U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Decarbonization of Off-Road, Rail, Marine, and Aviation Program*

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June 21, 2022

*Previously *Advanced Engine and Fuels Technologies Program*

Who We Are

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Rail, SuperTruck, Emission Control

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Marine, Aviation, Fuel Technologies

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Off-Road Vehicles, Combustion

Program has Shifted to Non-Road Decarbonization Sectors

- Advanced Engine and Fuels Technologies has been renamed to Decarbonization of Off-Road, Rail, Marine and Aviation Program

- Focus on efficient utilization of renewable fuels, such as advanced biofuels, hydrogen, and e-fuels, to reduce GHG emissions for off-road, rail, marine and aviation sectors.
- Impact of renewable fuels on emission control systems to reduce criteria emissions to near-zero levels.
- Vehicle-level system integration including hybridization, battery-electric and fuel cell applications for Non-Road sectors.
- Completing on-road engine projects.

High Efficiency, Low Mass Engines: Light- and Medium-Duty Trucks

Ford:

Objective: To develop an engine that will achieve 23% fuel economy (FE) improvement and 15% engine weight reduction relative to a 2016MY 3.5L V6 EcoBoost F150 baseline.

Status: 75% work completed. Technologies identified and included in design to achieve the FE and weight reduction targets. Expected to be completed this year.

GM:

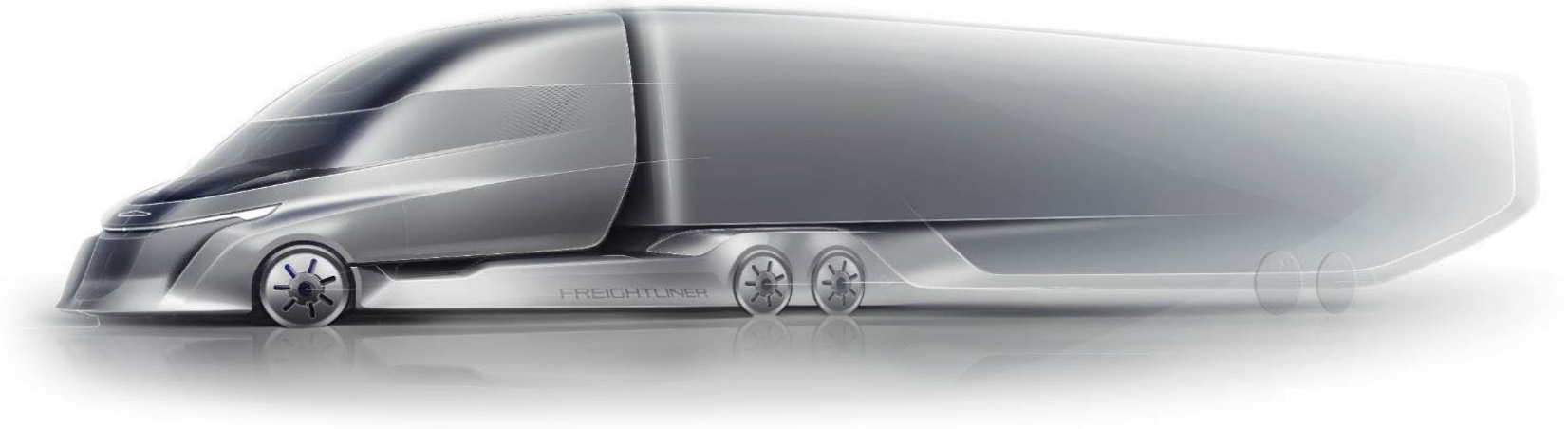
Objective: To develop a medium-duty truck engine capable of ≥10% fuel economy improvement and ≥15% engine weight reduction relative to a 2015 L96 VORTEC 6.0L V8 engine.

Status: 55% work completed. Task-1 achieved 7% FE improvements; Task-2, to be completed in 2023, aims to achieve more than 4% additional FE improvement and 20% weight reduction.

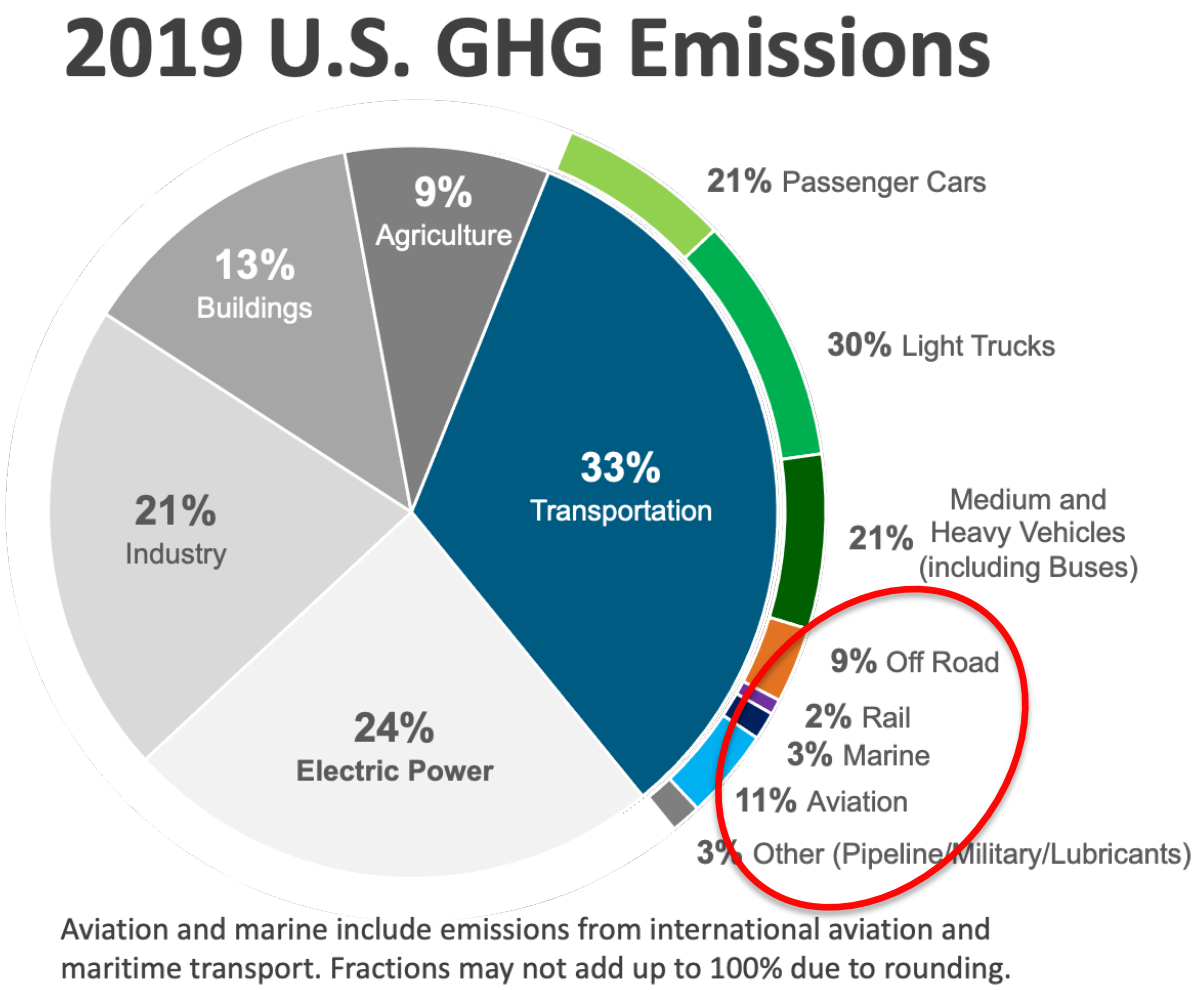
SuperTruck II

Objective: Demonstrate 55% engine brake thermal efficiency (BTE), and greater than 100% improvement in freight efficiency (ton-mpg)

- Cummins-Peterbilt and Navistar teams have demonstrated 55% engine BTE
- All teams are on track to demonstrate ≥100% freight efficiency targets in 2022-2023
- Initiated SuperTruck III: Ford, GM, and Daimler will develop Fuel Cell MD/HD trucks while Paccar and Volvo will develop battery-electric tractor trucks.



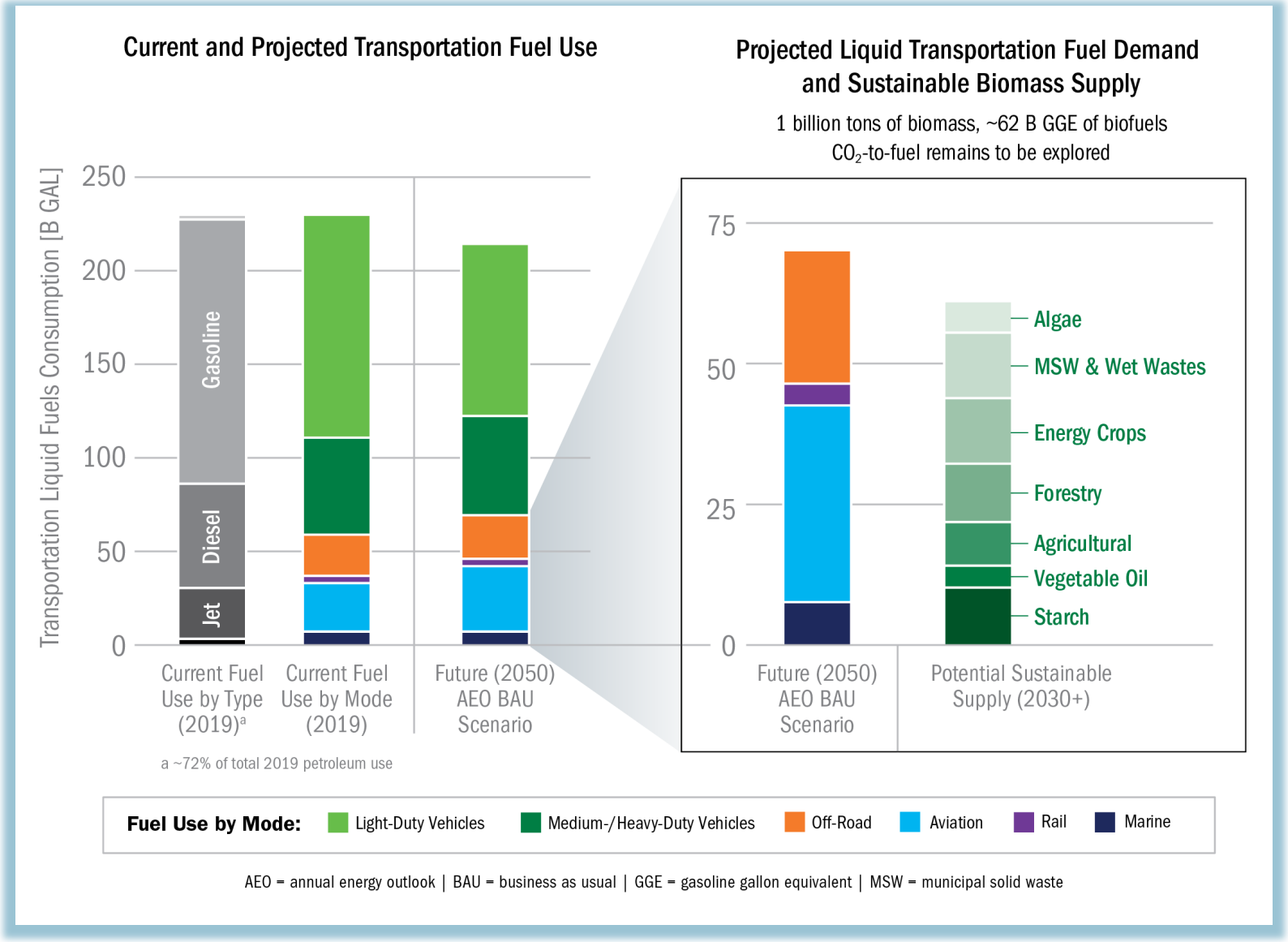
Non-Road Decarbonization Needs Multiple, Targeted Solutions



- **Light Duty** (cars/SUV/PU) largest share (~51%), and **MD/HD vehicles** (21%) can largely be electrified leveraging **clean electricity and hydrogen.**
- Strategy must also address **remaining 28% of transportation** (projected to grow more rapidly)
  - **Hydrogen** and **Biofuels** will be critical to these other sectors
  - **Electrification**
  - **Diversification** also improves resiliency

- Focus on solutions that can be **incrementally deployed**, delivering results by 2030
- Full **lifecycle emissions** must be addresses
- Effective **integration with the grid** and energy infrastructure

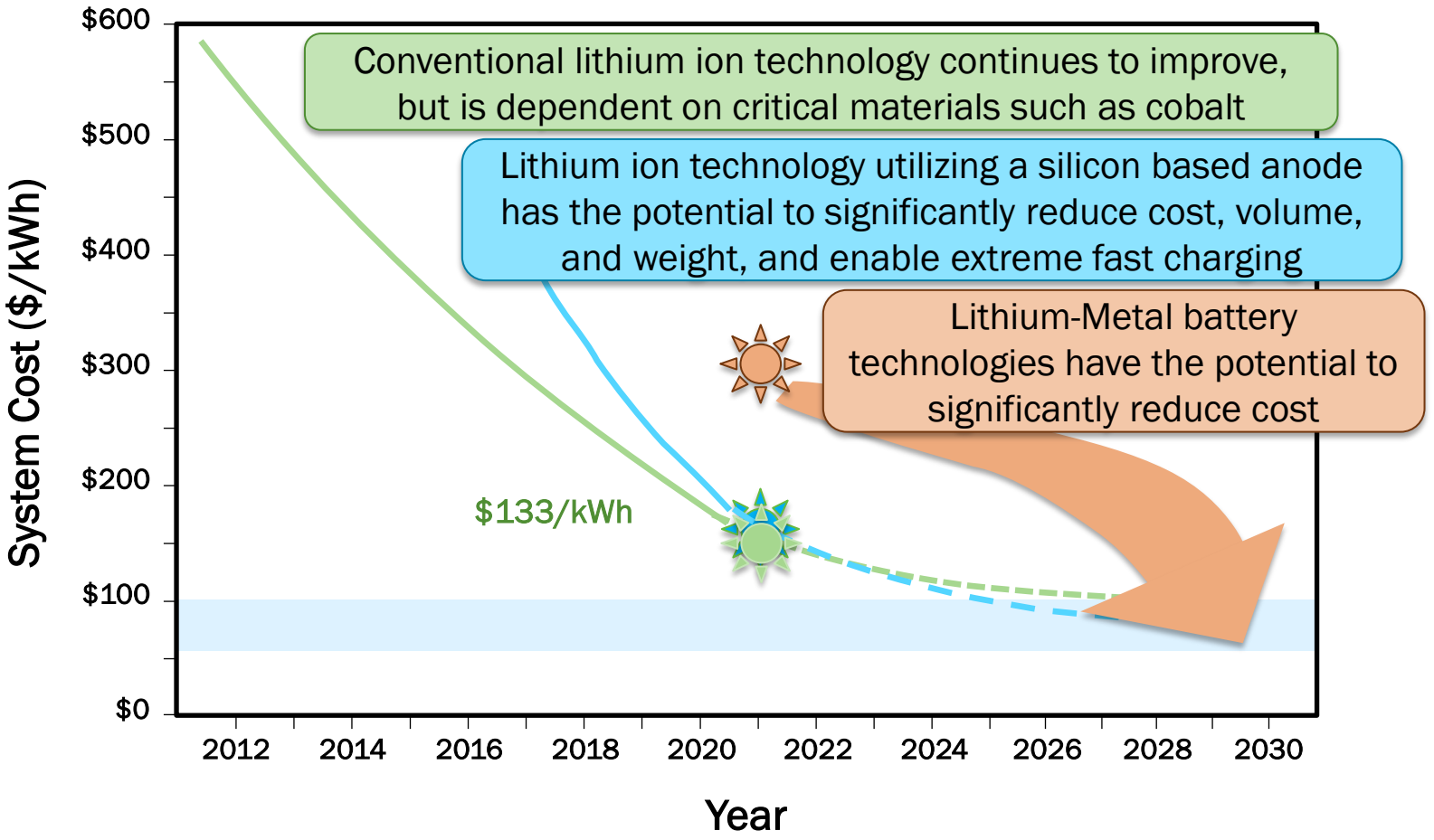
Fuel Demand and Sustainable Biomass Supply for Non-Road



AEO = annual energy outlook | BAU = business as usual | GGE = gasoline gallon equivalent | MSW = municipal solid waste

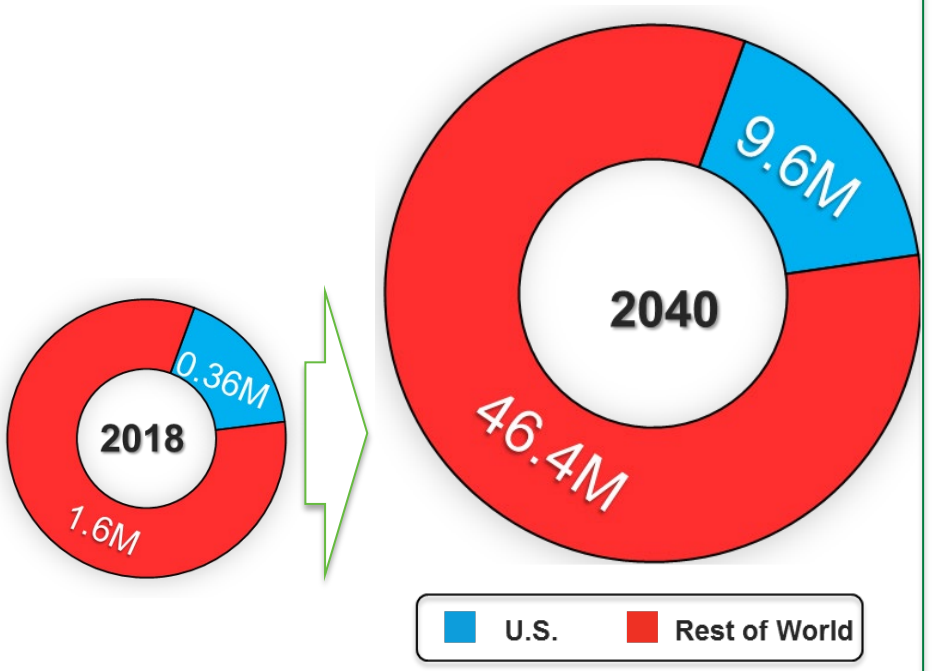
Reducing Costs and Market Opportunity for Batteries

VTO R&D has lowered the cost of EV battery packs to $133/kWh rated energy in 2021, a more than 80% reduction since 2008 based on an annual production volume of 100k EV packs.



Global projection of annual passenger EV sales is 56M EVs in 2040[1]

- **17% (~9.6M EVs) of those sales will be in the US market**
- **9.6M EV's equates to approximately a $100 billion battery market**



[1]Source: Bloomberg NEF Long-Term Electric Vehicle Outlook 2019
[2]Source: IBIS World, Market Size Statistics - United States 2018 NAICS Reports

Hydrogen Shot – ramping up the availability of clean H2

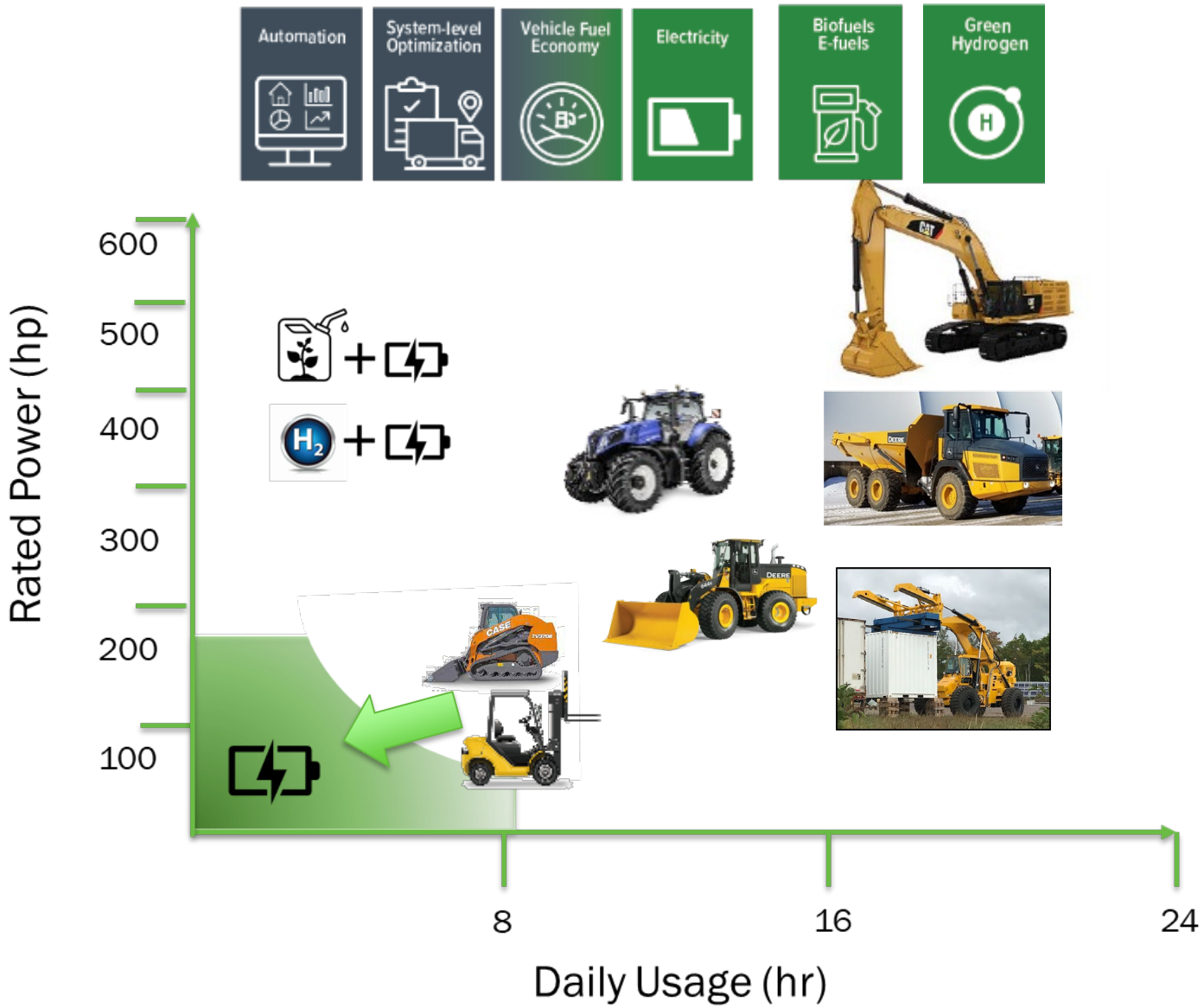
ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Off-road R&D strategy

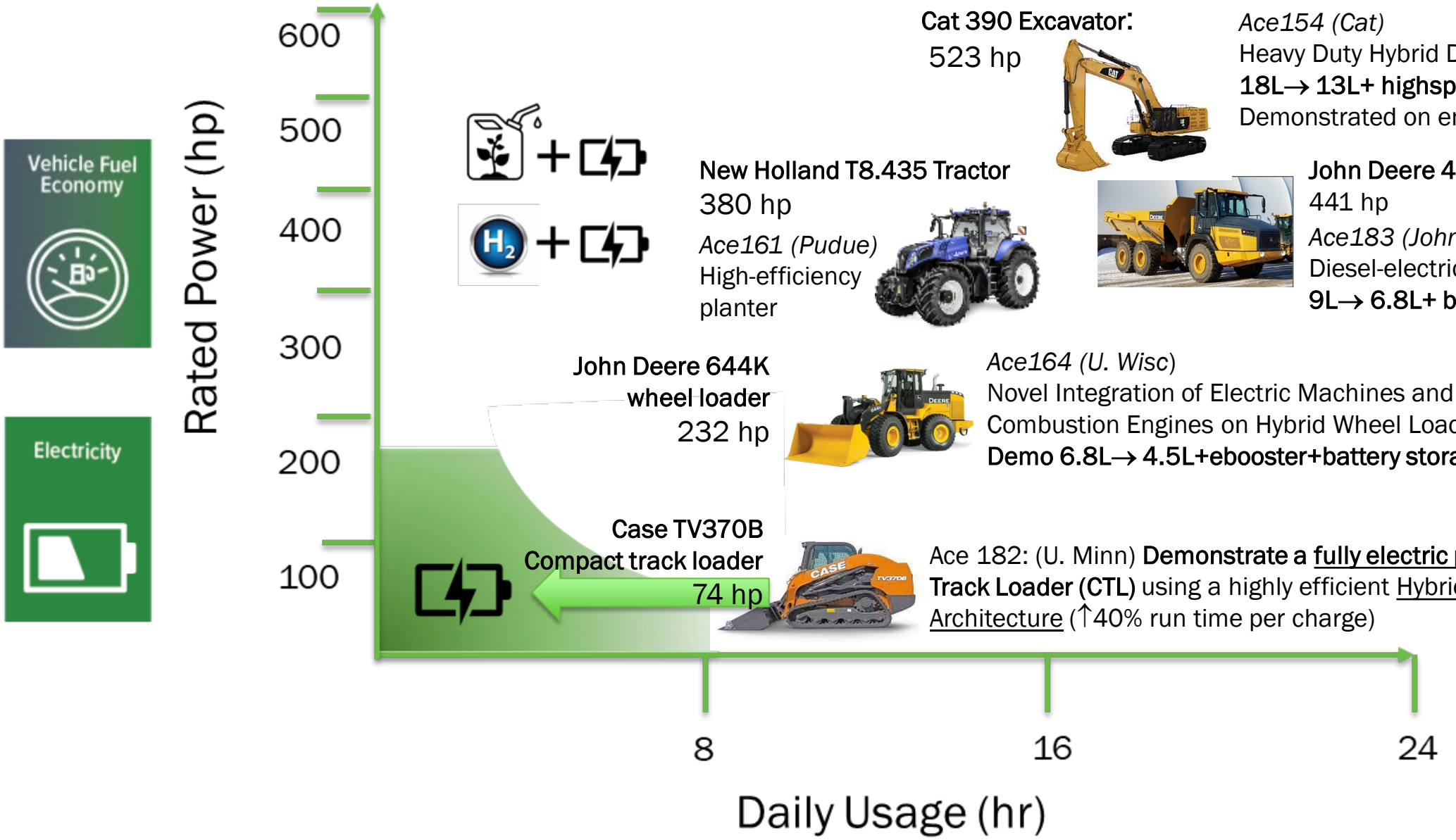
- Good opportunities for reducing energy and carbon intensity; activity expected to grow

- Battery electric equipment for <175hp/limited daily usage
  - Increase vehicle efficiency to allow longer daily usage per charge
  - Enable worksite charging for difficult situations
  - ZEV mandates at state/local level help facilitate this transition

- High power/usage and remote operation present barriers for battery-electric
  - Hybridization and engine-downsizing, other efficiency improvements for near-term impact
  - Enable use of low-carbon fuels
    - Liquid: RD100, E100, M100
    - Gaseous: Clean H_2 – in FC or H2ICE



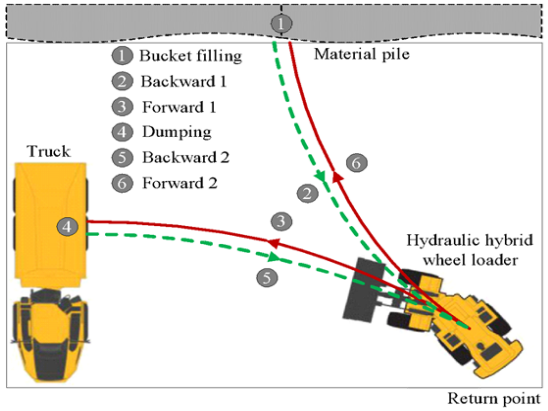
Select Off-Road Demonstrations in Progress



Off-road projects in progress

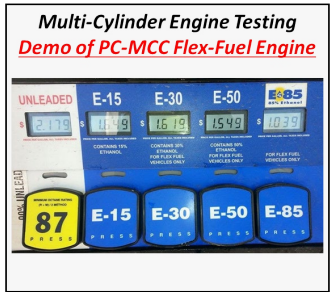
Automation

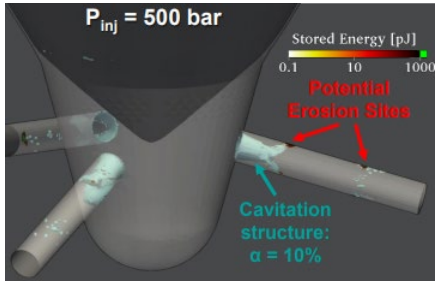
System-level Optimization



Ace160 (U. Minn)
Enable connected/automated operation at construction site
Increase efficiency by removing operator variance (up to 40%)

Biofuels E-fuels





Ace184 (Marquette)
Enable flex-fuel engine up-to E100

National lab CRADAs
Study impacts of RD, BD, EtOH, MeOH on fuel injection, combustion and emission control

Green Hydrogen

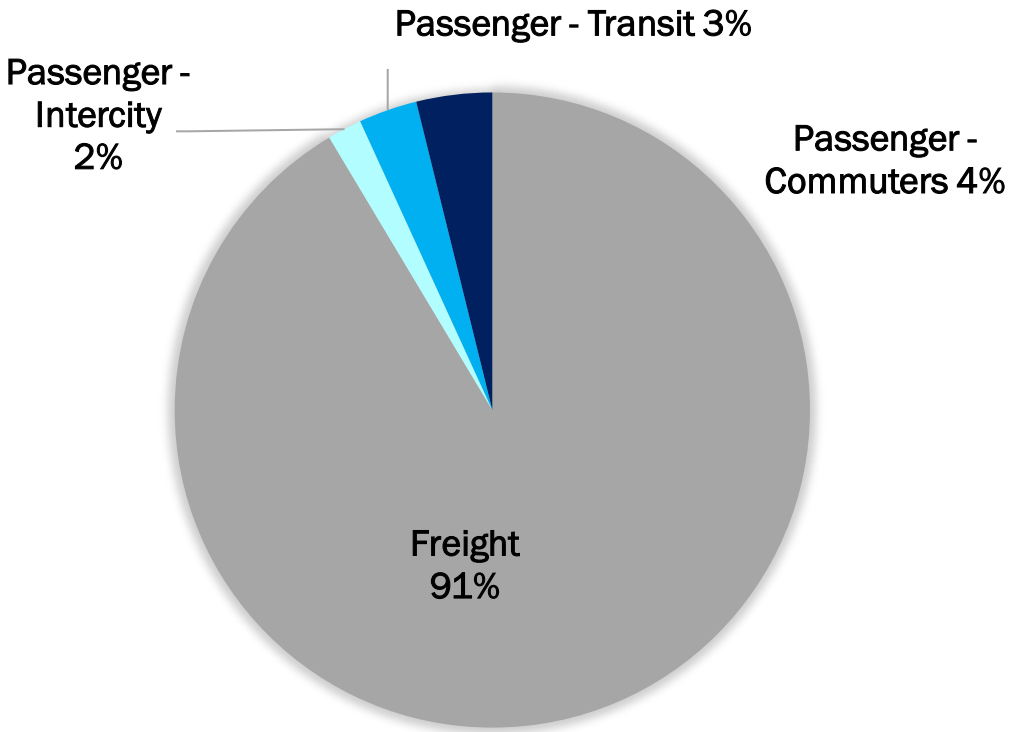
Argonne NATIONAL LABORATORY

Sandia National Laboratories

National lab CRADAs
Experiments and modeling to address barriers of large H2ICE engines

Overview of Rail Decarbonization

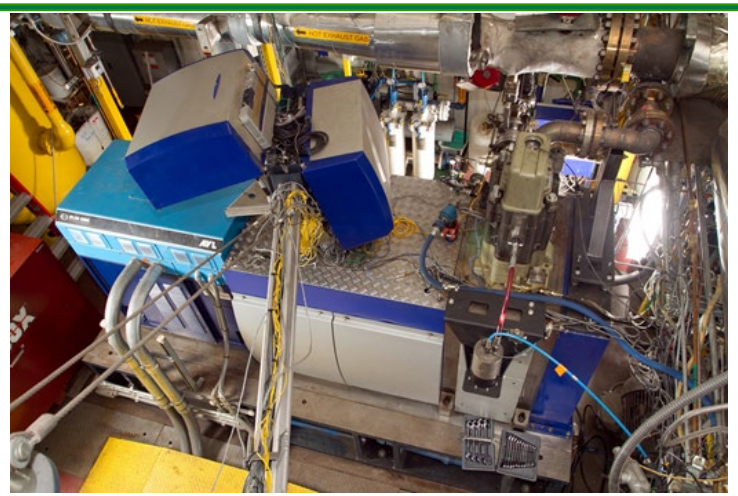
2019 U.S. Rail Transportation Energy Use (0.5 Quads)



- $80-billion freight rail industry provides 167,000 jobs and moves 28% of freight by ton-miles
- Multiple technology solutions to decarbonize rail sector: (Next slide for details)
- Direct or battery electrification,
  - H2, (Fuel Cells and ICE)
  - Low-Carbon fuels
- Segmentation remains uncertain, DOE is working with other Fed agency and industry to explore all options.
- No major supply limitation foreseen for electricit y/H2 but the sector needs to leverage solutions used in other applications to achieve scale

Projects on Rail Decarbonization

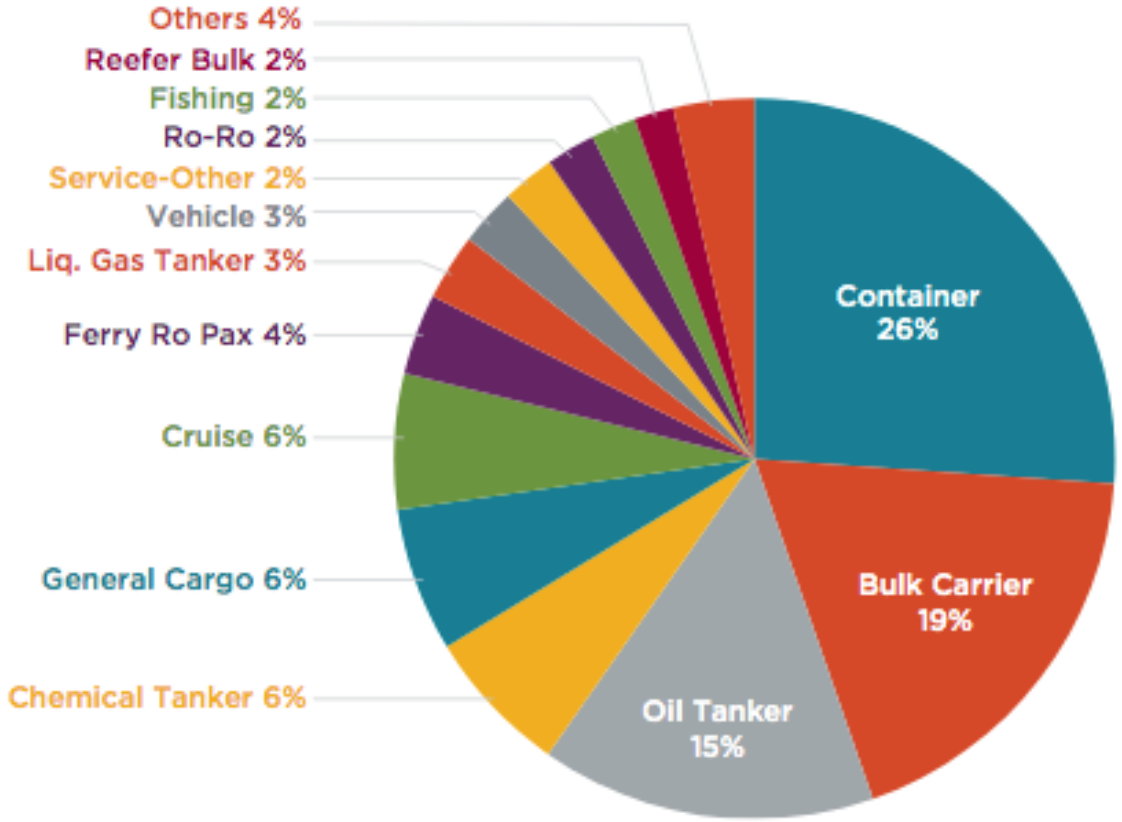
- Low Carbon Fuels for Rail Sector– ORNL and ANL with Wabtec
- Low Carbon Fuels for Rail and Marine Sectors - ANL with Progress Rail
- Impact of renewable and biofuels on emission control system
- ORNL/ANL Industry survey on powertrain and fuel choices
- ANL-DOE Railroad Workshop, May 17-18, 2022
  - Feedback from almost 200 attendees will help shape our R&D plans



Figures. (Top) Wabtec single cylinder research engine (bottom) Progress Rail 4-stroke 16L 1010- single cylinder engine

Overview of Marine Decarbonization

Global Carbon Emissions By Ship Class



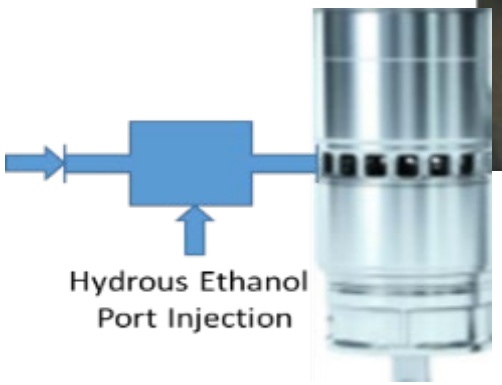
"Black Carbon Emissions and Fuel Use in Global Shipping, 2015." ICCT. https://theicct.org/sites/default/files/publications/Global-Marine-BC-Inventory-2015_ICCT-Report_15122017_vF.pdf

- US Fleet of Maritime Vessels
  - 38,000 commercial vessels
  - 11 million motorized recreational boats
  - 6,500 government-owned boats and ships
- 2/3 of GHG emissions from the largest ships
  - Very few large commercial ships – such as container ships – are owned or flagged in the US, but many visit US ports
  - US can be a supplier of low carbon liquid fuels
- Many of the smaller and medium vessels
  - Suitable for electrification
  - Near- and mid-term use of low carbon fuels.
- Government-owned vessels could be potential technology demonstration platforms

Dual Fuel (Ethanol/Diesel) CI Engines for Marine and Rail (ANL)

- Alcohol via port injection (can be “wet ethanol”) mixture into the intake air.
- Displace the Diesel fuel with low-carbon alcohols (ethanol), to reduce the greenhouse gas emissions
- This technology applies to a wide range of off-road applications, including marine and locomotive sectors. The target application areas are locomotive yards and seaports to lower their CO2 and NOx emissions.

2-Stroke 710-PR 11.6 L Engine

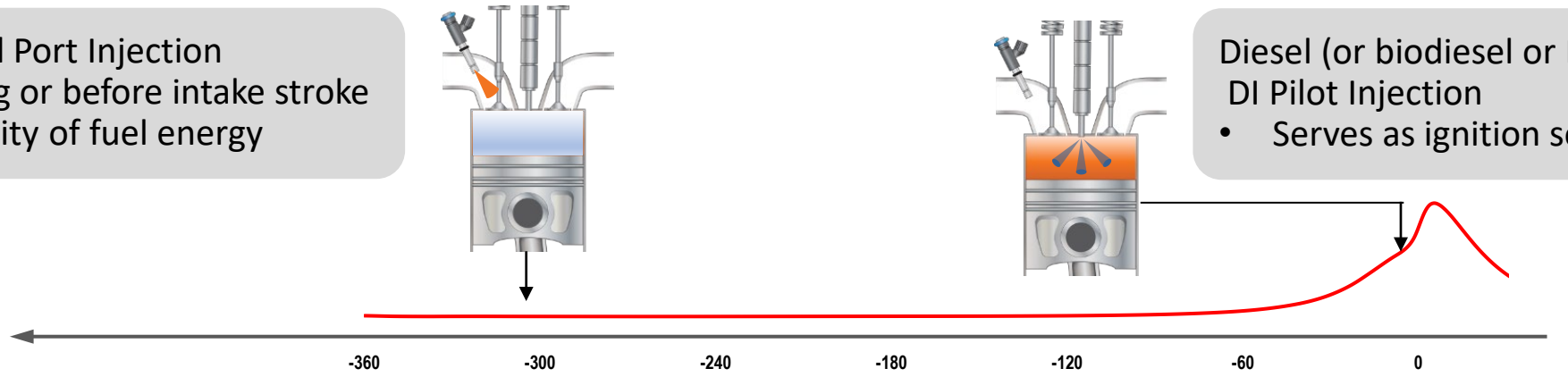


Port-injection in the Air Box

Methanol Utilization in 4-stroke Marine Engines (ORNL)

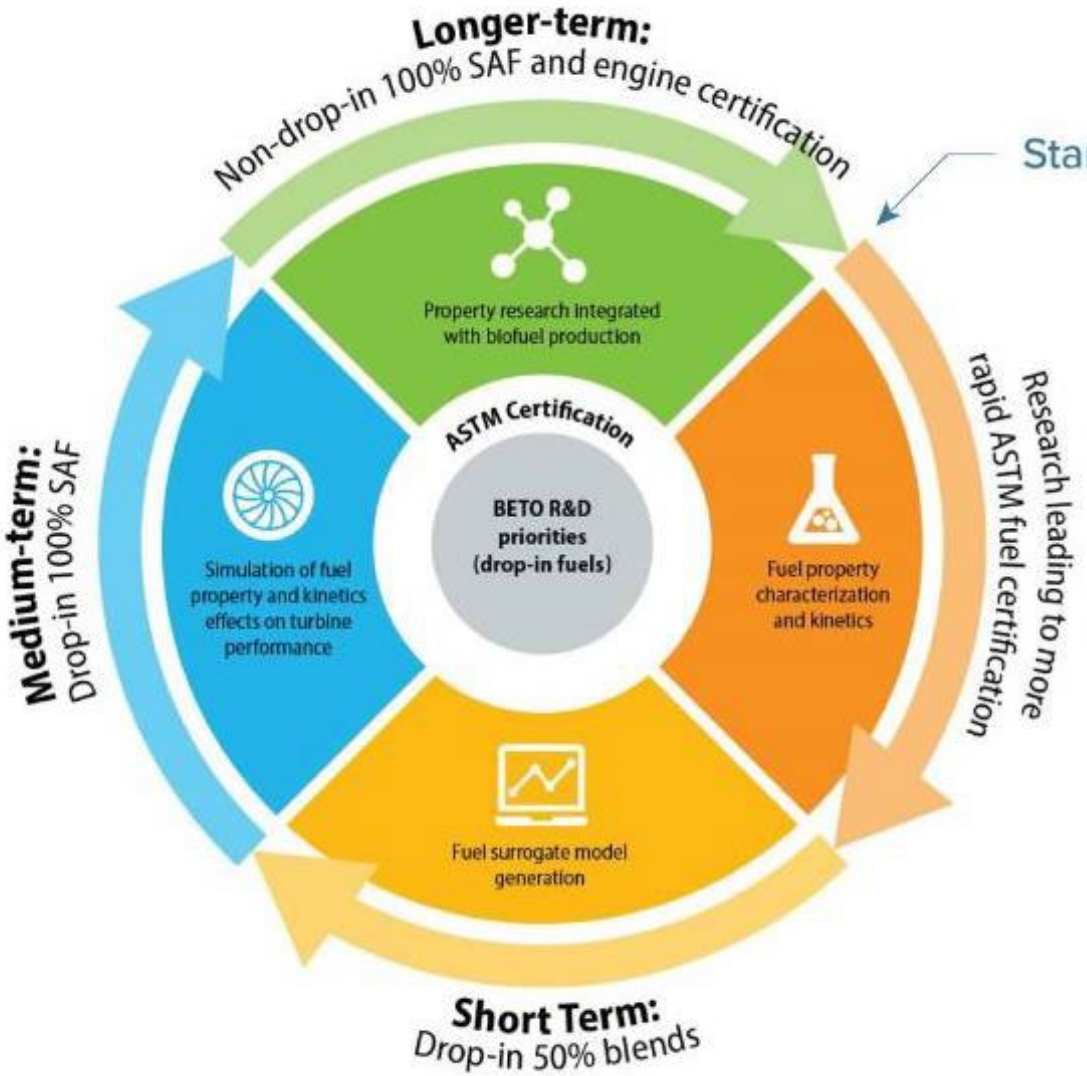
- **Net-zero carbon fuels are needed to reduce greenhouse gas (GHG) emissions in marine and other hard-to-electrify applications**
  - Methanol provides reasonable tradeoffs between energy density, safety, storability, and utilization
  - Methanol can be produced from a wide range of renewable carbon feedstocks
- **Methanol resists autoignition and requires an ignition source**
  - Diesel (or biodiesel or DME) pilot ignition source retains utility of current compression ignition engines
- **New ORNL project will address numerous challenges remaining for methanol engines**
  - Maximize diesel displacement while maintaining power density
  - Optimize combustion efficiency and minimize criteria pollutants
  - Identify suitable technology pathways for different engine sizes and applications

Methanol Port Injection
- During or before intake stroke
- Majority of fuel energy



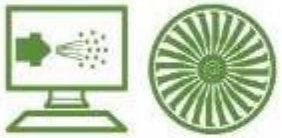
Diesel (or biodiesel or DME)
DI Pilot Injection
- Serves as ignition source

The Sustainable Aviation Fuel (SAF) Technology Landscape



Fuel production: BETO

Fuel property characterization: BETO and VTO



Fuel property mapping to turbine performance: VTO

Expanding boundaries of ASTM certification: VTO

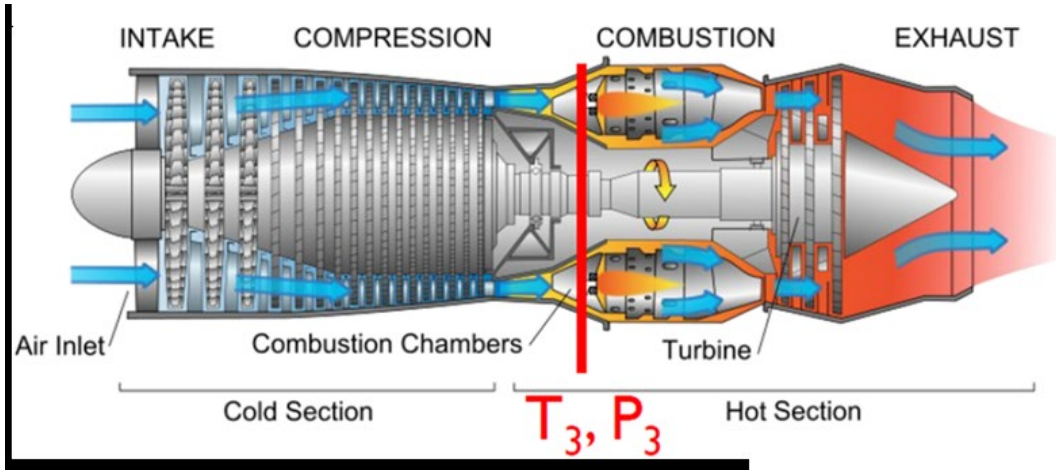
De-risking qualification of new fuels (drop-in and marginally drop in): VTO and BETO

Slide courtesy of NREL

End-Use Activities on SAF

- Most aviation will use liquid, hydrocarbon fuel for the foreseeable future.
- SAF fuels, though potentially drop-ins with engines, are not identical to conventional jet fuel.
- Modeling tools for jet engines are several years behind where comparable modeling is for terrestrial vehicle engines.

There is a role for the national laboratories to play in facilitating and accelerating SAF adoption to decarbonize the aviation sector by leveraging unique capabilities at DOE labs.



SAF End-Use Workshop Takeaways

- **ANL-DOE SAF End-Use Workshop, February 15-16, 2022**
  - 200 registrants from industry, academia, government and national labs
  - ~140 participants logged in each day

- **Key areas of interest to VTO**
  - **Fuel characterization** – physical and chemical kinetic libraries inadequate for CFD for most-viable fuel pathways
  - **Fuel Injection/Atomization** not predictable for conventional or novel fuels, and new (to this community) diagnostics offer unique value
  - **Combustion Simulation** currently has difficulty predicting operability effects (e.g., lean-blow-out and high-altitude relight) for SAFs
  - More work needed to **predict SAF emissions/soot** & link to **contrail formation** (for which SAFs may provide benefit)

New FY22 Aviation Projects

- **Fuel Characterization**
  - **NREL:** Measuring Critical Fuel Properties for Simulations to Accelerate Fuel Qualification
  - **NREL:** Integrated Support of VTO and BETO SAF Development
- **Fuel Injection / Atomization**
  - **Argonne:** X-Ray Interrogation of aviation combustors
  - **Sandia:** Droplet nucleation experiments in altitude chamber to study contrail formation
- **Combustion Simulation**
  - **Argonne:** Detailed Simulation of Aviation Combustor
- **Emissions**
  - **LLNL:** SAF Contrail Formation Modeling
  - **Sandia:** Soot measurements from SAFs with a single-hole atomizer

Summary

- Shifting focus of R&D to Non-Road sectors (Off-road, Rail, Marine and Aviation).
- Work closely with BETO, HFTO and Battery and Electrification to develop decarbonization solution for Non-Road vehicles.
- Impact of renewable fuels on emission control systems
- Continue working with industry to on vehicle-level system integration for Non-Road sectors.
- Completing on-road projects.