High Efficiency Fuel Cell Application for Medium Duty Truck Vocations

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Ford Motor Company

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May 2024

Project Goal

- Develop a ZEV Fuel Cell propulsion system for Ford Super Duty Chassis Cab vocation applications.
- Demonstrate ZEV capability without compromised customer attributes including 10k payload, 300-mile range and SAEJ2601 refueling times.
- Evaluate the technology in real-world environments with three fleet customers (varied vocations and locations) to provide insight into fuel cell durability, usage, efficiency, refueling, and operating costs.
- Evaluate GHG and TCO utilizing H2 infrastructure and economy projections for comparison with today's ICE products.

Super Duty Chassis Cab FCEV ZEV

Overview

Timeline

Project Start:	Mar-2022
Project End:	Dec-2026
Complete:	~40%

Budget

Total Project Budget: $49.9M

Cost Share: 50%
DOE Funds Spent: $16.7M*
DOE Funds Received: $4.48M

**through Dec 2023*

Barriers and Challenges

- H2 Infrastructure and cost
- Commercial vehicle lifetime durability
- Capability in extreme cold environments

Partners and Fleet Customers

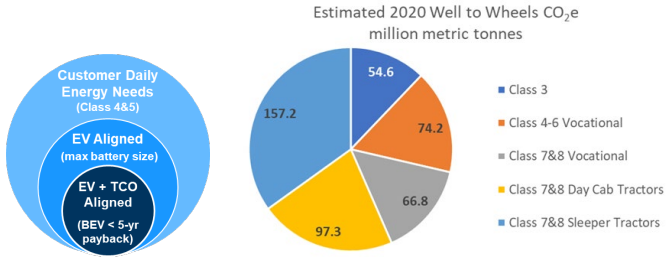
Ford, FEV, NREL Transforming ENERGY, Consumers Energy Count on Us®, FERGUSON, SoCalGas

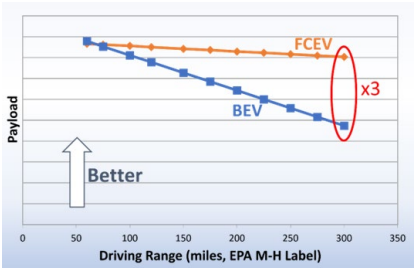
~$50M / Two Partners / Three Customers

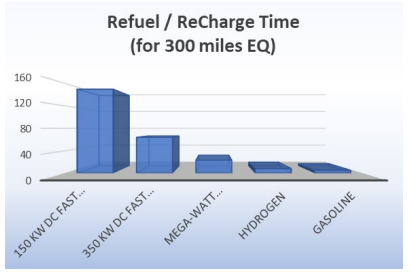
Any proposed future work is subject to change based on funding levels

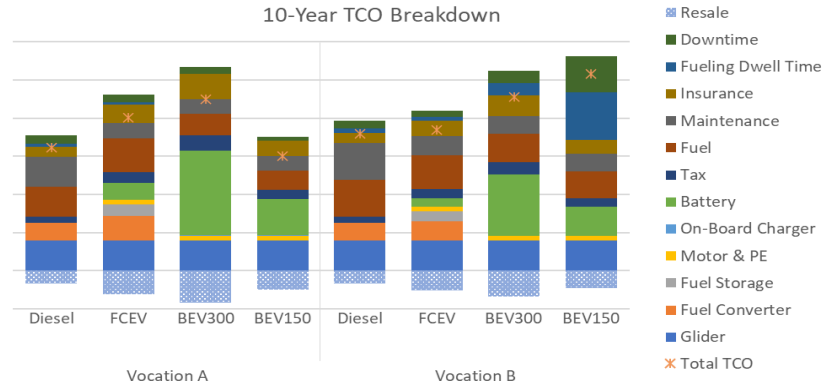
Relevance and Potential Impact

- **The vocational CV market is a significant portion of the CV CO2/GHG contributions and presents diverse decarbonization challenges.**
  - Work trucks operate in rugged environments, with high payload demands and in some cases 24/7 uptime requirements.
  - BEVs are challenged to meet CV energy demands (>300 kWh) and/or uptime requirements.
  - The class 3-6 Chassis Cab vocational market is especially important to Ford as a leader in this segment.
- **Fuel Cell powertrain offers favorable attributes**
  - Zero emissions
  - Minimal payload compromise and re-fill time similar to ICE
  - Favorable TCO (accounting for down time) for high energy users
- **Overall Goals**
  - Achieve 300-mile range and maintain customer payload
  - Meet high energy daily usage / full capability in hot and cold ambient
  - Capable of going where the work is
  - Meet or better gas ICE TCO









Fuel Cell is the better ZEV solution for highest energy users

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

Approach: Focus Areas per Phase

2022/2023 - Phase 1
Simulation/Analysis/Design

Virtual Design and Analysis (NREL)
Use Cases, Application and Infrastructure Modeling
System Sizing and Simulation

100% ✓ → Component Development

2023/2024 - Phase 2
Vehicle Integration/Build

Fuel Cell Technology (FEV)
Cell Stacks, Balance of Plant
Thermal, H2 Storage, Controls

Electrification Technology
Battery, HV EDS/Power Electronics
Thermal, eAxle, Brakes, Steering, Controls

70% → Development Vehicles

2024/2025 - Phase 3
Vehicle Development

Propulsion System and Vehicle Development
Development, Controls, Calibration
DV, Robustness, Durability, HMI, FuSa

→ Fleet Vehicles Deployed

2025/2026 - Phase 4
Pilot Vehicles

Fleet Vehicles (SoCalGas, Ferguson, Consumers Energy)
H2 Infrastructure, Real World Validation
Model validation and future scenario projections, Lessons learned for scaling

Go / No Go Criteria

Analytical Confirmation - System will achieve FC net power, net vehicle power, efficiency improvements relative to gasoline ICE, range and payload/towing requirements

Bench Testing and Builds - Internal development builds and FC net power bench validation complete

Vehicle Validation / Deployment – Customer requirements and vehicle attributes confirmed: 75% tank-to-wheel efficiency improvement, 300-mile range, 700 bar tank package, SAE J2601 fill time and 10k payload

Four phase, multi-year approach

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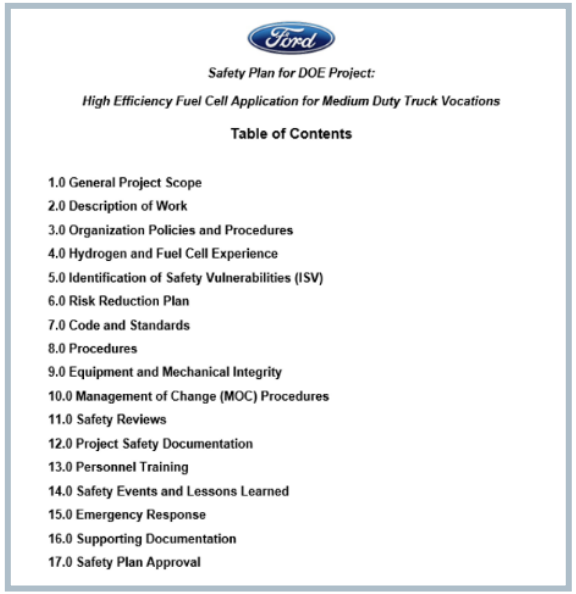
Safety Planning and Culture

- **Safety Plan for the Ford SuperTruck 3 Project was approved by the DOE Hydrogen Safety Panel**
- **For over 30 years, Ford has been conducting research into hydrogen vehicles and hydrogen storage technologies (incl DOE funded projects) with a culture that emphasizes safety first in design, testing, and vehicle operation.**
  - 1999 – Ford P2000 Fuel Cell Vehicle
  - 2000 – Ford Focus Fuel Cell Vehicle
  - 2005 – 2009: Focus FCEV DOE Technology Validation program – 30 vehicle fleet
  - 2005 – 2009: Hydrogen ICE bus program – 30 vehicle fleet
  - 2007 – HySeries Plug-in Edge Fuel Cell Vehicle
  - 2009 – Ford Explorer Fuel Cell Demonstration Vehicle
  - 2016 – Ford Plug-in Fusion Fuel Cell Vehicle
  - 2019 – Ford F550 Fuel Cell Demonstration Vehicle
- **Internal and external research activities address hazards using risk assessments including completing Failure Mode & Effects Analyses(FMEAs), Standard Operating Procedures, Authorized Trained Operators, Safety Reviews, Incident Reporting, Emergency Response Plans and Industry Codes & Standards.**



Safety Plan for DOE Project:

High Efficiency Fuel Cell Application for Medium Duty Truck Vocations

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Previous Ford fuel cell fleet accumulated over 1.3 million miles without a hydrogen safety incident.

Ford has conducted extensive research on Fuel Cell and Hydrogen Storage Technologies while emphasizing safety culture

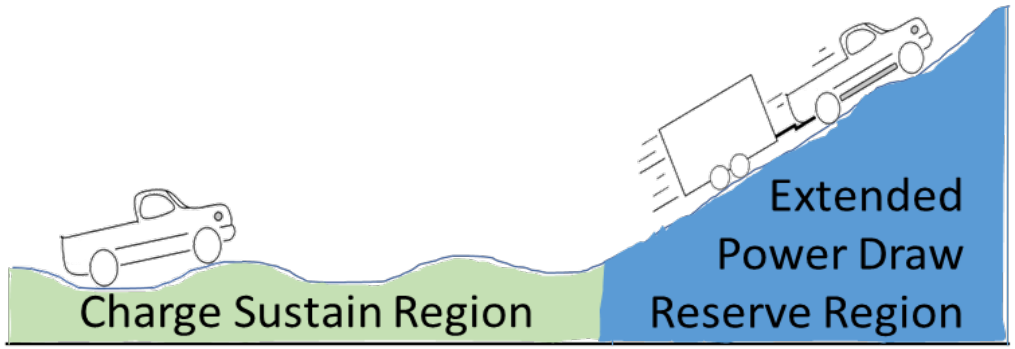
Any proposed future work is subject to change based on funding levels

Accomplishments and Progress

Analytical Concept Evaluation – System Sizing

FCEV Super Duty F550 Chassis Cab

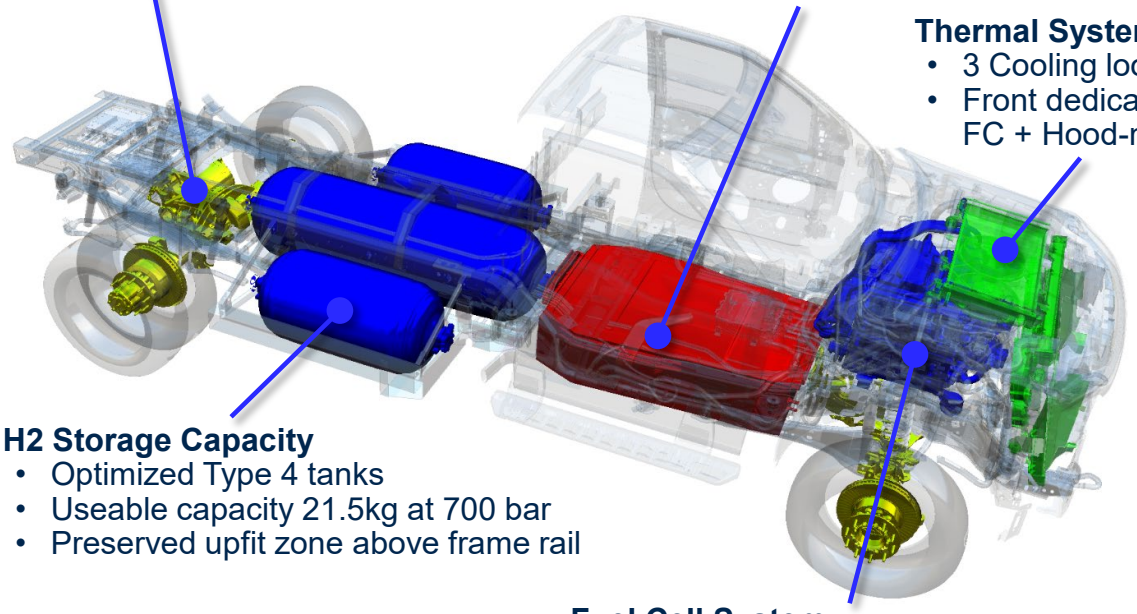
- Zero Emissions
- 10,000 lb payload / 20,000 lb towing capacity
- Meet or exceed 7.3L gas performance feel
- 300 mile range in shorter wheelbase variant
- Comparable refueling time to ICE (<10 minutes)



Twin eAxles
- 200kW continuous power (each)
- 13,000Nm Peak wheel torque (each)

HV Battery
- 350kW peak power
- Transient fill-in
- 40kWHr usable energy

Thermal System
- 3 Cooling loops
- Front dedicated HTR for FC + Hood-mounted LTR



H2 Storage Capacity
- Optimized Type 4 tanks
- Useable capacity 21.5kg at 700 bar
- Preserved upfit zone above frame rail

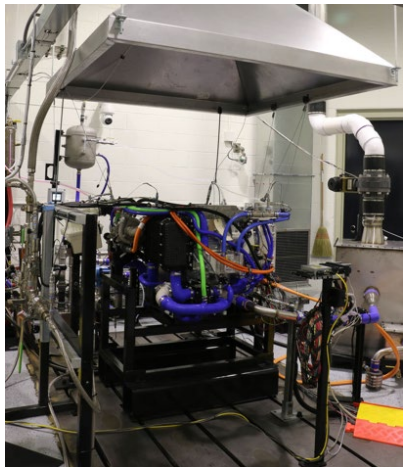
Fuel Cell System
- Optimized 2-row stack & BOP
- 140kW continuous power @38°C

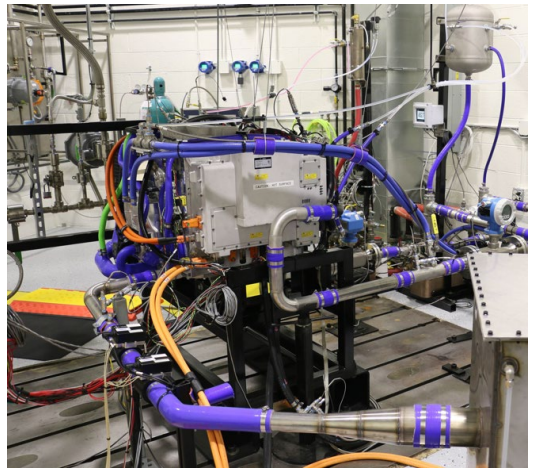
Super Duty FCEV Concept

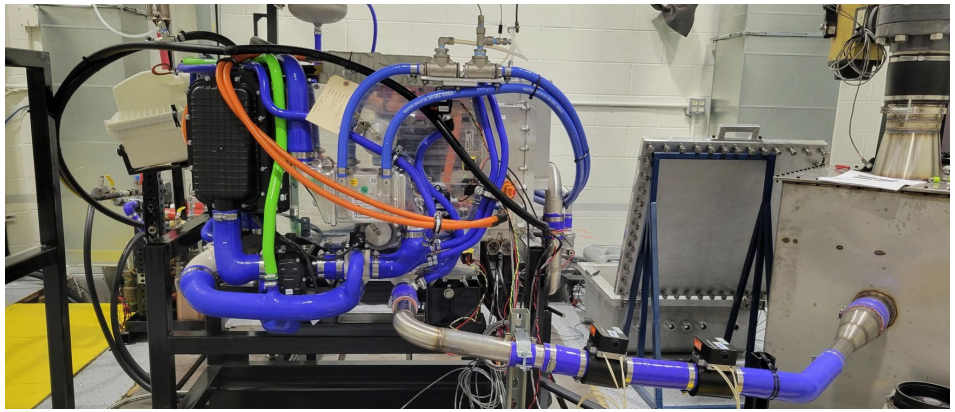
Accomplishments and Progress

Fuel Cell System Validation

✓ Phase 2 Go/No Go
140kW FC net power







Requirement Description	Project Targets	Pilot System
Continuous net power to vehicle (20°C, BoL)	≥ 140kW	✓
Steady state peak efficiency	≥ 60%	✓
Steady state efficiency at rated continuous net power	≥ 45%	✓
Waste heat to coolant at continuous max power	≤ 150kW	✓
Up-transient dynamic response τ_{90} time	≤ 6sec	✓

Fuel Cell system exceeds 140kW target

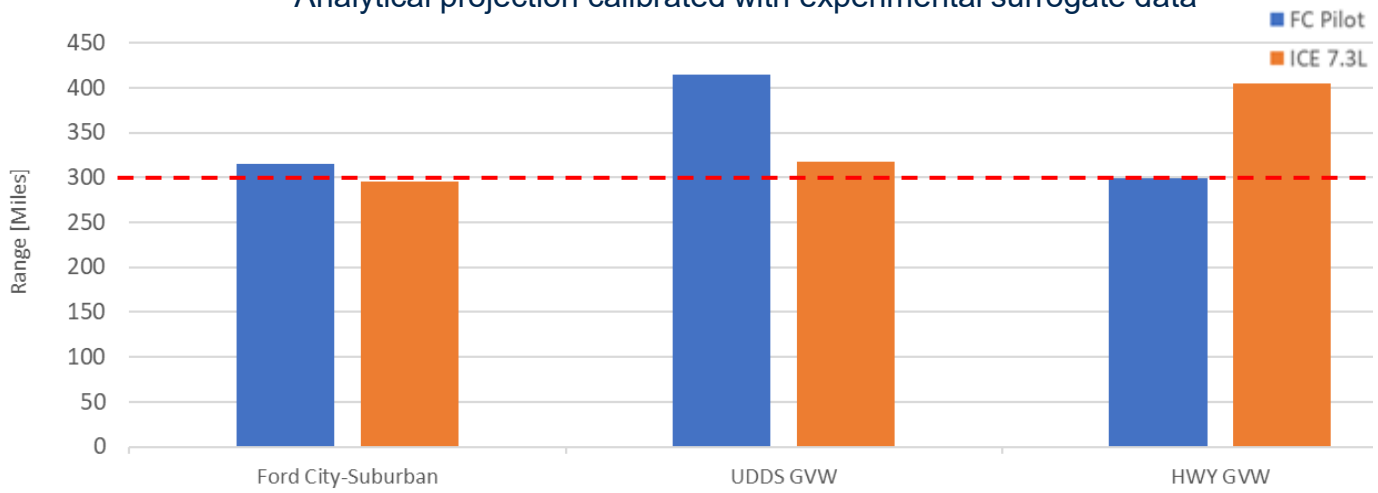
Any proposed future work is subject to change based on funding levels

Accomplishments and Progress

Vehicle Range

- 300-mile range target achieved with 21.5kg H_2 (Ford City-Suburban cycle)

Analytical projection calibrated with experimental surrogate data



Projections support 300-mile range target

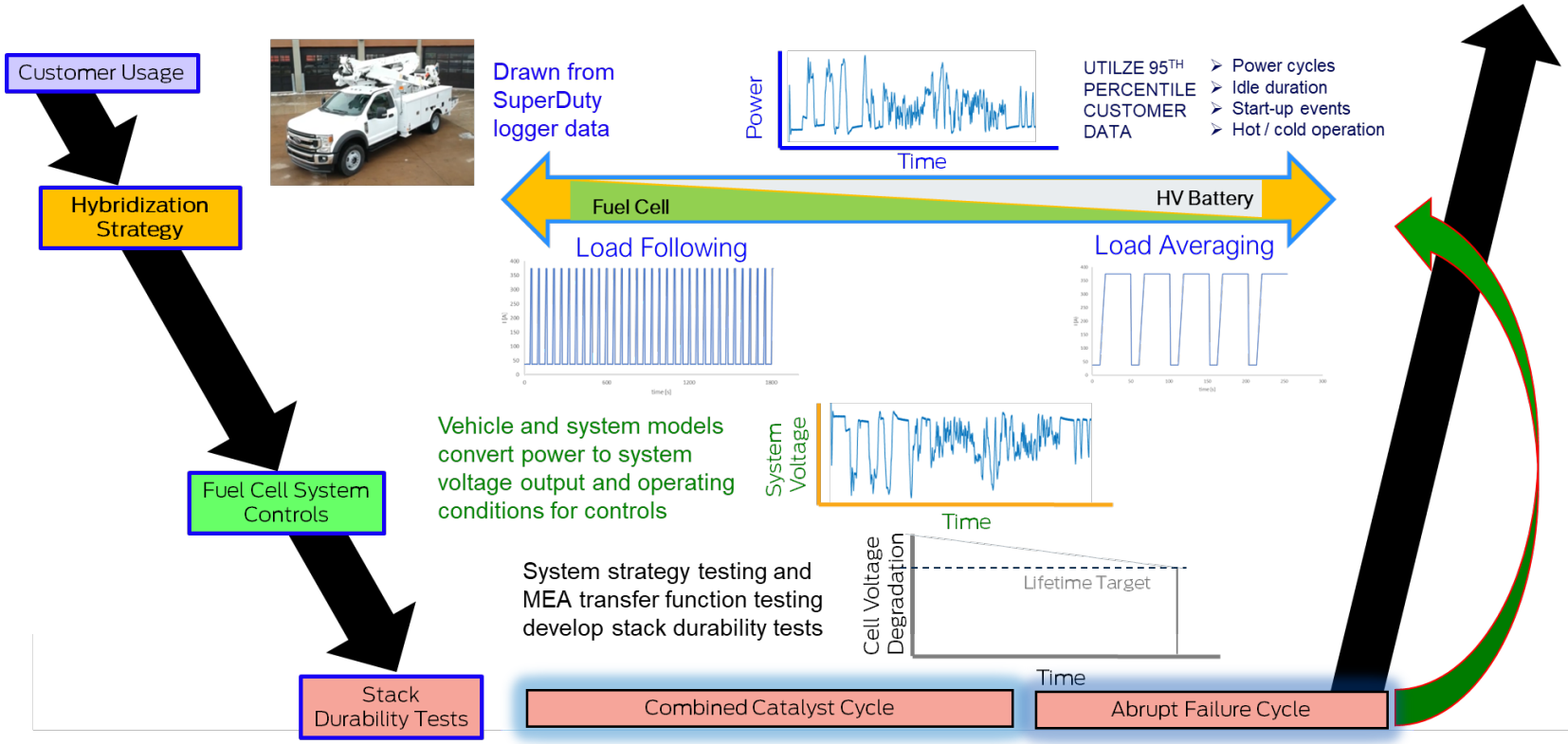
Accomplishments and Progress

Fuel Cell Durability and Strategies

Useful Life Target: 15 Years / 350K miles / 17K hours

Super Duty Lifetime Durability Approach

- Created transfer function for key FC stressors
- Developed operating strategies with degrees of freedom relative to key stressors
- Created a vehicle model to expose system and strategy to over 1M miles of customer detailed logger data
- Developed key life tests based on worst case use cases



Accelerated key life tests derived from real customer use cases

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

Accomplishments and Progress

Fuel Cell Durability and Strategies

Abrupt Failure Cycle: test completed 15 years equivalent operation

- Designed to test membrane stressors.
- The test represented the 95th percentile for stressors to the membrane including high/low power cycling, low power operation, freeze preparation, and hot operation.
- ***Lifetime End-of-Test Results:***
  - ✓ **No membrane failures**
  - ✓ **Bleed down times were ~2.5x better than the lifetime target.**

Combined Catalyst Cycle: test completed 15 years equivalent operation

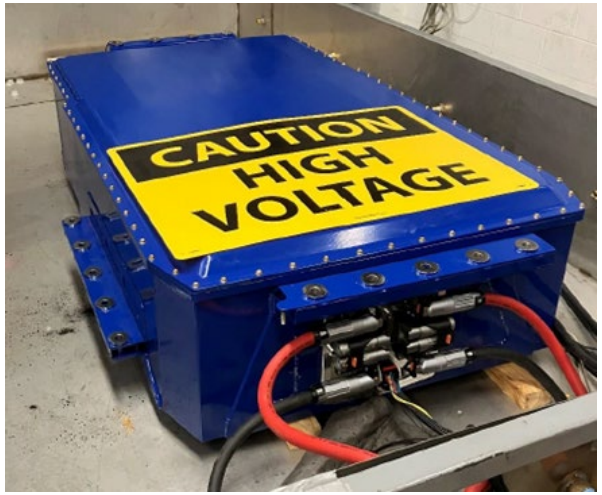
- Designed to test catalyst stressors.
- The test represented the 95th percentile for stressors to the catalyst including high/low power cycling, start-up cycles, and shut-down cycles.
- ***Lifetime End-of-Test Results:***
  - ✓ **No catalyst failures**
  - ✓ **Voltage degradation was only 57% of the lifetime budget.**

Fuel cell stack testing successfully demonstrated 15-year equivalent durability.

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

Accomplishments and Progress

Subsystem Development



- **Battery pack builds complete**
- **eAxles builds complete and delivered**
- **H_2 tank manufacturing in process**
- **Vehicle breadboard in operation**

Major Propulsion Subsystems on track and pre-build Breadboard prove-out in progress

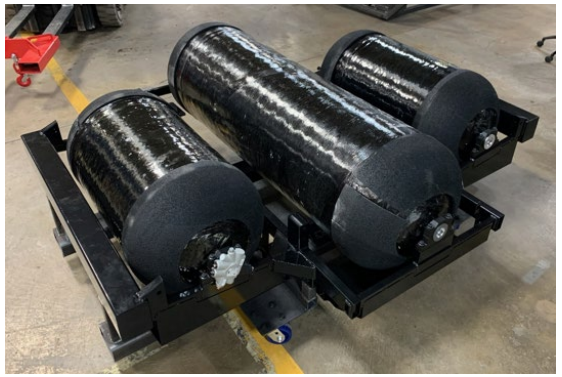
Any proposed future work is subject to change based on funding levels

Accomplishments and Progress

Vehicle Build Status

Development Vehicle #1

- Chassis modifications complete
- Fuel cell system and supporting components installed
- Underhood build complete
- Electrical harness builds in-process
- eAxles installed
- Build complete target – May 2024



1st Development Build Target Completion – May 2024

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Accomplishments and Progress

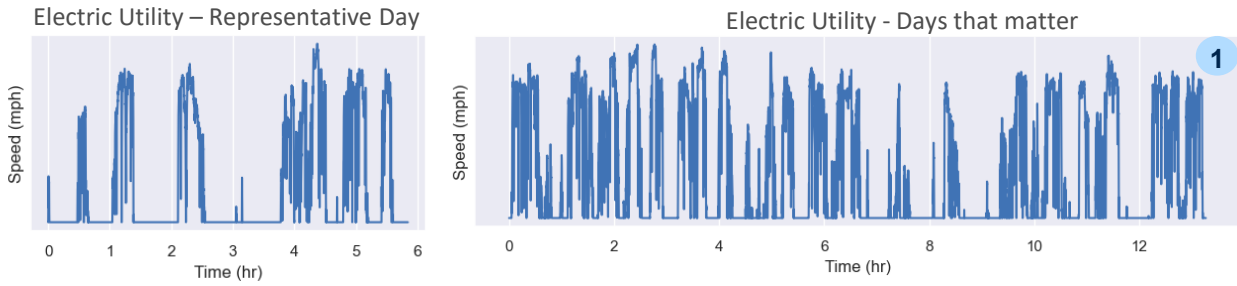
TCO Analysis

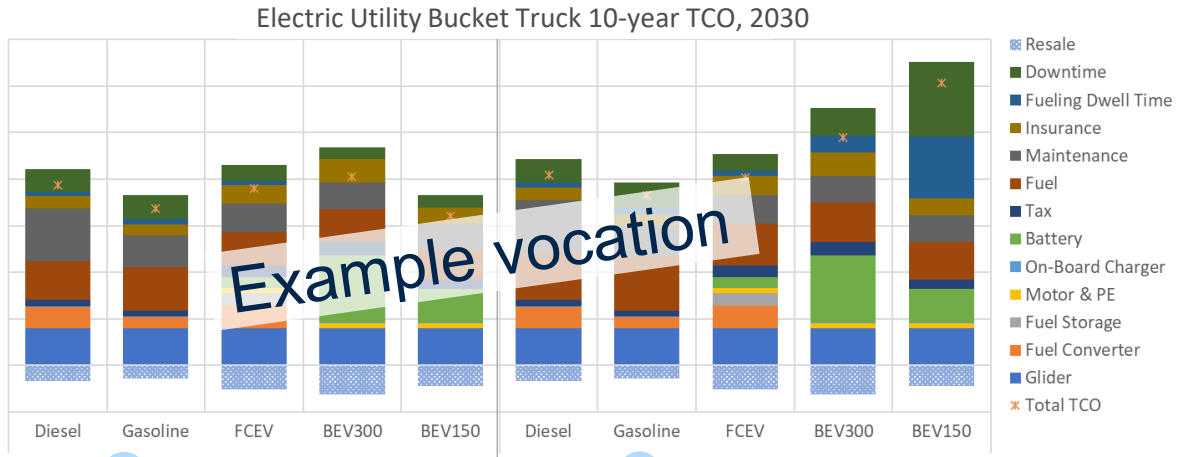
- Initial TCO results were calculated assuming all days in the vehicle's life follow a given "representative day" cycle derived from statistical analysis of the fleet [1]
- "**Days that matter**" were added to capture the impact of high energy demand days

	Representative	High Demand	Difference
Driving Distance (mi)	84	298	256%
Total Engine-out Energy (kWh)	114	467	312%

  - The frequency and duration of charging to meet high demand days drives changes TCO equation [2]

- Subsequent TCO will evaluate a full year of driving cycles to get a more realistic "year in the life"





NREL's T3CO model with Ford's fleet partner data is being used to evaluate 10-year TCO
"Days that matter" is an important consideration for real world applicability

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Accomplishments and Progress

Responses to Previous Year Reviewers' Comments

- More details on operating strategies ✓
- Range vs gas ✓
- Safety plan ✓
- Cold weather strategies – successfully demonstrated -30C cold start in test cell. Winter validation upcoming.
- Pilot customer data sets being developed. Will have real time telematics for critical parameters and deeper data downloads
- Customer roles – adapt upfits to new propulsion system. Help with H2 infrastructure. Do what you normally do with the vehicles when deployed.
- Customer applications – Crane truck for SoCal gas, Bucket truck for Consumers Energy (incl ePTO surrogate for Boom operation), Box truck for Ferguson

Collaboration and Coordination

Subcontractors

NREL – Transforming ENERGY

- Assess Total Cost of Ownership
- Commercial Vehicle Partner Fleet Systems Analysis
- Freight and Vocational Fleet Systems Analysis
- Battery lifetime modeling
- Hydrogen fueling rate

FEV

- Fuel Cell System Development and Testing Services
- Vehicle Testing Facilities
- Netcom and LV architecture services
- Functional Safety engineering services

Customers

SoCalGas

- Crane Truck
- High Ambient/Altitude/Grades
- On-Road/Off-Road/High GVW

- California - Gas Utility
- Servicing Southern California

Consumers Energy – Count on Us®

- Boom Truck
- Cold Climate
- On-Road/Off-Road/High GVW

- Michigan - Gas and Electric Utility
- Servicing all lower Michigan counties

FERGUSON

- Box Truck
- Various Conditions
- On-Road/Construction Site

- North Carolina - Plumbing, HVAC, Industrial
- Servicing all 50 States

Two Subcontractor Awards / Three Fleet Customers

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DEIA/Community Benefits Plan

Ford Global DEI

- Ford is committed to nurturing an equitable workplace where each person is valued and empowered to do their best work
- We are focused on the long-term cross-functional work required to equitably support our team members, customers, dealers and the communities where we live and operate
- Since 1978, Ford has spent more than $180B with diverse suppliers and is proud to be recognized as an industry leader for Supplier Diversity & Inclusion
- We aspire to achieve carbon neutrality by 2050, focusing on vehicles, operations and supply chain; Require suppliers to establish science-based GHG reduction targets, action plans and reporting mechanisms

Project Specific Benefits

- Pilot vehicle deployments selected for underserved or disadvantaged communities vulnerable to criteria emissions and GHG effects
- Flint, MI (Consumers Energy) / Bakersfield, CA (SoCal Gas)

76%

REDUCTION IN SCOPE 1 AND 2 GHG EMISSIONS FROM OUR OPERATIONS BY 2035 FROM A 2017 BASELINE

50%

REDUCTION IN SCOPE 3 GHG EMISSIONS PER VEHICLE KILOMETER FROM USE OF SOLD PRODUCTS BY 2035 FROM A 2019 BASELINE

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Remaining Challenges and Barriers

Challenges

- Extreme cold weather operation
  - Fuel cell, battery and propulsion system operating strategies are being developed to ensure robust operation in extreme cold climates.
  - Successful -30C freeze start in test cell. Climate chamber and winter ‘24/’25 confirmation in vehicle
- Ford Super Duty Lifetime Durability
  - Successfully completed key life tests equivalent to 15 years in the field.
  - Internal development fleet and Pilot deployments will validate.
- ICE parity in MD CV applications (including TCO, uptime, payload)

Barriers

- Pilot fleet hydrogen infrastructure
  - Ford has a fully capable hydrogen H70-T40D station for fueling the pilot vehicles on-site for testing.
  - Off-site mobile or semi-permanent solutions are prohibitive due to acquisition cost, electrical utility interfaces, additional hydrogen storage trailers, location permitting and/or site preparation.
  - Mobile refueling solutions are needed to enable:
    1. Development of fuel cell electric vehicles at real-world testing sites throughout the US.
    2. Deployment of fuel cell electric vehicles at customer sites for limited trial fleet evaluation.

Off-site H2 infrastructure is the major barrier to the SuperTruck 3 Project

Proposed Future Work

2024

- **Phase 2 Go/No Go Milestones**

Bench Confirmation of FC 140kW+ net power capability ✓

Complete Development Builds

- **Fuel Cell:** EOL (end of line) testing on all pilot vehicle fuel cell systems
- **Propulsion System:** Commissioning and start of development on first two development vehicles
- **H2 Infrastructure:** Continue search for development and Pilot fleet needs

2025

- **Attribute, DV and Durability Testing:** Complete controls and calibration development, robustness and durability testing, and altitude and environmental testing
- **Fleet Vehicles:** Complete upfitter modifications (mid-2025) and deploy to customers by year-end

Phase 2 is on track for 2024

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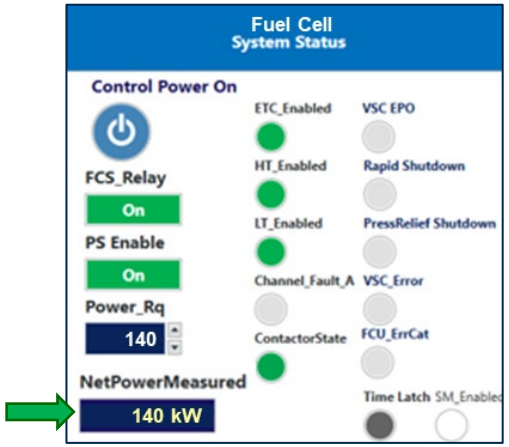
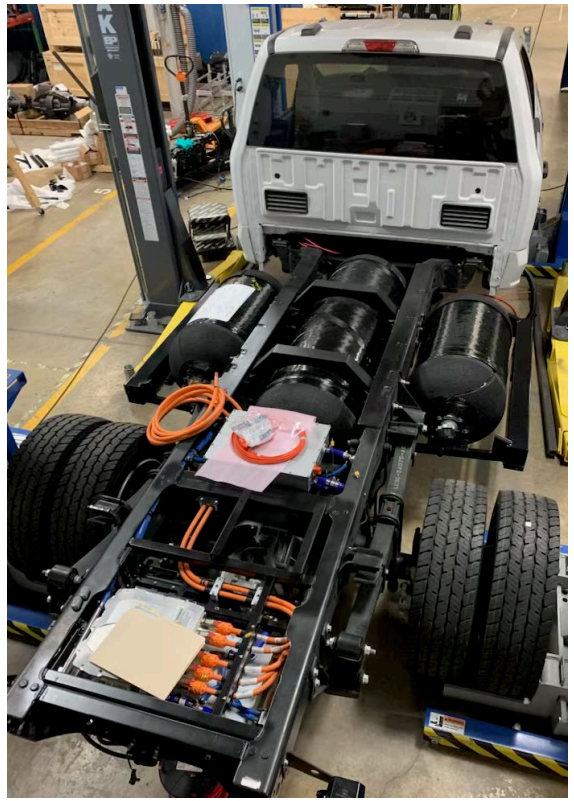
Summary

- Concept selection and analysis of an F550 Chassis Cab Fuel Cell Propulsion system that meets the target attributes is complete
- Go / No Go experimental confirmation of FC net power complete
- 1st complete vehicle build expected in May
- TCO, GHG and environmental impact studies are providing useful insight for future planning.





THANK YOU

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