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Evaluation of Advanced Powertrain Technologies for Large Agricultural Tractors: Insights on Energy Consumption and Life Cycle Environmental Impact

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Abstract

This study aims to assess how alternative electrified powertrain technologies affect energy use for agricultural tractors in the Autonomie simulation tool. The goal of this study is also to assess the feasibility and performance of hydrogen internal combustion engines as a suitable alternative for the agricultural tractor powertrains. The energy consumption and efficiencies of alternative powertrains and fuel options are analyzed and compared across a variety of duty cycles using modeling and simulation methodologies. The considered alternative powertrains are series, parallel, power-split hybrid electric, fuel cell, and battery electric powertrains. The alternative fuel and powertrains are evaluated for their energy efficiency as well as their potential to reduce greenhouse gas emissions and improve overall tractor performance in a variety of agricultural applications.

Following a methodology developed by Argonne National Laboratory and Aramco Americas, the study applied prospective future technology scenarios to the agricultural sector. The simulation results suggest that battery electric powertrains and fuel cell electric powertrains offer long-term greenhouse gas reduction potential when combined with renewable energy production, while alternative powertrains with hydrogen engines can be considered as one of intermediate solutions that offer more practical and competitive operating costs while leveraging existing powertrain component manufacturing infrastructure. The results of this study provide insight into the benefits and challenges of integrating alternative fuel and alternative powertrain technologies into agricultural machinery and point the way toward more sustainable and energy-efficient agriculture.

History

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Introduction

Reducing greenhouse gas (GHG) emissions has become an important consideration in energy and transportation policy worldwide. The IPCC notes the role of GHG mitigation in supporting long-term environmental and economic goals. Various international initiatives promote GHG reductions through improvements in energy efficiency, the adoption of low-emission technologies, and transitions to low-carbon footprint fuels [1].

International policy and regulation increasingly emphasize reducing GHG emissions from human activities. The European Union is leading this effort by implementing comprehensive frameworks such as the European Green Deal, with the goal of achieving emissions neutrality by 2050 and setting stringent interim targets such as a 55% reduction in GHG emissions by 2030 compared to 1990 [2]. China, which accounts for nearly a third of global emissions, has pledged to achieve emissions neutrality by 2060, after peaking its emissions in 2030, underscoring the growing international commitment to reduce emissions [3].

While substantial attention has historically focused on transportation-related emissions from on-road vehicles, industrial processes, and energy production, the off-road sector remains an underrepresented yet significant contributor to global greenhouse gas emissions. Non-road equipment, including construction machinery, agricultural equipment, mining vehicles, and forestry machinery, contributed 219 teragrams of carbon dioxide equivalent greenhouse gases in the US in 2022, which is approximately 10% of on-road transportation greenhouse gas emissions [4]. Despite this substantial contribution, emissions from the off-road sector have received relatively limited attention in climate policy discussions compared to on-road transportation.

The off-road sector's emissions stem primarily from diesel-powered equipment, which contributes significantly to carbon dioxide, particulate matter, and nitrogen oxides. With ongoing urbanization, increasing mechanization in agriculture, and infrastructure development globally, off-road vehicle use and the associated emissions are projected to rise further, underscoring the critical need to address this sector.

Recognizing the potential environmental and public health impacts of off-road sector emissions, various countries have begun incorporating this sector into their emissions reduction strategies. For example, the European Union has introduced stringent regulations, such as Stage V emissions standards, aiming to significantly reduce air pollutants [5]. Similarly, the US Environmental Protection Agency (EPA) has progressively tightened emission standards for off-road engines, aligning them closely with on-road vehicle regulations [6]. China's national policies have increasingly emphasized cleaner machinery through standards such as the Non-road Mobile Machinery (NRMM) Stage IV, progressively tightening emission limits [7].

In the off-road sector, agricultural machinery is a significant contributor to energy consumption. Agricultural field work relies heavily on diesel-powered equipment, such as tractors, combines, and irrigation equipment, which contribute to air pollution and greenhouse gas emissions. Furthermore, greenhouse gases emitted by agricultural operations have a direct impact on the sustainability of the food system. Since agriculture plays a vital role in ensuring food security and also contributes to global warming, reducing greenhouse gases and energy consumption from agriculture is of utmost importance. Therefore, converting agricultural machinery to new, sustainable powertrains can provide significant opportunities for both reductions in greenhouse gas emissions and energy consumption.

To date, research has focused on reducing emissions through increased efficiency of internal combustion engines and incremental technological advancements. However, there is growing recognition that achieving profound energy consumption and emission reductions in the agricultural and off-road sectors will require a dramatic shift to alternative electrification of powertrains or alternative fuels. Technologies such as hybrid electric vehicles, fuel cell electric vehicles, battery electric vehicles, and hydrogen internal combustion engine vehicles can offer promising ways to significantly reduce greenhouse gas emissions and energy consumption.

Battery electric vehicles (BEVs) have high energy efficiency compared to internal combustion engine powertrains. They have significant potential in small power capacity segments, but there are challenges such as the need for high-capacity batteries to meet sufficient operating hours, long charging times, and limited charging infrastructure in agricultural environments [8]. The high initial purchase cost of batteries and concerns about long-term durability make the wide adoption of BEVs in agriculture more difficult.

Fuel cell electric vehicles (FCEVs) use hydrogen to generate electricity, so they do not require battery charging like BEVs. They have quick refueling times and offer higher energy efficiency. This is particularly advantageous in sectors with long operating seasons and high power demands. However, hydrogen production and distribution remain significant barriers to entry, as the cost of producing environmentally friendly hydrogen fuel is high and charging infrastructure is limited in agricultural environments [9]. Fuel cell systems can also be affected by varying temperature and humidity conditions in agricultural environments. However, continued technological advancements are expected to improve their durability and efficiency in these environments [10].

Hydrogen internal combustion engine vehicles (H_2 ICEVs) utilize existing internal combustion engine technology but operate using hydrogen fuel, which can significantly reduce emissions. This could provide a potential transition path by reducing emissions while reusing existing engine manufacturing infrastructure. While nitrogen oxide emissions still exist, recent technological advances have made it possible to reduce nitrogen oxides. It has been demonstrated that compliance with regulations is possible for certain targeted emission tiers even without the need for aftertreatment devices [11]. As with FCEVs, hydrogen production and transportation will present challenges for the mobile off-road sector, but could provide an intermediate transition path to bridge the gap with FCEVs by sharing the same fueling infrastructure.

Research Gap and Scope of the Study

Despite advances in alternative electrified powertrain technologies for on-road vehicles, there is still a significant gap in understanding the comparative performance of alternative powertrains in the agricultural sector. While most studies of on-road vehicles have focused on road transport, there is a need to evaluate how these technologies perform across a range of work cycles and operating environmental conditions for agricultural tractors.

Beligoj et al. [12] conducted a comparative analysis of hybrid electric architectures for specialized agricultural tractors, focusing on parallel, series, and electro-hydraulic configurations. Their findings highlighted the superior peak power performance of parallel powertrains and the fuel savings associated with series configurations, while also introducing the concept of electro-hydraulic configurations for enhanced transmission efficiency. Martelli et al. [13] conducted a life cycle assessment comparing diesel and hydrogen fuel cell–powered orchard tractors, demonstrating significant reductions in environmental impact, particularly in human toxicity and climate change categories, with hydrogen fuel cells. This study emphasized the potential for further improvements with green hydrogen. Varlese et al. [14] validated a predictive energy management strategy for agricultural fuel cell electric tractors, showcasing the benefits of stationary fuel cell operation in reducing degradation and enhancing overall tractor performance. This study highlighted the importance of energy management strategies in optimizing fuel cell efficiency. Jeon et al. [15] analyzed the efficiency of powertrains for internal combustion engine and hydrogen fuel cell tractors, demonstrating the higher efficiency of hydrogen fuel cells compared to traditional engines. Their research suggests the suitability of hydrogen fuel cells for eco-friendly and high-efficiency applications. Mocera et al. [16] explored hybrid electric architectures for agricultural tractors, emphasizing the importance of hybridization factors and the potential for energy efficiency improvements through downsized engines and electric motor assistance.

This study aimed to present a numerical modeling and simulation approach for investigating the potential of alternative electrified powertrain technologies for off-road applications in agricultural tractors, focusing on evaluating powertrain efficiency and energy consumption under a range of operating scenarios. The selected technologies, including hybrid electric vehicles (HEVs), FCEVs, BEVs, and H_2-ICEVs, represent some of the most promising pathways to achieving sustainable off-road operation, using appropriate assumptions and simulation methods. In addition to quantifying energy consumption comparisons across a range of duty cycles, this study aims to provide insight into the economic feasibility and greenhouse gas emissions of each alternative powertrain. Furthermore, by evaluating these technologies in a realistic operating environment, we aim to contribute to the broader goals of sustainable agricultural development and reduced energy consumption and emissions in the off-road sector.

Materials and Methods

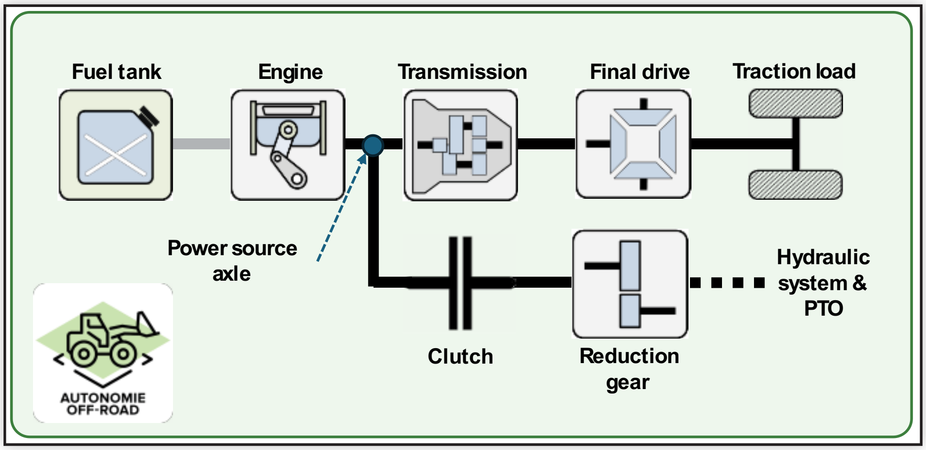
Baseline Model Development and Validation

The Autonomie software was used for tractor model development and simulation execution across various duty cycles. Developed by Argonne National Laboratory, Autonomie is a vehicle system simulation tool designed to assess the energy consumption, performance, and cost of advanced powertrain technologies for a wide range of vehicle types. Simulations and model configurations were executed using Argonne National Laboratory's next-generation advanced model–based engineering resource (AMBER), a dedicated interface developed as a universal graphical user interface for various simulation applications [17]. AMBER enables seamless integration with multiple software tools developed by Argonne to facilitate workflow execution. All simulations were conducted using AMBER, where model development was performed within Autonomie, while configuration and parameterization were carried out in AMBER.

The baseline diesel engine agricultural tractor model was simulated using measured traction loads and vehicle speed to analyze the driving duty cycle. The simulation results were then compared and validated against test data from the Nebraska Tractor Test Reports.

Baseline Diesel Engine Model The early version of the agricultural tractor model, which applies a distance-based simulation approach, was developed in collaboration with the University of Helsinki, focusing on previous studies that established baseline tractor models and explored tractor electrification [18]. The previously developed simulation model was designed for an agricultural tractor with a rated power capacity of 300 horsepower. For this study, the tractor model was updated to represent a large-sized

FIGURE 1 Powertrain configuration of baseline tractor model in Autonomie.



tractor, featuring an engine with a rated power of 380 horsepower [19]. Additionally, operational cycle data measured from agricultural field tests were incorporated to develop a more representative duty cycle.

The baseline powertrain model was parameterized based on the performance of a conventional tractor equipped with a diesel engine and transmission, as illustrated in Figure 1 and summarized in Table 1.

Operating Cycles Agricultural tractors operate in variable working environments, performing a wide range of complex tasks and being controlled by operators with different levels of expertise. Due to the absence of a standardized duty cycle, capturing overall dynamics and fuel consumption rates can be challenging. However, a duty cycle that considers operation under various loads from an engine perspective can be examined.

In a previous study [18], experimental measurements were conducted at the Viikki Research Farm of the University of Helsinki to collect data for evaluating various levels of load resistance during the operation cycle. This experiment utilized a conventional agricultural tractor

TABLE 1 Conventional tractor powertrain and general technical specifications.

Component	Description
Diesel engine	8.7 L 6-cyl diesel, rated power 320 kW
PTO	Rated power 307 kW
Transmission	Four-wheel drive, eight-speed dual-clutch transmission (DCT) with three ranges
Front axle	bevel set ratio of 2.48:1 and planetary gear ratio of 6:1
Rear axle	bevel set ratio of 3.28:1 and planetary gear ratio of 6:1
Tires	front: 420/85R34, rear: 480/80R50
Weight	11,880 kg

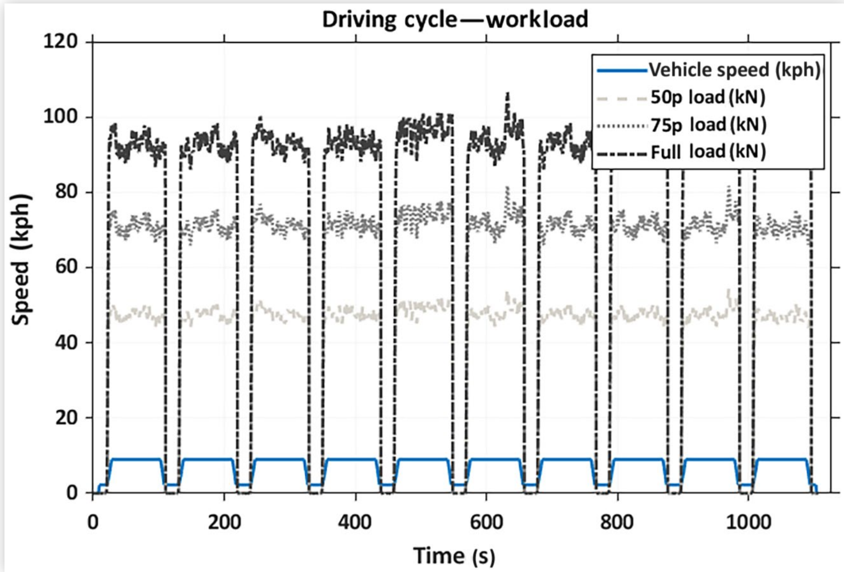
(Valtra N141) and a towing plow. Three levels of load resistance—light, medium, and high—were defined for a single tillage cycle with a target speed of 8 km/h. The load resistance was applied only when the machine was in operation.

Based on the measured tillage cycles, the load resistance was adjusted using the drawbar performance data from the Nebraska Tractor Test Report [20] for a large tractor, specifically the New Holland T8 435 model, which has a similar engine capacity to the base tractor model selected for this study. The adjusted tillage cycle is illustrated in Figure 2, showing the load resistance of the large tractor with different levels of force at the target speed (about 9 km/h).

Fuel Consumption Verification The validation of the baseline agricultural tractor model was conducted based on the Nebraska Tractor Test Report [20] for three different load resistances. As described on the duty cycle, drawbar pull loads of approximately 46.5, 69.6, and 92.7 kN were applied, and the energy consumption was measured while maintaining a tractor speed of around 8 km/h. These values were then compared with the measured test data. Table 2 presents a comparison between the simulation results and the reported energy consumption values. According to the results, the fuel consumption from the duty cycle simulation measured 11.7, 15.0, and 17.7 gal/h, respectively, showing error within 4%, a difference of 0.9%, −3.2%, and −3.8%, respectively, compared to the test data.

Figure 3 displays the engine operating points when drawbar pull loads of 46.5, 69.6, and 92.7 kN are applied, showing that the engine operates at about 2000–2050 rpm. The fuel consumption results in the test report are also compared to the fuel rate under conditions where the engine operates at around 2000 rpm. The simulation results show that the engine operates in a similar range to the engine operation points in the rest data report.

FIGURE 2 Tillage cycle with three defined load resistance profiles for the large-sized tractor.



Electrified Powertrain Model Development

Using the developed baseline agricultural tractor model, hybrid electrified hydrogen internal combustion engines, fuel cell electric, and battery electric powertrains were modeled and simulated based on the developed duty cycle. The simulations for the alternative powertrain models were conducted by applying different workload conditions to evaluate energy consumption and operational performance.

Hydrogen Internal Combustion Engine In this study, the hydrogen engine developed by KEYOU GmbH [21] was used as a reference, and to match the diesel engine's maximum power output, linearly scaled the hydrogen engine's maximum torque curve and fuel rate map. This engine employs a lean-burn combustion strategy with exhaust gas recirculation (EGR) to achieve high power output while minimizing nitrogen oxides emissions. The concept includes port fuel injection, optimized turbocharging, and a selective catalytic reduction with hydrogen, enhancing both efficiency and performance. The study has shown the crucial role of EGR in improving combustion stability, increasing efficiency, and enabling high power density. Based on this engine design and performance, the output was scaled to achieve a maximum power of 320 kW at 1900 rpm, with an effective torque of approximately 1670 Nm. Figure 4 presents the scaled efficiency map of the hydrogen internal combustion engine applied in this study.

TABLE 2 Fuel consumption comparison of test data and Autonomie simulation results.

Fuel consumption (gal/h)	Simulation	Test [20]	Error (%)
50% of pull (46.5 kN)	11.7	11.6	0.9
75% of pull (69.6 kN)	15.0	15.5	−3.2
Power of pull (92.7 kN)	17.7	18.4	−3.8

Fuel Cell System The proton-exchange membrane fuel cell stack considered in this study was designed to meet the requirements of heavy-duty trucks, incorporating liquid stack cooling, air management, and active fuel recirculation. The complete model equations and assumptions for the system model can be found in previous publications [22, 23], and an average efficiency map was used by integrating multiple performance curves. The fuel cell system is sized to meet the vehicle's power requirements at end-of-life (EOL), ensuring that the application's demands are met throughout the vehicle's lifespan. The modeled efficiency curve of the fuel cell system is shown in Figure 5.

Compared to diesel or hydrogen internal combustion engines, fuel cells exhibit a greater efficiency difference at lower engine loads. However, the efficiency of ICEs increases as engine load rises, since more fuel is burned, leading to higher engine temperatures and improved system efficiency.

Hybrid and Electric Powertrain Tractor Models The advanced powertrain options in this study build upon a baseline conventional diesel engine (Conv) and include HEVs with an H_2-ICEV, an FCEV, and a BEV. The conventional model uses a diesel engine as the sole power source, combined with a transmission system. The parallel HEV (Par HEV) integrates an electric motor into the conventional drivetrain alongside a hydrogen engine. The

FIGURE 3 Diesel engine operation points for tillage cycle with 50%, 75%, and power of pull load.

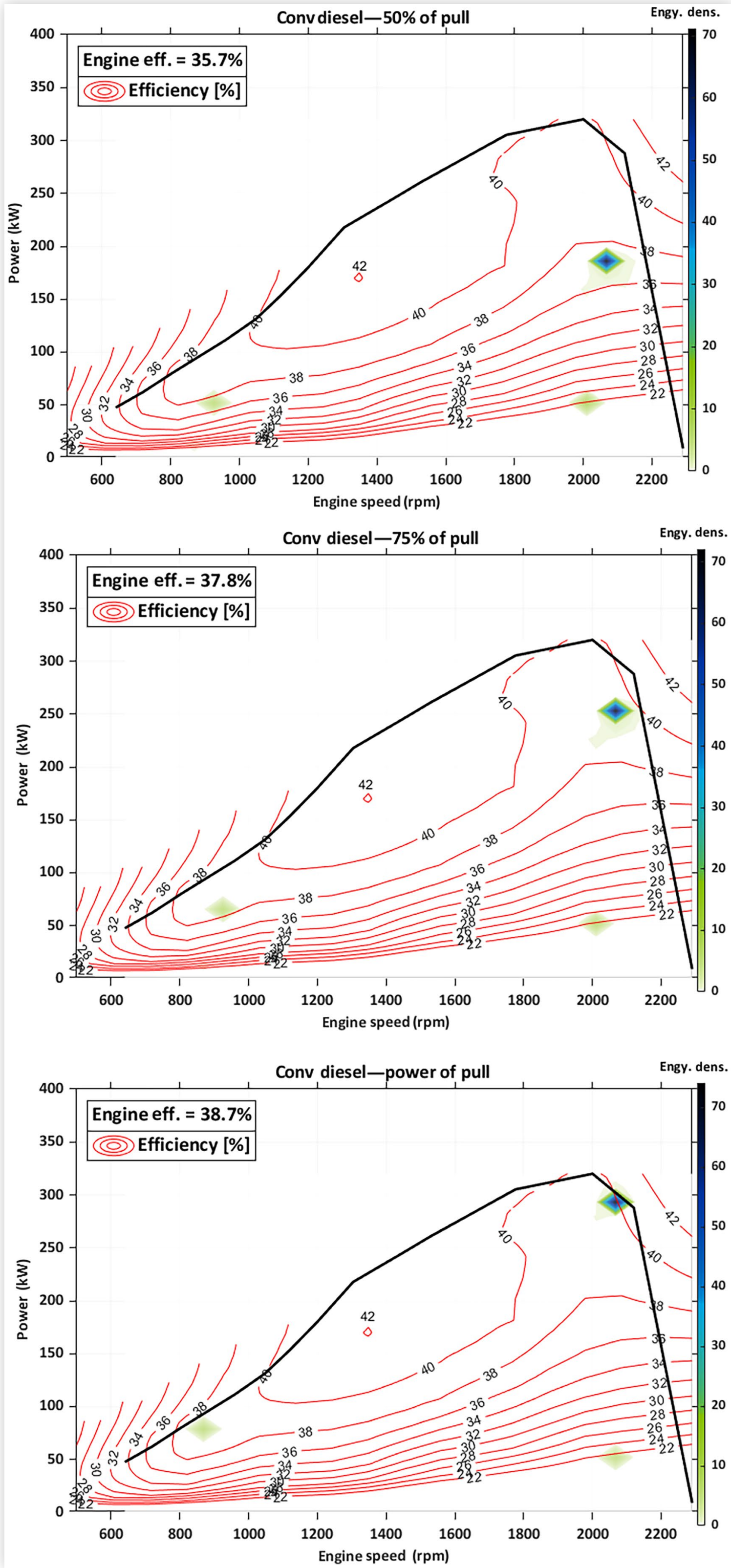


FIGURE 4 Effective efficiency map for hydrogen internal combustion engine.

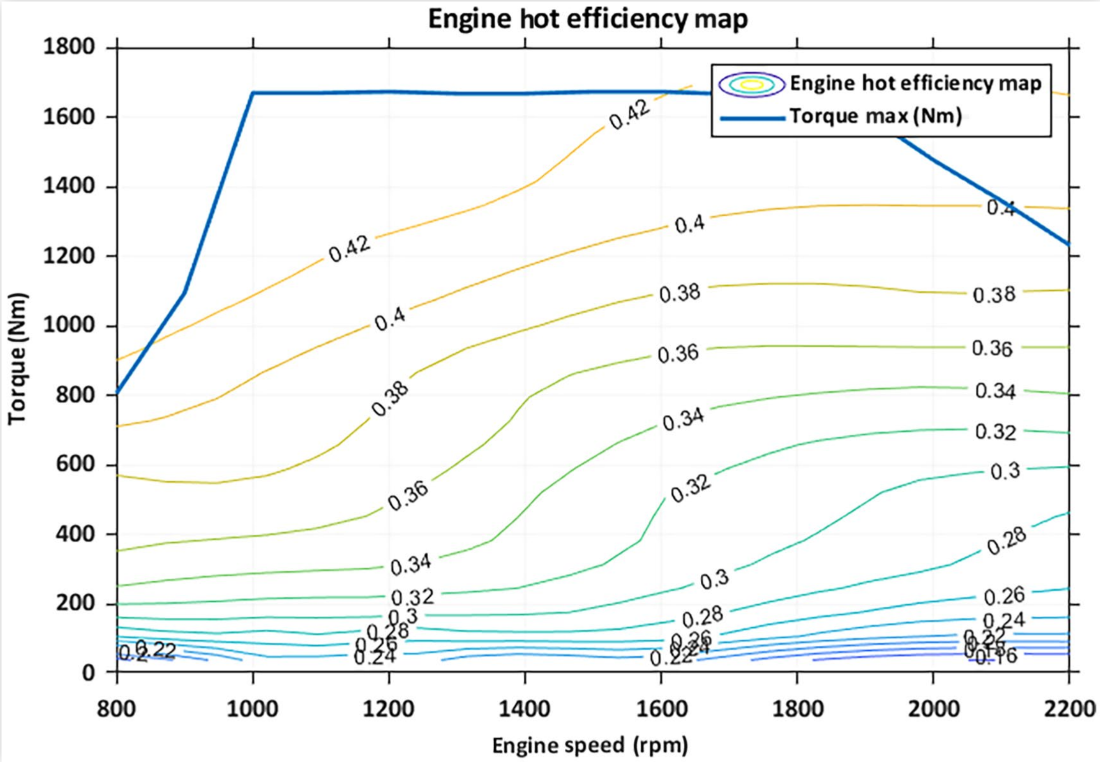
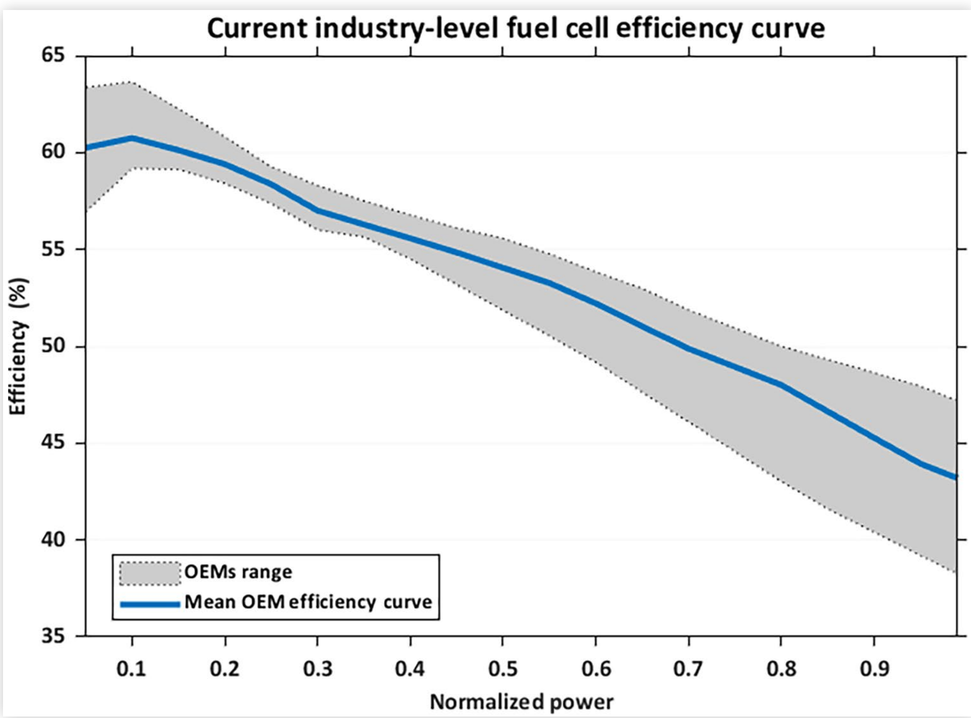


FIGURE 5 Fuel cell system efficiency curves.



series HEV (Ser HEV) replaces the mechanical connection between the engine and wheels with a hydrogen engine driving a generator, which powers an electric motor coupled with a three-speed gearbox. The power-split HEV (split HEV) utilizes a planetary gear system and two electric motors, allowing the engine to operate independently from the drive shaft, enabling an electric continuously variable transmission (CVT) [24].

One of the primary focuses of this study is to evaluate how hybridized powertrains can enhance agricultural tractor performance, particularly through optimized control strategies and powertrain configurations. To achieve this, hybrid powertrains have been carefully calibrated to maximize efficiency and operational effectiveness in agricultural applications.

Both the FCEV and BEV tractor models are equipped with a fully electric powertrain consisting of a battery, one electric drive motor, and a three-speed gearbox. In the HEVs and FCEV models, the hydrogen engine or fuel cell stack serves as the primary power source, supplemented by a small battery pack for power load leveling. The battery electric tractor includes a large-capacity energy-type battery pack as its energy storage system.

All electric simulation models use a lithium-ion battery model as the energy storage unit. Figure 6 illustrates the powertrain layouts of various tractor models available in Autonomie software.

Model Parameters

The sizing of alternative powertrain components was determined to ensure at least equivalent traction performance compared to the baseline diesel engine–powered tractor model. Additionally, the fuel or energy capacity of the primary power source was sized to enable a minimum of approximately 10 h of operation without refueling or recharging [25], based on the medium workload profile defined in the duty cycle described above.

As a result, considering the vehicle's total weight, the hydrogen capacity or hydrogen storage tank size for hydrogen engine and fuel cell hybrid vehicles was determined. For the battery electric powertrains, two different models were considered:

- BEV short-range (BEV SR): Battery capacity was determined to match the weight of the baseline diesel engine tractor.

FIGURE 6 Hybrid and electric powertrain layouts of the modeled tractors in Autonomie.

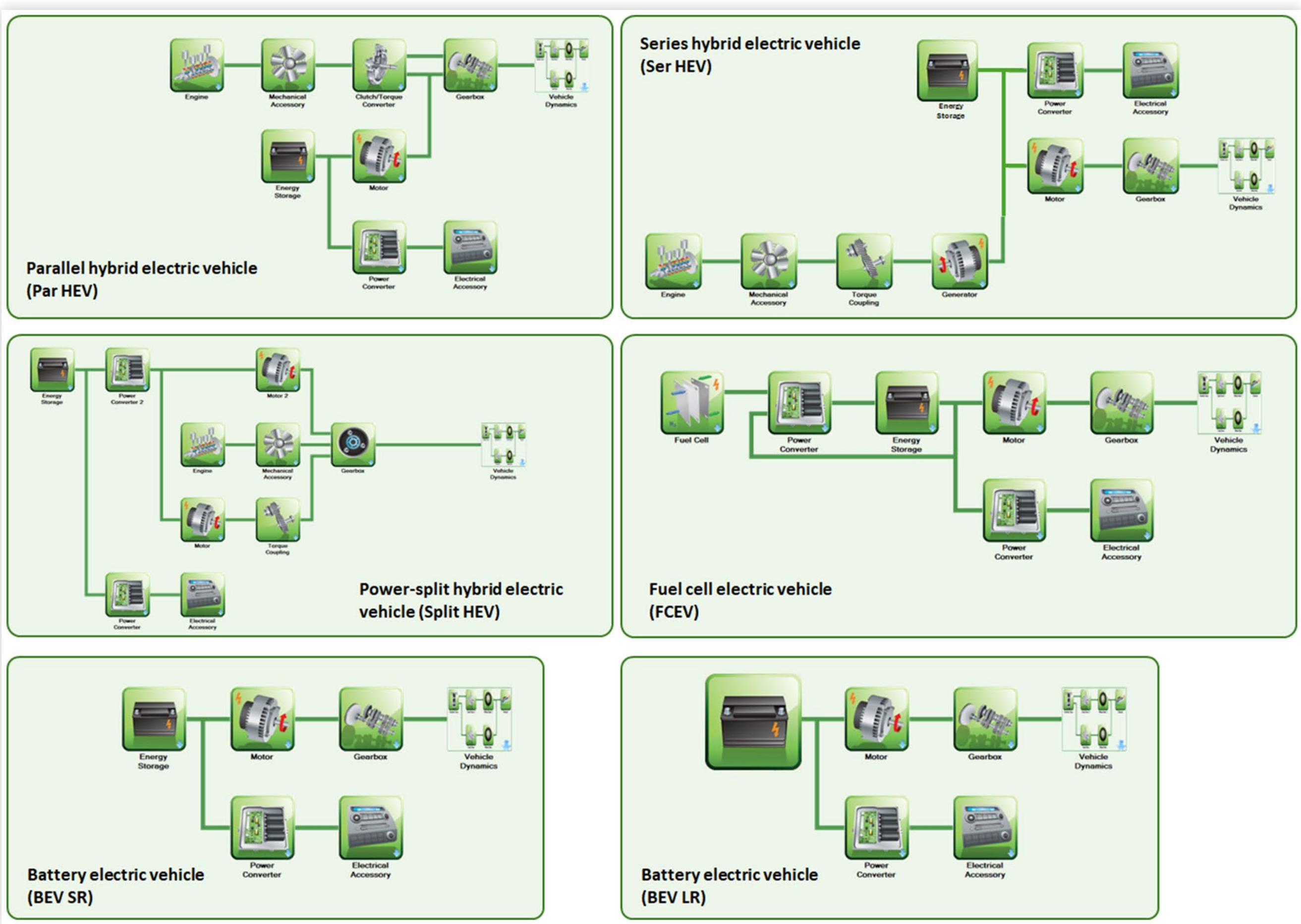
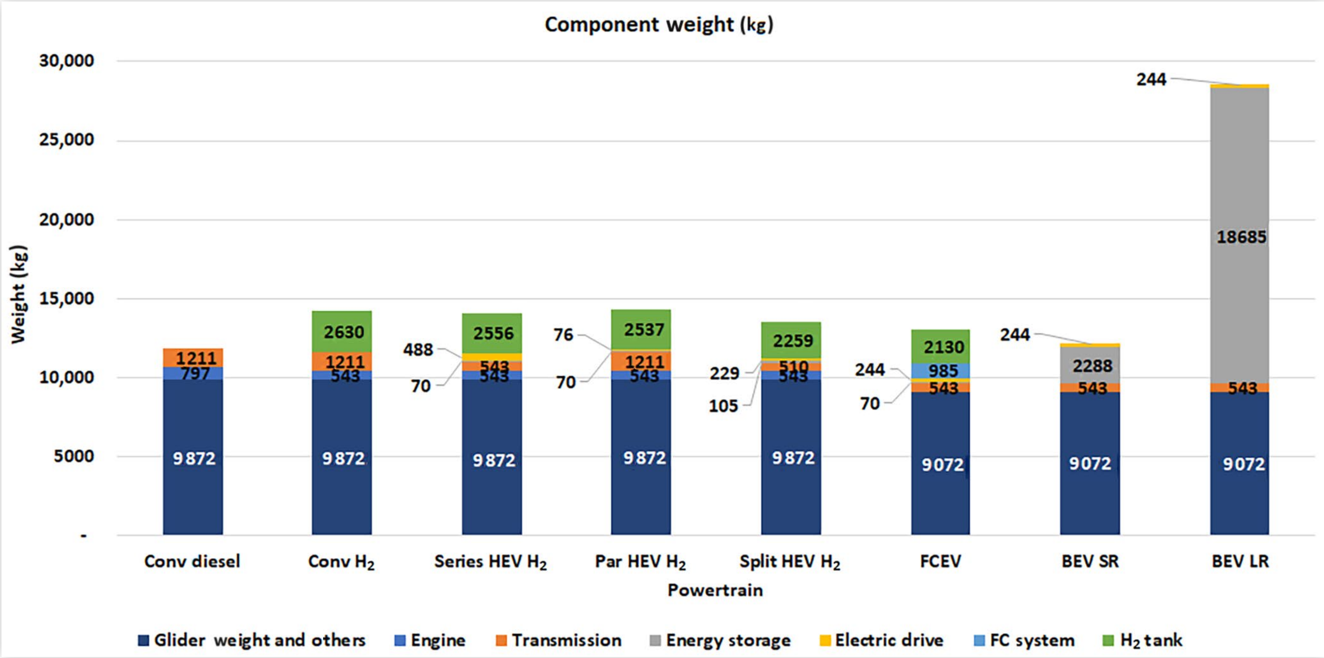


FIGURE 7 Vehicle-specific component weights for each powertrain option.



- BEV long-range (BEV LR): Battery capacity was designed to enable at least 10 h of operation, similar to the baseline diesel engine tractor's runtime.

The component weights for each powertrain option are shown in Figure 7. The hydrogen storage tank weight per unit of hydrogen capacity was assumed to be 18.5 kg/kg of H_2, and the energy battery weight was estimated using an energy density of 150 Wh/kg, and the power battery weight was estimated using a power density of 3000 W/kg [26]. For powertrains using hydrogen as the primary fuel, additional hydrogen storage tanks are required, leading to an approximate weight increase of 2500 kg. For a fully battery electric powertrain, a large-capacity battery (~2.3 MWh) was needed to maintain continuous operation throughout a full workday, similar to a diesel engine powertrain. As a result, compared to the ICE powertrain, the total weight of the tractor with the BEV long-range powertrain increases significantly by about 16,000 kg.

Table 3 provides a detailed overview of the powertrain specifications for the alternative powertrain tractor models equipped with a hydrogen engine. The general technical specifications include the front and rear axle gear reductions and tire sizes for all tractor models. The parallel, series, and power-split hybrid configurations, as well as the conventional powertrain adapted with a hydrogen engine, all utilize hydrogen engines. The parallel hybrid features a dual-clutch transmission similar to conventional tractors, while the power-split hybrid uses a planetary gear system to maintain equivalent driving performance.

TABLE 3 Specifications of each powertrain for the large-sized tractor models.

Component	Conv diesel	Conv H_2	Par HEV H_2	Ser HEV H_2	Split HEV H_2	FCEV	BEV SR	BEV LR
Engine/fuel cell stack	Diesel engine: peak power 320 kW peak torque 1642 Nm	H_2 engine: peak power 320 kW peak torque 1672 Nm	H_2 engine: peak power 320 kW peak torque 1672 Nm	H_2 engine: peak power 320 kW peak torque 1672 Nm	H_2 engine: peak power 320 kW peak torque 1672 Nm	Fuel cell stack: peak power 320 kW	—	—
Transmission	8 speeds with 3 ranges	8 speeds with 3 ranges	8 speeds with 3 ranges	3 speeds gearbox	Planetary gearset	3 speeds gearbox	3 speeds gearbox	3 speeds gearbox
Battery configuration	—	—	240 cells in pack, 6.4 kWh	240 cells in pack, 6.4 kWh	360 cells in pack, 9.6 kWh	240 cells in pack, 6.4 kWh	2304 cells in pack, 286 kWh	17,856 cells in pack, 2.3 MWh
Electric motor	—	—	Peak power 100 kW	Peak power 320 kW	Peak power 150 kW × 2	Peak power 320 kW	Peak power 320 kW	Peak power 320 kW
Test weight	11,880 kg	14,255 kg	14,309 kg	14,071 kg	13,517 kg	13,043 kg	12,147 kg	28,544 kg

All hybrid models are equipped with relatively small battery packs, as they are primarily used for reducing peak power demands and storing regenerated braking energy. For split HEV, there are specific speed ranges where system efficiency significantly drops due to power circulation. To achieve performance comparable to other powertrains in these ranges, a relatively larger battery was selected. For powertrains driven directly by an electric motor, an evaluation of typical field operations confirmed that a three-speed gearbox is sufficient to handle common agricultural tractor tasks while providing high energy efficiency. The electric drive motor was dimensioned according to the performance requirements set by the baseline conventional tractor. In this study, a rule-based approach was used for sizing electrification components. However, it can be conducted to evaluate how the size of components affects energy efficiency and operational performance based on various duty cycles and workloads.

Results

Driving Performance

The simulation results were analyzed using the Autonomie tool. Overall, all simulations were conducted successfully, and it was confirmed that all tractor models properly tracked the vehicle target speed and drawbar pull loads specified by the given duty cycles. The load resistance of the tillage cycle had a slight impact on driving dynamics, which will be a focus for future research when developing a more advanced driver model for agricultural tractors.

Figure 8 illustrates the fuel or electric power input required for each powertrain when executing the tillage cycle under medium workload conditions. Due to differences in energy transfer efficiency across powertrains under the same medium workload, variations in input power were observed. For the split HEV, its ability to operate the engine within a more efficient range resulted in power consumption similar to the fuel cell powertrain. Notably in the BEV, the higher efficiency of the battery and motor compared to internal combustion engines or fuel cell stacks led to a significant reduction in input power. However, from an energy life cycle perspective, BEV efficiency should also account for electricity generation efficiency, which typically ranges from 30% to 50%, depending on the energy mix [27]. This factor was not included in this study but is crucial for a comprehensive evaluation of overall energy efficiency.

The operating points of diesel and hydrogen engines, as well as the fuel cell, were compared in Figure 9, along with their efficiency values under medium workload conditions during the tillage cycle.

For the conventional powertrain and parallel hybrid powertrain, both diesel and hydrogen engine configurations share the same transmission, resulting in similar

FIGURE 8 Power values of each source power under medium workload.

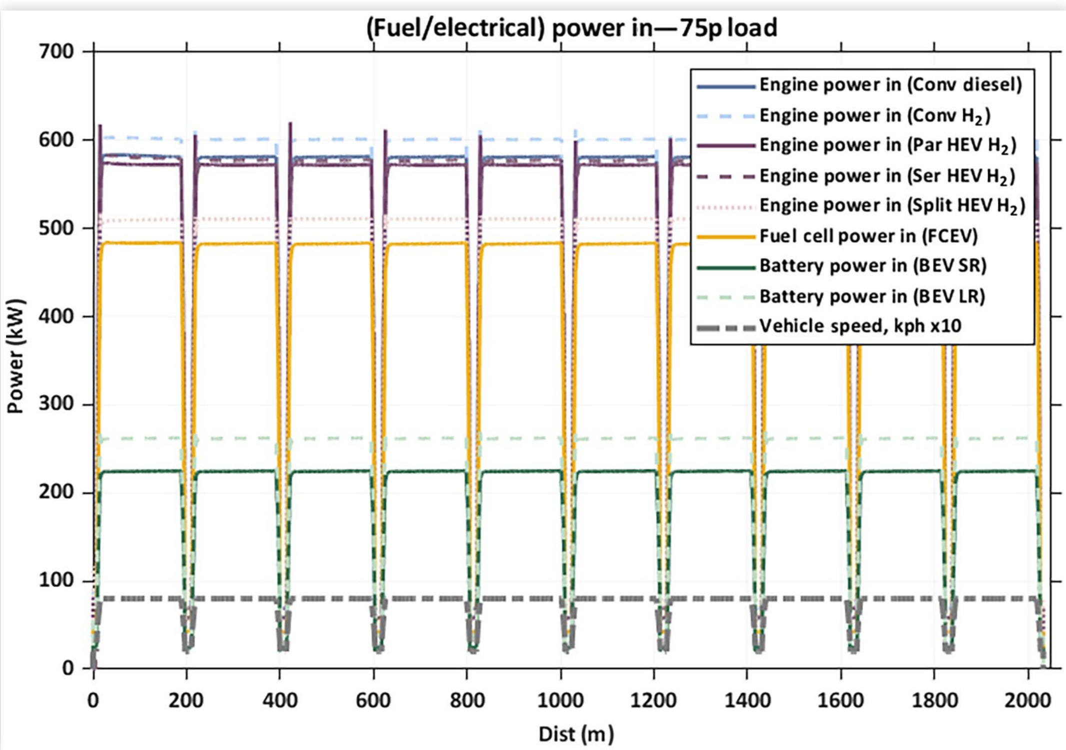


FIGURE 9 Operation points of internal combustion engines and fuel cell systems under medium workload.

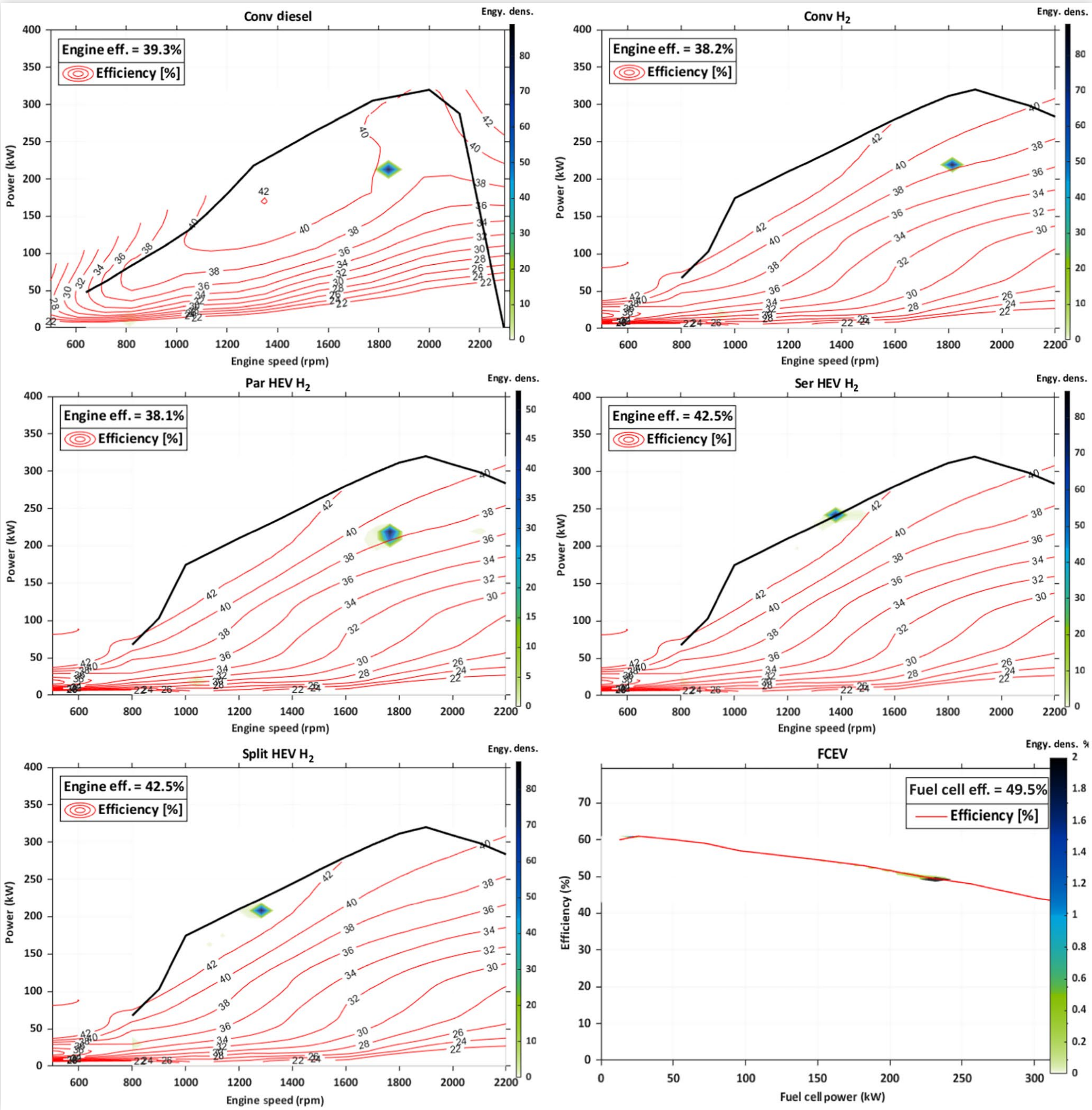
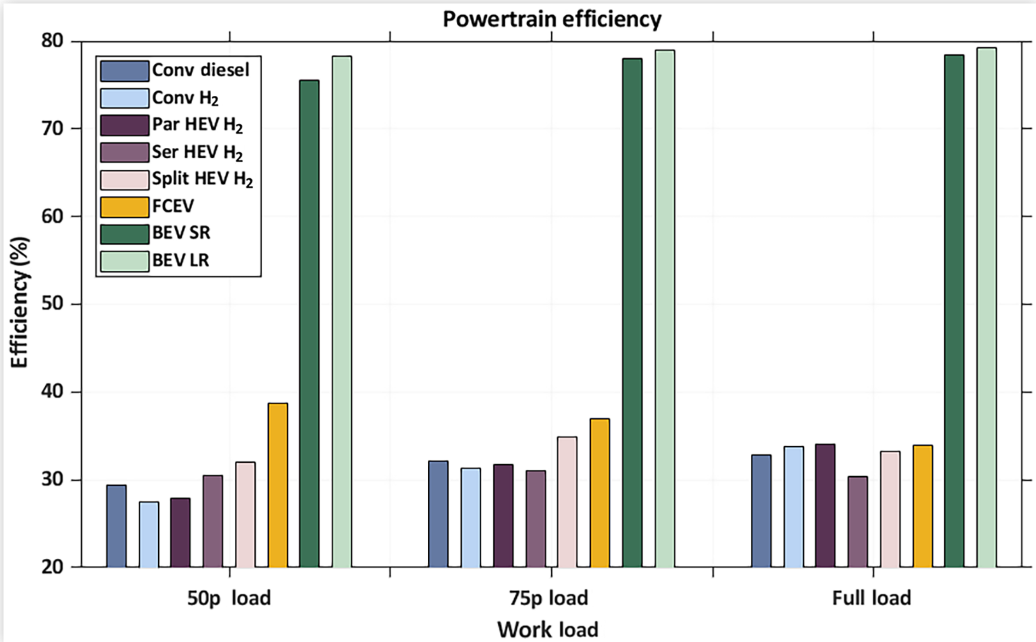


FIGURE 10 Powertrain efficiency for all tillage cycles.



engine operating points. However, the diesel engine operates at a slightly higher efficiency compared to the hydrogen engine for medium workload. In contrast, the series hybrid and power-split hybrid offer the advantage of decoupling the engine operating point from the drive axle, allowing the hydrogen engine to be controlled and operated within a more efficient operating region (about 42%).

For the fuel cell system, it operates in a mid-to-high power demand region, which results in lower efficiency compared to its low-power, high-efficiency zone. However, despite this, the fuel cell still achieves a high efficiency of approximately 50%, which is higher than that of internal combustion engines.

Figure 10 provides a summary of energy transmission efficiency from the power source to the drive axle for each powertrain under different workloads. Due to the variations in energy transmission efficiency across powertrains at the same workload, differences in input power were observed, as shown in Figure 8.

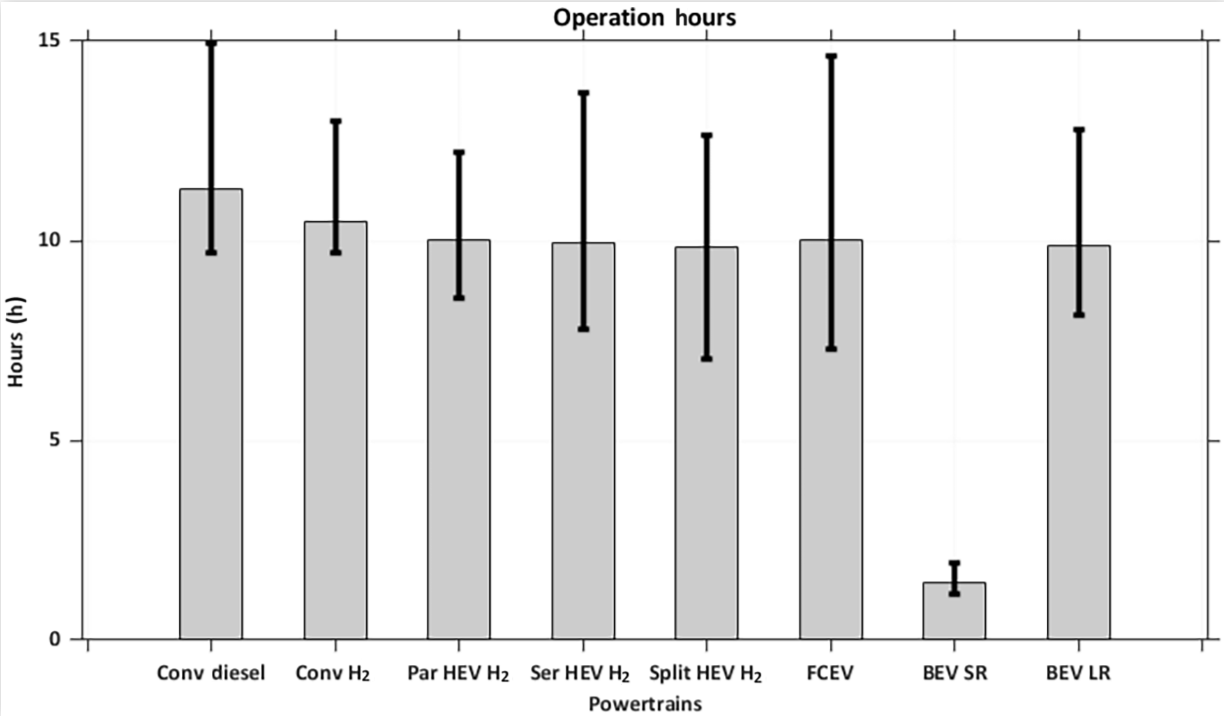
For hydrogen engine powertrains, the overall powertrain efficiency at 50% workload is lower than that of the diesel engine due to the lower efficiency of the hydrogen engine's operating point. However, at 75% workload (medium workload), the efficiency becomes comparable to that of the diesel engine. At full workload, the higher engine efficiency of the hydrogen engine results in a powertrain efficiency that surpasses both diesel engine powertrains and fuel cell powertrains.

In the parallel hybrid powertrain, the powertrain efficiency is slightly higher than that of the conventional powertrain. Meanwhile, in the series hybrid powertrain, the ability to operate the engine at a high-efficiency point enables high powertrain efficiency at 50% workload. However, as the workload increases, power conversion losses cause a significant reduction in powertrain efficiency. Similarly, in the power-split hybrid powertrain, the advantage of controlling the engine to operate at a highly efficient point results in high powertrain efficiency at low workloads. However, as the workload increases, power conversion losses lead to a decline in powertrain efficiency, similar to the series hybrid system.

For BEVs, the BEV long-range demonstrated relatively higher efficiency compared to the BEV short-range powertrain. Although the BEV long-range consumes more absolute energy due to the heavier vehicle weight from the larger battery capacity, the electric motor operates in a more efficient high torque range. Additionally, the battery is used at a higher SOC level, which has relatively lower internal resistance.

Based on the simulation results, we estimated the operating time achievable on a single refueling or charging. We assumed a fuel tank size of approximately 500 L for the conventional diesel tractor, and for the alternative powertrains, as mentioned earlier, the fuel or energy capacity of the primary power source was sized to enable at least about 10 h of operation. The variation in operating time across different workloads is shown in Figure 11. The bars represent the medium workload case, and the error bars indicate the results for the light and full workloads. It is evident that achievable operating time varies significantly across all powertrains depending on workload. The conventional diesel tractor, as is typical for today's agricultural tractors, offers very long operating times without refueling. For the BEV short-range, because the battery capacity was set to be comparable to the total weight of

FIGURE 11 Calculated variation in operating time for all tillage cycles.



the conventional tractor, the operating time is very short, about 2–3 h. For the BEV long-range, adding battery capacity provides about 10 h of operation, though accessing high power charging may be challenging in agricultural environments.

Figure 12 shows the battery state of charge (SOC) trajectory for simulations under medium workload for HEV powertrains, including the FCEV powertrain. Since the tractor model performs plowing operations at low speeds below 10 kph, most of the required power is provided using engine or fuel cell power, except for acceleration, where the battery supports. During the operation, the battery is recharged, and by the time the operation is completed, the total net energy of the battery remains at a level similar to the initial SOC (within ±1%).

Energy Consumption

Figure 13 presents the energy consumption of each powertrain under different workloads. Since energy consumption was calculated based on energy usage within the vehicle, charging losses were not considered. To compare energy consumption across different cycles, values were expressed in kWh/km. While this unit may not be the most relevant in the context of agricultural operations, it allows for direct comparison of results obtained from various simulations. Energy consumption increased rapidly as a function of workload in both tillage cycles, though the increase was less pronounced in the battery electric powertrain models.

The potential for reducing energy consumption using alternative fuels and powertrains is illustrated in Figure 14. The results clearly indicate that battery electric powertrains offer significant potential for energy reduction. However, this energy consumption value represents the vehicle-level energy consumption, and future analysis should consider electricity generation efficiency. For the hydrogen engine in a conventional powertrain, energy consumption was higher at 50% and 75% loads, but similar to conventional diesel powertrains only at full load. However, with the parallel hybrid powertrain, energy consumption could be further reduced to 2%. For the series hybrid powertrain, energy consumption was similar to conventional diesel powertrains only at 50% load, while higher loads led to increased energy consumption due to reduced powertrain efficiency. The fuel cell hybrid powertrain demonstrated an energy consumption reduction potential ranging from 4.6% to 22%, depending on workload conditions.

Distribution of Losses

To evaluate the energy loss for the alternative electrified powertrain, the energy loss of each powertrain component was calculated for various workloads. Figure 15 shows the powertrain loss distribution of the tractor models in the tillage cycle, and the total bar length indicates the total energy consumption in kWh. For the powertrain with an internal combustion engine, the main energy loss occurs from the heat loss of the diesel or

FIGURE 12 Battery SOC trajectory of HEVs under medium workload.

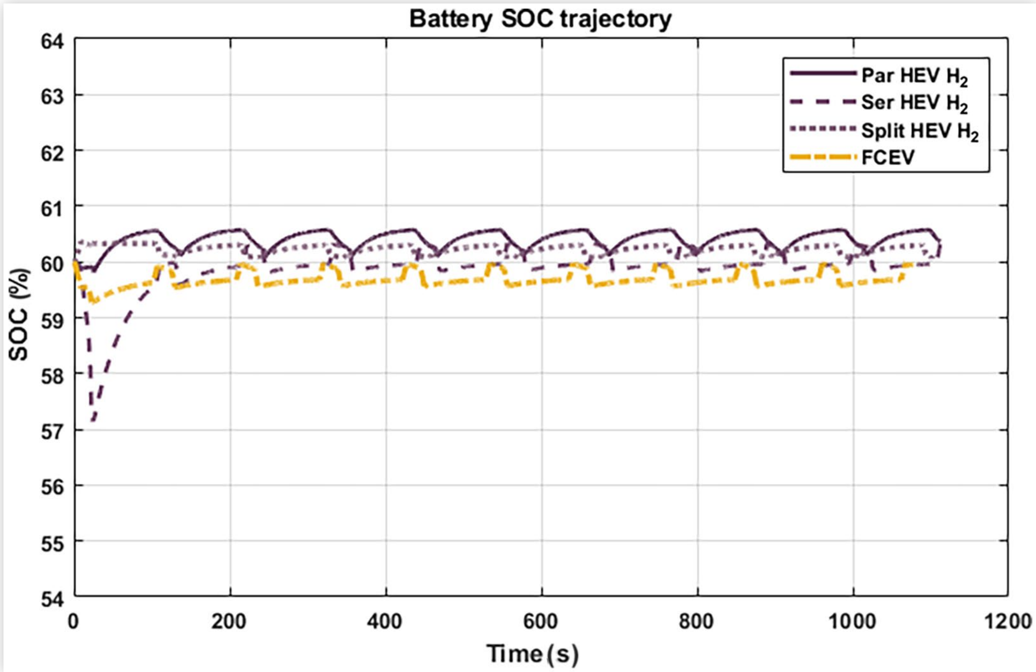


FIGURE 13 Energy consumption in kWh/km for all tillage cycles.

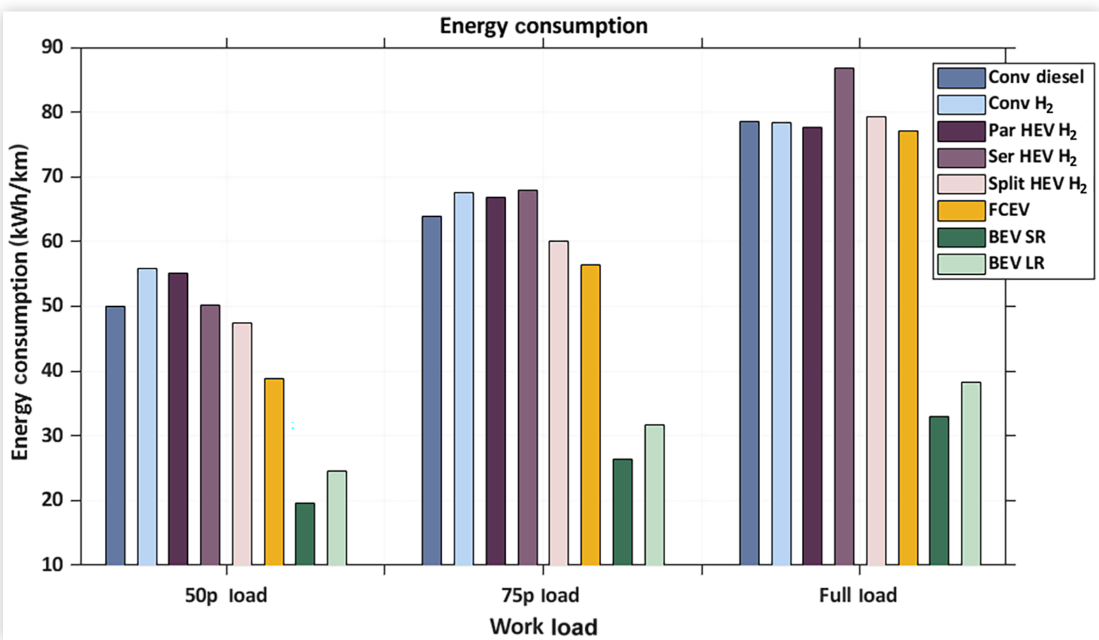


FIGURE 14 Potential for reducing energy consumption in the tillage cycles.

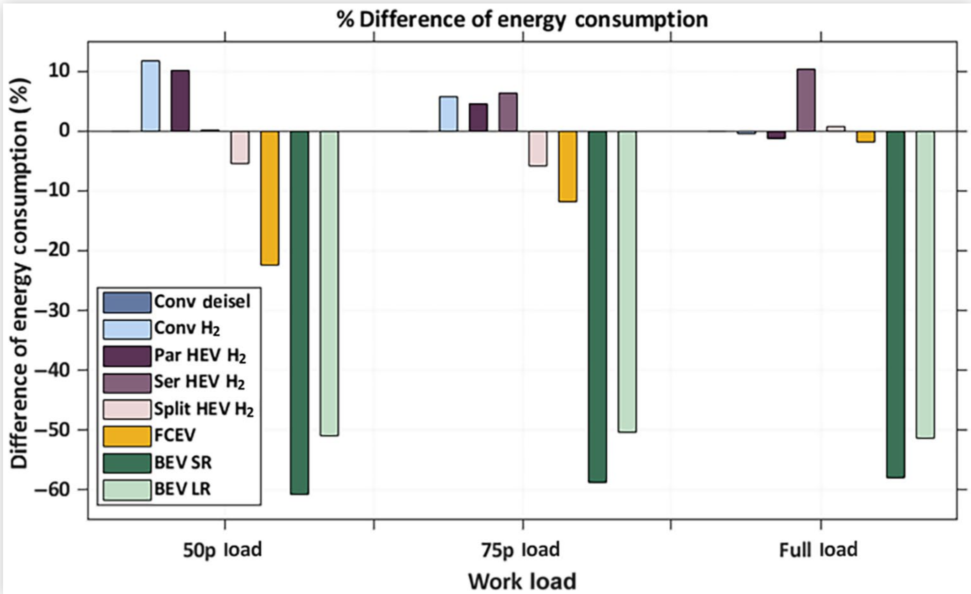
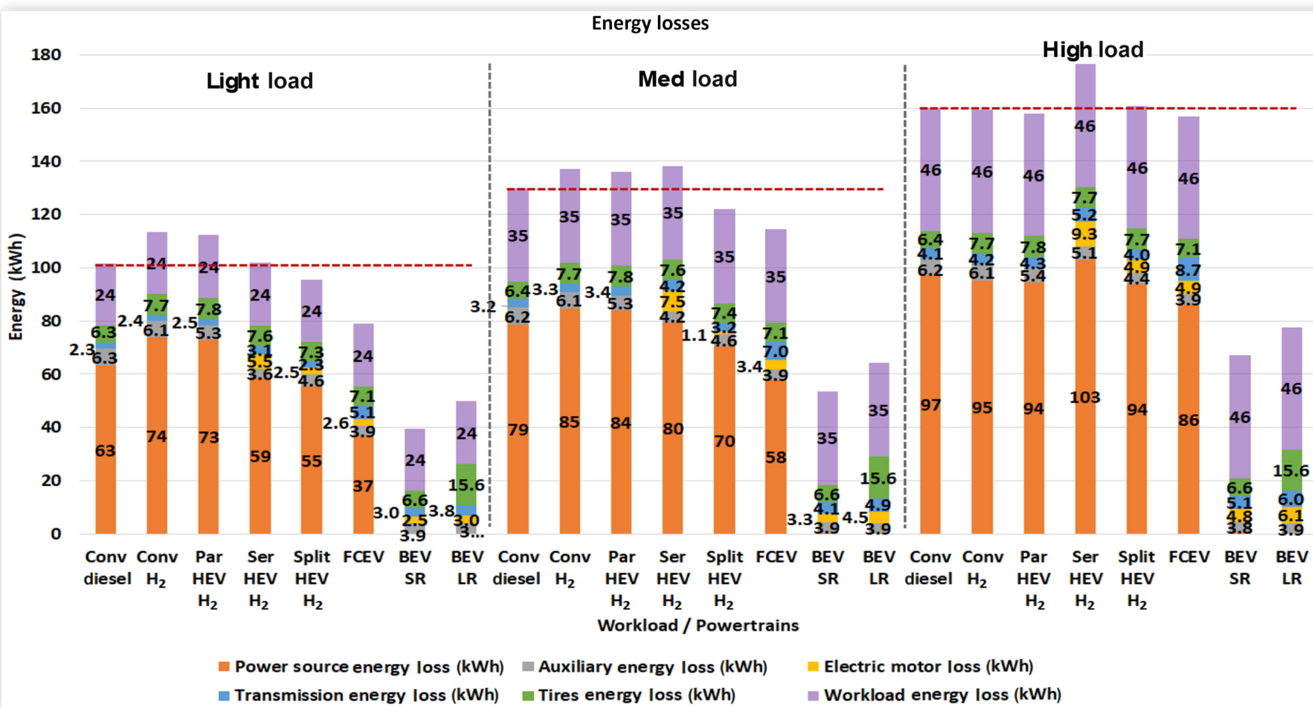


FIGURE 15 Distribution of losses under light/medium/high workload.



hydrogen engine as the power source. Depending on the workload, the energy loss from the power source in the total energy consumption is about 61%–62% for the diesel engine powertrain, 60%–65% for the conv powertrain with the hydrogen engine, 57%–65% for the hybrid powertrain with the hydrogen engine, and about 46%–55% for the fuel cell powertrain.

In cases where the power of the power source has to be converted to another form, such as in Ser HEV, split HEV, or FCEV, the transmission and electric motor loss shown in the yellow and blue bar accounts for a relatively large portion of the total energy loss. Auxiliary load losses, which are used for cooling or lubricating the powertrain, also contribute significantly to the total energy loss, especially compared to transmission losses. As the workload increases during the tillage cycle, the total energy consumption increases significantly, and the energy of the workload shown in the purple color bar is confirmed to be the same for each powertrain.

For powertrains equipped with hydrogen engines or battery powertrains, the increased weight from hydrogen tanks and batteries leads to greater tire losses, including rolling resistance and friction loss, compared to conventional diesel powertrains

Levelized Cost of Operation

Despite the benefits of high system efficiency of alternative electrified powertrains, the economic feasibility of these technologies must also be ensured. To assess this, the life cycle levelized cost of operation (LCOO) was calculated by taking into account the initial alternative powertrain production cost and the fuel cost over the vehicle life cycle and dividing this by the operating hours. This method allows for a comparison of the economic feasibility of various alternative powertrains. To simplify the calculation assumptions, only the costs related to the powertrain components (e.g., power system, energy storage, electric drive, fuel storage) and fuel costs were considered in the LCOO calculation. The costs of chassis and additional accessories were assumed to be the same for each powertrain, and common cost factors such as labor and insurance were excluded. The Autonomie Lite off-road tool [28], previously developed for estimating the production cost of electric powertrains, was extended to agricultural tractors, and the LCOO results are shown in Figure 16.

The key powertrain cost assumptions used in the LCOO calculations are summarized in Table 4. The assumptions were made for two scenarios, year 2025 and 2035, with different assumptions for the main powertrain and fuel cost accordingly. For 2025, the battery cost is assumed to be $163/kWh, the fuel cell stack system cost $249/kW, and the hydrogen tank cost $309/kg of hydrogen capacity (based on 700 bar). However, for 2035, the cost assumptions are lower: the battery is $116/kWh, the fuel cell system is $182/kW, and the hydrogen tank is $274/kg. These assumptions are based on those used in previous Autonomie MD/HD vehicle analysis [26]. However, these cost estimates will vary depending on supplier relationships and specific production volumes of each off-road equipment OEM.

Overall, fuel costs for operation dominate the LCOO of the tractor. Agricultural tractors are assumed to have a service life of approximately 15 years, with an operating time of approximately 475 h/year [29]. The diesel fuel price used here is assumed to be approximately $3.4/gal and $3.6/gal [30], the hydrogen fuel price is assumed to be $6.8/kg and $4/kg [31, 32], and the electricity cost is assumed to be $0.18/kWh [30].

In the 2025 scenario, fuel costs account for about 75%–83% of the total LCOO for diesel engine powertrains, while for hydrogen engine conventional powertrains, they account for 79%–84%. This is because hydrogen fuel is relatively more expensive than diesel fuel. However, in the 2035 scenario, the proportion of fuel costs remains similar for diesel powertrains, but for hydrogen engine powertrains, it decreases to 70%–74% due to a reduction in hydrogen fuel costs. Despite this, in the 2035 scenario, the initial purchase cost for hydrogen engine powertrains remains higher than that of diesel engine powertrains due to the additional hydrogen tank costs. Although the total LCOO for hydrogen engine powertrains is still higher than that of diesel engine powertrains, the cost gap narrows as the hydrogen fuel price decreases by 2035.

In both 2025 and 2035, the cost of hydrogen engine powertrains is similar to or lower than that of fuel cell electric vehicle powertrains at higher workloads. For BEV long-range, a high-capacity battery is required to achieve similar operating hours to conventional diesel powertrains, resulting in a higher initial purchase cost. Consequently, battery costs account for a larger proportion of total costs than fuel costs, and this proportion remains high even in 2035.

Life Cycle GHG Emissions

Alternative electrified powertrains were evaluated for their potential to reduce greenhouse gas emissions, as well as for energy efficiency and economic analysis. The greenhouse gas emissions calculations were based on a well-to-wheel (WTW) life cycle assessment using Argonne's greenhouse gas, regulated emissions, and energy use in transportation (GREET) model [33]. This model was used to generate greenhouse gas emission factors based on the required energy consumption. The WTW analysis is divided into two phases: the well-to-pump (WTP) phase covers the recovery of fuel feedstock, fuel production, and delivery to the gas station. The second phase, the pump-to-wheel (PTW) phase, represents the operational activities of the vehicle.

To accurately compare alternative powertrains, it is essential to analyze greenhouse gas emissions on a WTW

FIGURE 16 Levelized cost of operation driving under light/medium/high workload (for years 2025 and 2035).

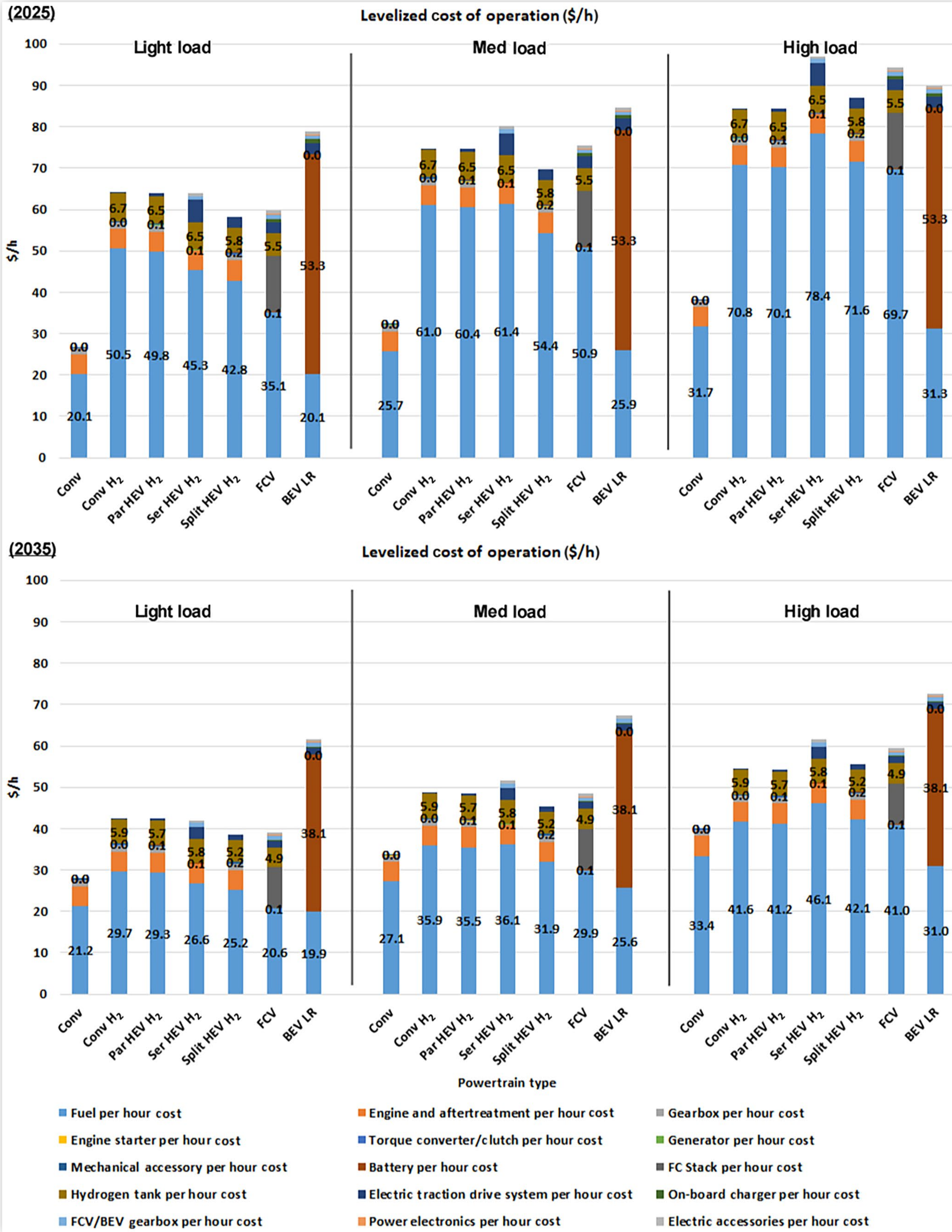


TABLE 4 Main cost assumptions.

Year	2025	2035
Battery	$163/kWh	$116/kWh
Electric motor	$36/kW	$27/kW
Fuel cell system	$249/kW	$182/kW
Hydrogen tank (fixed cost term + cost coefficient × usable H_2 mass)	$3801 (fixed cost term)	$3366 (fixed cost term)
	$309/usable kg H_2 (cost coefficient)	$274/usable kg H_2 (cost coefficient)
Hydrogen fuel cost	$6.84/kg H_2	$4.02/kg H_2
Diesel fuel cost	$3.4/gde	$3.6/gde

basis, as upstream fuel production and processing activities consume significant amounts of energy and generate significant emissions, especially when operating a tractor.

The criteria presented in Table 5 were used for this analysis. Hydrogen production is assumed to be from a central steam methane reforming (SMR) power plant or a fueling station, and wind-based hydrogen production is also considered. Generation is analyzed using the average US grid configuration and regional grid configurations for the top five agricultural tractor usage regions [34]. Renewable energy generation sources are also considered. However, greenhouse gas emissions from additional component production for batteries or hydrogen storage tanks are not included in this analysis.

The total cradle-to-grave GHG emissions normalized to driving hours over the vehicle life cycle are presented in Figure 17. Using the GREET model, GHG emissions from feedstock, fuel production, and vehicle emissions are compared for different workloads by powertrain.

For Conv diesel powertrains, GHG emissions from tractor operation activities account for the majority, while for hydrogen-powered or BEV powertrains, all GHG emissions occur in the WTP phase. For hydrogen-powered

TABLE 5 Well-to-wheel GHG analysis criteria.

Fuel/Electricity	Description
Fuels	Diesel
	Hydrogen—steam methane reforming, central plants
	Hydrogen—steam methane reforming, refueling plants
	Hydrogen—wind electricity
Electricity	Electricity—US average
	Electricity—top five grids for tractors: MRO, SERC, TRE, SPP, and RFC
	Electricity—renewal (wind and solar)
Duty cycles	Tillage cycle: 50%, 75%, and 100% workloads
Model	2025 annual GHG emissions based on GREET 2023

powertrains, GHG emissions from fuel production at the central SMR plant are represented as bar values, while for BEVs, GHG emissions from the average US power mix are represented as bar values. GHG emissions from other fuel production methods are represented as error bars.

Even assuming that hydrogen is produced at SMR plants, GHG emissions of hydrogen-powered powertrains, except for Ser HEVs, are estimated to be slightly higher than, or at high workload conditions nearly comparable to, those of the baseline Conv diesel powertrain. Although not considered in this study, a diesel engine hybrid powertrain could further reduce GHG emissions relative to Conv diesel powertrain. However, when hydrogen is produced from renewable energy sources, even the Conv hydrogen engine powertrain, rather than the electrified powertrain, showed similar greenhouse gas reductions to the fuel cell powertrain, especially at high workloads.

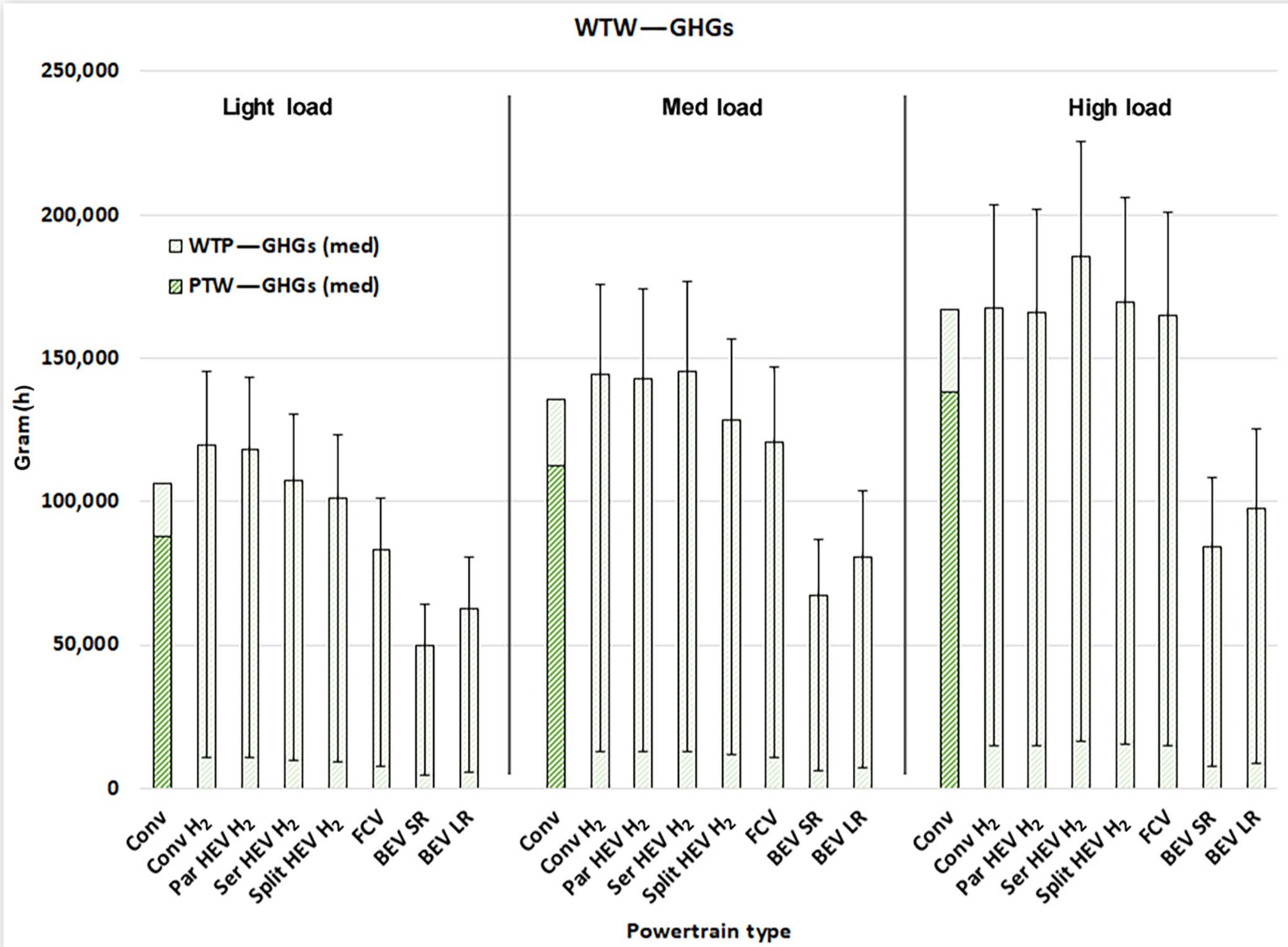
Summary/Conclusions

Using Autonomie software, simulation models for conv diesel, conv hydrogen engine, HEVs with hydrogen engine, FCEV, and BEV agricultural tractors were developed. Simulations were performed with various workloads over the tillage work cycle to evaluate energy consumption and operating performance. The fuel consumption of the conv diesel powertrain was compared to the fuel consumption of the published Nebraska test report, and it was verified that the energy consumption was within an error of about 3.8%.

The simulation results for the alternative powertrains showed that the battery electric powertrain provides the most energy-efficient powertrain option for agricultural tractors. However, the energy density of lithium-ion batteries requires a battery capacity of about 2.3 MWh or more to provide sufficient operating time, which may cause problems due to battery space issues or increased tractor weight. Although this study did not analyze the implications of added volume, it may necessitate future modifications to tractor designs. A small-capacity battery can be considered, but they would not provide adequate operating time and would substantially reduce operational performance; moreover, fast charging may be challenging in agricultural environments.

The simulation results showed that the hybrid powertrain equipped with a hydrogen engine showed different energy efficiency results depending on the workload. The Ser HEV powertrain has the advantage of controlling the engine to operate in the optimal efficiency range, but it also shows higher energy consumption compared to the Conv diesel powertrain due to energy conversion issues. The Par HEV powertrain provides a very small energy saving effect while reducing system complexity, but the split HEV powertrain shows a relatively high energy efficiency reduction at various workloads.

FIGURE 17 Lifetime total greenhouse gas emission from fuel cycle.



To examine the economic feasibility as well as the system efficiency of the alternative powertrain, the LCOO including purchase cost and fuel cost was analyzed. The analysis covered both current and future (2035) scenarios, and it was found that all hydrogen engine tractors are more expensive than diesel engine tractors. However, the cost difference is expected to decrease only if hydrogen fuel prices drop by 2035. Hydrogen engine–equipped HEV powertrains are anticipated to have the LCOO similar to FCEV powertrains, except for Ser HEV, and are expected to be lower at higher workloads. The initial cost of BEV tractors is higher due to the need for high-capacity battery packs to ensure similar operating hours. FCEV powertrains and hydrogen engine powertrains also showed relatively high costs due to the initial expenses of fuel cell systems and hydrogen tanks.

In terms of greenhouse gas emissions, even assuming hydrogen production through SMR, hydrogen-powered powertrains have similar levels of emissions to Conv diesel powertrains, depending on the workload. To achieve actual greenhouse gas reduction, decarbonizing hydrogen production is crucial. The greenhouse gas emissions of hydrogen engine powertrains, FCEVs, and BEVs can be significantly reduced if hydrogen or electricity is produced from renewable energy sources. However, for hydrogen engine powertrains, even if tailpipe greenhouse emissions can be eliminated, meeting stringent pollutant emissions regulations, such as for nitrogen oxide emissions, will require additional research or aftertreatment systems. Additionally, for widespread adoption, reductions in component costs, hydrogen costs, and infrastructure must be considered essential.

While BEV and FCEV offer long-term GHG reduction potential with renewable energy, hybrid powertrains equipped with hydrogen engines could be considered a practical and manageable interim solution, but only under the premise of decreasing hydrogen fuel prices and leveraging existing powertrain component manufacturing infrastructure. Moreover, to make fueling hydrogen-powered tractors practical, the development of substantial new hydrogen infrastructure would also be required.

Future research should focus on model validation through additional real field tests to improve the accuracy of low-emission off-road powertrain assessments. Additionally, evaluations could include renewable alternative fuels such as biodiesel, ethanol, and methanol, beyond hydrogen. Tractors equipped with new powertrains can be introduced progressively, and alternative fuels can serve as interim measures to reduce emissions in the short-term while advanced technologies mature. The TechScape tool [35], recently designed to enable efficient and accurate total cost of ownership (TCO) and GHG analyses, will be utilized in future studies.

Conflict of Interest

The authors and SAE International declare that one of the authors of this article is on the editorial board of the journal. SAE warrants that confidentiality was maintained throughout the peer-review process and no partiality was granted to the work. SAE further warrants that the editorial board member had no influence and did not take part in any type of decision-making or peer review.

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Declaration of AI-Assisted Technologies

During the writing of this manuscript, the author(s) used ARGO, a generative AI service for Argonne, to correct errors in spelling, grammar, word choice, and phrasing. The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Definitions/Abbreviations

BEV - Battery electric vehicle
CVT - Continuously variable transmission
DCT - Dual-clutch transmission
DOE - US Department of Energy
EGR - Exhaust gas recirculation
EOL - End of lite
EPA - US Environmental Protection Agency
FCEV - Fuel cell electric vehicle
GHG - Greenhouse gas
GREET - Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model
H_2-ICE - Hydrogen internal combustion engine
HP - Horsepower
ICE - Internal combustion engine
LCOO - Levelized cost of operation
MOVES - Motor vehicle emission simulator
MRO - Midwest Reliability Organization
NRMM - Non-road Mobile Machinery
OEM - Original equipment manufacture
PTO - Power takeoff
PTW - Pump-to-wheel
RFC - Reliability First Corporation
SCR - Selective catalytic reduction
SERC - Southeastern Electric Reliability Council
SMR - Steam methane reforming
SOC - State of charge
SPP - Southwest Power Pool (regional entity)
TCO - Total cost of ownership
TRE - Texas Reliability Entity
VTO - DOE Vehicle Technologies Office
WTP - Well-to-pump
WTW - Well-to-wheel
ZEV - Zero emission vehicle

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Appendix: Powertrain Efficiency

The powertrain efficiency is defined as the fraction of fuel (or battery) energy that becomes useful mechanical output at the tractor's shafts over a given duty cycle:

$$\text{Powertrain efficiency}\left(\text{tank to axle/PTO/drawbar powertrain efficiency}\right): \frac{\int\left(P_{axle}\left(t\right)+P_{PTO}\left(t\right)+P_{drawbar}\left(t\right)\right)dt}{\int\dot{m}_{fuel}\left(t\right)dt\times LHV}$$

$$\text{or } \frac{\int\left(P_{axle}\left(t\right)+P_{PTO}\left(t\right)+P_{drawbar}\left(t\right)\right)dt}{\int P_{battery}\left(t\right)dt}$$

where P_{axle} is axle power, P_{PTO} is power-takeoff power, $P_{drawbar}$ is drawbar traction power, $P_{battery}$ is high voltage battery power, $\dot{m}_{fuel}$ is fuel mass rate, and *LHV* is the lower heating value of fuel.