World Electric Vehicle Journal

MDPI

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Simulation-Based Assessment of Energy Consumption of Alternative Powertrains in Agricultural Tractors

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Abstract: The objectives of this research were to develop simulation models for agricultural tractors with different powertrain technologies and evaluate the energy consumption in typical agricultural operations. Simulation models were developed for conventional, parallel hybrid electric, series hybrid electric, fuel cell hybrid, and battery electric powertrains. Autonomie vehicle simulation software (version 2022) was used for the simulations and the tractor models were simulated in two tilling cycles and in a road transport cycle with a trailer. The alternative powertrains were configured to have at least the same tractive performance as the conventional, diesel engine-powered tractor model. The simulation results showed that the potential of the parallel and series hybrid powertrains to improve energy efficiency depends heavily on the tractor size and the operating cycle conditions. The fuel cell hybrid and battery electric powertrains have a higher potential to reduce energy consumption and emissions but still have inherent technical challenges for practical operation. The battery-powered electric tractor would require improvements in the storage energy density to have a comparable operational performance in comparison to other powertrains. The fuel cell hybrid tractor already provided an adequate operating performance but the availability of hydrogen and refueling infrastructure could be challenging to resolve in the farming context.

Keywords: energy consumption; agricultural tractor; modeling; alternative powertrain; simulation

Citation: Lajunen, A.; Kivekäs, K.; Freyermuth, V.; Vijayagopal, R.; Kim, N. Simulation-Based Assessment of Energy Consumption of Alternative Powertrains in Agricultural Tractors. *World Electr. Veh. J.* **2024**, *15*, 86. https://doi.org/10.3390/wevj15030086

Academic Editors: Joeri Van Mierlo and Genevieve Cullen

Received: 12 January 2024
Revised: 8 February 2024
Accepted: 21 February 2024
Published: 27 February 2024

1. Introduction

Alternative powertrains have been increasingly implemented in different types of on-road vehicles for increasing energy efficiency and reducing emissions [1,2] and electrification is also on the way for off-road machinery [3,4]. The recent technological developments in powertrain electrification [5] and increased fossil fuel prices are also starting to make alternative powertrains and fuels relevant options for agricultural tractors. Unlike passenger vehicles, agricultural tractors have not yet been the most interesting application for powertrain electrification. The uncertainties about future developments regarding fossil fuels, environmental legislation, and emission standards have increased interest in the development of hybrid electric, fully electric, and fuel cell hybrid powertrain solutions [6]. Therefore, it is reasonable to believe that powertrain electrification will also be one of the major technology trends for agricultural tractors in the coming years. Recent scientific research results indicate that there could be a significant potential to increase energy efficiency with alternative powertrains [7]. The main architectures for suitable alternative electrified powertrains have been studied and the benefits of using electric power for numerous agricultural implements have been well recognized [8,9]; however, most of the existing research studies evaluating alternative powertrains for agricultural tractors focus only on single powertrain options and, therefore, a balanced comparison between the different technologies is required. This research presents a comparison—in terms of energy consumption and operational performance—by taking into account the most relevant alternative powertrain options for agricultural tractors. This article is a revised and expanded version of a paper entitled "Simulation of Alternative Powertrains in Agricultural Tractors" [7], which was presented at EVS36 in Sacramento on 12 June 2023.

Some agricultural tractor manufacturers have introduced new concepts for alternative powertrains and have launched prototype tractor models; they are even starting to produce versions of hybrid electric powertrains, but large-scale electrification still has many challenges to overcome. Several companies and research institutions are working on prototype battery electric tractors to reduce greenhouse gas emissions and dependence on fossil fuels in agriculture. John Deere has planned to launch an electric tractor by 2026, the small electric tractor by Fendt (e100 V Vario) has already been launched, and CNH Industrial is developing the New Holland T4 Electric Power and Farmall 75C Electric, which are both lithium-ion battery-powered all-electric utility tractors. Research has been ongoing to improve battery technologies for electric tractors. Increased energy density, longer battery life, and faster charging times are crucial aspects of the success of electric agricultural tractors [10]. The integration of electrified tractors with precision agriculture technologies is also a growing area of interest for manufacturers. Some governments have been offering incentives and subsidies to encourage the adoption of electric vehicles in agriculture. These policies aim to reduce emissions, promote sustainable farming, and support the transition to cleaner energy sources.

Powertrain electrification has spread steadily from passenger cars to utility vehicles and, today, even to heavy on-road vehicles [11,12]. There is also increasing development for off-road machinery, especially since 2021 as energy costs have increased exceptionally and there are many uncertainties surrounding the use of fossil fuels in the future. Higher technology costs can be a major barrier to using alternative powertrains in agricultural tractors, although previous research on heavy vehicles and off-road machinery suggests that the higher development and component costs can be paid off with benefits when assessing the cost on a lifecycle basis [13,14]. The electrification of farm vehicles started with small-sized machines, for example, there are already electrified versions of telehandlers and small loaders available for purchase [15]. Because modern agricultural tractors are used for a wide variety of field operations, road transport, and other supporting work such as front-end loading or mixer wagon operation, there are several different variants of basic agricultural tractors. However, from very small-sized tractors (engine power < 50 kW) up to very large tractors (engine power up to 300 kW), conventional agricultural tractors have quite a similar powertrain topology [16]. This similarity might limit the opportunities to introduce new powertrain designs and favor the minimal modification of the existing layout to avoid too many modifications in the production lines. This is also the case due to the multipurpose aspect of agricultural tractors, providing a universal operator for a vast variety of farm purposes.

Over the last few years, research studies have been carried out to estimate the benefits and feasibility of hybrid electric powertrains in agricultural tractors. For many reasons, compact and medium-sized tractors (engine power between 50 and 100 kW) have often been the baseline for hybridization studies. Troncon et al. (2019) studied the feasibility of hybridization for specialized orchard and vineyard tractors using a mild parallel-hybrid system [17,18]. The challenge was to fit the electric system in a rather limited space and deliver an adequate performance. Their simulated research results indicated that fuel consumption would be 15–35% lower depending on the duty cycle operation. In another study, an ICE-based platform was converted to a parallel hybrid powertrain with a downsized engine and electric motor [19]. The downsizing was about 29% (from 77 kW to 55 kW of engine power), the electric motor maximum power was 60 kW, and the battery size was 25 kWh. The fuel economy savings were evaluated using simulations of high and low power duty cycles, which clearly showed that hybridization had only a marginal benefit on high power cycles (on average about a 5% reduction) and a significant benefit on low power cycles, having a reduction of over 30% on average [19]. Mendes et al. (2019)

investigated the hybridization of a tractor backhoe loader by focusing on using electrical power produced by a generator for the hydraulic system with supercapacitors as the energy storage [20]. Simulations on real-world recorded duty cycles indicated over a 50% reduction in fuel consumption. Mocera and Martini (2022) proposed a hybrid eCVT power-split hybridization for a specialized agricultural tractor [21]. Their performance simulations showed that the hybrid tractor would have a comparable performance in typical use of the tractor and fuel savings of 10–20%.

Alternative fuels, such as biodiesel, biogas, e-fuels, or hydrogen for internal combustion engines, have the potential to lower greenhouse gas emissions compared to traditional fossil fuels. This can contribute to mitigating environmental impacts associated with agricultural activities. Some alternative fuels are derived from renewable sources, offering the advantage of sustainability. For instance, biofuels can be produced from crop residue or organic waste, providing a renewable and potentially carbon-neutral energy source. Certain alternative fuels, like biogas, can be produced locally, promoting regional economic development. The adoption of alternative fuels is hindered by the lack of widespread infrastructure for production, distribution, and refueling [22]. Establishing a robust infrastructure is crucial for the successful integration of alternative fuels into agricultural practices. Some alternative fuels have a lower energy density than traditional fossil fuels, which can impact the overall range and efficiency of agricultural tractors [23]. This challenge requires advancements in fuel storage and utilization technologies.

Considering off-road vehicles and machinery in general, agricultural tractors differ from other machinery because they are often used for various purposes and many different types of field operations. Therefore, it is important to develop methods that provide the tools for evaluating the benefits of powertrain electrification of agricultural tractors [24]. Vehicle modeling and simulation methods are a practical and rather fast way of analyzing and comparing different powertrain solutions. Different from many other vehicles, agricultural tractors are used on different types of field surfaces and in different conditions, which creates specific challenges for modeling [25]. Reliably and accurately simulating tire–soil interactions need high-fidelity models, e.g., FEM—(Finite Element Method) or DEM—(Discrete Element Method) based models, that need laborious development and require significant amounts of computational capacity [26,27]. In addition, acquiring reliable validation data for high-fidelity tire–soil interaction models from field operations can be rather challenging [28]. For effectively comparing and evaluating the performance of alternative powertrains, less computationally intensive models are typically used, such as numerical simulation.

This research presents a numerical modeling and simulation approach for evaluating alternative powertrains in agricultural tractors using Autonomie vehicle simulation software [29]. Off-road vehicles and machinery are typically simulated in a different way to on-road vehicles because they usually perform repetitive tasks and do not have a traditional speed profile to follow. Instead, agricultural tractors are simulated based on distance, by giving a target speed based on the distance traveled. Also, as these types of machines often do heavy work, the resistance force from implements must be integrated into the model by, for example, simulating agricultural field work such as plowing or harrowing. Naturally, in typical field work, like field cultivation, the power requirement can consist of a passive draft force or an active power that uses the power take-off (PTO) or hydraulic power in an implement. For evaluating alternative powertrains in agricultural tractors, numerical modeling and simulation provide an effective approach to generating different simulation cases, comparing component sizing, and then evaluating the benefits in several use cases.

In this research, conventional, parallel hybrid electric, series hybrid electric, fuel cell hybrid, and battery electric powertrains were modeled and simulated in dedicated operating cycles. The powertrain models were parametrized based on the performance of a conventional tractor with a diesel engine and dual-clutch transmission. The operating cycles were generated based on field measurements carried out in the Viikki Research Farm at the University of Helsinki, Finland. According to the simulation results, the benefits of hybridization and electrification were evaluated and the operating performance was analyzed.

2. Materials and Methods

2.1. Simulation Model Development

Autonomie software (version 2022) [29] was used for the tractor model development and for running the simulations in multiple cycles. This software has been developed by the Argonne National Laboratory (ANL), to be used as a vehicle system simulation tool for assessing the energy consumption, performance, and cost of advanced vehicle powertrain technologies in various types of vehicles [12]. The simulations and model configurations can be executed in a dedicated interface called AMBER, which has been developed as a universal graphical user interface for multiple simulation applications and allows workflows to be run with different software developed by ANL [30]. All the simulations were carried out by using AMBER and, thus, the model development was performed in Autonomie, and configuration and parametrization were performed in AMBER. Autonomie was originally designed for on-road vehicle simulations and, therefore, implementing off-road simulation models with distance-based cycles required some modifications to the driver and vehicle control systems. Otherwise, the software is well suited to off-road vehicle simulation as long as a representative operating cycle can be generated. The first versions of the agricultural tractor models with a time-based simulation approach were developed during previous research, which focused on conventional tractor model development and the electrification of agricultural tractors [31]. The previously developed simulation models were updated by modifying them to be suitable for distance-based cycle simulations. Also, more representative operating cycles were developed based on the measurements carried out in an agricultural field environment and during road transport tractor tests.

The modeled powertrain options included diesel-powered conventional, parallel hybrid electric, series hybrid electric, fuel cell hybrid, and battery electric powertrains. The conventional and parallel hybrid models have a diesel engine as a power source and a dual-clutch transmission; dual-clutch transmission was chosen for its high energy efficiency [32]. The parallel hybrid has a pre-transmission layout with an electric drive and uses a battery pack for electrical energy storage. The series hybrid tractor model also has a conventional diesel engine attached to a generator, one electric drive motor, and a three-speed gearbox. The fuel cell hybrid and electric tractor models have a fully electric powertrain consisting of a battery, one electric drive motor, and a three-speed gearbox. The fuel cell hybrid model has a fuel cell stack as the primary power source and a small battery pack for power load leveling. The electric tractor has a large energy-type battery pack for energy storage. A lithium-ion battery model was used for energy storage in all of the electrified simulation models. Figures 1 and 2 present the powertrain layouts of the different tractor models in the Autonomie software. The vehicle dynamics block is illustrated in Figure 2 and includes a transfer case, front and rear final drives, wheels, and chassis model. The transfer case splits the driving power between the front and rear axles. All the tractor models have the same driver model, which determines the speed and acceleration demand. The external loads generated by an implement or trailer are taken into account in the chassis block of the models. The hybrid powertrains have dedicated energy management strategies (EMSs) for ensuring driving performance and minimizing energy consumption when possible. Power-following and charge-sustaining EMSs were used for all the hybrid powertrains to ensure performance and keep the battery state of charge within predetermined limits.

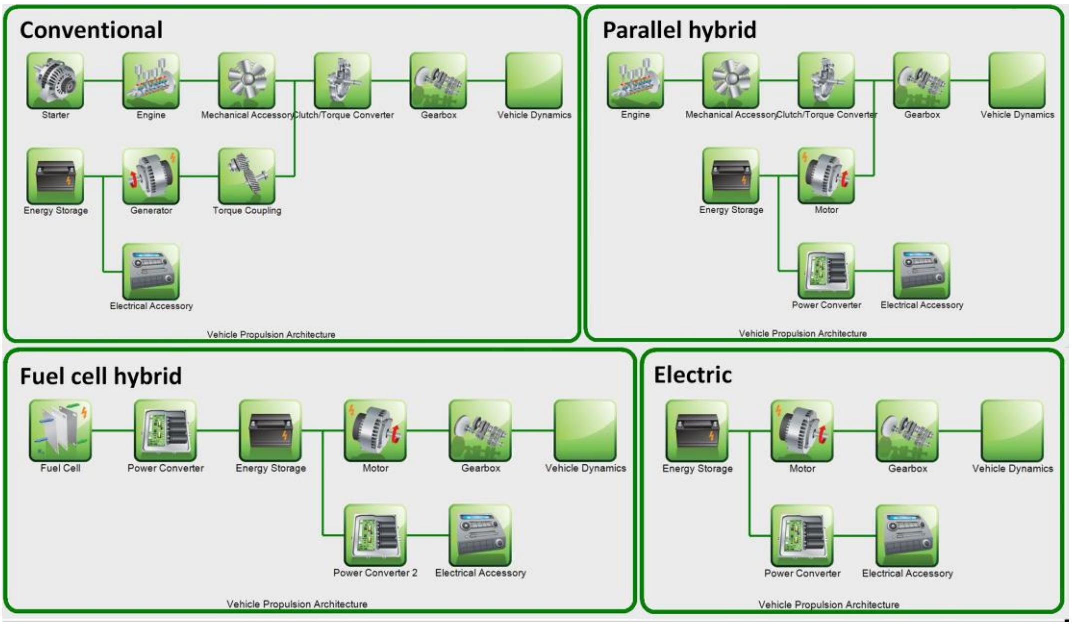

Figure 1. Powertrain layouts of the conventional, parallel hybrid, fuel cell hybrid, and electric tractor models in the Autonomie software.

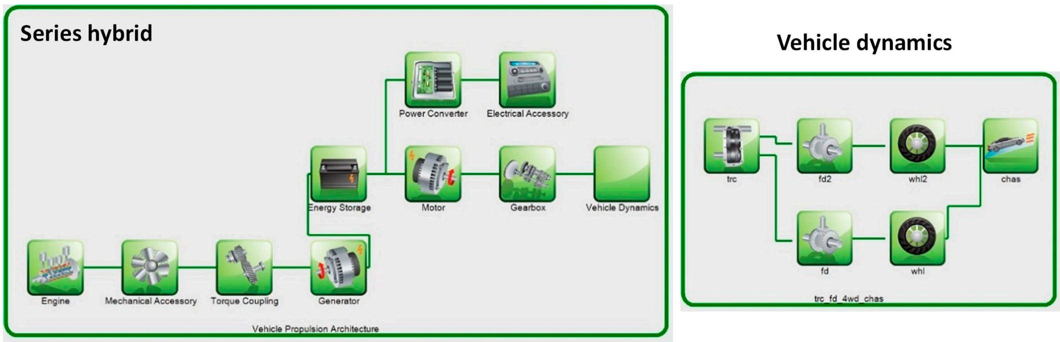

Figure 2. Series hybrid powertrain layouts and vehicle dynamics block layouts of the tractor models.

2.2. Model Parameters

Two different baseline tractor sizes were chosen for the conventional tractor models—a medium size with an engine-rated power of 112 kW, and a large size with an engine-rated power of 225 kW. The tractor models were configured using the Autonomie libraries that provide component initialization data for a wide range of components used in light- and heavy-duty vehicles. The powertrain component sizing was determined in a way that the alternative powertrains had at least the same tractive performance in comparison to the conventional, diesel-engine-powered tractor models. The total weight of each powertrain was estimated based on the main component weights, and the results indicated that no major differences in total weight needed to be considered. Therefore, all the models were simulated with the same total weights of 5000 kg (medium size) and 10,000 kg (large size). The size of the battery in the electric tractor model was limited to less than 200 kWh for the large-sized tractor and 100 kWh for the medium size tractor to not exceed the total tractor weight. Table 1 presents the general technical specifications of the conventional tractor models and, thus, the engine and transmission parameters. The general technical specifications include the front and rear axle gear reductions, tire sizes, and total weights, which were the same for all the tractor models.

Table 1. Conventional tractor powertrain and general technical specifications.

Component	Medium-Sized Tractor	Large-Sized Tractor
Diesel engine	maximum power 112 kW, maximum torque 580 Nm	maximum power 225 kW, maximum torque 1154 Nm
Transmission	eight-speed dual-clutch transmission (DCT) with three ranges	eight-speed dual-clutch transmission (DCT) with three ranges
Rear axle [1]	bevel set ratio of 2.93:1 and planetary gear ratio of 6:1	bevel set ratio of 3.28:1 and planetary gear ratio of 6:1
Front axle [1]	bevel set ratio of 2.30:1 and planetary gear ratio of 6:1	bevel set ratio of 2.48:1 and planetary gear ratio of 6:1
Tires [1]	front: 380/85R28, rear: 460/85R38	front: 540/65R30, rear: 650/65R42
Weight [1]	5000 kg	10,000 kg

[1] Same parameters for all tractor models.

Tables 2 and 3 show the powertrain specifications for the parallel hybrid, series hybrid, fuel cell hybrid, and battery electric tractor models. Parallel and series hybrid types have a downsized diesel engine. The parallel hybrid has a similar dual-clutch transmission to the conventional tractor but needs only two ranges for the same driving performance. All the hybrid models have a rather small battery pack because this is mostly used for peak power shaving and storing regenerated braking energy. Based on the evaluation of the typical field and road operations, it was determined that a three-speed gearbox is sufficient to cover the typical agricultural tractor operations and provide high energy efficiency. The electric driving motor was dimensioned based on the performance requirement set by the baseline conventional tractor. Depending on the different duty cycles and operations, an optimization study could be carried out to evaluate the influence of the component sizes on the operating performance. However, this would be more interesting if the design and operating costs were included in the analysis.

Table 2. Specifications for the hybrid and electric powertrains of the medium-sized tractor models.

Component	Parallel Hybrid	Series Hybrid	Fuel Cell Hybrid	Electric
Diesel engine/Fuel cell stack	Diesel engine: power 90 kW, torque 466 Nm	Diesel engine: power 92.5 kW, torque 480 Nm	Fuel cell stack: max power 80 kW	---
Transmission	Eight-speed (DCT) with two ranges	Three-speed gearbox	Three-speed gearbox	Three-speed gearbox
Battery configuration	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	33 Ah cell, four packs in parallel, 192 cells in series in a pack, 720 V, 95 kWh
Electric motor	max power 50 kW, max torque 201 Nm, max speed 4400 rpm	max power 112 kW, max torque 304 Nm, max speed 8000 rpm	max power 112 kW, max torque 304 Nm, max speed 8000 rpm	max power 112 kW, max torque 304 Nm, max speed 8000 rpm

Table 3. Specifications of the hybrid and electric powertrains of the large-sized tractor models.

Component	Parallel Hybrid	Series Hybrid	Fuel Cell Hybrid	Electric
Diesel engine/Fuel cell stack	Diesel engine: power 175 kW, torque 898 Nm	Diesel engine: power 185 kW, torque 949 Nm	Fuel cell stack: max power 160 kW	---
Transmission	Eight-speed (DCT) with two ranges	Three-speed gearbox	Three-speed gearbox	Three-speed gearbox

Table 3. *Cont.*

Component	Parallel Hybrid	Series Hybrid	Fuel Cell Hybrid	Electric
Battery configuration	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	33 Ah cell, eight packs in parallel, 192 cells in series in a pack, 720 V, 190 kWh
Electric motor	max power 100 kW, max torque 542 Nm, max speed 4400 rpm	max power 225 kW, max torque 611 Nm, max speed 8000 rpm	max power 225 kW, max torque 611 Nm, max speed 8000 rpm	max power 225 kW, max torque 611 Nm, max speed 8000 rpm

2.3. Operating Cycles

Experimental measurements were carried out in the Viikki Research Farm at the University of Helsinki using a typical agricultural tractor (Valtra N141) and a chisel plow to acquire data to evaluate different levels of load resistances for the operating cycles. The measurements were made in October 2022 in a stubbled field, as presented in Figure 3. The tractor data were measured from the CAN bus by a developed data logger consisting of a mini-computer, CAN shield logger, and a GPS module. Location data were logged using a u-blox ZED-F9P GPS module, which was connected to a u-blox ANN-MB-00 GPS antenna. The operational data that were recorded from the CAN bus included, among other things, engine data, vehicle speed, and the linkage draft force.

Figure 3. Field measurements with a tractor and chisel plow.

Two tillage cycles were generated with target speeds of 8 and 12 km/h. For both cycles, three levels of load resistance were defined—light, medium, and high. The resistance load was applied only when the implement was in use during operation. The tillage cycles are illustrated in Figure 4 with the target speed and the different levels of force as load resistances for the large-sized tractor. For the medium-sized tractor, the target speed and the lowest load resistance were the same as for the large-sized tractor. The higher loads were gradually lowered, being approximately 50% of the load resistance in comparison to the large-sized tractor cycles.

Figure 5 shows the 27 km long measured road cycle with the elevation profile and the 20 km long generated road cycle. The measured road cycle corresponds to a typical road transport operation performed with agricultural tractors with a trailer between fields and a farm. The 27 km roundtrip cycle was measured from the route that has been used for tractor comparison tests by a Finnish magazine. The road cycle data included multiple tractor test recordings containing tractor operational data. The large-sized tractor was simulated in the measured cycle and the medium-sized tractor in the generated cycle, which has a lower top speed and elevation. Simulations were carried out with a trailer, having total weights of 10,000 kg and 15,500 kg for the large-sized tractor, and 6400 kg and 10,000 kg for the medium-sized tractor. These loads correspond to payloads of 30% and 60% for 18 t (large tractor) and 12 t (medium tractor) trailers.

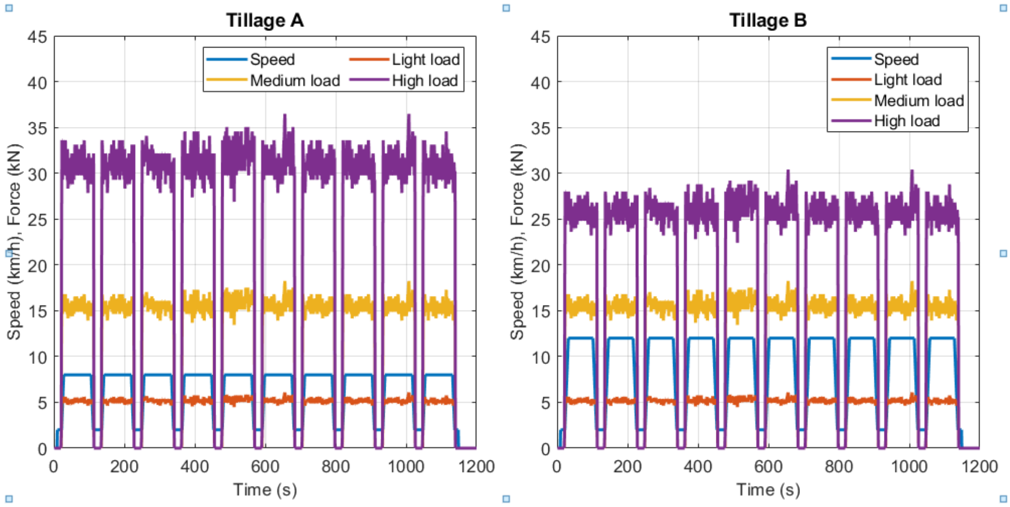

Figure 4. Generated tillage cycles (Tillage A and B) with three defined load resistance profiles for the large-sized tractor.

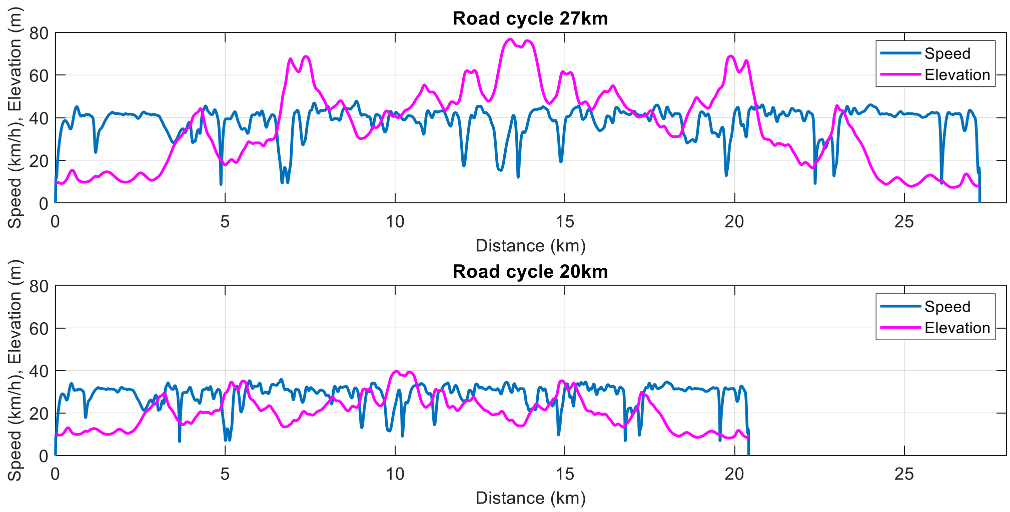

Figure 5. Measured and generated road cycles for tractor–trailer simulations.

3. Results

3.1. Driving Performance

MATLAB software (version 2021b) was used for analyzing the simulation results. Overall, all the simulations were successfully carried out and it was concluded that all the models were operating correctly. It was observed that the target speed was followed quite well, without any major deviations in all cycles, although the electrified powertrains did have more precise control for following the target speed, especially during slow-speed driving that did not need gear changes. The speed traces in the Tillage A cycle for all the large tractor models are illustrated in Figure 6. The conventional tractor did not follow the lower target speed very closely, but at higher speeds, the speed control worked fine. Also, the load resistance in the tillage cycles had some influence on the driving dynamics, and this will be a focus point in future research when developing more advanced driver models for agricultural tractors. In the road cycles, there was very little difference in the driving speeds between the tractor models due to the more dynamic nature of the cycle. Only the hard acceleration phases generated some lagging for the conventional and parallel hybrid tractor models, because of the consecutive gear shifting.

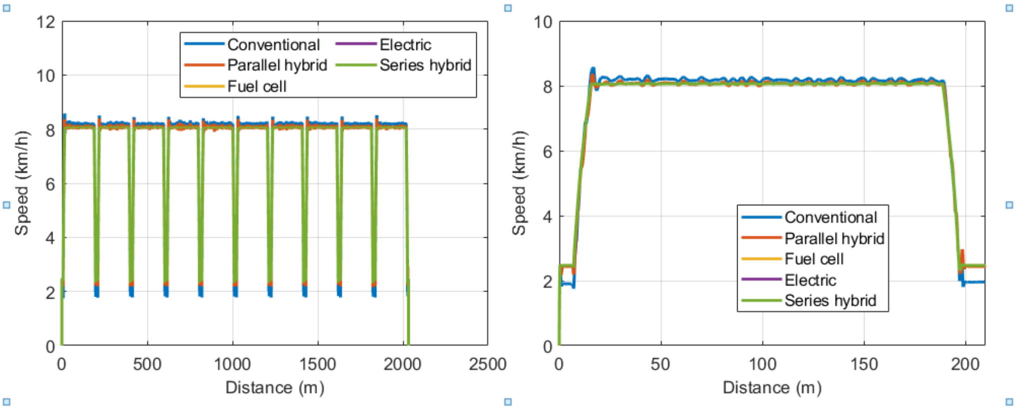

Figure 6. Speed traces of large tractor models in Tillage A cycle.

3.2. Energy Consumption

Energy consumption was calculated as on-board energy use and, therefore, no charging losses were considered. Figures 7 and 8 present the cumulative energy consumption for the simulated tractor models in the Tillage A and road cycles. The results correspond to the medium workload for the Tillage A cycle and the higher payload for the road cycle. The cumulative energy consumption illustrates that there was a gradual energy-saving potential along the tillage cycle due to the higher powertrain efficiency. Only the series hybrid powertrain was less efficient than the conventional powertrain under the higher load situations. In the road cycle, the advantage of regenerating braking energy increased energy savings, especially for tractor models that had the fully electric powertrain. The alternative powertrains showed better performance (in terms of energy consumption) for the medium-sized tractor compared to the large-sized tractor.

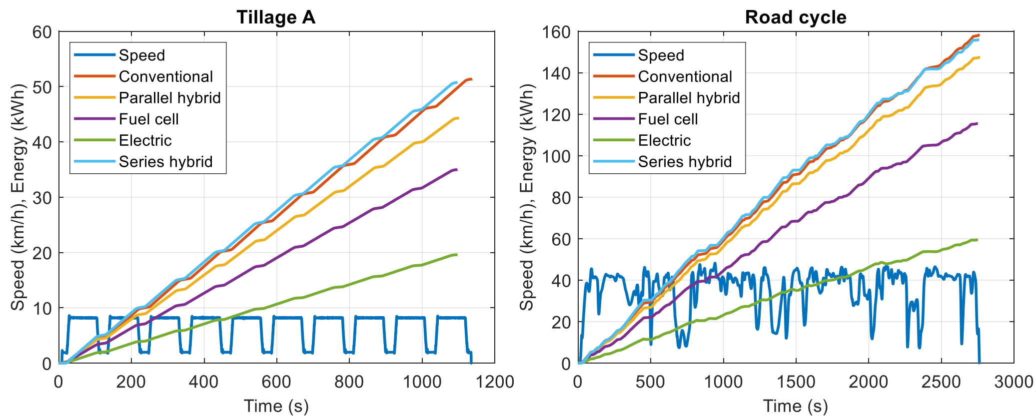

Figure 7. Cumulative energy consumption in the Tillage A and Road cycles for the large-sized tractor models.

A comparison of the energy consumption between the different cycles was made using the units of kWh/km. These units are not necessarily useful in terms of agricultural work but allow a comparison of the results obtained from different simulations. Figures 9 and 10 show the calculated energy consumption results for all the simulated cycles. The highest consumption was obtained in the Tillage A cycle with the high workload. The consumption increased quite rapidly in the function of the workload in both tillage cycles. Only for the electric tractor model was the increase less strong. Distance-based energy consumption was much lower in the Road cycle, which is due to the much higher driving speed. The payload increase had less influence on the energy consumption in the road cycle than the increase in the workload in the tillage cycles.

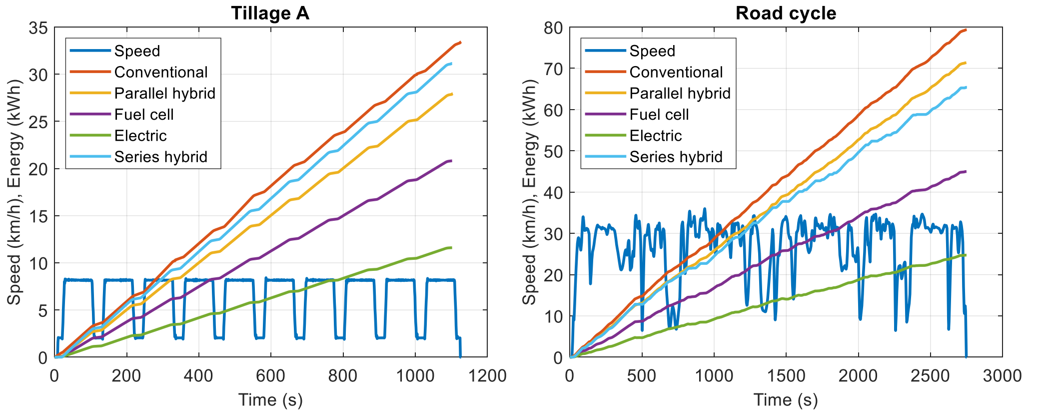

Figure 8. Cumulative energy consumption in the Tillage A and Road cycles for the medium-sized tractor models.

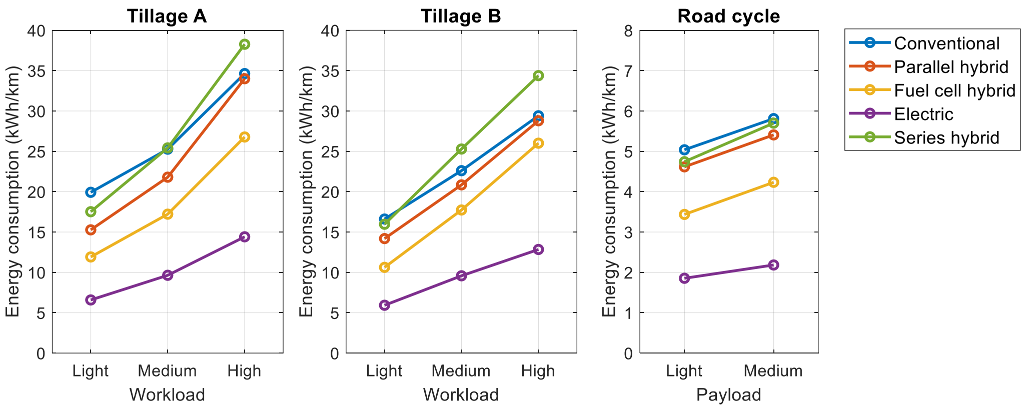

Figure 9. Energy consumption in kWh/km for all simulated cycles for the large-sized tractor.

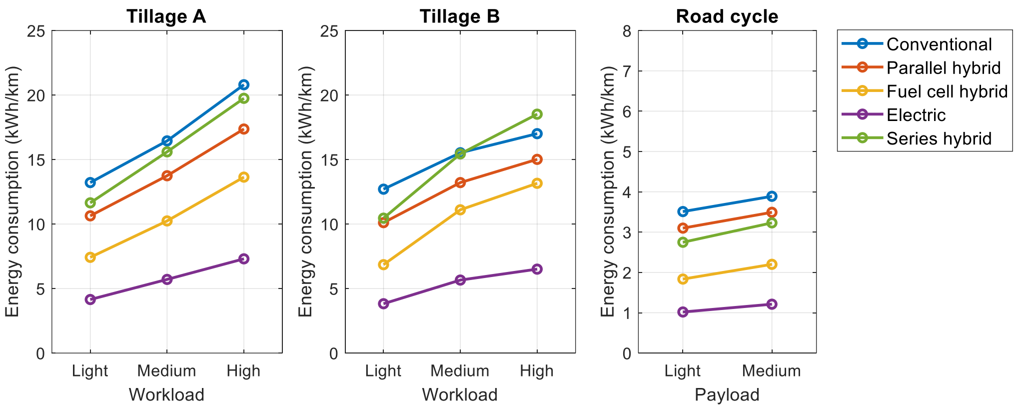

Figure 10. Energy consumption in kWh/km for all simulated cycles for the medium-sized tractor.

Depending on the workload, the fuel consumption of the large conventional tractor model was 12.7–23.0 L per hour (L/h) in the Tillage A cycle, 14.9–27.1 L/h in the Tillage B cycle, and 18.2–20.9 L/h in the Road cycle. For the medium-sized tractor, the fuel consumption values were 8.6–13.8 L/h (Tillage A), 11.6–15.7 L/h (Tillage B), and 9.5–10.5 L/h (Road cycle). These values correspond to typical the fuel consumption of diesel-powered tractors in tillage operations. The hydrogen consumption of the large fuel cell hybrid tractor model was 2.4–5.4 kg per hour (kg/h) in the Tillage A cycle, 3.0–7.3 kg/h in the Tillage B cycle, and 3.7–4.5 kg/h in the Road cycle. For the medium-sized fuel cell hybrid tractor, the hydrogen consumption was 1.5–2. 7 kg/h (Tillage A), 1.9–3.7 kg/h (Tillage B), and 1.5–1.8 kg/h (Road cycle).

The reduction potential in the energy consumption of the alternative powertrains is shown in Figures 11 and 12. These results clearly show that there is a significant potential for reducing energy consumption with the battery electric powertrain. The average reduction potential was 60–70% in the tillage and road cycle. The potential to reduce energy consumption with the fuel cell hybrid varied from 20% to 30% for the large tractor and from 35% to 45% for the medium-sized tractor. The parallel hybrid had on average 10–15% higher energy efficiency than the conventional tractor, but the gain was reduced with higher load resistance so that the variation in the potential was due to the operating conditions; thus, less reduction can be achieved with higher workload cycles with the hybrid powertrains. The series hybrid powertrain has a much higher potential to reduce energy consumption with the medium-sized tractor than with the large-sized tractor; however, not all the electrification benefits can be demonstrated with the passive duty cycle and, therefore, the powertrain benefits should also be evaluated in different types of operating cycles. There were no major differences in simulation results between the two tillage cycles, with the Tillage B cycle being slightly more demanding due to the 50% higher target speed.

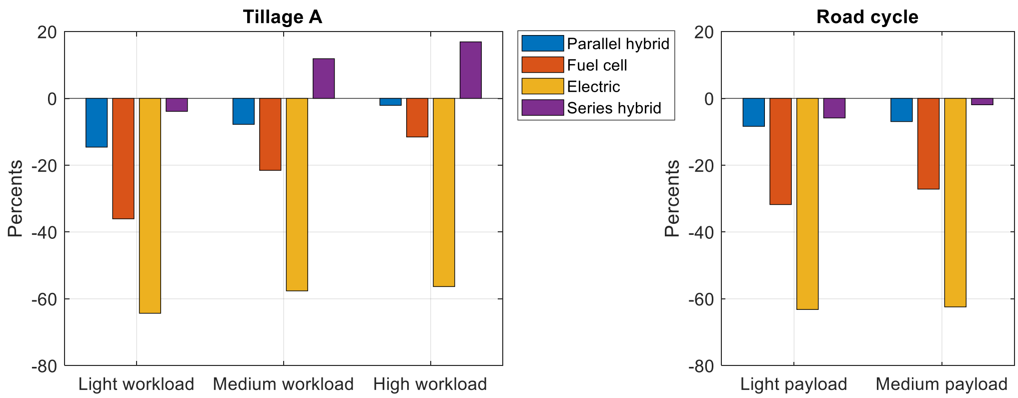

Figure 11. Potential for reducing energy consumption in the Tillage A and Road cycles of the large-sized tractor.

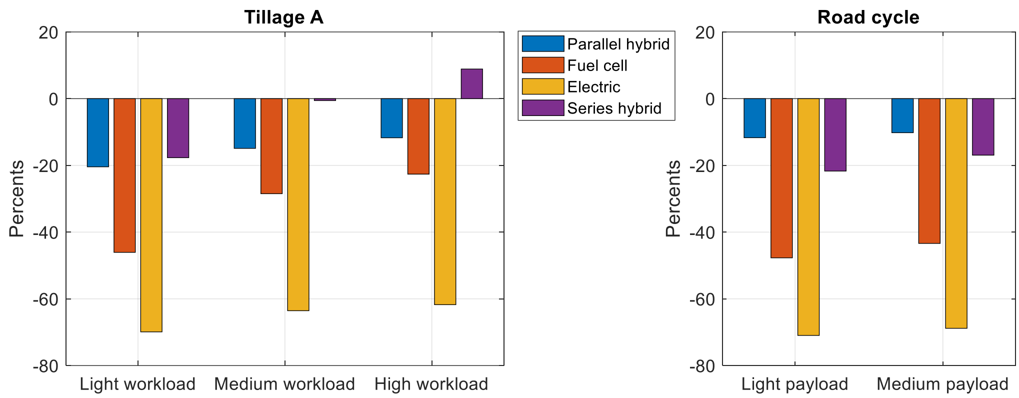

Figure 12. Potential for reducing energy consumption in the Tillage A and Road cycles of the medium-sized tractor.

3.3. Distribution of Losses

From the simulation results, the breakdown of powertrain losses was calculated for all simulations in order to evaluate the energy losses between the different powertrains. Figures 13 and 14 present the distribution of the powertrain losses of the large-sized tractor models in the Tillage A and Road cycles. The presented bar diagrams illustrate the total energy consumption in units of kWh. For the conventional, parallel hybrid, and series hybrid tractors, the major energy losses were generated by the heat losses of the power source (PS), i.e., the diesel engine. Depending on the cycle and workload, the energy loss portion of the power source was 65–70% for the conventional, parallel hybrid, and series hybrid tractor, 44–48% for the fuel cell hybrid, and 7–10% for the electric tractor. It is important to notice that the portions of the auxiliary loads in the energy losses were significant, especially when compared to the transmission losses. The increase in workload in the tillage cycles significantly increased the overall energy consumption. The highest increase occurred in the work and power source losses, especially for the conventional, parallel hybrid, and series hybrid tractor models. The increase in the payload in the Road cycle had much less of an influence on the overall energy consumption than the increase in the workload in the tillage cycles.

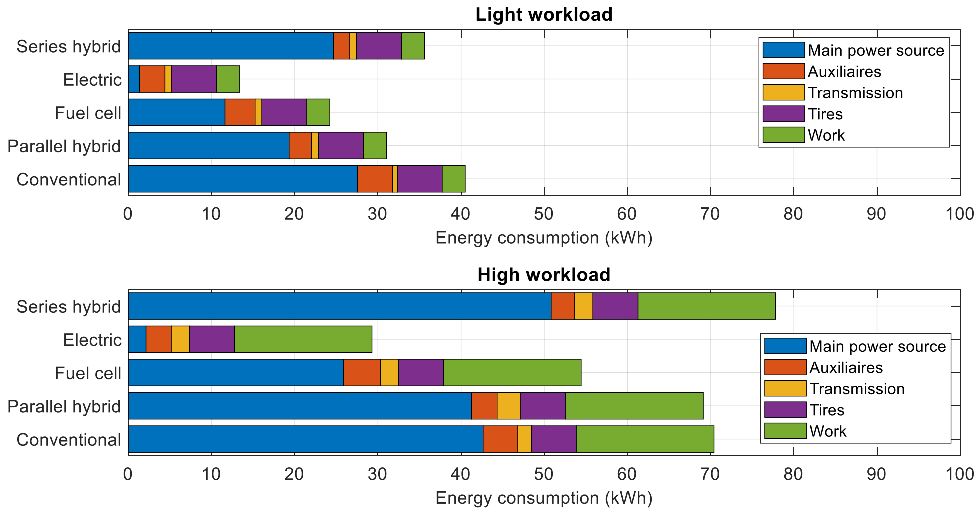

Figure 13. Distribution of energy losses for the different large tractor models in the Tillage A cycle with two workloads.

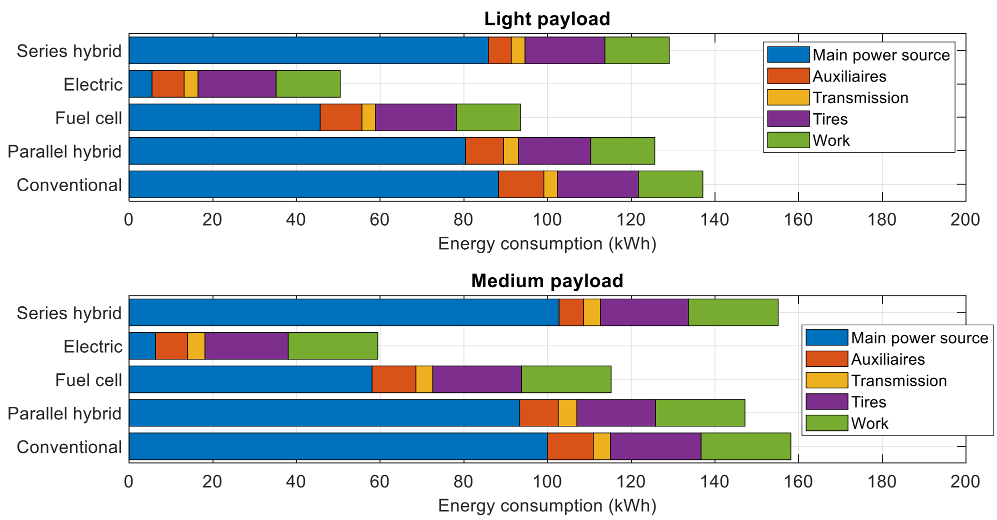

Figure 14. Distribution of energy losses for the different large tractor models in the Road cycle with two payloads.

3.4. Operating Time

The operating performance was evaluated based on the calculated operating times in the simulated cycles. The fuel tank size for the conventional large-sized tractor was 500 L and 350 L for the parallel and series hybrid. The hydrogen storage was assumed to be 36 kg of compressed hydrogen at 700 bars. This is comparable to the amount of hydrogen storage capacity in the fuel cells of hybrid city buses. The on-board energy capacities were 50%

less for the medium-sized tractor model. The operating time variations in the simulated cycles are presented in Figures 15 and 16. It can be observed that there were no major differences between the cycles but very significant differences between the tractor models. The conventional, parallel, and series hybrid tractors had very long operation times without refueling, which is typical nowadays for agricultural tractors. The fuel cell hybrid already offers quite a reasonable operating time without refueling, from 5 h up to 15 h. The major challenge for battery electric tractors is the low energy density of the energy storage and, therefore, the operating time remained very low in comparison to the other tractor models. The operating time could be increased by adding battery capacity, but this is challenging in terms of weight and available volume. Another solution could be fast charging, but access to high-power charging in the farming context could prove difficult.

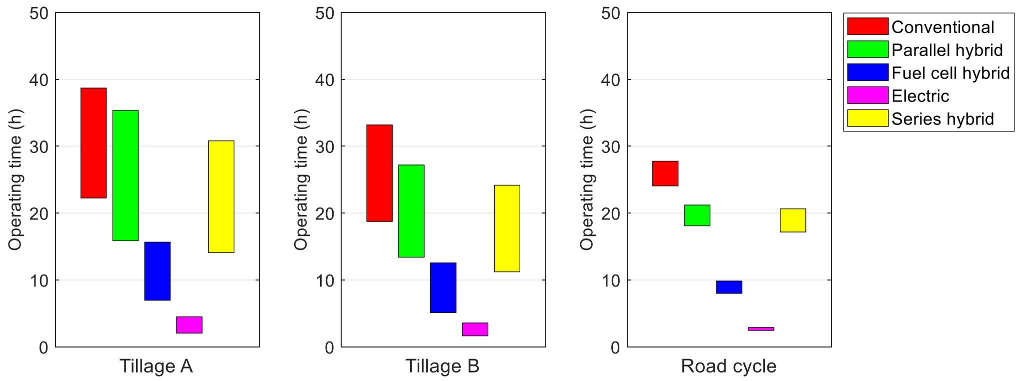

Figure 15. Calculated variations in operating times for different cycles for the large-sized tractor.

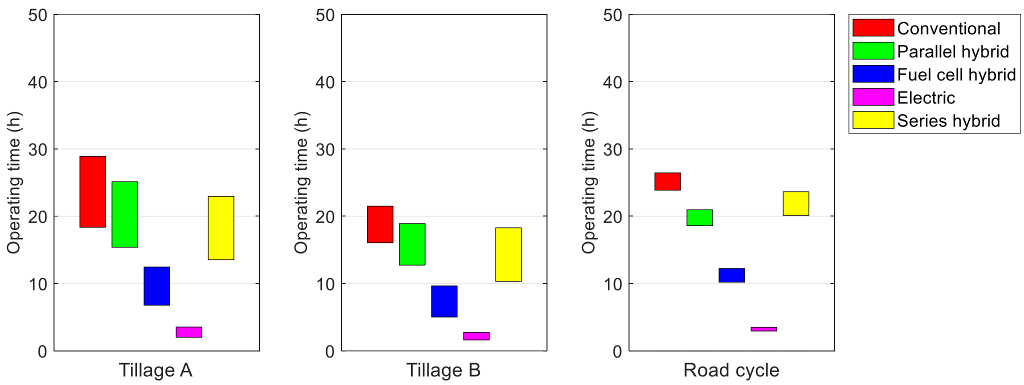

Figure 16. Calculated variations in operating times for different cycles for the medium-sized tractor.

4. Discussion

The research results clearly indicate the significant potential to reduce the energy consumption of agricultural tractors by powertrain electrification. Over the years, different electrified powertrain topologies have been proposed for vehicles, and as with other types of vehicles, such as city buses [14], the benefit of electrified powertrains for agricultural tractors is typically dependent on the duty cycle or work task carried out with the vehicle. In many scientific and practical research studies [17–19,33,34], parallel hybrid electric powertrain topology has been recognized as being suitable for agricultural tractors. One of the main reasons for this could be that it would not need any major modifications to conventional tractor designs but, instead, could be implemented by adding a motor/generator in the place of the flywheel along with a small battery pack or even supercapacitors [20]. The results indicate that the parallel hybrid electric powertrain would provide meaningful energy savings for medium-sized tractors and, when operating with lighter loads, large-sized tractors. Similar conclusions were drawn in recent research by Beligoj et al. (2022), who evaluated the feasibility and life-cycle cost of a parallel hybrid powertrain for different sizes of agricultural tractors [35]. They concluded that very little energy consumption reduction or cost saving would be attained with large-sized tractor (engine power of 210 kW) hybridization, but small-sized orchard tractors and medium–large-sized tractors with medium workloads would provide considerable savings in life-cycle costs. The lower fuel consumption would offer reductions in operational costs and decrease the carbon footprint of these tractors.

The series hybrid electric powertrain has shown to be less interesting for vehicle applications that do not have very repeatable duty cycles or for which there are several use cases. This is the case for passenger vehicles and for agricultural tractors because these are used for a wide variety of purposes by different types of professional and individual users. The simulation results showed the variable potential of a series hybrid electric powertrain, including notable benefits for the medium-sized tractor but less encouraging results in the case of the large-sized tractor. Nevertheless, more detailed simulations should be performed to evaluate the potential of the series hybrid powertrain for different types of agricultural tasks. In comparison to parallel hybrid powertrains, the series hybrid powertrain could provide the possibility of using the electric power take-off (ePTO) and electrified implements, which would be much harder to accomplish with the parallel hybrid due to the limited amount of on-board electric power [35].

Hydrogen as a vehicle fuel is gaining more and more interest as a method for reducing the use of fossil fuels and harmful emissions. Fuel cell systems have been used as the main power sources in vehicles for a long time, but the technological cost and lack of fueling infrastructure are still barriers that have not been fully resolved. Even though fuel cells can be considered as a mature technology, it is not technologically easy to design an agricultural tractor with a fuel cell system because of the spatial requirements for the stack, hydrogen storage, and auxiliary systems. Recent research by Ahluwalia et al. (2022) concluded that the fuel cell system could be cost competitive for agricultural tractors if the targeted improvements to the cost, performance, and durability of the technology could be achieved [36]. Much more research is needed to find the best solutions for alternative fuels for use in agricultural vehicles. For example, methane or methanol might be preferred over hydrogen because of its low volumetric energy density and adapted infrastructure requirements [37]. As a potential fuel for internal combustion engines, burning hydrogen in an engine also has some challenges in terms of NOx emissions and engine knocking [38], and the storage challenge would remain the same as for the fuel cell systems.

Adopting alternative fuels allows for a diversification of energy sources in agriculture. This reduces dependency on a single energy resource by enhancing energy security and resilience in the face of changing market conditions. Using alternative fuels may reduce reliance on imported fossil fuels, providing a pathway towards greater energy independence for agricultural operations. However, implementing alternative fuel technologies in agricultural tractors may require substantial upfront investments. Farmers may be hesitant to adopt these technologies due to concerns about costs and the need for specialized equipment. The compatibility of alternative fuels with existing tractor engines and performance characteristics is a critical consideration. Adapting engines to run efficiently on alternative fuels without compromising power output and durability is still a technical challenge.

The batteries in electric vehicles have seen tremendous technological development and market success, essentially in all on-road vehicle categories; even for 40 ton heavy-duty trucks and battery-powered tractors have been designed and manufactured. Hence, battery and power electronics technology is certainly mature enough even for heavy-duty machinery. The simulation results show that energy consumption could be reduced by up to 70%, which comes from a much higher powertrain efficiency. However, this higher powertrain efficiency does not mitigate the fact that many agricultural field operations require high power or high workload operation. This ultimately leads to high energy requirements and, therefore, the focus must be on the total amount of required on-board energy. The simulations in this research were performed with the consideration that all the tractor models have the same performance and, therefore, the total weight was limited. It could be said that a higher battery capacity than was used in this research could be installed into battery-powered electric tractors [39]. In this case, the tractor weight would increase, which would have some influence on performance and energy consumption, but this influence would need to be evaluated with more detailed simulations. Another challenge that remains to be resolved is battery charging; it is not clear whether every farm could have access to high-power fast charging. Thus, preliminary studies on the fully electrification of agricultural tractors have concluded that it would be more profitable to have a battery exchange system rather than high-power charging systems [40].

Overall, electrification is being applied to agricultural tractors and there are more possibilities than challenges. More research is needed to evaluate the different use cases, namely duty cycle operations, and, especially, life-cycle energy consumption, emissions, and cost [41]. Available electric power would allow the electrification of many auxiliary devices that could lead to additional savings by reducing the idling losses that are quite important for agricultural tractors [42]; Molari et al. (2019) stated that agricultural tractors may remain idle from 10% to 43% of their entire operating time [43]. This would provide additional savings with electrification because unnecessary idling could be easily avoided by shutting down the engine.

5. Conclusions

Simulation models for conventional, parallel hybrid electric, series hybrid electric, fuel cell electric, and battery electric agricultural tractors were developed using Autonomie software. Simulations of three different work cycles were carried out with different workloads to evaluate energy consumption and operating performance. The results show that the battery electric powertrain provided the most energy-efficient powertrain option for agricultural tractors. However, the operating performance was relatively poor because the energy density of lithium-ion batteries does not provide a long enough operating time without fast charging. Furthermore, providing fast charging in agricultural contexts could prove challenging. The simulation results indicate that fuel cell hybrid tractors could provide substantial energy savings in comparison to the diesel-powered, conventional powertrain. The major advantage is the much higher efficiency of the fuel cell system compared to diesel engines. A reasonable amount of hydrogen storage would provide an adequate operating performance of more than 10 h of operation without refueling. It remains to be validated whether the fuel cell system with storage tanks would be a feasible solution, especially for larger-sized tractors. The parallel hybrid powertrain does not provide significant energy savings with high workloads, but medium-sized parallel hybrid tractor models show relatively good performance in terms of energy consumption and operating time.

Author Contributions: Conceptualization, A.L. and N.K.; methodology, A.L.; software, A.L. and R.V.; validation, A.L. and N.K.; formal analysis, K.K.; investigation, A.L. and K.K.; resources, V.F., R.V. and N.K.; data curation, A.L.; writing—original draft preparation, A.L.; writing—review and editing, A.L., K.K. and N.K.; visualization, A.L. and N.K.; supervision, V.F., R.V. and N.K.; project administration, N.K. and V.F.; funding acquisition, N.K. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to acknowledge the financial support of Gurpreet Singh (Vehicle Technologies Office, U.S. Department of Energy). The submitted manuscript was created by the UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. 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. Open access funding provided by University of Helsinki.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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