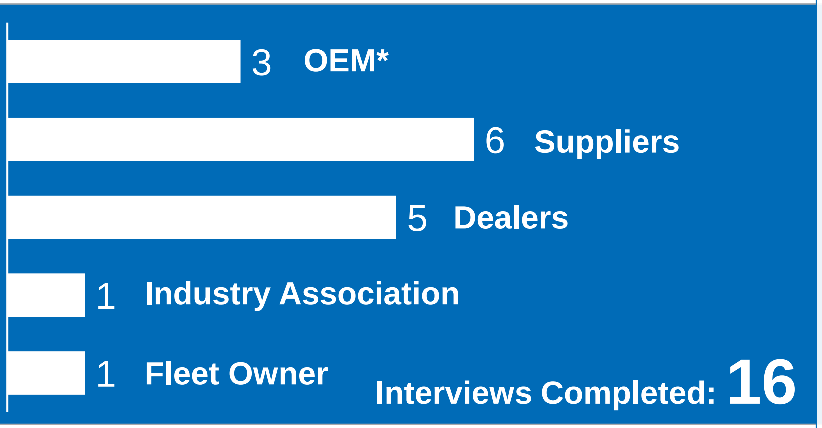


Cost Reduction

- Ricardo identified learning rate estimates for the Battery Electric Truck and the Fuel Cell Truck subsystems:
  - Considered independent studies, and discussions with industry experts
  - Utilized technological roadmaps to highlight cost reduction opportunities
- Cost reduction opportunities identified in the following sub-systems by 2030
  - Battery Pack (50%)
  - Fuel Cell System (65%)
  - Hydrogen Storage (40%)
  - eDrive (70%)
- Diesel equivalent expected to ***increase 9% by 2030*** *(based on GHG Phase II regulatory impact analysis)*
- BEV Truck price expected to ***decrease 40% by 2030***
- Fuel Cell Truck price expected to ***decrease 55% by 2030***



Interviews with industry stakeholders provided feedback on truck and system costs as well as additional viewpoints on ZEV trucks



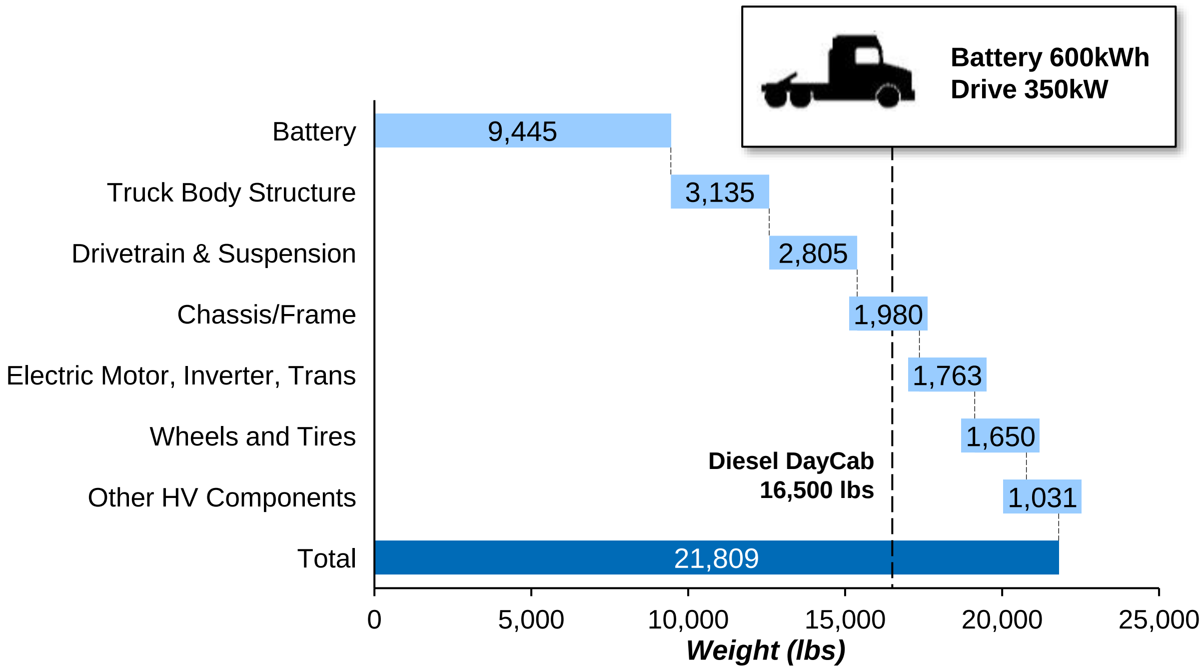
* Only OEM currently offering or deploying Class 8 FCV and BEV Trucks

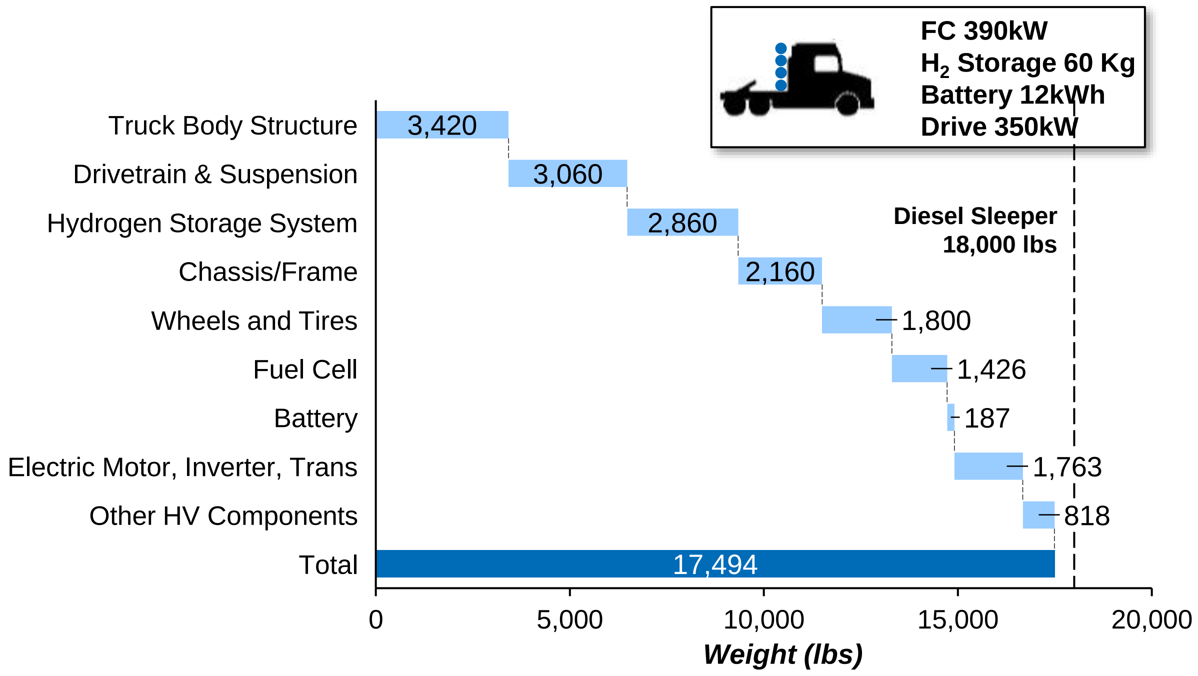
Key Interview Takeaways:

- Zero emission truck price should be viewed in the wider context of overall TCO
- In the near term, battery electric trucks are likely to be considered for niche application routes due to cost limitations
- Battery pack for Class 8 truck applications can drop below $150/kWh by 2030
- Gravimetric energy density of battery packs are more of a barrier to increasing on-board battery energy content than volumetric energy density. For example, a Class 8 truck can accommodate 1,000 kWh battery pack based on available volume
- There is a need to standardize specifications for electric trucks components to accelerate cost reduction. For example, continuous power testing methodology for eDrive should be standard across the industry
- The motors are integrated into central drive units today due to the legacy chassis design, but will transition to eAxle in future
  - Traditional OEM volumes will drive significant growth in the next five years in the eDrive market
- Medium-Duty market is expected to adopted electrification faster than the Heavy-Duty market, architecture strategies are following a trend to scale HD architectures from MD architectures
- Efficiency improvements can accelerate cost reduction, especially in Fuel Cells i.e., producing higher net power while utilizing the same amount raw materials and can lead to better $/kW
- Demand for Diesel trucks are currently high due to the restart of the economy after COVID crisis
- Automotive synergies is allowing new high voltage accessories to enter the commercial vehicle market, such as high voltage air conditioning
  - Additionally, new suppliers are emerging, offering high voltage products dedicated to MD and HD market

The main contributor to the Battery Electric truck weight is the battery pack; the weight of the Fuel Cell truck is approximately the same as the diesel equivalent

Weight Analysis of BEV and Fuel Cells Electric Truck





Sub-systems details:

- Truck body structure includes cab-in-white, sleeper unit, hood and fairings, interior and glass
- Drivetrain and suspension includes drive axles, steer axle, and suspension system.
- Chassis/frame includes frame rails and crossmembers, fifth wheel and brackets. Wheels and tires include a set of 10 aluminum wheels, plus tires
- Other High Voltage components include electric air compressor, electric steering pump, HVAC Heater+Aircon, On-board charger, DC/DC converter, High Voltage distribution system, Battery Thermal Management

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By 2030 key subsystems can achieve up to 40% to 60% cost reduction driven by technology and manufacturing scalability

Cost Reduction Overview

Battery Pack

- Commercial Vehicle Lithium battery pack prices forecasted to decline ~40% by 2030 and attain as low as ~$120/kWh
- Technology improvements driven by the Light Duty vehicle sector helps accelerate the cost reduction of cells and certain commercial vehicle battery technologies

Driveline

- Up to ~57% price reduction in 2025 expected for motor/inverters, primarily driven by higher volumes and material improvements
- Motors are incorporated into central drive units today due to the legacy chassis design. Moving forward, these can move to eAxle integration

HV Components

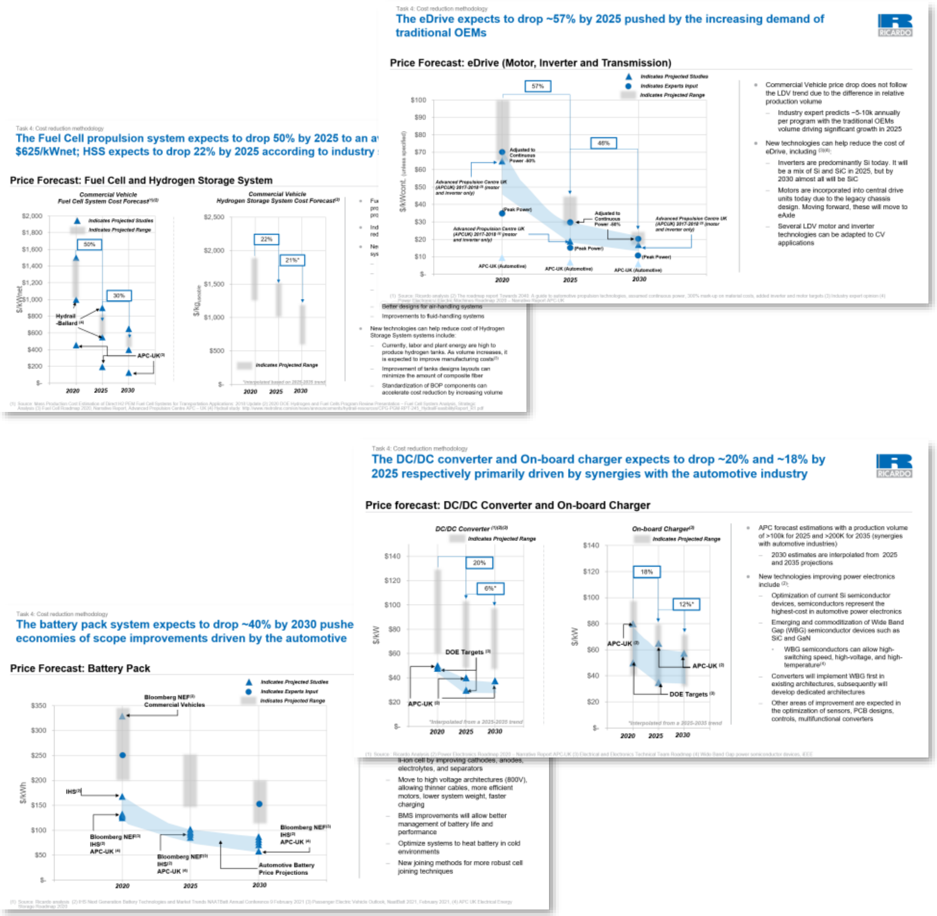
- Price reduction to be driven by material improvement, system integration, and transition of light-duty into 800V
- On-board charger and DC/DC converter prices to reduce by 25-30% by 2030

Fuel Cell System

- Fuel cell system prices expected to undergo 50% reduction by 2025, primarily driven by economies of scale from light-duty sector and ramp-up of manufacturing facilities

H2 storage and fuel system

- Economies of scale will affect H2 storage price as well
- Expected 35-45% reduction expected by 2030 as material cost of carbon fiber likely to continue to be the dominant cost driver



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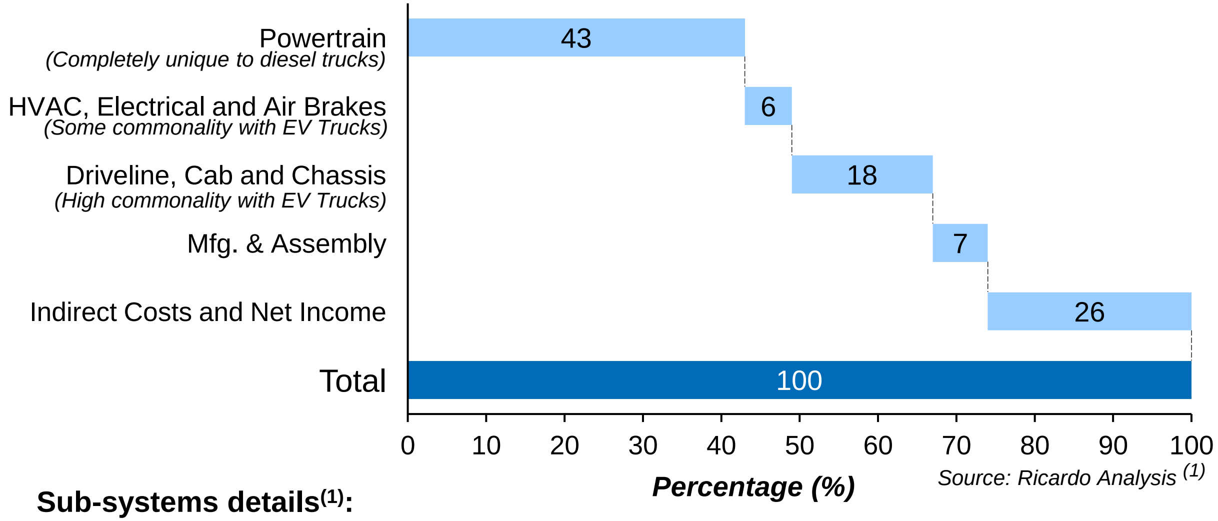
Diesel truck price breakdown estimated utilizing RICARDO database, indirect cost multipliers and industry stakeholder inputs

Cost distribution of a typical class 8 truck tractor (Day Cab)



Source: Ricardo Analysis [1]

Day Cab Tractor
Market Price: ~$92K - ~$143K
Average: ~117K

Sleeper Tractor
Market Price: ~$135K - ~$155K
Average: ~145K

Sub-systems details[1]:

- Powertrain includes engine, engine accessories, aftertreatment, fuel, Diesel Exhaust Fluid (DEF) tank, transmission
- Heating, Ventilation, and Air Conditioning (HVAC), electrical and air brakes includes HVAC, low voltage system, air brakes, powertrain cooling
- Driveline, cab and chassis includes axles, suspension, wheels, steering, cab exteriors interiors
- Manufacturing and assembly assumes 9% of total direct cost[2] [3]
- Price is estimated by using a Retail Price Equivalent (RPE) multiplier of 1.36 [3] on direct cost and includes
  - Production overhead (warranty, research and development, depreciation and amortization, maintenance, repair, and operations of manufacturing facilities and equipment)
  - Corporate overhead costs (general and administrative, retirement, healthcare)
  - Selling costs (transportation & marketing)
  - Dealer costs (dealer new vehicle net income, dealer new vehicle selling expense)
  - Net income
- Taxes, registration, insurance and any other costs over and above the MSRP are excluded

Summary of inputs from fleet owners and dealerships:

- The market currently is in high demand for Class 8 trucks primarily due to restart of economy after recent recession caused by COVID
- Market price varies primarily due to vehicle brand, vehicle features, powertrain and cab types (sleeper sizes)
  - Observed price variation for a Day Cab ~$92K - ~$143K
  - Observed price variation for a Sleeper Cab ~$135K - ~$155K
- Discount in prices may apply if multiple units are purchased. Feedback from one of the dealerships was as follows:
  - $1000 off per unit for 3+ trucks
  - $2000 off per unit for 5+ trucks
  - Discounts vary with brand and market conditions

(1) Source: Ricardo analysis (2) Source: "Typical American Automobile: Price/Cost Breakdown", Dr. Chris Borroni-Bird, Chrysler Corporation (3) Source: Office of Transportation and Air Quality, Research Triangle Institute (RTI) international, price does not include Federal Excise Tax (FET), Image source: Volvo

RPE multiplier from EPA study has been used for converting direct cost to price; The RPE is based on financial statements of leading truck manufacturers studies

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Heavy duty truck RPE multipliers and cost contributors(1)

Vehicle Manufacturing	Heavy Duty Truck Industry (Census/reports)	Truck Manufacturers Industry Average
Manufacturing cost: Cost of materials and labor cost	1.00	1.00
Production Overhead: Warranty	0.03	0.04
Production Overhead: R&D (product development)	0.05	0.05
Production Overhead: Depreciation and amortization	0.05	0.04
Production Overhead: Maintenance, repair, operations cost	0.02	0.02
Corporate Overhead: General and administrative	0.12	0.07
Corporate Overhead: Retirement	0.01	0.01
Corporate Overhead: Health	0.01	0.01
Selling: Transportation	0.00	0.00
Selling: Marketing	0.01	0.01
Dealers: Dealer new vehicle net income	< 0.01	< 0.01
Dealers: Dealer new vehicle selling expense	0.06	0.06
Sum of Indirect Costs	0.37	0.31
Net Income	0.05	0.05
RPE multiplier	1.42	**1.36**

Used in this study for diesel trucks

- Retail Price Equivalent (RPE) provides at an aggregate level the relative shares of revenue to direct manufacturing costs
  - RPE multiplier = (direct costs + indirect costs + net income)/(direct costs)
- RTI International, under EPA contract, developed RPEs estimated from financial information of four HD truck manufacturers (PACCAR, Navistar, Daimler, and Volvo) and Supplier Relations LLC industry report
  - The four heavy duty truck companies account for an 80% share of the heavy-duty truck industry in North America(1)
  - When financial statements did not provide enough details, multiplier contributors were adjusted from industry reports, stakeholders' inputs or other public sources
  - Industry RPE average was calculated weighing the annual production of the truck manufacturers
- Furthermore, the industry report by Supplier Relations LLC collected heavy duty truck industry income statements and balance sheets
  - Supplier Relations LLC considered manufacturing wages to be ~5% of total direct manufacturing costs
  - ***For manufacturing and assembly costs, Ricardo assumes an average of between Supplier Relations findings (5%) and Barroni-Bird automotive ratio (13%)***

(1) Office of Transportation and Air Quality, RTI international

Assembly labor and other manufacturing costs are assumed to be 9% of direct cost based on average of Supplier Relations and Barroni-Bird estimates

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Automotive retail price equivalent and indirect cost multipliers[1]

Price/Cost Breakdown Based on Borroni-Bird Presentation[1]

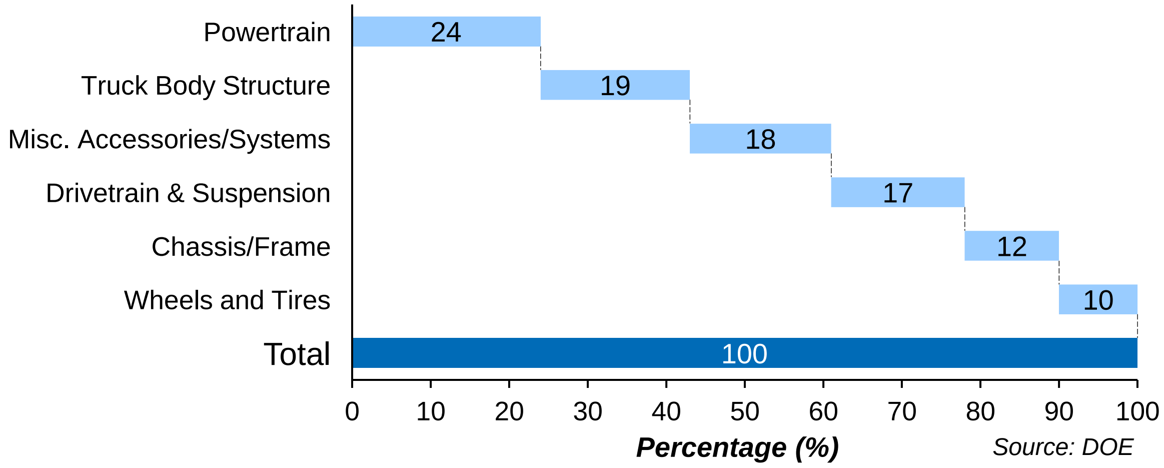
Cost Category	Relative to Cost of Vehicle Manufacturing	Share of MSRP (%)
Vehicle Manufacturing: Material Cost	**0.87**	42.5
Vehicle Manufacturing: Assembly Labor and Other manufacturing cost	**0.13**	6.5
Fixed Cost: Transportation/Warranty	0.09	4.5
Fixed Cost: Amortization and Depreciation, R&D, Pension and Health, Advertising, and Overhead	0.44	21.5
Selling: Price Discounts	0.1	5.0
Selling: Dealer Markup	0.36	17.5
Profit	0.06	2.5
MSRP	2.05	100

- Several published multipliers in the automotive industry are available, including [1] :
  - Argonne National Laboratory's (ANL's)
  - Energy and Environmental Analysis, Inc. (EEA)
  - "Typical American Automobile: Price/Cost Breakdown", Dr. Chris Borroni-Bird, Chrysler Corporation
- Comparison between these multipliers are summarized in the technical memorandum: Comparison of indirect cost multipliers for vehicle manufacturing[1] sponsored by the DOE
  - Traditionally, the cost multipliers are used for scaling a component costs to retail prices
- Borroni-Bird analysis provides a typical American automobile price/cost breakdown including the ratio between material cost and assembly labor (and other manufacturing costs)
  - ***For manufacturing and assembly costs, Ricardo assumes an average of between Supplier Relations findings (5%) and Barroni-Bird automotive ratio (13%)***

(1) Source: DOE- Comparison of indirect cost multipliers for vehicle manufacturing

Average curb weight of daycab and sleeper tractors are assumed to be 16,500 lb and 18,000 lb respectively; Powertrain typically accounts for quarter of the weight

Weight distribution of a typical class 8 truck tractor



Sub-systems details(1):

- Powertrain includes engine, cooling system, transmission and accessories.
- Truck body structure includes cab-in-white, sleeper unit, hood and fairings, interior and glass
- Miscellaneous accessories/systems includes batteries, fuel system, and exhaust hardware
- Drivetrain and suspension includes drive axles, steer axle, and suspension system.
- Chassis/frame includes frame rails and crossmembers, fifth wheel and brackets. Wheels and tires include a set of 10 aluminum wheels, plus tires

Day Cab Tractor
Curb Weight: ~15,000 lbs - ~18,000 lbs
Average: ~16,500 lbs

Sleeper Tractor
Curb Weight: ~17,000 lbs - ~19,000 lbs
Average: ~18,000 lbs

Volvo D13
Full Dress Dry Weight: 2605 lbs

Volvo I-shift
Dry Weight w/clutch and Oil Cooler: 805 lbs

(1) DOE, National Academy of Sciences, Technologies and Approaches to Reducing the Fuel Consumption of Medium and Heavy-Duty Vehicles, prepublication copy, March 2010, p. 5-42.
(2) Image source: Volvo
(3) Curb Weight variation due to vehicle brand, powertrain, capacity, and features, based on dealer survey

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There is significant variation in battery capacity offered in Class 8 battery electric trucks; Limited fuel cell trucks are in operation currently in the market

NON-EXHAUSTIVE

Key specifications for Battery-electric and Fuel Cell trucks

	Model	GCWR (lbs.)	Motor Power (kW)	Battery (kWh)	Charging (kW)	Range (Miles)	Fuel Cell Power (kW)	Hydrogen Storage (kg)	Market Readiness
Battery Electric	**Volvo VNR Electric Tractor**	*82,000*	*340*	*264*	*150*	*Up to 120*	*Not applicable*	*Not applicable*	*Production*
	eCascadia	*82,000*	*391*	*475*	*250**	*250*	*Not applicable*	*Not applicable*	*Production Development*
	BYD 8TT	*105,000*	*360*	*435*	*300*	*124*	*Not applicable*	*Not Applicable*	*Production*
	Nikola Tre	*80,000**	*480***	*750*	*350*	*300*	*Not disclosed*	*Not disclosed*	*Development*
	Tesla Semi	*80,000**	*Not disclosed*	*600**	*250kW****	*300**	*Not applicable*	*Not Applicable*	*Development*
Fuel Cell	**Nikola Two**	*80,000**	*480***	*Not disclosed*	*Not disclosed*	*500-750*	*Not disclosed*	*Not disclosed*	*Development*
	Toyota FC Semi	*80,000**	*500*	*12*	*Not disclosed*	*300*	*226*	*60*	*Development*
	US Hybrid – Navistar	*80,000**	*320*	*>22*	*6.6*	*200*	*80*	*20*	*Development Early Prototype*


Volvo NR4


eCascadia


Tesla Semi


BYD 8TT


Toyota FC

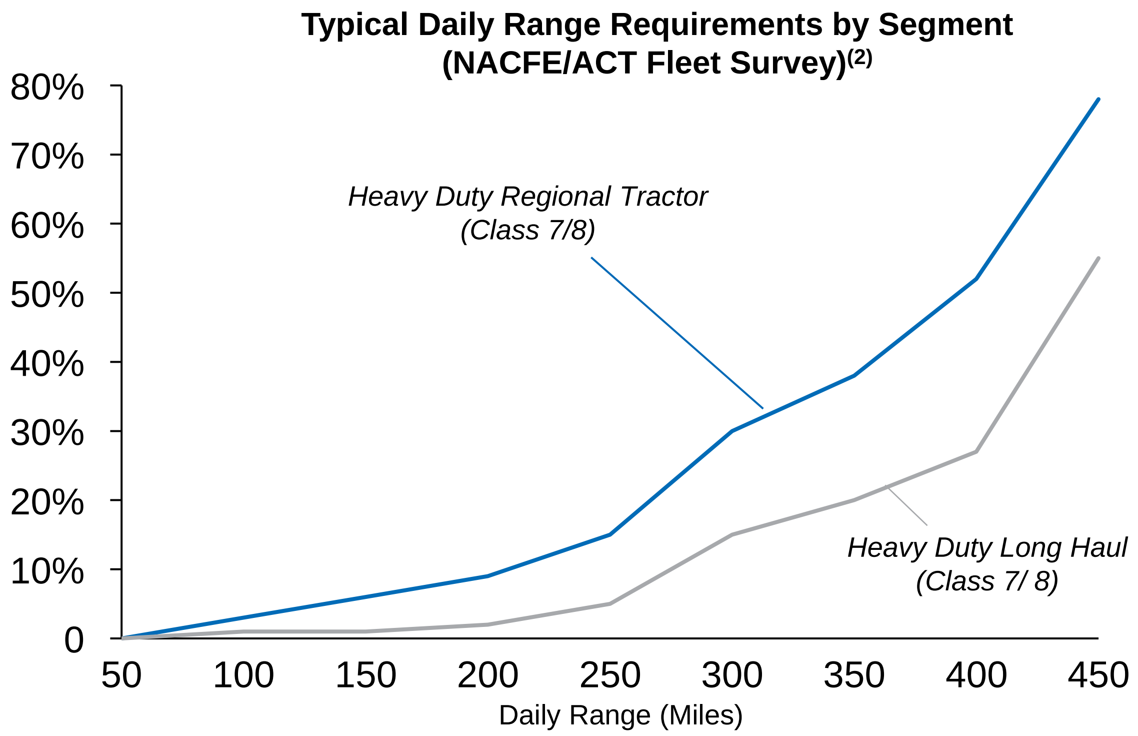

Nikola Two

(1) Source: Public sources, Green car reports, Volvo, Freightliner, Tesla, Toyota, BYD, Nikola ZF, US Hybrid
(2) (*) Estimated, (**) Continuous power (***) Tesla Super Charger Ratings
(3) Tesla Semi advertise 300 miles and 500 miles, energy consumption 2kWh/mile
(4) GCWR: Gross Combined Weight Ratings

Public domain sources suggest that 300-mile range covers 30% of the regional haul market while 600-miles cover 80th percentile of long-haul distances

Truck operating range for regional-haul tractor trailers and long-haul tractor trailers

- ***NACFE/ACT survey illustrates 30% of the regional tractor operates 300 miles or less per day(2)***
  - A 500-mile regional tractor will be able to cover 80% of the market
- NREL fleet DNA commercial fleet vehicle program collected data from 70 tractors operating in the United States and 1,150 days of driving data
  - The tractor category includes beverage delivery tractors, semis, sleeper semis, and refrigerated trucks
  - Size from class 7 to class 8 and includes regional and long-hauling activities
  - ***Fleet DNA illustrates the long-haul tractor trailer the approximately 80th percentile of daily distance is 600 miles***

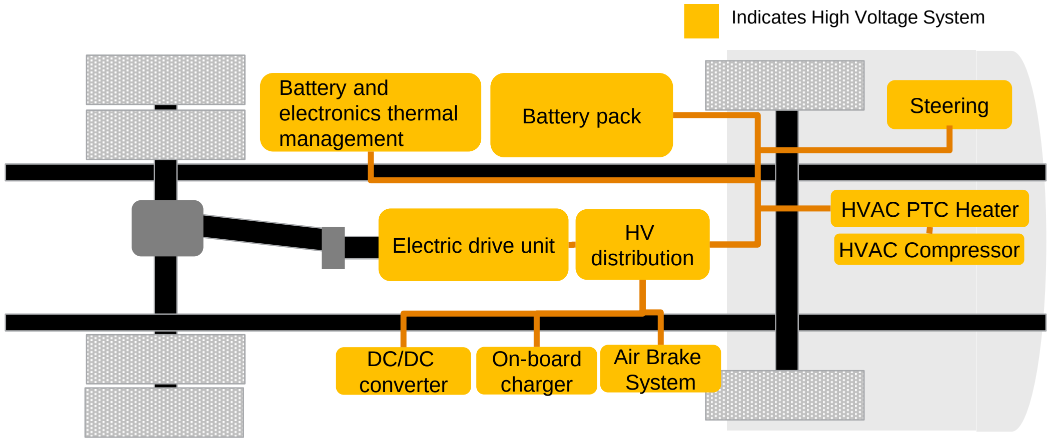


(1) Fleet DNA Project Data." (2019). National Renewable Energy Laboratory. Accessed January 15, 2019: www.nrel.gov/fleetdna
(2) NACFE Guidance Report: Electric Trucks Where They Make Sense

List of subsystems defined for Class 8 battery-electric truck based on representative trucks demonstrated or deployed in North America

Battery Electric truck architecture overview

Battery Electric Truck	Common to Diesel
Battery pack	
High Voltage components (DCDC converter / OBC / HV distribution system)	
Battery and electronics thermal management	
Electric HVAC systems	
Electric drive unit (Motor / Inverter / Transmission)	
Electric air brake compressor system	
Electric steering pump system	
Cab	●
Electrical and Wiring Harness	●
Air Brakes	●
HVAC/ cooling modules	●
Chassis & Driveline	●

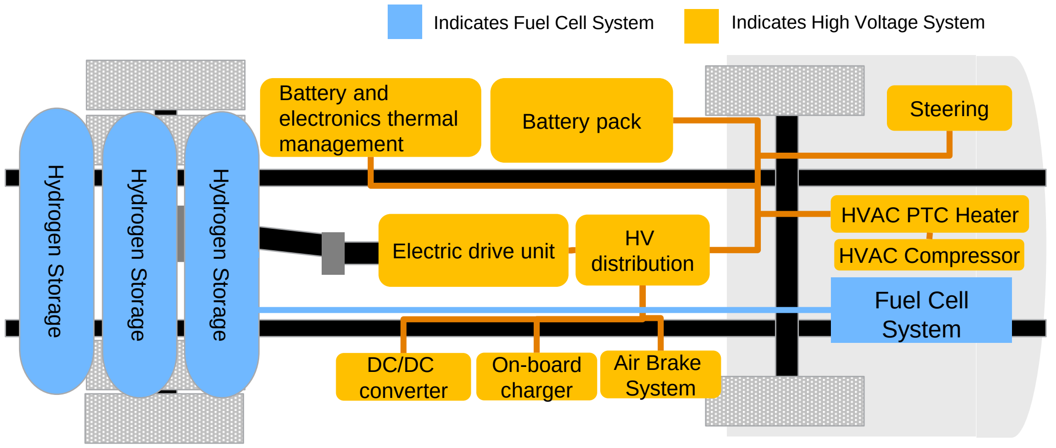


- A battery electric truck is propelled by the chemical energy stored in the battery system
  - Battery electric vehicle use High Voltage (HV) DC current as the main method to transfer energy
  - The energy is transmitted to the wheels utilizing an inverter, electric motor, transmission (Driveline)
- Some of these components share same working principle as the ICE engine driven systems i.e. compressed air, hydraulic power, liquid cooled fluids
  - However new technologies are utilized in the EV market to maximize efficiency

List of subsystems defined for Class 8 fuel cell electric trucks based on representative trucks demonstrated or deployed in North America

Fuel Cell truck architecture overview

Fuel Cell Truck	Common to Diesel
Battery pack	
High Voltage components (DCDC converter / OBC / HV distribution system)	
Battery and electronics thermal management	
Electric HVAC systems	
Electric drive unit (Motor / Inverter / Transmission)	
Electric air brake compressor system	
Electric steering pump system	
Fuel Cell Propulsion System - FCPS	
Hydrogen Storage System - HSS	
Cab	●
Electrical and Wiring Harness	●
Air Brakes	●
HVAC/ cooling modules	●
Chassis & Driveline	●



- Fuel Cell truck utilizes High Voltage DC current as the main method to transfer energy across sub-systems
  - Similar to a Battery Electric vehicle requires additional sub-systems to provide required vehicle functionalities
- Fuel Cell Electric Truck utilizes Fuel Cells to generate electricity from compressed hydrogen
  - Requires additional sub-systems such as Balance Of Plant (BOP), Hydrogen Storage System (HSS), HV energy converter and Fuel Cell dedicated cooling systems
- Fuel Cells can be the primary source of energy or act as range extenders

Battery system utilizes the chemical reaction of cells to store energy with capacity as the main cost driver

Battery pack system

- A battery system stores chemistry energy. Major subcomponents include:
  - **Battery cells:** Chemical reaction of cells allows the flow of electrons in the circuit during operation
    - Common cells geometries available in the market include cylindrical cells, prismatic cells and pouch cells
    - Chemistries utilized in the transportation sector are Li-Fe Phosphate (LFP), Li-Manganese / Spinel (LMO), Li-Nickel Manganese Cobalt (NMC), Li-Nickel Cobalt Aluminum (NCA)
    - Cell is the highest cost in the component in the battery pack
  - **Battery Management System (BMS):** Controls the proper operation of the cells and performs functions as balancing
    - A BMS includes a master board, slave boards (controlling individual modules and harness)
  - **Other battery sub-systems include:**
    - HV management system including the following components: High voltage contactors, busbars, harnessing, and current transducers
    - Internal cooling system including cooling plates, internal piping, or air circulation systems
    - Structure including module and electronics supports, battery enclosures, and vehicle mounting structures

Primary cost driver

- Capacity to store energy expressed in kWh

(For illustration purposes only)

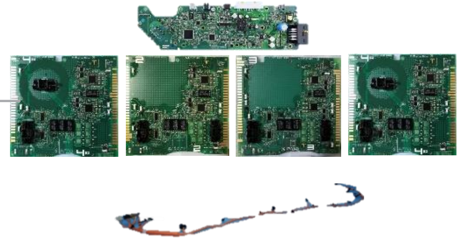
Battery cell

(For illustration purposes only)

Cylindrical Pouch Prismatic

Battery Management System - BMS

(For illustration purposes only)



Other battery systems

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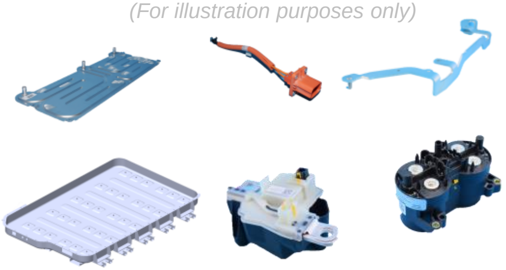


Source: Ricardo Analysis, Proterra, A2MAC1

High Voltage components manage the energy during charge and drive mode; Primary cost driver is system capacity

High Voltage components

- High voltage accessories supply power to the battery pack during charge mode, distributes energy during drive mode, and supplies power to the low voltage system:
  - **DC/DC converter:** It is a power electronic that supplies energy to the low voltage system and replaces the alternators' functionality.
    - Offered in the market in discrete size, the most common size is a 3kW, 400V to 12V system
    - Traditionally a liquid cooled system, and can be integrated into the On-board Charger (OBC)
  - **On-board Charger (OBC):** It is a power electronic that supplies energy to the high voltage system during charge mode.
    - Offered in the market in discrete sizes 3.3kW, 6.6kW, 11kW and 22kW
    - Traditionally a liquid cooled system, and can be integrated into the battery pack
  - **HV distribution system:** Manages and distributes energy through the vehicle. It includes HV contactors, fuses, current transducers, connectors, and HV harnessing

(For illustration purposes only)

HV distribution module

(For illustration purposes only)

Heavy Duty HV charger

(For illustration purposes only)

DC/DC Converter

Primary cost driver

- System capacity expressed in kW
  - DC/DC and OBC offered in discrete sizes

Source: Brusa, Eaton, Danfoss, Bosch, Newportelec NPT

Cooling system is critical for optimal performance of electric vehicles with system capacity as the primary cost driver

Battery and electronics thermal management

- Battery and electronics systems require to operate at specific temperatures. The battery and electronics thermal management system includes in the following components:
  - **Chiller / Heat exchanger:** Traditionally operates with the air conditioning compressor system to control the heat generated by the battery and power electronics
  - **High Voltage or Low Voltage pumps:** Replaces the engine driven pumps to circulate fluid through the battery, power electronics and motor
  - **High Voltage PTC Heater:** Supplies heat to the cooling loop to keep battery and power electronics at optimal operational conditions
    - Market traditionally offers 6kW units and it has automotive sector synergies

Primary cost driver

- Capacity of the cooling system in kW

(For illustration purposes only)

High Voltage PTC heater

(For illustration purposes only)

Electric pumps

(For illustration purposes only)

Chiller

Source: AVID, Eberspaecher, Dana

HVAC system requires high voltage components to replace engine-driven compressor and engine heat

Electric HVAC systems

- Electric vehicle and Fuel Cell vehicle HVAC systems utilize high voltage components to replace engine driven air conditioning compressor and engine heat and includes the following components:
  - **High Voltage PTC Heater:** Supplies heat to the HVAC system generated by ceramic resistors
    - Market offers 6kW units and it has automotive sector synergies
    - HVAC PTC heaters can heat up coolant or air
  - **High Voltage Air compressor:** Replaces engine-driven air conditioning compressor
    - Contains an integrated inverter
    - Product has automotive sector synergies

(For illustration purposes only)

High Voltage PTC heater

(For illustration purposes only)

High Voltage AirCon Compressor

(For illustration purposes only)

Air PTC Heater

Primary cost driver

- Power capacity driven by cab size in kW

Source: Eberspaecher, MHI compressor

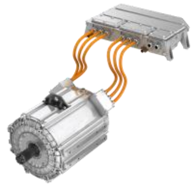
Electric drive unit consists of electric motor, inverter and a transmission; Key cost driver is power capacity in kW

Electric drive unit

- Electric drive units provides mechanical power to wheels and includes the following components:
  - **Inverter:** It is a power electronic unit that converts the Vdc power to Vac to drive the electric motor
    - It requires interface with the liquid cooling system
    - It can be integrated with the electric motor for compact solutions
  - **Electric Motor:** Main function of the motor is to convert electrical energy to mechanical energy
    - Current trend is the use of Permanent Magnet technology
    - For commercial vehicles motors are offered typically in 200kW to 540kW range
  - **Gearbox / transmission**
    - Mechanical interface of the motor to vehicle driveline
    - Market can offer multi-speed transmission for commercial electric vehicles

Primary cost driver
- Power capacity in kW

(For illustration purposes only)



Inverter and motor e-drive

(For illustration purposes only)

Integrated e-drive

(For illustration purposes only)

Motor and gearbox e-drive

Source: Dana TM4 SUMOTM HP, Volvo

Electric-driven air compressor primary cost driver is the power requirement

Electric air brake compressor system

- Electric air brake compressor system powers the air brake circuit. It replaces the engine-driven unit
  - High voltage inputs and single compressor needed due to the power requirements
- The primary cost driver is the power capacity, driven by air brake system needs
- Market starting to offer products for electric commercial vehicles, many products adopted from other markets such as rail or transit

(For illustration purposes only)

Vane Integrated e-compressor

(For illustration purposes only)

Integrated e-compressor

Primary cost driver

- Power requirement driven by vehicle size in kW

Source: Mattei vane compressor, Wabco e-compressor

Electric-driven steering pumps primary cost driver is the power requirement

Electric steering pump system

- Electric steering system supplies hydraulic power to the steering circuit. It replaces the engine-driven unit
  - The market starting to offer electric driven pump systems to achieve power needs of HD applications
- The primary cost driver is the power needs driven by size of the vehicle, and steering effort needs

(For illustration purposes only)

Dual hydraulic pump

(For illustration purposes only)

Integrated e-hydraulic pump

Primary cost driver

- Cost is driven by power steering capacity in kW which in turn is driven by vehicle GVWR

Source: SAE Development of Hybrid Power Steering System for Commercial Vehicle Hyundai Mobis, Terzo Power

Fuel Cell System primarily consists of the Fuel Cell stack and Balance of Plant; Key cost driver is the power of the fuel cell system (kW)

Fuel Cell System - FCPS

- Fuel Cell System consists of two main components
  - **Fuel Cell Stack:** Electrochemical component that utilizes hydrogen to produce electricity
    - A catalyst at the anode separates hydrogen molecules into protons and electrons, electrons then flow through the external circuit
    - Current trend to utilize automotive fuel cells in commercial applications observed i.e., Toyota FC, Nikola-GM
  - **Balance of Plant (BOP):** It is a system that allows the fuel cell stack to operate and includes air compressor, fuel loop, high temperature loop, and sensors
  - **Fuel cell boost converter:** It is a power electronic that modulates Fuel Cell output to vehicle architecture needs

Primary cost driver

- Net fuel cell power capacity expressed in kW

(For illustration purposes only)

Fuel Cell Stack

(For illustration purposes only)

Fuel Cell with BOP

Source: DOE, Toyota Mirai, GM Fuel Cell

Hydrogen is stored in high-pressure composite tanks and the primary cost driver is the useable stored amount

Hydrogen Storage System - HSS

- Hydrogen Storage System consists in two main components
  - **Hydrogen storage tanks:** Composite tanks with an internal hydrogen membrane to minimize permeation.
    - In the on-highway industry system operates at 70MPa
  - **Balance of Plant (BOP):** Components managing the distribution of hydrogen through the system. Includes high pressure valves, thermal protection, regulators (drop pressure to FC needs), high pressure piping, and low-pressure piping
  - **Structure:** Consists of structural members and straps to hold hydrogen storage. Structural members allow tank expansion. Traditionally packaging follows CNG architectures

(For illustration purposes only)

Type IV HSS System

(For illustration purposes only)

HSS in Semi

Primary cost driver

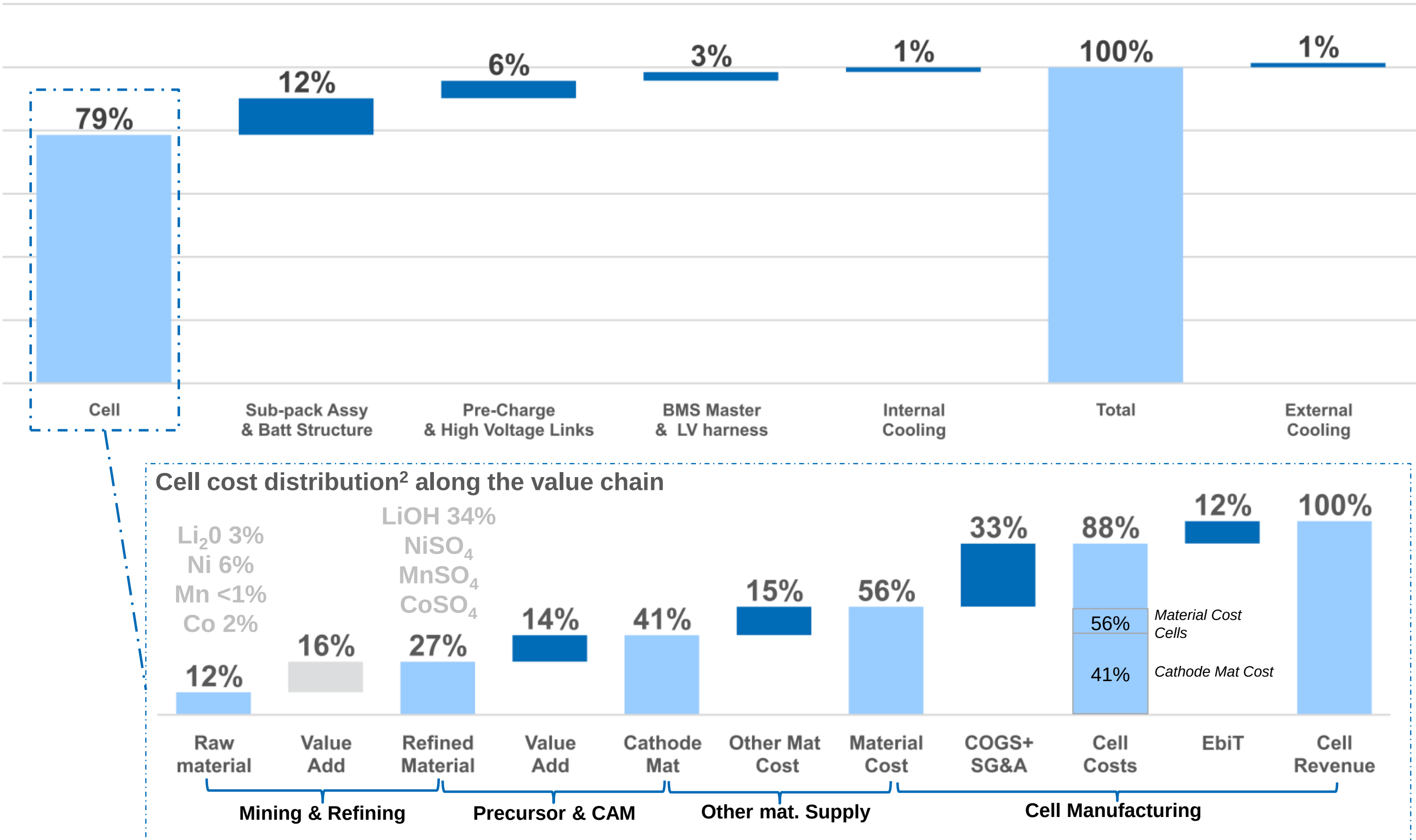
- Energy storage capacity expressed in useable kg of hydrogen

Source: Ricardo analysis, Quantum hydrogen tanks, Toyota (public domain)

Contents

Cell is the main cost driver of a battery pack and accounts for ~80% of the BOM cost; material cost represents up to ~56% of cell costs

Battery pack: Overview



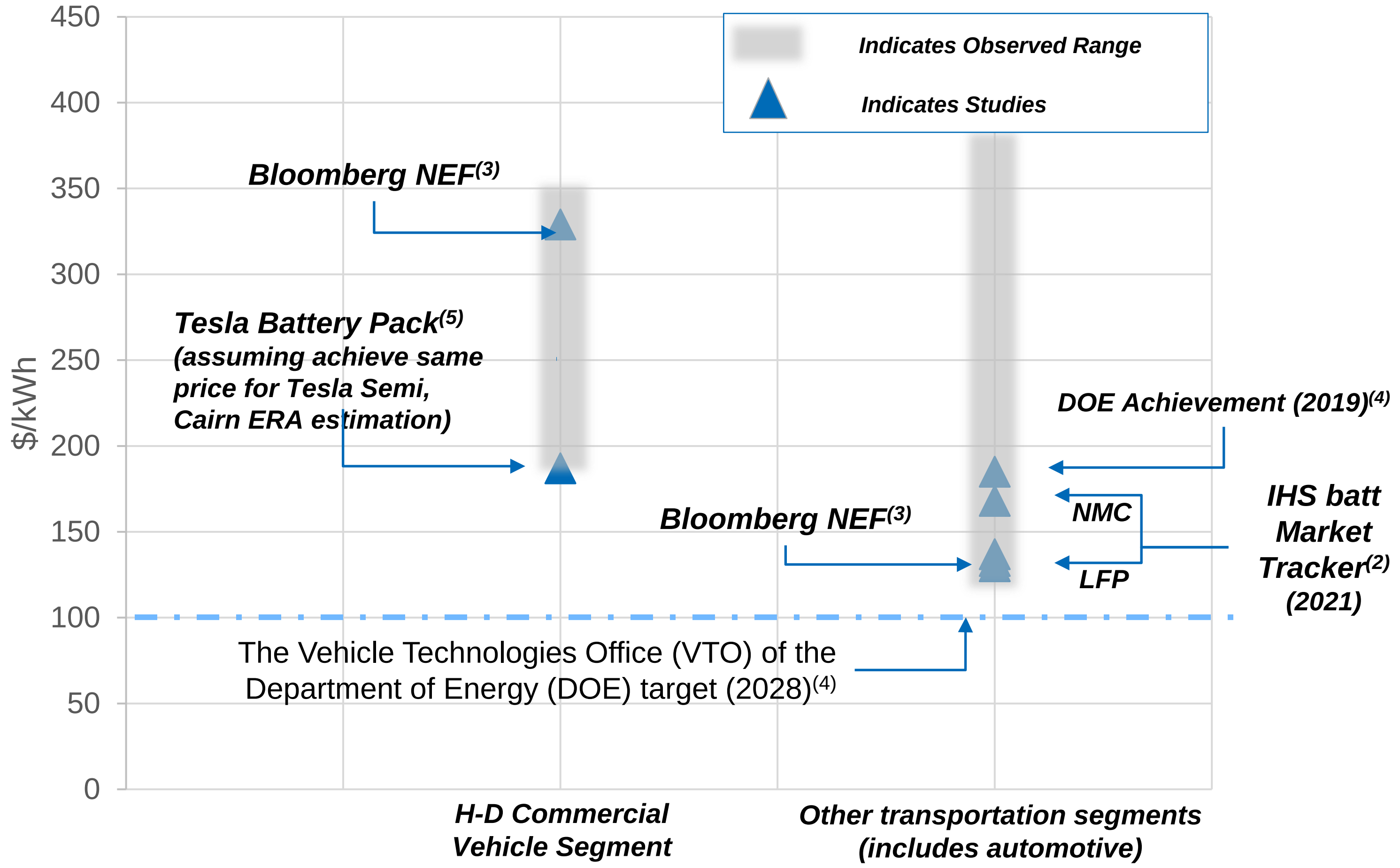
COSG = Cost of Good Sold, SG&A = Selling, General and Administrative Expenses
Li_2O: Lithium Spodumene Concentrate 6%
*Based on 2018 **NCM811** cell costs, Cathode material includes a +6% surcharge for cell inefficiencies*

- The automotive battery cell represents the highest cost in a battery pack BOM cost (~80%)
- Material costs represents ~56% of cell cost, cost reduction focus on material management and manufacturing efficiency improvements(3)
- Automotive industry is driving the cost reduction of battery packs
  - Major automakers have committed over $300B towards development of battery packs(3)

Source: (1) Ricardo analysis based on Chevy Bolt battery pack is estimated to cost 100K per year production, this assumes a $142/kWh cell price, does not include assembly costs and indirect costs (2) Source: Wolfgang Bernhard, Roland Berger, 2019 Source: 27th Aachen Colloquium Automobile and Engine Technology 2018 Dr. Wolfgang Bernhart, Dr. Christian-Simo (3) Lithium-ion battery supply chain technology development and investment opportunities, Vivas Kumar Principal Benchmark Mineral Intelligence

H-D commercial vehicle battery cost observed between ~$190kWh and ~$350/kWh with an average of ~$250/kWh

Battery pack: Observed price ranges



- Ricardo observed price ranges from interviews, cost studies, cost roadmaps and public domain for commercial and other electric vehicle segments
  - Industry interview experts conveyed a $250/kWh status
- Automotive industry has lower battery costs mainly due to volume in cell and other battery components (internal cooling, internal structure, BMS, etc.)
  - The volume savings of other battery components in automotive segment does not necessarily transfer to commercial vehicle due to different architectures
  - Other factors influencing the price difference between LDV and HDV can be production volume, supplier size, chemistry type, OEM negotiation power, OEM LDV and HDV shared portfolio, supplier negotiation power
- Data timeframe 2019 – 2021[2][3][4][5]

(1) Source: Ricardo analysis (2) IHS Next Generation Battery Technologies and Market Trends NAATBatt Annual Conference 9 February 2021 (3) Passenger Electric Vehicle Outlook, NaatBatt 2021, February 2021, (4) DOE Batteries 2019 Annual Progress Report, Vehicle Technologies Office (5) Cairn ERA estimation $187/kWh, https://www.cnbc.com/2021/03/10/teslas-lead-in-batteries-will-last-through-decade-while-gm-closes-in-.html

The estimated cost of a 600kWh battery pack is between ~$115K and ~$210K; the cost for the FC vehicle battery pack is between ~$6.6K and ~$8.4K

Battery pack: Estimated price range and weight

Energy Cells	Low	Average*	High
Parameter ($/kWh)	$190	$250	$350
600kWh (BEV)	**$115,000**	**$150,000**	**$210,000**

Power Cells	Low	Average*	High
Parameter ($/kWh)	$550	$600	$700
12kWh (FC)	**$6,600**	**$7,200**	**$8,400**

(*) Indicates average of Ricardo Data Points

Battery size	Estimated Weight lbs (kg)
600kWh	**9,445 (4,285)**
12kWh	**187 (85)**

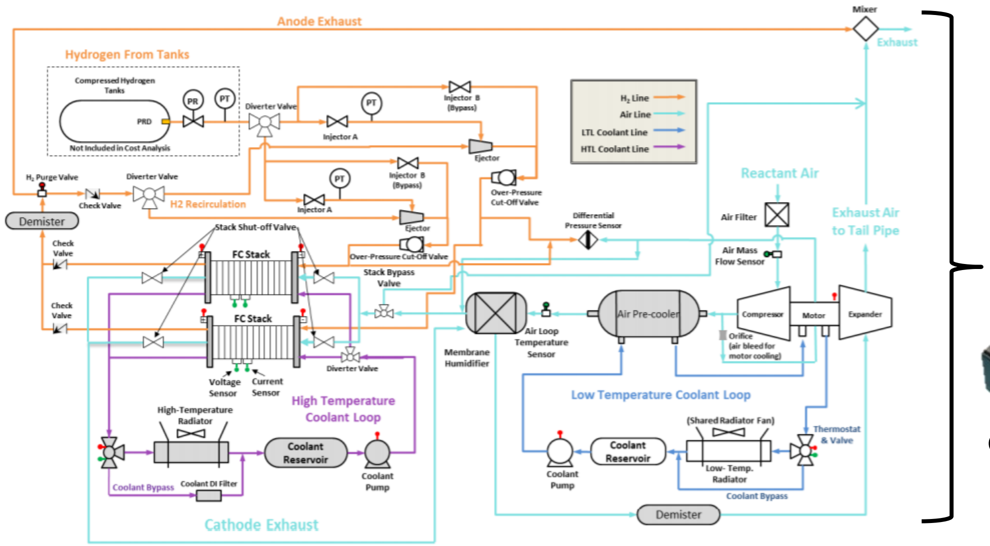
- Cost of the battery pack includes all internal thermal, electrical and mechanical for an integrated solution for commercial vehicle
  - Assumed a supplier providing the assembly units to an OEM, supplier profit and indirect costs included
- Cost does not include external subsystem such as HV connections, external cooling system and mechanical structures
- Manufacturers have different ways of specifying rated battery kWh and allowable Depth of Discharge. We have provided a low and high for the electric range (miles) which covers the variability in usable battery kWh
- Battery weight calculated assuming an energy density of ~0.13 – 0.15 kWh/kg(2)

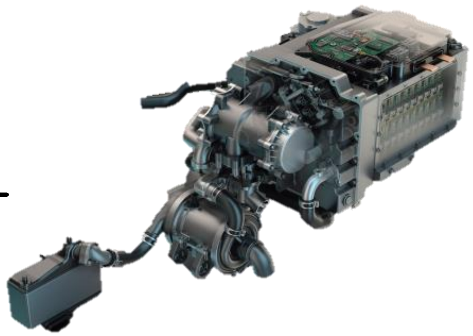
(1) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs (2) UBS Research

Fuel Cell system includes Fuel Cell Stack, Balance of Plant components and DC/DC Converter

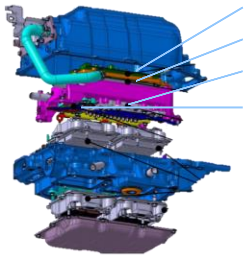
Fuel Cell System: Overview

Fuel Cell System: Fuel Cell Stack and Balance of Plant Components (1)





General Motors/Honda Fuel Cell System(4)



Toyota-Mirai Booster Converter (DC/DC Converter)(3)

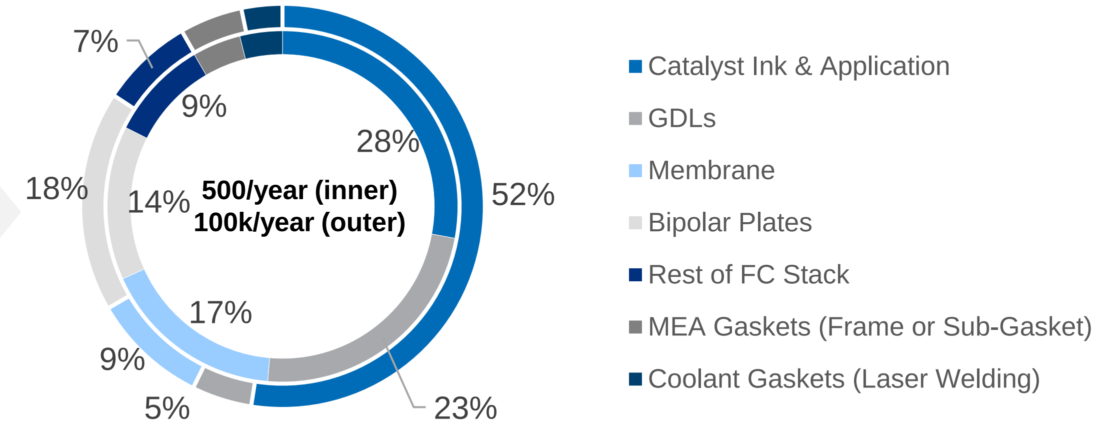
- The Fuel Cell Propulsion system includes fuel cell stacks, air loop, humidifier and water recovery loop, high-temperature coolant loop, low-temperature coolant loop, fuel loop (but not hydrogen storage), fuel cell system controller, and sensors (1)
- The Fuel Cell system may require a DC/DC converter to boost the voltage to system voltage
  - OEMs can use existing automotive developments
- Scenarios reducing the durability of the FC system include start-up and shut-down conditions, dynamic loads, idling and heavy loads (2)
  - Active research including material improvements and system approach (hybrid architectures) is currently performed to obtain desired durability for automotive and commercial vehicle application

(1) Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update
(2) Powertrain System Durability in Proton Exchange Membrane Fuel Cell Electric Vehicles (3) SAE Development of Fuel Cell System for the Toyota Mirai (4) General Motors

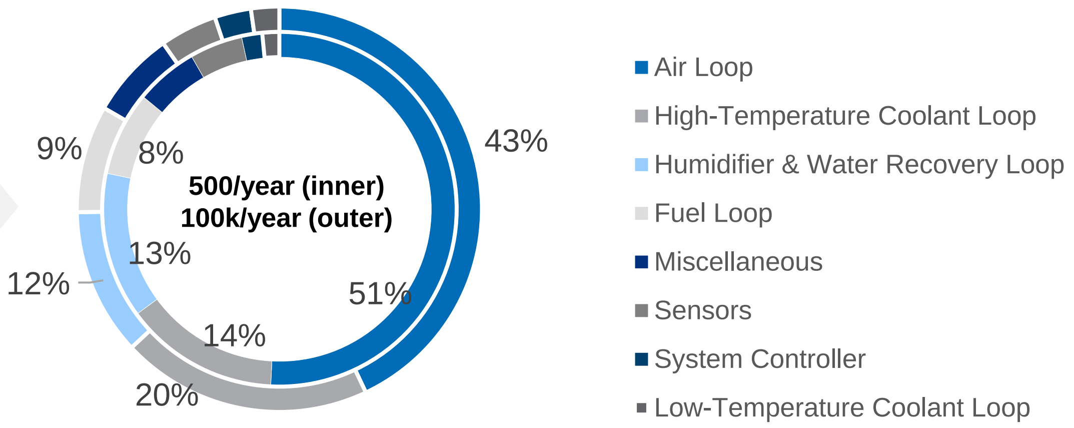
Economies of scale unevenly affects Fuel Cell stack and BOP subcomponents cost

Fuel Cell System: Overview

FC Stack Breakdown



BoP Breakdown



- The Fuel Cell stack breakdown includes Bipolar plates, membrane, catalyst ink & application, gas diffusion layers (GDLs), membrane electrode assemblies (MEA), coolant gaskets, and other FCS components
- The FCPS Balance of Plant (BOP) components include the air loop, humidifier & water recovery loop, high-temperature coolant loop, low-temperature coolant loop, fuel loop, system controller, sensors, and other miscellaneous components
- Fuel Cell Stack and BOP breakdowns are based on manufacturing costs assuming 500 units per year and 100k units per year production rate to illustrate sensitivity to economies of scale
- Estimations extracted from DOE-Strategic Analysis (1) bottom-up study, assuming a medium-duty truck system with a net power output of 160kWnet

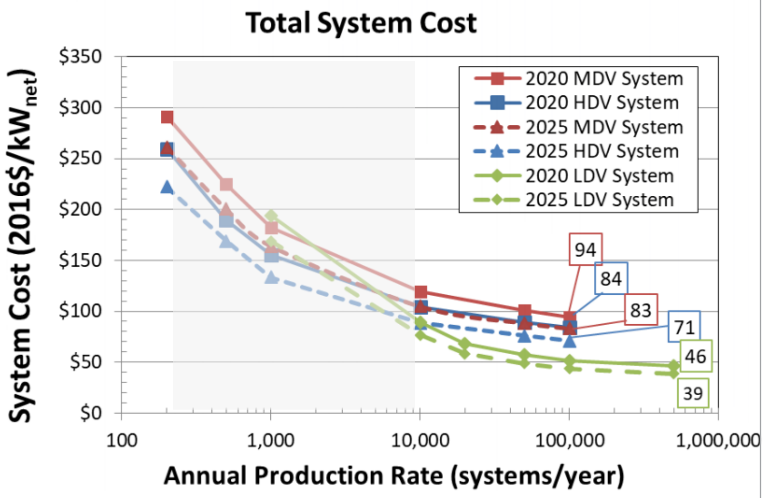
(1) Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update

Ricardo evaluated independent studies and engaged discussions with industry experts to estimate Fuel Cell system costs for HDV systems

Fuel Cell System: Observed price ranges

Fuel Cell System: Fuel Cell Stack and Balance of Plant Cost Studies

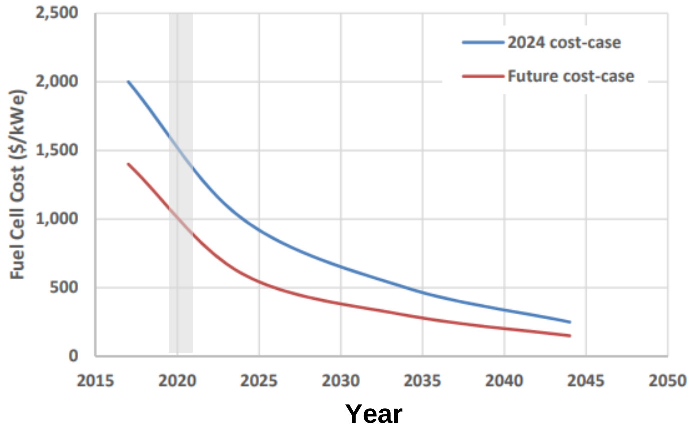
Fuel Cell Manufacturing costs DOE - SA *(1)*



Cost differences between light duty vehicle (LDV) and Medium Duty (MDV)/Heavy Duty (HDV) due to:

- Total Pt loading and MDV/HDV systems
- Assumes a nonvertical integration, sourcing sub-systems from lower Tier

Fuel Cell Costs Projections Hydrail – Ballard(4)



2024-Cost Case: This is the high-cost scenario these are projected to decline as the volume of grows

Future-Cost Case: This is a low-cost case where the component costs presume projected future costs reflecting both design advances and increasing volume of production as demand from other applications of hydrogen technology grow

- Ricardo identified public studies to estimate the price of the FC system, additionally engaged in discussions with leading industry stakeholders to confirm these estimations. Two relevant independent studies were evaluated:
  - DOE-Strategic Analysis study valuates ***the cost of manufacturing*** transportation fuel cell systems (1)
    - Markup rate for the final system assembler to account for the business expenses of general and administrative (G&A), R&D, scrap, and profit is not included in the cost estimates of the DOE-SA study (1)
    - The HD baseline is a 275kW HD Class 8 truck(2)
  - Ballard supplied fuel cell costs projections in the Regional Express Rail Program Hydrail Feasibility Study Report(4). The study concludes that by 2020 the FC systems $/kW projected to be between $1,000 to $1,500(4)
- Estimations are highly dependable on production volumes. Toyota Mirai sold 10,000+ units globally since its start of production in 2014(3)
  - ***Toyota sees global sales of fuel cell electric vehicles (FCEV) increasing significantly after 2020, to at least 30,000 per year from today's 3,000***(5)

(1) Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update (2) 2020 DOE Hydrogen and Fuel Cells Program Review Presentation – Fuel Cell System Analysis, Strategic Analysis (3) Toyota Annual Financial Report 2019, New Mirai Press information (4) Hydrail study: http://www.metrolinx.com/en/news/announcements/hydrail-resources/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf (5)Toyota https://global.toyota/en/newsroom/corporate/22647198.html,

The estimated cost for a 390kW Fuel Cell System is between ~$390K and ~$585K

RICARDO

Fuel Cell System: Estimated price range and weight

	Low	Average*	High
Parameter ($/kW)	$1000	$1250	$1500
390kW	**$390,000**	**$487,500**	**$585,000**

(*) Indicates average of Ricardo Data Points
kW indicates electrical net power

Fuel Cell size (kW)	Estimated Weight lbs (kg)
390	**1426 (647)**

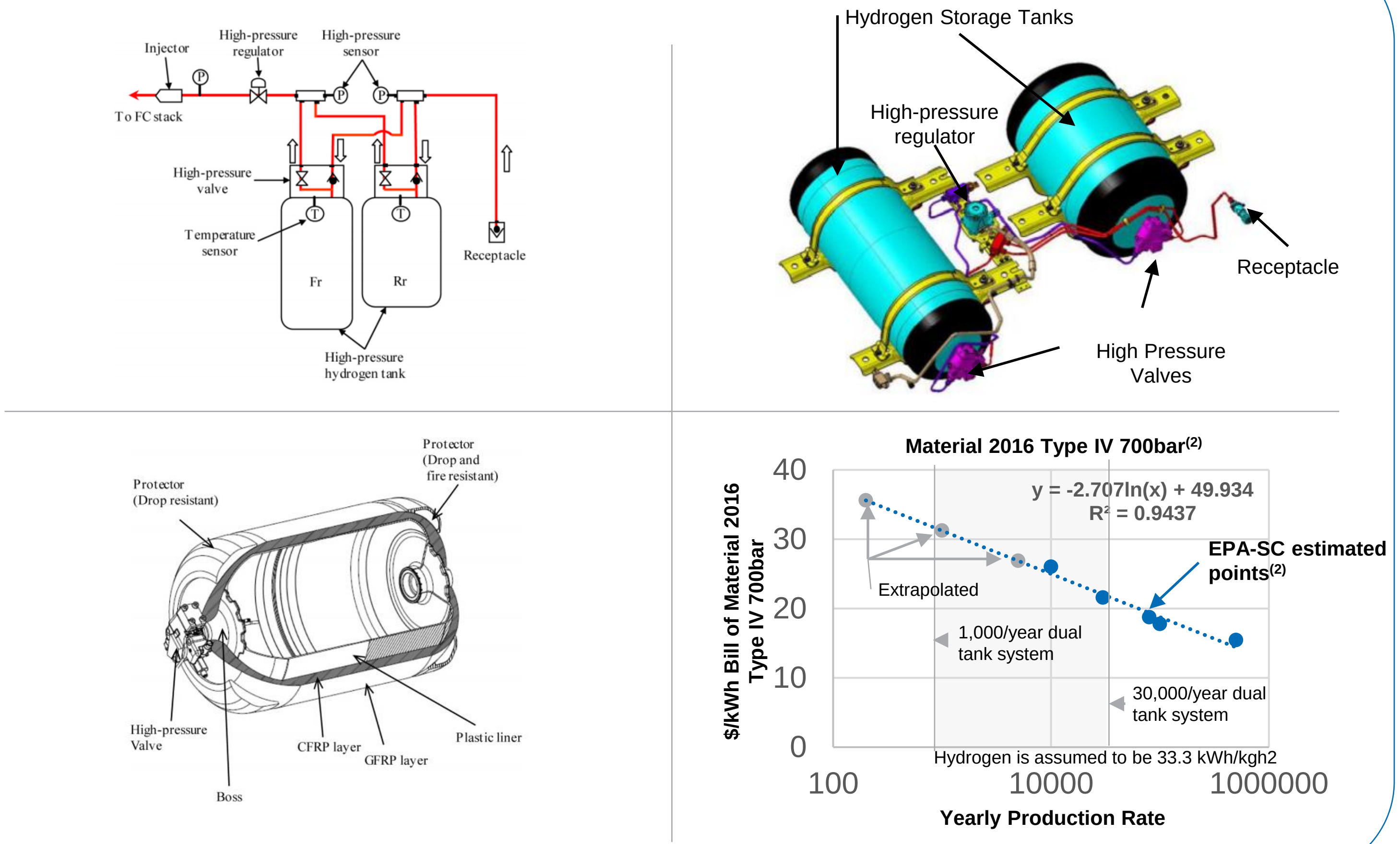
- ***Fuel cell industry leaders did not disagree with estimations of the hydrail program*** and suggested using Hydrail estimations over DOE-SA manufacturing costs for current market status
- Other factors to consider in the cost reduction are performance improvements of a new generation of fuel cells
- Weight includes DC/DC converter and assumes an FC system power density of 659 W/kg [(2)]

(1) Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers, RTI International
(2) DOE Technical Targets for Fuel Cell Systems and Stacks for Transportation Applications, Hydrogen and Fuel Cell Technologies Office
(3) Hydrail study: http://www.metrolinx.com/en/news/announcements/hydrail-resources/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf
(4) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

Hydrogen Storage system includes Type 4 tanks and Balance of Plant Components

Hydrogen Storage System: Overview and observed price ranges

Hydrogen Storage System and Balance of Plant Components (1)



- The Hydrogen Storage System includes type 4 70MPa tanks, high pressure sensor, high pressure regulator, receptable, receptable communication sensor, and high-pressure valve
- The efficiency of a hydrogen storage system is driven by liner material thickness, carbon fiber composite efficiency and minimum pressure allowed to operate
  - Advanced hydrogen storage tanks can achieve up 5.7 Wt%(1) (Wt% is defined as the weight of usable hydrogen divided by total tank weight)
- Ricardo utilized bottom-up system costs estimated in EPA – Strategic Analysis Consulting study. The analysis valuates the cost of manufacturing Hydrogen Storage System (2), Ricardo extrapolated for values below 10,000 units/year

(1) Development of High-Pressure Hydrogen Storage System for the Toyota "Mirai"
(2) Final Report: Hydrogen Storage System Cost Analysis, September 2016, OSTI

Hydrogen Storage System benchmark price estimated to be $77K-$112K for total on-board storage capacity of 75 kg; 60kg useable

RICARDO

Hydrogen Storage System: Estimated price range and weight

	Low	Average*	High
Parameter ($/ useable kg)	$1,288	$1,578	$1,865
60kg useable	**$77,300**	**$94,700**	**$111,900**

(*) Indicates average of Ricardo Data Points

Hydrogen Storage Capacity	Estimated Weight lbs (kg)
60kg	**~2860 (~1,300)**

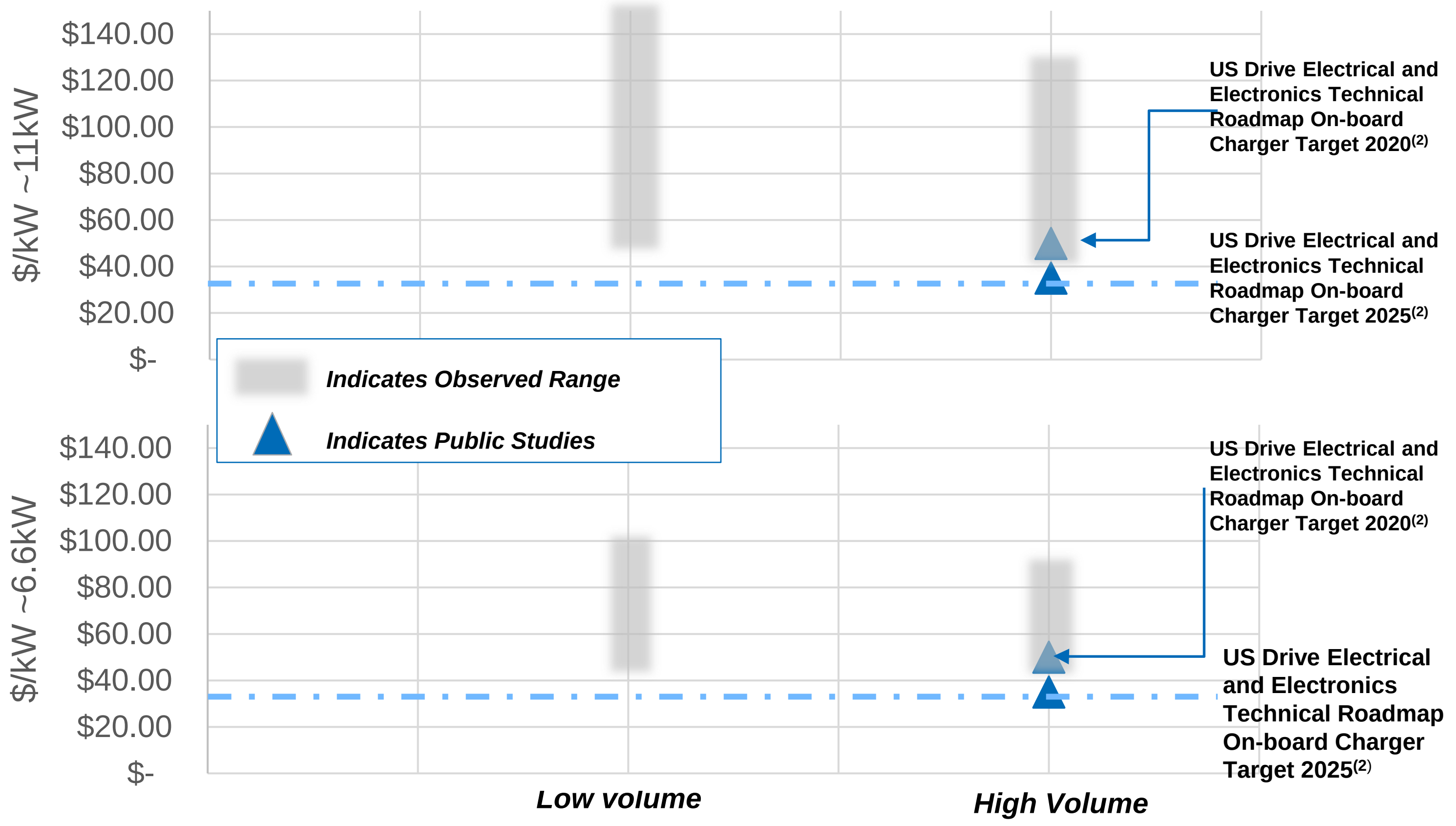
- Analysis is based on Type IV tanks at 70 MPa; 12.5 kg x 6 tanks (10kg usable per tank)
- The low value corresponds to a HSS manufacturing cost at low production volumes (1000 dual tank configuration units per year)(2), it assumes an indirect cost RPE of 1.3 (4)
- The low value corresponds to a HSS manufacturing cost at low production volumes (30,000 dual tank configuration units per year)(2) it assumes an indirect cost RPE of 1.3 (4)
- Average system price is ~$1500/kg usable, ~$1200/kg total volume
- It assumes a system weight efficiency of 4.55 Wt% (ratio between useable hydrogen and max system mass)(1)
- Main companies operating in this industry includes Hexagon (Agility), Faurecia, Iljin
- Hydrail program estimated a hydrogen storage system range between $870/kg to $1087/kg **equivalent to $65,250 and $81,525**, volumes for these estimations are not disclosed(3)

(1) DOE Technical Targets for Onboard Hydrogen Storage for Light-Duty Vehicles, Hydrogen and Fuel Cell Technologies Office (2) https://www.osti.gov/servlets/purl/1343975 ; https://www.nrel.gov/docs/fy19osti/73353.pdf ; (3) http://www.metrolinx.com/en/news/announcements/hydrail-resources/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf (4) Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers, RTI International

Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

On-board charger costs range is between $40/kW for high volume lower power and $150/kW for low volume high power

On-board charger: Observed price ranges



- Ricardo observed price ranges from interviews, cost studies, cost roadmaps and public domain for commercial and other electric vehicle segments
  - Ricardo considered only on-board chargers ranging between 6.6kW and 22kW power output
- Cost variance primarily driven by volume, technology, features and application
  - Automotive OBC operate in lower power ranges and produced at higher rates than commercial vehicle chargers
  - Other features such as 3-Phase charging, integrated DC/DC converter, bidirectional features
- On-board chargers considered are liquid cooled and voltage range between 400V – 800V

(1) Source: Ricardo analysis (2) US DRIVE

The estimated OBC cost for the Battery Electric vehicle is $3,170 and for the Fuel Cell Vehicle is $442

On-board charger: Estimated price range and weight

	Low	Average*	High
Parameter ($/kW) ~6.6kW	$40	$67	$100
Parameter ($/kW) 11kW – 22kW	$45	$72	$150
44 kW (BEV)	**$2,000**	**$3,170**	**$6,600**
6.6 kW (FC)	**$264**	**$442**	**$660**

(*) Indicates average of Ricardo Data Points

OBC Power (kW)	Estimated Weight lbs (kg)
44kW	**101 (46)**
6.6kW	**13 (6)**

- On-board charger cost assumes a Tier-1 supplier providing the component
- Cost does not include external subsystem such as HV connections, and external cooling system (considered in other sub-systems in this study)
- Estimation based on market observations between 2019 and 2020
- It is assumed a weight density of 0.95kW/kg for high power OBC and 1.12kW/kg for low power OBC

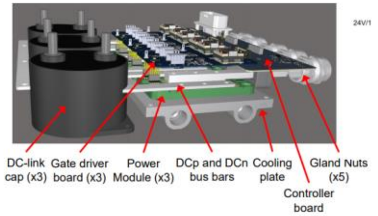
(1) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

Electric drive unit includes electric machine, inverter and gearbox; technology still evolving driven by the automotive industry

Electric Drive unit: Overview

Inverter[5]
(For visualization only)

- Inverters incorporate a wide variety of components, including insulated-gate bipolar transistor (IGBT) power devices, high-voltage DC line capacitors, main circuit busbars, a power module drive circuit board, a motor control circuit board, three-phase current sensors, and DC and heavy-current AC connectors[9]
- Several technologies are disrupting the inverters including Silicon Carbide (SiC). Ricardo is developing with DOE a SiC inverter with DOE for Heavy Duty Trucks



High Efficiency Powertrain for Heavy Duty Trucks using Silicon Carbide (SiC) Inverter Ricardo[8]

Motor [6]
(For visualization only)

- Induction motor is a robust motor technology, free of permanent magnets, good efficiency but relatively low in power density
- Reluctance motors (Switched or Synchronous) motors are robust and low cost, without permanent magnets, but may have some NVH issues
- Interior permanent magnet motors benefit from superior power density, torque and efficiency. However, they require Rare Earth Elements (REE).
- Axial flux motor is a robust permanent magnet motor with very low aspect ratio, which enables packaging location between engine and transmission for HEV, or other mobility applications
- Hybrid motors are a combination of Internal Permanent Magnet motor technology with other technology such as Synchronous Reluctance

Transmission [7]
(For visualization only)

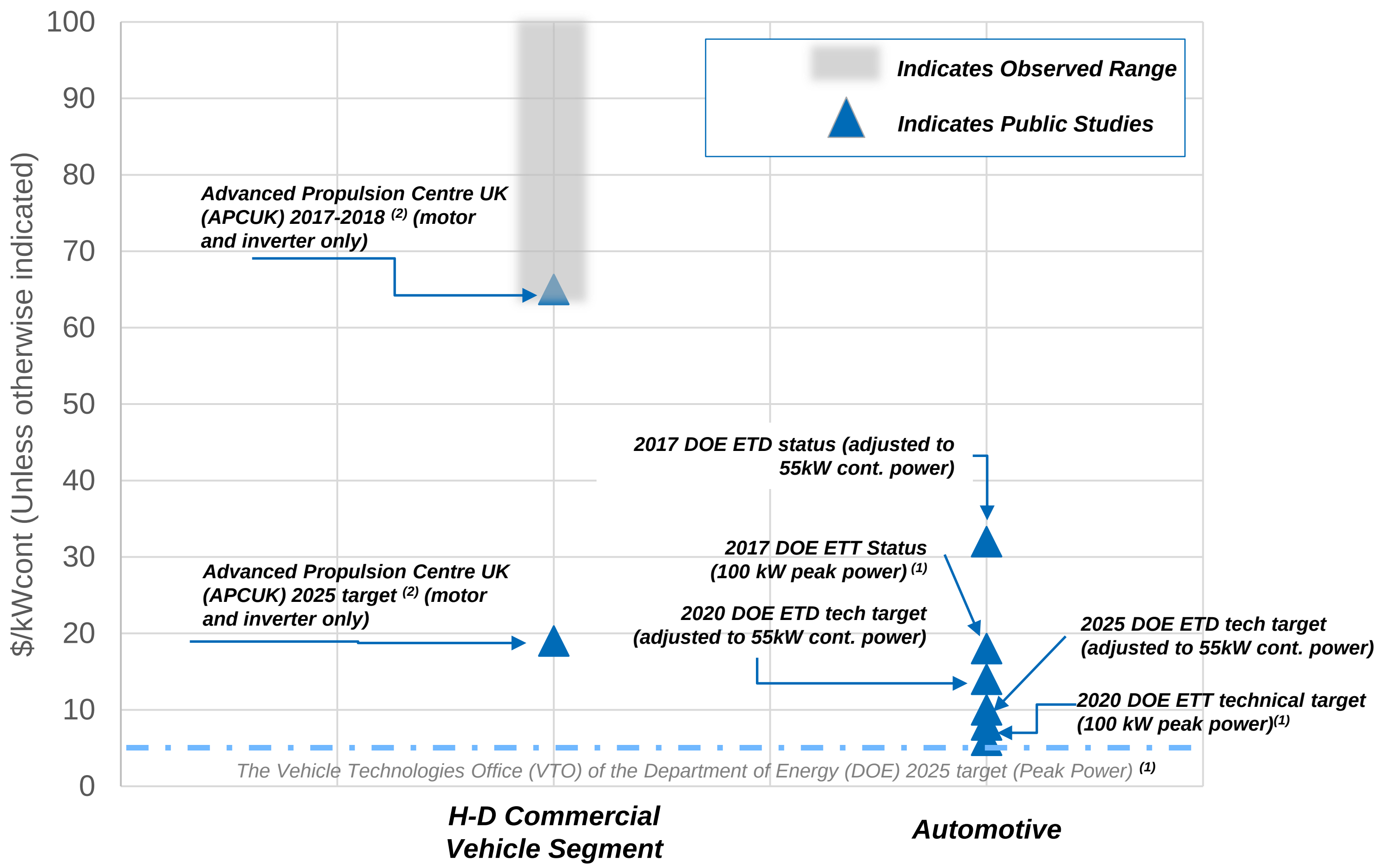
- Transmission transfer the mechanical energy from the motor to the rear axle/wheels
- Research shows the energy consumption of heavy-duty electric trucks may be optimized with transmissions[10]

- On-road application of e-driveline technology is not at steady state[1] There are many technologies emerging including but not limited to:
  - Architecture: Use of motors integrated with rear axle[2], dual motors with prop shaft and transmission[3], integrated cooling system, system voltage
  - Motor: Induction machines, Permanent Magnet machines, Synchronous Reluctance machines, Hair Pin Stator
  - Inverter: Integrated units, SIC technology
- Industry experts agrees that multispeed gear box application will be led first by commercial vehicle application and performance light duty vehicles
- The most common technology observed in the market is currently Permanent Magnet motors [4]

(1) Industry expert opinion survey 2021 20+ (2) Tesla (3) Volvo (4) Ricardo Survey 2019 (5) Zhejiang Alpha Electric, (6) Zhejiang Alpha Electric, (7) Antonov (8) Ricardo – DOE (9) High-power-density Inverter Technology for Hybrid and Electric Vehicle Applications – Hitachi (10) Design, Analysis, and Optimization of a Multi-Speed Powertrain for Class-7 Electric Trucks

H-D commercial eDriveline average price per kW is $82/kW and includes motor, inverter and transmission for heavy duty application

Electric Drive unit: Observed price ranges



- Ricardo observed price ranges from interviews, cost studies, cost roadmaps and public domain for commercial and other electric vehicle segments
- Observed a price gap between HD and LDV applications, potentially due:
  - Production volume rate, LDV OEMs are developing motor/inverter for multi-platforms hence increasing the yearly production rate[1]
  - LDV application is driving to highly compact and powerful units developing integrated inverter/gearbox units
  - Different requirements on mechanical loads, durability and packaging than LDV applications

(1) Source: Technical Targets for Electric Traction Drive System (2) The roadmap report Towards 2040: A guide to automotive propulsion technologies, assumed continuous power, 300% mark-up on material costs, added inverter and motor targets

The estimated cost of a 350kW continuous eDrive is between ~$22k and ~$35k with an average weight of 800kg

Electric Drive unit: Estimated price range and weight

	Low	Average	High
Parameter ($/kW)	$65	$82	$100
350kW$_{cont}$	**$22,750**	**$28,700**	**$35,000**

E-drive size	Estimated Weight lbs (kg)
350kW$_{cont}$	**~1763 (800)**

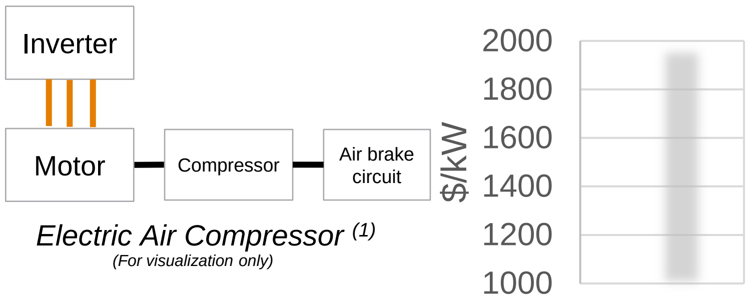
- This study assumes an inverter driving a single electric motor (PM) with a multi-speed transmission connected to a prop-shaft
- Cost does not include brackets, cooling system or installation costs to the vehicle
  - Supplier providing an integrated unit, motor, inverter and transmission
- E-drive weight is based on averaging density of studies

(1) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

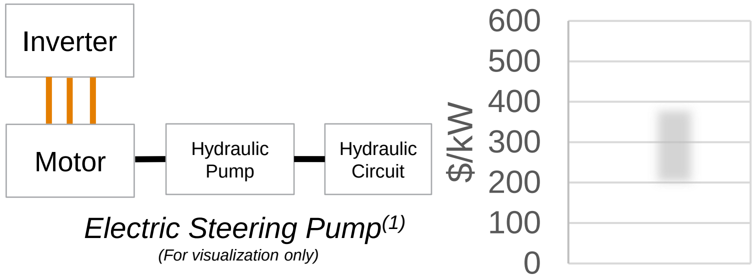
Study includes a high voltage electric air compressor for the brake system and electric hydraulic pump for the steering system

High Voltage Air Compressor and Steering: Overview

Indicates observed range



Electric Air Compressor [(1)]
(For visualization only)



Electric Steering Pump[(1)]
(For visualization only)

- It does not include high voltage harness (included in high voltage subsystems), adapting features from compressor to vehicle air braking system, output sensing feedback to vehicle controller, any air dryer or air filtering system modifications

- It does not include high voltage harness (included in high voltage subsystems), other hydraulic system mechanisms, hoses and heaters (assumed part of chassis)

- Ricardo observed price ranges from interviews, cost studies, cost roadmaps and public domain for commercial and other electric vehicle segments
- The electric air brake system supplies air to the air brakes and substitutes the engine driven compressor. It has three main components: compressor, electric motor and inverter
  - Observed Vane compressors and induction machines
- The electric steering pump hydraulically assists the steering system and substitutes the engine driven pump. It has three main components: steering pump, electric motor and inverter
  - Observed gear and vane hydraulic pumps driven by induction machines
- It is observed that the market offers solutions for this application utilizing mass produced components
  - Adapted from other industries such as rail, industrial or transportation

(1) Ricardo Analysis

The estimated cost of an 6kW electric air compressor is between ~$6.5k and ~$11.4k and the estimated cost of a 9kW electric steering pump is between ~$1.8K and ~$3.5K

High Voltage Air Compressor and Steering: Estimated price range and weight

Electric Air Compressor Cost Estimations

	Low	Average	High
Parameter ($/kW)	1,080	1,500	1,900
~6kW	**~$6,480**	**~$9,000**	**~$11,400**

Electric Steering Pump Cost Estimations

	Low	Average	High
Parameter ($/kW)	200	300	390
~9kW	**~$1,800**	**~$2,700**	**~$3,500**

Electric Air Compressor Weight Estimations

Electric Air Compressor assumed size	Estimated Weight lbs (kg)
~6kW	**152 (69)**

Electric Steering Pump Weight Estimations

Electric Steering assumed size	Estimated Weight lbs (kg)
~9kW	**275 (125)**

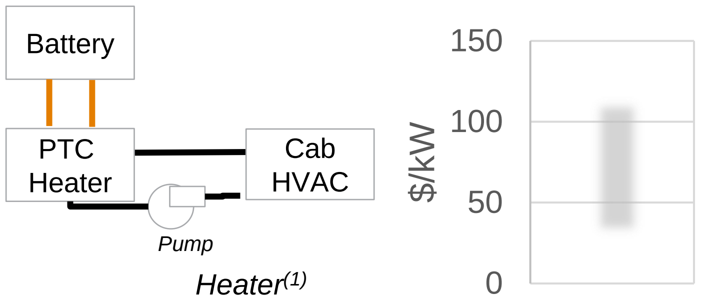
- Electric compressor considers a Vane compressor with an induction machine
  - Considerations to include advanced inverter technology from automotive sector in the low end of range
- Electric steering pump considers a Vane and Gear solution with an induction machine
  - Considerations to include advanced inverter technology from automotive sector in the low end of range
- Considers a system assembled and supplied to the OEM as a custom solution for packaging
  - NRE may be required to adapt design to OEM packaging requirements
- Weight does not include system related component such as connecting hoses to vehicle but includes
  - Air filter intake, brackets (for motor and compressor/pump support only), motor and compressor connecting hardware, motor and pump connecting hardware

(1) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

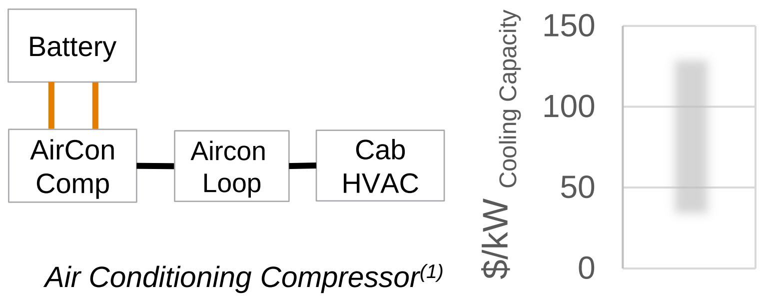
Study includes a high voltage heating system and high voltage air conditioning system supplying to existing HVAC system

Heater and Air-Conditioning compressor: Overview

Indicates observed range



Heater(1)
(For visualization only)



Air Conditioning Compressor(1)
(For visualization only)

- It does not include high voltage harness (included in high voltage subsystems), and hoses to Cab HVAC blower
- Considers no modifications in existing platform cabin HVAC
- Commonly the industry uses PTC (positive temperature coefficient) as heater elements

- It does not include high voltage harness (included in high voltage subsystems), and hoses to refrigerant loop
- Considers no modification to existing air conditioning loop and cabin HVAC
- Commonly the industry uses scroll compressors with integrated inverters operating in ~400V or ~600V

- Ricardo observed price ranges from interviews, cost studies, cost roadmaps and public domain for commercial and other electric vehicle segments
- The electric air conditioning compressors replaces the diesel driven compressor. It is assumed an integrated compressor with inverter
- The heater supplies energy to the HVAC heating loop. Heater operates in Vdc with integrated power driver
- BEV optimizes use of energy consequently vehicle may need additional defrosting features for windshield or additional heater solutions in cold regions
- Development of a modified heater and Air-Conditioning compressor may be required. Off-the-shelf automotive solution may require validation for Heavy Duty commercial applications

(1) Ricardo Analysis

The average observed heater cost per kW is \$75/kW; the average observed compressor cost per cooling capacity kW is \$70/kW

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Heater and Air-Conditioning compressor: Estimated price range and weight

Heater Cost Estimations (includes pump)

	Low	Average	High
Parameter ($/kW)	45	75	115
~10kW Day Cab	**$450**	**$750**	**$1150**
~25kW Sleeper	**$1125**	**$1875**	**$2875**

Air Conditioning Cost Estimations

	Low	Average	High
Parameter ($/$kW_{\text{cooling Capacity}}$)	47	70	125
~$10kW_{\text{cooling capacity}}$ Day Cab	**$470**	**$700**	**$1,250**
~$25kW_{\text{cooling capacity}}$ Sleeper	**$1,175**	**$1,750**	**$3,125**

Heater Weight Estimations (includes pump)

PTC heater assumed size	Estimated Weight lbs (kg)
~10kW Day Cab	**22 (10)**
~25kW Sleeper	**44 (20)**

Air Conditioning Weight Estimations

Electric Air Conditioning assumed size	Estimated Weight lbs (kg)
~$10kW_{\text{cooling capacity}}$ Day Cab	**24 (11)**
~$25kW_{\text{cooling capacity}}$ Sleeper	**62 (28)**

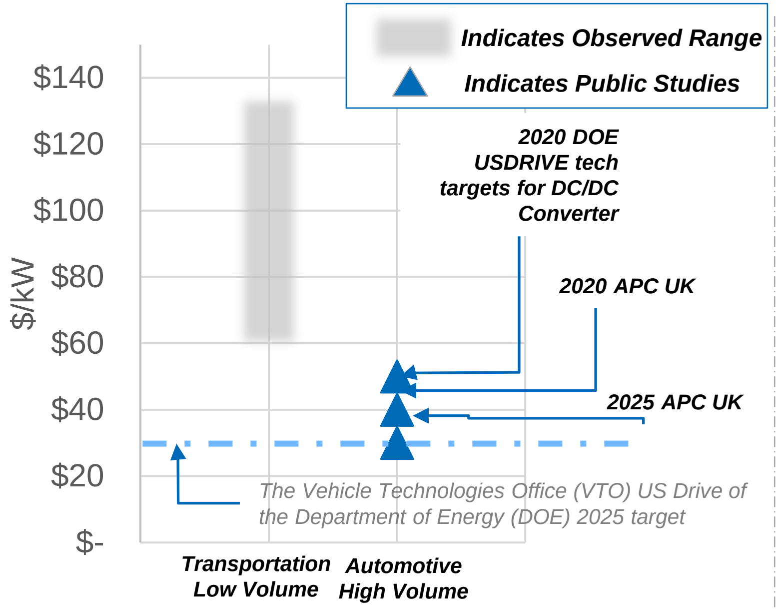
- This analysis considers a liquid heater and a scroll compressor for cost and weight
  - The cost and weight of hoses and other HVAC related components included in the diesel HVAC system
- Considers heater and air-conditioning compressor adopting technology from the automotive sector and economies of scope
  - The analysis does not consider modified technologies from other industries
  - Additional NRE may be required
- Heater kW indicates the nominal power of heater system, Compressor $kW_{\text{cooling capacity}}$ indicates maximum cooling capacity of the compressor
- Estimated heater and compressor weight is based on averaging density of several solutions

(1) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

The HV distribution system includes all components to manage the high voltage architecture; DC/DC converter supplies power to the LV system

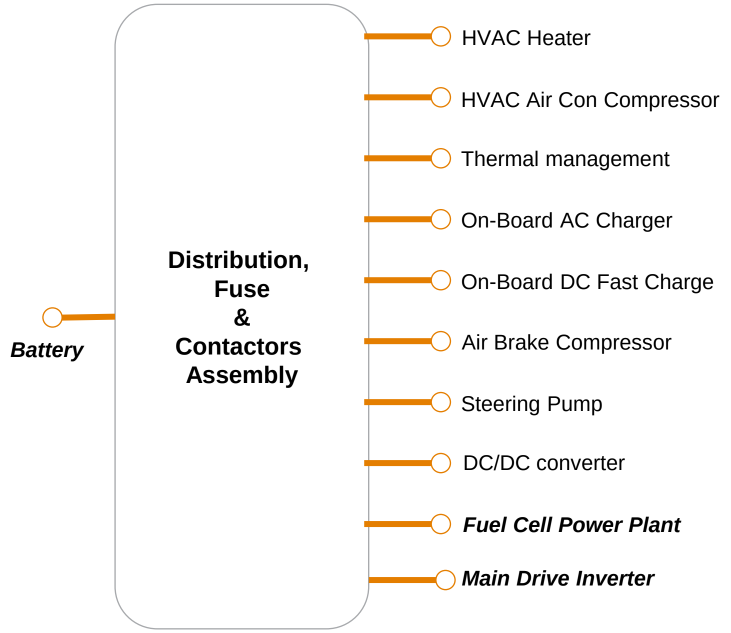
HV distribution system and DC/DC Converter: Overview

DC/DC Converter(1)(2)



- It does not include high voltage harness (included in high voltage subsystems)
- Considers no modifications to existing 12Vdc systems

HV distribution system



- Ricardo observed price ranges from interviews, cost studies, cost roadmaps and public domain for commercial and other electric vehicle segments
- The high voltage DC/DC converter transforms HVDC input to low DC voltage (12V), subsequently powers the low voltage electrical system
  - It replaces the function of the alternator
- The high voltage distribution system is divided into the HV junction box and HV harnessing
  - High voltage harnessing (considers the estimated length, power capacity, and high voltage rated connectors)
    - High power connectors can be divided into multiple inputs to reduce the load and use market available products
    - Battery is divided into strings due to its large capacity
    - Harnesses installation performed by OEM, supplier provides assembled harnesses
  - The High voltage junction box includes
    - Fuses to each circuit considering the current load
    - Contactors to outputs, DC fast charging, and OBC
    - Internal busbars and current sensors to monitor circuit
    - Automotive rated aluminum enclosure, it does not include brackets
    - Assembly costs and indirect cost for junction box
    - Assumes multiple inputs form battery pack strings
      - JB includes a master BMS to communicate with battery string BMS and vehicle

(1) Technical Targets for Electric Traction Drive System US DRIVE 2017 (2) Power Electronics Roadmap 2020 Narrative Report, February 2021, Advanced Propulsion Centre UK

The estimated cost of the DC/DC converter is ~$360 and ~$780; High Voltage BEV distribution box estimated between ~$6,650 and ~$12,950

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HV distribution system and DC/DC Converter: Estimated price range and weight

DC/DC Converter

	Low	Average	High
Parameter ($/kW)	60	90	130
~6kW	**~$360**	**~$540**	**~$780**

High Voltage Distribution System - BEV 600kWh Battery

	Low	Average	High
Parameter ($/kW)	~19	~27	~37
eDrive (350kW cont.)	**$6,650**	**$9,450**	**$12,950**

High Voltage Distribution System - 12kWh Battery 390kW FC

	Low	Average	High
Parameter ($/kW)	~19	~25	~32
eDrive (350kW cont.)	**$6,650**	**$8,750**	**$11,200**

DC/DC Converter

Size	Estimated Weight lbs (kg)
~6kW	**17 (8)**

High Voltage Distribution System

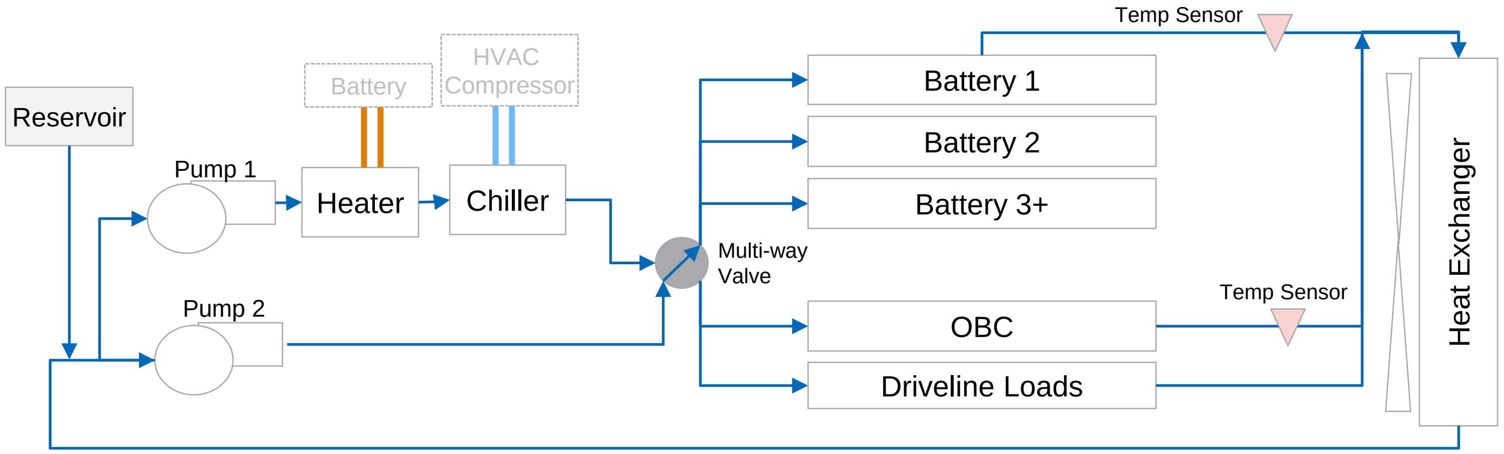
Size	Estimated Weight lbs (kg)
BEV (350kW)	**213 (97)**
Fuel Cell (350kW)	**154 (70)**

- Even though there are synergies between automotive DC/DC converters and commercial vehicle DC/DC converters, the cost savings might not translate due to lower volumes
  - DC/DC converter will require NRE for durability validation
- HV junction box will need NRE and Tooling not included in the piece price for aluminum die casting enclosure
  - Industry stakeholders agree this component is usually a custom-made solution and requires extensive validation
- Main cost drivers of the high voltage junction box are system power requirements, number of I/Os, and high voltage contactors
- For harness length estimations, the study considers battery installation underbody (multiple strings), high voltage components to be located under the hood, and HVJB located behind cab
- FC junction box does not include master controller due to smaller battery

(1) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

Traditional cooling system for battery electric trucks is a liquid cooling system with an interface to a refrigerant system

Battery and electronics thermal management: Overview



*for visualization only, does not represent actual system but standard components of a cooling system

- The battery electronics thermal management is a liquid cooling system with a heating and cooling system (chiller and heat exchangers)
  - Traditionally the heating system utilizes a PTC liquid element
  - To dissipate heat, the cooling system uses heat exchangers as well as a chiller (with interface with the HVAC compressor)
- The system in this analysis includes PTC heater, Chiller, two high power pumps, multi-way valve, temperature sensors, and heat exchanger with fans
  - This analysis assumes high voltage pumps
  - The heat sources to dissipate include batteries (multiple strings), on-board charger, air compressor inverter, steering pump inverter, main motor inverter, drive motor, and DC/DC converter
  - Battery requires approximately cooling (BEV) and significant heating (BEV)
    - FCPS cooling system is included in the FCPS cost/weight section

(1) Ricardo analysis

The estimated cost for the BEV cooling system is between ~$6,000 and ~$9,700 driven primarily by the high voltage heating system

Battery and electronics thermal management : Estimated price range and weight

Battery and electronics thermal management – 600kWh battery

	Low	Average	High
Parameter ($/kW)	~17	~21	~27
BEV (350kW)	**$6,000**	**$7,600**	**$9,700**

Battery and electronics thermal management – 12kWh battery

	Low	Average	High
Parameter ($/kW)	~8	~9	~11
Fuel Cell (350kW)	**$2,900**	**$3,200**	**$3,700**

**FCPS cooling system not included in this sub-system*

Battery and electronics thermal management

Size	Estimated Weight lbs (kg)
BEV	**227 (103)**
Fuel Cell	**101 (46)**

- The primary cost driver in the BEV is the high voltage heater system due to the large battery pack
- The primary cost driver in the FCV power electronics cooling system is the radiator and pumps
  - FCPS is considered an independent system; consequently, cooling cost and weights included in the FCPS system
- Estimated price includes heater, pumps, chiller, valves, hoses, radiator, temperature sensor, expansion tank, and hose clamps
  - Installation cost are not considered as assumed to be part of the OEM labor costs
  - The cooling system requires NRE for high power pump development and heat exchangers
  - Lower end cost and weight considers advanced inverters

(1) Multipliers in this report are a correlation between cost and a primary driver for the analyzed architecture. Any changes on specification require additional analysis to estimate costs

Contents

Fuel Cell system cost expected to decline by 50% in 2025 to $625/kWnet average while HSS cost expected to reduce by 22% by 2025 according to industry studies

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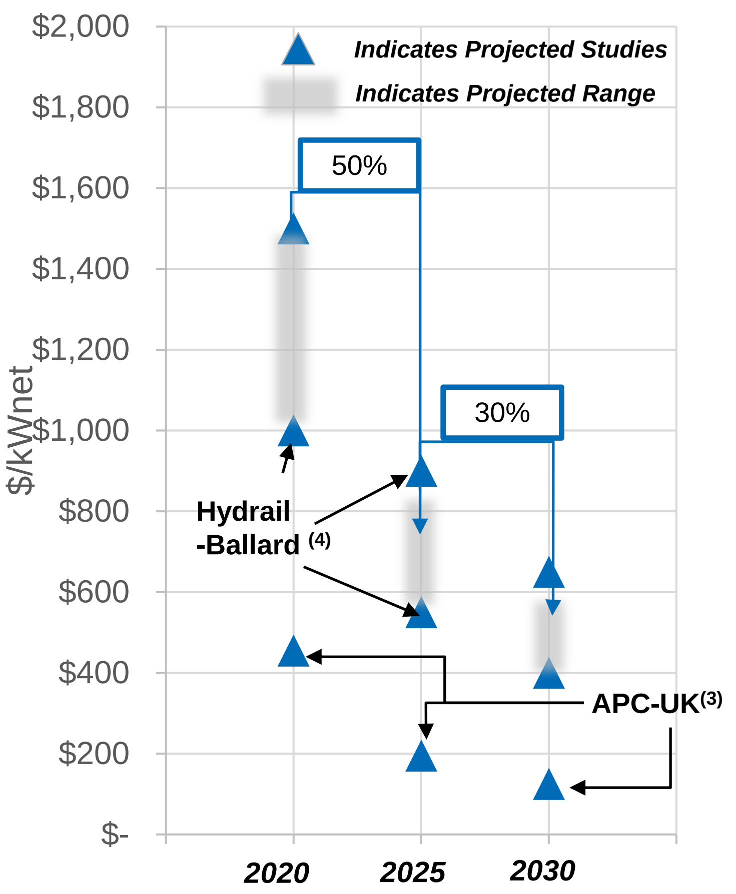
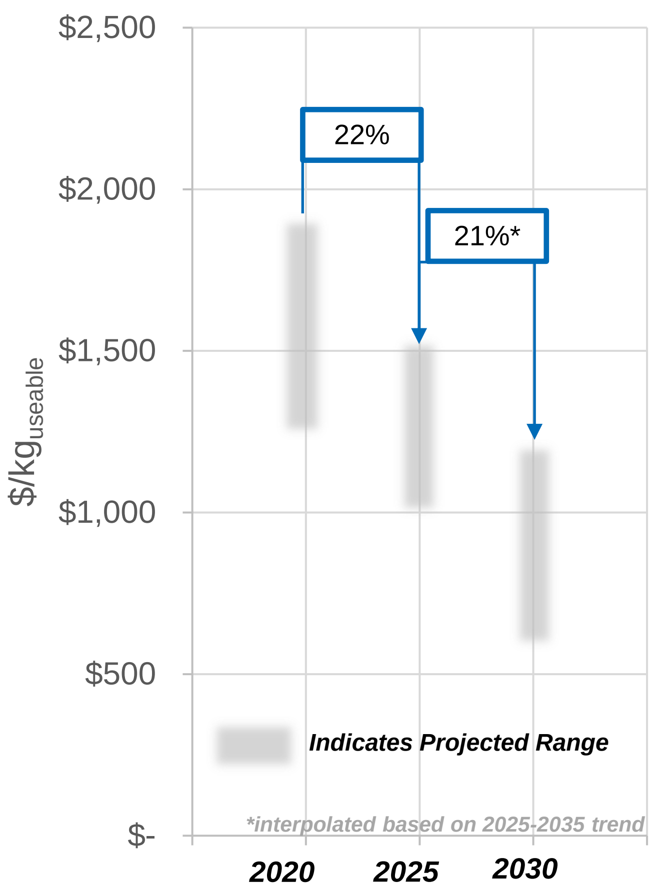
Price Forecast: Fuel Cell and Hydrogen Storage System

Commercial Vehicle Fuel Cell System Cost Forecast[(1)(2)]



Commercial Vehicle Hydrogen Storage System Cost Forecast[(3)]

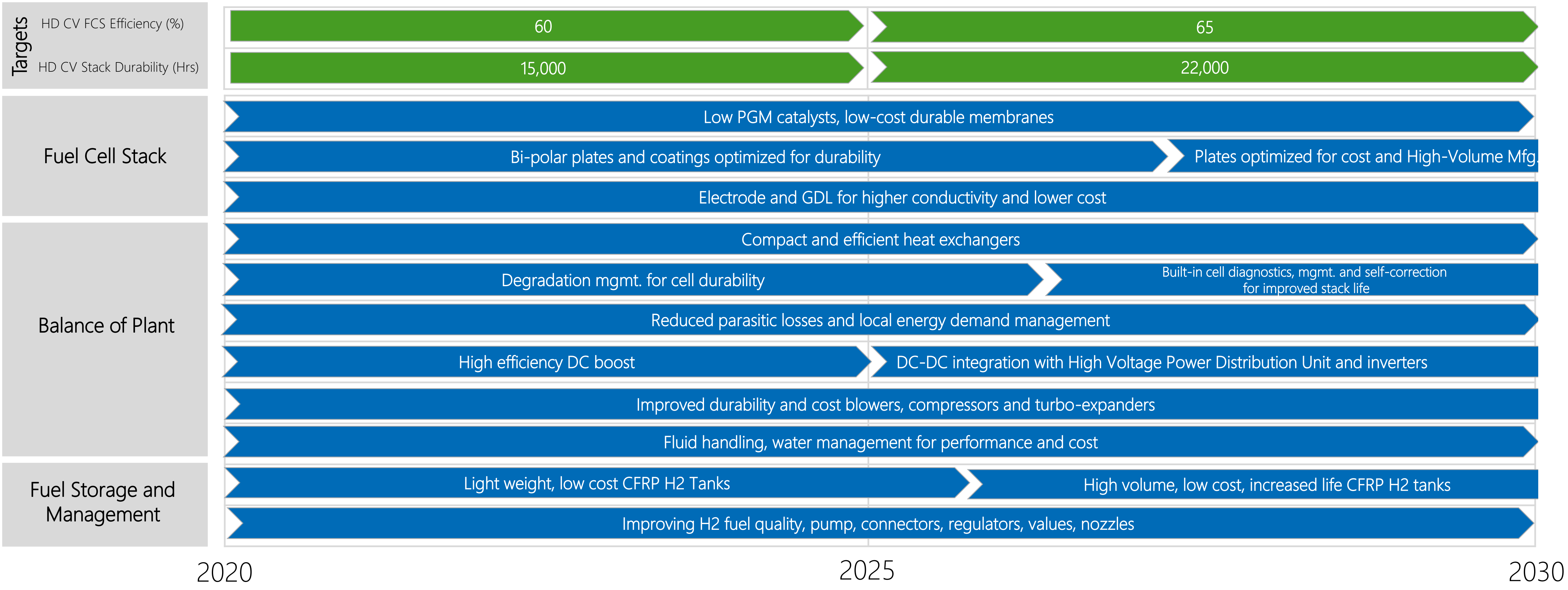


- Fuel Cell price reduction consider an average of projected price of APC-UK study and Hydrail-Ballard projections, APC-UK study considers 50,000 production volume by 2025
  - Toyota sees global sales of fuel cell electric vehicles (FCEV) increasing significantly after 2020, to at least 30,000 per year from today's 3,000[(5)]
- Industry experts did not disagree with projected price reduction of hydrogen storage system
- New technologies that can help reduce cost of fuel cell systems include[(3)]:
  - Reduction of platinum group metals content
  - Material improvements for bi-polar plates and electrode and gas diffusion layers
  - Improving thermal management with advanced heat exchangers
  - Better designs for air-handling systems
  - Improvements to fluid-handling systems
- Cost reduction opportunities for Hydrogen Storage System include:
  - Improvement in manufacturing cost as volume increase, which otherwise is labor and energy intensive[(3)]
  - Improvement of tanks designs layouts can minimize the amount of composite fiber
  - Standardization of BOP components can accelerate cost reduction by increasing volume
- APC estimations are for transportation applications. Ricardo estimated ranges center on commercial vehicles

(1) Source: Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update (2) 2020 DOE Hydrogen and Fuel Cells Program Review Presentation – Fuel Cell System Analysis, Strategic Analysis (3) Fuel Cell Roadmap 2020, Narrative Report, Advanced Propulsion Centre APC – UK (4) Hydrail study: http://www.metrolinx.com/en/news/announcements/hydrail-resources/CPG-PGM-RPT-245_HydrailFeasibilityReport_R1.pdf , (5)Toyota https://global.toyota/en/newsroom/corporate/22647198.html

Technology roadmap indicates continued development of new technologies to improve fuel cell and hydrogen storage performance

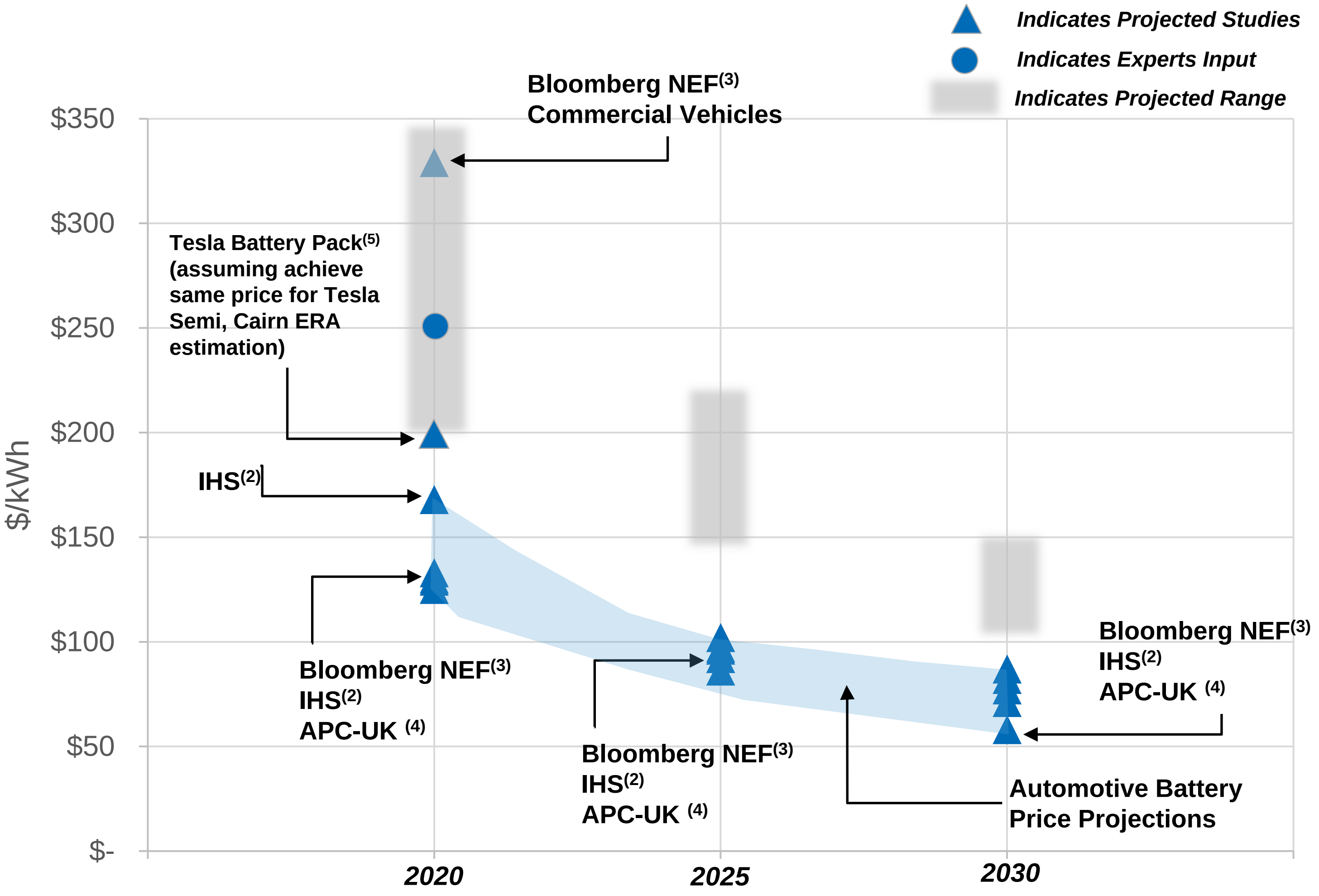
Technology Roadmaps: Fuel Cell and Hydrogen Storage System



(1) Source: APC

Battery pack prices for commercial vehicles expected to experience ~50% decline by 2030 due to higher demand and continued price decline in automotive market

Price Forecast: Battery Pack



- Considers technological and manufacturing synergies between LDV and HDV batteries
  - The price drop of HD battery assumes to follow the LDV trend
- New technologies can help reduce the cost of a battery pack, including (4):
  - Improvements in cost and performance of li-ion cell by improving cathodes, anodes, electrolytes, and separators
  - Move to high voltage architectures (800V), allowing thinner cables, more efficient motors, lower system weight, faster charging
  - BMS improvements will allow better management of battery life and performance
  - Optimize systems to heat battery in cold environments
  - New joining methods for more robust cell joining techniques
- APC estimations are for transportation applications. Ricardo estimated ranges are focused on commercial vehicles

(1) Source: Ricardo analysis (2) IHS Next Generation Battery Technologies and Market Trends NAATBatt Annual Conference 9 February 2021 (3) Passenger Electric Vehicle Outlook, NaatBatt 2021, February 2021, (4) APC UK Electrical Energy Storage Roadmap 2020 (5)Cairn ERA estimation $187/kWh, https://www.cnbc.com/2021/03/10/teslas-lead-in-batteries-will-last-through-decade-while-gm-closes-in-.html

Technology roadmap indicates a continue development of new technologies to improve cell and battery performance

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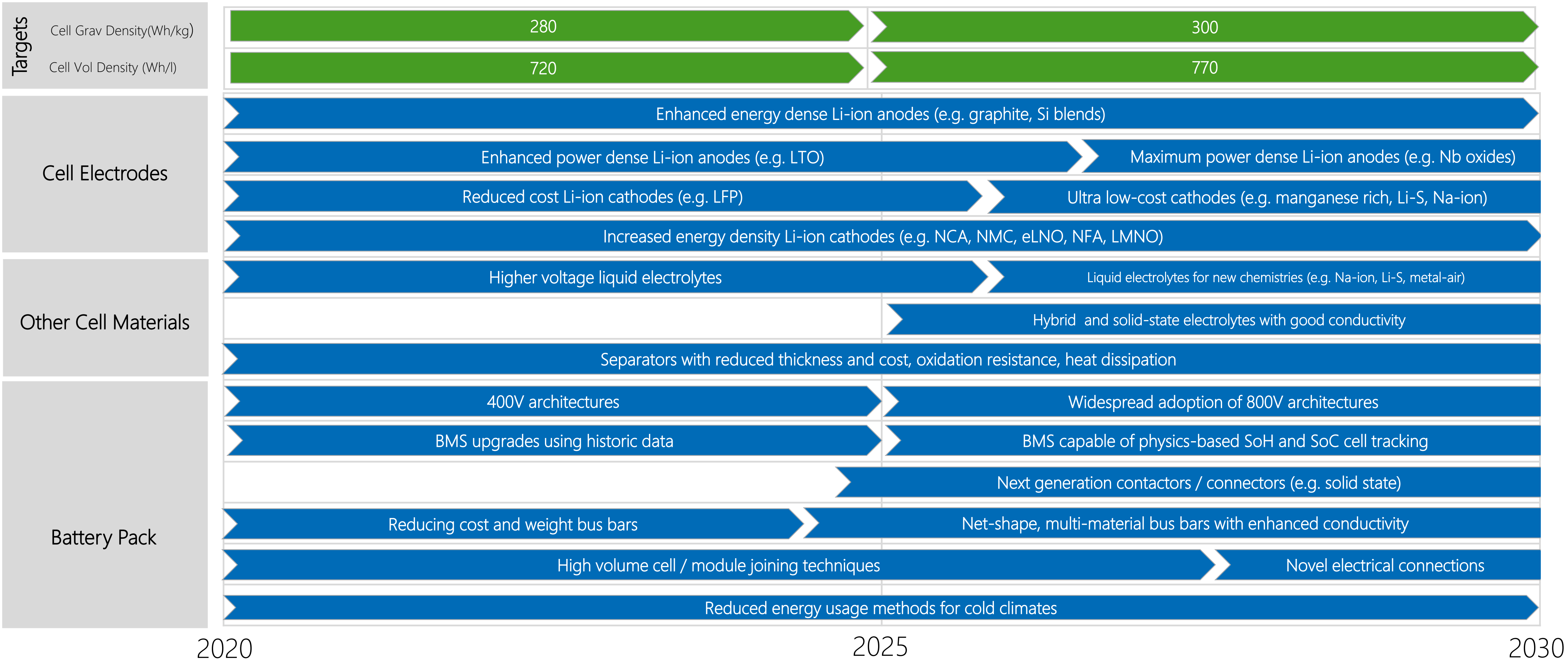
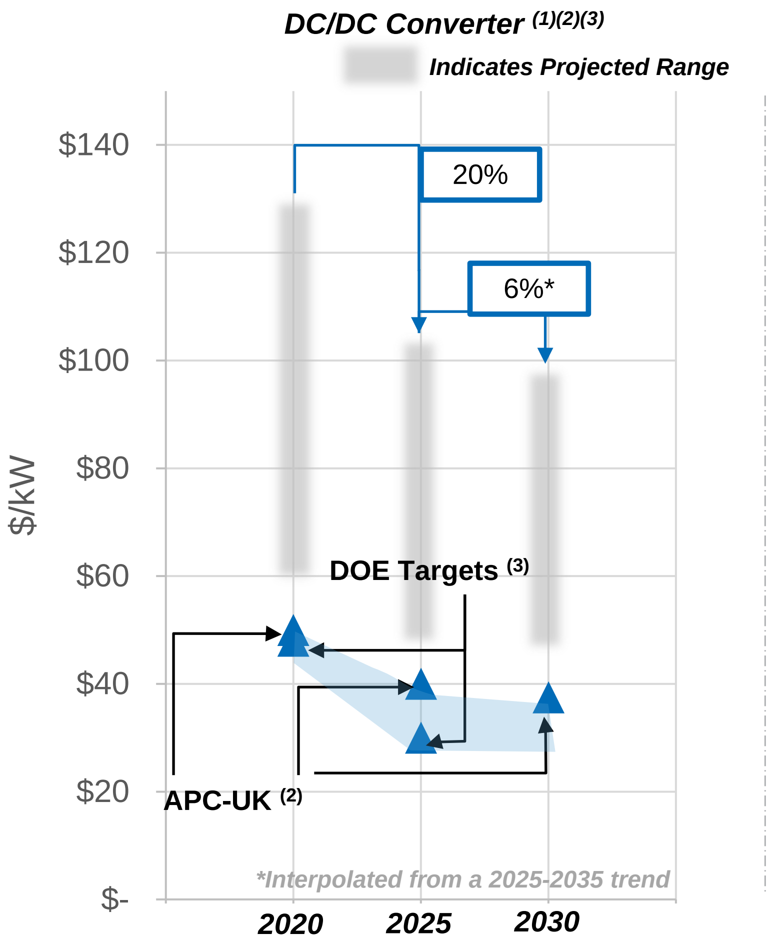
Technology Roadmaps: Battery pack

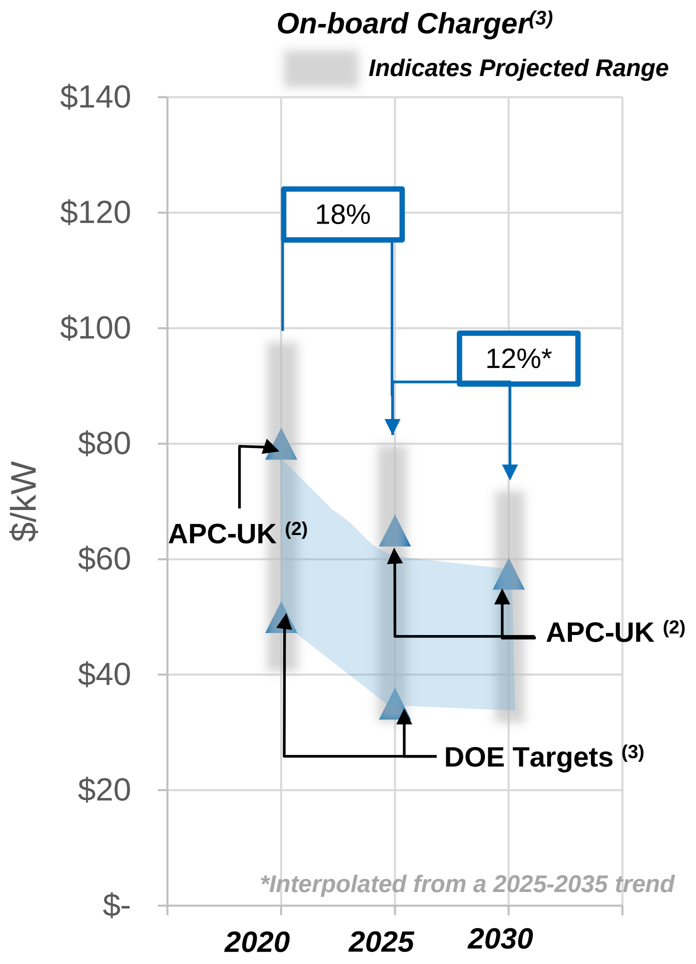


(1) Source: APC UK Roadmaps

The DC/DC converter and On-board charger cost expected to drop ~20% and ~18% by 2025 respectively primarily driven by synergies with the automotive industry

Price forecast: DC/DC Converter and On-board Charger



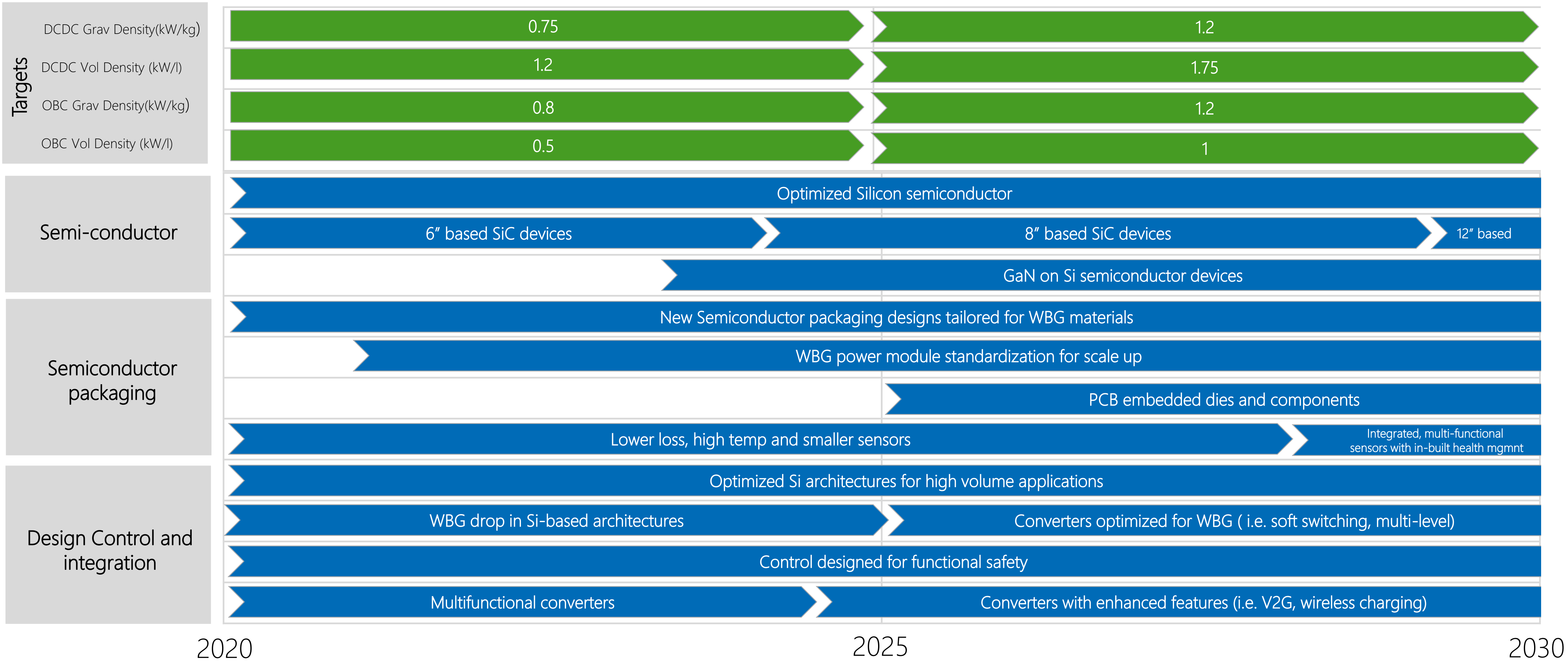


- APC forecast estimations with a production volume of >100k for 2025 and >200K for 2035 (synergies with automotive industries)
  - 2030 estimates are interpolated from 2025 and 2035 projections
- New technologies improving power electronics include (2):
  - Optimization of current Si semiconductor devices, semiconductors represent the highest-cost in automotive power electronics
  - Emerging and commoditization of Wide Band Gap (WBG) semiconductor devices such as SiC and GaN
    - WBG semiconductors can allow high-switching speed, high-voltage, and high-temperature(4)
  - Converters will implement WBG first in existing architectures, subsequently will develop dedicated architectures
  - Other areas of improvement are expected in the optimization of sensors, PCB designs, controls, multifunctional converters
- APC estimations are for transportation applications. Ricardo estimated ranges center on commercial vehicles

(1) Source : Ricardo Analysis (2) Power Electronics Roadmap 2020 – Narrative Report APC-UK (3) Electrical and Electronics Technical Team Roadmap (4) Wide Band Gap power semiconductor devices, iEEE

Technology roadmap indicates a continue development of new technologies to improve power electronics performance

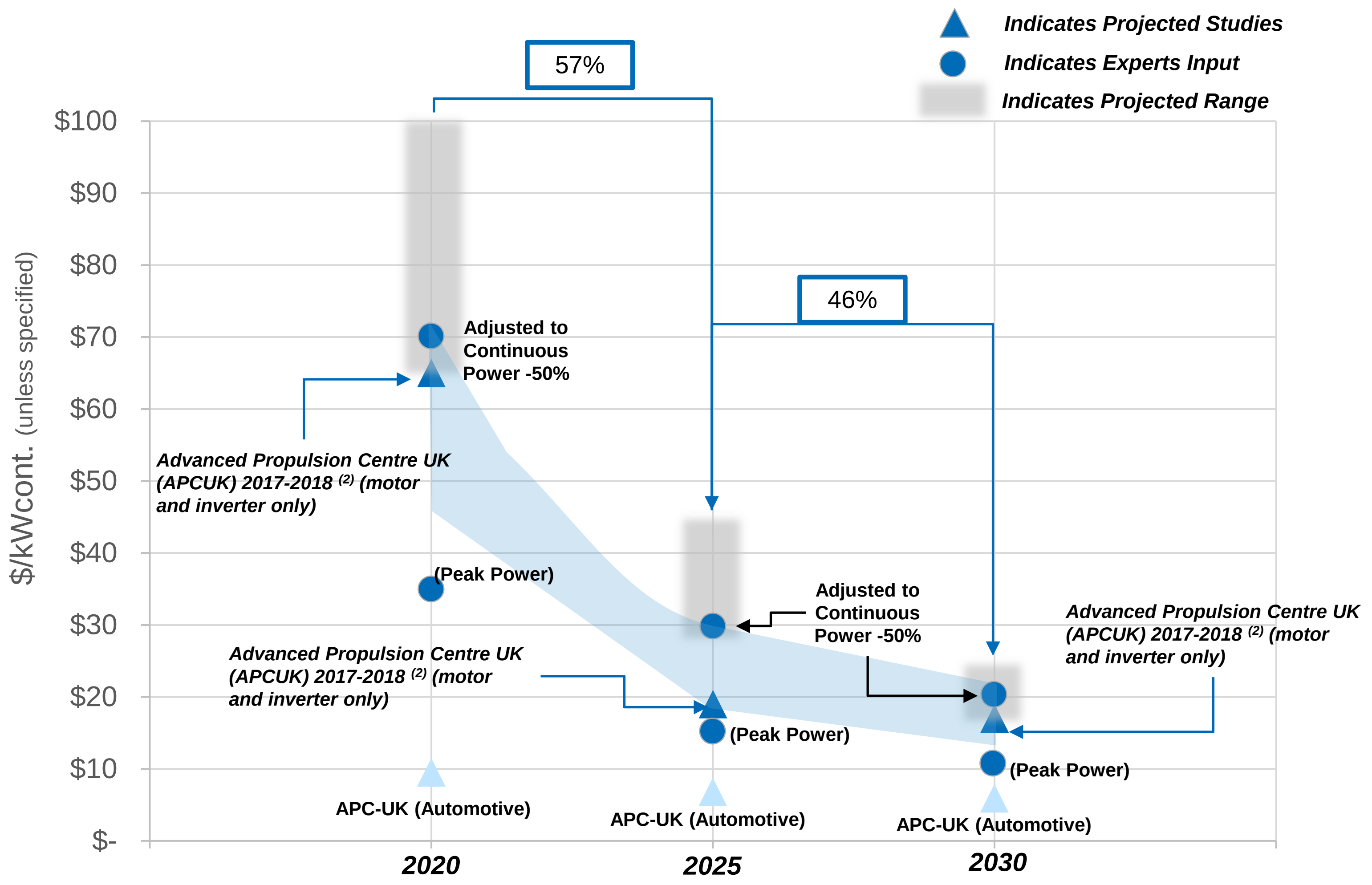
Technology Roadmaps: DC/DC Converter and On-board Charger



(1) Source: APC UK Roadmaps

eDrive system cost expected to drop ~57% by 2025 due to increase in demand from commercial vehicle OEMs

Price Forecast: eDrive (Motor, Inverter and Transmission)



- Commercial Vehicle price drop does not follow the LDV trend due to the difference in relative production volume
  - Industry expert predicts ~5-10k annually per program with the traditional OEMs volume driving significant growth in 2025
- New technologies can help reduce the cost of eDrive, including (3)(4):
  - Inverters are predominantly Si today. It will be a mix of Si and SiC in 2025, but by 2030 almost all will be SiC
  - Motors are incorporated into central drive units today due to the legacy chassis design. Moving forward, these will move to eAxle
  - Several LDV motor and inverter technologies can be adapted to CV applications
- APC estimations are for transportation applications. Ricardo estimated ranges center on commercial vehicles

(1) Source: Ricardo analysis (2) The roadmap report Towards 2040: A guide to automotive propulsion technologies, assumed continuous power, 300% mark-up on material costs, added inverter and motor targets (3) Industry expert opinion (4) Power Electronics/ Electric Machines Roadmap 2020 – Narrative Report APC-UK

Technology roadmap indicates a continue development of new technologies to improve eDrive motor performance

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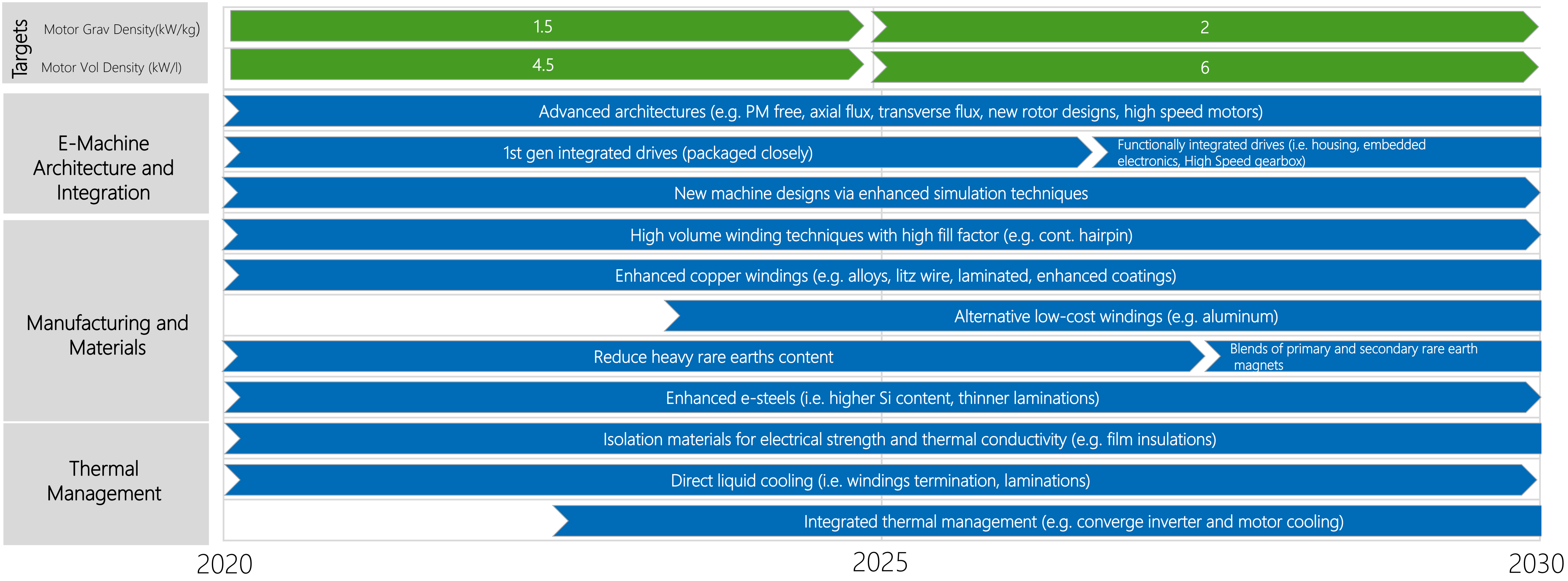
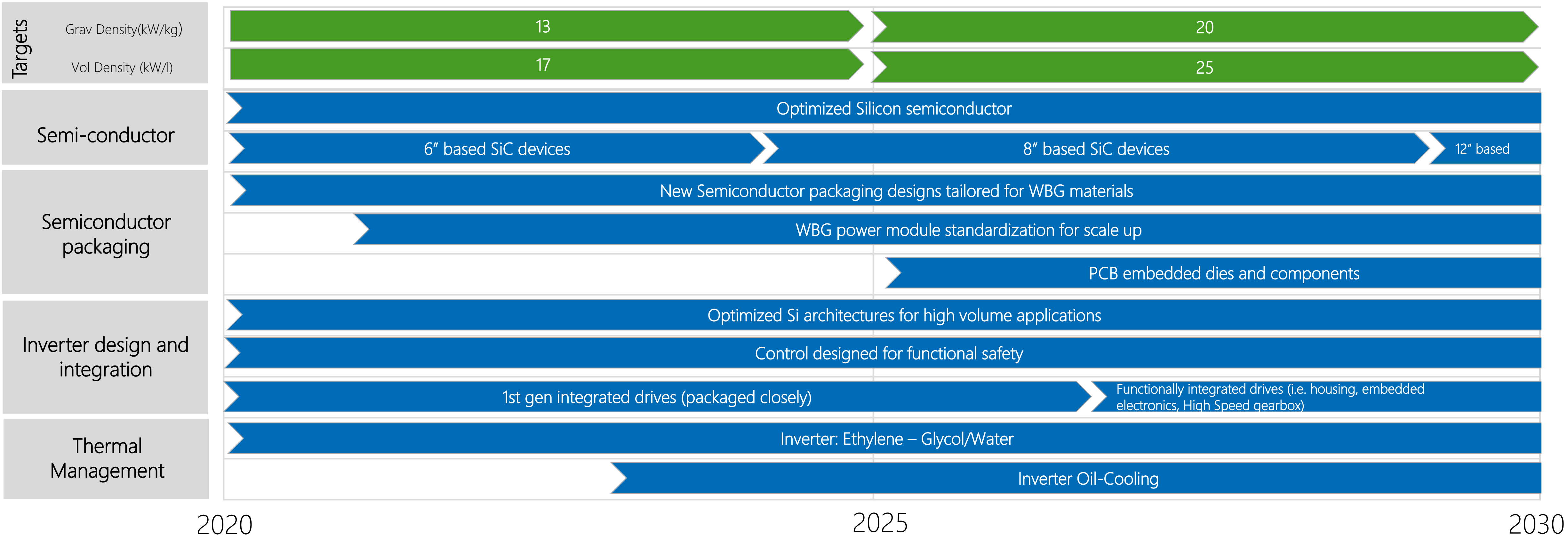
Technology Roadmaps: eDrive Motor



(1) Source: APC UK Roadmaps

Technology roadmap indicates a continue development of new technologies to improve Inverter performance

Technology Roadmaps: eDrive Inverter



(1) Source: APC UK Roadmaps

Projected global volumes from IHS indicate diesel will be the driving technology in Class 8 trucks with battery electric trucks as emerging alternative in this decade

Forecast on Global BEV and FCEV volumes for Class 8 Trucks(1)

Class 8 Trucks	2020	2025	2028**
BEV	2751 (85% is China)	30905 (63% is China)	55241 (63% is China)
FCEV	207 (32% is China)	8005 (66% is China)	16904 (74% is China)

**** 2030 projections not available**

- Diesel vehicles are projected to be the main technology in the Class 8 truck segment
- Electrification will increase mainly in the EU, Mainland China and the United States
  - Two-thirds of projected global volume is in China and remaining one-third is in NA, EU, Japan and rest of the world
  - The remaining volumes will be further split between several OEMs and suppliers
- FCEV is expected to have significant growth in the second half of this decade
  - Chinese market still the leading on implementation of this technology
  - Top truck Chinese OEMs are accelerating their strategic layout of FCV

(1) Source: IHS

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