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Optimizing Custom Hybrid Solutions for Low-Volume Specialist Equipment

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Abstract

Off-road vehicles are typically powered by diesel engines, sized to cover the highest peak loads in their dutycycles. Such applications can be designed with downsized engines, using hybridization to supplement engine power with electrical power for short periods. However, many applications are low-volume and specialized, making it impractical to deploy heavy engineering resources to optimize each one. For this reason, manufacturers tend to produce maid-of-all-work vehicles to cover every situation. This paper demonstrates the benefits of custom hybridization for specialist applications, and addresses the lack of accessible software tools for evaluating such opportunities. Analysis is applied with a fast, low-cost, Concept-based software tool named "ePOP Concept", suited to original equipment manufacturers (OEMs) who seek to provide custom low-volume vehicles. It allows many different powertrain architectures to be evaluated rapidly at the product planning stage, and can be quickly set up and used by non-specialists in simulation. Agricultural load cases are analyzed, showing the benefits of adding hybridization through electric motors and stored energy, supplementing engine power for demand peaks to enable engine downsizing. Use cases for four Fendt diesel tractors were taken from a dataset generated by Götz et al, at the agricultural facilities of the Technical University of Munich, which has been made publicly available by the authors to address the absence of standard load cycle data for the analysis of tractor electrification. The results show benefits for a customizable hybridization architecture to accommodate specific use cases, and the benefits of quick, accessible analysis methods for small engineering teams, to support early product decisions and what-if analyses.

Introduction

Off-road vehicles are used for a wide variety of tasks, that present significant differences in the dutycycles required of their powertrains. A tractor used almost exclusively for maximum-power operation with the largest possible implements might be relatively easy to specify or select, as would be a small tractor used exclusively at low power levels. Some dutycycles, however, include events that require high power or high wheel torque for only short periods of time. An extreme example can be found in a boom lift, whose dutycycle consists mostly of boom movements requiring very little power, but requires a short burst of power to climb onto its transporting trailer. Such dutycycles mandate a much larger power capacity than is required for most of the operating life of the vehicle, and this can drive the selection of an engine that is oversized for most purposes.

This paper examines use cases for tractors engaged in a wide range of farming tasks such as plowing, harrowing and seeding. Whereas a farm tractor will often be selected to cover many different tasks throughout the year and will therefore typically follow a general-purpose pattern of design which is available in mass-produced form, the tendency for farms to become more specialized may offer opportunities for very task-specific dedicated tractors to be customized and sold in smaller numbers.

Background

Vehicle electrification applications are growing in scope and variety, as enabling technologies appear in the marketplace, including among off-highway vehicles that are traditionally powered by diesel engines alone. However, interested vehicle manufacturers, wishing to weigh the cost and benefits of electrifying a specialist vehicle, must access complex and expensive simulation processes before they can make even a simple stage-gate decision. Software tools are required to estimate the benefits, the most important being fuel efficiency.

Götz et al [3] used their dataset of logged tractor activities [1] to simulate different architectures for fully electrified tractors, focusing on the differences between different transmission and axle configurations. Their results indicated that several farming activities performed by tractors would be achievable with a fully electric tractor, but very few types of activities could be sustained for a full work shift of 8 hours without recharging. Their analysis method was thorough, but highly complex and suitable for replication only by experts in simulation. A range of software tools is commercially available for the analysis of powertrain efficiency, including Advisor, AMESIM, Alpha, Autonomie, AVL Cruise, FASTSIM, GT Suite and Simulink. These all require significant investments in preparation work, and/or simulation expertise. Even more input is required if, as an alternative to commercial software, a simulation is built from scratch – enabling customization and avoiding licensing costs, but requiring great expertise in simulation and much labor. At the other end of the scale, the most accessible method now available is FASTSIM, which is a free Excel-based tool available from NREL, but it lacks instruction materials, and still requires simulation expertise to set up correctly. The effort required to set up each tool, and in many cases the significant cost of the license, are prohibitive for a small manufacturer when considering a design change for a low-volume vehicle. For this reason, ePOP Concept was selected for this study. ePOP Concept is a software tool from ZeBeyond Ltd., that is intended to provide accessibility for non-expert users, requiring minimal setup and data gathering effort. It provides automatic evaluation of multiple architectures from a single setup. These advantages are not to be found in any of the alternative software tools that are commercially available.

Beligoj et al [4] analyzed parallel-hybrid powertrains rather than fully electric. The objective of their paper was to demonstrate a thorough and complex analysis methodology, involving a heavy burden of data collection and processing, for information such as individual component costs of different sizes. The authors describe their work as an "exhaustive economical feasibility study" and they present the main conclusion of the study as follows: "... for small specialized tractors which perform a lot of low power operations, significant savings can be obtained from powertrain electrification. On larger size tractors, which perform more power-intensive operations, operating cost savings are very small, leading to limited... savings for the most realistic price combinations."

Lagnelöv et al [5] analyzed self-driving battery-electric farm tractors and centered their analysis on battery cost and the degradation of battery life over time. Their subject vehicle had a battery capacity of 146 kWh, normally not sufficient for an 8h shift, but autonomous control enabled them to work through the 24 hour day, with more frequent recharging intervals than once per day.

Lajunen et al [6] used Autonomie software to simulate conventional, parallel hybrid electric, series hybrid electric, fuel cell electric, and battery electric agricultural tractors. They produced interesting results for the relative efficiency and practicality of these solutions, including that "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." The pure-electric examples gave operating times much less than 8 hours between recharges, making them less suitable for daytime-only operation. The Autonomie software, like most other commercially available vehicle simulation tools, appears to be thorough and accurate, but requires significant expertise and effort in data discovery and preparation, to set up and use.

Ali et al [7] propose a techno-economic tool to assist farmers in evaluating the total costs of ownership of electric and hybrid tractors, including an estimate of nitrous oxide (NOx) emissions, along with a model predictive controller for powertrain energy management. They isolate the less invasive alternative of electrifying accessory loads, like cooling fans, HVAC and detachable accessories such as augers. Regarding full vehicle electrification, their study concludes that "electric tractors are more cost-effective for light-duty farming activities (engine loads less than 20%). On the other hand, hybrid powertrains are more economical for medium-duty tasks, where engine loads range from 20% to 60%." [7]. The tool is research-grade methodology rather than commercially available software, so although it is intended to assist farmers, it would require significant simulation expertise and effort to replicate and apply.

Regazzi et al [8] analyze the tractive efficiency of agricultural tractors, assessing the work lost to wheel slip. This phenomenon would form an important part of a complex analysis method, but has been ignored in the simplified methodology presented here, which is based on the ePOP Concept software tool from ZeBeyond Ltd. [9, 10].

Mocera et al [14] introduce two numerical models, for calculating the operating costs of a parallel-hybrid tractor and the diesel equivalent, and exercise the models using dutycycle data for an orchard tractor. They separated the power take-off (PTO) loads from drawbar loads as these could be driven by separate electric motors, and they introduced an energy management strategy with the aim of improving battery sizing. They state "Modeling an agricultural tractor is quite a demanding task due to complexity of the mechanical architecture and of the power split among its several subsystems." [14]. Their method is potentially of interest for research purposes but does not offer a means of access for entities lacking engineering resources and expertise in vehicle simulation.

Motivation

While farms are becoming more specialized, powertrain technologies are also offering new architectural possibilities through the development of electrification, which presents opportunities either to substitute electricity for diesel fuel through the use of large batteries, or to reduce diesel fuel usage through mild hybridization that uses smaller batteries without recharging. Costs for diesel and electrical energy are both projected to rise in line with average inflation over the next 10 years [2], and the total cost of ownership (TCO) for farm tractors over a 10-year period is greatly dominated by the cost of energy, so it is worthwhile for both OEMs and farmers to take a fresh, analytical look at the possibilities of electrification for certain tractor applications in farming. Such a study, however, quickly escalates into a complicated multivariate optimization exercise, not least because electrification is better suited to some tasks than others. Battery capacity, for example, limits the length of a shift that a fully electric tractor can complete, and a mild hybrid (without recharging) is limited by the amount of energy needed for the short bursts of demand that exceed the capacity of a downsized engine. The load pattern in such cases is very task-specific.

If market opportunities exist for custom-hybridized tractors, an OEM must also consider the engineering overhead required for any new design. As these opportunities would by definition be low-volume, it follows that the engineering processes used to evaluate and implement such custom designs would have to be quicker and cheaper than the typical design cycle for a tractor. Customized vehicles are often associated with high profit margins, but these quickly evaporate if extensive engineering processes are used for low-volume products. Therefore there is a need for quick, low-cost methods of evaluating such opportunities without diverting significant resources, such as simulation engineers or expensive CAE tools.

Combining the synergistic opportunities presented by farm specialization, electrification, the attraction of customized vehicles for specific tasks, and newly available methodologies, this paper explores quick, low-cost methods for evaluating the cost savings available over a 10-year period, where customized electrification solutions are applied to off-road powertrains, using the example of conventional farming processes carried out by agricultural tractors.

Farming Use Cases

Tractors

Test data were taken from four Fendt diesel tractors (models 211, 314, 722 and 724), published in Götz, T., Korb, L., Bosch, T., & Bernhardt, H. (2025), *Agricultural Load Cycles: Tractor Mission Profiles From Recorded GNSS and CAN Bus Data,* [1]. This dataset, generated at the agricultural facilities of the Technical University of Munich, has been made publicly available by the authors, to address the absence of standard load cycle data for the analysis of tractor electrification.

The Fendt 722 and 724 are classed as “row crop” tractors, ideally matched with the largest possible implements and used for tasks requiring continuous periods of maximum power. The Fendt 211 is considered a “utility tractor”, used for multiple miscellaneous tasks mostly requiring low power, while the 314 (shown in Figure 1) is suited for both purposes.

FIGURE 1 Fendt 820 Vario tractor. Image by joost j. bakker, licensed under CC-BY 2.0. Source: Wikimedia Commons (File: Fendt 820 Vario TMS.jpg).

Farming Activites

The tractors performed the tasks listed in Table 1. The path followed in traversing one of the fields is shown in Figure 2.

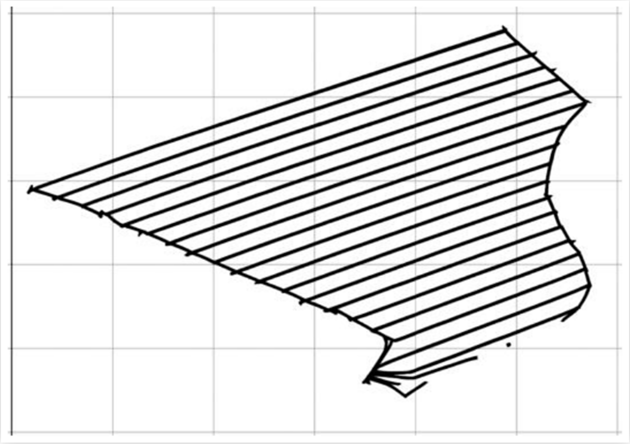
The tasks may be described as follows:

Power Harrowing – Uses a power take-off (PTO) rotary harrow, to create a fine seedbed by breaking and leveling soil before seeding.

TABLE 1 **Tractor models, power, and work types** *(Adapted from Götz et al., 2025 Data in Brief 60 (111494)) [1]*

Tractor model	Tractor power [kW]	Work type
Fendt 211 Gen3	77	Power harrowing
		Precision air seeding
Fendt 314 Gen4	104	Fertilizing
		Spraying
		Seed drill combination
		Disc harrow
		Mowing (front)
		Mowing (large-scale)
		Swathing
		Silage transport
Fendt 722 Gen6	163	Fertilizing
		Seedbed combination
		Cultivating (deep)
		Cultivating (shallow)
		Power harrowing
		Disc harrowing
		Mulching
		Plowing
		Seed drill combination
		Transport
Fendt 724 Gen6	174	Cultivating
		Plowing
		Silage transport

FIGURE 2 A map representation of the path followed by the Fendt 314 tractor, during a 3 m seed drill combination operation. For scale, the length of the field in this view is approximately 390 m. The patterns of motion for all the activities in this data set are similar, over several different fields. Reproduced from Götz et al [1]



Precision Air Seeding – Places individual seeds accurately, using an air stream and metering system to achieve uniform crop spacing.

Fertilizing – Applies fertilizer across the field using a spreader or sprayer, driven by the PTO.

Spraying – Distributes crop-protection chemicals through nozzles supplied by a pump, powered by the PTO.

Seed Drill Combination – Integrates a PTO-drive harrow and seed drill in one pass, to prepare soil and deposit seed simultaneously.

Disc Harrowing – Uses concave discs pulled by the drawbar to cut, mix, and loosen soil for weed control or seedbed preparation.

Mowing – Cuts grass or forage crops using rotary or disc mower units, driven by the PTO.

Swathing – Rakes mown material into rows for drying or collection using PTO-driven rotating tines.

Silage Transport – Hauls chopped forage from the field to storage, using drawbar-towed tipper or silage trailers.

Cultivating (deep or shallow) – Loosens and aerates soil with tines drawn through the ground to improve structure and weed control.

Mulching – Shreds crop residues or vegetation on the soil surface using a PTO-driven flail or rotary cutter.

Rotary Tilling – Uses rotating blades powered by the PTO to pulverize and mix the upper soil layer.

Seedbed Combination – Combines passive harrow and roller elements to level and firm soil before seeding.

Plowing – Turns and inverts soil with moldboards pulled by the drawbar, to bury residues and prepare for planting.

Time-series data were logged for all these tasks by Götz et al, comprising multiple data channels measured at a frequency of 10 Hz, including engine RPM, engine torque, ground speed, wheel speed and fuel consumption [1]. For the purpose of high-level powertrain architecture analysis, the most useful parameter is the engine power output, derived from engine RPM and torque, as it indicates the patterns of full-load, part-load and light-load operation required for each task. The analysis for this paper did not require 10 Hz resolution, so the data were averaged to a coarser time scale of 1 Hz using simple Python code.

Energy Savings by Operating Condition

Power Take Off

Eight of the fourteen farming tasks listed in Table 1 require PTO drives, which tend to have less options for gear ratio selection, compared to the forward speed of the vehicle. Hydraulic PTO drives are available, offering speed control, but they are less efficient than mechanical linkages. Electrification offers the opportunity for a separate electrical PTO drive, offering both speed control and better efficiency.

Idle

There are occasions between task events when the tractor is required neither to move nor to run the PTO, but the engine is still kept running, usually in order to power accessories (such as cabin climate control). There may also be other occasions when movement or PTO operation is required but with very low power. In both these situations, engine-off operation becomes possible if the vehicle is partially or fully electrified, saving energy. However this does require one of the more expensive hybrid architectures where the engine can be disconnected while the e-motor drives the wheels and PTO. An electrified powertrain can also be designed to deliver frequent engine restarts, with greater durability than a conventional Bendix starter gear.

Part Load Operation and Engine Downsizing

Part load operation is clearly not ideal, as it implies a powertrain that is oversized for the task, but it is a common occurrence because the best tool is not always available for the job. Diesel engines (unlike gasoline engines) operate most efficiently at full load, so a task performed by a larger engine at part load tends to use more fuel than the same task performed by a smaller engine at full load. Therefore the downsizing of diesel engines can improve efficiency, provided the peaks of power demand can be met. Electric drive can also deliver better part-load efficiency than with an internal combustion engine (ICE), although the ability to use electric drive with the engine off depends on the architecture selected.

By supplementing the power of the engine with stored electrical energy, a mild or full hybrid can increase the maximum available power for work, enabling downsizing, but only for as long as the stored energy can last. Some tasks require short bursts of maximum power whereas others demand long periods of continuous maximum power. It is necessary to ensure that the powertrain architecture is matched to the required tasks, if the engine is downsized to take advantage of hybridization.

Electrification Architectures

P0 – P5 Configurations

Parallel-hybrid powertrains comprise an ICE and at least one electric traction motor-generator. Their configurations are described by the automotive industry's Px notation in Table 2.

P0 (parallel) is the easiest architecture to add to an existing tractor design, e.g. if the motor can drive the nose end of the crankshaft, but, along with P1, it offers the least benefit in fuel savings, as it does not allow the motor to work without the engine turning. P5 offers independent wheel torque control together with the lowest losses, but it requires very large and expensive motors owing to the lack of gearing, and is probably impractical for a tractor. For a completely new tractor with full freedom of design, the P2 parallel hybrid is probably the most attractive hybrid option, offering significant efficiency benefits while being cheaper to implement than P3-P5 or the series hybrid. In on-road vehicles a P2 hybrid requires control over gear selection, i.e. automatic gear shifting, but tractors often operate from rest without changing gear, so this might not be required.

Series-hybrid powertrains comprise an ICE, a generator driven by the ICE, and at least one motor-generator driving the wheels. A series hybrid offers great flexibility by completely detaching engine rotation from wheel rotation, but has an efficiency penalty because all the energy passes through two inverters and two electrical machines. The relative benefits of a series hybrid are therefore highly task-specific.

TABLE 2 Parallel Hybrid powertrain nomenclature

Notation	Traction motor drive connection	Functional Characteristics
P0	Crankshaft, at front of engine (opposite end to transmission)	Motor cannot work with engine off.
P1	Crankshaft, at rear of engine	Motor cannot work with engine off.
P2	Between engine and transmission, after a disconnect clutch	Motor can work with engine off, saving fuel.
P3	On output shaft of transmission, before axle	Motor can work with engine off. But gearing is less advantageous than P2, and the motor must cover a large speed range.
P4	On axle	As P3.
P5	Inside wheels (hub motors)	As P3; lowest losses but highest costs.

Mild Hybridization (Without Charging)

Mild hybridization can take any of the forms P0-P5, and comprises an ICE, plus battery storage with one or more electric traction motors that provide supplemental power to the powertrain. The motors also act as generators when needed, taking power from the engine to recharge the battery. The label “mild” indicates that a smaller battery is used than for full hybridization. In P2-P5 and serial form, this architecture can save costs by enabling engine shutoff instead of idling, and by transferring work from less efficient to more efficient engine operating points. In all forms, i.e. P0 to P5 and serial, engines can be downsized at the point of selection, providing short-term power boosting if the maximum power is required only for short periods of time. An example of the short-burst phenomenon is a combine harvester, which runs at a high constant speed along a row, but must slow down, turn, and then accelerate back up to operating speed for the next row. The acceleration requires more power and is important to increase the speed of the work, but is needed only for a comparatively short period, making this a potential application for electrical energy storage, which can be replenished using engine power during the run along each row. The efficiency advantage would derive partly from recouping energy during deceleration, but mostly from downsizing the engine.

Full Hybridization (With Charging)

Full hybridization comprises the same equipment as mild hybridization, but with a much larger battery, and the addition of on-board and off-board components to facilitate recharging from the electrical grid. The ICE can be downsized to the extent that the energy storage is sufficient to accommodate the periods when full power is required. This architecture can save cost by substituting electrical energy for diesel fuel energy, in addition to the methods used in partial hybridization.

Battery Electrification

The chief advantage of 100% battery electrification (i.e. eliminating the ICE) from a TCO perspective is the reduction of energy cost in $/kWh. Energy, viewed in isolation, is generally cheaper from electrical sources than from diesel fuel, and maintenance is also cheaper for fully electrified tractors [10]. Against this (along with the capital cost of the equipment) there are practical considerations that are case-specific, including the installation costs of chargers, the associated increase in electricity supply capacity (which adds to the cost of electricity for a commercial electricity tariff), the length of time the tractor can operate between charges, and the practicality of charging between shifts. The size and weight of the battery also presents a practical limitation to the range of a battery-electric tractor, which ideally would last the length of a daytime work shift.

Matching Powertrain Architectures to Tasks

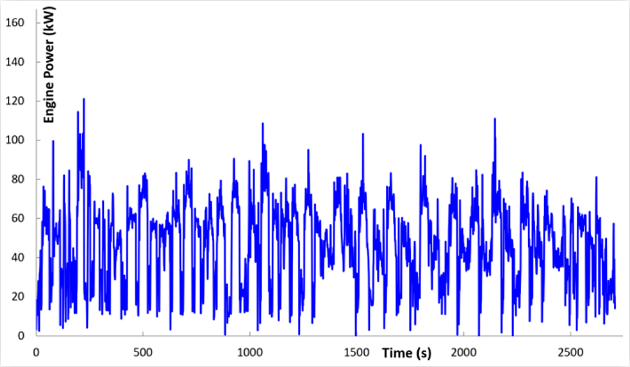
Tasks Requiring Continuous Full Power

Mowing, disc harrowing, cultivating, plowing and seed drill combination are all poor candidates for electrification, as they were all conducted at or near the maximum power of the tractor for extended periods. This rules out full electrification on the grounds of battery weight, as the capacity required to complete a full shift requires a battery weight incompatible with the weight of the tractor. It also rules out hybridization, because there are insufficient opportunities between full-power events for the engine to recharge the battery.

Tasks Requiring Only Intermittent Full Power

As an example of part load operation, the Mulching activity in this dataset was conducted with a 3m implement towed behind the 722 tractor, at the very slow speed of 0.6 m/s (2.2 km/h). A flail/rotary mulcher has a limited capacity to mulch the biomass that it uses, and it operates at a fixed PTO speed. In this case the engine was operating at around 40% of maximum power or less for the whole operation, as can be seen in Figure 3, but the speed of mulching could not be increased by speeding up the tractor, owing to the limited capacity of the implement. In a perfect scenario a smaller tractor might have been chosen for this task, using less fuel, but in practice only a larger tractor may be available. However, lower power is not necessarily ideal, since more engine power is occasionally used, for example in traveling from field to field at higher speed, which is a shorter-duration requirement quite well suited to a hybridized powertrain architecture. Where travel between fields involves public roads, there is also a safety advantage in being able to keep up with some minimum speed.

FIGURE 3 Graph of Engine Power (kW) versus Time (s) for the Fendt 722 tractor, during a mulching operation. This tractor has a maximum power of 163 kW, so it uses less than half the available power for this operation.



Grouping Tasks for Specific Architectures

The tasks that are suitable for electrification are conveniently aligned with the "utility tractor" class of vehicles, which are generally used for any tasks where the larger row-crop tractors are not needed. However, most of the utility-tractor tasks can also be performed by row-crop tractors, at the cost of additional fuel usage and the disadvantage of diverting those tractors from the tasks where they are essential. So it seems practical to identify suitable candidates among the annual farming activities, and select or design electrified tractors that could perform them more efficiently than the diesel alternatives. Figure 5, taken from a study by Varani et al of the University of Bologna [11], shows the cumulative usage of utility, row-crop and high-power row-crop tractors through the year. It can be seen that high power row crop tractors, which use the most fuel, are used intensively for 3 months of the year and otherwise not at all, whereas tractors in the utility and row-crop classes are used throughout the year. Figure 6, from the same paper, shows that all tractor types experience a significant proportion of idling and headland turns, requiring low power, and also transport, which conversely may require more power than some field work, in order to keep up with road traffic. Therefore there may be efficiency opportunities with architectures that are more efficient at part load, but also capable of short-term bursts of maximum power.

FIGURE 4 Graph of Engine Power (kW) versus Time (s) for the Fendt 724 tractor, during a plowing operation. This tractor has a maximum rated power of 174 kW, so it uses almost all the available power for this operation.

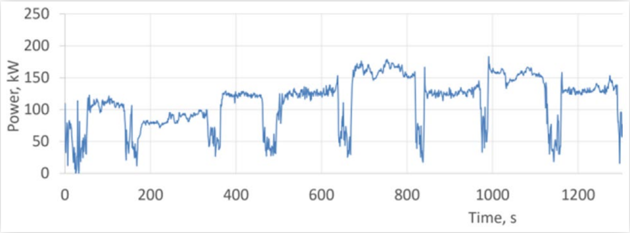


FIGURE 5 Cumulative percentage of tractor working hours by tractor type. Reproduced from Varani et al [11]. Utility tractors (UTx) are used most heavily in Feb-June, row crop tractors (RCx) are used evenly through the year, and high power row crop tractors (HPx) are used during harvest season (July-Oct).

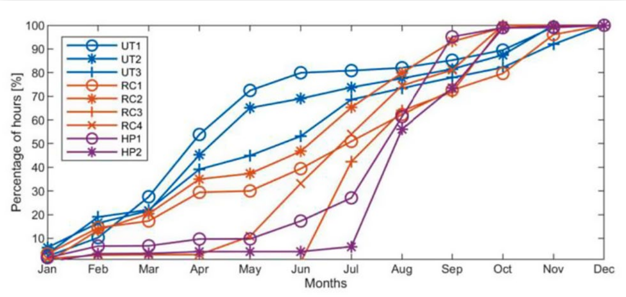
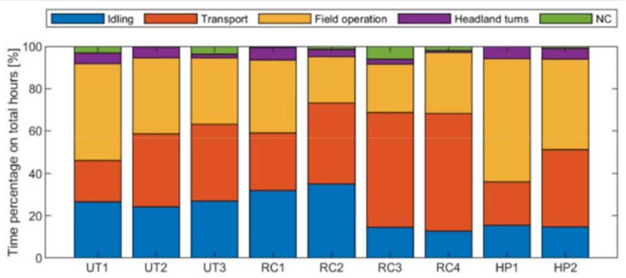


FIGURE 6 Activity percentage by tractor type. Reproduced from Varani et al [11]. Utility tractors (UTx), row crop tractors (RCx) and high power row crop tractors (HPx) all experience significant periods of idling, transport and headland turns, i.e. activities other than field work.



Estimating Dutycycles for Utility Tractors

Combining the percentage usage data of Figure 6 from Varani et al [11] with the time-series data from Götz et al [1], a dutycycle was compiled to represent an 8-hour shift to represent the annual workload mix for a utility tractor, comprising the following tasks:

1. Power Harrowing (small implement)
2. Precision Air Seeding
3. Fertilizing
4. Spraying
5. Swathing

These activities were selected because they do not involve long periods of continuous high power. In order to scale these dutycycle components correctly, it is necessary to estimate the total hours for each activity. Annual tractor hours for these activities on a 300 ha farm, including field efficiencies (idle, transport etc), are shown in Table 3. These were estimated using data from ASABE D497.7 [11], KTBL Faustzahlen [12] and the Scottish FAS Labour & Machinery Guide [13].

TABLE 3 Estimated tractor hours per activity per year, for a utility tractor on a 300 hectare farm, [11, 12, 13].

Operation	Speed m/s	Total Annual Hours
Harrowing	1.1	337
Seeding	1.0	396
Fertilizing (18m)	3.3	38
Spraying (18m)	3.3	60
Swathing	1.8	32
Total		863

Analysis

Input Data Preparation

The time series of engine power (kW) versus time (s) was assembled from the Goetz dataset [1] for the selected activities, adjusted to represent an 8-hour daily shift, and fed into the ePOP Concept software tool. A sample of each activity is shown in Figures 7-11.

FIGURE 7 Engine power used during Harrowing.

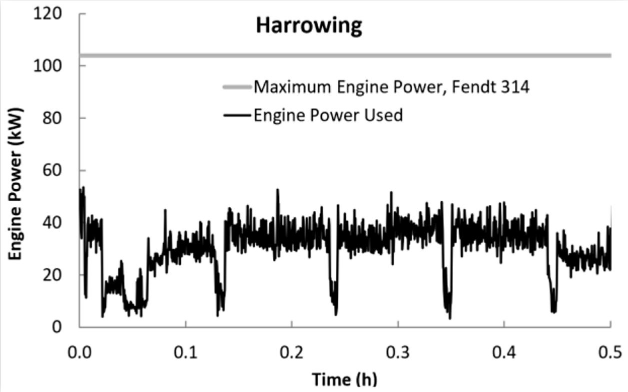


FIGURE 8 Engine power used during Seeding.

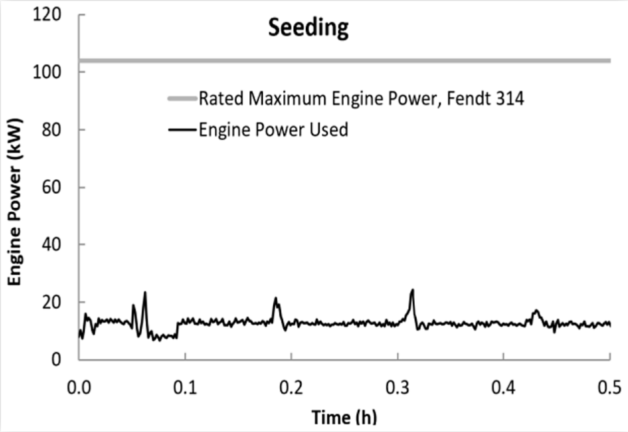


FIGURE 9 Engine power used during Fertilizing.

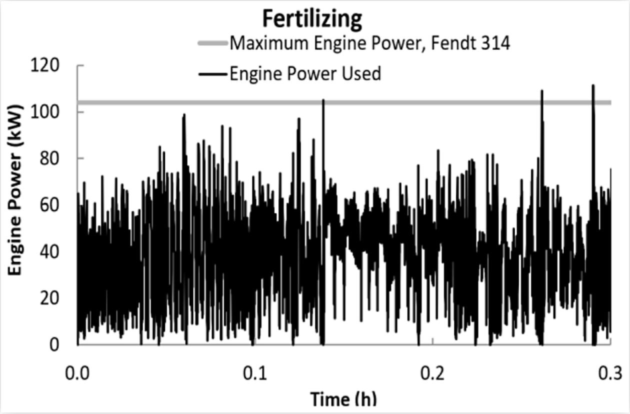


FIGURE 10 Engine power used during Spraying.

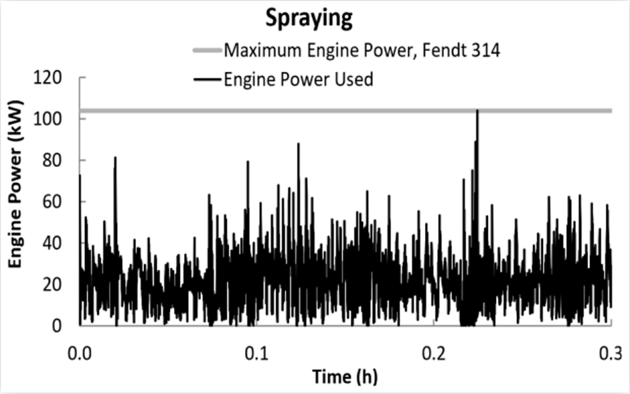
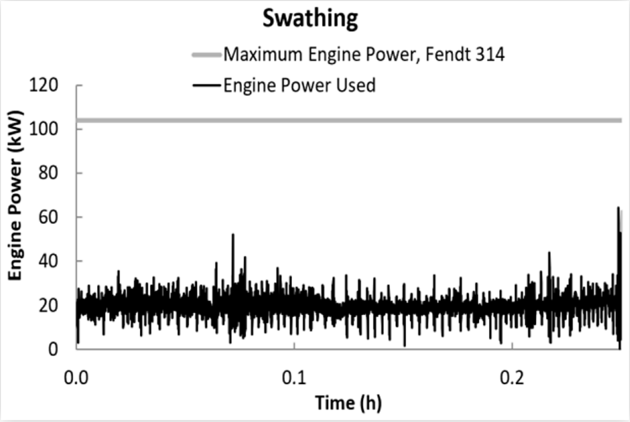


FIGURE 11 Engine power used during Swathing.



Simulation Tool and Assumptions

ePOP Concept models the efficiencies of the powertrain components using simplifying assumptions. ICE brake specific fuel consumption (BSFC) is assigned according to a choice of engine type made by the user (e.g. off-highway diesel, or gasoline) and assumed constant under all conditions. Similarly, fixed efficiency values are assigned for inverters, electric motors, batteries, transmissions and hydraulic components, according to the component type selected. The estimated errors are not intended to be definitive, but simply to illustrate the approximate scale of errors that may be introduced when a fixed efficiency value is assumed. In practice the estimated errors are reduced, partly because the worst cases are usually found at edges of the operating envelope that are rarely visited, and partly because powertrain duty cycles usually demonstrate higher residency in operating regions with better efficiency, so the average efficiency is significantly better than the worst cases.

An important feature of the ePOP Concept software is that the load cycles are the only data inputs required. Some internal parameters are available for adjustment, but the program is ready to run with load cycle data alone.

The ePOP Concept tool takes this time series as its only input, and creates a first analysis without further prompting, proposing a powertrain architecture to match. The user then adjusts parameters, e.g. electricity and diesel costs, to refine the result. This approach allows a new user to set up and interact with the program in a very short time, without the need for expertise in simulation.

The ePOP Concept tool offers a quick analysis methodology with minimal setup, which automatically selects and sizes powertrain components to match an input load cycle, although the exact component sizes that result may not be commercially available. In order to make this possible without a heavy burden of data discovery on the user, several simplifying assumptions are made in the software, including that the cost, weight, package and functional characteristics of components are defined in constant or simply scaled form, so that they automatically adjust with the size of the component. The engine power output is sized to accommodate the input duty cycle and accessory/cooling load, with an added margin for the possible losses of the powertrain after optimization. All engine characteristics are scaled during optimization according to the power output, using simple relationships such as a linear relationship between engine power and cost. The remaining components are also sized similarly, with reference to the power requirements in the duty cycle. This method produces highly simplified results, but enables a rapid optimization of multiple architectures. Once the user has been given a solution, they can constrain the sizing of each component manually with minimum and maximum limits, if further refinement is desired.

The key output metric is TCO over 10 years. This is simplified to include only the capital cost of the powertrain and off-board charger (excluding the rest of the vehicle), and the cost of fuel and electricity over 10 years, as required to complete the input dutycycle (which represents an 8 hour shift), a specified number of times per year.

Powertrain Architectures

For this case, it quickly became apparent that a fully-electrified powertrain would not be able to complete the dutycycle. The analysis initially looked promising, but it required a battery weight exceeding 25% of the base weight of the vehicle in order to complete an 8 hour shift between charges, so it was eliminated from the analysis.

Two P0 parallel-hybrid solutions and two series-hybrid solutions were compared with the conventional ICE-only baseline (a Fendt 314). Powertrain A, shown in Figure 12, is a parallel hybrid with recharging. Powertrain B, shown in Figure 13, is the same but without recharging. Powertrain C, shown in Figure 14, is a series hybrid with recharging, and Powertrain D, shown in Figure 15, is a series hybrid without recharging.

Results

Figure 16 shows the ePOP Concept result derived from this input data for Powertrains A and B. The upper line represents one of the two solutions, which is a hybrid without the ability to recharge (B). The lower line represents the same architecture but with recharging (A), so it can be charged between shifts. The graph shows TCO versus the degree of electrification, with 0% indicating a pure ICE diesel solution (conventional), and 100% indicating a fully battery-electric solution with no engine.

FIGURE 12 ePOP Concept schematic for Powertrain A: P0/P1 Parallel Hybrid with recharging. From left to right – Grid, charger, battery, fuel tank, inverter, engine, motor/generator, transmission, drive.

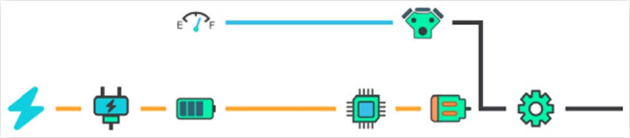


FIGURE 13 Powertrain B: P0/P1 Parallel Hybrid without recharging

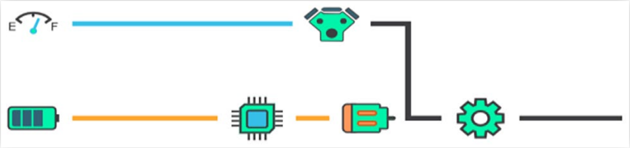


FIGURE 14 Powertrain C: Series Hybrid with recharging

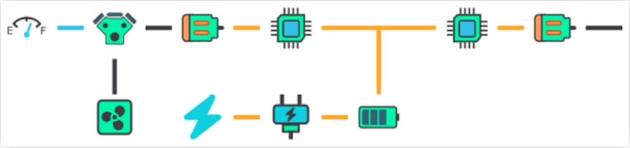


FIGURE 15 Powertrain D: Series Hybrid without recharging

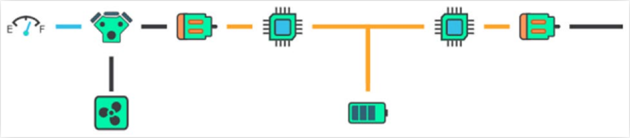
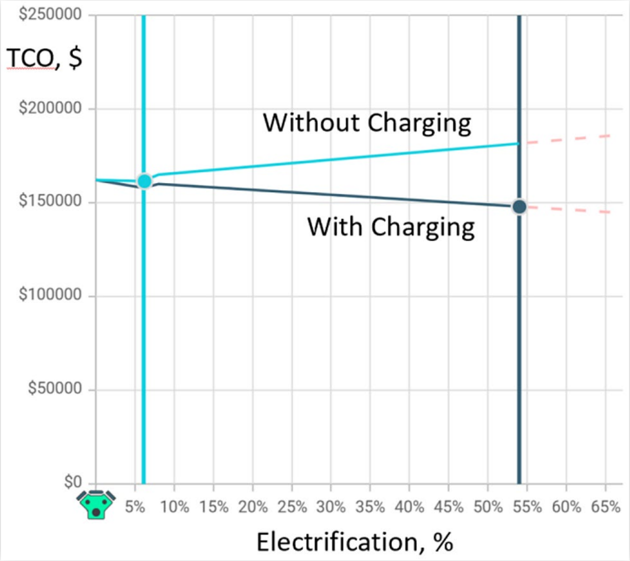


FIGURE 16 ePOP Concept graph of Total Cost of Ownership over 10 years ($) for the P0 parallel hybrid solutions, including powertrain cost and fuel cost, but excluding other costs, versus proportion of electrification (0% = pure ICE, 100% = pure electric). The vertical lines represent the optimal configuration without charging (left) and with charging (right). The degree of electrification is limited at about 54% by the maximum battery weight allowed.



The upper line, showing a parallel hybrid without charging (B), shows a small initial cost reduction with electrification, but this quickly reaches a minimum, and thereafter the cost increases. The increase in electrification after this point principally comprises an increase in battery size, but in fact this brings no further benefits after the minimum, because this powertrain cannot recharge.

FIGURE 17 Waterfall chart of Total Cost of Ownership over 10 years ($), showing the walk from the ICE-only baseline ($162,170) to the P0 Hybrid with charging ($147,999)

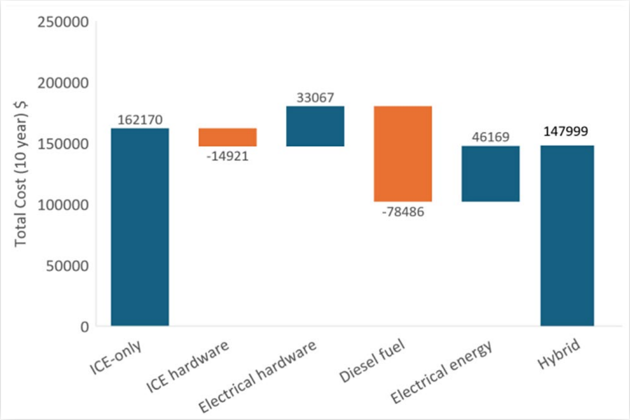


TABLE 4 Estimated cost of ownership (10 year) for ICE versus hybrid architectures.

	ICE	A Parallel Hybrid	B Parallel Hybrid	C Series Hybrid	D Series Hybrid
Charging	No	Yes	No	Yes	No
ICE Power, kW	111	11	40	15	33
E-motor Power, kW	0	104	66	104	104
Powertrain Cost $	16826	34972	16271	36921	23547
Diesel Cost $	145344	66858	145344	85711	186328
Electricity Cost $	0	46169	0	46169	0
TCO $ (10 year)	162170	147999	161615	168801	209875

The lower line, showing a parallel hybrid with charging (A), shows a near-continuous reduction in TCO as the battery increases in size. This is due to the replacement of diesel energy with electrical energy, which is cheaper. However, it becomes impractical once the battery reaches an arbitrary limit selected for this study, i.e. the point where the battery weight exceeds 25% of the original tractor weight, corresponding to about 54% on the x axis. This limit was selected as the point where the load bearing structure of the tractor would become overloaded, and the downsizing of the engine partially offsets the total weight, but the exact value is arbitrary for the purposes of this study. After this point, the line in Figure 16 changes from solid to dashed to indicate that the solution is not feasible.

Figure 17 shows a waterfall chart indicating the cost steps for each component of the TCO, walking from the baseline (with ICE but no electrification) to the maximum possible degree of electrification in the P0 hybrid with charging, represented by the second vertical line in Figure 16. It can be seen that the reductions in fuel costs and ICE hardware costs exceed the added costs of electricity and electrical hardware.

Table 4 compares the major cost elements for the five architectures that were compared, leading to the following observations about the potential benefits of tractor electrification for the selected group of tasks:

1. The energy cost over 10 years is several times larger than the capital cost of the powertrain.
2. The ePOP Concept tool selected the baseline ICE engine power of 111 kW to give a margin of error above the dutycycle data, where the highest value is 104 kW. The ICE power is greatly downsized by all forms of hybridization, but the cost reductions are offset and usually exceeded by the costs of the electrical hardware.
3. The downsizing of the ICE in cases A and C seems extreme. It is doubtful if the tractor could do more than “limp home” with so little power, in the case of a fully discharged battery. A more realistic approach would be to increase the minimum power allowed for the ICE, which is possible in ePOP Concept.
4. The parallel hybrid without charging (B) recoups the additional cost of the electrical system by downsizing the engine, but the resulting TCO saving is so small as not to be worth considering.
5. The parallel hybrid with charging (A) delivers a 9% reduction in TCO over 10 years. This is significant, but it is not so large as to be conclusive, and the user should be cautious of the assumptions and simplifications in the analysis method.
6. The series-hybrid solutions result in increased TCO, so they should be eliminated from consideration. This is primarily because of the round-trip efficiency losses of passing all the energy through two electrical machines and two inverters, not the added cost of the components.
7. The P2 configuration is absent from this analysis but it could be expected to deliver more TCO benefit, combining the efficiency advantage of direct-drive with the ability to disengage and shut off the engine for electric-only operation. However it requires a much greater redesign than a P0.
8. The powertrain costs “with charger” are significantly higher than without, highlighting the fact that each tractor would need its own dedicated overnight charger of at least 13 kW capacity.
9. The ePOP Concept software tool makes this type of preliminary analysis accessible to a user without the expense of dedicated simulation engineering staff, delivering results with minimal time expended on data collection and analysis.

Summary/Conclusions

The agricultural tasks in this study were analyzed using logged data from a published source. The results indicated that they should be divided into those with long periods of high power demand, which were found to be unsuitable for electrification in any form, and those with only intermittent, short periods of high power demand, which were potentially suitable for hybridization. The second group aligned conveniently with those normally performed by a “utility tractor”, denoting a tractor used for any tasks where the power capacity of a row-crop tractor is not required.

Analysis of the results using the ePOP Concept software tool showed that 100% battery electrification was not feasible for the selected group of tasks, as a battery with sufficient capacity to work for an 8-hour shift would add very much more than 25% of additional weight to the base tractor. This limit was arbitrarily selected to eliminate solutions weighing more than the vehicle structure could bear, for the purposes of this study.

These two conclusions are very similar to those reported in the Introduction in [3, 4, 5, 6, 7], but were arrived at with a much more easily accessible tool (ePOP Concept), requiring very little data discovery or preparation, and little or no expertise in simulation.

Four hybrid architectures were analyzed using ePOP Concept, and their results, shown in Table 4, indicated which architectures were potentially beneficial to reduce TCO over 10 years, and which could be eliminated from consideration. A total cost saving of 9% was indicated for the best solution, a parallel P0 hybrid with charging. This benefit is not considered conclusive, however, as it is probably comparable with the margin of error for this simplified process of analysis.

The primary purpose of the paper was to investigate tractor electrification at a conceptual level without great detail, and thus to illustrate a quick, affordable method to compare potential powertrain architectures using ePOP Concept. The results show how it can be set up and used very quickly without expertise in simulation methods. In the course of the study, interesting conclusions are reached about tractor electrification, but the methodology is introduced with a view to serving a wider range of off-road vehicles where specific load cycles may be found to align beneficially with custom hybrid architectures.

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