Performance and Cost of Fuel Cells for Off-Road Heavy-Duty Vehicles

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ABSTRACT

Replacing hydrocarbon-powered off-road vehicles with hydrogen fuel cell-powered off-road vehicles can reduce carbon dioxide and criteria pollutant emissions in the agriculture, construction, and mining industries. Off-road vehicles perform challenging work in harsh environments that complicate deployment of their fuel cell-powered counterparts. Customers and vehicle manufacturers recognize the health and environmental benefits of emissions reductions but are compelled by the total cost of ownership of their vehicles. This study provides a novel technoeconomic comparison of hydrogen fuel cell + battery hybrid powertrains to traditional diesel powertrains for three hallmark off-road vehicles: tractors, wheel loaders, and excavators. Performance metrics include fuel cell engine power, hydrogen consumption rate, hydrogen storage system volume, energy-regenerative drivetrain efficiency, cost of capital, operating and maintenance cost, fuel cost, and fuel storage cost. Results demonstrate that state-of-the-art fuel cell-powered wheel loaders and excavators are currently cost competitive with diesel platforms by total cost of ownership: compact wheel loaders are 19% less expensive, large wheel loaders are equally expensive, mini/compact excavators are 11% more expensive, and standard/full excavators are 9% less expensive. If targeted improvements to cost, performance, and durability of fuel cell stacks and storage systems are achieved, fuel cell systems would be cost competitive for tractors and significantly lower total cost of ownership options for wheel loaders and excavators. This study also elucidates the relationship between performance, cost, and vehicle duty cycle and provides guidance for optimal deployment of fuel cell off-road vehicles.

Keywords: *Hydrogen, Fuel Cell, Off-Road Vehicle, Tractor, Wheel Loader, Excavator*

1 INTRODUCTION

Hydrogen is an energy carrier critical to achieving decarbonization goals that have been declared and will be adopted over the next several decades. The recently announced Energy Earthshot: Hydrogen initiative [1] builds upon the United States Department of Energy's H2@Scale initiative [2] which, together, form a strategic roadmap for innovation, research, development, and deployment of emerging hydrogen-related technologies. Similar plans have been developed and are being implemented across many nations [3]. Hydrogen can replace hydrocarbons in several applications throughout the economy. Hydrogen is suitable as a fuel for both centralized power generation and distributed, combined heat-and-power generation in residential and commercial applications [1][2][3]. Hydrogen is also being pursued for mobility applications spanning light- and heavy-duty vehicles, rail, maritime transportation, uncrewed aerial vehicles, and commercial aviation [1][2][3]. Synthetic fuels can be generated and/or refined using hydrogen, as can oils and biomass [1][2][3]. Using sustainably powered water electrolysis to generate "green" hydrogen, chemical industry can decarbonize ammonia production, metals production, and hydrogenation and reduction reactions across the chemical and industrial sectors [1][2][3].

Hydrogen (H_2) fuel cells generate electric power without tailpipe emissions and are excellent candidates to replace internal combustion engines (ICE) in the transportation sector. Previous studies on hydrogen fuel cells for mobility applications include locomotives [4], maritime [5], and aviation [6]. Long-haul and heavy-duty vehicles (HDV) particularly require and benefit from hydrogen's larger gravimetric energy capacity compared to battery energy storage. Heavy-duty, on-road fuel cell systems (FCS) can be deployed to critical transportation applications like the shipping of finished goods [7]. The fuel cell stacks being developed and optimized for on-road HDVs can also be adopted in off-road heavy-duty vehicles. To take advantage of manufacturing economies of scale of stack and balance-of-plant components, fuel cell stacks are commonly sized at ca. 100 kW then packaged into racks and modules comprised of standardized stacks to power larger systems. This may allow FCS to penetrate more markets and speed adoption and experiential learning.

Off-road vehicles are essential for agriculture, construction, and mining. The hallmark equipment of these industries are tractors, wheel loaders, and excavators [8]. Tractors tow and power implements that enable the agricultural cycle of growing and harvesting crops. Wheel loaders and excavators both accomplish earthmoving, but wheel loaders travel during most their duty cycle while excavators often remain stationary, only rotating and moving the implement arm. 6.7 M tractors were sold in the US in 2018, projected to increase to 8.6 M in 2025, and the US agricultural industry spent $13.5 B on fuel, gas, and oil [9]. The global excavator market size in 2018 was $44 B and projected to reach $63 B in 2026 [10]. The global loader market size in 2018 was $27 B, projected to reach $38 B in 2026 [11]. Nearly all tractors, wheel loaders, and excavators are powered by diesel powertrains that emit carbon dioxide and criteria pollutants inconsistent with emerging environmental and health standards [12]. Transiently operated diesel engines can emit one or two orders of magnitude more NO_x and particulate matter versus quasi-steady engines [13]. Hydraulic excavators comprise 60% of all construction equipment CO_2 emissions [14]. Mining was responsible for 4% - 7% of all greenhouse gas emissions, globally, as reported in January 2020 [15]. In a Korean study, on-site construction equipment was found responsible for 6.8% of the total emissions generated in the country [16]. Off-road equipment emitted 20% - 40% of all 2.5 micron aerosolized particulate matter in USA and Europe in 2011 [16]. A 2014 study in Finland found that off-road mobile machinery emitted 49% of all CO and 42% of all particulate matter [17].

Toward meeting decarbonization goals, hydrogen production and electrification for vehicle applications have received considerable research attention. In an excellent review, Masrur explained the unique design requirements of hybrid- and fully-electric vehicles for off-road applications [18]. Masrur provided a framework for vehicle deployment decision making and compared the advantages to disadvantages of the underlying design choices. Liukkonen et al. compared five distinct fuel cell hybrid topologies concluding that DC-DC converter efficiencies could be the difference between a practical or impractical (inadequately efficient) powertrain, depending on the duty cycle [19]. They also showed that incorporation of a high-power battery in the powertrain minimized the system weight and size while further inclusion of an ultracapacitor may reduce cost but at the expense of increased weight and size [20]. Lajunen et al. showed that high component costs currently hinder the adoption rate of electrified non-road vehicles and that life cycle management of components may be critical given anticipated production volumes [21]. Colella et al. quantified the emissions reductions that can be achieved by replacing fossil-fuel vehicles with hydrogen or hybrid vehicles [22]. Munoz et al. modeled a hybrid off-road powertrain to analyze vehicle power losses under varying operating conditions and across varying terrain [23]. Hermann and Rothfuss reviewed and compared the merits of electric powertrain components for on-road vehicles [24]. Salkuyeh et al. conducted techno-economic analysis of hydrogen production methods [25]. Through techno-economic analysis, Wang et al., Li et al., and Ma et al. showed that a coal-to-hydrogen process and a biomass-to-hydrogen process were similarly energy efficient but the biomass process had lower total production cost [26][27][28]. Ghenai et al. demonstrated an optimal operating strategy of a coupled photovoltaic-fuel cell power system for distributed energy generation [29]. Pelaez-Pelaez et al. showed that a hybrid photovoltaic-FCS for power generation with CHP applications using electrolyzer hydrogen was technically feasible although still expensive with current technology [30]. Prince-Richard et al. evaluated the capital, maintenance and energy costs of hydrogen and showed [31].

This study presents a technical and economic evaluation of off-road mobile vehicles with alternative drivetrains using hydrogen FCS being developed for HDVs. Specifically, tractors, wheel loaders, and excavators are focused on because of their ubiquitous use in the agriculture, mining, and construction sectors. This allows facile comparison of the advantages of hydrogen fuel cells across vehicle types and therefore, across industries. Each type of vehicle is manufactured in various sizes and grouped according to class based on customer needs. For example, 2WD farm tractors with 25 horsepower are commonly purchased by homeowners or hobby farmers with 1-10 acres. In contrast, 4WD tractors are commonly purchased by full-time farmers or agricultural corporations with hundreds up to tens of thousands of farmed acres. Categories of vehicle sizes are displayed in Table 1. For each category of vehicle, a representative model size is selected, and a technical evaluation is performed. The analysis for each vehicle considers fuel cell engine power, efficiency, and lifetime; hydrogen consumption; and storage system volume. The economic evaluation considers capital cost, operating and maintenance cost, fuel cost, and the total cost of ownership (TCO). Fuel consumption rates and annual operating hours were obtained from Reference [32].

Table 1 – Tractor, Wheel Loader, and Excavators classes and the respective engine class size range.

Farm Tractors	**Engine Size (hp)**		**Fuel Consumption gal/h**	**Annual Operating Hours**
Class/Category	**John Deere**	**Study Model**		
2 WD Category	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**	**Annual Operating**
Class/Bucket Capacity	**Caterpillar**	**Study Model**	**gal/h**	**Hours**
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**	**Annual Operating**
Class/Weight Class	**Caterpillar**	**Study Model**	**gal/h**	**Hours**
<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

2 METHODOLOGY

2.1 FUEL CELL SYSTEM

The polymer electrolyte fuel cell (PEFC) stack considered in this study is designed according to targets for heavy duty trucks including liquid stack coolant, air management, active fuel recycling, and no external humidifier. Complete model equations and assumptions for the system model can be found in previous publications [33][34][35]. The FCS are sized to satisfy the given vehicle's power requirement at end of life (EOL) to ensure the given application's demands are always met over the lifetime of the vehicle. The modeled efficiency curves of the PEFC system as a function of percentage of power (engine load) at beginning of life (BOL) and at EOL are shown in Figure 1 along with a 477-horsepower diesel engine and a 50-horsepower diesel engine [35][36]. The fuel cell is more efficient than the diesel engines across the entire power range with a larger efficiency difference at lower engine load. Empirically, diesel engine efficiency increases as engine load increases and as engine size increases [36][37]. Although these trends depend on multiple engine design factors, larger diesel engines are typically more efficient because less energy is lost to heat and friction per kilogram of fuel [38][39]. And as diesel engine load increases, more fuel is burned per cycle during the combustion step which increases engine temperature. For a constant volume engine, the fuel conversion efficiency increases with temperature [38][39].

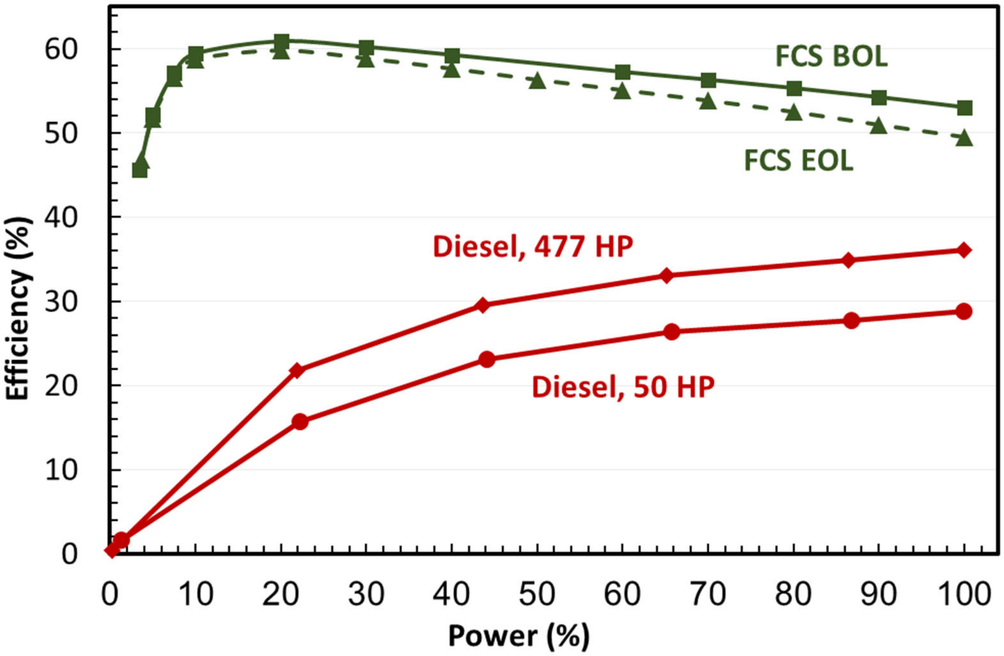


Figure 1 - Modeled FCS efficiency curves for beginning of life (BOL) and end of life (EOL) compared to diesel tractor engine efficiency curves for two engine sizes, 477 hp and 50 hp

In all FCS systems, the fan and radiator frontal area are sized for the FCS heat load at the rated power. At the heat rejection design point, the FCS exit coolant temperature is 90 °C and the diesel exit coolant temperature is 105°C. The design-condition ambient temperature for the FCS is 40 °C. The FCS model includes an intake air filter as would be designed for a heavy-duty fuel cell truck. However, the model does not consider air filtration over-and-above these requirements. For the harshest environments such as undergrounds mines, follow up studies to assess parasitic losses due to additional filtration and cell degradation are warranted.

2.2 LIQUID HYDROGEN STORAGE SYSTEM

The amount of time a vehicle can operate without refueling is referred to as “autonomy” and is crucial for agriculture, mining, and construction. For example, during planting or harvesting season, tractors are commonly operated for sixteen hours per day or even more to meet the demands and constraints of the agricultural cycle. For consideration of FCS replacing diesel powertrains, twelve hours of autonomy is reported as desirable, eight hours is viewed as satisfactory, and four hours is considered an absolute minimum to accomplish agriculture, mining, and construction [40]. Moreover, ease of FCS vehicle adoption into existing operations would make the transition to a decarbonize off-road fleet much faster and cheaper. For all vehicles in this study, the storage systems are designed so that the diesel system and FCS system, at EOL, operate with equal autonomy.

To increase fuel storage, and therefore autonomy, we assume that hydrogen is stored on-board as liquid (LH_2). Compressed hydrogen was considered but deemed insufficiently energy dense by volume to be viable given the high autonomy demanded coupled with practical system packaging constraints on vehicles. The LH_2 storage system was adapted from an analogous system being developed for heavy-duty trucks [41]. Stored LH_2 (mass of H_2 plus mass storage system) is roughly two to three times more energy dense by mass than compressed hydrogen at 350 bar and 700 bar, respectively [41]. Note that on the lower heating value (LHV) basis, H_2 (120 MJ/kg LHV) embodies 2.8 times more energy than diesel fuel (43.1 MJ/kg LHV). The DOE cost targets for LH_2 storage on-board HDVs is 9 \$/kWh by year 2030 decreasing to 8 \$/kWh in the ultimate scenario [41]. Previous studies suggest that the cost of LH_2 enabled cryo-compressed storage for HDVs can approach 10 \$/kWh [42][43].

2.3 DUTY CYCLES

Tractors, wheel loaders, and excavators operate in extreme, variable work sites, perform a complex range of tasks, and may be controlled by different operators with varying levels of expertise [44]. Duty cycles are typically specified over short times, a few minutes to as low as several seconds, and may not capture the full dynamics and fuel consumption rate experienced by an off-road vehicle over its entire lifetime [45]. The purpose of this study is to generate a representative, sector-wide evaluation of hydrogen fuel cell powered vehicles, to compare their relative merits, and to evaluate the TCO. Accordingly, the duty cycles are instead defined implicitly by the fuel consumption rate of each vehicle and its average annual operating hours. Diesel engine average operating efficiencies are back calculated from the fuel consumption rates and heavy-duty diesel engine efficiency maps [36][32]. Engine lifetime average operating power is determined from an empirical engine efficiency curve at the known lifetime fuel consumption given in Table 1. Lifetime average engine efficiency is thus determined from the lifetime average operating power.

For excavators and wheel loaders, industry-published data, reports, and academic studies are incorporated to determine the fraction of operating time for each sub-drive within the powertrain (e.g., travel drive versus implement drive) [46][47]. Vehicle average annual operating hours are given in Table 1 [32]. Tractors spend nearly 100% of their operating time traveling. Wheel loaders spend approximately 45% of their total time operating idling and 55% traveling and earthmoving [48]. Excavators spend approximately 25% of their total time idling, 15% traveling, and 60% earthmoving which included slew and implement motion [46].

2.4 TRACTOR POWERTRAIN

The tractor diesel system is modeled as a conventional internal combustion engine (ICE) delivering power via gearbox to provide traction and power the implement (also referred to as "power take off", PTO) [49][50]. In the FCS, a hydrogen fuel cell replaced the ICE, and the drivetrain transforms electric power to mechanical power via inverter and motor. The tractor system efficiency equations are given in the Appendix and the system diagrams are shown in Figure A1. Tractors mostly travel while towing a powered implement [51]. The FCS includes a small battery to extend PEFC stack lifetime by clipping the cell voltage and minimizing the number of startups and shutdowns but is not sized for regenerative energy capture. Voltage clipping prevents the cell voltage from drifting to high values that rapidly accelerate cell degradation. The FCS rated power is sized for equal PTO power in both systems.

2.5 WHEEL LOADER POWERTRAIN

In the diesel wheel loader, the engine delivers power to the wheels via gearbox for traction (travel) [52]. Separately, a hydraulic pump circulates hydraulic fluid via main control valve and hydraulic circuit with throttle valves [52]. The FCS wheel loader includes an electrified drive to power the wheels and electric motor-driven hydraulic pumps to actuate the implement [52][53]. Although electromechanical actuation for off-road heavy equipment has been demonstrated [54], they are not commercially available. Therefore, hydraulic actuation is retained for the design considered in this study. The FCS wheel loader powertrain includes a battery to extend PEFC lifetime and capture regenerable energy. Regenerative energy is captured from the travel drive and the boom actuator. Regenerative energy is stored in the battery while idling, when lowering the boom, or when decelerating the wheel loader from traveling to stationary. The wheel loader system efficiency equations are given in the appendix and the system diagrams are shown in Figure A2.

Wheel loaders spend considerable time traveling while earthmoving. The prototype duty cycle is referred to as a 'Y'-pattern [55][56]; the loader travels forward one direction, collects earth, reverses, then travels forward the other direction and dumps the earth. The pathing forms a Y-shape as viewed from above. To average power and energy flows in the wheel loader, estimates of time spent traveling with duty-cycle-averaged power are coupled with the average engine efficiency determined via industry-reported fuel consumption rate.

2.6 EXCAVATOR POWERTRAIN

Excavator powertrains are more complex than wheel loader powertrains. In addition to actuating the implement and occasional travel, excavators rotate around the chassis while actuating the implement to move earth. A common excavator operation is the "dig and dump" cycle whereby the excavator digs and collects earth, rotates, and deposits the earth in a truck to be hauled away. Like the wheel loader, hydraulic actuation of the implement is ubiquitously used. Because excavators travel much less than wheel loaders, all three drives (travel, slew, and actuator) are typically connected and powered by one hydraulic circuit [57]. Hydraulic fluid throttling and friction decrease the efficiency of the powertrain. Moreover, to accommodate the uncertainty and rugged environments encounter in mining and construction, excavators are often built for high peak power but operate at a small fraction of peak power on average. This implies low average operating efficiency of the diesel engine; altogether, excavators are commonly ca. 10% efficient, or even less. Control and optimization of the hydraulic circuit remains an active area of research. The electrified FCS powertrain removes the travel and slew (rotation) drives from the hydraulic circuit favoring more efficient electric motors and gearboxes [48][49]. Inclusion of a substantial battery also enables recovery of an appreciable fraction of the energy while decelerating the slew and lowering the boom of the implement [46][50]. The excavator system efficiency equations are given in the Appendix and the system diagrams are shown in Figure A3.

2.7 ENERGY STORAGE CONTROL STRATEGY

For the tractor platforms, the battery provides power when the power demand drops to or below the FCS idle power. Idle power is assumed controlled to 10% of the FCS net power. The battery is sized to generate twice the FCS idle power with a power-to-energy ratio (P/E) of 10 kW/kWh [58]. The battery capacity is therefore two times the idle power divided by the P/E ratio. The battery state of charge (SOC) is assumed to be maintained near the lower limit, ca. 30%, to minimize number of FCS shutdowns [59]. The battery in the wheel loaders provides the same function and are sized the same way as for farm tractors. For the excavator platform, the battery provides power when the power demand drops below the FCS idle power. Excavators perform cyclic tasks which make them excellent candidates for regenerative energy storage through a battery. The battery is sized to capture regenerative power up to the FCS rated power and has a P/E ratio of 10 kW/kWh. With FCS rated power and P/E specified, the battery is determined as FCS rated power divided by P/E. A battery charge-discharge cycle efficiency of 96.2% is assumed [58][60]. The excavator battery SOC is also assumed to be maintained near the lower limit to maximize regenerative energy capture during operation. The electric powertrain wheel loader includes a battery sized from 2.2 kWh for compact loader up to 25.7 kWh for the large loader to extend PEFC stack lifetime and regenerate energy during deceleration and lowering of the boom. The FCS excavators are hybridized with a battery from 3.4 kWh for the mini/compact excavator up to 33.1 kWh for the standard/full excavator to extend PEFC stack lifetime and store regenerated energy.

2.8 ECONOMIC ASSUMPTIONS

FCS cost metrics applied in this TCO, along with their anticipated improvements, are given in Table 2. Manufacturing volume affects FCS cost; the ‘FCS Status’ cost is the modeled cost as if the present state of the art technology for the FCS system were scaled up to 1,000 systems per year manufacturing volume [61]. The ‘FCS Ultimate’ cost is a cost target based on fundamental technology targets and targets for technology scale-up [61][62]. The cost per system accounts for new materials allowances and the durability they provide; higher platinum catalyst loading (0.4 mg/cm^2 total), a thicker membrane (20 microns), and the updated anticipated performance degradation over 25,000 hours of lifetime [46]. The commonly accepted status of FCS lifetime is 25,000 hours for HDVs which is taken from fuel cell buses [42]. The higher system cost of $\$323/kW_e$ would likely be accepted by customers because the system provides higher vehicle autonomy and stack durability. The electric drivetrains include motors, controls, power electronics, and gearboxes. Drivetrain status costs in Table 2 assume a manufacturing rate of 50,000 units/year [63]. The FCS ultimate drivetrain cost is based on 2025 targets at high production volume established by the United States Department of Energy’s Vehicle Technology Office [64].

Table 2 – Costs for Status and Ultimate target values are reported for FCS systems.

Variable	Engine	Battery	Fuel	Fuel Storage	Drivetrain
Diesel	\$80 / kW	-	\$3.25 / gal	\$1000 / m^3	\$15 / kW
FCS Status	\$323 / kW	\$268 / kW	\$5 / kg	\$9.5 / kWh	\$30 / kW
FCS Ultimate	\$60 / kW	\$125 / kW	\$4 / kg	\$8.0 / kWh	\$12 / kW

The capital recovery factor (CRF) is determined by $\mathrm{CRF} = i(1+i)^t \div ((1+i)^t - 1)$ for real interest rate, i, and time, t. All upfront costs are amortized over the vehicle economic lifetime. Additional assumptions include a vehicle economic lifetime of 15 years for tractors and 10 years for wheel loaders and excavators. Salvage values are 23% of list price, installation cost is 30% of list price, internal rate of return is 7%, and the average inflation rate is 2%. Data from a fuel cell electric bus evaluation program [65] suggests that the current fuel cost is \$5 per kilogram for delivered H_2 as LH_2 with an ultimate forecast of \$4 per kilogram. This assumes that all DOE fuel cell performance and LH_2 storage cost targets will be met. The current target for battery cost is 268 \$/kWh with a DOE ultimate target of 125 \$/kWh again assuming that cost reduction targets are met [61][62].

3 RESULTS

3.1 PERFORMANCE

Efficiency versus engine load for fuel cell and diesel engines is shown in Figure 1. Higher efficiency equates to lower fuel consumption, an important contribution to the TCO. Although engine efficiency affects fuel consumption, the overall powertrain efficiency determines the final vehicle fuel consumption. Powertrain efficiency includes the engine and drivetrain efficiencies. The end-of-life efficiencies at rated power are plotted in Figure 2. Each class within each vehicle type is plotted according to its diesel power. For the tractor, the PTO efficiency is shown, for the wheel loader, the travel powertrain is shown, and for the excavator, the actuator powertrain is shown because they are the largest consumers for each vehicle type. The FCS engine efficiency is 49% at all engine sizes.

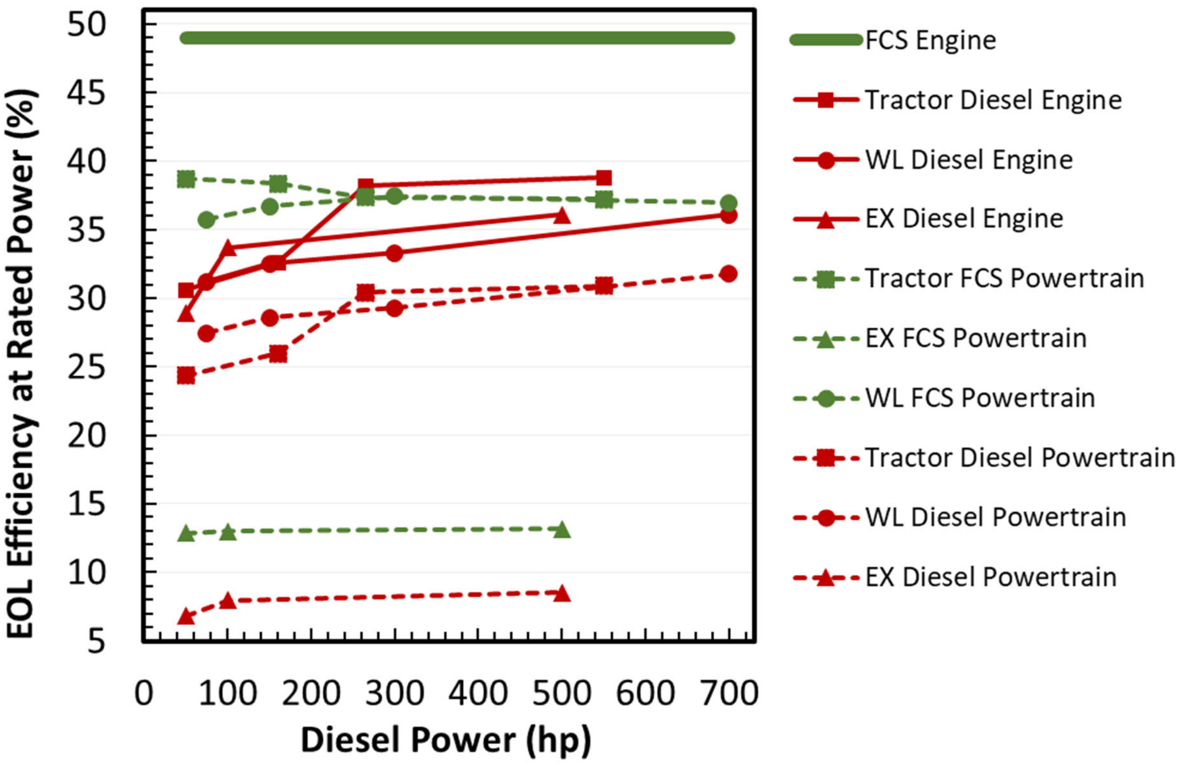


Figure 2 - Engine and powertrain efficiencies for each vehicle. Engine values are plotted with solid lines. Powertrain values are plotted with dashed lines. Wheel loaders are abbreviated by 'WL' and excavators are abbreviated by 'EX'.

Tractor engine efficiency is 60% higher in the FCS versus diesels system at the 2WD Compact, 50 diesel hp size and decreases to 26% higher for FCS versus diesel at the 4WD, 550 diesel hp size. At rated power, the electric drivetrain is 90% efficient compared to the mechanical (diesel) drivetrain which is 86% efficient. The PTO efficiency is 59% to 20% higher for the FCS (38.7% - 37.1%) versus the diesel system (24.4 - 30.9%). By convention, the indicated FCS and diesel engine efficiencies exclude fan power losses. The powertrain efficiencies include fan power losses.

The wheel loader engine efficiencies are 57% (compact size) down to 36% higher (large size) for the FCS versus the diesel engines which are 31.2% - 36.1% efficient. At rated power, the wheel loader electric drivetrain has lower efficiency for travel, 83.6%, compared to the diesel system's mechanical drivetrain which was 95% efficient. However, the FCS powertrain efficiencies are still 30% - 16% higher for wheel loader sizes due to higher FCS engine efficiency. The powertrain efficiencies are 35.7% - 36.9% versus the diesel powertrain efficiencies of 27.4% - 31.8%.

The electric drivetrain for the excavator actuator is slightly more efficient at 30% than the diesel hydraulic drivetrain at 25%. The FCS engine efficiency is 69% - 36% higher for FCS (49%) than the diesel engine (28.9% - 36.1%) across the three excavators. The powertrain efficiency for the actuator is 90% - 53% higher for the FCS (13%) than the diesel system (6.8% - 8.5%). Extremely low inefficiencies in hydraulic excavators are common as they must be sized for high power to meet application demands but, on average over time, operate far below peak power [34].

The EOL FCS power is plotted versus diesel horsepower in Figure 3. For the tractors, the higher FCS drivetrain efficiency permits a nearly equal FCS power even after accounting for higher radiator fan power and lifetime performance degradation. For the wheel loaders, the FCS engine power is sized slightly larger to compensate for the lower travel drivetrain efficiency. The FCS excavator engine power could be significantly downsized due to the due to the low efficiency of the diesel hydraulic drivetrain which the electrified FCS partially avoided.

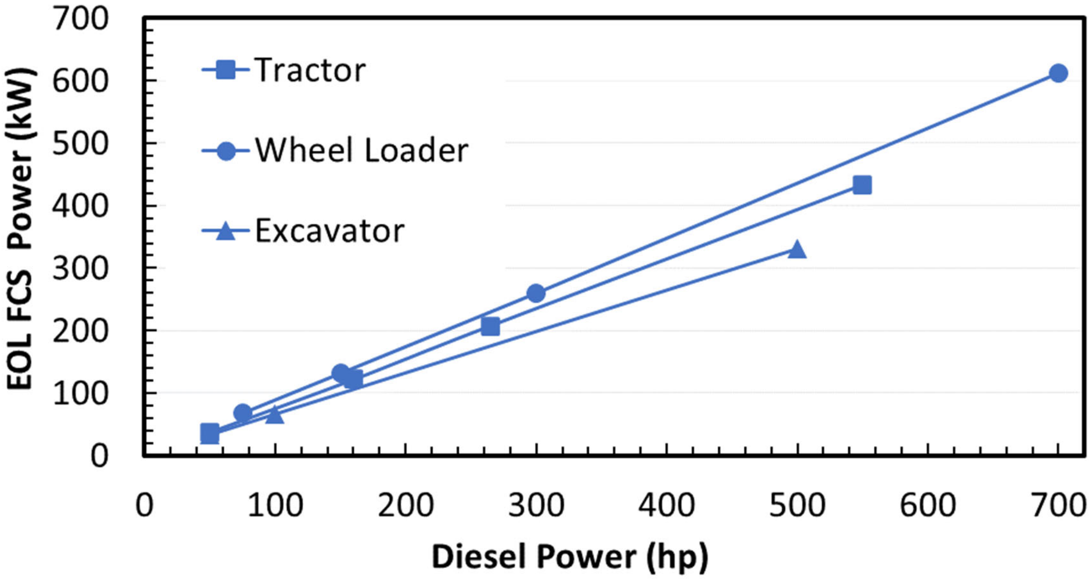


Figure 3 - EOL FCS Power versus Diesel Engine Horsepower for each vehicle type and class.

Heat rejection can be challenging in FCS systems, especially for higher power systems. In Figure 4, the heat duty and fan power at end of life are plotted versus the diesel system power. The FCS system results in a 28% - 69%, 60% - 74%, and up to 32% higher heat duty for the tractor, wheel loader, and excavator systems, respectively, despite the higher efficiency engine. To offset the larger heat duties, the FCS systems require 68% - 124%, 107% - 132%, and 43% - 76% larger fans and radiators for the tractor, wheel loader, and excavator systems, increasing proportionally with engine power. Packaging the components onto the tractor while maintaining safety and clear field of vision for the tractor operator can be an issue in the larger tractors.

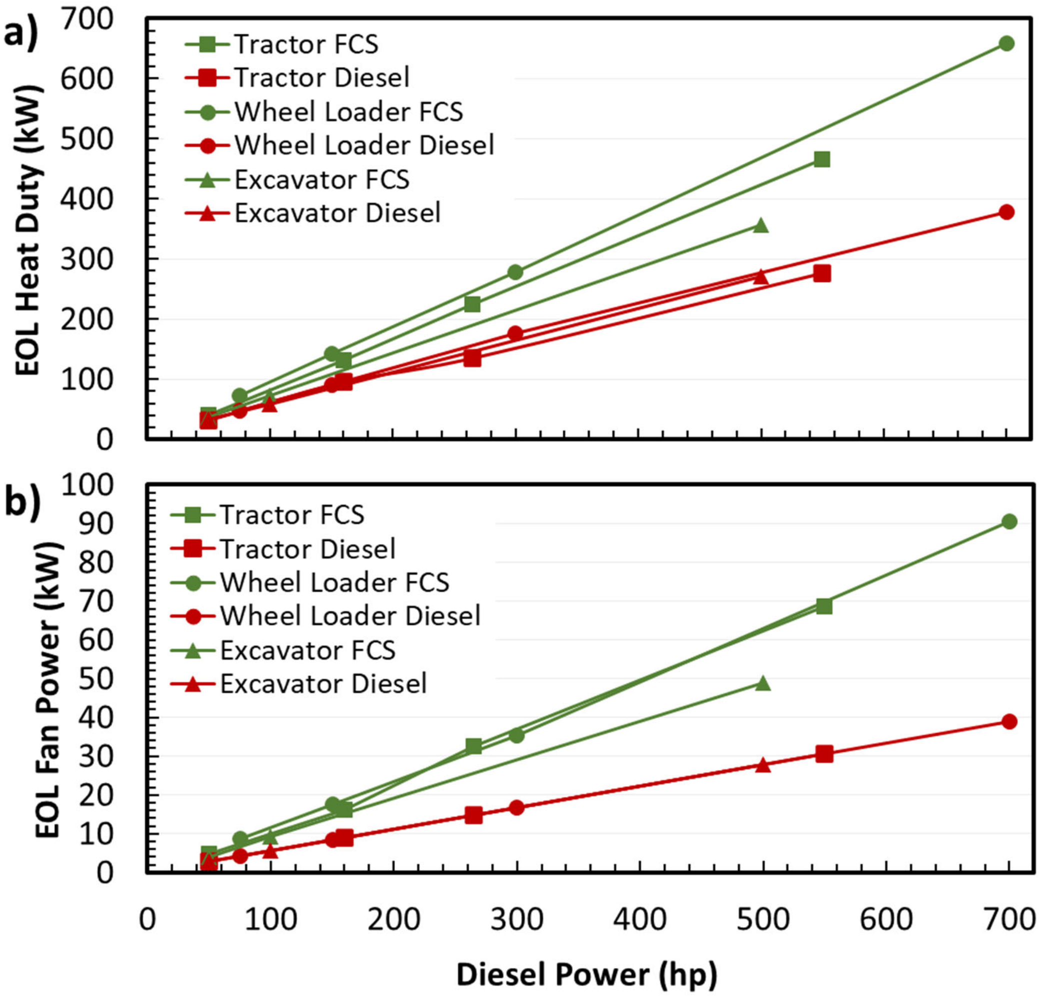


Figure 4 - EOL Heat Duty (a) and EOL Fan Power (b) versus the diesel horsepower size for all vehicle types and classes.

Reducing fuel consumption in off-road equipment would be a major benefit to agriculture, mining, and construction industries, for both diesel and FCS equipment. In Figure 5, the lifetime operating efficiency (the average of BOL and EOL), lifetime fuel consumption, and fuel storage of the FCS and diesel systems are plotted versus the diesel system horsepower. Kilograms of H_2 and gallons of diesel can be compared on the basis of energy equivalence of the two fuels. The FCS systems have 162% - 39%, 180% - 91%, and 142% - 71% higher efficiency at operating power for tractor, wheel loader, and excavator but still require considerable fuel to equal the autonomy of the diesel tractor. Autonomy may have to be sacrificed in larger tractors requiring more than ca. 200 kg LH_2 storage. Compressed H_2 storage may be feasible for the compact (50 diesel hp) tractor, which required only 7.6 kg of H_2 for equal autonomy. Autonomy may also have to be sacrificed in the largest wheel loader, which required 164 kg LH_2 storage. The standard/full size excavator required only 92 kg of LH_2 storage for equal autonomy as the diesel engine. This likely does not pose a problem for packaging.

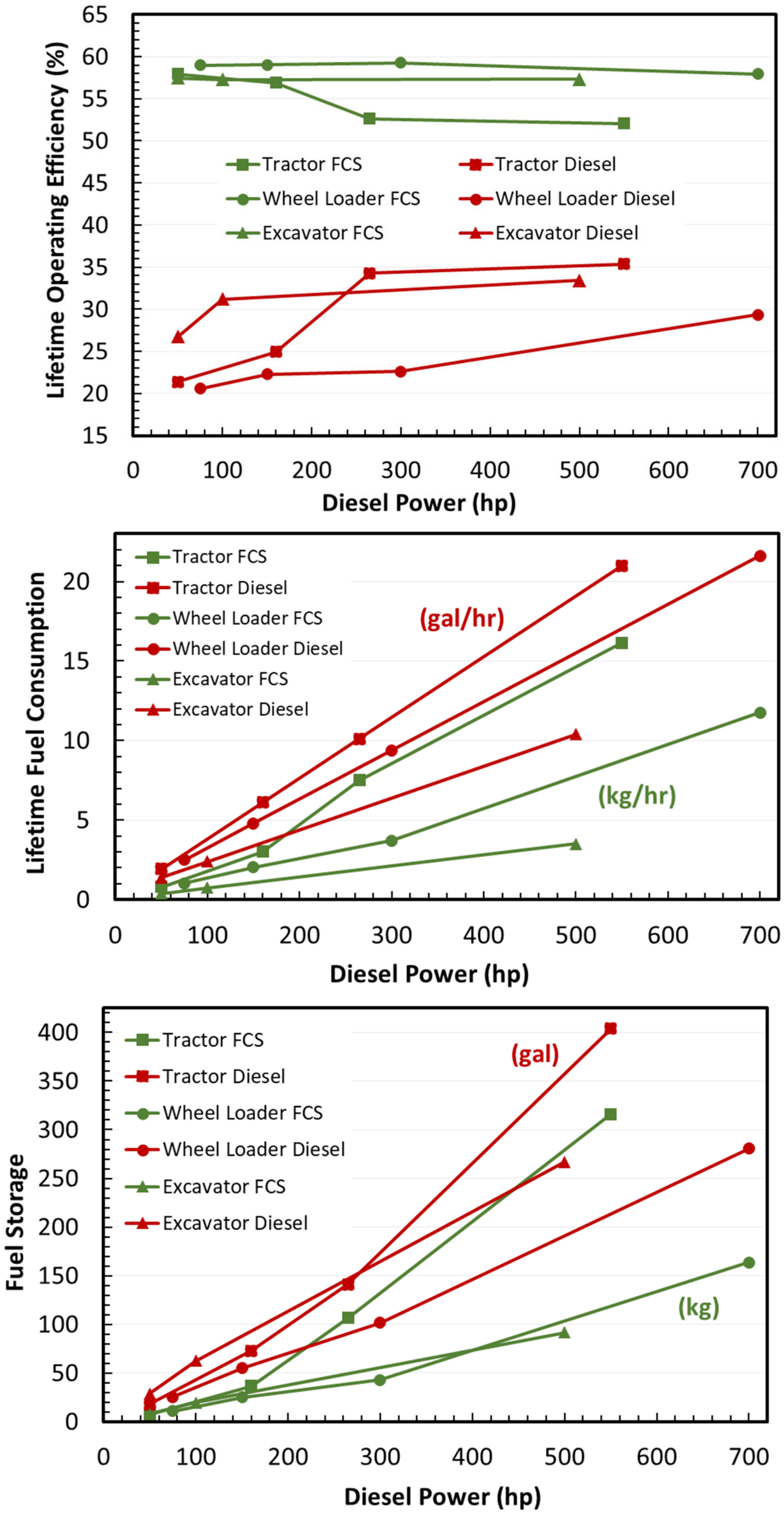


Figure 5 – Lifetime operating efficiency, lifetime fuel consumption, and fuel storage in kilograms (FCS) and gallons (diesel) for each vehicle type and class

3.2 SANKEY DIAGRAMS

Sankey diagrams for the 700 hp equivalent wheel loaders at their average operating power illustrate the energy flows of the diesel and FCS powertrains in Figure 6. Sankey diagrams for tractors were omitted because the systems do not include regenerative energy capture; the energy flows are straightforward. The largest vehicle sizes were chosen for wheel loader and excavator because they consume the most fuel per vehicle. The travel portion of the wheel loader drivetrain is less efficient in the FCS system, 83%, as compared to the diesel system at 95%. And a larger fraction of the energy of hydrogen fuel is lost to fan power, 2.3% versus 1.1%, due to the larger heat rejection requirement. However, the actuator portion of the FCS platform is slightly more efficient, 47%, versus the diesel platform at 41%. Considerably more energy of the fuel is delivered as net work in the FCS, 36.3% versus 19.0% for the travel drive and 5.4% versus 2.8% for the actuator. The FCS energy regeneration efficiency is 83% for energy recovered from the travel drive and 61% for energy recovered from the actuators. 6.2% net energy is recovered and returned to the battery after accounting for idling loss due to voltage clipping.

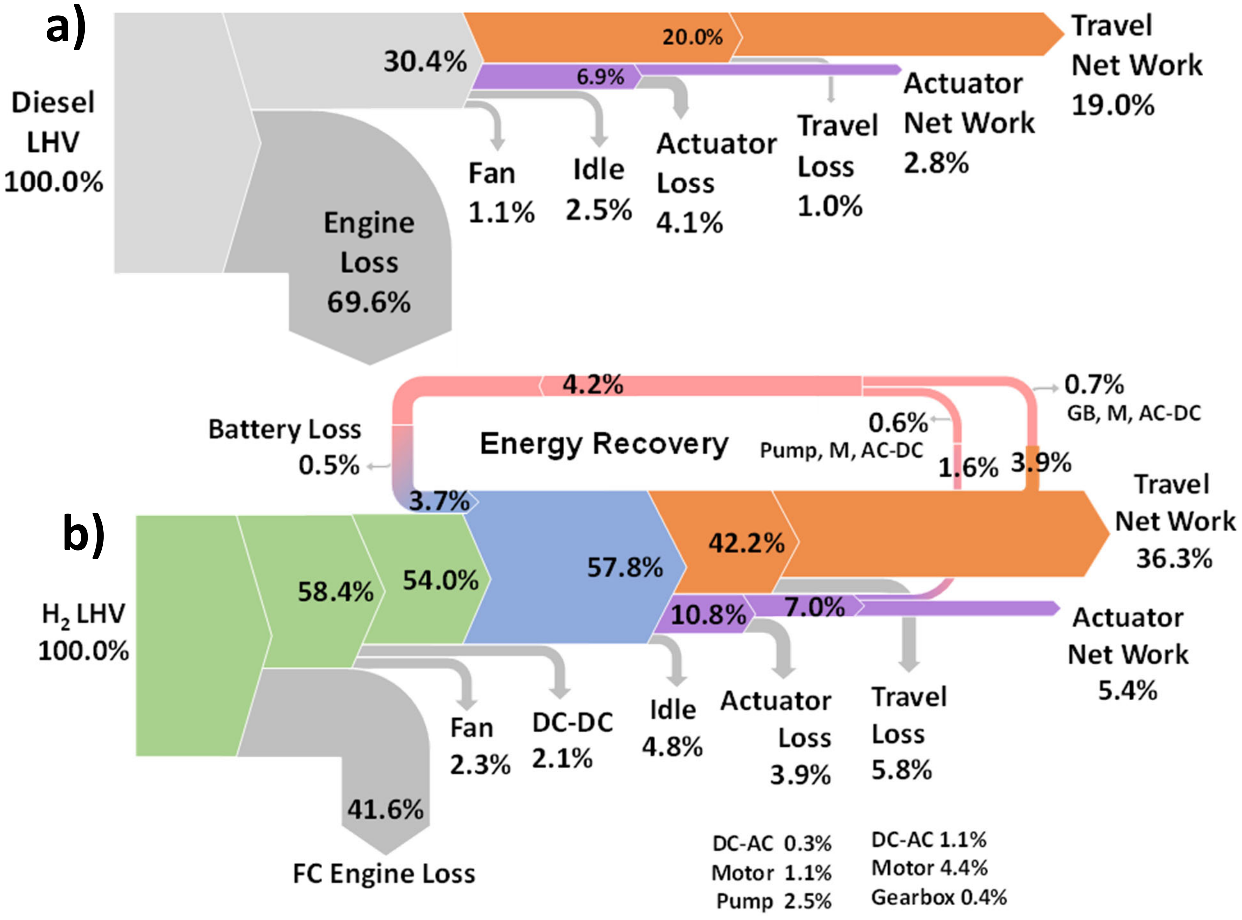


Figure 6 - Sankey diagrams for the wheel loader diesel system (a) and FCS (b) at the 700 hp equivalent size at average operating power

Sankey diagrams for the 500 hp equivalent excavator at average operating power are shown in Figure 7. As with the wheel loader, a higher percentage of the fuel energy is lost to fan and idling in the FCS. However, the travel and slew portions of the drivetrain are much more efficient in the FCS system, 83%, as compared to the diesel system at 30%. The actuator portion of the FCS drivetrain is also slightly more efficient, 30% in FCS versus 25% in the diesel system. The FCS energy regeneration efficiency is 83% for energy recovered from both the travel and slew drives and 61% for energy recovered from the boom actuator. 17% net energy is recovered and returned to the battery after accounting for idling loss due to voltage clipping. Altogether, a much larger percentage of the fuel energy went toward net work in the FCS as compared to the diesel system: 16.8% actuator, 3.4% travel, and 6.7% slew for FCS compared to 3.8% actuator, 0.8% travel, and 1.5% slew in the diesel system.

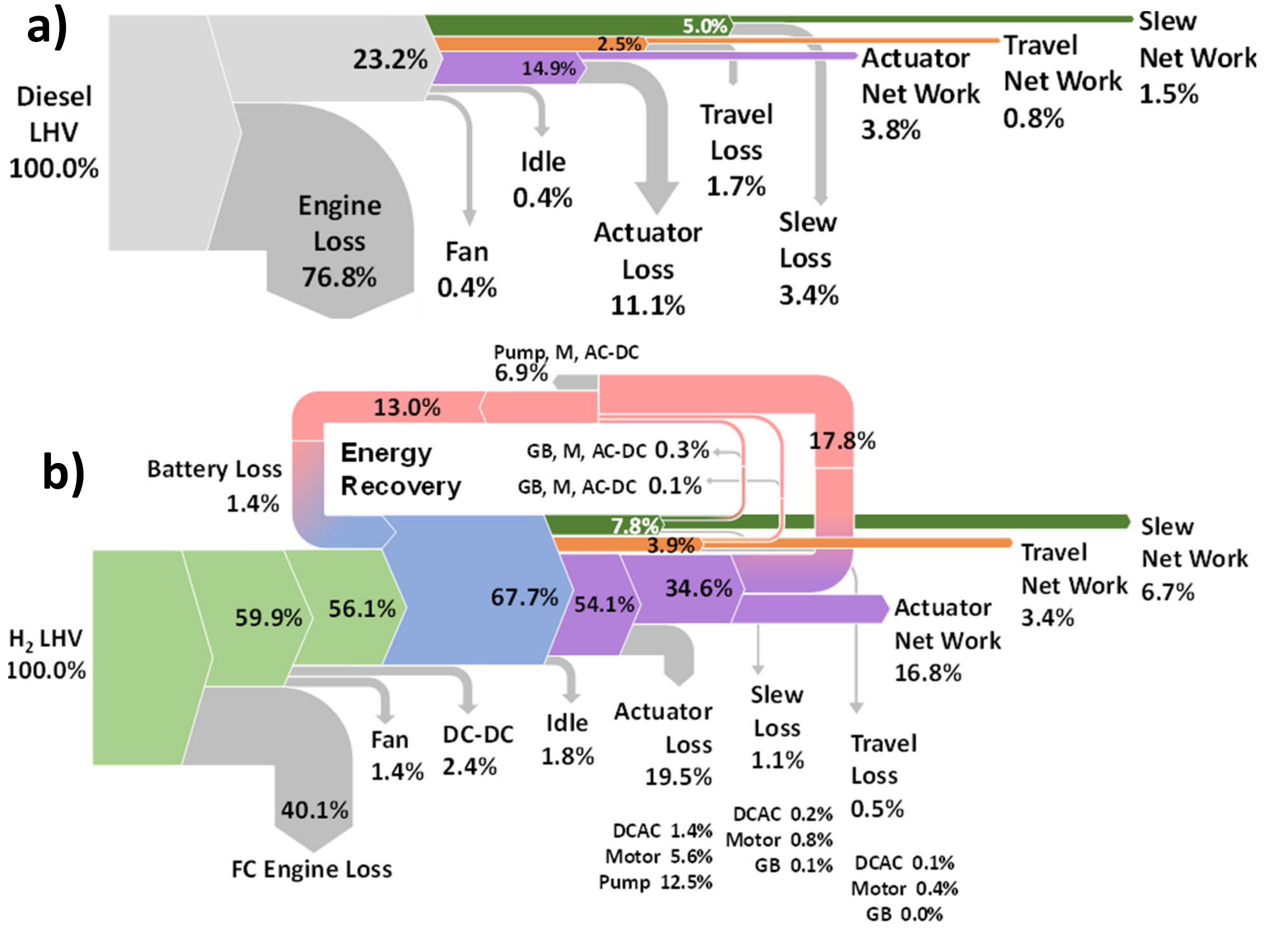


Figure 7 - Sankey diagrams for the excavator diesel system (a) and FCS (b) at the 500 hp equivalent size at average operating power

3.3 TOTAL COST OF OWNERSHIP (TCO)

Despite powertrain efficiency benefits in the FCS system, hydrogen FCS must be economically cost-effective. The TCO for each vehicle under status and ultimate conditions are plotted below. For ease of comparison, the TCO only includes the capital costs of the power system, energy storage, electric drive and fuel storage; fuel cost; and operating and maintenance cost. TCO excludes the common cost elements such as labor, insurance, chassis, and other attachments. Tractor TCO results are plotted in Figure 8. The tractor 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. Fuel cells are lower cost options for compact (50 hp), utility (160 hp), and row crop tractors (265 hp) if the ultimate targets are met for costs of LH_2, FCS, and H_2 storage. Fuel cells remain slightly more expensive platforms versus diesel for the 4-WD tractors primarily because of the cost of the LH_2 storage system.

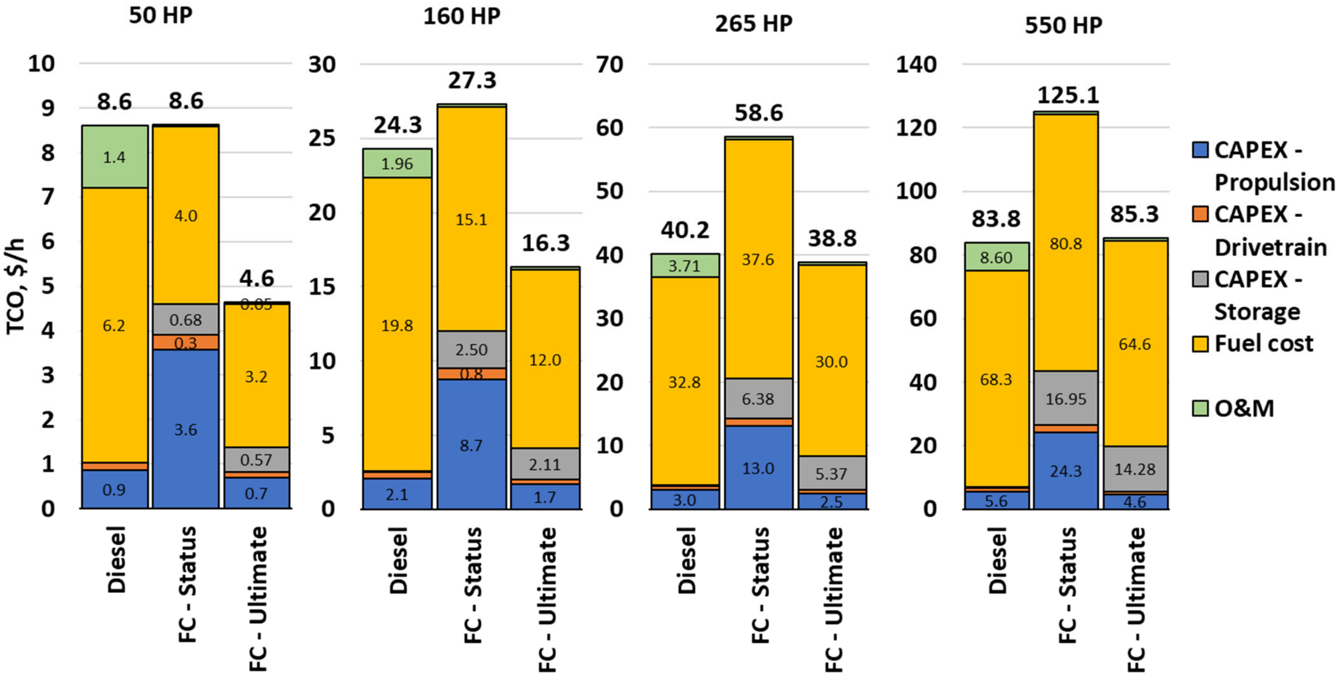


Figure 8 - Total cost of ownership plots for the diesel, FCS Status, and FCS Ultimate tractors at each class/size

Figure 9 shows the TCO for wheel loaders. At \$3.25/gal diesel and \$4/kg H_2, fuel accounts for 73% - 76% of TCO in diesel wheel loaders and 74% - 76% of TCO in the ultimate FCS wheel loaders. Fuel cells are cost competitive with diesel engines for compact (75 hp), small (150 hp), and medium (300 hp) wheel loaders even at \$5/kg H_2 (Status). Fuel cells are substantially lower total 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.

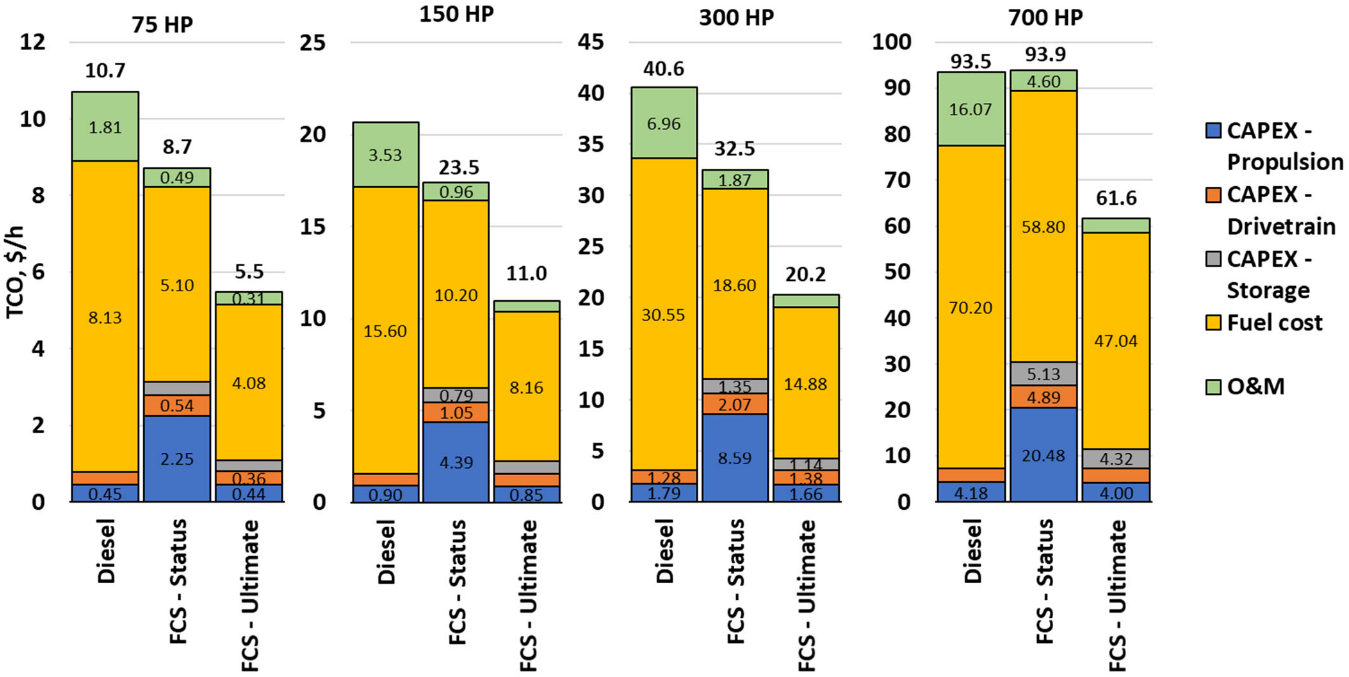


Figure 9 - Total cost of ownership plots for the diesel, FCS Status, and FCS Ultimate wheel loaders at each class/size

Excavator TCO plots are shown in Figure 10. Fuel accounts for 50% - 64% of the TCO in diesel excavators but only 30% - 50% of TCO in FCS excavators. Fuel cells are cost competitive with diesel engines for compact (50 hp), medium (100 hp), and standard/full (500 hp) excavators even at $5/kg H_2 and $3.25/gal diesel. The fuel cell powertrains would be the lower cost option for each excavator size if ultimate targets are met for H_2, FCS and LH_2 storage costs. When the ultimate H_2 and FCS targets are met, the capital expenditure (CAPEX) costs for propulsion, drivetrain, and LH_2 storage far exceeds the fuel cost in compact and medium excavators.

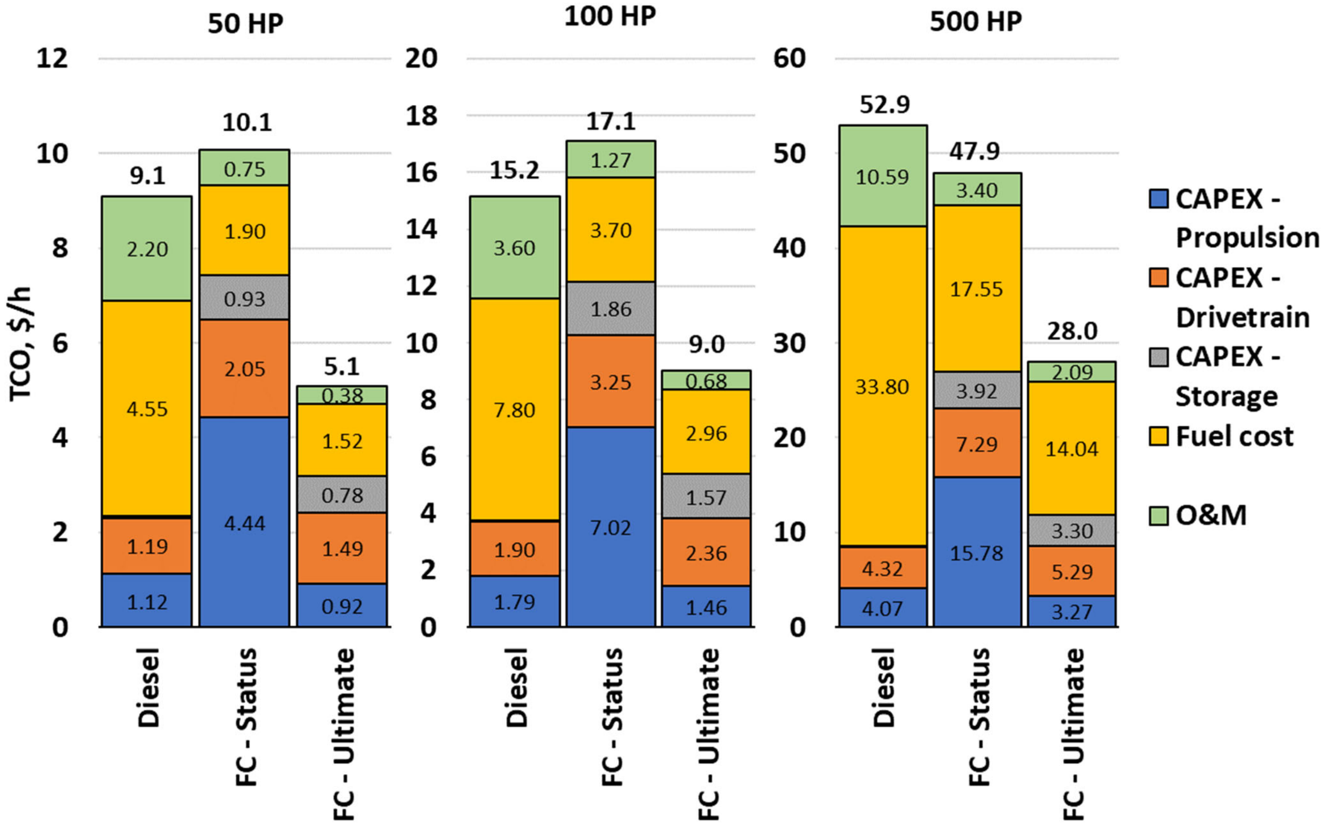


Figure 10 - Total cost of ownership plots for the diesel, FCS Status, and FCS Ultimate excavators at each class/size

The cost difference of each vehicle type can be further examined by breaking out the individual cost contributors, CAPEX, fuel cost, and O&M. These are shown in Figure 11. Each graph plots the diesel system cost minus the FCS ultimate cost for each respective category. The Δ is positive when the FCS platform is cheaper and negative when the diesel platform is cheaper.

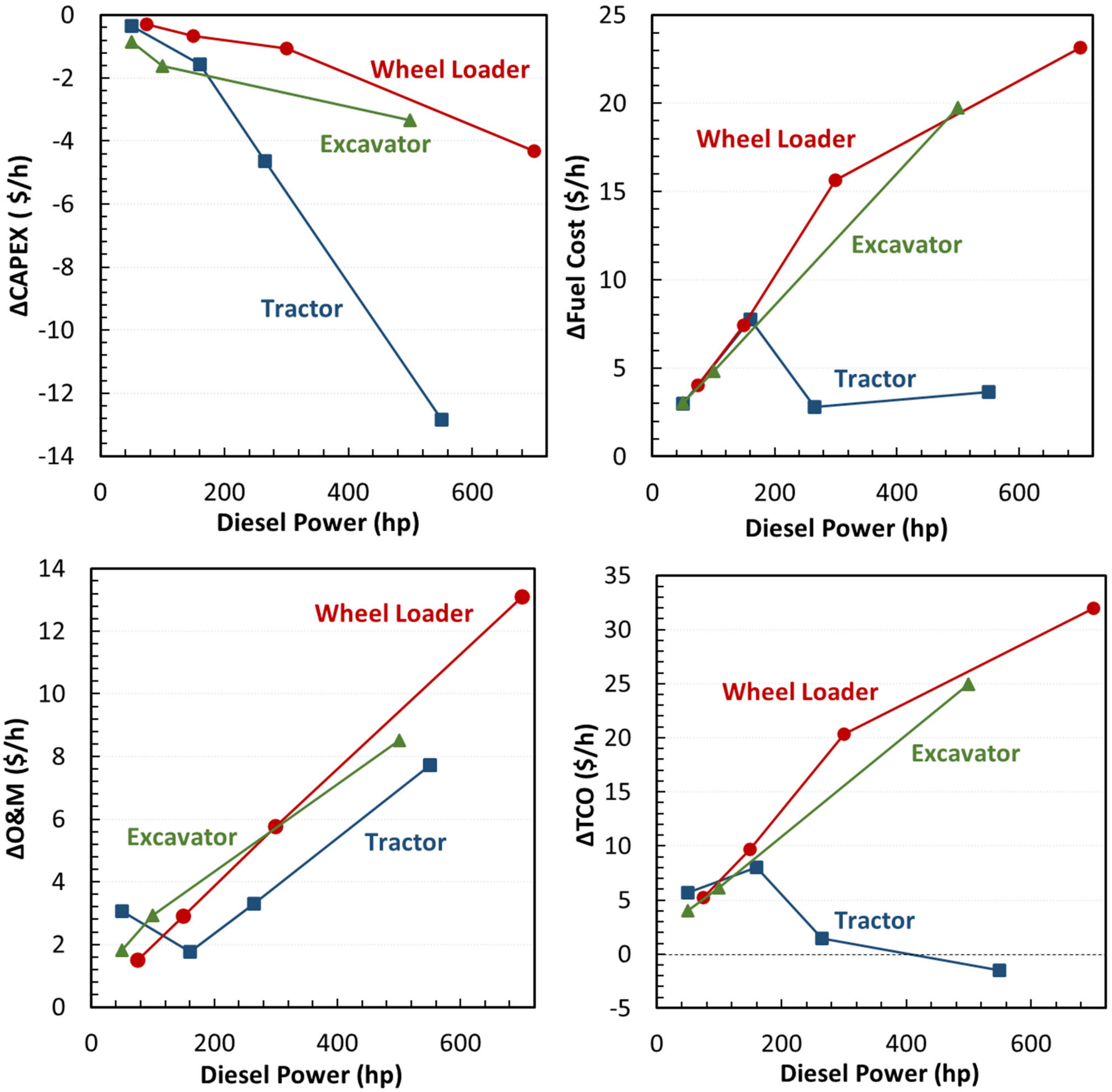


Figure 11 - Differential cost for each cost category. Δ = diesel TCO minus FCS Ultimate TCO.

If the ultimate FCS targets are met, FCS wheel loaders and excavators become the preferred TCO options with TCO advantage proportional to vehicle size (diesel power). FCS tractors become preferred for smaller diesel power sizes and have approximately equal TCO to diesel tractors at larger diesel horsepower. O&M favors FCS for all vehicle types and all vehicle sizes, again with increasing advantage as size increases. This suggests further advantage for the FCS not captured in this study as vehicle downtime implies business opportunity losses. Cost of fuel overwhelmingly favors FCS platforms for wheel loaders and excavators and slightly advantages FCS platforms for tractors. Overall, if ultimate targets are met, the agriculture, mining, and constructions industries may be able to convert to decarbonized FCS platforms while simultaneously reducing their TCO and preserving equal or similar operations.

4 CONCLUSIONS

This study considers off-road equipment representative of the full product lines for the agriculture, mining, and construction industries. Eleven off-road vehicles are modeled and compared. Fuel cell and on-board LH_2 storage systems being developed for heavy-duty trucks offer modularity and can achieve cost reduction via economies of scale that can lead to FCS adoption for diesel tractors, wheel loaders, and excavators. The primary technical advantage of fuel cell powertrains is the substantial gain in lifetime operating efficiency, between 40% - 180%. Electrifying the drivetrains and hybridizing with a battery resulted in 12% - 17% reduction in fuel consumption possible through regenerative energy capture in wheel loaders and excavators. Heat rejection remains a challenge; a 28% - 74% higher heat load was determined which required 43% - 132% larger fans and radiators. Hydrogen storage also remained a challenge; 92 - 316 kg H_2 needed to be stored in the 500 hp - 700 hp equivalent vehicles. This may necessitate an autonomy reduction in the 4-WD tractor and standard/full excavator absent significant innovation in system packaging.

The TCO considers the capital costs of power system, energy storage, electric drive and fuel storage, fuel cost, and the operating and maintenance cost. Common cost elements were omitted. The TCO for tractors and wheel loaders is dominated by fuel costs. At \$3.25/gal diesel and \$4/kg H_2, fuel accounts for 70% - 82% of the TCO in diesel and ultimate FCS. In the ultimate scenario, excavator fuel consumption was substantially reduced by the electrified drivetrain and TCO was reduced to nearly half of diesel excavator TCO for all vehicle sizes. Future studies could further investigate emerging diesel powertrains to electric powertrains, fuel cell powertrains hybridized with an ultracapacitor, battery electric powertrains, and/or the TCO of biodiesel powertrains.

5 ACKNOWLEDGMENTS

Argonne National Laboratory's work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel cell Technologies Office, under contract DE AC02 06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

6 APPENDIX

Efficiency Equations

Tractor

Diesel

Powertrain Efficiency (η) (Engine, Mechanical Drive)

$\eta = \eta_E \eta_{MD}$

Drivetrain Efficiency (η_{MD}) (Gear Box)

$\eta_{MD} = \eta_{GB}$

Fuel Cell

Fuel Cell Powertrain Efficiency (FCS, Electric Drive)

$\eta = \eta_{FC} \eta_{ED}$

Electric Drivetrain Efficiency (DC-DC, DC-AC, Motor, Gear Box)

$\eta_{ED} = \eta_{DC} \eta_{AC} \eta_{MT} \eta_{GB}$

Battery Powertrain Drivetrain Efficiency (Battery Discharge)

$\eta_{BD} = \eta_B \eta_{ED}$

Wheel Loader

Diesel

Powertrain Efficiency (η)

$\eta = \eta_E \eta_{MD}$

Travel Drivetrain (TD) Efficiency: (Gearbox)

$\eta_{TD} = \eta_{GB}$

Actuator Drivetrain (AD) Efficiency (Hydraulic Pump, Main Valve, Throttle Valve)

$\eta_{AD} = \eta_{HP} \eta_{MV} \eta_{TV}$

Fuel Cell

Powertrain Efficiency (η)

$\eta = \eta_{FC}\eta_{TD}$

Travel Drivetrain (TD) Efficiency
$\eta_{TD} = \eta_{DC}\eta_{AC}\eta_{MT}\eta_{GB}$

Actuator Drivetrain (AD) Efficiency
$\eta_{AD} = \eta_{DC}\eta_{AC}\eta_{MT}\eta_{HP}$

Regenerative Drivetrain Efficiency
$\eta_{TD}^{R} = \eta_{GB}\eta_{MT}\eta_{AC}\eta_{DC}\eta_{B}$
$\eta_{AD}^{R} = \eta_{HP}\eta_{MT}\eta_{AC}\eta_{DC}\eta_{B}$

Battery Drivetrain (BT, BA) Efficiency
$\eta_{BT} = \eta_{B}\eta_{TD}$
$\eta_{BA} = \eta_{B}\eta_{AD}$

Excavator

Diesel
Powertrain Efficiency (η), Hydraulic Drive
$\eta = \eta_{E}\eta_{HD}$

Travel Drivetrain (TD) Efficiency: Torque Converter, Hydraulic Pump, Main Control Valve, Throttle Valve, Hydraulic Motor)
$\eta_{TD} = \eta_{TC}\eta_{HP}\eta_{MV}\eta_{TV}\eta_{HM}$

Slew Drivetrain (SD) Efficiency
$\eta_{SD} = \eta_{TC}\eta_{HP}\eta_{MV}\eta_{TV}\eta_{HM}$

Actuator Drivetrain (AD) Efficiency
$\eta_{AD} = \eta_{TC}\eta_{HP}\eta_{MV}\eta_{TV}$

Fuel Cell
Powertrain Efficiency (η)
$\eta = \eta_{E}\eta_{ED}$

Travel Drivetrain (TD) Efficiency

$\eta_{TD} = \eta_{DC}\eta_{AC}\eta_{MT}\eta_{GB}$

Slew Drivetrain (SD) Efficiency

$\eta_{SD} = \eta_{DC}\eta_{AC}\eta_{MT}\eta_{GB}$

Actuator Drivetrain (AD) Efficiency

$\eta_{AD} = \eta_{DC}\eta_{AC}\eta_{MT}\eta_{HP}$

Regenerative Drivetrain Efficiency

$\eta_{TD}^{R} = \eta_{GB}\eta_{MT}\eta_{AC}\eta_{DC}\eta_{B}$
$\eta_{SD}^{R} = \eta_{GB}\eta_{MT}\eta_{AC}\eta_{DC}\eta_{B}$
$\eta_{AD}^{R} = \eta_{HP}\eta_{MT}\eta_{AC}\eta_{DC}\eta_{B}$

Battery Powertrain (BT, BS, BA) Efficiency

$\eta_{BT} = \eta_{B}\eta_{TD}$
$\eta_{BS} = \eta_{B}\eta_{SD}$
$\eta_{BA} = \eta_{B}\eta_{AD}$

System Diagrams

Figure A1: tractor system diagrams for diesel and fuel cell systems

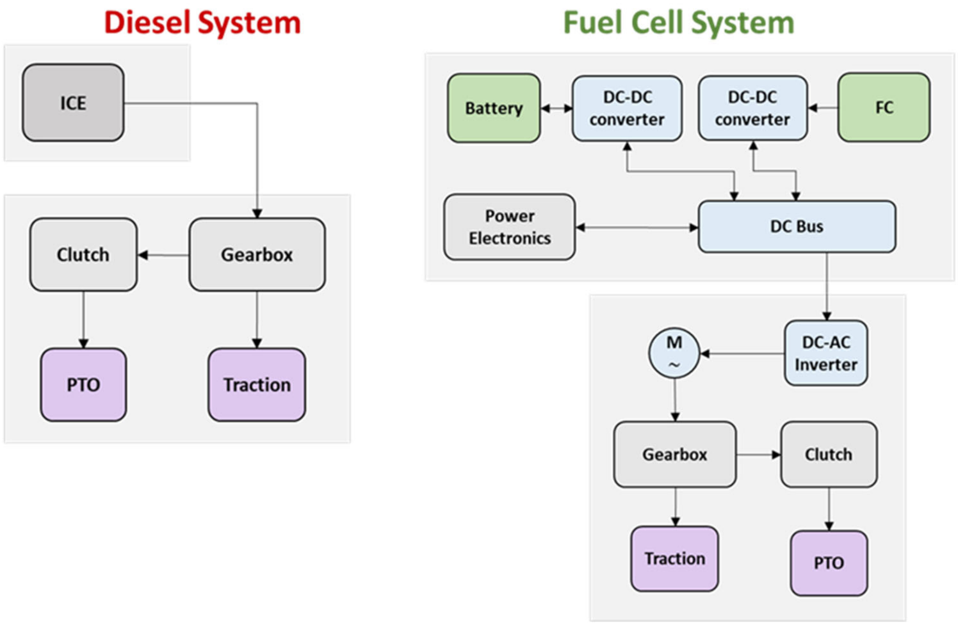


Figure A2: wheel loader diagrams for diesel and fuel cell systems

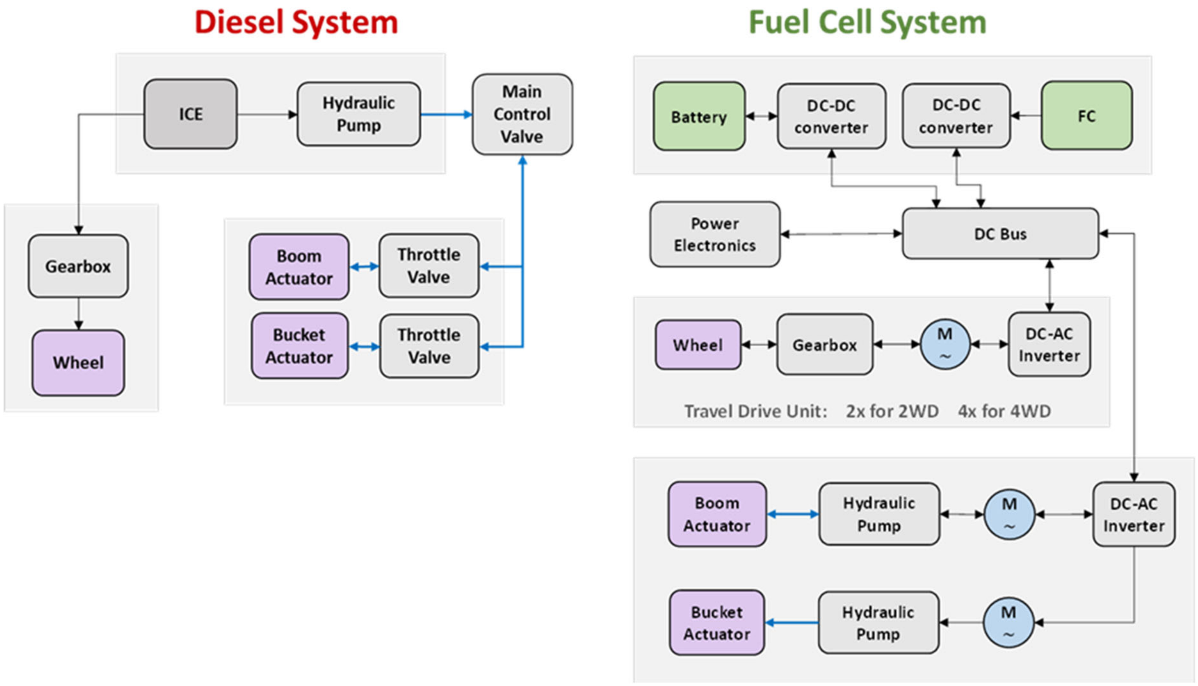
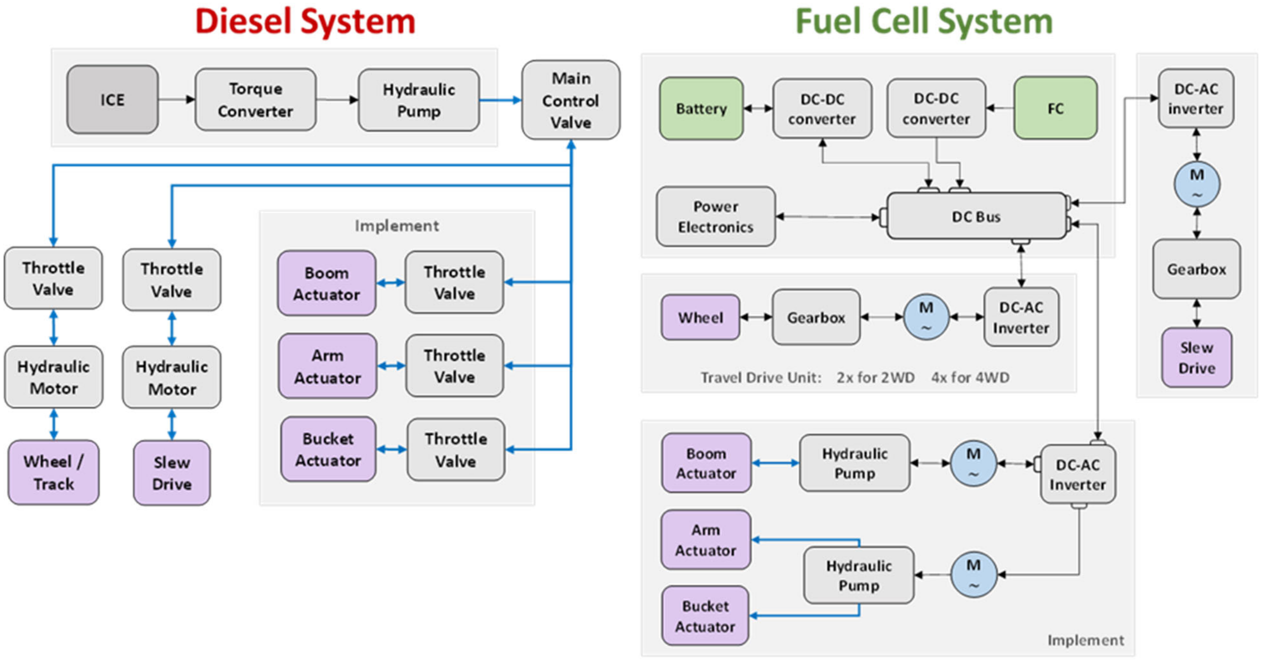


Figure A3: excavator diagrams for diesel and fuel cell systems



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