Project ID: TA 059

Medium Duty Truck TCO and Target Development



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9700 S Cass Ave
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Annual Merit Review 2023, Washington DC

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Objective

Support fuel cell targets for medium duty fuel cell electric trucks (FCETs) under real world driving conditions.

- Support **medium duty fuel cell target development** through vehicle simulations.
  - –Identify medium duty applications where FCETs are most impactful
  - –Quantify real world energy consumption & cost of ownership of FCETs
  - –Determine FC targets (cost, efficiency) required for FCETs to achieve cost parity with competing technologies under real world conditions.

Background & Relevance

- FY22 work examined FCET's ownership cost (TCO) parity against diesel trucks and also quantified durability requirements in selected applications.
- FY23 effort examines
  - –How do **FCETs compete with battery electric** trucks (BETs).
  - –What is the sensitivity of **TCO** to **performance and range** requirements.

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Project Overview

Timeline	Barriers
Start date : Sep 2021 End date : Aug 2023 Percent complete : 70%	• Future market behavior (A) • Inconsistent data, assumptions, and guidelines (C) • Insufficient suite of models and tools (D) https://www.energy.gov/sites/default/files/2015/08/f26/fcto_myrdd_systems_analysis.pdf
Budget	**Partners**
FY22 : $300k Percent utilized : 80%	• NREL (FleetDNA) • 21CTP tech teams • SA Inc

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Milestones & Deliverables

FY22: Competing with ICEV

FY22 Q2

- Identify the MD truck applications based on 21CTP roadmap,
- Quantify the energy consumption of FCHEVs and ICEVs for the identified applications

FY22 Q4

- Purchase price and TCO parity analysis against diesel baseline vehicles
- Detailed FC simulations to quantify design changes to meet durability requirements in selected truck applications

FY23: Competing with BEV

FY23 Q2

- Expand analysis to include BETs as competing vehicles.
- Develop competing BET models based on range requirements for specific applications.
- Identify the 'design range' where FCHEVs have lower TCO than BETs

FY23 Q4

- Validate truck choices and range assumptions with VIUS data (Fall 2023)
- Determine FC efficiency, cost, storage & fuel cost sensitivity to purchase price parity and TCO parity to support MD target setting by HFTO

Approach: Medium Duty Fuel Cell Technology Targets

For performance, durability and cost parity with other advanced technologies.

Component Specs
- DOE (VTO/HFTO)
- ISAJTT, Engine TT, FC TT, SA

Classes & Vocations
- DOE & 21CTP feedback
- VIUS data

Performance Criteria
- Acceleration time
  - 0-30mph, 0-60mph
- Cruising speed
- Daily driving Range
- 6% & highway grade speed
- Launch & Tow capability

Technology Status & Forecast
- National Labs, VTO, HFTO
- Super truck, Industry partners
- U.S.DRIVE, 21CTP, AEO

Real world requirements
Short & long range variants.
Towing, PTO & HVAC loads

Real world usage
real world cycles, typical and extreme payload characteristics



AUTONOMIE

Simulation results
Energy consumption, weight & cost

Production volume
Modular design choices
Component cost vs. production volume



BEAN

VMT, Fuel cost,
TCO assumptions
(VTO multi-lab working group)
[VAN038]

Outputs

Energy consumption, Component sizes, Manufacturing cost, TCO
Targets for cost parity

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Selection of Medium-duty Applications and Powertrain Architectures

7 applications


Class 3 pickup


Class 3 Van


Class 4 Step Van


Class 4 Service


Class 6 pickup


Class 8 Transit


Class 8 Refuse

Fuel cell powertrain variants

- FCV: Fuel cell dominant
  - Fuel cell is primary source of power → used to meet all performance requirements
  - Battery assists with short term power dynamics
  - Battery power is sized based on regen power

- FCHEV: Fuel cell hybrid
  - Fuel cell is sized to meet highway driving requirements
    - atleast 40% downsizing of FC system
  - Battery is sized to meet energy needs from grade requirement (for example: 6% at 30 mph) for 11 miles
  - Vehicle performance depends on battery

Transit buses and refuse trucks are categorized as heavy duty but they were included in this project, as their duty cycle and use is similar to other medium duty applications rather than heavy duty tractor trailer combination trucks.

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HFTO Inputs & Industry Feedback Serve as the Starting Point for Target Development Activities

- 21CTP provided inputs on vehicle performance & sizing requirements
- Battery, electric drive system, aerodynamics, tires and light weighting related assumptions are from VTO technology managers and tech teams.
- The FC cost and efficiency targets can be further refined based on the purchase price parity or TCO parity requirements.
- Simulation analysis will provide sensitivity to various input assumptions.

Class 4-8 Vocational (390,000 - 460,000 mile life)

Assuming 100,000 units/year

		Status	Interim	Ultimate
Fuel cell specific power	(W/kg)	600	800	1000
Fuel cell peak efficiency	(%)	64	67	70
Fuel cell cost	($/kW)	171	70	50

Storage cost

Assuming 100,000 units/year

		Status	Interim	Ultimate
Storage gravimetric energy density	(kWh/kg)	1.7	2.0	2.2
Tank fixed cost (high APV, 100k/yr)	$	3,820	3,029	2,693
Tank variable cost (high APV, 100k/yr)	$/kg	311	247	219
Total tank cost	$/kWh	11.35	9.00	8.00

Energy storage

		Status	Interim	Ultimate
Power battery	$/kW	20	15	13
Energy battery (based on useable energy)	$/kWhr	170	75	60

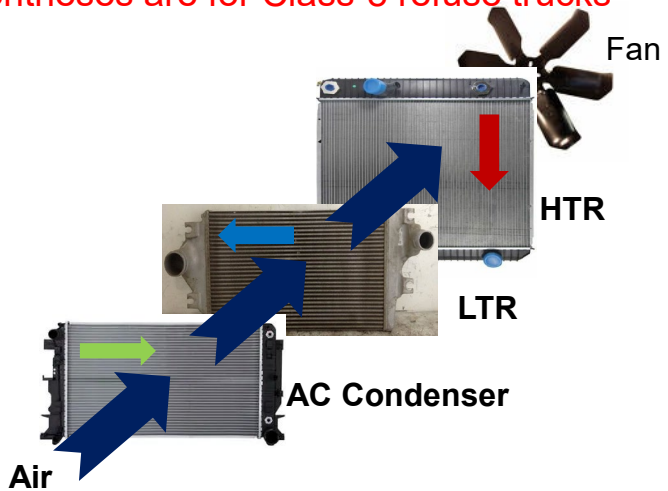
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Fuel Cell System Heat Rejection

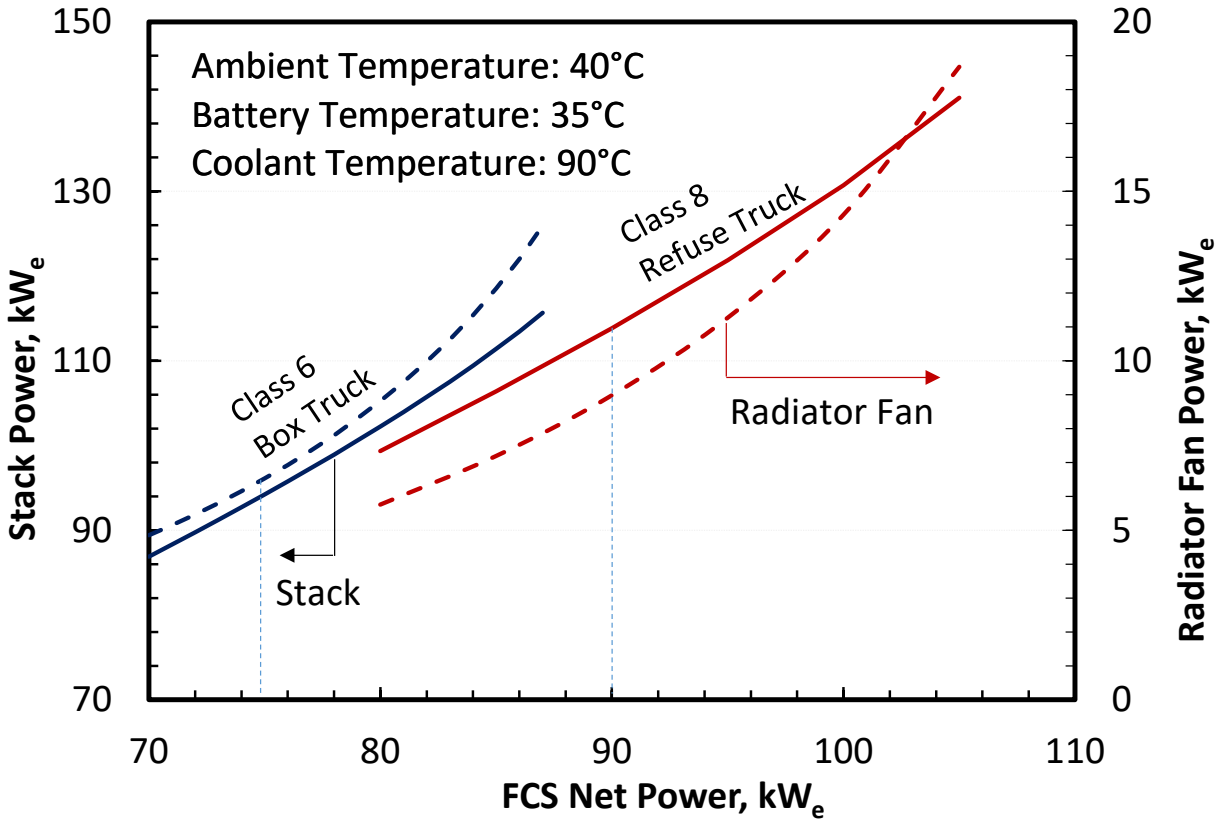
*Throughout this report, red numbers in parentheses are for Class-8 refuse trucks

Maximum FCS rated power constrained by heat rejection during 15 (27) min, 6%-grade hill climb at 45 (25) mph and 40°C ambient temperature

- Minimum FCS Continuous Power: 76 (79) kW_e for cruise at 60 (50) mph on 0% grade
- Optimum FCS Size: 75 (90) kW_e FCS with 94 (114) kW_e stack and 6.5 (9.0) kW_e fan
- Battery Power Requirement during Hill Climb: 110 (115) kW_e



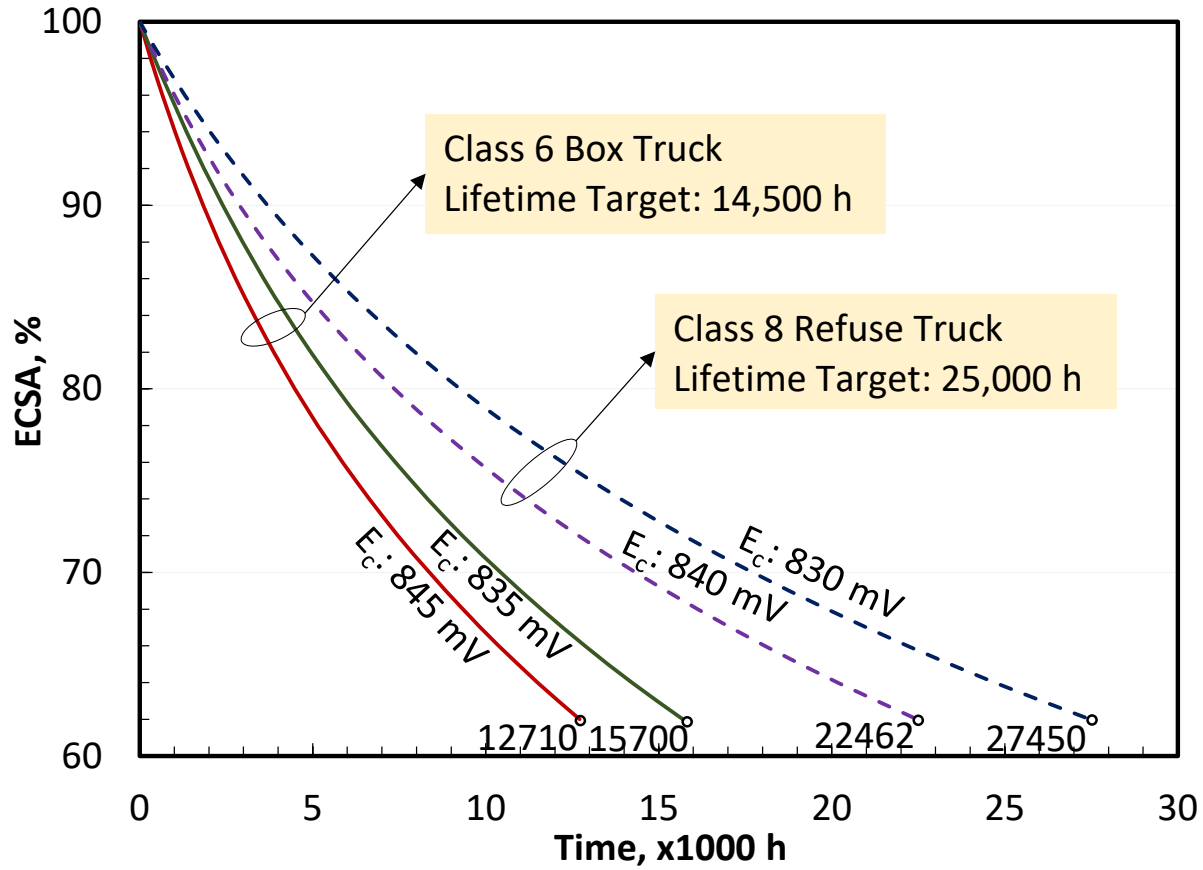
	Units	Class 6 Box Truck		Class 8 Refuse Truck	
		Diesel	FCH	Diesel	FCH
FCS Performance Parameters					
Power @ 6% Grade	kW	171	185	188	205
Stack Power	kW_e		94		114
CEM Parasitic Power	kW_e		8.0		9.7
Radiator Fan	kW_e	12.4	6.5	14.0	9.0
FCS Net Power	kW_e		75		90
Battery Power	kW_e		110		115
BTMS	kW_e		2.4		2.5
Heat Duty Parameters					
High Temperature Radiator	kW	86	76	108	92
Low Temperature Radiator	kW	30	15	33	18
A/C Condenser	kW	10	10	10	10
TCO Related Parameters					
Stack Efficiency	%		55.3		55.3
FCS Efficiency	%		44.0		43.7
Cell Active Area	m^2		13.7		15.2



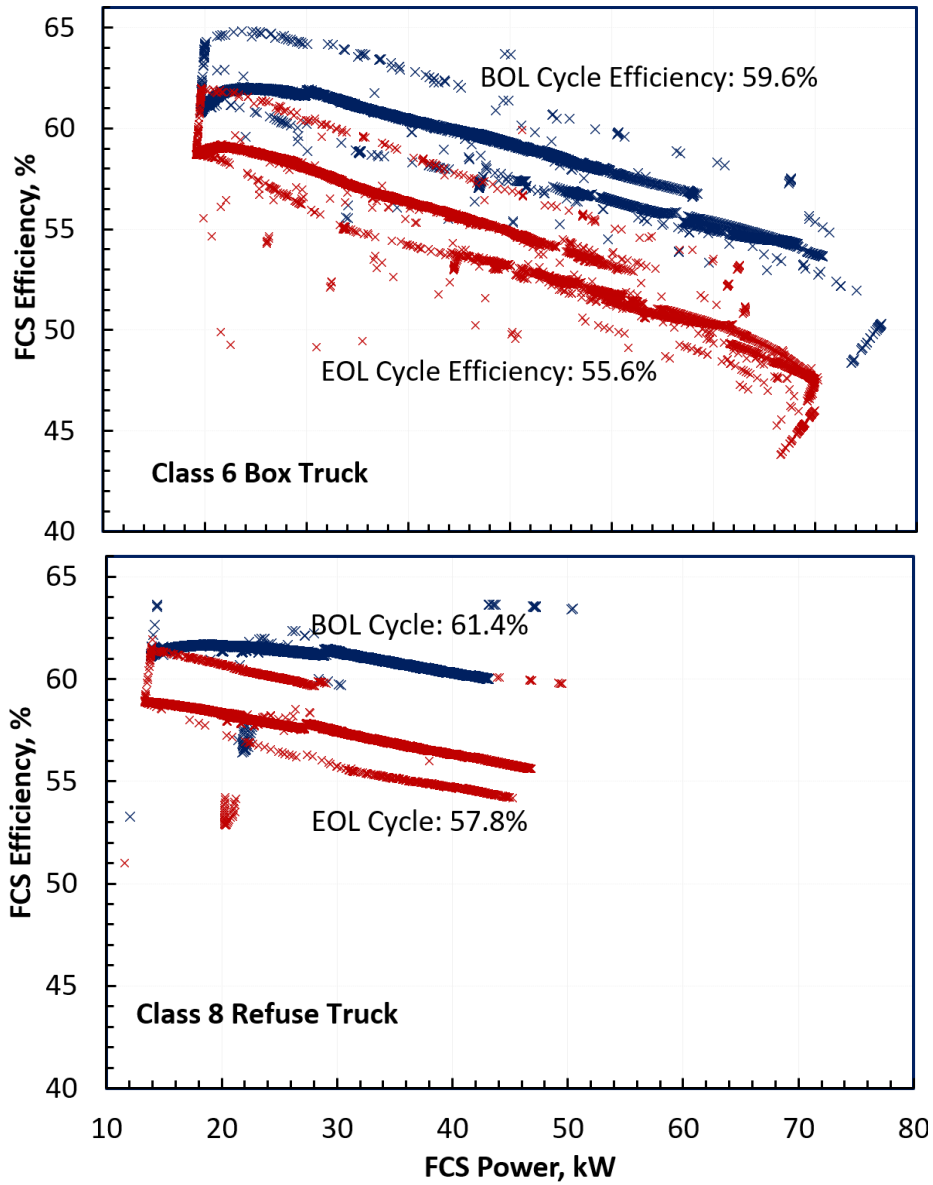
Stack Lifetime

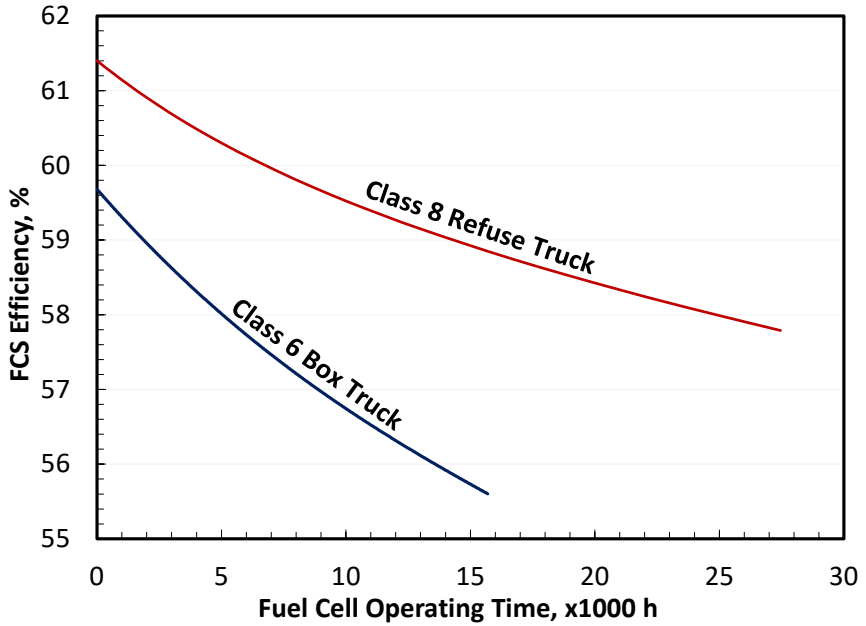
Approach to reaching 25,000 h vehicle drive cycle time and 750 mW/cm² EOL power density at 0.7 V

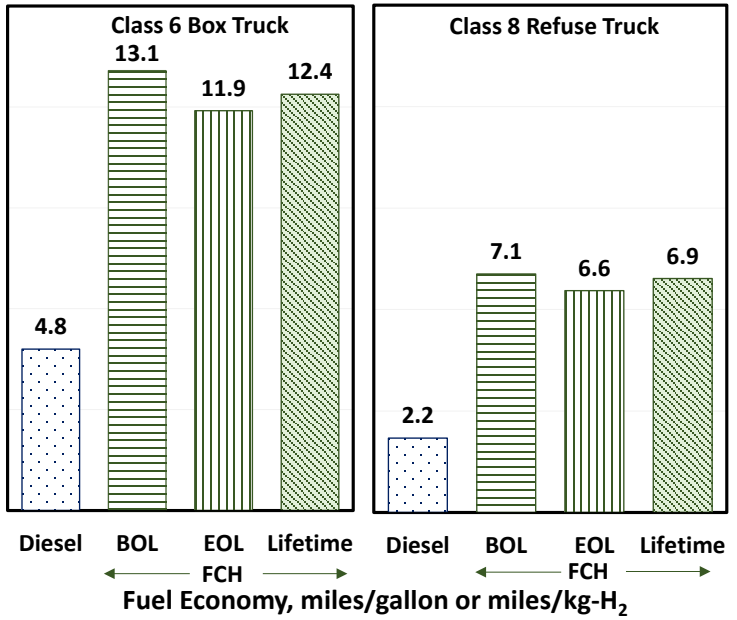
- **Limit stack idle power to 10 (13.5) kW and maximum cell voltage to 835 (830) mV at 1.1 SR (c)**
- **Overload catalyst: 0.45 mg/cm² total Pt loading**
- **Oversize active membrane area by 44% for 38% ECSA loss**
- **Limit FCS transients by sharing load with ESS**
- **Minimize run-time stack start-ups and shutdowns to 33 (0)**



Degradation Adjusted Performance – Efficiency and Fuel Consumption



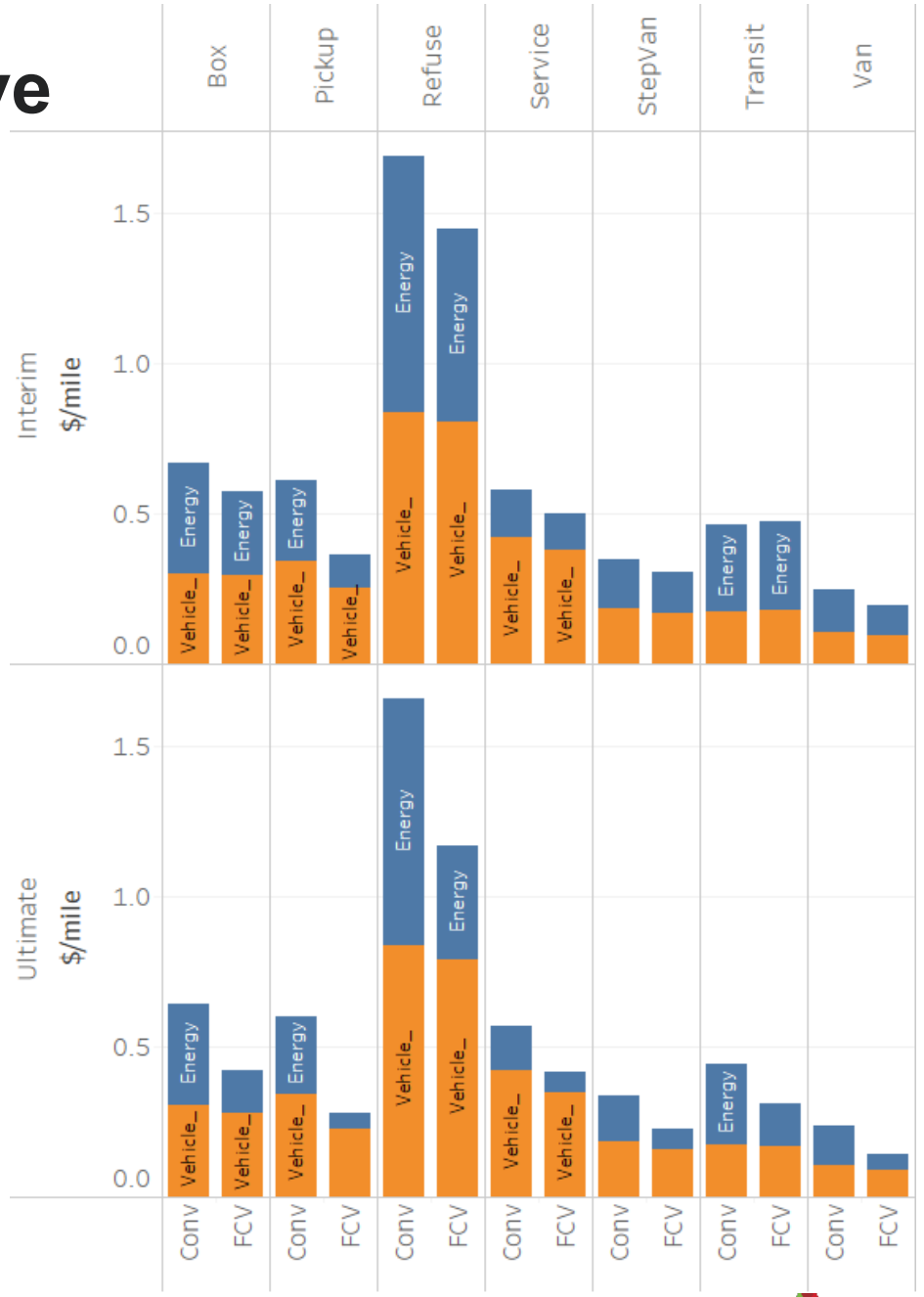




FY22 Analysis showed FCHEVs can achieve TCO parity with diesel vehicles

If FC technology progresses as per assumptions laid out for the interim time frame.

- In the interim case, TCO is lower for all fuel cell vehicles except transit bus when compared to conventional vehicles
- In the ultimate case, TCO is always lower for fuel cell vehicles
- Most of the benefits for fuel cell vehicles come from having a lower energy cost
- Benefits of **modular components** and resulting increase in production volume and cost benefits were also quantified in FY22 work.



- Based on various reports*, BETs are likely to be the main competitor in MD truck domain in interim period.
  - In FY23, the focus shifted to comparison of FCET viability against competing BETs.

U.S. DOE VTO/HFTO R&D Benefits - Vehicle & Mobility Systems Department - Argonne National Laboratory (anl.gov)
Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks (nrel.gov)

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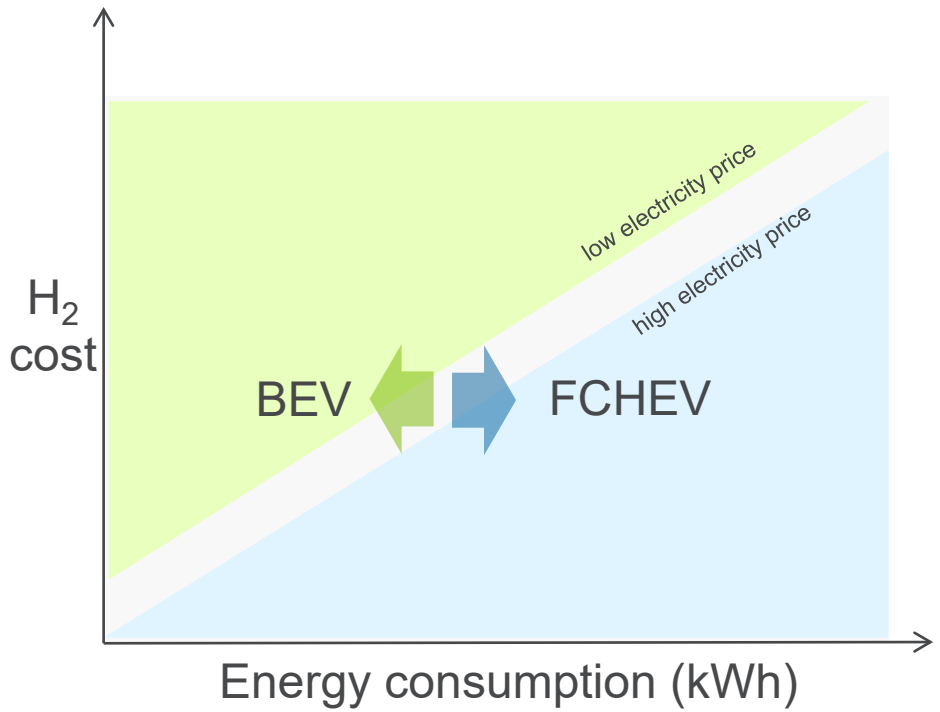
‘Short’ range vehicles can be electrified. The viable range for electric trucks depends on application, usage and energy cost.

- Evaluating BEVs and FCHEVs for 80% to 95% daily driving requirements

- Case study : 2030
  – high & low technology progress scenario

- Energy price impact:
  –Electricity cost: 15c – 25c per kWh
  based on NREL estimates of breakeven condition for chargers
  –Hydrogen cost: $4 – $8 per kg
  based on present costs, HFTO interim & ultimate targets

- Annual VMT (vehicle miles travelled) impact
  – Two cases: Low and High VMT
  based on NAS estimates, VIUS, 21CTP feedback



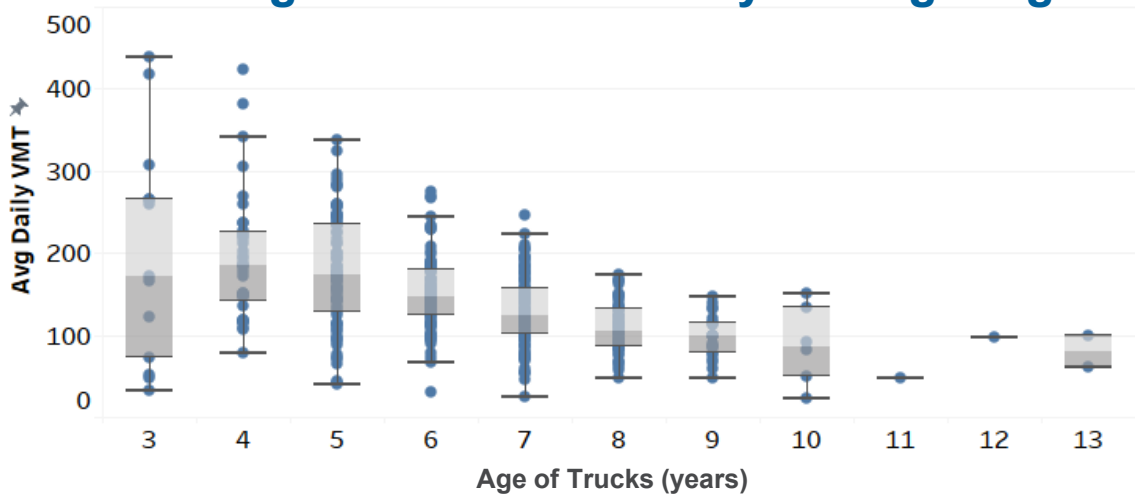
Impact of winter temperatures, HVAC loads, towing requirements and their impact on driving range is not yet considered in this work. Awaiting directions from DOE and 21CTP on these topics.

‘Designed Driving Range’ is Critical Factor to Determine the Price & TCO Parity of BETs & FCETs

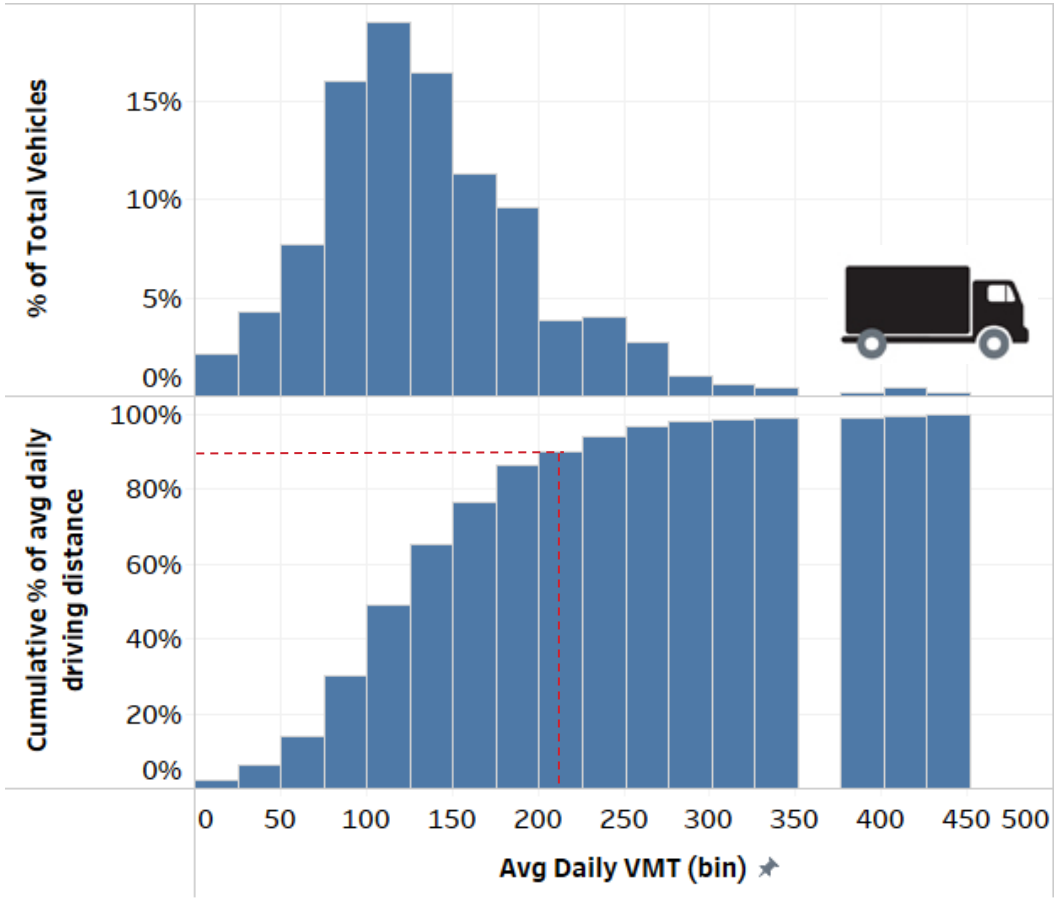
Example: Class 6 Box

- 2022 VIUS data is expected to provide information on prominent vehicle types and their usage. Data from Livewire, FleetDNA and industry sources are informing our present analysis.

Average vs. maximum daily driving range



Vehicle miles travelled (VMT) information for Class 6 Box trucks shows that 90% of vehicles had an **average of ~200 mile/day.***



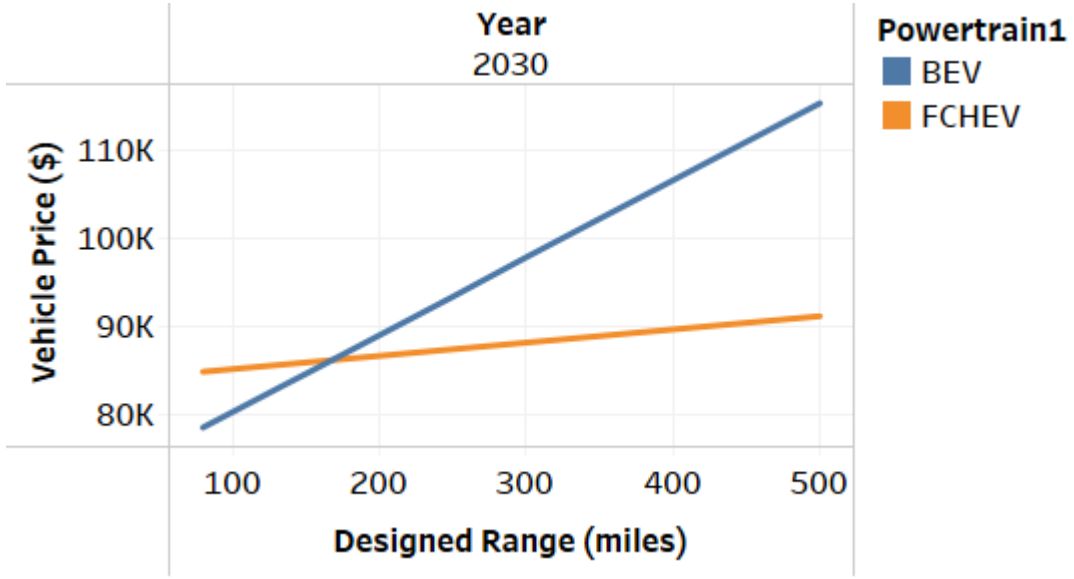
** From a sample of 470 vehicles across US from a major truck leasing company. Derived from lifetime miles, age of the vehicle and assumption of 250 days of operation per year.*

21CTP roadmap efforts now include FCET as well. Feedback from 21CTP is critical in identifying the range requirements for each application

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By 2030, if HFTO & VTO Targets are Achieved, Class 6 Box FCETs will Achieve Purchase Price Parity with Competing Vehicles

Electric and FCETs were evaluated for a designed driving range of 80-500 miles.



By 2030, if FC cost targets & storage density targets are met,

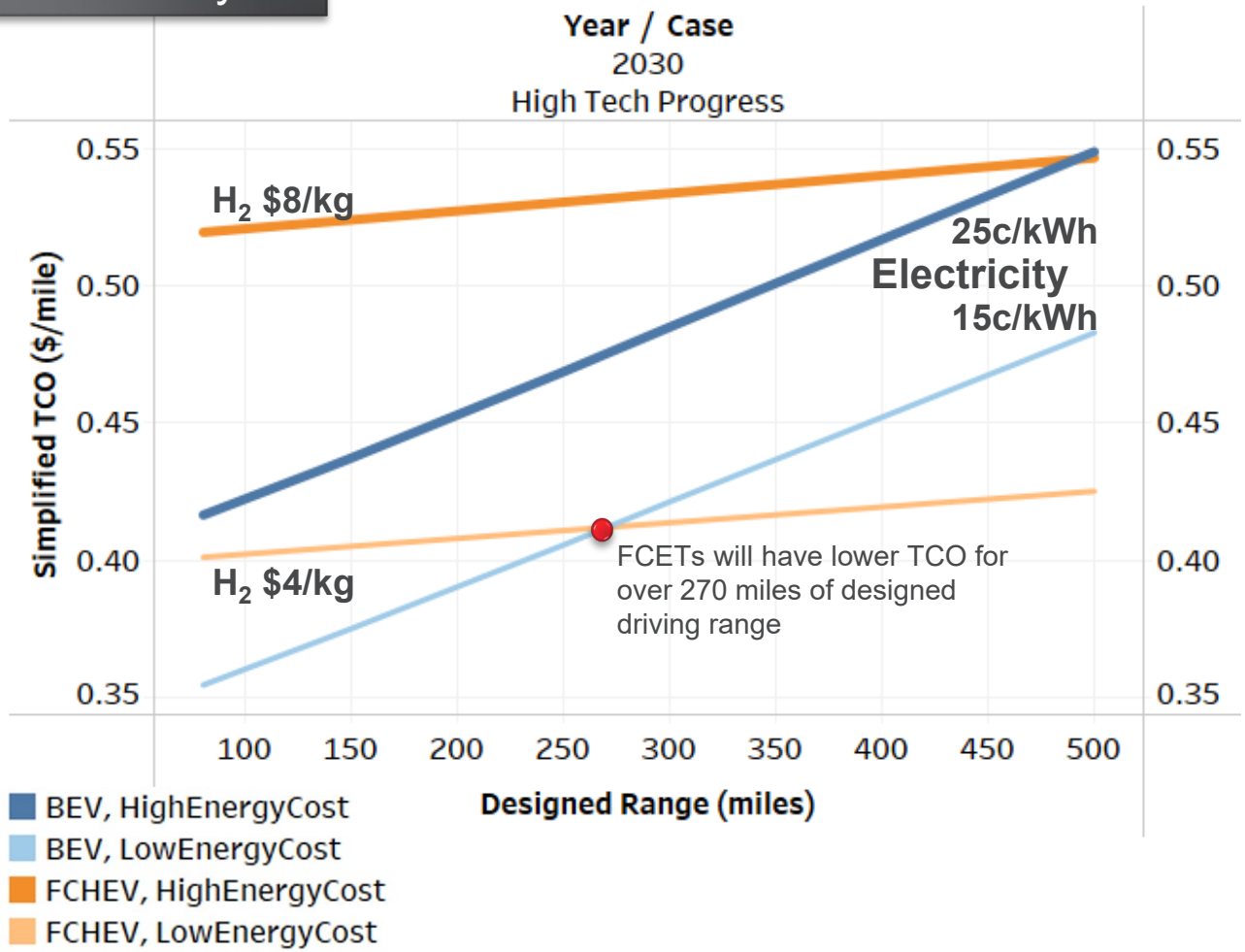
- FCETs will achieve purchase price parity for Class 6 Box truck, if vehicles are designed for >170 miles of driving range.
- FCETs will also have lower curb weight for vehicles designed for over 90 miles range.

Simplified TCO analysis assumptions:

- Ownership period : 15 years
  - *No residual value, no component replacements during lifetime*
- Annual VMT : 20k – 40k miles
- Discount rate : 7%
- Vehicle price is 1.2 times the manufacturing cost estimate.
- No penalties assigned for charging or refueling time.
  - *Overnight charging & fast H2 refueling is assumed.*
- Insurance, taxes, wages, permits etc are considered to be the same across powertrains

By 2030, if HFTO & VTO targets are Achieved, FCETs can Effectively Provide a Longer Range Alternative to Electric Trucks

20k miles/year



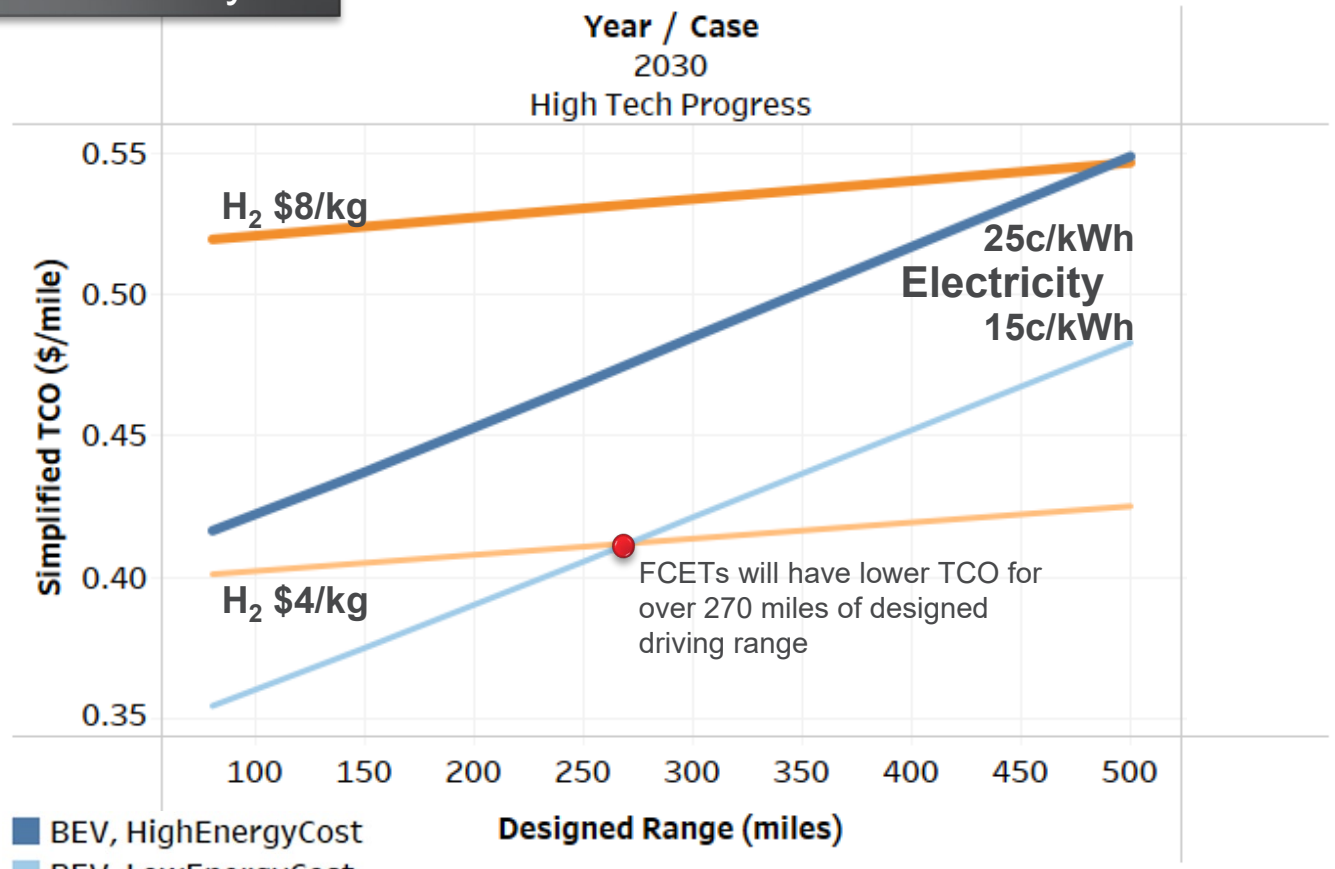
- As desired driving range increases from 80 miles to 500 miles,
  - Usable battery energy varies from 76kWh to 440kWh in this example.
  - Usable H_2 onboard storage requirement varies from 4 to 30kg
  - Propulsion power requirements are unchanged.

- For applications with higher VMT, BEVs will have an advantage due to the lower operational cost.

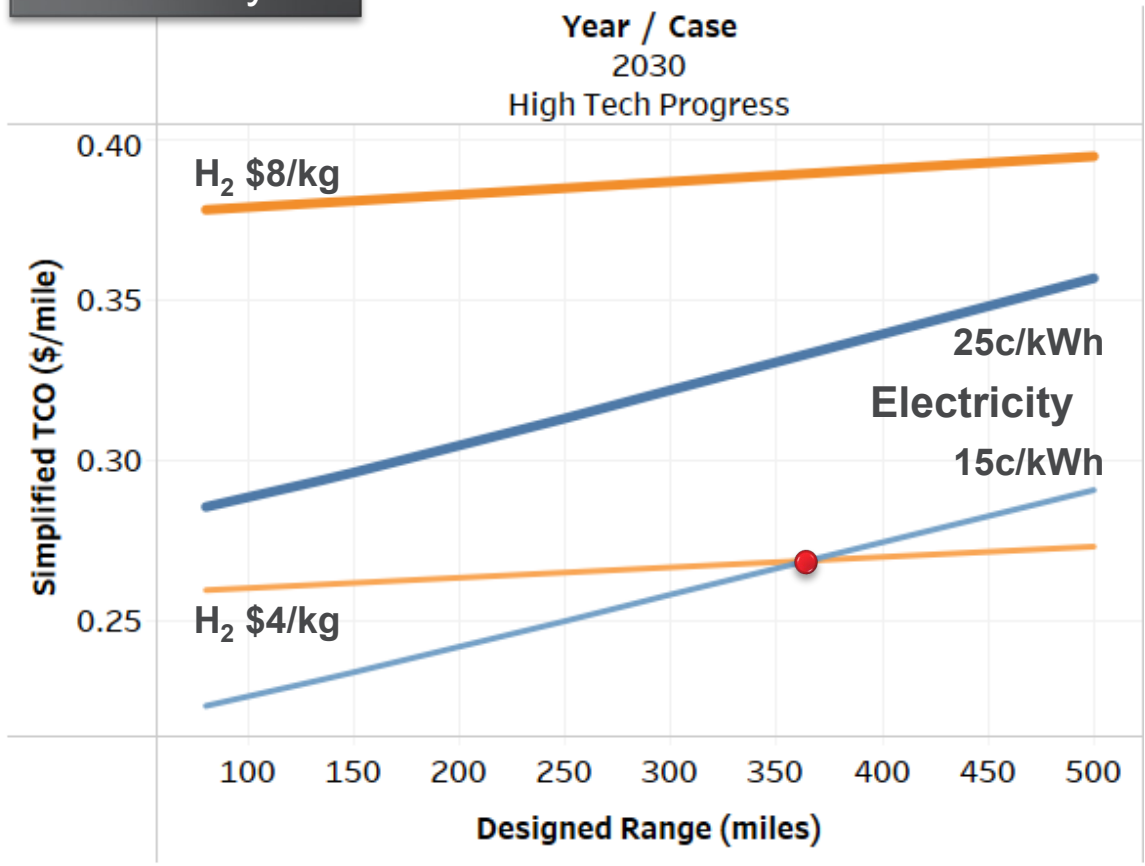
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By 2030, if HFTO & VTO targets are Achieved, FCETs can Effectively Provide a Longer Range Alternative to Electric Trucks

20k miles/year



40k miles/year



Similar analysis is underway for more medium duty truck applications

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Remaining Challenges and Next Steps for FY23

- Run sensitivity study to component cost and H_2 cost
  - Identify how the fuel cost & component cost and efficiency affects TCO parity

- Complete the durability analysis for all 7 medium duty applications.
  - Determine design changes and component size impacts due to durability needs
  - NREL will provide feedback on any other MD applications we need to consider.

- Quantify technical targets for FCET to be cost competitive with incumbent & other competing technologies

- Continue to support HFTO in understanding the unique requirements of Medium and Heavy duty vocational trucks across classes and applications

Future Work

- Examine the impact of component degradation on truck performance and whether/how it affects the usefulness of the truck.

- Evaluate future scenarios at the system level
  – Synthetic real world cycles are generated from transportation system models for inter and intra city freight movement under DOE funded initiatives (e.g., SMART Mobility Workflow)

- Identify how FCETs can adapt to potential future changes related to vehicle usage and consumer behavior
  –Connected and automated vehicles can change freight movement. Does this change the preferences for vehicles, powertrains, fuel choices?
  –How changes in consumer behavior can alter the last mile delivery needs ?

Any proposed future work is subject to change based on funding levels

Summary

The analysis shows that if the technology progress as envisioned by DOE, FCETs will be a viable solution for longer range medium duty applications in the near future.

- **Comparison with Diesels**
  - –With current assumptions, fuel cell powertrains will provide a lower TCO for most applications in the interim period itself when compared to diesel trucks. FCETs are attractive than ICEVs for all applications considered in this work, under the ultimate scenario.
- **Comparison with BETs**
  - –BETs designed for short ranges have TCO advantage over FCETs
  - –FCETs have the TCO advantage over BETs when vehicles are designed for longer range and challenging operational requirements.

- **This work quantifies**
  - –Design space where FCETs will achieve purchase price parity and TCO parity with BETs
  - –The impact of the following factors on TCO parity with BETs
    - •energy cost ($/kWh & $/kg of H_2).
    - •component cost targets
  - –Impact of PTO, towing & HVAC usage on onboard energy storage requirements.
- **This work will provide**
  - –the information needed by HFTO to set medium duty specific technology development targets

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Thank you!

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Technology Transfer & Data Dissemination Activities

- All the models, drive cycles, vehicle related assumptions and sizing methods developed as part of this work are published and distributed as part of Autonomie & BEAN.

- Compiled versions of the models used for this work are available at no charge to support any research activity.
  - They can be used even without Simulink, Stateflow or Autonomie licenses.

- These models are available to support USDRIVE, 21CTP, Supertruck and several other DOE funded activities.

AUTONOMIE

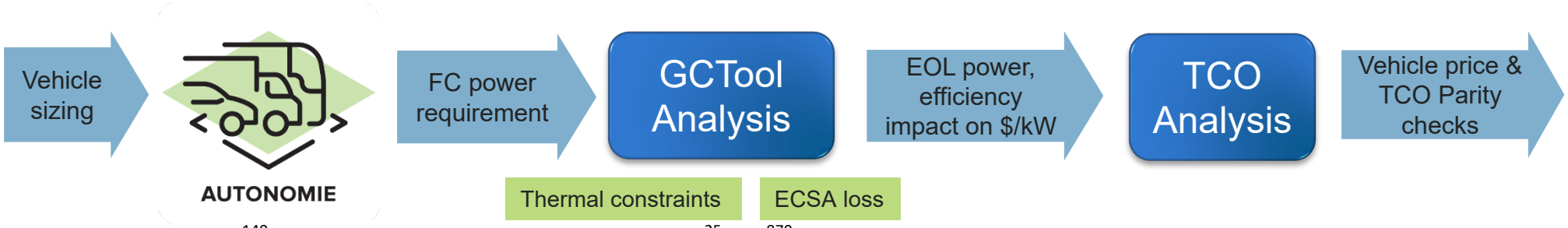
Available Vehicles

Class	Purpose
2	Van
3	PnD
3	Van
3	School
3	Pickup
4	WalkIn
4	Service
5	Utility
6	StepVan
6	Box
6	Construction
7	Tractor
7	Vocational
7	Van
7	School
8	Longhaul
8	Tractor
8	Beverage
8	Drayage
8	Vocational
8	Transit
8	Refuse
8	Regional

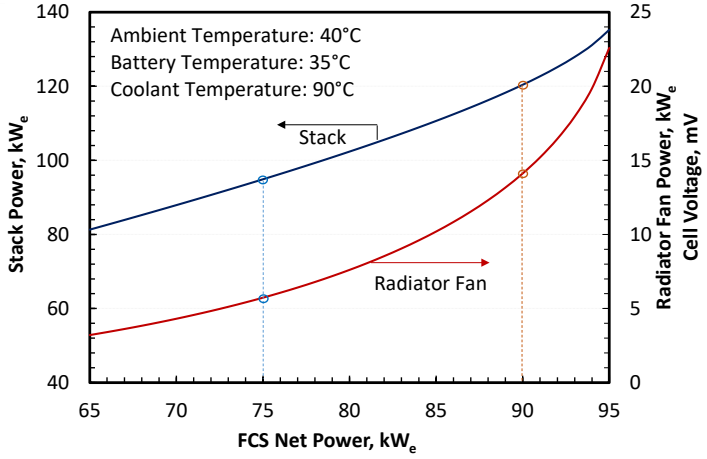
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End of Life (EOL) performance degradation was examined based on the operational requirements on representative real world duty cycles

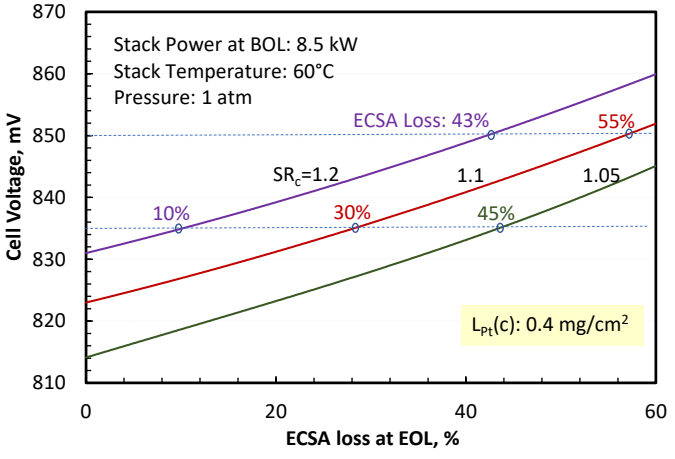
- Minimum size requirements are based on Autonomie simulations
- GCTool thermal analysis provides the maximum limit on FC size, based on cooling constraints
- Durability analysis provides insights into design change needs to ensure durability
  - provides a better $/kW estimate for the TCO analysis



Thermal constraints



ECSA loss



Similar analysis is underway for more medium duty truck applications

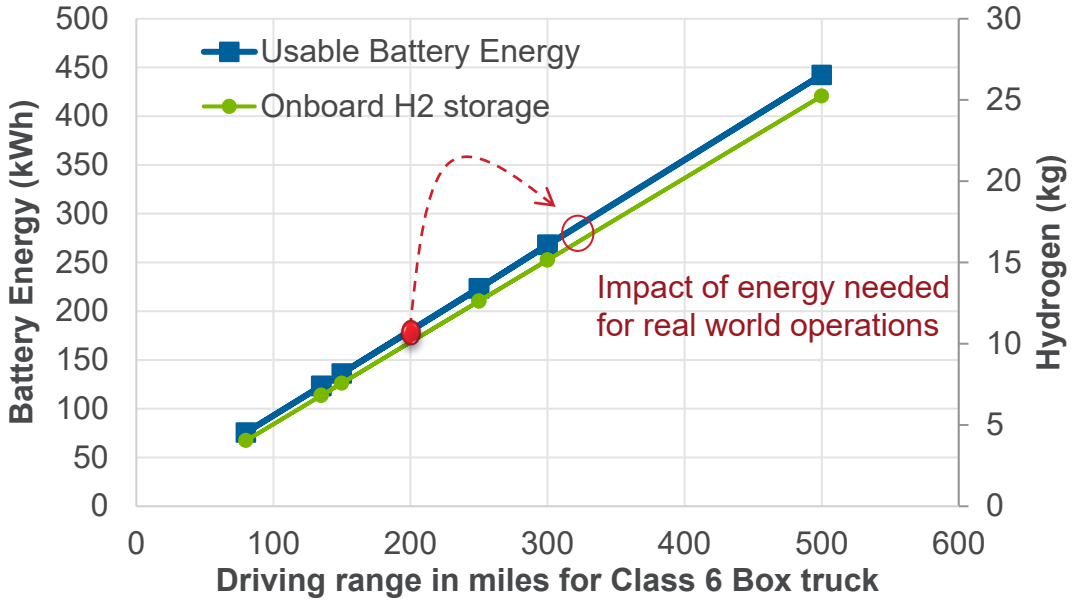
Driving range is often used as a proxy for the onboard energy storage requirement.

Several factors such as Towing, PTO & HVAC loads can also affect the energy storage requirement

- **PTO**: Two separate studies (by NREL & EPRI) have shown that 10% additional fuel is needed to meet PTO requirements in medium duty pickup trucks and service trucks.

- **Towing**: Power requirement for towing is already accounted in sizing logic employed in Autonomie. However range tests are done for highway driving without towing. Preliminary analysis shows that towing at highway speeds can increase the onboard energy storage requirement by ~40%. More data is awaited from 'F150 Lightning' tests being carried out at Argonne.

- **HVAC loads**: Heating loads can reduce range of 'people movers' significantly. CTE showed ~40% reduction in driving range for electric buses, and up to 25% reduction for fuel cell buses.



Towing simulation: test weight and aerodynamics

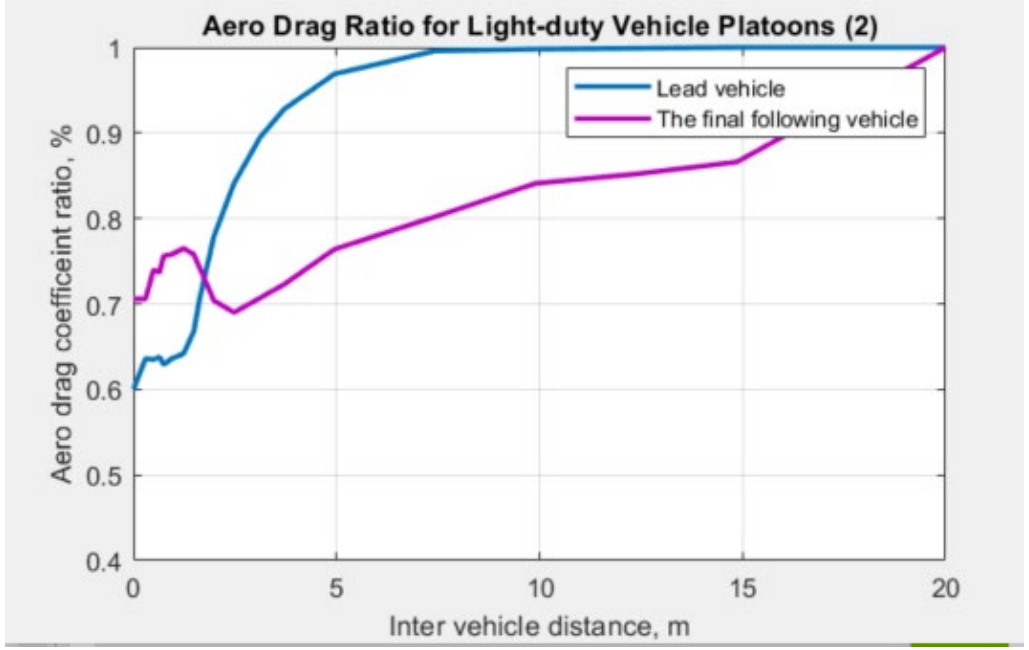


Based on studies done on vehicle platooning, we can estimate the effective Cd for towing.

- Test case for Class3 pickup truck
  - Frontal area is doubled.
  - Coefficient of drag of trailer : 0.82 (assumed)
  - Effective aero drag of the combination is less than the sum of individual units as demonstrated in platooning studies
    - 35% Cd reduction for lead vehicle
    - 25% Cd reduction for trailer

- 6% Grade @30mph, with 7000 & 14000 lb test weight
  - 90% increase in energy consumption.
- 0% Grade @ 60mph, with 7000 & 14000 lb test weight
  - 76% increase in energy consumption.

- Aero impact is significant at highway speeds.
- For fully loaded class3 pickup truck,
  - Aero loads associated with towing can add 44% energy consumption.
  - At 30mph on 6% grade, the impact of aero drag from the towed unit is <4%



"The Aerodynamic Performance of Platoons: Final Report - Michael Zabat, Nick Stabile, Stefano Frascaroli, and Frederick Browand"

Range determination and component sizing could be improved by including the aero impact of towing for pickup trucks.

>> Awaiting data from a detailed field test planned at Argonne for during the test of F150 Lightning

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Potential Impact : Focus research on specific challenges that face Medium Duty applications.

- In prior years, light duty and heavy duty FC targets were set by HFTO.
- This helped focus research to achieve cost reduction & efficiency gains.

This project will quantify

- FC system requirements for several medium and some heavy duty applications.
  - »Can common targets be developed for Class 3-8 vocational vehicles
- FC Durability needs:
  - »Moving from miles to hours. Find design changes needed to avoid performance degradation.
  - »Quantify the impact of such design changes in efficiency, cost, weight etc.
- FC sizing options:
  - »Tradeoff between custom vs. modular choices in FC designs. Production volume and cost benefits
- Driving range & VMT
  - »For achieving TCO parity with diesels and BEVs
- Hydrogen cost:
  - »For achieving TCO parity with diesels and BEVs

Collaboration & Coordination

- Argonne has shared all vehicles and sizing assumptions through reports & Autonomie Lite.
- This project provides data to SA Inc for the costing analysis.

- NREL Fleet DNA was the primary source for duty cycle used for fuel economy estimation
- As part of the 21CTP Powertrain System Analysis working group, Argonne worked with OEMs to establish common assumptions for truck modelling and technology evaluation.
  – Provided inputs on vehicle technical specifications
  – Reviewed the powertrain sizing assumptions & methodology.
- The 21CTP Battery tech team reviewed simulation outputs and allayed concerns about battery durability for FCHEVs.
- The 21CTP Hydrogen tech team reviewed and provided feedback on the architecture and component assumptions.
- The 21CTP Engine tech team provided engine efficiency improvements expected during the time period considered.
- CTE shared their findings on impact of heating loads on buses during winter
- HFTO requested BTS for early access to VIUS 2022 data.
- Argonne's vehicle testing team provided inputs on towing test requirements.

Response to Previous Reviewer Comments

This is a new project.

- On similar projects in the past HFTO & VTO reviewers had stressed on the need to make results and tools freely available for other researchers
  - Argonne now distributes a free version of Autonomie that has the vehicles and processes developed to support DOE funded research