Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-Duty Applications – Preliminary Results

R. K. Ahluwalia, X. Wang, A. Star, and D. D. Papadias

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Hydrogen Fuel Cells for Tractors, Wheel Loaders, and Excavators

Objective: Determine the potential role of hydrogen and low-temperature polymer electrolyte fuel cells (PEFC) in off road heavy-duty applications by analyzing their performance and total cost of ownership (TCO)

Farm Tractors	**Engine Size (hp)**		**Fuel Consumption, gal/h**	**Annual Operating Hours**
Class/Category	**John Deere**	**Study Model**		
2 WD Compact	22 - 65	50	1.9	400
2 WD Utility	45 - 250	160	6.1	525
2 WD Row Crop	140 - 400	265	10.2	600
4 WD	370 - 620	550	21.0	670
Wheel Loaders	**Engine Size (hp)**		**Fuel Consumption, gal/h**	**Annual Operating Hours**
Class/Bucket Capacity	**Caterpillar**	**Study Model**		
1.0 - 2.5 CY Compact	40 - 100	75	2.5	1500
2.5 - 6.5 CY Small	115 - 180	150	4.8	1500
3.75 - 15 CY Medium	230 - 400	300	9.4	1500
>30 CY Large	< 1800	700	21.6	1500
Excavators	**Engine Size (hp)**		**Fuel Consumption, gal/h**	**Annual Operating Hours**
Class/Weight Class	**Caterpillar**	**Study Model**		
<13,227 lbs Mini/Compact	13 - 70	50	1.4	400
<22,046 lbs Medium	75 - 200	100	2.4	500
<198,416 lbs Standard/Full	273 - 543	500	10.4	1100

1. Fuel consumption and annual operating hours from DOE Hydrogen Program Request for Information (CNH Industrial), # DE-FOA-0002529
2. Class/category/bucket capacity and engine sizes from John Deere Tractor, Wheel Loader, Excavator Product Lines: https://www.deere.com/en/; Case IH Product Line, https://www.caseih.com/northamerica/en-us/home; Case CE Product Line, https://www.casece.com/northamerica/en-us/products; Caterpillar Wheel Loader and Excavator Product Line, https://www.cat.com/en_US/products/new/equipment.html

Approach

Power System

- Use fuel cell systems (FCS) being developed for heavy-duty trucks, leverage economies of scale
- Size FCS to satisfy power requirement at end of life (EOL)

Heat Rejection

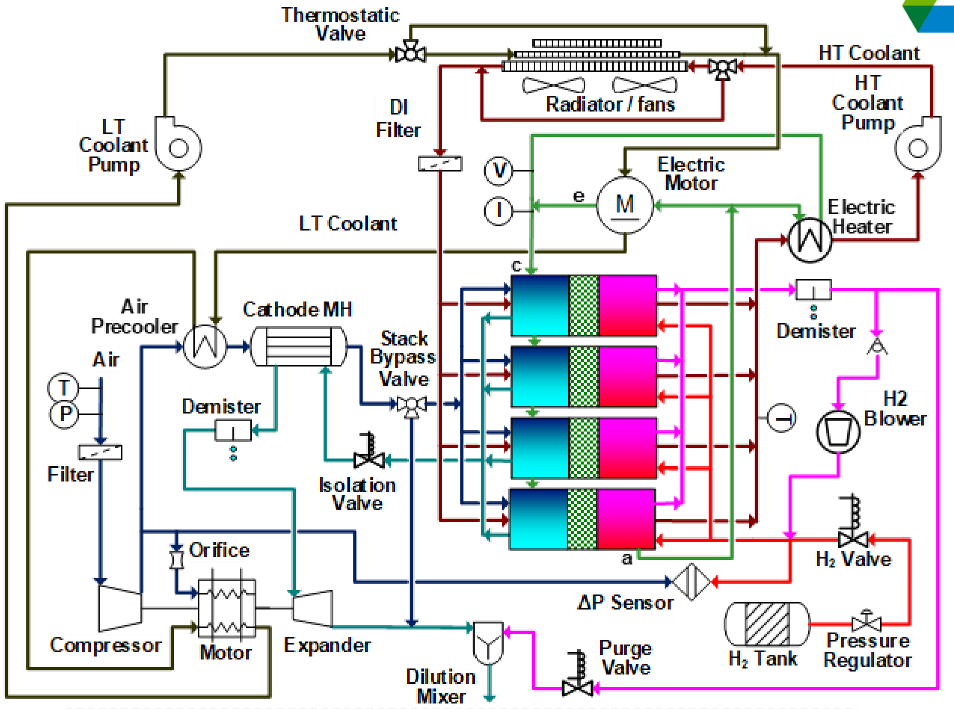
- Size fan and radiator frontal area for FCS heat load and operating temperature

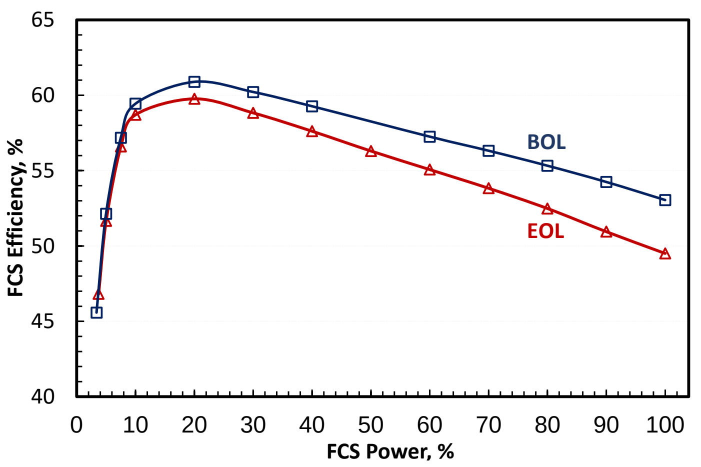
Fuel System

- Adapt LH_2 storage systems being developed for heavy-duty trucks
- Select fuel storage capacity for equal autonomy (time between refueling) at EOL

Energy Storage System

- Extend PEFC stack lifetime by voltage clipping
- Improve fuel economy by capturing regenerative energy



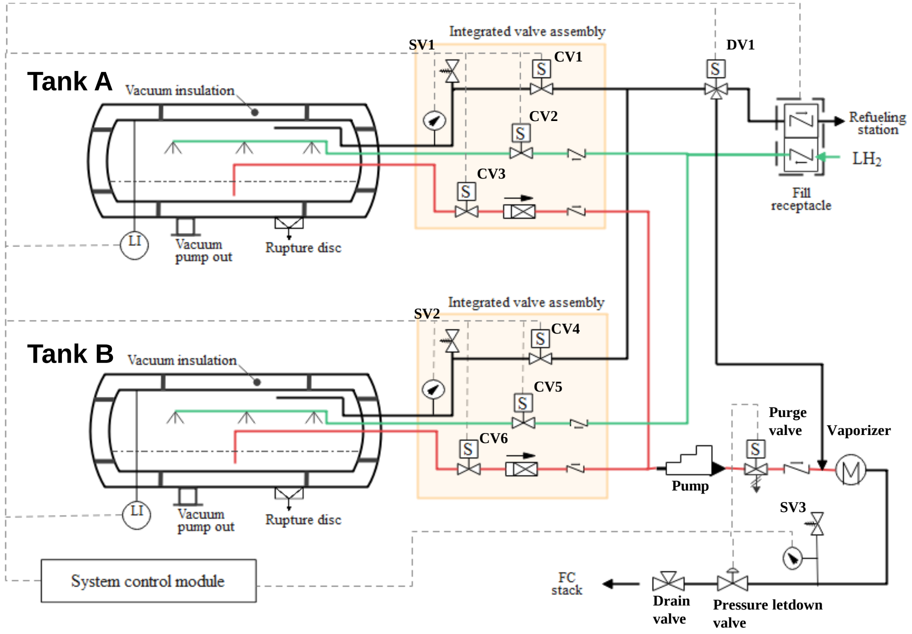


Cost Assumptions					
	Engine	Battery	Fuel	Fuel Storage	Drivetrain
Diesel	\$80/kW		\$3.25/gal	\$1000/m^3	\$15/kW
HFC Status	\$323/kW	\$268/kWh	\$5/kg	\$9.50/kWh	\$30/kW
HFC Ultimate	\$60/kW	\$125/kWh	\$4/kg	\$8/kWh	\$12/kW
Hydraulic Pump					\$70/kW

Economic Analysis			
Economic Lifetime	10 y		
Salvage Value	23% of list price	Installation Cost	30%
IRR	7%	Inflation	2%

Notes

- HFC status \$323/kW FCS cost from DOE/EERE/HFTO 2021 record for 1000 truck systems/year.
- HFC ultimate costs for FCS, H_2 and H_2 storage refer to DOE/EERE/HFTO targets for heavy duty trucks
- Battery and electric drivetrain costs refer to DOE/EERE/VTO status and ultimate targets.



Tractor Powertrain

Drivetrain Electrification with Common DC Bus

- At rated power, the electric drivetrain has higher efficiency (90%) than the mechanical drivetrain (86%)

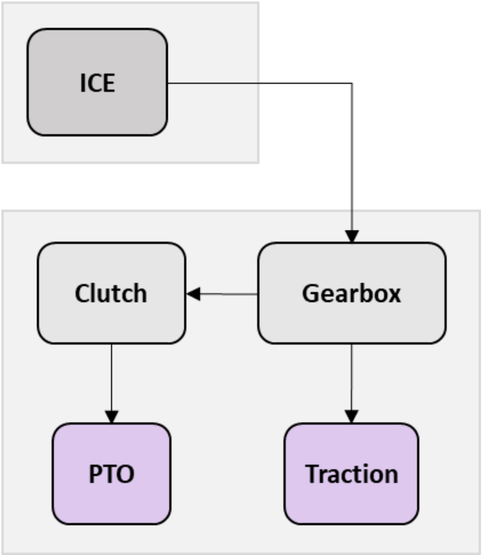
Engine and Powertrain

- Engine Efficiency: 60-26% higher for FCS (49%) than the diesel engine (30.6-38.8%)
- Powertrain Efficiency for PTO: 59-20% higher for FCS (38.7-37.1%) than the diesel engine (24.4-30.9%)

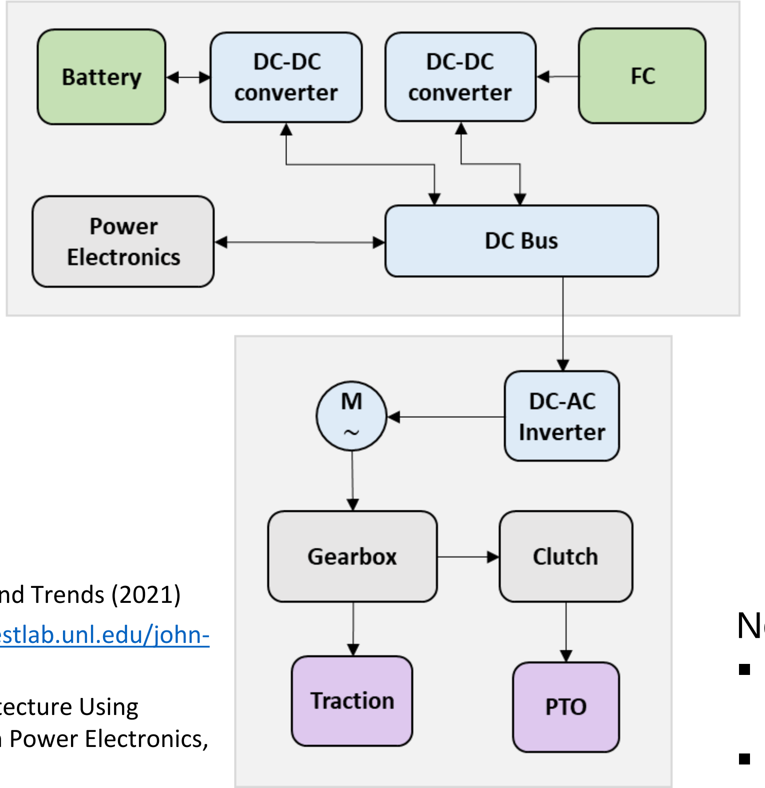
Energy Storage

- Includes a small battery (0.8-9.7 kWh) to extend PEFC stack lifetime by clipping cell voltage and minimizing startups/shutdowns

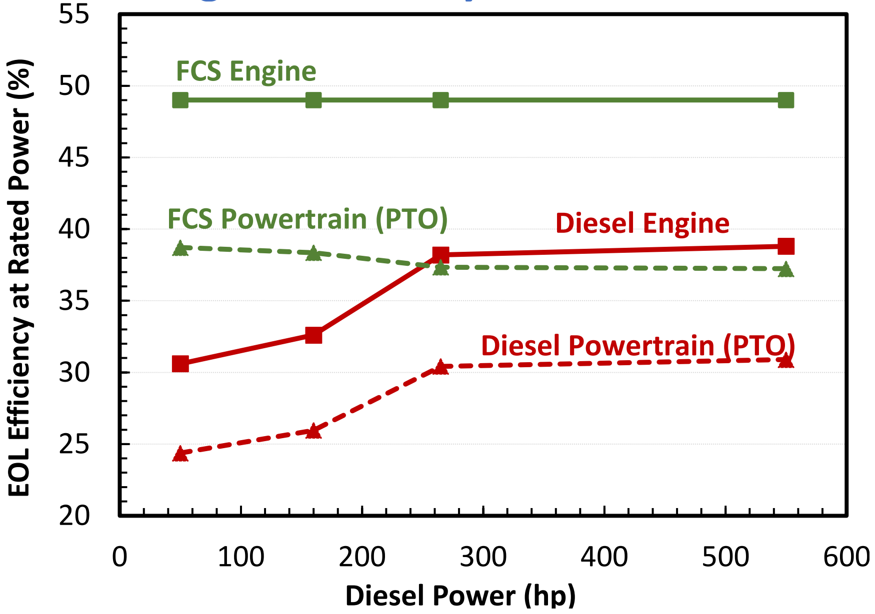
Diesel System



Fuel Cell System



Engine Efficiency at Rated Power*



1. Patel et al., Electric Vehicles: Modern Technology and Trends (2021)
2. Nebraska Tractor Test Laboratory, https://tractortestlab.unl.edu/john-deere
3. Hua et al., Electrified Automotive Powertrain Architecture Using Composite DC–DC Converters, IEEE Transactions on Power Electronics, 32, 1 (2017)

Notes*

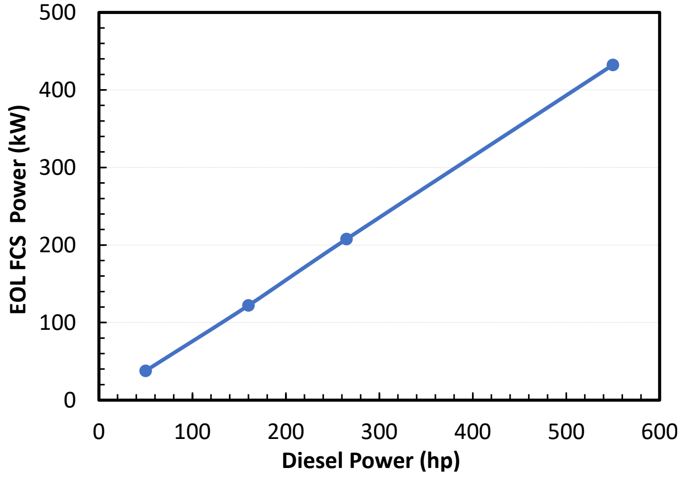
- By convention, the indicated FCS and diesel engine efficiencies exclude fan power losses.
- The powertrain efficiencies include fan power losses.

Tractor Performance

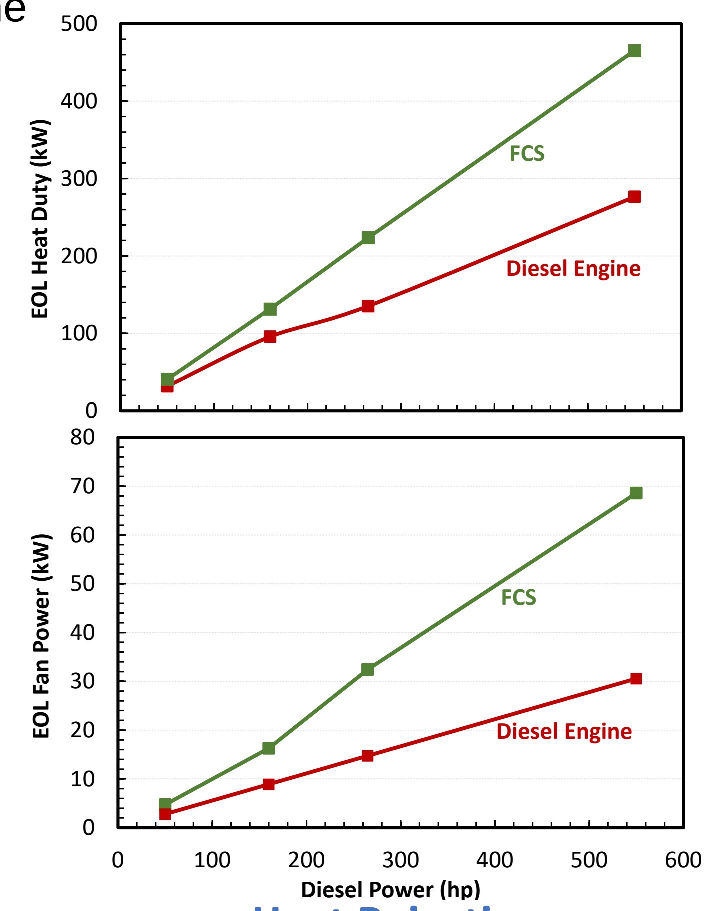
FCS Power: Higher drivetrain efficiency permits a smaller FCS power even after accounting for higher radiator fan power and lifetime performance degradation.

FCS Heat Rejection: 28-69% higher heat load despite higher efficiency. Requires 68-124% larger fan and radiator. Packaging can be an issue in larger tractors.

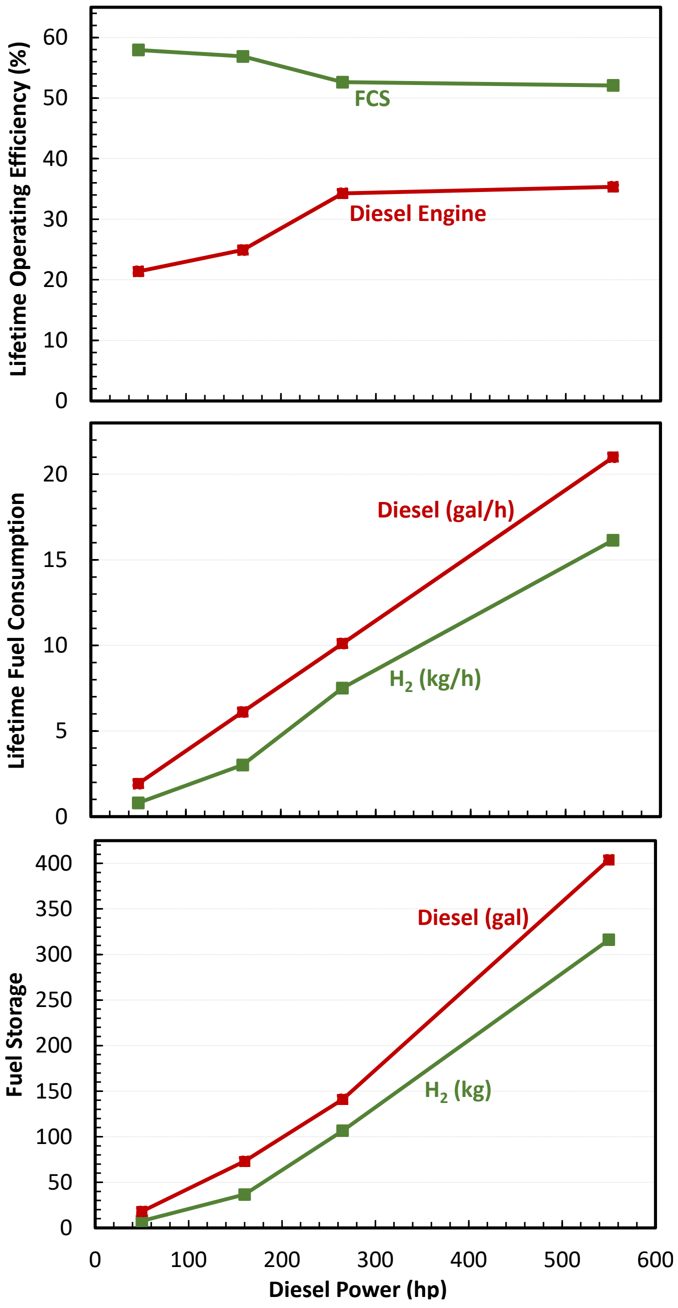
FCS Operating Efficiency and Fuel Storage: 162-39% higher efficiency but autonomy may have to be sacrificed in larger tractors requiring more than 200 kg LH_2 storage. cH2 storage may be feasible for the compact tractor.



Engine Size



Heat Rejection



Fuel Storage

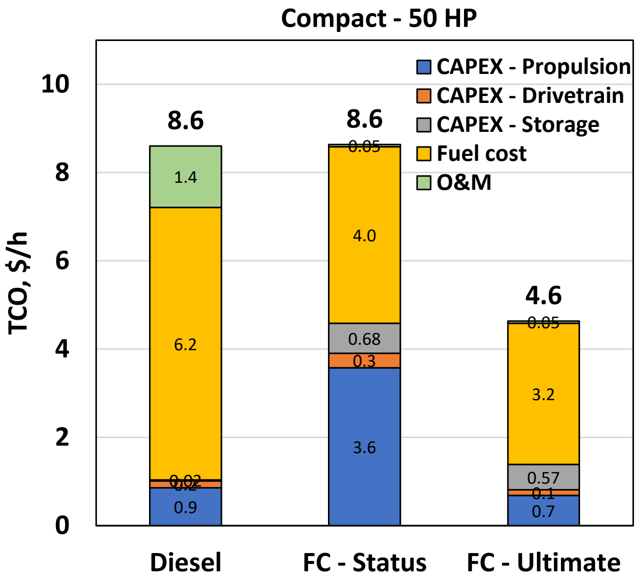
Tractor TCO

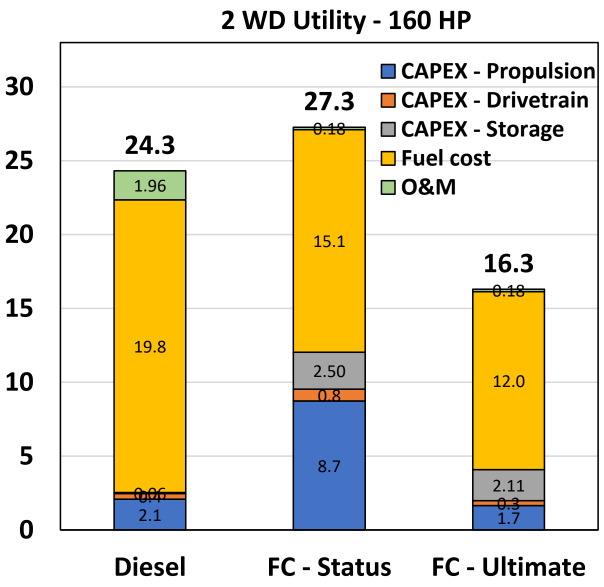
TCO: Only includes 1) levelized capital costs of power system, energy storage, electric drive and fuel storage, 2) fuel cost, and 3) operating and maintenance cost. TCO excludes the common cost elements such as labor, insurance, chassis, and other attachments.

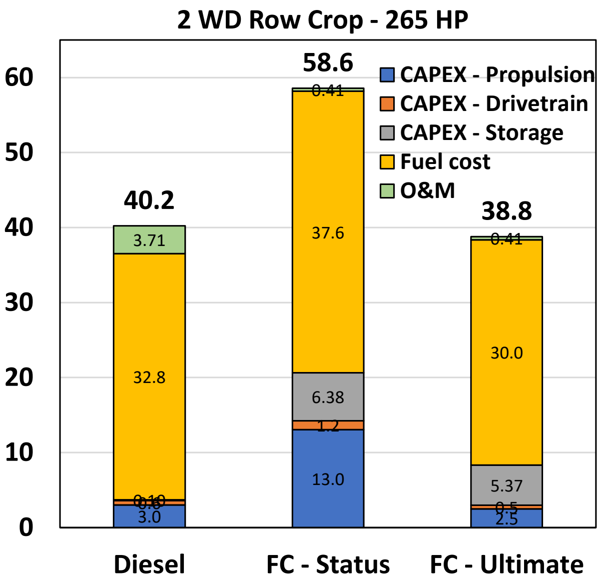
Fuel Costs: TCO is dominated by fuel costs. At \$3.25/gal diesel and \$4/kg H_2, fuel accounts for 72-82% of TCO in diesel tractors and 70-77% of TCO in ultimate FCS tractors.

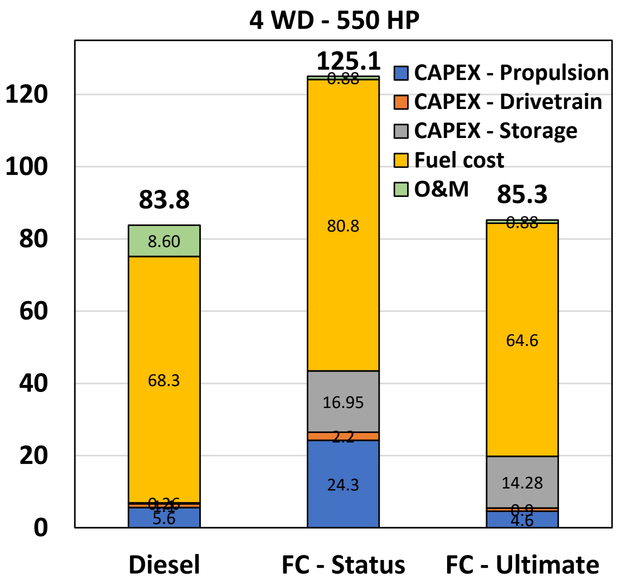
Tractor Platforms

- Fuel cells are lower cost options for compact, utility and row crop tractors (< 265 hp diesel engines) if the ultimate targets are met for costs of H_2, FCS and H_2 storage.
- Fuel cells are slightly more expensive than diesel for the 4-WD tractors primarily because of the cost of on-board LH_2 storage system.









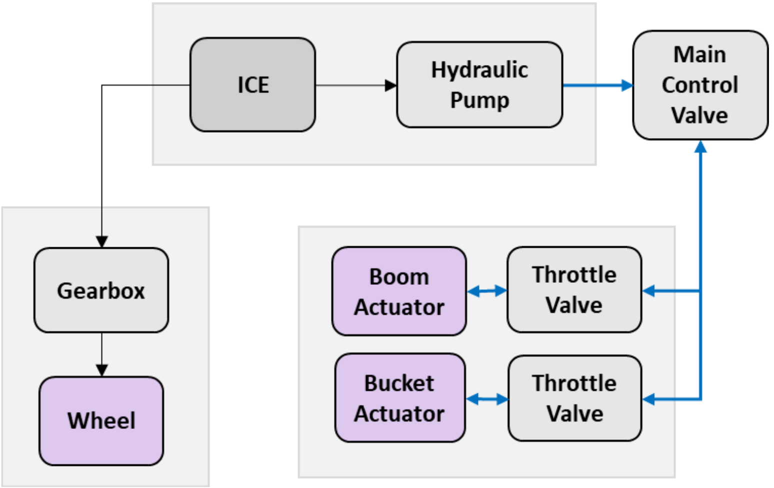
Wheel Loader Powertrain

Drivetrain Electrification with Common DC Bus
- At rated power, the electric drivetrain has lower efficiency for travel (83.6%) than the mechanical drivetrain (95%)

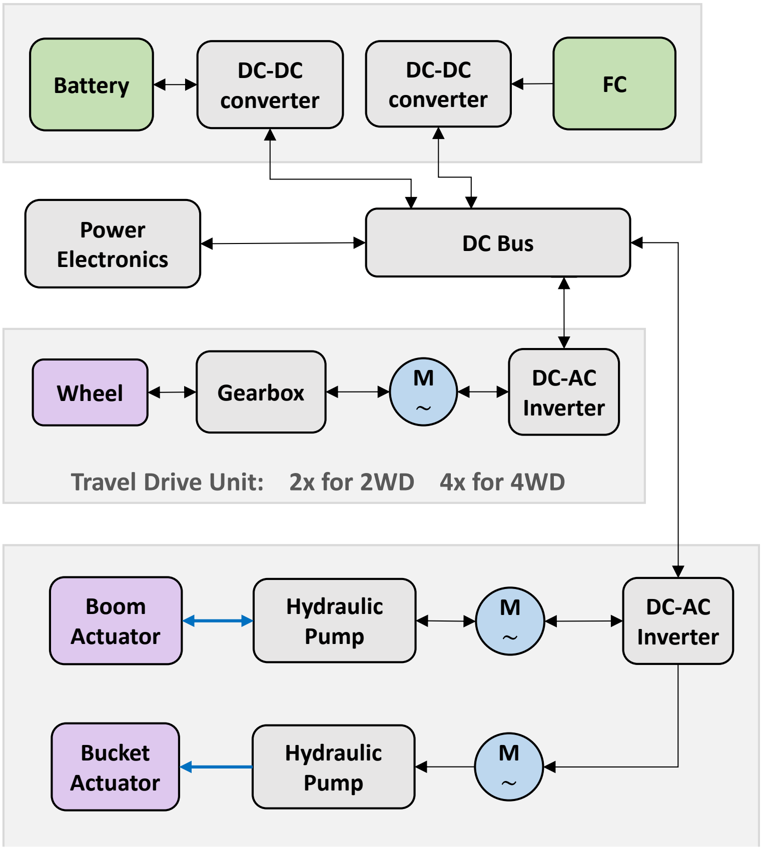
Engine and Powertrain
- Engine Efficiency: 57-36% higher for FCS (49%) than the diesel engine (31.2-36.1%)
- Powertrain Efficiency: 30-16% higher for FCS (35.7-36.9%) than the diesel engine (27.4-31.8%)

Energy Storage
- Includes a battery (2.2-25.7 kWh) to extend PEFC stack lifetime and capture regenerative energy

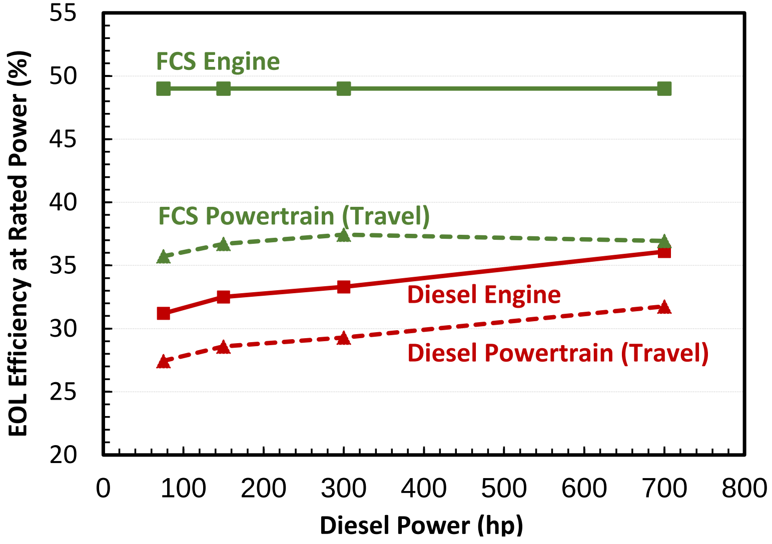
Diesel System



Fuel Cell System



Engine Efficiency at Rated Power



Diesel System
- Mechanical drivetrain for travel
- Hydraulic drivetrain for actuator

Fuel Cell System
- Electric drivetrain for travel
- Electric-hydraulic drivetrain for actuator

1. Roth et al., Optimization-based Component Sizing Method for Electrified Heavy-Duty Powertrain Concepts, 19th Drivetrain Technology Conference (2021)
2. Alan et al., Optimal Sizing of an Energy Storage System for a Hybrid Vehicle Applied to an Off-Road Application, IEEE/ASME Intl. Conf. on Advanced Intelligent Mechatronics (2014)

Wheel Loader Sankey Diagram

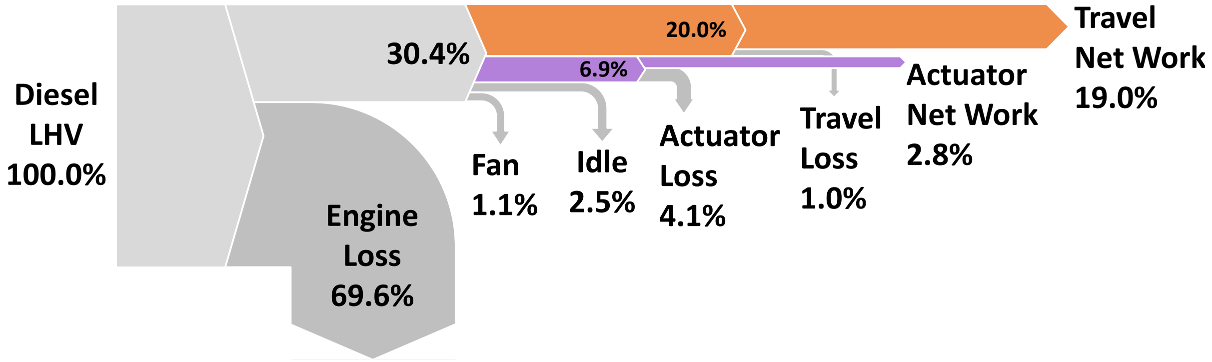
Drivetrain Efficiencies

- Travel: Lower in FCS platform, 83% in FCS vs 95% in diesel
- Actuator: Slightly higher in FCS platform, 47% in FCS vs. 41% in diesel
- FCS Regen: 83% for travel, 61% for actuator

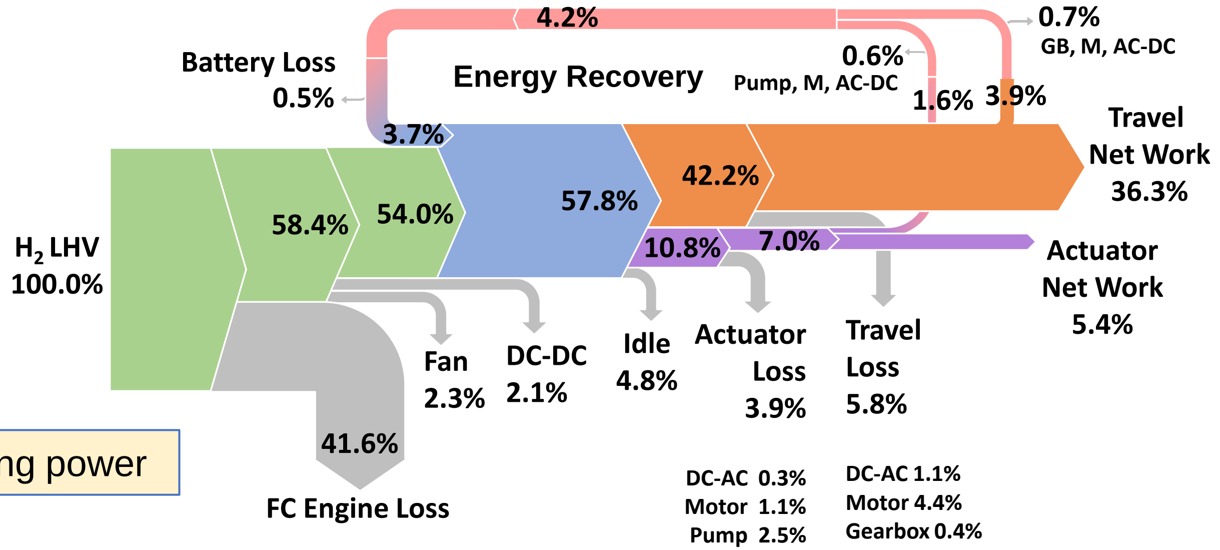
Regenerative Energy in FCS Wheel Loader

- Duty Cycle: 46% idling time, 54% travel and actuator (load/unload) time
- Regenerative Energy: 6.2% of DC bus power returned to battery

Diesel System



Fuel Cell System



Sankey diagrams for 700-hp equivalent wheel loaders at average operating power

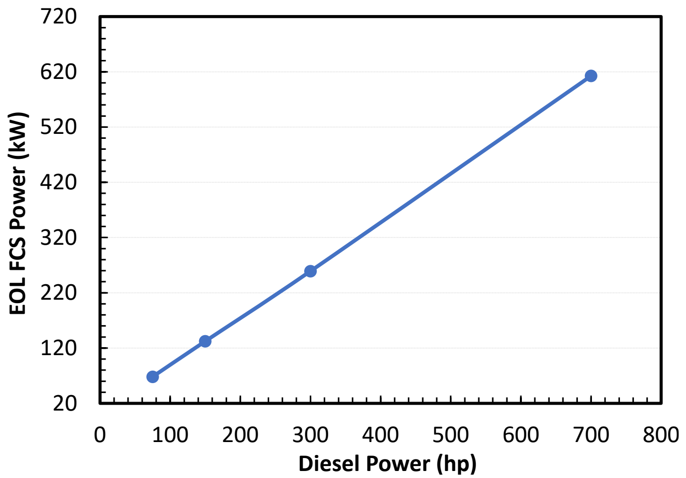
1. Schneider et al., Green wheel loader – improving fuel economy through energy efficient drive and control concepts, 10th International Fluid Power Conference, (2016), https://core.ac.uk/download/pdf/236373143.pdf;
2. Heikkila et al., Fuel Efficiency Optimization of a Baseline Wheel Loader and its Hydraulic Hybrid Variants Using Dynamic Programming, Fluid Power Systems Technology Proceedings Paper (2018) https://asmedigitalcollection.asme.org/FPST/proceedings-abstract/FPMC2018/51968/V001T01A024/271082;
3. Wen et al., Improving the Fuel Efficiency of Compact Wheel Loader With a Series Hydraulic Hybrid Powertrain, IEEE Trans. on Vehicular Tech., **69**, 10 (2020), https://ieeexplore.ieee.org/document/9130152
4. Karlsson et al., Analyses of a Wheel Loader Usage Whitepaper (2010), http://www.diva-portal.org/smash/get/diva2:378714/FULLTEXT01.pdf
5. Hua et al., Electrified Automotive Powertrain Architecture Using Composite DC–DC Converters, IEEE Transactions on Power Electronics, 32, 1 (2017)

Wheel Loader Performance

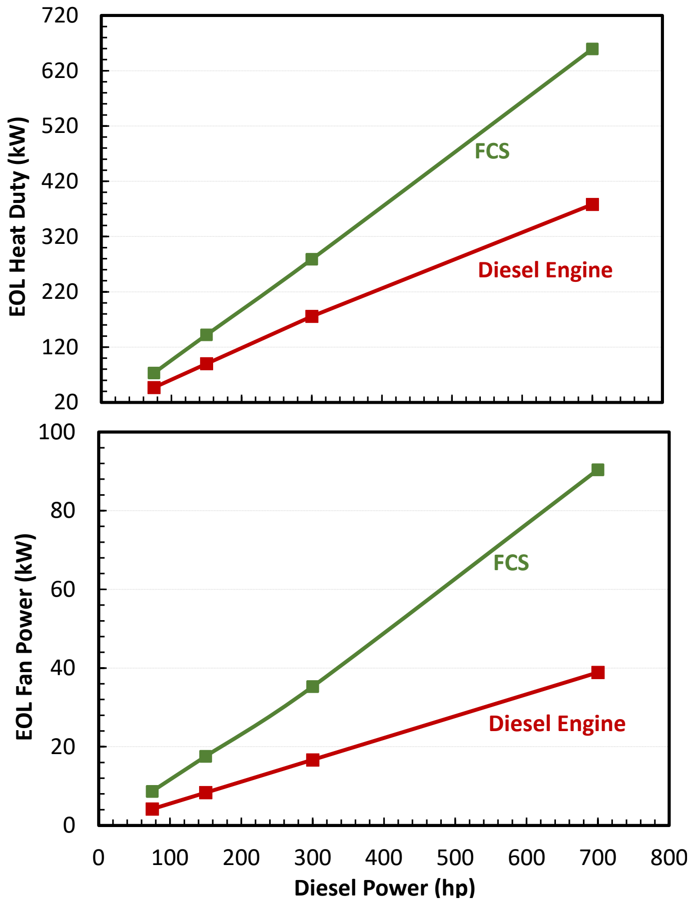
FCS Power: Slightly larger to compensate for lower drivetrain efficiency.

FCS Heat Rejection: 60-74% higher heat load, requiring 107-132% larger fan and radiator. Packaging can be an issue in larger tractors.

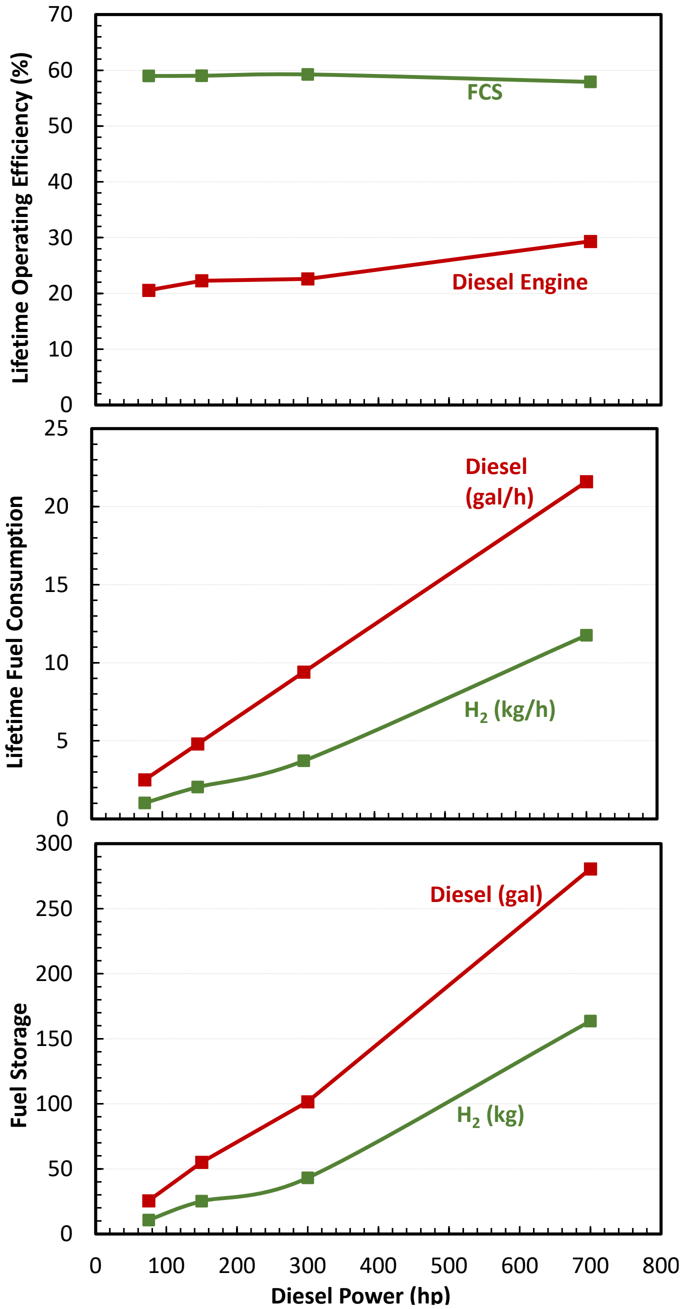
FCS Operating Efficiency and Fuel Storage: 180-91% higher efficiency but autonomy may have to be sacrificed in larger tractors requiring 164 kg LH_2 storage.



Engine Size



Heat Rejection



Fuel Storage

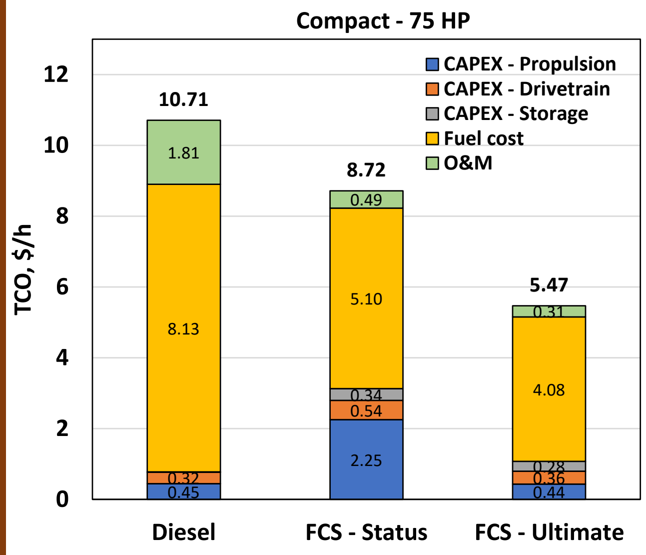
Wheel Loader TCO

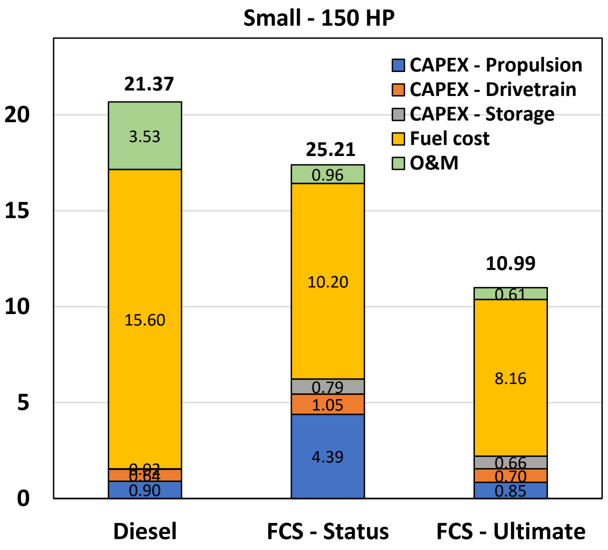
Fuel Costs

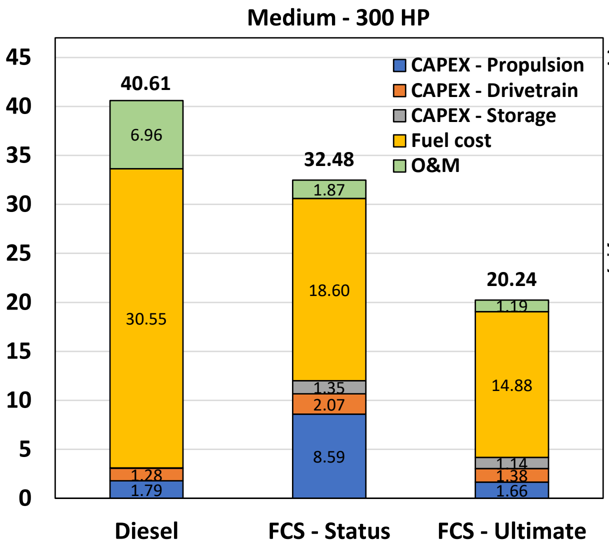
- At \$3.25/gal diesel and \$4/kg H_2, fuel accounts for 73-76% of TCO in diesel and ultimate FCS wheel loaders.

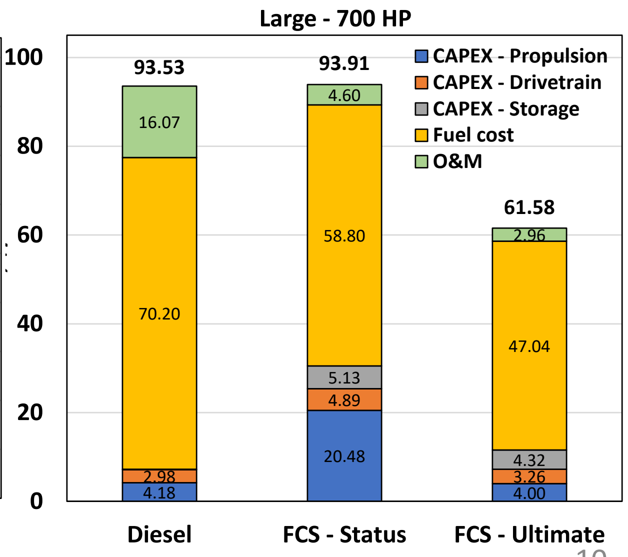
Wheel Loader Platforms

- Status fuel cells are cost competitive with diesel engines even at \$5/kg H_2.
- Fuel cells are lower cost options for all wheel loader sizes considered if the ultimate targets are met for H_2, FCS and on-board H_2 storage costs.









Excavator Powertrain

Drivetrain Electrification with Common DC Bus

- At rated power, the electric drivetrain for the actuator has higher efficiency (30%) than the diesel hydraulic drivetrain (25%)

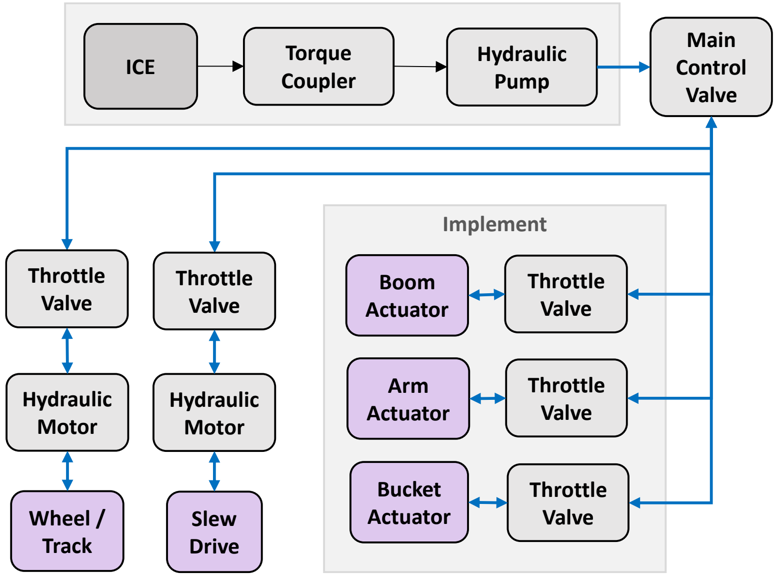
Engine and Powertrain

- Engine Efficiency: 69-36% higher for FCS (49%) than the diesel engine (28.9-36.1%)
- Powertrain Efficiency for Actuator: 90-53% higher for FCS (13%) than the diesel engine (6.8-8.5%)

Energy Storage

- Includes a battery (3.4-33.1 kWh) to extend PEFC stack lifetime and store regenerative energy

Diesel System



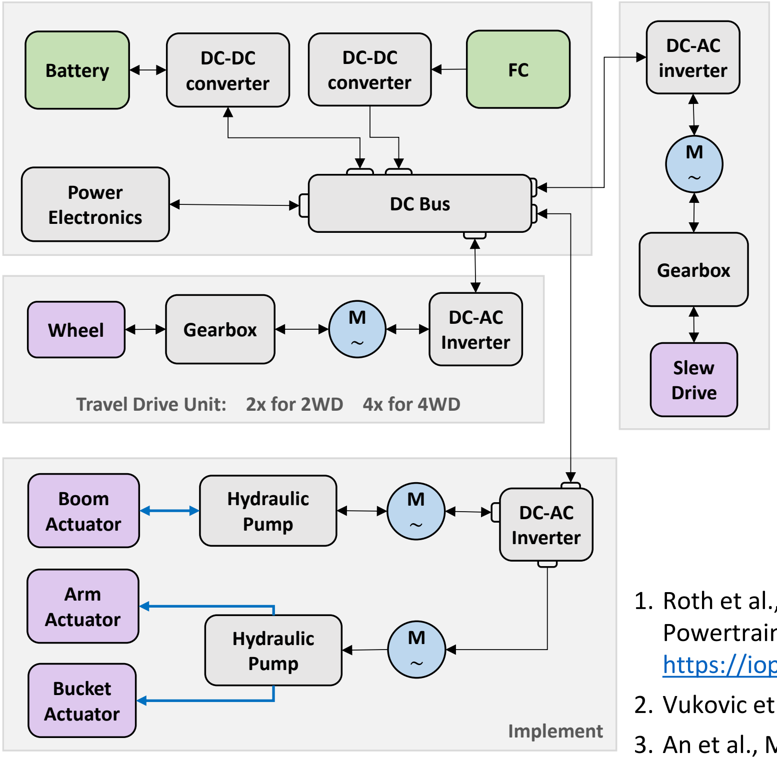
Diesel Drivetrains

- Hydraulic for travel, slew and actuator

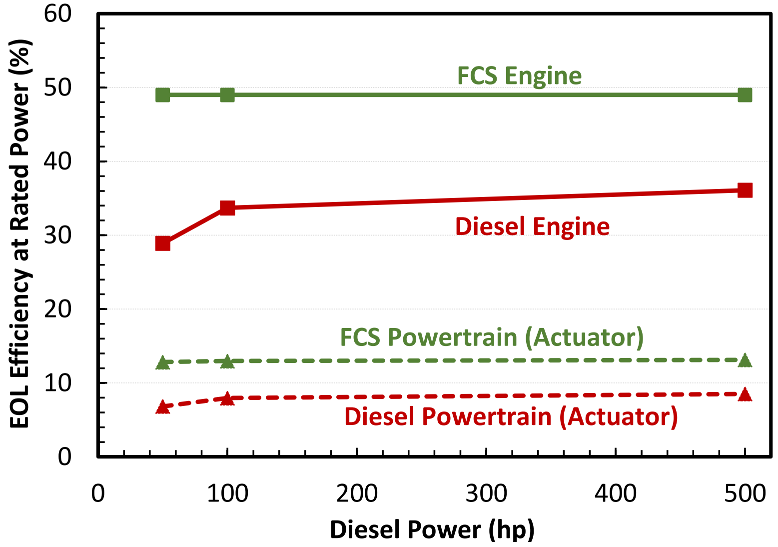
FCS Drivetrains

- Electric drivetrain for travel and slew
- Electric-hydraulic drivetrain for actuator

Fuel Cell System



Engine Efficiency at Rated Power



1. Roth et al., Optimization-based Component Sizing Method for Electrified Heavy-Duty Powertrain Concepts, 19th Drivetrain Technology Conference (2021), https://iopscience.iop.org/article/10.1088/1757-899X/1097/1/012002
2. Vukovic et al., Reducing Fuel Consumption in Hydraulic Excavators, *Energies*, 2017, 10 (5)
3. An et al., Methodology of excavator system energy flow-down, *Energies*, 2020, 13 (4)

Excavator Sankey Diagram

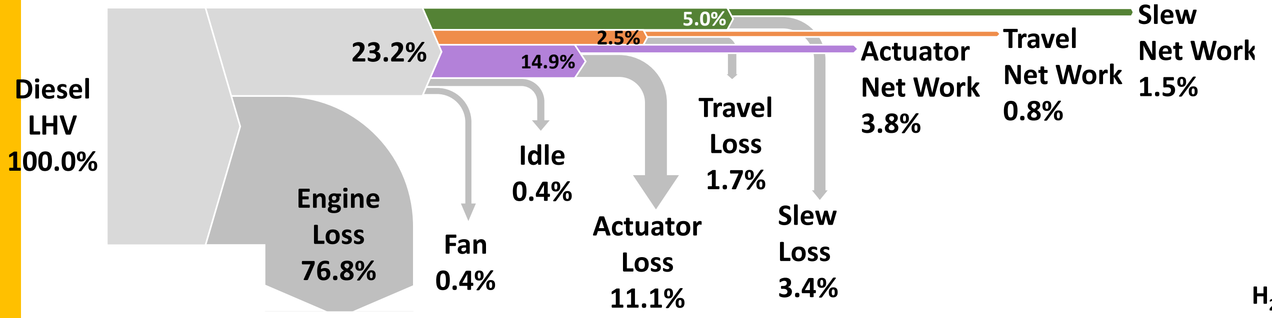
Drivetrain Efficiencies

- Travel and Slew: much higher in FCS platform, 83% in FCS vs 30% in diesel
- Actuator: Slightly higher in FCS platform, 30% in FCS vs. 25% in diesel
- FCS Regen: 83% for travel and slew, 61% for actuator

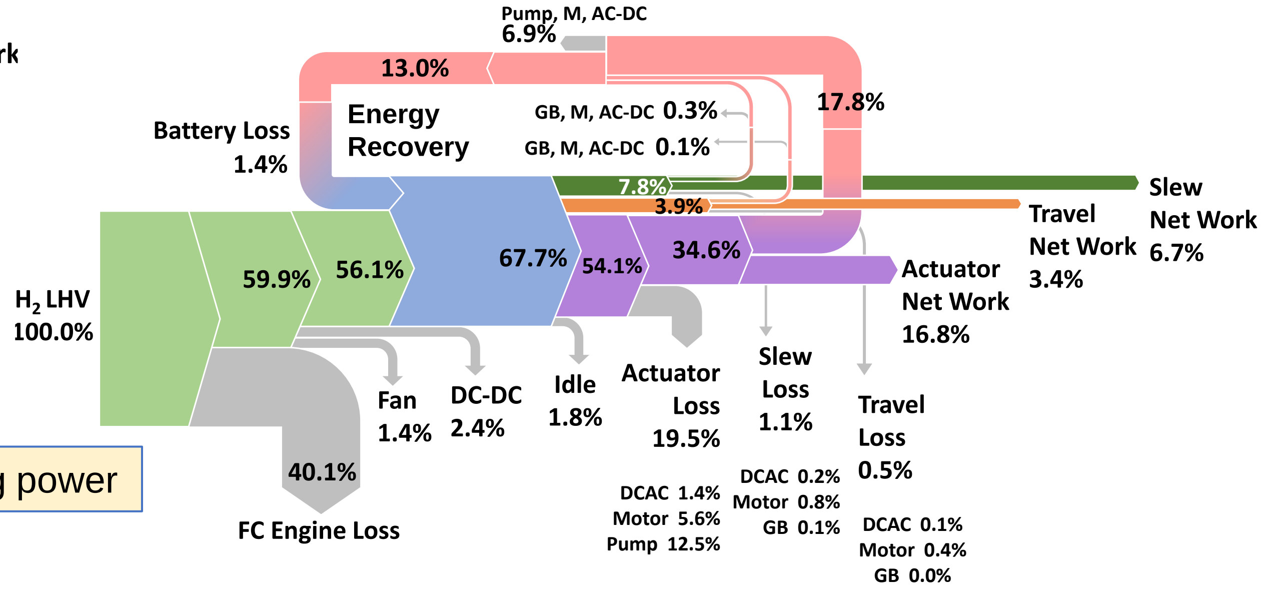
Regenerative Energy Capture in FCS Excavator

- Duty Cycle: 25% idling time, 60% slew and actuator (earth-moving) time, 15% travel time
- Regenerative Energy: 17.1% of DC bus power returned to battery

Diesel System



Fuel Cell System



Sankey diagrams for 500-hp equivalent excavators at average operating power

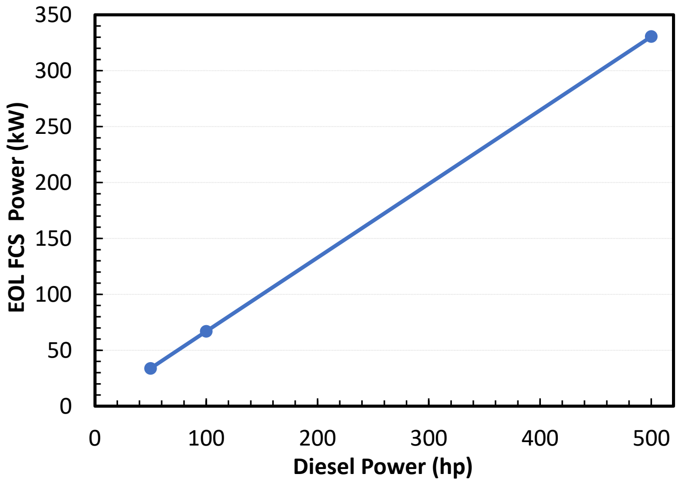
1. An et al., Methodology of excavator system energy flow-down, *Energies*, 2020, 13 (4)
2. Vukovic et al., Reducing Fuel Consumption in Hydraulic Excavators, *Energies*, 2017, 10 (5)
3. Hua et al., Electrified Automotive Powertrain Architecture Using Composite DC–DC Converters, IEEE Transactions on Power Electronics, 32, 1 (2017)

Excavator Performance

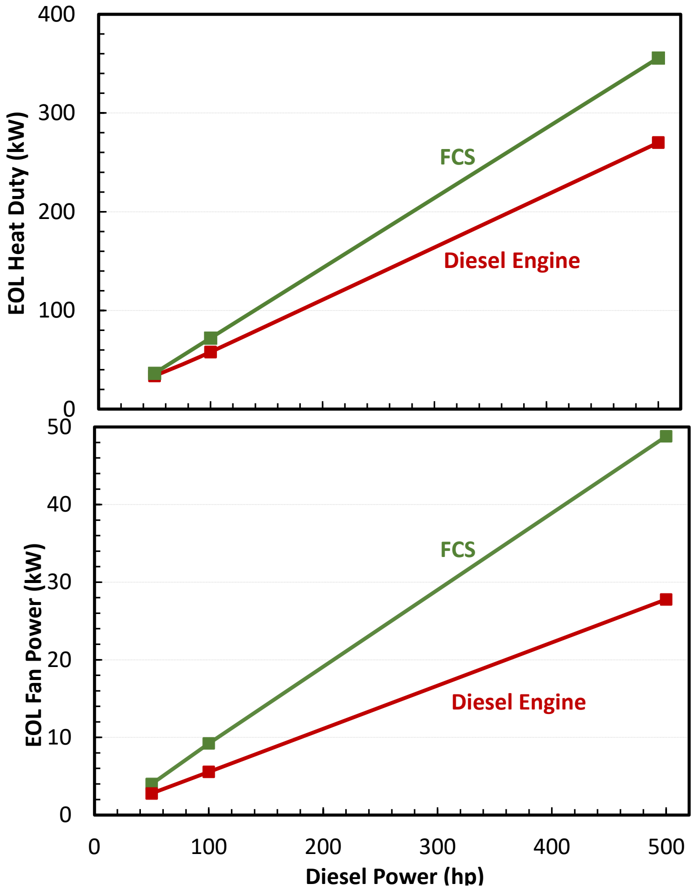
FCS Power: Slightly smaller because of higher drivetrain efficiency.

FCS Heat Rejection: Up to 32% higher heat load, requiring 43-76% larger fan and radiator.

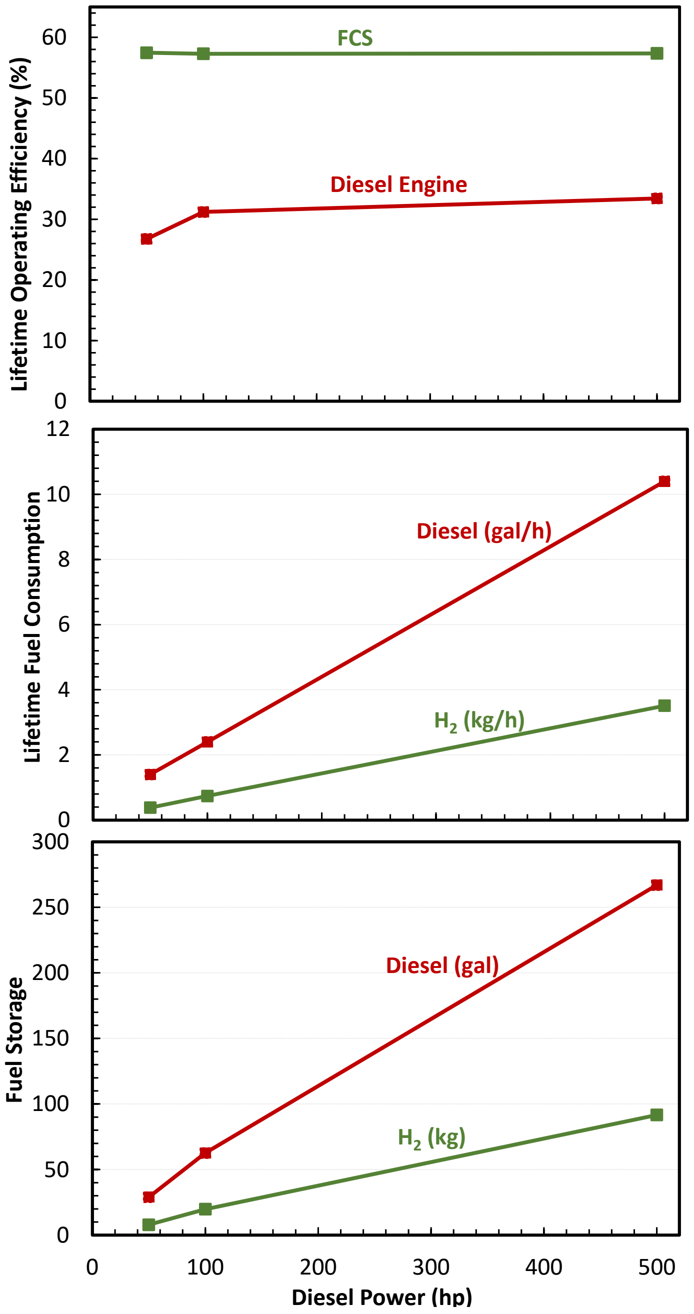
FCS Operating Efficiency and Fuel Storage: 142-71% higher efficiency. Standard/full size excavator requires 92-kg LH_2 storage for same autonomy as the diesel engine.



Engine Size



Heat Rejection



Fuel Storage

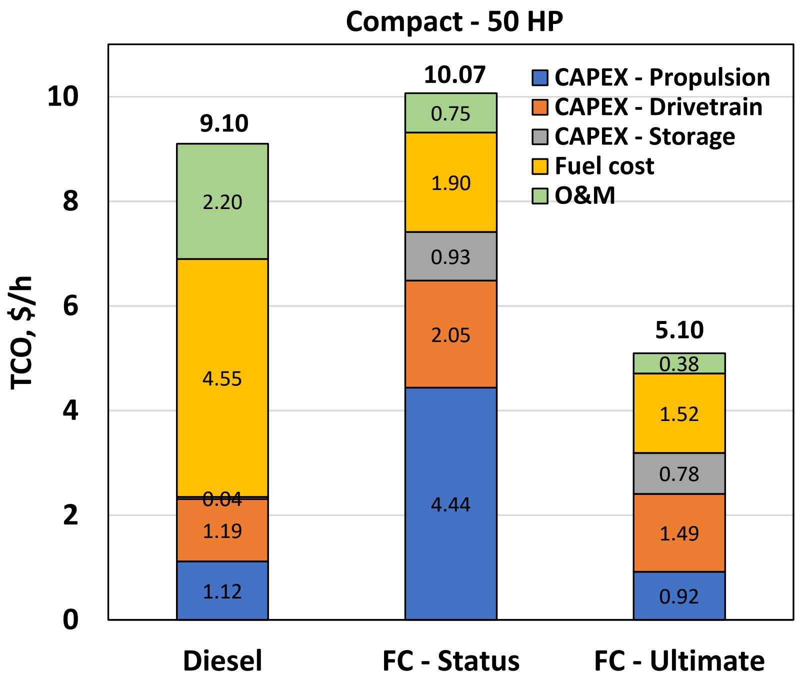
Excavator TCO

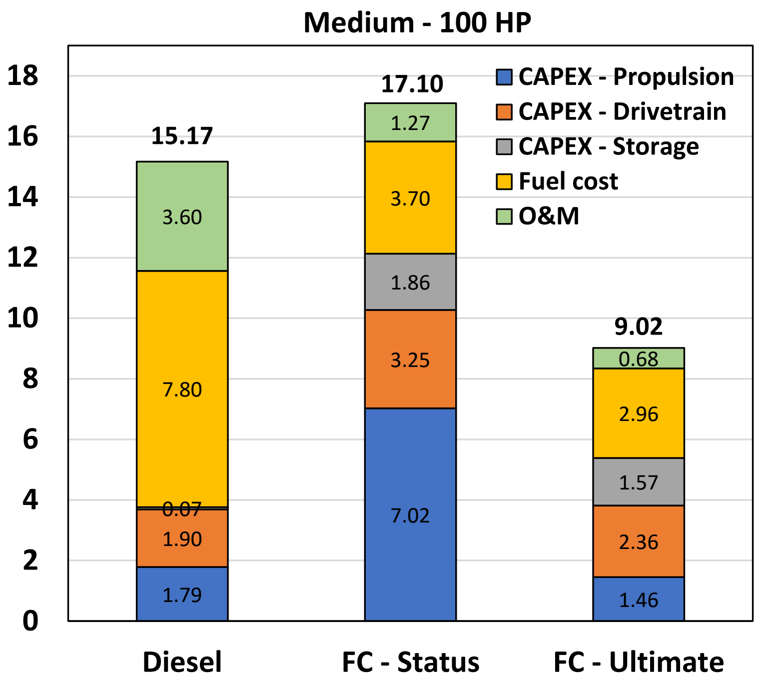
Fuel Costs

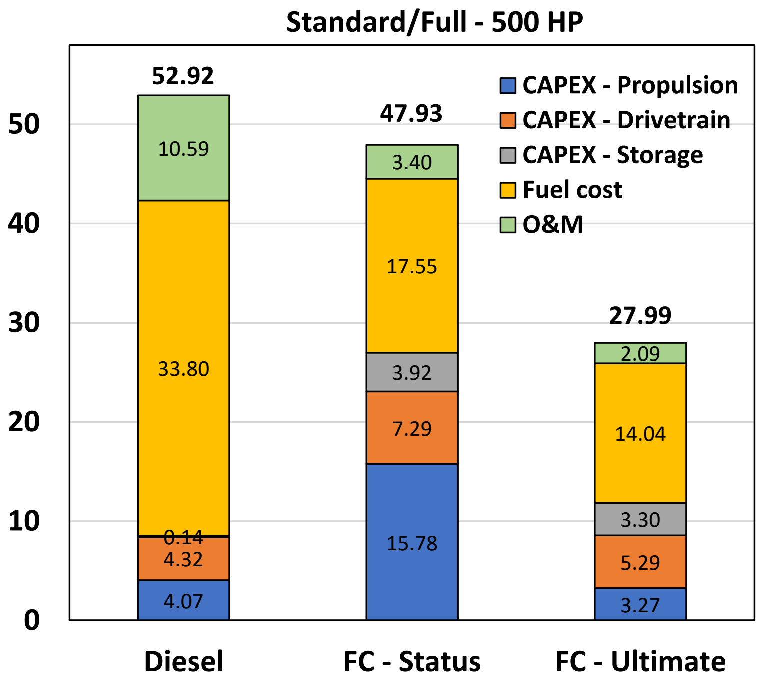
- Fuel accounts for 50-64% of TCO in diesel excavators and 30-50% of TCO in FCS excavators.

Excavator Platforms

- Status fuel cells are cost competitive with diesel engines for compact, medium and standard/full excavators even at \$5/kg H_2 and \$3.25/gal diesel.
- Fuel cells are lower cost options for all excavator sizes considered if the ultimate targets are met for H_2, FCS and on-board H_2 storage costs.
- When the ultimate H_2 and FCS targets are met, the levelized CAPEX for propulsion, drivetrain and LH_2 storage far exceeds the fuel cost in compact and medium excavators.







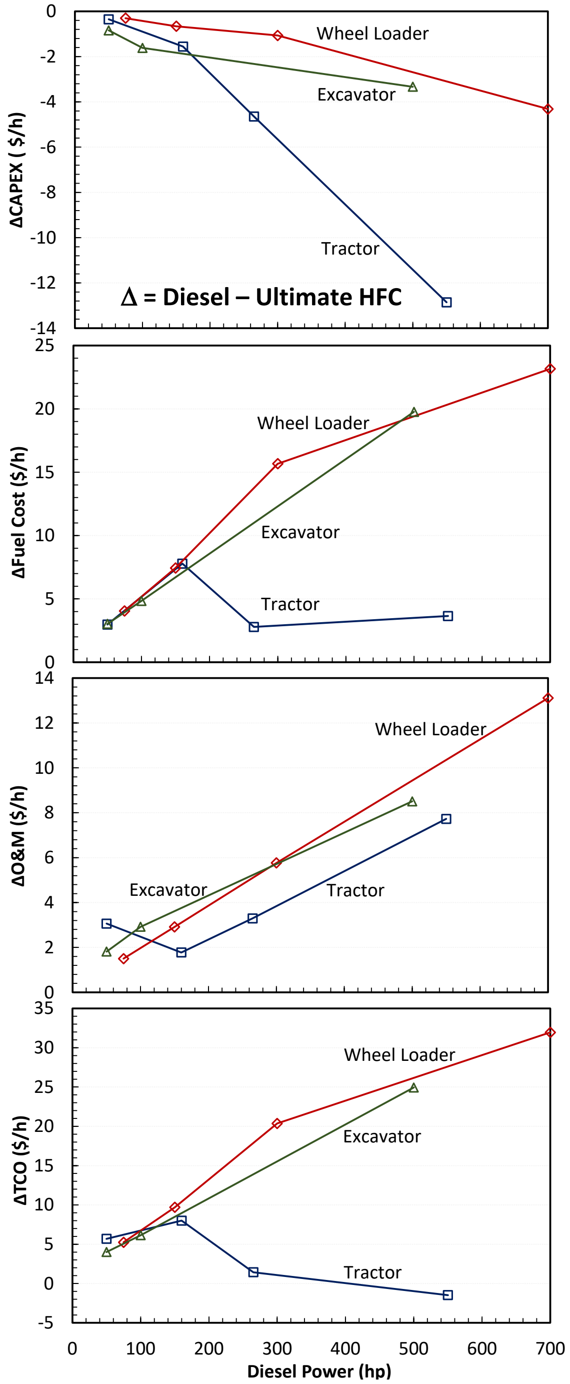
Summary and Conclusions

Fuel cell and on-board LH_2 storage systems being developed for heavy-duty trucks offer modularity and economy of scale for adoption in diesel tractors, wheel loaders and excavators.

- Primary advantage: 40-180% gain in lifetime operating efficiency
- Drivetrain electrification: potential 6-17% reduction in fuel consumption possible through regenerative energy capture in wheel loaders and excavators
- Heat rejection challenge: 28-74% higher heat load requiring 43-132% larger fans and radiators
- H_2 storage challenge: 92-316 kg H_2 needs to be stored in the 500-700 hp equivalent machines. May have to sacrifice autonomy in the 4-WD tractor and standard/full excavator.

Total cost of ownership only includes 1) levelized capital costs of power system, energy storage, electric drive and fuel storage, 2) fuel cost, and 3) operating and maintenance cost

- Tractors and wheel loaders: TCO is dominated by fuel costs. At \$3.25/gal diesel and \$4/kg H_2, fuel accounts for 70-82% of TCO in diesel and ultimate fuel cell systems.
- Compact and medium excavators: When the ultimate H_2 and FCS targets are met, the levelized CAPEX for propulsion, drivetrain and LH_2 storage far exceeds the fuel cost.
- Status fuel cells are cost competitive with diesel engines for even at \$5/kg H_2.
- Fuel cells are lower cost options for all platforms and sizes considered if the ultimate targets are met for H_2, FCS and on-board H_2 storage costs.



Breakdown of ΔTCO