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Tractors with alternative energy carriers: A simulation-based evaluation in different agricultural contexts

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Climate targets and persistent fuel-price uncertainty are increasing the pressure to evaluate alternative energy carriers for tractors. Their suitability depends not only on drivetrain efficiency but also on farm structure, annual utilization and the cost of providing capital-intensive machines. This paper couples a year-long simulation of selected tractor-dominated agricultural operations with a KTBL-based machinery-cost model for two contrasting German farms covering 48 ha and 1,190 ha, respectively, and compares diesel, HVO, battery-electric, hydrogen and methanol range-extender concepts for the years 2025, 2030 and 2040. Competitiveness is governed by the interaction of utilization and cost structure rather than by nominal efficiency alone. On the small farm, only a mixed battery-electric and HVO fleet approaches diesel parity by 2040, at approximately EUR 11,400 against EUR 11,700 for diesel. On the large farm, a mixed HVO and hydrogen fuel-cell fleet reaches approximately EUR 160,400, compared with EUR 163,400 for the diesel reference. These findings are conditional and exclude external charging and refueling infrastructure costs.

Keywords

Agricultural machinery, alternative energy carriers, tractor drivetrain, process simulation, scenario analysis, machinery costs, utilization

Tractors are the backbone of mechanized agriculture. A single machine has to provide traction power, power take-off (PTO) power and hydraulic power across highly heterogeneous tasks that range from heavy primary tillage to precision seeding, from fertilization to transport, and from loader work to on-farm handling. This breadth of duty is one of the defining features of the tractor as a work machine, because it forces a single drivetrain to remain efficient and controllable over a wide range of loads, speeds and operating durations. Diesel propulsion has remained dominant in this role because it combines high volumetric and gravimetric energy density, robust transient performance under fluctuating field loads, established maintenance know-how, and a mature and widely available refueling infrastructure. Together these properties have made diesel the reference against which every alternative concept is measured.

At the same time, diesel-powered traction contributes directly to agricultural greenhouse gas emissions and exposes farms to fuel price uncertainty. The pressure to act is increasing through climate targets, taxation mechanisms, renewable-fuel mandates and sustainability requirements that are propagated along agricultural value chains. Regulatory instruments such as emissions trading and rising carbon-related compliance costs translate these targets into direct operating-cost signals for energy-intensive field work. Farm managers, contractors and manufacturers therefore face strategic

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decisions about propulsion alternatives that must deliver both ecological and economic performance without compromising the operational reliability on which the farming calendar depends. Because tractors are long-lived investments, these decisions commit a farm to a given technology for many years, which makes an assessment that reflects realistic operating conditions particularly valuable.

A key difficulty is that the operational and economic suitability of a tractor concept cannot be evaluated from nominal efficiency or drivetrain specifications alone. Agricultural work is organized in process chains that are bound to strict agronomic time windows. These windows create pronounced peak-load periods during seeding and other time-critical field operations, in which several machines must operate in parallel and often for long workdays. Field structure and the distances between farmstead and fields add non-productive travel time and additional energy demand that do not contribute to work output but still consume operating hours and onboard energy. As a consequence, the annual utilization that a given tractor reaches, and the way its energy demand is distributed over the season, are properties of the farm and its field layout rather than of the drivetrain in isolation. The same tractor concept can therefore be viable on one farm and impractical on another even under identical energy prices.

Several alternative energy carriers and drivetrain concepts are currently discussed for agricultural tractors, but their suitability is constrained by the specific requirements of field operation. Battery-electric tractors offer high tank-to-wheel efficiency and low local emissions, yet their use in high-power field work is limited by the comparatively low energy density of battery storage, by the resulting restrictions on onboard energy capacity, and by the time required for recharging. These constraints are particularly relevant during long workdays and narrow agronomic time windows, when interrupting field work to recharge directly reduces the area that can be completed within a window. Hydrogen-based concepts offer short refueling times and can therefore limit downtime during peak periods. However, compressed hydrogen has a low volumetric energy density, which leads to large and costly storage systems and creates packaging challenges for conventional tractor architectures. Hydrotreated vegetable oil (HVO) provides the highest compatibility with existing diesel tractors, because it can be used in compression-ignition engines with only limited hardware changes, but its long-term availability depends on a sustainable feedstock supply. Methanol is considered in this study only as part of a fuel-cell range-extender concept. It offers the logistical advantages of a liquid fuel, but it adds onboard conversion steps and increases system complexity. This diversity of strengths and weaknesses is the reason why a comparison must place each concept in the context of a concrete farm and a concrete workload.

To support robust decisions, this paper applies an operational simulation that represents selected tractor-dominated farm process chains and links them to a transparent cost model. The simulation yields tractor-specific annual utilization and energy demand based on operation-specific process chains and seasonal time-window constraints, which are then used to compute annual costs with a machinery-cost model based on the KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft) framework. The coupling of an operational model with a cost model is central to the approach, because it ensures that the economic results are driven by the same utilization and workload that the field simulation produces rather than by generic assumptions. Compared with shortened conference versions of the study (Reuter and Frerichs 2025), this manuscript expands the methodological background, states the scenario scope more explicitly, and separates the model results from the discussion and the limitations. The analysis is designed as a scenario-based techno-economic comparison. It does not claim to forecast future market shares, nor to provide a complete energy-system assessment, and its conclusions are therefore stated as conditional if-then results that hold under the assumptions made explicit in the following sections.

State of knowledge and research gap

Alternative propulsion concepts for agricultural tractors are discussed against the background of greenhouse-gas mitigation, fuel-price uncertainty and the need to maintain productivity during narrow agronomic time windows. The relevant state of knowledge spans three levels that must be considered jointly. First, vehicle and energy-carrier properties determine tank-to-wheel efficiency, onboard energy density, replenishment time, driveline architecture and the integration effort associated with batteries, fuel cells, high-pressure tanks or liquid renewable fuels. Second, agricultural process organization determines annual utilization and workload through the crop-production processes, the field geometry, the farm-to-field distances, the allocation of machines and the seasonal concentration of work. Third, cost allocation determines whether higher investment costs can be compensated by lower variable costs at the annual operating hours that are actually realized. Each level has been studied in its own right, but the suitability of a concept only becomes visible when the three levels are combined for a specific farm context.

Recent system-oriented assessments of renewable propulsion energies for agricultural machinery emphasize that the suitability of an energy carrier cannot be assessed independently of the drivetrain and of the agricultural use case. Key criteria include machine power demand, operating duration, working location, replenishment time, storage density, infrastructure, fuel availability and practical acceptance. This perspective is particularly important for tractors, because one machine often has to cover heterogeneous field, transport and on-farm tasks with a single onboard energy store. Following this reasoning, battery-electric systems are mainly suited to lower-power and intermittently used machines or to time-limited high-load tasks, whereas liquid renewable fuels remain relevant for medium- and heavy-duty work with long operating periods. Paraffinic diesel fuels such as HVO are technically attractive for diesel-compatible machines, because they can use existing combustion architectures with little adaptation. Hydrogen combustion and hydrogen fuel-cell systems are technically feasible, but their broad agricultural use is constrained by storage density, supply logistics and infrastructure requirements (KTBL 2023).

Existing agricultural process-modeling work shows that operating time and fuel consumption depend strongly on farm structure and on the configuration of the process chain (Hanke et al. 2018, Trösken et al. 2020). Machinery-cost frameworks emphasize the role of annual utilization, because the fixed costs of a machine are distributed over the workload that is actually realized (KTBL 2024, Schroers et al. 2020). Component-level literature provides assumptions for individual drivetrain stages, for the development of battery costs, for hydrogen storage, for fuel-cell systems and for methanol reforming (Bietresato et al. 2012, Wei et al. 2017, Mauler et al. 2021, Kampker et al. 2023, Li et al. 2023, Shin and Ha 2023). However, these three levels are most often treated separately, so that vehicle-side efficiency, process-level utilization and cost allocation are rarely resolved within a single consistent framework. This separation motivates an integrated treatment of the three levels within a single farm-specific analysis.

This paper builds on these findings by linking the technical energy-carrier perspective with farm-specific process simulation and with cost allocation. The research gap therefore concerns the consistent coupling of farm structure, tractor utilization, drivetrain efficiency, onboard energy constraints and annual machinery costs within mixed-fleet scenarios, which is what allows the present study to explain why a given concept succeeds on one farm and fails on another.

Objective, research questions and scope

The objective of this paper is to quantify how farm structure, annual tractor utilization and drivetrain-specific energy conversion affect the annual work-completion costs of selected alternative tractor concepts under defined scenario assumptions. The analysis addresses three research questions. First, how do two contrasting farm structures affect annual tractor utilization and the allocation of fixed machinery costs in alternative drivetrain scenarios? Second, how do tank-to-wheel efficiencies, onboard storage limits, replenishment rates and energy-carrier prices translate a common simulated workload into different final energy demands and variable costs? Third, which scenario conclusions are supported directly by the model results, and which conclusions remain conditional on assumptions regarding infrastructure, energy prices, machine costs and environmental performance? Answering these three questions in combination is what distinguishes the present coupled assessment from a purely technical or a purely economic comparison.

The scope is limited to tractor-dominated field operations and farm-to-field travel within one production year. Harvest machinery such as combine harvesters and forage harvesters is excluded, because these machines combine very high continuous power demand with short seasonal operating windows and with machine-specific logistics. Including them would require separate assumptions for energy storage, replenishment behavior and cost allocation, and would blur the structural effects that this study aims to isolate. Charging and refueling times are represented in the process simulation through finite onboard energy capacities and carrier-specific replenishment rates. They can therefore affect the simulated operating time whenever energy replenishment becomes necessary. However, replenishment events are not reported as a separate result dimension in this paper. The economic model covers vehicle- and operation-related work-completion costs. It does not include investments in external infrastructure such as grid upgrades, chargers, hydrogen compression and storage, dispensers or safety systems. Environmental impacts are used to motivate the study, but a full well-to-wheel greenhouse-gas balance lies outside the base model. Making these boundaries explicit is essential for the correct interpretation of the cost results, because several of the excluded items would fall disproportionately on the hydrogen and battery-electric concepts.

Materials and methods

The assessment combines an agricultural process simulation with a subsequent energy and economic evaluation. Tractor operations are simulated over one full year of plant production for two structurally contrasting German model farms. The simulation represents selected tractor-dominated process chains that include both field work and farm-to-field travel, and it respects the agronomic time windows that constrain when each operation can be executed. The simulated annual operating hours and operation-specific workload are then used to derive the tractor-specific energy demand of each drivetrain concept through tank-to-wheel efficiencies. Annual costs are calculated with a machinery-cost framework based on the KTBL method, which allocates fixed costs to the simulated utilization and derives variable costs from the simulated energy-carrier demand. The overall procedure therefore consists of three linked stages, namely operational simulation, energy conversion and cost allocation.

A few terms are used with a specific meaning in this paper. An agronomic time window is the calendar period in which an operation can be carried out without violating crop-production constraints. The work rate is the area completed per hour by a given tractor-implement combination and follows from working width, operating speed and field efficiency. Productive operating time covers the field work, while non-productive operating time covers the farm-to-field travel, the movements between fields and work preparation time. Work-completion costs are the annual costs of carrying out the modeled tractor operations, including machinery costs, energy, repairs and operator labor.

Starting from the model farms, the process chains and the tractor fleets, the simulation schedules the field operations within their agronomic time windows, assigns tractors and implements, and calculates field-work time, travel time and energy demand for each operation. Each tractor is represented with a finite onboard energy capacity. If the remaining onboard energy is insufficient for the next operation segment, an energy replenishment event is triggered. Replenishment is assumed to take place at the farmstead. The duration of a replenishment event follows from the required energy amount and from the carrier-specific transfer or charging rate, so that slow-replenishing carriers extend the operating time more than fast-replenishing ones. The simulation output therefore contains the annual operating hours and the energy demand under realistic storage and replenishment constraints. These outputs are subsequently transferred to the machinery-cost model based on the KTBL method.

The process simulation represents farm work as standardized field operations that are organized in crop-specific process chains. Each process step is parameterized by the implement working width, the operating speed and a defined time window. These parameters determine the operation-specific work rate and the time requirement per hectare. Field-specific routes and farm-to-field distances add travel time and the corresponding energy demand. This construction links the spatial structure of the farm to the annual utilization, to the seasonal concentration of the workload, and to the logistical sensitivity of charging or refueling concepts, because a farm with many small and distant fields accumulates more non-productive time than a farm with few large fields (Trösken and Frerichs 2020).

Within the simulation, tractors and machine-implement combinations are represented in an object-oriented structure that enables procedure-dependent modeling of the operating-time shares. Field operations are resolved through simplified rules that reflect the field geometry and the operational sequence, so that the simulated time shares capture both the working passes and the turning-related overhead at the headlands. Time accounting follows a structured approach that supports the aggregation of operation time into comparable categories across procedures and farms. This provides the basis for reporting annual operating hours per tractor class and for linking the operational time demand to the energy demand and to the cost allocation. Harvest-related operations are excluded from the scope of this study. The modeled chains therefore focus on tractor-dominated field operations and on the associated travel components within the investigated production year (Hanke et al. 2018).

To ensure that the simulated energy demand corresponds to realistic agricultural operating levels, diesel consumption serves as the empirical baseline for comparison and plausibility checking. The underlying approach is aligned with established modeling work in which the model farms are parameterized through iterative consultation with regional farmers, advisors and partners from industry and academia. Based on these characteristics, the model calculates the diesel demand of the agricultural machinery within the process chains, and this diesel demand serves as the common reference against which the alternative carriers are evaluated (Trösken et al. 2020).

The energy demand of each alternative drivetrain is obtained by applying its tank-to-wheel efficiency to the simulated mechanical workload, which is held constant across all concepts so that they are compared under an identical mechanical duty. The resulting energy-carrier quantities enter the cost model based on the KTBL method, where they drive the variable costs, while the simulated annual utilization drives the allocation of the fixed costs. The tank-to-wheel efficiencies themselves are defined and derived in the section on the evaluated drivetrains.

Model farms and process chains

Two German model farms were selected to represent contrasting agricultural contexts and to make the sensitivity of the alternative drivetrain concepts to utilization and logistics explicit. The first case reflects a small-scale, structurally compact operation with comparatively low annual tractor utilization and short travel distances. The second case reflects a large-scale arable operation with extensive fields, longer travel distances and high annual utilization. This contrast is deliberate and central to the study, because alternative drivetrains are typically associated with higher upfront investment and, depending on the concept, with additional infrastructure requirements. These additional costs are amortized more easily when the annual utilization and the annual energy throughput are high, whereas low-utilization contexts tend to penalize capital-intensive technologies through higher fixed costs per operating hour. The two farms can therefore be understood as bounding cases that span a large part of the structural variation found in practice. They are not intended to represent all crop rotations in the respective regions. They are deliberately simplified archetypes that isolate the structural effects of scale, field size and travel distance.

The Southern Bavaria model farm is used as a simplified small-farm archetype. It covers 48 ha of agricultural land and includes wheat, barley and grassland in the modeled crop rotation. The selected rotation is not intended to reproduce every plausible production branch in Southern Bavaria. Instead, it keeps the number of process chains manageable and isolates the effect of a small area, compact fields and short farm-to-field distances on tractor utilization. The Southern Bavaria case is not intended to represent a complete dairy-farm system. Silage maize and its associated harvesting and transport chains are therefore outside the present base-case definition. The field structure is characterized by compact parcels with an average field size of 3.4 ha and an average farm-to-field distance of 1.6 km. Figure 1 shows the spatial layout of this farm, with the farmstead, the field entrances and the network of roads and field paths. These characteristics imply frequent field changes and a comparatively high share of non-productive time per unit of work output, which is exactly the condition under which capital-intensive drivetrains are hardest to amortize. Because all drivetrain scenarios use the same farm structure and the same crop rotation, the cost differences between scenarios arise from the drivetrain and energy-carrier assumptions rather than from differences in the agronomic system.

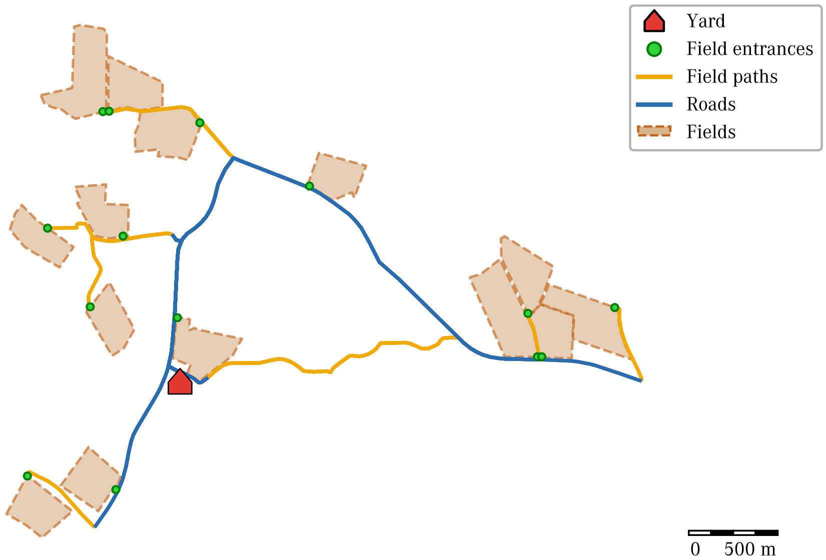

Figure 1: Spatial overview of the model farm in Southern Bavaria

The Western Pomerania model farm is used as a simplified large arable-farm archetype. It covers 1,190 ha of agricultural land with wheat, barley and maize in the modeled crop rotation. The fields are large and contiguous, with an average field size of 42.5 ha and an average farm-to-field distance of 4.6 km. Figure 2 shows the corresponding spatial layout. This case is designed to represent long continuous operating blocks, higher fleet utilization and higher annual energy throughput, so that the potential of efficient but capital-intensive drivetrains can express itself. The rotation is again kept deliberately limited in order to keep the scenario comparison transparent. Additional crops such as rapeseed, sugar beet or potatoes would require further process chains, additional implement assumptions and possibly a different machinery allocation. Extending the analysis to these crops is therefore identified as a task for future work rather than as part of the present base comparison.

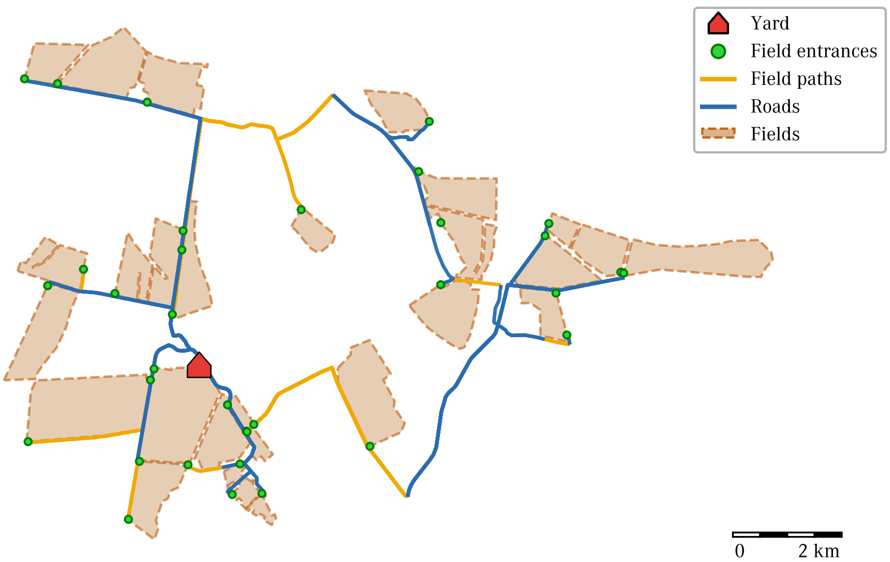

Figure 2: Spatial overview of the model farm in Western Pomerania

To reflect realistic mechanization structures and to link tractor power classes to the operational requirements, mechanization levels and tractor fleets were defined for both farms. Here, the mechanization level is expressed as the nominal power of the dominant tractor class that is assumed to perform the main field operations. This reference power level is used to derive typical implement sizes and work rates from the KTBL procedure descriptions, which ensures that the simulated process chains represent plausible capacities for each farm context. The Southern Bavaria model farm is characterized by a mechanization level of 102 kW and by a fleet of three tractors covering the power ranges 60–74 kW, 75–92 kW and 93–111 kW. The Western Pomerania model farm is characterized by a mechanization level of 230 kW and by a fleet of seven tractors. Given the larger workload and the need to cover overlapping time windows, the mid-range tractor classes are doubled, specifically the 75–92 kW class and the 130–147 kW class. The remaining tractors are allocated to the ranges 60–74 kW, 216–250 kW and 251–300 kW. This fleet structure allows the simulation to represent parallel work during peak periods and aligns the machine capacity with the scale-specific operational requirements, which is a precondition for a fair comparison between the two farms.

For each model farm, three representative process chains were modeled on the basis of the KTBL 'Verfahrensrechner Pflanze', a crop-production process calculator. The chains focus on the tractor-dominated field operations that fall within the scope of this study. They comprise primary tillage and seedbed preparation, planting and seeding operations, fertilizer applications, and the associated transport and travel components that occur within these operation windows. Each chain incorporates crop-specific work intensity and performance requirements in order to represent a realistic range of operating conditions. Tillage-related chains represent high-load and longer-duration operations with high traction demand, which is where drivetrains with limited onboard energy are most likely to reach their storage limits. Planting and fertilizer operations represent medium-load activities with greater organizational flexibility. As harvest is outside the modeled scope, the results describe the energy and cost demand of the tractor-dominated process share rather than the complete crop-production energy demand per hectare (KTBL 2017).

Farm-to-field travel is represented explicitly in the simulation and is assigned to the tractors that carry out the corresponding operations. In this way, the model captures not only the field work itself but also the associated logistical overhead. This overhead is particularly relevant for alternative energy carriers, because during seasonal peak periods and under limited charging or refueling options the additional travel time and energy demand reduce the area that can be completed within an agronomic time window. The explicit treatment of travel is therefore one of the principal mechanisms through which the farm structure influences the resulting work-completion costs.

Evaluated drivetrains

The drivetrain concepts investigated in this study are parameterized through their tank-to-wheel efficiencies. Tank-to-wheel efficiency is defined as the ratio between the mechanical energy delivered at the wheels and the energy content of the onboard energy carrier required to provide this work. It is used as a consistent interface between the operational simulation, which yields the tractor-specific annual mechanical work demand, and the subsequent calculation of the energy-carrier consumption. This approach captures the dominant vehicle-side conversion losses in a transparent and reproducible manner, even when detailed transient component maps are not available for every concept. The efficiency therefore serves as a deliberately robust summary of the energy path rather than as a high-resolution powertrain model, which is appropriate for a comparison that spans concepts at very different levels of technological maturity. The assessed efficiencies for the considered drivetrains are shown in Table 1.

Table 1: Considered tractor drivetrains and tank-to-wheel efficiencies

Drivetrain concept[1)]	**Abbreviation**	**Tank-to-wheel efficiency**
Diesel combustion engine with CVT	Diesel (CVT)	0.29
Battery-electric vehicle with CVT	BEV (CVT)	0.67
Battery-electric vehicle with EA	BEV (EA)	0.84
HVO combustion engine with CVT	HVO-ICE (CVT)	0.29
Hydrogen fuel cell with EA	H_2-FC (EA)	0.44
Fuel cell with methanol range-extender and EA	FC-MeOH-REEV (EA)	0.33
Hydrogen combustion engine with CVT	H_2-ICE (CVT)	0.30

[1)] CVT = Continuously Variable Transmission; EA = electrified axle with individual-wheel electric drives.

Representative stage efficiencies were selected within the ranges reported in the literature for off-road diesel engines, tractor drivelines and electric traction components, and they were chosen so as to reproduce the diesel reference efficiency in a transparent manner. The tank-to-wheel efficiencies are derived from a component-based efficiency chain, which Figure 3 illustrates for a combustion-engine tractor and for a hydrogen fuel-cell tractor with an electrified axle. Representative part-load efficiencies are assigned to the stages that dominate the losses along the energy path. These stages comprise the prime mover, such as a combustion engine or a fuel-cell system, the energy storage and buffering in the battery where applicable, the power electronics, such as converters and DC-to-DC conversion, the driveline architecture, such as a continuously variable transmission or an electrified axle, and the auxiliary demand. The overall tank-to-wheel efficiency is calculated as the product of the stage efficiencies. For the diesel reference with a continuously variable transmission, representative efficiencies of 0.38 for the engine, 0.80 for the driveline and 0.94 for the auxiliaries yield an overall tank-to-wheel efficiency of 0.29, which matches the diesel value used as the reference in this study. Hydrotreated vegetable oil is treated as a drop-in fuel in an otherwise equivalent combustion drivetrain and is therefore assigned the same tank-to-wheel efficiency (Bietresato et al. 2012, Trösken et al. 2020, Vijaya Sambhavi and Ramachandran 2023).

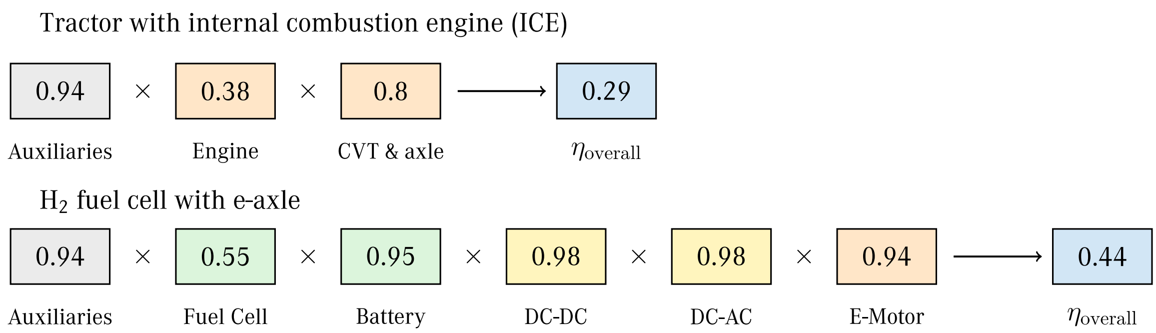

Figure 3: Component efficiency chain and overall drivetrain efficiency for an ICE tractor (top) and a hydrogen fuel-cell e-axle drivetrain (bottom)

For the liquid-fuel reference concepts, the process simulation uses class-dependent tractor-side tank capacities that are expressed as onboard chemical energy. The modeled tank capacities range from approximately 180 to 660 L, depending on the tractor power class. Diesel and HVO follow the same replenishment logic, with a refueling rate of approximately 50 L/min. Owing to their comparatively high onboard energy capacity and rapid refueling, diesel and HVO provide the logistical reference against which the alternative concepts are evaluated.

Battery-electric tractors are represented in two architectures in order to reflect the influence of the driveline layout on the conversion losses. In the battery-electric concept with a continuously variable transmission, the conversion chain comprises battery discharge with an efficiency of 0.95, a converter with 0.98, a DC-to-DC stage with 0.98, an electric motor with 0.94, a mechanical driveline stage with 0.80 and auxiliaries with 0.97. The product of these stages yields a tank-to-wheel efficiency of 0.67. In the battery-electric concept with an electrified axle, the conventional mechanical driveline stage is omitted. With the battery at 0.95, the converter at 0.98, the DC-to-DC stage at 0.98, the motor at 0.94 and the auxiliaries at 0.98, the resulting tank-to-wheel efficiency is 0.84. The difference between the two layouts therefore isolates the effect of the mechanical driveline, which is the main source of loss that the electrified axle avoids. In the process simulation, the battery-electric tractors are represented with a tractor battery of 100 kWh and a tractor-side charging limit of 80 kW. These parameters allow the recharging time to affect the operating schedule whenever the onboard battery is depleted, which is the mechanism through which the limited energy density of the battery becomes visible in the results. Despite their high tank-to-wheel efficiency, battery-electric tractors require substantially more storage mass and installation volume than liquid-fuel tractors for a comparable amount of usable mechanical work.

Hydrogen-based concepts are modeled along two conversion routes that differ in efficiency and in system characteristics. Hydrogen combustion with a continuously variable transmission retains the combustion architecture and is assigned a tank-to-wheel efficiency of 0.30, derived from an engine efficiency of 0.40, a driveline efficiency of 0.80 and an auxiliary factor of 0.94. This value is close to the diesel reference, so that the competitiveness of this route depends mainly on the delivered hydrogen price, on the storage cost and on the maturity of the supply chain rather than on any efficiency advantage. Hydrogen fuel-cell systems, by contrast, convert hydrogen electrochemically into electricity and then use electric traction. For the hydrogen fuel-cell concept with an electrified axle, the efficiency chain comprises a fuel-cell efficiency of 0.55, a battery efficiency of 0.95, a converter efficiency of 0.98, a DC-to-DC efficiency of 0.98, a motor efficiency of 0.94 and auxiliaries of 0.94. The product yields a tank-to-wheel efficiency of 0.44, which is markedly higher than that of hydrogen combustion and reduces the hydrogen demand for the same mechanical work. In this study, the hydrogen tractors are represented with approximately 700 kWh of onboard hydrogen energy, corresponding to about 21 kg H_2 per tractor stored at a pressure of 700 bar, which corresponds to the Fendt HELIOS prototype tractor (Nöss and Weller 2023). The refueling rate is 5 kg H_2/min, so that hydrogen combines a comparatively large onboard energy store with a fast replenishment, in contrast to the battery-electric concepts.

The fuel-cell-based methanol range-extender concept with an electrified axle introduces an additional onboard conversion stage upstream of the fuel cell and the electric drivetrain. This stage is represented by a reformer efficiency of 0.75. Together with the fuel cell at 0.55, the battery at 0.95, the converter at 0.98, the DC-to-DC stage at 0.98, the motor at 0.94 and the auxiliaries at 0.93, the resulting tank-to-wheel efficiency is 0.33. The concept therefore has a lower vehicle-side efficiency than the direct hydrogen fuel-cell route, because of the additional conversion step, but in return it uses a liquid energy carrier with the logistical advantages of conventional refueling. In the process simulation, the methanol range-extender tractors are represented with a class-dependent onboard methanol storage between 110 and 180 L. This storage volume is smaller than the diesel tank of the corresponding power class, because the onboard steam-reforming process requires water to be carried in addition to the methanol, so that part of the available tank volume is occupied by the water supply and less methanol is stored on board. The methanol refueling rate is 50 L/min. The range extender is treated as a permanently integrated energy-supply concept in the base scenarios. Detailed operating strategies, such as continuous operation, peak-load support or intermittent range extension, are not differentiated, because they would require assumptions about the control strategy that lie outside the present scope.

Across all concepts, the resulting tank-to-wheel efficiencies are used to translate the simulated annual mechanical work demand into the corresponding energy-carrier consumption. The differences in annual consumption therefore arise from the interaction between the workload and the conversion efficiency, and not from any change in the mechanical duty. The resulting energy demand then feeds directly into the economic evaluation within the cost framework, in which the utilization, the investment-related cost components, the maintenance assumptions and the energy-price trajectories jointly determine the total cost outcome.

Cost model

The economic assessment applies the KTBL machinery-cost model in order to quantify the annual machinery costs and the work-completion costs of the simulated tractor operations. The KTBL approach treats agricultural machinery as a durable production asset and distinguishes between fixed annual provision costs and variable use-related operating costs. Fixed costs occur independently of the actual annual workload and represent the cost of keeping the machine available. Variable costs arise from the use of the machine and increase with the operating hours or with other usage units. In this study, the KTBL structure is implemented at the level of the individual tractor and is coupled directly to the operational simulation. The simulation provides the tractor-specific annual operating hours and the annual mechanical work demand. These outputs are used to allocate the fixed costs according to the realistic utilization and to derive the annual energy-carrier consumption. The cost differences across farms and scenarios therefore reflect genuine differences in workload, utilization, drivetrain efficiency and energy-carrier prices rather than generic operating assumptions, which is the property that makes the comparison meaningful (KTBL 2024).

The fixed provision costs comprise time-based depreciation, interest on the tied capital, insurance, taxes where applicable, housing, and the utilization-independent technical inspections and maintenance. Time-based depreciation accounts for the loss of value due to ageing and technological obsolescence and is determined from the purchase price, the residual value and the economic lifetime. Interest costs represent the opportunity cost of the tied capital and are calculated with a uniform interest rate applied to the average tied capital, which is approximated as the mean of the purchase price and the residual value. Housing, insurance, taxes and inspection-related costs are treated as annual cost items that occur regardless of the actual machine use. Taken together, these components represent the annual cost of providing the machine for agricultural operations, and they are the components that respond most strongly to a high acquisition price (KTBL 2024).

Repair and maintenance costs capture the replacement of wear parts and the corrective maintenance over the service life. Robust technology-specific field data for the emerging tractor drivetrains are not yet available, because these concepts have not accumulated comparable operating experience. The same repair costs are applied to all concepts. This deliberately avoids introducing unsupported drivetrain-specific repair advantages or disadvantages that could not be substantiated. The uncertainty that this simplification introduces is addressed explicitly in the sensitivity analysis through a variation of the repair intensity.

A central methodological concept is the utilization threshold, which is defined as the annual workload at which the economic lifetime of the machine in years and its technical lifetime in usage units are exhausted at the same time. In the KTBL framework, this reference corresponds to full machine utilization. It is commonly represented by an economic lifetime of 12 years together with a technical lifetime of 10,000 operating hours. This combination implies an annual utilization of 833.33 hours and provides a standardized anchor for the depreciation behavior and for the residual-value conventions. In contemporary KTBL calculations, the residual value at the utilization threshold is commonly set to approximately 20 percent of the purchase price. The utilization threshold is also relevant for interpreting the cost degression. As the annual utilization increases, the fixed provision costs are distributed over more operating hours, which reduces the unit costs in euro per hour and improves the economic performance of capital-intensive machines. This degression is the mechanism that later explains why the same drivetrain behaves so differently on the two model farms (KTBL 2024).

In the present study, the utilization is not imposed as a fixed reference value but is obtained from the process simulation, where it varies across farms, power classes and scenarios according to the total workload, the field structure and the travel distances. The KTBL assumption of full utilization is therefore replaced by the simulated annual operating hours, and the annual total costs are converted into unit costs per operating hour. This makes the economic assessment sensitive to the penalty of low-utilization contexts and to the advantage of high-utilization contexts, which is decisive when small-scale and large-scale farms and capital-intensive technologies are compared, because a high acquisition cost is hardest to recover precisely at low utilization.

The work-completion costs are calculated by adding the operator-labor costs to the tractor-related machinery costs. The operator time is derived from the simulated operating time and therefore reflects both the productive field work and the farm-to-field travel that is assigned to the executing tractors. Labor is represented as a fully loaded hourly rate that includes the wage components and the employer-related overheads. The labor rate is set to EUR 26.16 per hour for 2025 and is escalated with a uniform annual increase of 2 percent to EUR 28.88 per hour for 2030 and EUR 35.21 per hour for 2040. This escalation ensures that the labor component increases in nominal terms even in those scenarios in which the energy prices decline, which is relevant on farms with lower utilization and a higher share of overhead time (Watts and Helmers 1981, Schroers et al. 2020).

Cost forecasting is treated separately from the KTBL machinery-cost structure and is implemented through exogenous energy-carrier price trajectories for 2025, 2030 and 2040. All monetary values are expressed in nominal euro of the respective time slice. A uniform annual escalation rate of 2 percent is applied to labor and to the other cost items that are not explicitly scenario dependent. The energy-carrier trajectories are chosen to reflect the dominant techno-economic and regulatory drivers for each carrier, and they are described in the following in order to make the assumptions traceable. Diesel prices are assumed to increase over time. This reflects the upward pressure from crude-oil market dynamics and from rising carbon-related compliance costs, in particular from the EU Emissions Trading System and the associated CO_2 certificate costs. These factors directly raise the variable operating costs of energy-intensive field operations. HVO is assumed to become slightly cheaper towards 2030 as the production volumes increase and the supply chains scale up. By 2040, its price is assumed to rise again. This later increase is attributed to the limited availability of certified sustainable feedstocks and to stricter sustainability criteria, both of which constrain the supply and raise the marginal production cost. Electricity is assumed at approximately EUR 0.23 per kilowatt-hour in 2025. The price is assumed to decline towards 2030 and 2040, mainly because of a decreasing wholesale component as the share of renewable electricity increases. Realized farm-gate electricity prices can nevertheless deviate from this trend, because they also depend on grid charges, tariff structures and possible demand-related charges. Renewable methanol from power-to-methanol or biomass pathways is assumed to become cheaper over time. The main drivers are the decreasing cost of green hydrogen, the scaling of the synthesis capacity and the associated learning effects. Green hydrogen is assumed to decrease from about EUR 19 per kilogram in 2025 to EUR 12 per kilogram in 2030 and EUR 8 per kilogram in 2040. This trajectory reflects the capital-cost reductions for electrolyzers and balance-of-plant components, the improved system integration and the higher capacity factors that are expected as renewable generation and hydrogen infrastructure mature. Taken together, these assumptions make it possible to quantify how changes in the energy-input prices interact with the drivetrain efficiency and with the farm-specific utilization to shape the long-term cost competitiveness. An overview of the assumed costs is given in Table 2.

Table 2: Assumed energy-carrier prices for 2025, 2030 and 2040. Energy-equivalent fuel prices are based on lower heating values.

Energy carrier	**2025**	**2030**	**2040**
Diesel	1.50 EUR/L 0.153 EUR/kWh	1.83 EUR/L 0.187 EUR/kWh	2.25 EUR/L 0.230 EUR/kWh
HVO	1.60 EUR/L 0.170 EUR/kWh	1.53 EUR/L 0.163 EUR/kWh	1.60 EUR/L 0.170 EUR/kWh
Electricity	0.23 EUR/kWh	0.20 EUR/kWh	0.17 EUR/kWh
Methanol	1.10 EUR/L 0.250 EUR/kWh	0.90 EUR/L 0.205 EUR/kWh	0.76 EUR/L 0.173 EUR/kWh
Hydrogen (green)	19.25 EUR/kg 0.578 EUR/kWh	12.38 EUR/kg 0.371 EUR/kWh	8.25 EUR/kg 0.248 EUR/kWh

Future machine costs are expressed as relative cost indices, with the diesel reference tractor set to 100 percent in each target year. A relative formulation is used because absolute purchase prices differ across power classes, equipment levels and manufacturers, while the normalized indices isolate the drivetrain-specific technology premium. The absolute purchase prices of the diesel reference tractors were derived from a market survey of representative new tractors from a single established manufacturer in the respective nominal power classes. Using tractors from the same manufacturer provided a consistent reference across the investigated power range and reduced price variation caused by brand-specific positioning. For each tractor class, the drivetrain-specific cost index from Table 3 is applied to the corresponding absolute diesel reference purchase price. The resulting absolute investment value is then used within the KTBL-based machinery-cost framework to calculate depreciation, interest, insurance, housing, and repair and maintenance costs. Together with the simulated energy-carrier and labor costs, these components form the absolute annual scenario costs reported in the results.

Table 3: Assumed relative machine cost indices for alternative tractor drivetrains in 2030 and 2040, normalized to the diesel reference (= 100 %)

Drivetrain concept	**2030**	**2040**
HVO-ICE (CVT)	105 %	95 %
H_2-ICE (CVT)	120 %	100 %
BEV (CVT)	130 %	100 %
BEV (EA)	140 %	110 %
H_2-FC (EA)	145 %	110 %
FC-MeOH-REEV (EA)	185 %	140 %

In Table 3, the indices for the alternative drivetrains represent the scenario assumptions for the vehicle-side technology premiums and for the learning effects. The HVO internal-combustion concept is treated as a near-diesel case because it uses an otherwise conventional compression-ignition drivetrain. The small deviation around diesel parity is not interpreted as a fundamentally different HVO-specific tractor architecture. It instead represents a bounded transition assumption that accounts for procurement, approval, warranty and low-volume market effects. The HVO machine-cost indices are scenario assumptions and do not represent a technically necessary HVO-specific tractor premium. Since the underlying hardware remains close to the diesel reference, the HVO results are interpreted as near-parity machine-cost cases, and the sensitivity analysis indicates how the remaining acquisition-cost uncertainty affects the conclusions. The larger premiums for the hydrogen, battery-electric and fuel-cell concepts reflect the additional vehicle-side components, such as batteries, power electronics, electric axles, fuel-cell stacks, high-pressure tanks and balance-of-plant systems (Reuter and Frerichs 2025).

The comparatively small cost spread of the HVO internal-combustion concept is consistent with the characterization of HVO as a renewable, diesel-like fuel that can be used in compression-ignition engines with only limited hardware adaptation in many applications. Empirical and review-based studies emphasize that the main differences between diesel and HVO concern the fuel properties and the combustion behavior rather than the fundamental drivetrain architecture. This supports the assumption that the tractor purchase price remains close to the diesel reference once the approvals and the production-volume effects have been resolved, and it is the reason why HVO enters the comparison as a near-parity case rather than as a distinct hardware concept (Hartikka et al. 2012, No 2014, Dimitriadis et al. 2018).

The external energy-supply infrastructure is not included in the cost model. This boundary is important for the BEV, H_2-ICE, H_2-FC and methanol-based concepts because chargers, grid-connection upgrades, hydrogen storage, compression, dispensing equipment, safety systems or methanol logistics can cause substantial additional costs that fall unevenly across the concepts. The base comparison therefore evaluates the fleet operation under the modeled tractor-side storage and replenishment assumptions, but it is deliberately not a complete infrastructure-cost comparison. This distinction has to be kept in mind whenever the hydrogen-based scenarios are interpreted because their real-world cost would be shifted upward more than that of the liquid-fuel concepts.

For hydrogen internal combustion, the premium assumed for 2030 is primarily justified by the cost and packaging implications of the onboard hydrogen storage and of the associated fuel system. Peer-reviewed cost analyses of compressed-hydrogen storage repeatedly identify the composite pressure vessel, and in particular the carbon-fiber-related manufacturing cost, as a dominant cost driver at the current production scales. Under scaling and learning, the same analyses also show a substantial reduction potential. This supports the assumption that the hydrogen internal-combustion concept can approach diesel parity by 2040 if the storage systems reach mature manufacturing volumes, while it also makes clear that this convergence is conditional rather than guaranteed (Shin and Ha 2023).

For the battery-electric tractors, the reduction of the index between 2030 and 2040 is motivated by the robust evidence base on the decline of lithium-ion battery-pack costs under industrial learning and scale-up. Reviews of battery-cost forecasting show that a wide range of methods still yields a consistent direction of travel, namely that pack costs continue to decline with cumulative production and with process improvements, even though uncertainty remains regarding the raw-material price dynamics and the design choices. Bottom-up production modeling further supports a substantial reduction potential by the end of the decade under plausible manufacturing improvements. This body of evidence is aligned with the assumed convergence of the battery-electric CVT concept towards parity by 2040 in the cost-index approach (Mauler et al. 2021, Orangi et al. 2024).

The battery-electric concept with an electrified axle remains more expensive than the battery-electric CVT concept in both target years because it represents a more deeply electrified propulsion layout with a higher integration demand in the traction motors, the inverters and the axle-level assemblies. Cost-analysis work on electric-axle manufacturing highlights that the assembly layout, the level of automation and the variant management are non-trivial contributors to the system cost, which supports retaining a residual premium even under learning. In the tractor context, this is a conservative way to reflect that an electrified axle can deliver benefits in efficiency and controllability, but that it may not minimize the purchase cost once the packaging, the durability and the redundancy requirements of agricultural duty are taken into account (Hadi et al. 2022).

For the hydrogen fuel-cell concepts, the higher indices in 2030 and the remaining premium in 2040 are consistent with the literature on the cost structure of fuel-cell systems and on the experience-driven reductions. Experience-curve analyses show that cost reductions are achievable with cumulative deployment, but they also indicate that several cost components have to improve in parallel, including the stacks, the balance of plant and the manufacturing throughput. Process-based cost modeling of PEM fuel-cell systems likewise emphasizes that the production scale and the design for manufacturability are decisive for reducing the unit costs, and that the pathway to parity depends on reaching high volumes and on simplifying the component set. This supports the assumption that a fuel-cell drivetrain can move towards diesel competitiveness over time while still remaining above the diesel reference in a tractor application in 2040 (Wei et al. 2017, Kampker et al. 2023).

The fuel-cell methanol range-extender concept with an electrified axle is assumed to remain the most expensive option because it combines an electric traction system with a reforming-based hydrogen supply and with fuel-cell conversion, which increases both the component count and the integration effort. Reviews of integrated methanol-steam-reforming and high-temperature PEM fuel-cell systems emphasize the challenges related to compact integration, thermal management, start-up behavior and system control, all of which translate into additional balance-of-plant and engineering effort compared with a pure battery-electric concept or with a single-carrier hydrogen fuel-cell concept. Even under learning, this multi-conversion architecture therefore retains a pronounced premium in the cost indices through 2040 (Li et al. 2023).

Modular range-extender concepts, which could provide a temporary energy supply for electric tractors during long operating periods and could serve as stationary power units outside field operation, were not included in the present scenario set. They represent a relevant extension for future work because their cost profile and their utilization pattern would differ from those of the permanently integrated range-extender architecture considered here, and because their shared use across several tasks could change the amortization fundamentally.

Results

This section reports the model results for the defined scenarios. The results are presented in seven steps: scenario definition, operating hours, total annual work-completion costs, cost composition, drivetrain-level cost allocation, energy-carrier costs, and sensitivity analysis. The reported totals combine the tractor-related machinery costs, the repair costs, the energy-carrier costs and the operator labor for the modeled tractor-dominated operations. All scenarios are compared with the diesel reference of the respective farm under an identical agronomic workload and under identical time-window constraints, so that any difference in cost can be attributed to the drivetrain and energy-carrier assumptions.

Scenario definition

Three technology-pathway scenarios were defined for each model farm. Tables 4 and 5 summarize the fleet composition by drivetrain concept and by nominal power class. The scenario selection is not an exhaustive optimization of all possible drivetrain combinations. It instead represents plausible transition pathways with different degrees of electrification, liquid renewable-fuel use, hydrogen combustion, hydrogen fuel-cell propulsion and methanol range extension. The allocation of the drivetrain concepts to the tractor power classes was developed from three criteria, namely the compatibility with the simulated workload, the expected onboard energy-storage limits and the need to maintain the operating duration in high-load operations. The resulting fleet allocations were additionally reviewed through qualitative expert feedback from agricultural-machinery development. This review served only as a plausibility check for the allocations and did not replace or override the transparent, rule-based model assumptions described above.

Table 4: Fleet composition of the Southern Bavaria scenarios by tractor power class. Abbreviations as in Table 1

Nominal power class	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)
67 kW	BEV (CVT)	BEV (EA)	BEV (EA)
84 kW	HVO-ICE (CVT)	FC-MeOH-REEV (EA)	H_2-ICE (CVT)
102 kW	HVO-ICE (CVT)	FC-MeOH-REEV (EA)	H_2-ICE (CVT)

Table 5: Fleet composition of the Western Pomerania scenarios by tractor power class. Abbreviations as in Table 1

Nominal power class	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)
67 kW	BEV (CVT)	FC-MeOH-REEV (EA)	H_2-FC (EA)
2 × 84 kW	BEV (CVT)	FC-MeOH-REEV (EA)	H_2-FC (EA)
2 × 139 kW	H_2-ICE (CVT)	HVO-ICE (CVT)	HVO-ICE (CVT)
233 kW	H_2-ICE (CVT)	HVO-ICE (CVT)	HVO-ICE (CVT)
276 kW	H_2-ICE (CVT)	HVO-ICE (CVT)	HVO-ICE (CVT)

Operating hours and utilization

The simulated operating hours of the complete tractor fleet are reported in Table 6. They are identical in the three cost years, because the agronomic workload is held constant and only the prices and the cost indices change between 2025, 2030 and 2040. The values show how strongly the two farm structures differ in annual utilization and therefore in the dilution of the fixed costs.

Table 6: Simulated annual fleet operating hours and highest single-tractor utilization

Scenario	Southern Bavaria: fleet hours	Western Pomerania: fleet hours	Highest single tractor hours
Reference	296.8 h	2,257.1 h	SB 194.7 h, WP 646.3 h
Scenario 1 (S1)	331.3 h	2,753.1 h	SB 191.1 h, WP 690.3 h
Scenario 2 (S2)	331.0 h	2,248.2 h	SB 198.1 h, WP 653.6 h
Scenario 3 (S3)	339.4 h	2,229.7 h	SB 206.4 h, WP 653.1 h

The final energy-carrier demand follows from the simulated mechanical work and the drivetrain efficiencies of Table 1. Battery-electric concepts convert the same workload into a substantially lower final energy demand than the combustion-based concepts, and hydrogen fuel-cell tractors require less energy than hydrogen combustion. These conversion differences become economically relevant only in combination with utilization, acquisition cost and energy price.

Figures 4 and 5 report the simulated annual operating hours of the scenario fleets. Figure 4 shows the operating hours of each individual tractor in the Southern Bavaria fleet. In Figure 5, operating hours are aggregated by nominal power class. For the duplicated 84 kW and 139 kW classes, each bar represents the combined annual operating hours of both tractors in the respective class. The Southern Bavaria fleet remains below 340 fleet hours per year, whereas the Western Pomerania fleet reaches approximately 2,230 to 2,753 fleet hours per year. The highest single-tractor utilization is approximately 206 h in Southern Bavaria and approximately 690 h in Western Pomerania.

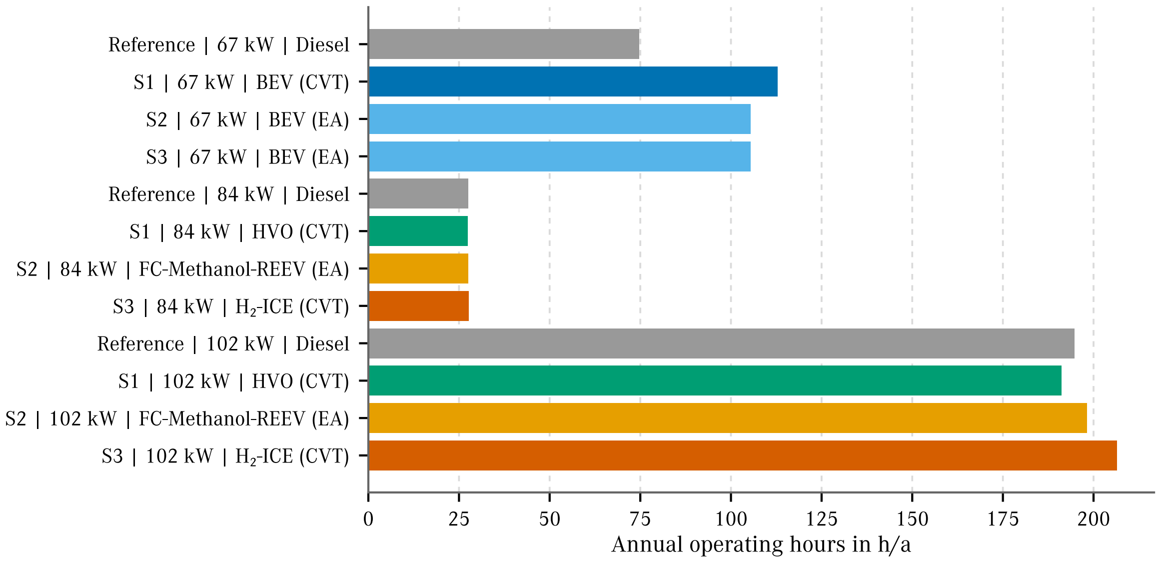

Figure 4: Annual operating hours per tractor for the Southern Bavaria scenarios

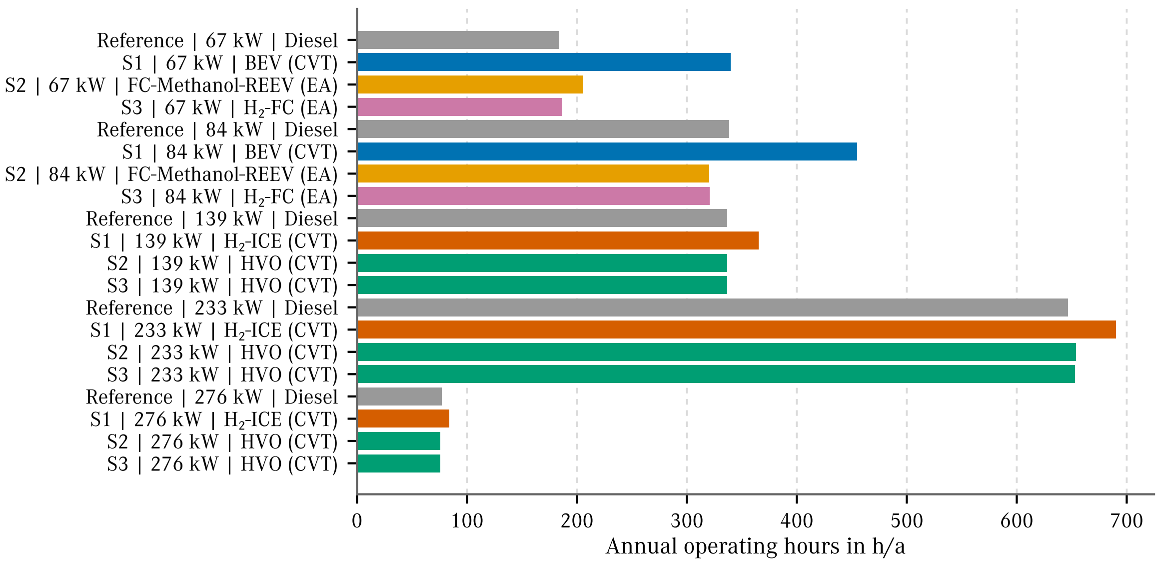

Figure 5: Annual operating hours by tractor power class for the Western Pomerania scenarios; for the duplicated 84 kW and 139 kW classes, each bar represents the combined annual operating hours of both tractors in the respective class

Annual work-completion costs

Figures 6 and 7 summarize the total annual work-completion costs for both model farms. The bars include the tractor-related machinery costs, the energy-carrier costs, the repairs and the operator labor for the modeled tractor-dominated operations. The infrastructure costs for charging, hydrogen storage, compression or dispensing are excluded. The figures therefore represent the vehicle- and operation-related scenario costs under the modeled storage and replenishment assumptions, and not the complete costs of the farm-level energy-supply system.

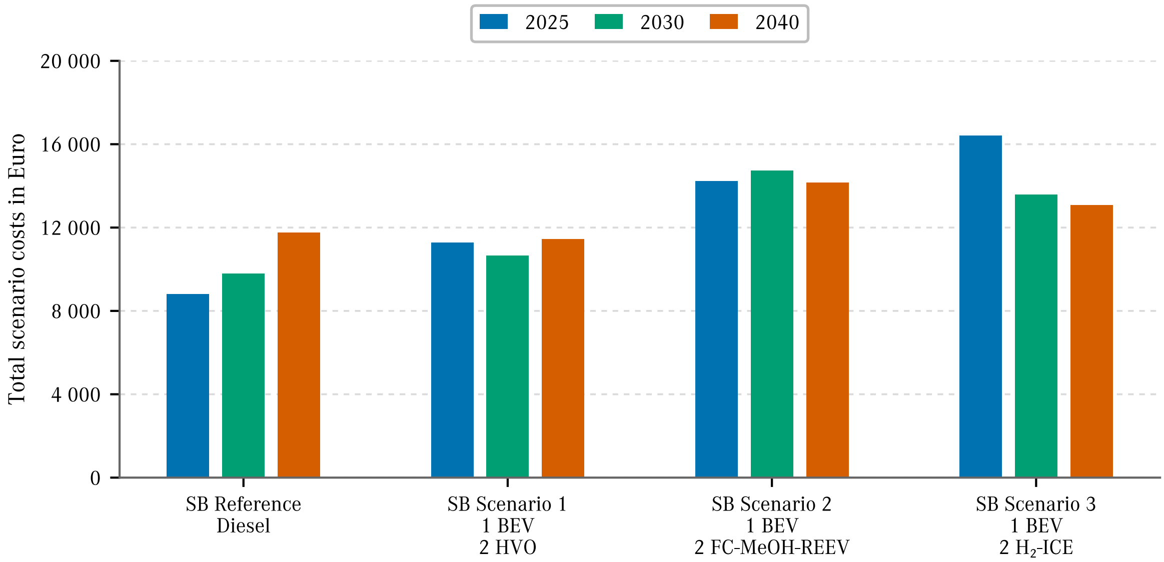

Figure 6: Overall annual scenario costs for the Southern Bavaria farm.

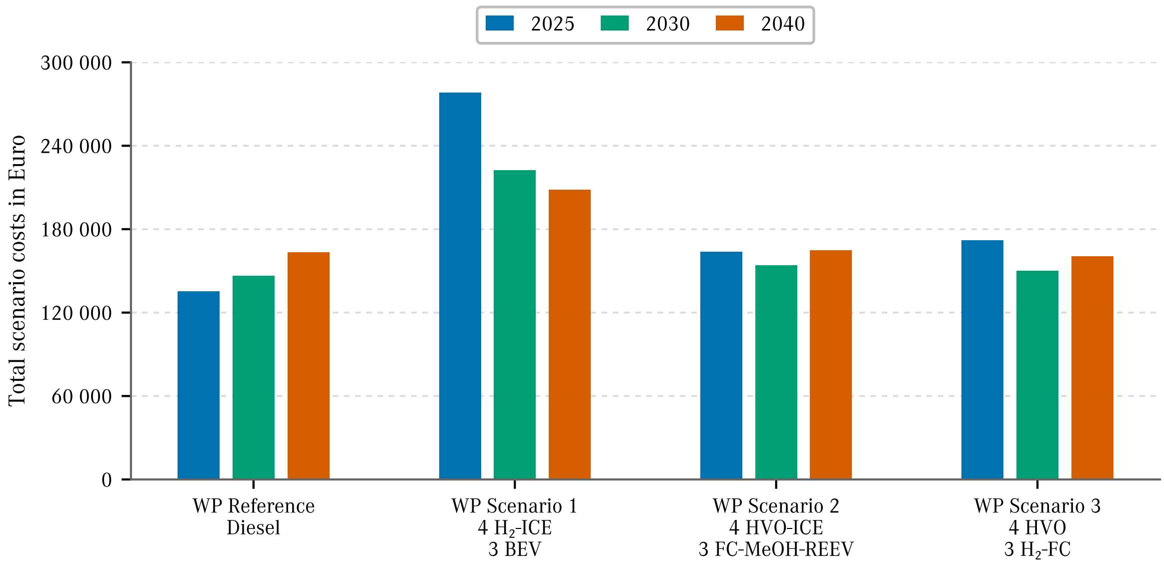

Figure 7: Overall annual scenario costs for the Western Pomerania farm

In Southern Bavaria, the diesel reference rises from approximately EUR 8,800 in 2025 to EUR 9,800 in 2030 and EUR 11,700 in 2040. Scenario 1, which combines one BEV tractor with two HVO tractors, decreases from approximately EUR 11,300 in 2025 to EUR 10,700 in 2030 and reaches EUR 11,400 in 2040. It is therefore the only Southern Bavaria alternative that reaches near parity with the diesel reference within the modeled horizon. Scenario 2 remains above the reference at approximately EUR 14,200, EUR 14,700 and EUR 14,200 in the three time slices. Scenario 3 decreases from approximately EUR 16,400 to EUR 13,600 and EUR 13,100, but it too remains above the diesel reference in 2040. Taken together, these results indicate that a low annual utilization penalizes the concepts with a high vehicle-side investment premium, even when the energy prices improve over time, because the improved energy price is spread over too few operating hours to compensate the higher fixed cost.

In Western Pomerania, the annual costs are much higher, because the modeled area, the fleet size and the operating hours are larger. The diesel reference increases from approximately EUR 135,200 in 2025 to EUR 146,200 in 2030 and EUR 163,400 in 2040. Scenario 1, with four H_2-ICE and three BEV tractors, remains the most expensive option despite a decline from approximately EUR 278,000 in 2025 to EUR 208,100 in 2040. Scenario 2, with four HVO and three FC-MeOH-REEV tractors, approaches the diesel reference and reaches approximately EUR 164,700 in 2040. Scenario 3, with four HVO and three H_2-FC tractors, reaches approximately EUR 160,400 in 2040 and is slightly below the diesel reference under the base assumptions. The comparison shows that a higher utilization can make the efficiency gains and the energy-price reductions economically more relevant, provided that the investment premiums and the excluded infrastructure costs remain within the assumed range.

Cost composition and drivetrain contributions

Figures 8 and 9 decompose the annual work-completion costs into depreciation, interest, insurance together with inspection and housing, energy-carrier costs, repairs and labor. In Southern Bavaria, depreciation and interest dominate the alternatives with a high acquisition-cost index, because the fleet utilization is low. In 2040, the fixed machinery-related costs amount to approximately EUR 7,700 in Scenario 1, EUR 10,400 in Scenario 2 and EUR 8,400 in Scenario 3, compared with approximately EUR 7,300 for the diesel reference. The variable and labor-related costs are lower in Scenario 1 than in the diesel reference, mainly because of the lower energy-cost component of the battery-electric and HVO mix. This explains why Scenario 1 can approach parity despite its higher fixed cost.

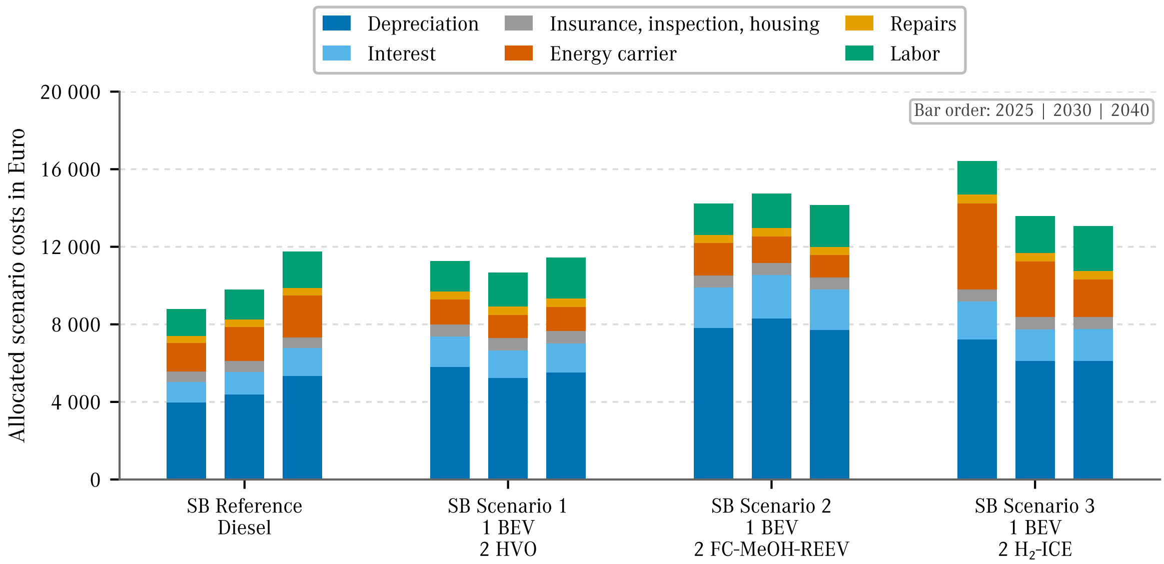

Figure 8: Cost breakdown by category for Southern Bavaria

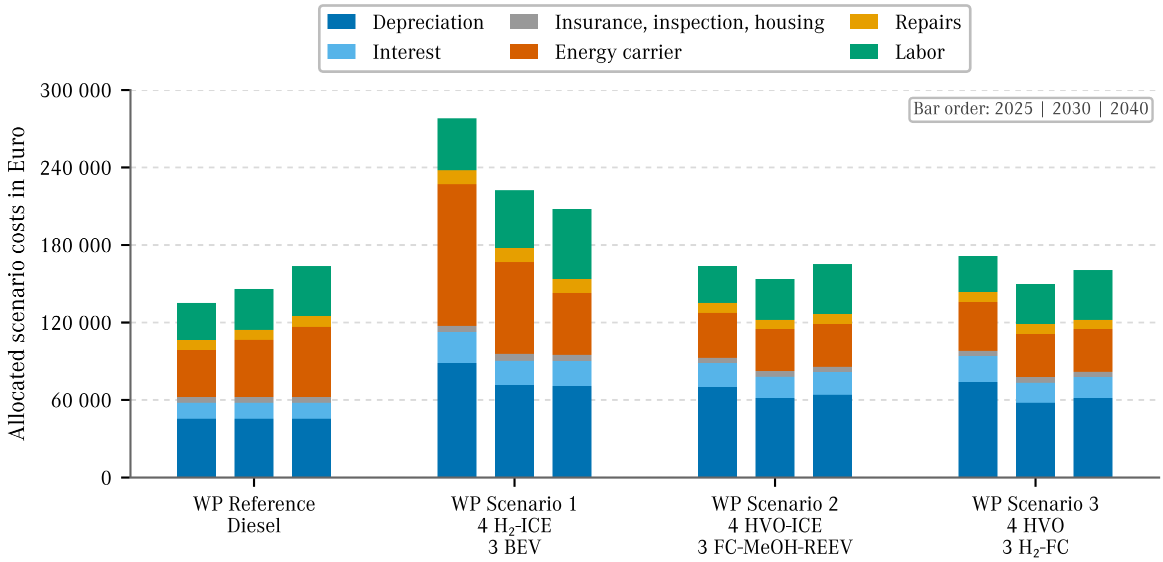

Figure 9: Cost breakdown by category for Western Pomerania

In Western Pomerania, the category split shows a different cost structure. In 2040, the diesel reference contains approximately EUR 54,800 of energy costs and EUR 38,600 of labor costs, while the fixed machinery-related costs amount to approximately EUR 62,200. Scenario 1 is dominated by the cost burden of the H_2-ICE tractors and reaches approximately EUR 95,200 in fixed machinery-related costs and EUR 48,000 in energy-carrier costs in 2040. Scenarios 2 and 3 reduce the energy-cost component to approximately EUR 32,900 and EUR 32,700 respectively. This reduction in the energy component is the main reason why these two scenarios approach diesel parity despite their higher acquisition-cost assumptions.

Figures 10 and 11 aggregate the same cost components into a fixed-cost allocation and a use-related and labor-cost allocation. The fixed-cost allocation comprises the depreciation, the interest and the insurance together with the inspection and the housing. The use-related and labor-cost group comprises energy-carrier costs, repairs and operator labor. This aggregation makes the utilization effect explicit. Southern Bavaria is primarily constrained by the dilution of its fixed costs over few operating hours, whereas Western Pomerania has a much larger variable-cost base and therefore reacts more strongly to the energy demand and to the energy-carrier prices.

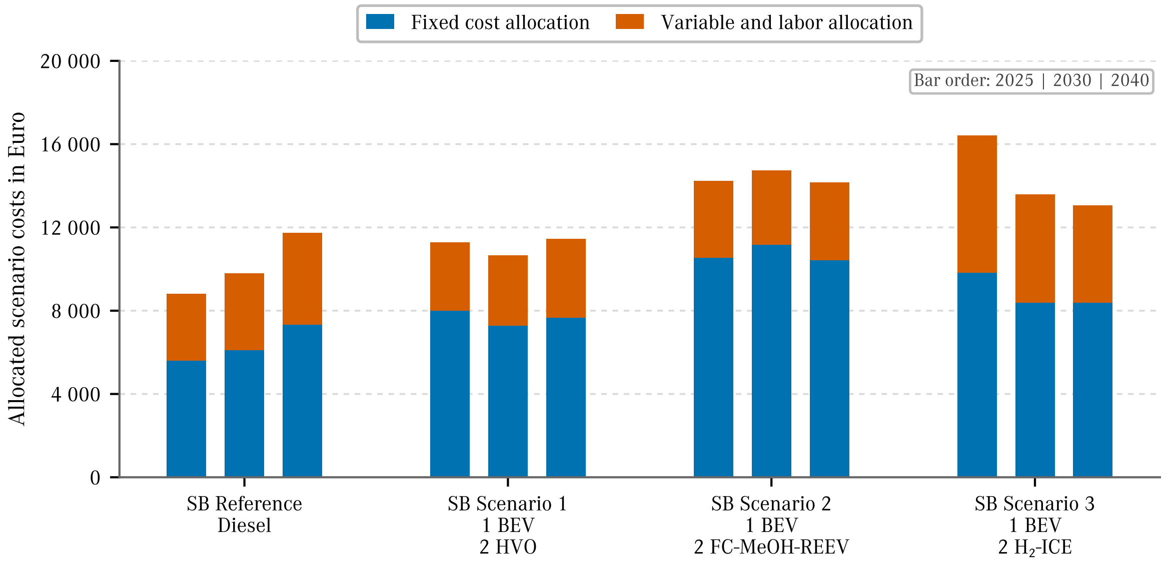

Figure 10: Fixed-cost allocation and use-related/labor allocation for Southern Bavaria

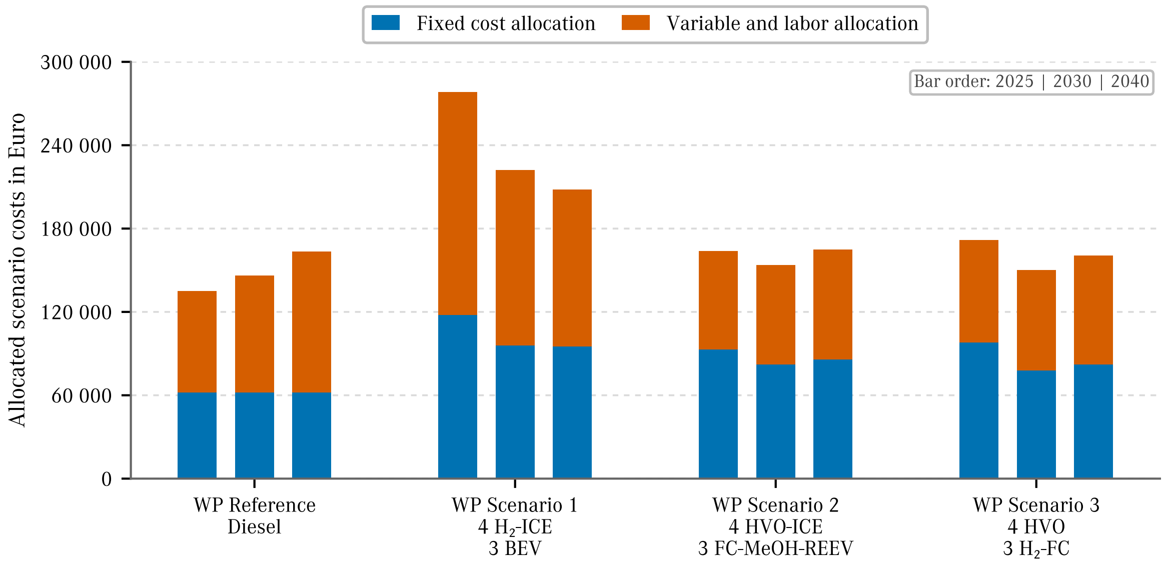

Figure 11: Fixed-cost allocation and use-related/labor allocation for Western Pomerania

Figures 12 and 13 split each scenario total into the contributions of the individual drivetrain concepts. This decomposition is necessary because the scenarios are mixed fleets, so that the scenario-level totals alone cannot reveal which drivetrain drives the cost of a given configuration. Reading the figures by color segment therefore shows how much each concept adds to the annual total and, together with the number of tractors of each type, how strongly a single high-cost concept can dominate a scenario. In Southern Bavaria, the 2040 cost of Scenario 1 consists of approximately EUR 2,800 for the single BEV tractor and EUR 8,700 for the two HVO tractors, so that the low-cost HVO tractors carry most of the scenario while the battery-electric tractor remains a minor contribution. Scenario

2 is dominated by the two FC-MeOH-REEV tractors, which account for approximately EUR 11,500 of the EUR 14,200 total in 2040, meaning that the range-extender concept alone determines more than three quarters of the scenario cost. Scenario 3 is dominated by the H_2-ICE tractors, which account for approximately EUR 10,400 of the EUR 13,100 total. Across the three Southern Bavaria scenarios, the drivetrain split therefore shows that the scenario ranking is governed by the two most capital-intensive tractors in each fleet rather than by the low-power battery-electric tractor, which explains why the scenarios with range-extender or hydrogen-combustion tractors remain above the diesel reference.

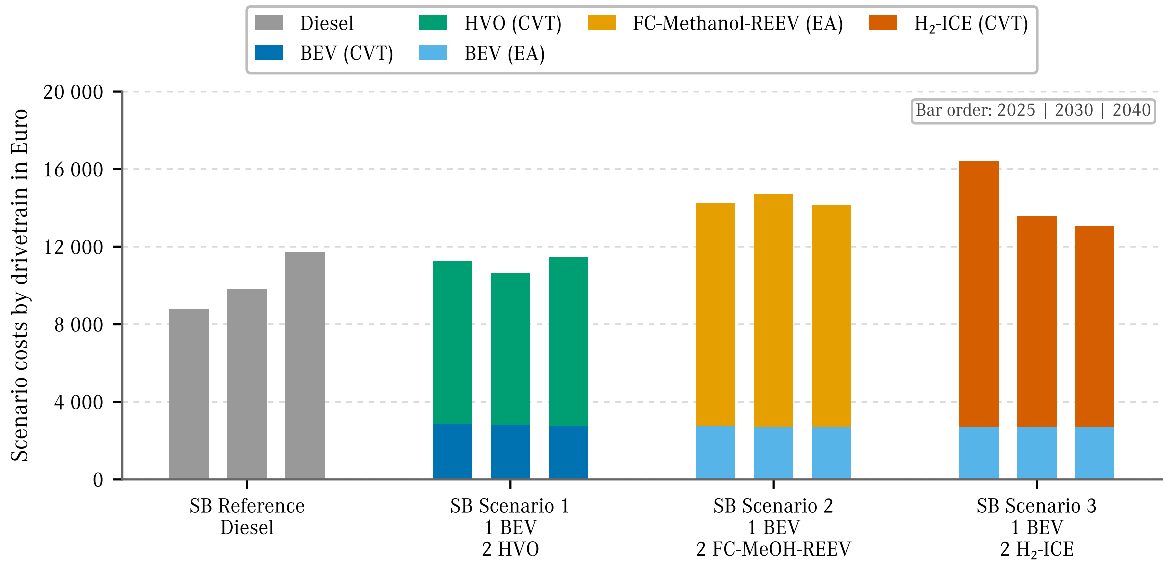

Figure 12: Cost contribution by drivetrain for Southern Bavaria.

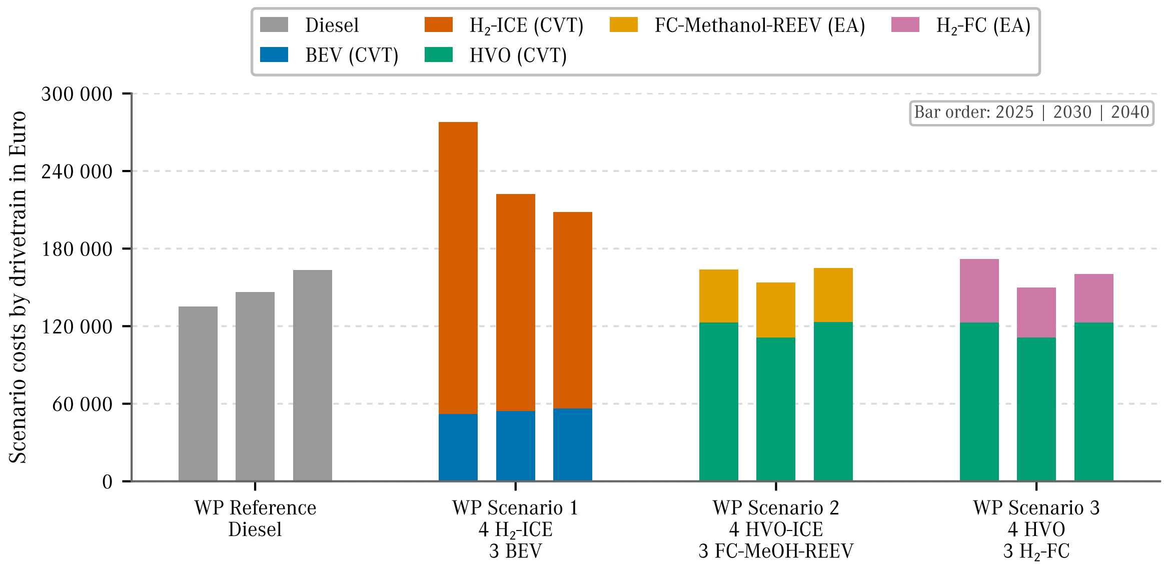

Figure 13: Cost contribution by drivetrain for Western Pomerania.

In Western Pomerania, drivetrain-level allocation shows why the H_2-ICE/BEV scenario remains expensive. In 2040, the H_2-ICE tractors contribute approximately EUR 151,600 and the BEV tractors approximately EUR 56,500 to Scenario 1. In Scenario 2, HVO tractors account for approximately EUR 123,200 and FC-MeOH-REEV tractors for approximately EUR 41,500. In Scenario 3, HVO tractors account for approximately EUR 123,100 and H_2-FC tractors for approximately EUR 37,300. In the comparable mixed fleet, the H_2-FC tractors therefore contribute less to the scenario total than the methanol range-extender tractors do, at approximately EUR 37,300 against EUR 41,500. Under the vehicle- and operation-related cost assumptions of the present model, the direct hydrogen fuel-cell route has a lower cost contribution than the methanol range-extender concept in the assigned lower and medium power classes.

Energy-carrier cost contribution

Figures 14 and 15 isolate the energy-carrier cost component of each drivetrain, that is, the cost of the diesel, HVO, electricity, hydrogen or methanol that a tractor consumes over the year, without the machinery, repair and labor components. Each bar therefore reflects the combined effect of three factors, namely the final energy price of the respective carrier from Table 2, the tank-to-wheel efficiency of the drivetrain from Table 1, and the annual workload assigned to the tractor. Reading the plots against these three factors makes the ranking interpretable. Electricity shows the lowest energy-cost bars in the battery-electric tractors, because the low electricity price is combined with the high tank-to-wheel efficiency of the electric drivetrain, yet this apparent advantage has to be read together with the high acquisition cost, the limited onboard storage and the feasibility of charging within the available time windows. Hydrogen combustion shows the highest bars, because its tank-to-wheel efficiency is close to that of diesel while the hydrogen price is far higher, so that the concept consumes a large amount of an expensive carrier. Hydrogen fuel-cell tractors fall between these extremes, because their higher vehicle-side efficiency reduces the hydrogen quantity required for the same mechanical work and therefore lowers the energy-cost bar relative to hydrogen combustion. HVO and methanol occupy an intermediate position that follows directly from their respective prices and efficiencies. Comparing the two farms, the energy-carrier cost bars are more than one order of magnitude higher in Western Pomerania than in Southern Bavaria. This difference reflects the much larger annual energy throughput of the large farm and explains why the energy-cost component drives the scenario ranking far more strongly in Western Pomerania, whereas in Southern Bavaria the fixed machinery costs dominate and the energy-cost differences between carriers have only a limited effect on the total.

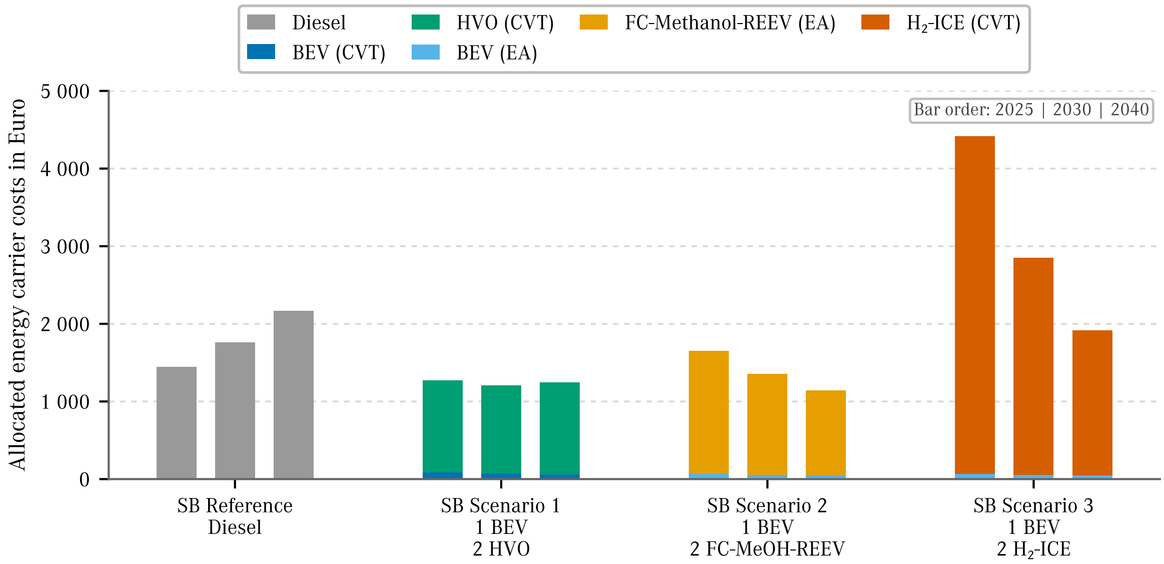

Figure 14: Energy-carrier cost contribution by drivetrain for Southern Bavaria.

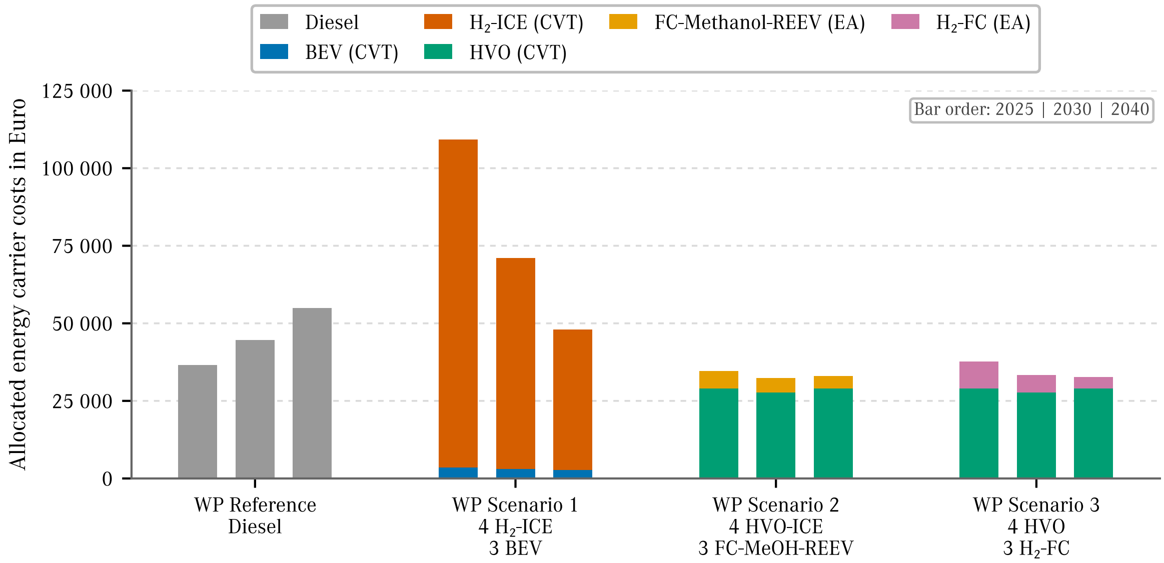

Figure 15: Energy-carrier cost contribution by drivetrain for Western Pomerania.

Sensitivity analysis

The sensitivity of the results to the underlying assumptions was examined through a local one-at-a-time analysis for the 2040 time slice, which is the horizon on which the transition assumptions have the largest effect. In this analysis, each input parameter is varied individually by plus or minus 20 percent while all other assumptions are held at their baseline values, so that the resulting change in the total annual scenario costs can be attributed unambiguously to the varied parameter. The parameters considered are the operating hours, the energy demand, the energy-carrier price, the machine acquisition price, the labor rate and the repair intensity. The operating hours and the energy demand are treated as model-level parameters, because they aggregate the workload and energy-use effects produced by the process simulation. Figures 16 and 17 present the results as farm-level tornado plots, in which the length of each bar indicates how strongly the corresponding parameter moves the total annual costs relative to the 2040 baseline, and the parameters are ordered from the most to the least influential. The analysis is local and does not replace a full uncertainty analysis, but it quantifies which assumptions have the largest effect on the conclusions and therefore indicates where the conclusions are most fragile.

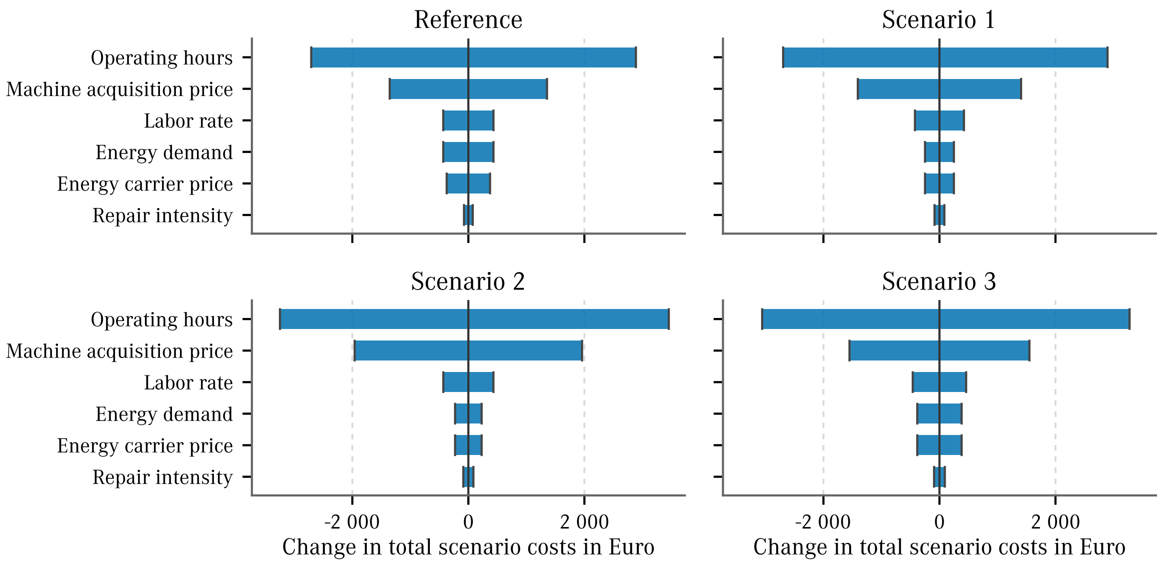

Figure 16: Local one-at-a-time sensitivity of total annual costs for Southern Bavaria in 2040.

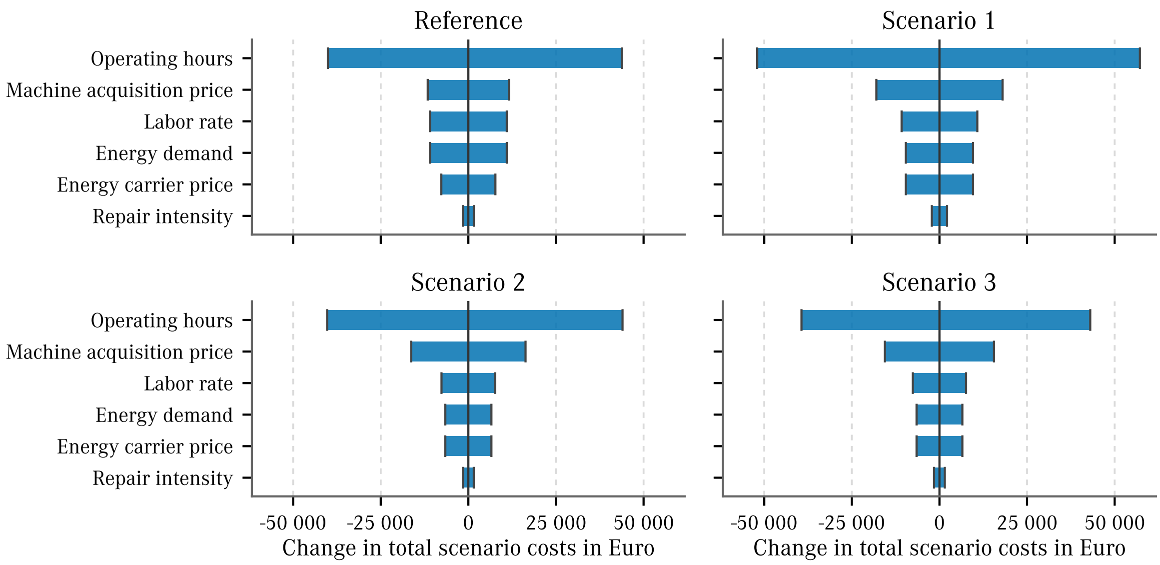

Figure 17: Local one-at-a-time sensitivity of total annual costs for Western Pomerania in 2040.

For Southern Bavaria, annual operating hours are the dominant sensitivity parameter in all scenarios. In Scenario 1, varying the operating hours by plus or minus 20 percent changes the total annual costs by approximately minus EUR 2,700 to plus EUR 2,900. The same variation of the machine acquisition price changes the costs by approximately plus or minus EUR 1,400. In Scenario 2, the operating hours cause a range from approximately minus EUR 3,200 to plus EUR 3,500, while the machine acquisition price changes the costs by approximately plus or minus EUR 2,000. The energy-carrier price, the energy demand, the labor rate and the repair intensity have smaller effects in this low-utilization context. This confirms that the near-parity result of Scenario 1 is primarily sensitive to the utilization and the investment assumptions rather than to the energy price alone. In a low-utilization context, the annual operating hours therefore act as the decisive lever, because they determine over how many hours the high fixed costs of the alternative concepts can be spread.

For Western Pomerania, the operating hours also have the largest effect, but the absolute changes are much larger, because the modeled workload is larger. In Scenario 3, varying the operating hours by plus or minus 20 percent changes the total annual costs by approximately minus EUR 39,400 to plus EUR 43,000. The machine acquisition price changes the costs by approximately plus or minus EUR 15,600, while the labor rate changes them by approximately plus or minus EUR 7,600. For the diesel reference, the energy-carrier price also remains relevant, and a variation of plus or minus 20 percent changes the annual costs by approximately plus or minus EUR 11,000. The sensitivity analysis therefore supports the interpretation that the scenario rankings are most sensitive to the utilization and the investment assumptions, while the sensitivity to the energy price becomes more important in the high-throughput farm context. Taken together across both farms, the ordering of the parameters is robust, with the operating hours dominating everywhere and the energy price gaining weight only where the annual energy throughput is high.

Discussion

Across both farms, the results show that the competitiveness of a concept is not driven by a single parameter such as the nominal efficiency or the projected energy price alone. It emerges from the interaction of utilization, cost structure, drivetrain composition and energy-carrier costs, while onboard storage and replenishment constraints are reflected in the simulated operating hours. This interaction is visible in the operating-hour plots, in the cost-category breakdown, in the drivetrain breakdown, in the energy-carrier cost plots and in the sensitivity analysis. The low-utilization Southern Bavaria case approaches parity only in the battery-electric and HVO scenario in 2040. In contrast, the high-utilization Western Pomerania case approaches parity in Scenarios 2 and 3, with the HVO and H_2-FC scenario falling slightly below the diesel reference in 2040. The following paragraphs develop the three mechanisms behind this pattern in turn.

First, the annual utilization governs how strongly a vehicle-side investment premium is converted into a penalty on the unit costs. The mechanism is the degression of the fixed provision costs, which are distributed over the realized operating hours, so that the same absolute premium is diluted very differently on the two farms. With only 297 to 339 fleet operating hours per year, Southern Bavaria offers almost an order of magnitude fewer hours over which to spread the fixed costs than Western Pomerania with 2,230 to 2,753 fleet operating hours per year. As a result, a capital-intensive concept that adds a fixed premium of a given size raises the euro-per-hour cost roughly seven to eight times more on the small farm than on the large one, which is why the same drivetrain can miss diesel parity in Southern Bavaria while approaching it in Western Pomerania. This also shifts the cost structure between the two farms. At low utilization the depreciation and the interest dominate the total, so that the scenario ranking is set almost entirely by the acquisition cost, and the lower energy price or higher efficiency of an alternative carrier can hardly compensate the premium. At high utilization the fixed costs are diluted and the variable energy costs and the drivetrain efficiency gain weight, so that an efficient but expensive concept has a realistic path to competitiveness. The sensitivity plots confirm this reading, because the operating hours are the single most influential parameter in every 2040 scenario on both farms. The practical implication is that the suitability of a capital-intensive drivetrain is, to a large extent, not a property of the drivetrain alone but of the annual hours the farm can provide, so that utilization should be treated as a primary selection criterion rather than as a secondary boundary condition.

Second, the balance between the fixed and the variable cost drivers differs by concept. The cost-breakdown figures show that HVO-based combustion remains close to diesel on the machine side and shifts most of the uncertainty to the fuel price and to the feedstock availability. Battery-electric concepts reduce the final energy demand through their high tank-to-wheel efficiency, but their competitiveness depends on the acquisition cost, on the onboard battery capacity, on the available charging power and on the usable charging windows. Hydrogen combustion remains highly sensitive to the hydrogen price, because its tank-to-wheel efficiency is close to that of diesel. Hydrogen fuel-cell concepts benefit from a higher vehicle-side efficiency, but they require hydrogen storage and refueling infrastructure that is not included in the base cost model. The concepts therefore differ not only in their cost level but also in the type of uncertainty to which they are most exposed.

A third aspect concerns the replenishment logistics. The process simulation accounts for the finite onboard storage and the carrier-specific replenishment rates, so that charging and refueling at the farmstead can extend the simulated operating time when replenishment is required. Because this study reports annual costs rather than the timing of individual replenishment events, the number, timing and location of these events are not evaluated here and are left to a dedicated operational analysis. The cost conclusions therefore hold under the modeled operational assumptions but do not replace a detailed infrastructure and scheduling study. This caveat is most relevant for the hydrogen scenarios, because the cost model assumes that hydrogen is operationally available at the farmstead without accounting for the external storage, compression or dispensing investments required to guarantee it.

The farm-specific results are consistent with previous system-level assessments (KTBL 2023). Battery-electric concepts are primarily allocated to lower power classes, whereas liquid renewable fuels remain advantageous for tractors with long operating periods and high energy demand. The calculated competitiveness of hydrogen fuel-cell tractors must nevertheless be interpreted together with the storage and infrastructure constraints emphasized in that assessment.

Overall, the evaluation indicates that mixed fleets can approach diesel parity in selected contexts under favorable long-term assumptions. In Southern Bavaria, the only near-parity alternative is the mixed battery-electric and HVO configuration in 2040. In Western Pomerania, the mixed HVO and methanol and the mixed HVO and H_2-FC configurations approach diesel parity, with the HVO and H_2-FC scenario falling slightly below the diesel reference in 2040. These conclusions are conditional if-then results. They remain sensitive to the machine-cost indices, to the energy prices, to the annual utilization and to the omitted infrastructure costs, and they should be read as directional findings rather than as point predictions.

Conclusions

This study evaluated tractor concepts based on hydrogen, methanol, hydrotreated vegetable oil and battery-electric propulsion against a diesel reference, using a full-year agricultural process simulation for two contrasting German model farms. The methodological contribution is the coupling of the operational simulation outputs with a machinery-cost model based on the KTBL method. The annual utilization and the workload are derived from process chains that include the farm-to-field travel, the seasonal work windows, the finite onboard energy storage and the carrier-specific replenishment rates. The energy-carrier demand is calculated from the simulated mechanical work through drivetrain-specific tank-to-wheel efficiencies. The economic performance is assessed by allocating the fixed provision costs to the simulated utilization and by deriving the variable costs from the energy demand in combination with scenario-based energy-price trajectories and investment-cost indices. The results report the operating hours, the total scenario costs, the cost categories, the fixed and variable cost allocation, the drivetrain contributions, the energy-carrier costs and the local sensitivity results, so that each conclusion can be traced back to an identifiable cost mechanism.

Across both farms and all time slices, the results show that alternative energy carriers cannot be ranked universally. In the Southern Bavaria case, the BEV/HVO scenario approaches diesel parity by 2040, while the methanol range-extender and hydrogen-combustion scenarios remain above the diesel reference. In the Western Pomerania case, the HVO/methanol and HVO/H_2-FC scenarios approach parity, and the HVO/H_2-FC scenario becomes slightly lower than the diesel reference in 2040 under the base assumptions. The cost breakdowns show that these results depend on both drivetrain composition and the balance between fixed machinery costs, energy costs, and labor costs.

In the low-utilization farm context, the investment-heavy concepts remain structurally disadvantaged even under favorable long-term energy-price assumptions. The cost-category plots show that the depreciation and the interest remain important cost components whenever the annual operating hours are low. The more robust transition options in this context are characterized by a limited deviation from the conventional tractor hardware, combined with the selective deployment of high-efficiency concepts in the power classes for which they are suited. The robustness of these transition options rests directly on the assumption that HVO can be used in near-diesel machines, because HVO is treated here as a near-parity machine-cost case rather than as a hardware-driven price difference.

In the high-utilization farm context, the higher annual operating hours and the higher energy throughput increase the economic relevance of the conversion efficiency and facilitate the cost degression of the capital-intensive technologies. Under the assumed trajectories for the electricity and hydrogen costs, and under the assumed learning-driven convergence of the machine-investment costs, fuel-cell electric tractors can become economically competitive by 2040 when they are embedded in mixed fleets. This conclusion is conditional on the represented onboard-storage and refueling parameters and on the exclusion of the external hydrogen infrastructure costs. If these infrastructure costs are included, the competitiveness of the hydrogen-based scenarios may change substantially. A dedicated assessment of the required charging and refueling infrastructure is therefore identified as an important topic for future research.

The findings suggest that the choice of the tractor drivetrain and the planning of the farm energy supply are best addressed jointly rather than in isolation. The cost model does not include the capital costs of the charging, storage, compression or dispensing infrastructure. For battery-electric systems, the availability of charging power, the grid-connection limits, the battery capacity and the charging schedule determine whether the vehicle-side efficiency advantage can be realized in practice. For hydrogen systems, the storage, the compression, the dispensing infrastructure and the reliability of the supply chain shape both the cost and the operational risk. Drop-in fuels have clear logistical advantages, but they remain constrained by the upstream availability and by the sustainability requirements of the feedstock.

Several boundaries of the study should be kept in mind when interpreting the results, and they define the priorities for future work. First, as stated in the scope and the cost model, the external charging and hydrogen-supply infrastructure is outside the cost boundary, which means that the reported competitiveness of the battery-electric and hydrogen concepts represents a lower bound on their real-world cost. Second, the study reports annual energy and cost results and does not resolve the individual charging and refueling events. The operational side of hydrogen replenishment on a comparable German farm, including the number and distribution of yard-based refueling events and the influence of the onboard storage pressure, is examined in a companion study (Wyszynski et al. 2026), to which the present results are complementary. Third, the repair and maintenance assumptions for the emerging technologies remain uncertain and are treated with a uniform logic across all concepts. Fourth, the tank-to-wheel approach provides a transparent vehicle-side comparison, but it does not capture the well-to-tank or well-to-wheel energy use, the greenhouse-gas emissions, or the transient and thermal effects under extreme duty cycles. Fifth, the energy-price and investment-cost trajectories are scenario assumptions rather than forecasts, and the conclusions must be read accordingly.

Future research can extend the framework along two axes. On the operational axis, the model can report the replenishment behavior explicitly, including the charging and refueling events, the storage constraints and the time losses during peak windows. Reporting this behavior explicitly and integrating such an operational replenishment analysis with the cost model used here is a natural continuation of the present study. On the economic axis, the cost model based on the KTBL method can be complemented with explicit infrastructure-cost modules and with scenario families that represent centralized contractor infrastructure, cooperative energy supply and farm-scale on-site generation. Combining these extensions with additional farm archetypes, broader crop rotations and regional energy-system assumptions would enable a more comprehensive assessment of the transition pathways for agricultural traction.

References

Bietresato, M.; Friso, D.; Sartori, L. (2012): Assessment of the efficiency of tractor transmissions using acceleration tests. Biosystems Engineering 112(3), pp. 171–180, https://doi.org/10.1016/j.biosystemseng.2012.03.009

Dimitriadis, A.; Natsios, I.; Dimaratos, A.; Katsaounis, D.; Samaras, Z.; Bezergianni, S.; Lehto, K. (2018): Evaluation of a Hydrotreated Vegetable Oil (HVO) and Effects on Emissions of a Passenger Car Diesel Engine. Frontiers in Mechanical Engineering 4, https://doi.org/10.3389/fmech.2018.00007

Hadi, M.A.; Brillinger, M.; Weinzerl, M. (2022): Parametric Evaluation and Cost Analysis in an e-Axle Assembly Layout. In: 5th EAI International Conference on Management of Manufacturing Systems. Eds. Knapčíková, L.; Peraković, D. et al., Cham, Springer International Publishing, pp. 39–55

Hanke, S.; Trösken, L.; Frerichs, L. (2018): Entwicklung und Parametrierung eines objektorientierten Modells zur Abbildung von landwirtschaftlichen Verfahrensschritten. Landtechnik 73(2), pp. 22–36, https://doi.org/10.15150/lt.2018.3179

Hartikka, T.; Kuronen, M.; Kiiski, U. (2012): Technical Performance of HVO (Hydrotreated Vegetable Oil) in Diesel Engines. In: SAE 2012 International Powertrains, Fuels & Lubricants Meeting, Malmo, Sweden, SAE International, 400 Commonwealth Drive, Warrendale, PA, United States

Kampker, A.; Heimes, H.; Kehrer, M.; Hagedorn, S.; Reims, P.; Kaul, O. (2023): Fuel cell system production cost modeling and analysis. Energy Reports 9, pp. 248–255, https://doi.org/10.1016/j.egyr.2022.10.364

KTBL (2017): Verfahrensrechner Pflanze. Darmstadt, Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V., https://www.ktbl.de/webanwendungen/verfahrensrechner-pflanze, accessed on 7 Sep 2026

KTBL (2023): Verwendung erneuerbarer Antriebsenergien in landwirtschaftlichen Maschinen. Darmstadt, Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V., https://www.ktbl.de/themen/alternative-energietraeger, accessed on 7 Sep 2026

KTBL (2024): Betriebsplanung Landwirtschaft 2024/25: Daten für die Betriebsplanung in der Landwirtschaft. Darmstadt, Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V.

Li, N.; Cui, X.; Zhu, J.; Zhou, M.; Liso, V.; Cinti, G.; Sahlin, S.L.; Araya, S.S. (2023): A review of reformed methanol-high temperature proton exchange membrane fuel cell systems. Renewable and Sustainable Energy Reviews 182, p. 113395, https://doi.org/10.1016/j.rser.2023.113395

Mauler, L.; Duffner, F.; Zeier, W.G.; Leker, J. (2021): Battery cost forecasting: a review of methods and results with an outlook to 2050. Energy & Environmental Science 14(9), pp. 4712–4739, https://doi.org/10.1039/D1EE01530C

No, S.-Y. (2014): Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines – A review. Fuel 115, pp. 88–96, https://doi.org/10.1016/j.fuel.2013.07.001

Nöß, C.; Weller, J. (2023): A Fuel Cell Tractor in Operation, Concepts and Field Data. In: 80th International Conference on Agricultural Engineering, VDI-MEG, 10–11 November 2023 in Hanover, VDI-Berichte Bd. 2427, VDI Verlag GmbH, pp. 39-47

Orangi, S.; Manjong, N.; Clos, D.P.; Usai, L.; Burheim, O.S.; Strømman, A.H. (2024): Historical and prospective lithium-ion battery cost trajectories from a bottom-up production modeling perspective. Journal of Energy Storage 76, p. 109800, https://doi.org/10.1016/j.est.2023.109800

Reuter, L.; Frerichs, L. (2025): Simulation-Based Evaluation of Tractors with Alternative Energy Carriers in Different Agricultural Contexts. In: 82nd International Conference on Agricultural Engineering, VDI-MEG, 7–8 November 2025 in Hanover, VDI-Berichte Bd. 2465, VDI Verlag GmbH, pp. 571–579

Schroers, J.O.; Sauer, N.; Krön, K.; Uppenkamp, N. (2020): Fixe und variable Maschinenkosten unter Berücksichtigung eines spezifischen Plan-Restwerts. Landtechnik 75(4), https://doi.org/10.15150/lt.2020.3250

Shin, H.K.; Ha, S.K. (2023): A Review on the Cost Analysis of Hydrogen Gas Storage Tanks for Fuel Cell Vehicles. Energies 16(13), p. 5233, https://doi.org/10.3390/en16135233

Trösken, L.; Frerichs, L. (2020): Process model for an economic evaluation of cultivation methods on agricultural farms. In: 78th International Conference on Agricultural Engineering, VDI-MEG, 3–4 November 2020 online, VDI-Berichte Bd. 2374, VDI Verlag GmbH, pp. 435–444

Trösken, L.; Meiners, A.; Frerichs, L.; Böttinger, S. (2020): Modellbasierte Berechnung von Kraftstoffverbräuchen landwirtschaftlicher Verfahrensketten. Landtechnik, 75(4), https://doi.org/10.15150/LT.2020.3253

Vijaya Sambhavi, Y.; Ramachandran, V. (2023): A technical review of modern traction inverter systems used in electric vehicle application. Energy Reports 10, pp. 3882–3907, https://doi.org/10.1016/j.egyr.2023.10.056

Watts, M.J.; Helmers, G.A. (1981): Machinery Costs and Inflation. Western Journal of Agricultural Economics 06, pp. 129–146, https://doi.org/10.22004/ag.econ.32573

Wei, M.; Smith, S.J.; Sohn, M.D. (2017): Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US. Applied Energy 191, pp. 346–357, https://doi.org/10.1016/j.apenergy.2017.01.056

Wyszynski, T.; Reuter, L.; Frerichs, L. (2026): Hydrogen Engine or Fuel Cell Tractors? Comparison of Operational Performance on Medium-Scale German Farms. In: 9th International VDI Conference Powertrain Systems in Mobile Machines 2026, Baden-Baden, VDI Verlag, pp. 171–190

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