Feasibility Evaluation of Hybrid Electric Agricultural Tractors Based on Life Cycle Cost Analysis

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ABSTRACT This paper presents a method to evaluate the economic feasibility of tractor powertrain electrification based on life cycle cost analysis. For a parallel hybrid, the best combustion engine downsizing, among some discrete values, was evaluated. The methodology was applied to three case studies with different power levels and operating cycles: a 76 kW orchard tractor, a 175 kW row crop tractor with medium duty use, and a 210 kW row crop tractor with heavy duty use. Fuel and electrical energy consumption were estimated through simulation. A range of powertrain components prices and fuel and electrical energy prices was taken into account, in order to cover price uncertainty and to show its effects. The results show that operating cost savings decrease when more power-intensive operations are performed. Considering a combination of system and energy prices deemed realistic by the authors, the operating cost savings, respectively for orchard, row crop medium duty, and row crop heavy duty, are approximately 8%, 3%, and 0.5%, which result in 6%, 1%, and 0.1% life cycle cost savings. Thus, powertrain electrification of high-power tractors should probably be avoided, whereas it could be beneficial for specialized orchard tractors. The developed method has proved to be suitable for such analyses.

INDEX TERMS Agricultural machinery, electric drives, heavy vehicles, hybrid electric tractors, off-road vehicles.

I. INTRODUCTION

Nowadays, global warming and carbon dioxide (CO_2) concentration in the atmosphere represent critical problems. The agriculture and forestry sectors were among the main contributors to global greenhouse gas emissions in 2017, with a contribution of 20% of the equivalent carbon dioxide emissions [1]. Whereas the larger part of this pollution is related to intensive animal farming and ground working, a considerable amount comes also from exhaust gas of Internal Combustion Engines (ICEs), which are the most widespread power sources in agriculture and forestry industry. Among ICEs,

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diesel engines are the most common worldwide, both for moving self-propelled machinery and for stationary stand-alone systems.

Exhaust gas emissions are particularly critical when diesel engines are operated outside their best operational range [2]. The maximum power region at high speed is one of the worst conditions in terms of exhaust emissions, but unfortunately this region is often exploited in agriculture operations [3]. Moreover, in tractors' working cycles, idling conditions have a relevant contribution in terms of environmental impact and engine life, without contributing to the effective required work [4], [5].

For the aforementioned reasons, several regulators tightened the emissions limits of Non-Road Mobile Machinery

(NRMM), to which agricultural vehicles belong. In order to meet the new European (Stage V) and US (Tier 4) standards, manufacturers are forced to equip the engines with additional exhaust gas treatment devices. Such components, in addition to an increased cost, make the diesel units bulkier, leading to a power density reduction. So, whereas this is not a major concern for high-power row crop vehicles, the design of narrow specialized tractors could become more challenging, due to strict size constraints of the vehicle chassis.

All these reasons encourage the manufacturers to modify the currently-adopted powertrain architectures of agricultural machinery and to push forward the industrial and academic research on this topic. Among various proposals, such as the ones described in [6], one feasible solution is the electrification of the conventional drivetrain, following the trend of the automotive industry towards the development of hybrid electric and full-electric on-road vehicles. In addition to fuel consumption and emission reductions, powertrain electrification can offer a variety of new functionalities, depending on the architecture. For example, using a power split unit for the front axle, as proposed in [7], allows to reduce the turning diameter of the tractor, whereas the independent actuation of each wheel can improve traction and stability [8], [9].

Despite the manufacturers' increasing interest, the research on agricultural machinery electrification is still at the beginning. In literature, some papers have already investigated the technical feasibility of hybrid electric tractors [10]–[12], and few of them have reported evaluations of operating costs too, mainly in terms of annual fuel savings [13]–[15]. Nevertheless, the total cost of ownership, also known as Life Cycle Cost (LCC) of hybrid electric tractors, received little attention, although the topic has been studied for full-electric farming vehicles [16], [17], [18], [19]. Furthermore, previous works on tractors electrification have dealt with this theme in a non-methodical way, focusing on single case studies, so that an effective method to establish whether a hybrid electric configuration could be worthwhile for a given tractor has not been found yet.

The purpose of this paper is to provide a method to evaluate the economic feasibility of farming tractor powertrain electrification through a simplified LCC analysis, and, at the same time, to determine the best ICE downsizing in the case of a parallel hybrid electric configuration. The proposed methodology is applied in this work to three case studies, i.e. to three tractors with different power sizes and operating cycles, but it can easily be extended to other cases, for example to different powertrain topologies. This paper differs from other LCC analyses, particularly from the ones referred to road vehicles, such as [20], [21], but also from several studies on electric tractors [16], [17], [18], [19], as it is based on precise field measurement data, due to the lack of standard load cycles that fully represent actual tractor operation.

The paper is structured as follows: Section II describes the conventional powertrain and introduces the hybrid electric topology chosen in this work; Section III introduces the considered case studies and their related operating cycles;
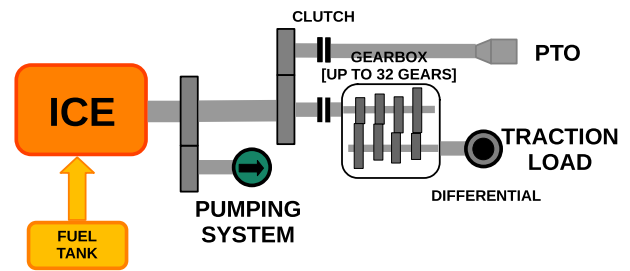

FIGURE 1. Traditional powertrain.

Section IV describes the simulation model that has been used; Section V covers the main design specifications and power management tuning; Section VI introduces the LCC analysis and the considered costs; Section VII presents the results; finally, Section VIII summarizes the conclusion of this paper.

II. CONVENTIONAL TRACTOR POWERTRAIN AND NOVEL ARCHITECTURE

In a conventional tractor the diesel engine is the only power source. Its mechanical power is used for traction, Power Take-Off (PTO, a mechanical power source for implements), hydraulic pump(s) for implement and three-point linkage operation, as well as for a variety of systems that are not strictly fundamental for the performed tasks (e.g. engine auxiliaries or air conditioning). Power is transmitted to the wheels through a stepped mechanical transmission, or through a Continuously Variable Transmission (CVT, splitting the power between a fixed mechanical path and a variable path, usually hydrostatic), whereas PTO and hydraulic pump(s) are powered using 'live' shafts, bypassing the traction transmission, so that they can be powered while the wheels are not moving. A conventional tractor powertrain is outlined in Fig. 1.

Various architectures are possible for powertrain electrification (Fig. 3). An exhaustive discussion has been made in [6]. In this work, a parallel hybrid architecture with a stepped transmission was chosen, due to its simple implementation (minimal changes compared to a conventional tractor) and superior transmission efficiency compared to the series architecture. A Li-ion battery pack was selected due to its high energy density. More advanced hybrid battery-supercapacitor storage systems are also suitable for this application and their use could be beneficial as they exploit the advantages of both technologies [22]–[24]. These hybrid storage system, however, were not considered in this work as they would heavily increase the complexity of such a general analysis. The configuration chosen for the hybrid tractor is outlined in Fig. 2.

III. CASE STUDIES AND OPERATING CYCLES

Farming vehicles cover a wide power range: they come from a few tens of kW for small family farming vehicles, to more than 250 kW for high-power row crop tractors, through
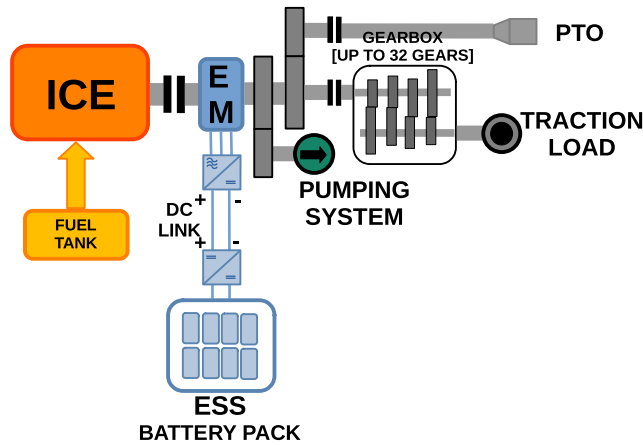
FIGURE 2. Parallel hybrid electric powertrain.

Architecture	Pros	Cons
Series	• ICE decoupled from loads • Suitable for e-CVT*a • Suitable for e-PTO*b and hydraulics electrification • Loads decoupled from each others	• Double energy conversions • Bulky electric machines • High initial overall cost
Parallel	• ICE downsizing feasible • Compact electric drive • Suitable for hydraulics electrification • Easier electrification of existing vehicles • Low overall cost	• ICE-loads speed coupling • Unsuitable for e-PTO and implements electrification
Series-parallel	• ICE decoupled from loads • ICE downsizing feasible • Suitable for e-CVT • Suitable for e-PTO and hydraulics electrification • Compact electric drives	• Mechanical complexity • High intial overall cost

*a) electric Continuously Variable Transmission
*b) electric Power Take Off (electric power supply to implements)

FIGURE 3. Summary of hybrid electric powertrain topologies. Adapted from [6].

medium-size specialized vehicles for orchards and vineyards. Moreover, tractors perform a great variety of different operations. There is still a lack of standard driving cycles that fully represent the working cycles of each tractor category and operation. For these reasons, this work is based on actual field measurements, of which some come from [14], [25]. Three different case studies were considered, distinguished by power size and application:

- Specialized orchard tractor, 76 kW rated power
- Row crop tractor, medium duty use, 175 kW rated power
- Row crop tractor, heavy duty use, 210 kW rated power

The simulations about the specialized and heavy row crop tractors were carried out using working cycles directly from

in-field measurements, whereas a scaled duty cycle was developed from measurements to represent a medium duty use of a row crop tractor.

In the following paragraphs, yearly time contribution and average power (avg. pwr.) are reported for each operating cycle.

A. ORCHARD TRACTOR

For the orchard/vineyard tractor the following operations were considered:

- weeder, 14.3%, avg. pwr. = 35.6 kW
- atomizer, 14.3%, avg. pwr. = 42.1 kW
- grape harvester, 14.3%, avg. pwr. = 20.7 kW
- plant lifting plow, 28.6%, avg. pwr. = 11.0 kW
- tying machine, 28.6%, avg. pwr. = 5.3 kW

assuming 1,000 hours of operation each year, as in [14].

B. ROW CROP TRACTOR MEDIUM DUTY USE

In order to represent the medium duty use of a row crop tractor, a mix of operations was considered, with a significant fraction of medium-power operations. The mix is composed as follows:

- heavy plowing, 33.4%, avg. pwr. = 96.6 kW
- medium plowing, 35.6%, avg. pwr. = 82.8 kW
- rotary harrow, 17.8%, avg. pwr. = 114.7 kW
- field transport + idle, 13.2%, avg. pwr. = 30.1 kW

where the first one is actually the only heavy operation, considering load peaks. 850 working hours per year were assumed [26].

C. ROW CROP TRACTOR HEAVY DUTY USE

The following mix of operations was considered for the row crop tractor with heavy duty use:

- subsoiler, 10.3%, avg. pwr. = 150.8 kW
- cultivator, 12.3%, avg. pwr. = 97.4 kW
- heavy plowing, 18.7%, avg. pwr. = 85.7 kW
- tiller, 10.3%, avg. pwr. = 145.5 kW
- rotary harrow, 10.3%, avg. pwr. = 122.7 kW
- road transport, with and without trailer, 10.3%, avg. pwr = 63.6 kW
- idle, 10.3%, avg. pwr. = 12.7 kW

considering 850 hours of operation each year [26].

Fig. 4 shows load distribution as a function of power/Pmax for each of the aforementioned categories, where Pmax is the maximum power of the original non-hybrid tractor. Plot (a) shows the fraction of operating time at each power level, whereas plot (b) shows the Cumulative Distribution Function (CDF). The latter indicates the operating time fraction that can be performed with a power level smaller than or equal to the x-axis value. From the CDF curves, it can be seen that for the orchard tractor approximately 75-80% of the operations, in terms of time, is performed at less than 40% of the maximum power. On the other hand, the same fraction of operations on the row crop medium duty tractor requires ~60% of the maximum power, whereas for the row crop
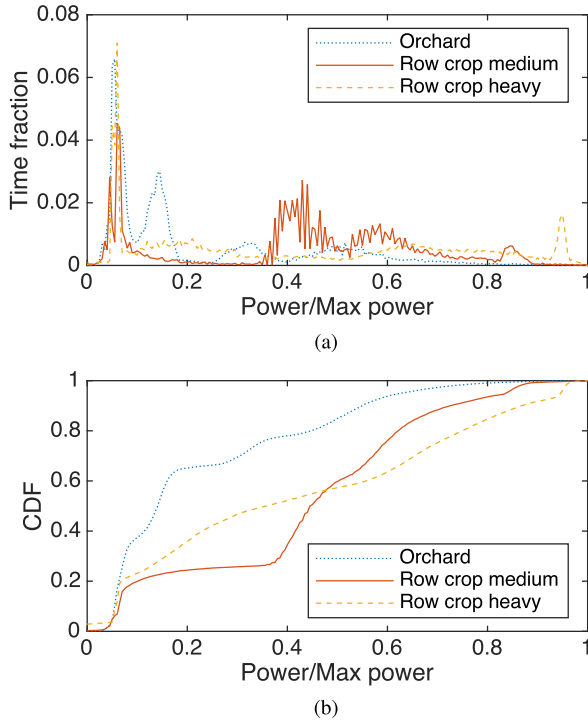
FIGURE 4. Operating time fraction at each power level (a) and cumulative distribution function CDF (b).

heavy duty this value exceeds 70% of Pmax. This suggests that the orchard tractor category will be more promising for powertrain electrification, compared to the two heavier categories.

IV. SYSTEM MODELING

A quasi-static backward-facing model was adopted to simulate both hybrid and conventional tractor. The simulation model is used to determine fuel and electrical energy consumption, as well as the specifications of the hybrid system. Load data was obtained through field tests, which makes them intrinsically reliable and allows to validate the simulated fuel consumption of the traditional non-hybrid tractors. Measurements were taken at engine shaft, and Engine Control Unit (ECU) data were acquired. Thus, loads are assumed to be applied directly to the powertrain, without modeling driver or speed controller behavior. Loads are evaluated at ICE crankshaft so all the transmission ratios and losses are already included in the load values.

The model was built in Simulink and MATLAB was used for the results post-processing, as well as for the iterative processes described in Section V-A, however any software that simulates dynamical systems can be used. Simulation was performed using the automatically selected, variable-step solver, with maximum step size equal to the sampling interval of field tests data.

A. ICE

The power management algorithm determines the amount of torque T_{ICE} provided by the ICE, whereas engine speed is

assumed equal to the field measurements. Fuel consumption estimation is based on engine torque and speed, using the Brake Specific Fuel Consumption (BSFC) map, if available, or a polynomial approximating function (poly), which was tuned to give a good match with the consumption measured by the ECU during field tests. Fig. 6 shows that the estimation is good for the purpose of this work.

B. EM + CONVERTER

Electric machine (EM) torque T_{EM} is determined by the difference between load torque and engine torque, times the speed ratio (ICE speed/EM speed), whereas EM speed is equal to ICE speed divided by the speed ratio. For simplicity, in this analysis the speed ratio was set to 1, i.e. a direct drive was chosen. A constant 0.85 efficiency is assumed to account for the combined losses of EM and converter. The value is in accordance with [27], [28].

C. BATTERY

The battery model is based on the steady-state model adopted by Schaltz [29], resulting in:

$$I_{cell} = \frac{U_{oc} - \sqrt{U_{oc}^2 - 4R_{cell}P_{cell}}}{2R_{cell}} \qquad (1)$$

with cell current $I_{cell} > 0$ and cell power $P_{cell} > 0$ when the battery is charged. R_{cell} is the battery internal resistance, and U_{oc} is the open-circuit voltage. Both are function ot the State of Charge (SoC). SoC at time t is computed as:

$$SoC(t) = SoC(t=0) + \int_0^t \frac{I_{cell}(\tau)}{Cap_{cell}} d\tau \qquad (2)$$

with Cap_{cell} being cell capacity [Ah]. Although not completely accurate [30], battery energy content E was estimated as:

$$E = SoC \cdot V_{nom} \cdot Cap_{cell} \cdot N_{cell} \qquad (3)$$

where V_{nom} is the nominal cell voltage and N_{cell} is the number of cells.

The following C-rate limitations were assumed:

- continuous
  - charge 1C
  - discharge 3C
- peak ($\leq$ 10 s)
  - charge 3C
  - discharge 6C

D. POWER MANAGEMENT

A simple rule-based power management strategy was chosen. The adopted rules are derived from the ones used in [14] and [15]. However, contrary to [15], a speed-independent EM torque is used for battery charging, instead of setting it to achieve the maximum ICE efficiency for the given speed. Charging with the maximum efficiency torque at medium to high engine speed would lead to a high battery current, easily
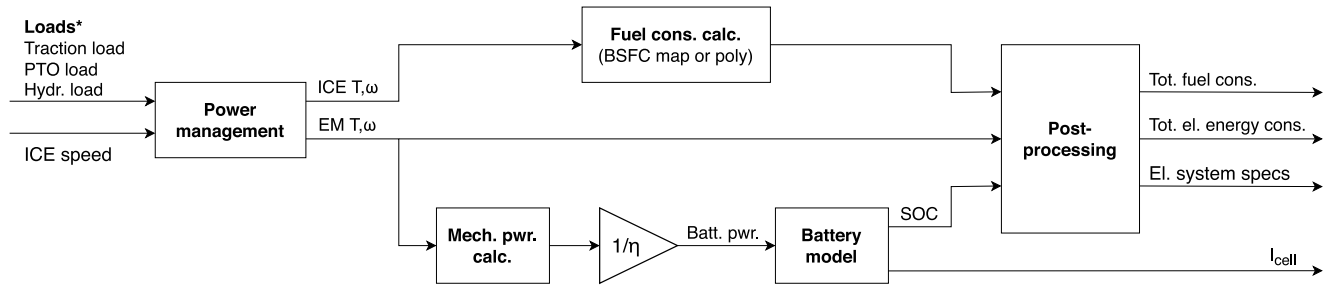
FIGURE 5. Model scheme. *Loads referred to ICE shaft.

exceeding battery limitations, unless a high-capacity battery is adopted.

If the load torque T_{req} is lower than a certain threshold (T_{Llim}), the ICE operates at the threshold, whereas the EM acts as a generator in order to match the load torque. If the load is greater than T_{Llim}, the ICE supplies the load torque up to a certain limit curve ($T_{Hlim}(\omega)$), then the EM covers the difference between the load torque and the ICE torque (electric boost mode). $T_{Hlim}(\omega)$ can correspond to the actual ICE torque limit or, when in a particular task EM boost is rarely needed, the ICE can be limited to a lower torque in order to use the energy stored in the battery to cover part of the load. Both torque thresholds are individual for each operating cycle, and they are chosen in order to minimize the required battery capacity and, if desired, to maximize electrical energy usage if a certain cycle is not particularly power intensive, while complying with the battery C-rate limitations. How the thresholds are chosen is explained in Section V-A. This method requires knowledge of the whole load cycle, thus it might have some limitations when implemented in real life. However, the strategy is simple and was deemed acceptable for this analysis. Equation (4) and Fig. 7 summarize the power management behavior.

$$
T_{ICE} = \begin{cases} T_{Llim}, & \text{if } T_{req} \leq T_{Llim} \\ T_{req}, & \text{if } T_{Llim} < T_{req} \leq T_{Hlim}(\omega) \\ T_{Hlim}(\omega), & \text{if } T_{req} > T_{Hlim}(\omega) \end{cases}
$$

$$
T_{EM} = \begin{cases} T_{req} - T_{Llim}, & \text{if } T_{req} \leq T_{Llim} \\ 0, & \text{if } T_{Llim} < T_{req} \leq T_{Hlim}(\omega) \\ T_{req} - T_{Hlim}(\omega), & \text{if } T_{req} > T_{Hlim}(\omega) \end{cases}
$$

(4)

E. CO₂ EMISSIONS ESTIMATION

Only CO_2 emissions derived from fuel and electrical energy consumption, and battery manufacturing are considered in this study, as these are assumed to be the cause of the vast majority of emissions difference between a hybrid and non-hybrid tractor.

CO_2 equivalent emissions are assumed to be proportional to fuel consumption (complete combustion), electrical energy
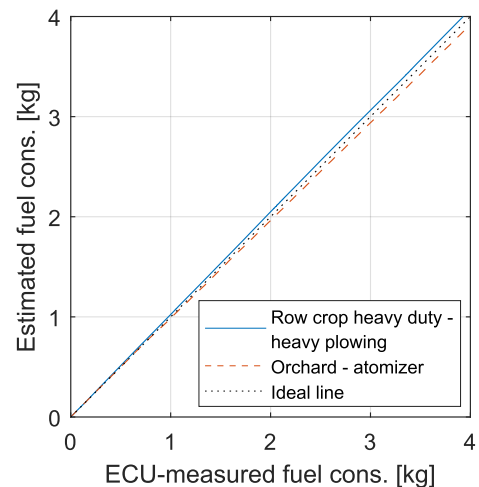

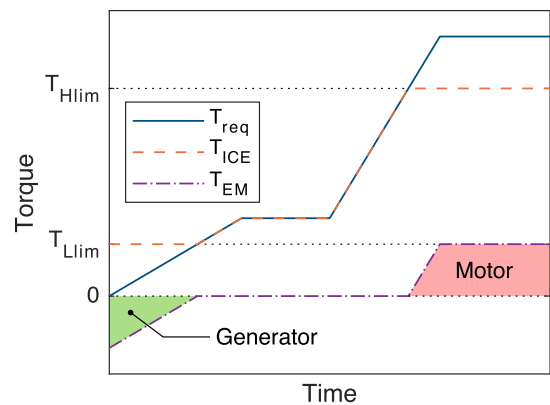**FIGURE 6.** Fuel consumption estimation accuracy.

FIGURE 7. Power management strategy example with demo operating cycle. Constant T_{Hlim} is shown here for simplicity. Colored areas highlight where the EM acts as a generator or as a motor.

consumption, and battery capacity. The considered emission factors are the following:

- $3.92 \text{ kg}_{CO_2}/\text{kg}_{Diesel}$
- $0.33 \text{ kg}_{CO_2}/\text{kWh}_{El.energy}$
- $100 \text{ kg}_{CO_2}/\text{kWh}_{Battery}$

These factors include the emissions of the whole process, including extraction of raw materials, transport, production,

delivery to the costumer, and, for the diesel fuel, also the emissions originating from its combustion. The direct measurement of the emission factors is not possible. The adopted value are based on estimations reported in literature. The value for fuel-related emissions was derived from [31], considering the energy based allocation method and lower heating value of diesel equal to 43.1 MJ/kg. As for electrical energy emissions, the assumed value is derived from [32], considering the average between the European mix emission factors for low voltage supply of 2016 and 2030. It is reasonable to take the average value because the assumed tractor life extends to a few years beyond 2030. In [33] a 61-106 kg_{CO_2}/kWh is reported for battery production. A value close to the upper limit was chosen because in this study the required battery capacity is relatively low if compared to BEVs (Battery Electric Vehicles), which often adopt batteries larger than 50 kWh.

V. DESIGN SPECIFICATIONS DETERMINATION AND POWER MANAGEMENT TUNING

The simulation model was used to determine the main design specifications of the hybrid powertrain, namely battery capacity, electric machine rated torque, converter rated power, downsized engine power, and power management parameters.

A. BATTERY CAPACITY SIZING AND POWER MANAGEMENT TUNING

The required battery capacity Cap_{req} for each load cycle was determined by multiplying the difference between the energy level at the beginning and at the end of the cycle by the number of cycle repetitions necessary to achieve at least the minimum required operating time (8 h), and adding the possible differences between maximum energy level and initial energy level, and between final energy level and minimum energy level. The obtained value was finally divided by a certain Depth of Discharge (DoD) that was deemed acceptable. In this analysis, a conservative 60% DoD was chosen in order to ensure a long battery life and to cope with the strong reliability requirements of the agricultural industry [34]. Equation (5) summarizes the capacity computation:

$$Cap_{req} = \left[\left(E_{in} - E_{fin} \right) \cdot ceil \left(\frac{t_{cycle}}{t_{min}} \right) + \right.$$
$$\left. + \left(E_{max} - E_{in} \right) + \left(E_{fin} - E_{min} \right) \right] \cdot \frac{1}{DoD} \quad (5)$$

where:
- E_{in} and E_{fin} are the battery energy levels respectively at the beginning and at the end of the operating cycle
- E_{max} and E_{min} are the maximum and minimum battery energy levels throughout the operating cycle, respectively
- t_{min} and t_{cycle} are the minimum required operating time and the cycle duration, respectively.

The obtained capacity value depends on the power management tuning. The objective was to keep the battery
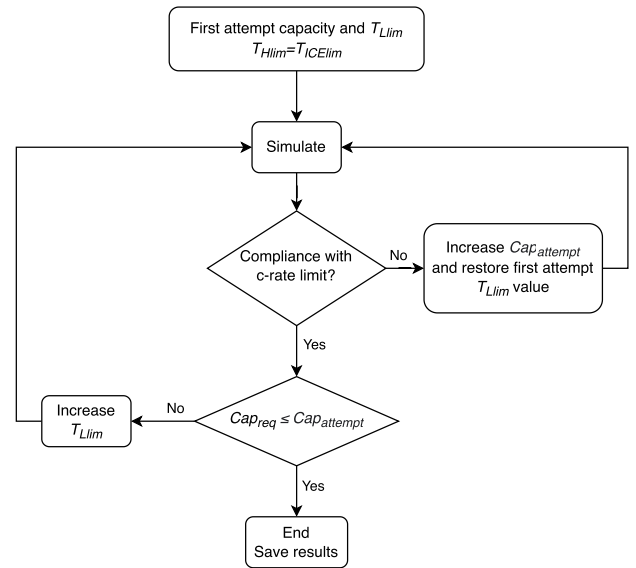
FIGURE 8. Battery capacity determination. Higher T_{Llim} results in more ICE-powered battery charging.

capacity as low as possible for each downsized engine that was simulated. To do so, low attempt values for T_{Llim} and battery capacity $Cap_{attempt}$ were used at first, while maintaining the upper limit T_{Hlim} equal to the actual ICE torque limit T_{ICElim}. Then, based on the simulation results, T_{Llim} and $Cap_{attempt}$ are adjusted iteratively according to Fig. 8. The process is repeated until both capacity and C-rate requirements are respected.

Once T_{Llim} and capacity are determined for each load cycle, the final battery capacity Cap_{act} is simply the maximum among the values required by each cycle. Having set Cap_{act}, the final value of T_{Llim} can be determined. The process shown in Fig. 8 sets T_{Llim} in order to minimize the battery capacity for each load cycle, but, except for the cycle that requires the maximum capacity, this results in an unnecessary high T_{Llim}, which leads to an increased fuel consumption. The process shown in Fig. 9 is used to determine the minimum possible T_{Llim} value, maintaining the battery capacity required by a given cycle below or equal to the actual battery capacity Cap_{act}. The lowest possible value for T_{Llim} is zero.

Finally, the upper threshold $T_{Hlim}(\omega)$ can be adjusted, maintaining the previously determined Cap_{act} and T_{Llim}. $T_{Hlim}(\omega)$ was obtained by multiplying the actual ICE torque limit by a coefficient $k_H \leq 1$. Such coefficient can be lower than 1 only for the operating cycles that have $T_{Llim} = 0$, otherwise a higher capacity battery or a higher T_{Llim} would be needed. The coefficient k_H is determined by gradually reducing it from 1, as shown in Fig. 10. The row crop tractors operating cycles are very power-demanding, compared to the orchard tractor ones, so lowering the amount of torque, and therefore power, that can be delivered by the ICE results in a rapid increase of required battery capacity but without significant operating cost savings. Thus it was decided to
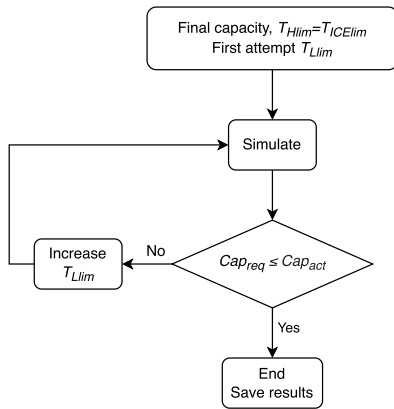
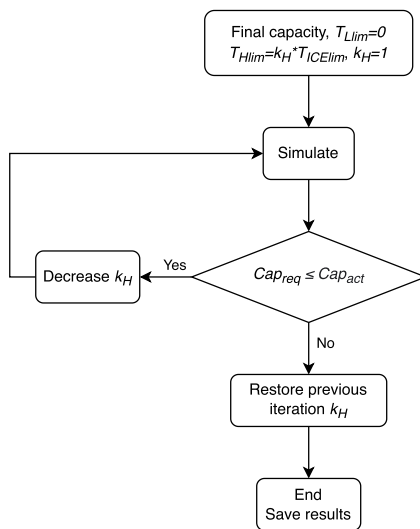**FIGURE 9.** Lower torque threshold T_{Llim} tuning.

FIGURE 10. Upper torque threshold T_{Hlim} tuning.

keep $k_H = 1$ on the row crop tractors, which also contributes to ensure a long battery life by reducing its number of cycles.

B. ELECTRIC MACHINE AND POWER ELECTRONICS DESIGN SPECS

The EM design torque was determined considering the thermal equivalent torque, as a design process based on peak torque would lead to an oversized machine. As in [35], a low pass filter was used, adopting as time constant τ the thermal time constant of the EM. The equivalent torque T_{eq} was computed from the instantaneous EM torque T_{EM} using equation (6).

$$T_{eq} = \sqrt{\frac{\tau}{\tau s + 1} T_{EM}^2} \tag{6}$$

Reasonable τ values for water cooled EMs were considered, ranging from 200 s for the orchard-vineyard tractor, to 500 s for the most downsized row crop, medium duty, tractor. Rated power for the EM was determined in the same way.

On the contrary, peak power was used as a design requirement for the power converter because usually the thermal time constant of power electronics is much lower than the EM time constant.

C. ICE DOWNSIZING

For the two row crop tractors, various levels of ICE downsizing were considered. In order to obtain a fine variation of ICE power level, the torque curve of a base engine was downscaled with a coefficient called *R*. At the same time, the operating cycles were kept constant to introduce a certain safety margin in terms of both performance and price and to favor the non-hybrid variant, although load torque should decrease with ICE downsizing, as some of the parasitic losses (e.g. cooling fan) were included in the load torque data.

On the orchard tractor, instead, a single 55 kW ICE was considered for the hybrid variant because the new emissions regulations are much less restrictive below 56 kW. Whereas this is controversial for emission reduction purposes, this approach has been adopted by several authors [12], [14], [15]. So, in the case of the orchard tractor, instead of varying ICE power, EM exploitation was varied while keeping the same battery size, as the objective was to keep it as small as possible. Three modes were considered:

- *hybrid 1* - use EM only in cycles in which ICE needs boosting; this mode is used to determine the battery capacity
- *hybrid 2* - maximize EM usage; electric assistance in medium duty cycles (atomizer and harvester) and entire parts of low-power duty cycles (plant lifting plow and tying machine) performed in purely electric mode (ICE off), until the battery reaches SoC=20% (consistent with a 60% discharge from an 80% initial SoC)
- *hybrid mix* - intermediate case between *hybrid 1* and *hybrid 2*; purely electric operation is limited in order to reduce the initial tractor cost compared to *hybrid 1*. This means that operation with the plant lifting plow is always performed with ICE on, as a higher power EM would be needed for purely electric operation.

For the 55 kW ICE, an actual BSFC map was available, whereas for the row crop tractors with downsized engines, BSFC maps and polynomial approximating functions where obtained by scaling them in the same way as engine torque. According to Dekraker *et al.* [36] such an approach is not completely accurate and some adjustment should be considered. However, the reported combined magnitude of these adjustments does not exceed 5 %. Moreover, the region in which the correction factor assumes the highest values is the knock-constrained region (high load and low speed), which is not an issue for compression ignition engines. As will be seen later, on the row crop tractors ICE downsizing is not extreme (the lowest *R* value is 0.8), this contributes to limiting the BSFC estimation error when no adjustments are considered. The simulation results obtained with this scaling approach are deemed accurate enough for this analysis, although no real

fuel consumption data are available for the hybrid tractor, so it was not possible to verify the actual consumption estimation error.

VI. LIFE CYCLE COST ANALYSIS

This work aims to provide a method to evaluate the economic feasibility of farming tractor powertrain electrification, and to determine the best ICE downsizing, with a wide variety of variables. To evaluate the economic convenience of a hybrid variant, a Life Cycle Cost (LCC) analysis was conducted. LCC is the total present value of all the costs that occur during the life cycle of a product. In this work, only user costs were considered, and maintenance and disposal costs were assumed equal for both hybrid electric and traditional powertrains (no battery replacement). Thus, they were ignored. As reported later, the best downsizing coefficient R resulted fairly close to 1, and also the orchard tractor downscaling to 55 kW did not result in an excessive change of engine size. This justifies the choice of constant maintenance costs. The LCC is computed as follows:

$$LCC = C_p + \sum_{t=0}^{n} \frac{C_t}{(1+d)^t} \qquad (7)$$

where:
- C_p is the initial cost (purchase)
- C_t are all the relevant costs that occur during the considered study period, fuel and electrical energy in this case
- t indicates the year when each cost occurs. In general C_p could be treated exactly as all the future costs, but a separate term was introduced for clarity.
- n is the study period, in this case the service life. A general global engine life requirement is 6,000 to 12,000 hours, increasing with the power level [37]. In this work a 10,000-h life was assumed, and life in years was computed dividing the life in hours by the annual operating time.
- d is the discount rate used to compute the present value of future costs. Papers on German agriculture report a discount rate ranging from 3.69% [38] to 13.87% [39]. For the present analysis an 8% discount rate was chosen.

A. TRACTOR COMPONENTS AND ENERGY PRICING

In order to perform a LCC analysis, consumer prices of the various elements, as well as energy costs (fuel and electricity), need to be determined. All the elements shared by both hybrid and ICE tractor were ignored, and all prices were intended as consumer prices. For all the considered tractor elements, a price range was taken into account, as price cannot be exactly determined and could change in the near future. Moreover, this choice allows to determine which elements have the higher impact on the LCC. Also for energy costs it is important to consider a price range in order to cover for possible country-related variations as well as future variations.

1) TRACTOR COMPONENTS

As for capital expenditure, the following were considered:
- *ICE* According to Renius [37], for a high-technology 150 kW tractor, the diesel engine represents 19% of the tractor cost. An analysis of the market prices of 86 tractors with power ranging from 75 kW to over 200 kW was conducted. Assuming the 19% valid for all of these, and performing a linear regression, the incremental price results in approximately 290 €/kW. As the fraction cited by Renius was intended for the production cost, the obtained cost per kW was rounded to 300 €/kW and used as the upper limit of the ICE price range. The considered price range was extended down to 50 €/kW. The latter is a very low value and is probably far from the real market price, but it was included to widen the payback time evaluation.
- *Battery* BNEF's 2020 Battery Price Survey [40] reports a 137 $/kWh volume-weighted average battery pack production price, so a 50–250 €/kWh price range was chosen in order to cover future price reductions as well as the higher prices (per kWh) of the power-oriented battery packs. Simulation showed that the number of battery cycles did not reach excessive values, considering the adopted DoD. Mid-life battery pack replacement, thus, is not necessary and battery cost should be accounted only once for LCC computation.
- *EM* The EETT Roadmap 2017 [41] states that the 2017 production cost of a 100 kW peak power EM is 600–800 $ (6-8 $/kW peak). Goss *et al.* [42] report an approximate material cost range of 250–600 $ for an Interior Permanent Magnet 50 kW motor (IPM) for automotive applications, depending on NeFeB price, and approximately 150 $ for a 50 kW copper rotor Induction Motor (IM). For both motors, a 2.5 consumer price to material cost ratio was considered by Goss *et al.*. This results in 7.5–30 $/kW peak power. Considering the lower production volumes of farming tractors compared to passenger vehicles, and the lower power of electric machines, as will be reported later in this paper, a 15–60 €/kW price range was used.
- *Power electronics (inverter + optional DC/DC)* The EETT Roadmap 2017 [41] reports, for a 100 kW peak power powertrain, a 1000 $ production cost (10 $/kW). Murugesan and Manickam [43] report a price range of approximately 800-8500 $ for a 60 kW inverter (13–142 $/kW), where the higher values refer to a considerably oversized system intended for increased reliability. In this paper, a 15–60 €/kW range was chosen, taking into account the production volume and power aspects presented above regarding EM price.

Other additional devices and systems needed for powertrain electrification, e.g. additional clutches or cooling systems, as well as development costs, were ignored.

TABLE 1. Operating costs savings each cycle.

Orchard				Row crop medium				Row crop heavy		
Opex % diff.	Hyb.1	Hyb. 2	Mix	Opex % diff.	R=0.8	R=0.86	R=0.92	Opex % diff.	R=0.88	R=0.92
Weeder	-3.31%	-3.31%	-3.31%	Heavy plowing	-1.56%	-1.95%	-1.74%	Subsoiler	+1.46%	+0.54%
Atomizer	-0.96%	-2.17%	-2.17%	Medium plowing	-5.33%	-4.32%	-3.30%	Cultivator	-0.11%	-0.16%
Grape harvester	-7.72%	-8.43%	-8.43%	Rotary harrow	-4.67%	-3.98%	-3.17%	Heavy plowing	-0.99%	-0.71%
Plant lifting	-14.85%	-17.99%	-14.85%	Field transport + idle	-1.42%	+0.35%	+2.57%	Tiller	-0.68%	-0.48%
Tying machine	-16.06%	-24.09%	-24.09%					Rotary harrow	-1.83%	-1.25%
								Road transport	-1.73%	-1.14%
								Idle	-3.00%	-1.92%
Average	-6.88%	-8.77%	-8.14%	Average	-3.60%	-3.14%	-2.41%	Average	-0.67%	-0.54%

Negative values represent savings compared to the traditional tractor.

Anyway, this is partially balanced by the fact that power absorption (load cycles) were considered constant despite ICE downsizing, resulting in slightly higher operating costs.

2) ENERGY

- *Fuel* In [4], [14] fuel prices around 0.9 €/L were used. The considered range is 0.7–1.3 €/L.
- *Electrical energy* Electrical energy price was based on data published by the Italian authority ARERA [44] for low-voltage non-household consumers. Depending on the time band, electricity price, without VAT, ranges from approximately 0.155 to 0.18 €/kWh (September 2021). A price equal to 0.16 €/kWh was chosen, as it was assumed that charging would happen mainly at night. The analysis was extended down to 0.1 €/kWh and up to 0.28 €/kWh.

3) STANDARD PRICES

For each tractor category, a "standard" combination of system and energy prices was selected in a preliminary analysis. The selection is based on prices deemed most realistic by the authors at the time of writing. The following were assumed equal for the three tractor categories, unless explicitly indicated:

- ICE 200 €/kW
- Battery 150 €/kWh
- EM 40 and 30 €/kW rated power, respectively for orchard and row crop. A higher value was assumed for the orchard tractor due to the considerably lower rating EM, as will be shown later.
- Power electronics 30 €/kW peak power
- Fuel 0.9 €/L
- Electrical energy 0.16 €/kWh

VII. RESULTS

Although at the beginning it was intended to cover a wide variation of ICE downsizing degree, preliminary simulations showed that a further reduction of ICE power leads to a high battery capacity, exceeding 40 kWh, that in turn leads to high initial costs and could possibly not comply with packaging requirements (∼200 Wh/L energy density [45]). On the contrary, R values very close to 1 were not investigated since all the hybrid system components would be needed anyway, increasing tractor complexity and cost without leading to significant operating costs savings. For the row crop medium tractor, a 0.8–0.92 R range was analyzed considering three discrete values, whereas for the heavy duty one the analysis was limited to two values: 0.88 and 0.92. For the orchard tractor, a battery capacity comparable to the ones of two larger tractors was obtained, however this was deemed acceptable, as ICE downsizing below 56 kW results in less restrictive emission regulations, so that some exhaust gas treatment devices can be removed, thus clearing more space onboard and limiting costs.

A. SAVINGS EACH CYCLE

Table 1 shows the savings on operating costs (Operational expenditure, Opex) for each hybrid tractor, compared to the traditional one, with the "standard" fuel and electrical energy prices. It clearly shows that the savings for the orchard tractor are far greater than the ones for row crop tractors, in particular when compared to the heavier one. This is due to the operating cycles, because, as shown by Fig. 4, moving from orchard to row crop heavy tractor the operations become progressively more power-intensive. In fact, the savings are higher when performing low-power cycles, as ICE operates in a low-efficiency region. Reducing engine size results in a better exploitation, moving the operating point to a higher efficiency region. Engine downsizing alone allows for approx. 15% savings in the very-low-power orchard cycles (plant lifting plow and tying machine), as shown by the "hyb. 1" column, where no EM use is considered when torque boost is not needed. Table 3 shows the fraction of useful work that comes from the electric grid. From a comparison with Table 1, it is possible to notice that there is no clear correlation between cost savings and fraction of useful work covered by electrical energy. Indeed, as shown by Table 2, if ICE is operated in a high-efficiency region (e.g. efficiency around 0.4), there is not a huge difference between diesel and electrical energy cost per unit useful work (∼20%). This means that, except for low-power (thus low ICE efficiency) cycles, for instance tying machine, the vast majority of the savings comes from ICE operating point shifting.

It is interesting to notice that in some load cycles, the operating costs of the hybrid variants are higher than the costs
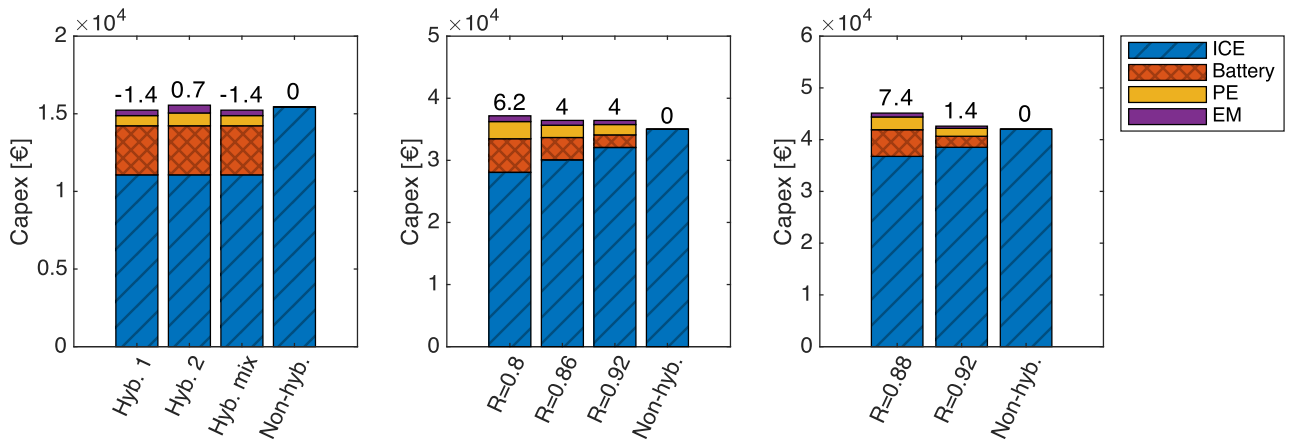
FIGURE 11. Capex - orchard, row crop medium and heavy. Percentage variation is shown above bars.
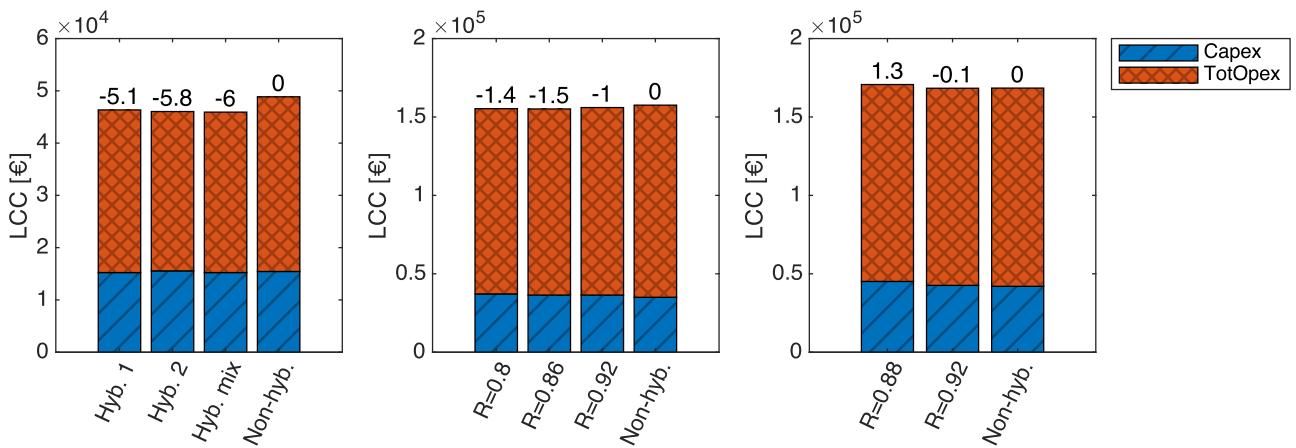

FIGURE 12. LCC - orchard, row crop medium and heavy. Percentage variation is shown above bars.

TABLE 2. Diesel vs. electrical energy cost per unit useful work.

Data	Efficiency[a]	Cost/useful work [€/GJ]
Diesel		
Cost = 0.9 €/L Density = 0.83 kg/l Heating val. = 43.1 MJ/kg	0.4	63
Electrical energy		
Cost 0.16 €/kWh	0.85	52

[a] Mechanical transmission, battery and charger losses were neglected.

of the conventional tractors. This happens because a lot of battery charging during operation is needed to ensure that the battery lasts enough to cover the minimum required operating time. This can lead to higher costs as ICE efficiency increase could not compensate for double energy conversion losses.

B. LCC AND PAYBACK TIME VARIATION DUE TO VARYING COMPONENT PRICING

ICE and battery are the components with the highest influence on the purchase price of a hybrid tractor, as they represent the two major fractions of the purchase price (Capital expenditure, Capex) (Fig. 11).

1) EFFECT ON LCC

Fig. 12 shows LCC composition and highlights the best engine downsizing or hybrid mode for the "standard" price combination. For the orchard tractor, the best mode results Hyb. mix, as the slightly higher operating costs savings achieved with Hyb. 2 are not enough to compensate for its higher purchase cost. Furthermore, all the three hybrid modes achieve a lower LCC than the non-hybrid tractor. As for the row crop medium duty tractor, the LCC benefit for the three R values is always very low. For this tractor category $R = 0.86$ is the best downsizing degree, although LCC is very close to the one obtained with $R = 0.8$. For row crop heavy duty tractor the best R value is 0.92. However, the benefit compared to the non-hybrid variant is negligible. With a more downsized ICE ($R = 0.88$) initial cost increase is significant whereas annual savings are not, resulting in a considerable LCC increase.

Figs. 13, 14, 15, 16 show the effects of ICE and battery cost on LCC when ICE downsizing (R) is varied, for the two row

TABLE 3. Fraction of work performed using electric grid energy.

| Orchard				Row crop medium				Row crop heavy		
Opex % diff.	Hyb.1	Hyb. 2	Mix	Opex % diff.	R=0.8	R=0.86	R=0.92	Opex % diff.	R=0.88	R=0.92
Weeder	4.09%	4.09%	4.09%	Heavy plowing	2.03%	1.35%	0.71%	Subsoiler	1.34%	0.55%
Atomizer	0.05%	2.77%	2.77%	Medium plowing	0%	0%	0%	Cultivator	~0%	0%
Grape harvester	0%	6.10%	6.10%	Rotary harrow	0.19%	0.04%	0.01%	Heavy plowing	0.2%	0.06%
Plant lifting plow	0%	12.16%	0%	Field transport + idle	6.62%	3.97%	0.84%	Tiller	1.43%	0.6%
Tying machine	0%	25.56%	25.56%					Rotary harrow	~0%	0%
								Road transport	1.89%	1.17%
								Idle	0%	0%
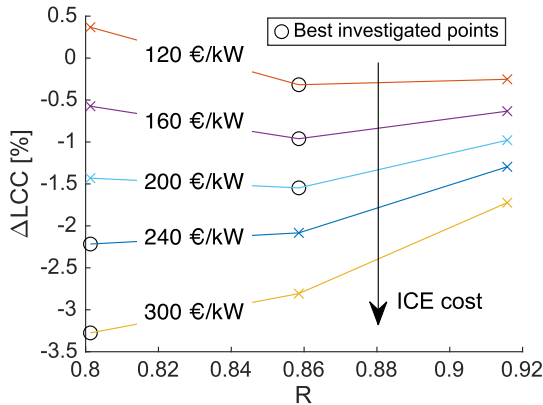
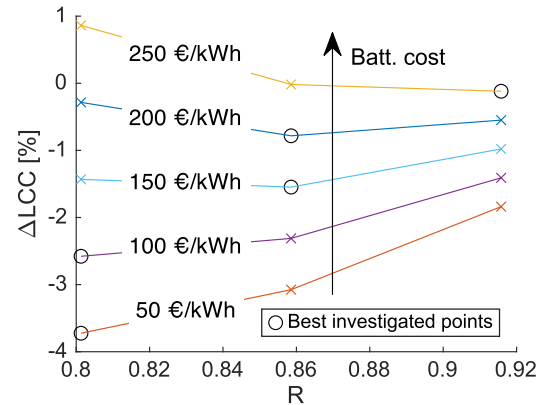**FIGURE 13.** Row crop medium tractor LCC variation due to ICE price.

FIGURE 14. Row crop medium tractor LCC variation due to battery price.

crop tractors, highlighting the best downsizing coefficient. When ICE cost variation was considered, battery price was fixed to 150 €/kWh, whereas for battery cost variation, ICE price was fixed to 200 €/kW. EM and PE prices are equal to the previously introduced "standard" values. As expected, the higher the ICE cost, the more convenient the ICE downsizing. Whereas this behavior is clearly distinguishable on the medium tractor, it is not so on the heavy tractor, because the less downsized hybrid variant remains always more convenient than the more downsized one. Only when a very high ICE cost is combined with a very low battery cost, the more downsized variant becomes more convenient (not shown here). The contrary happens when ICE cost is fixed and battery cost is varied.

2) EFFECT ON PAYBACK TIME

PayBack Time (PBT) is the minimum time for which an investment becomes profitable. In this work, it refers to the minimum time after which a hybrid tractor becomes more convenient than its non-hybrid counterpart. It is computed varying the reference period n in eqnarray (7). Figs. 17, 18, 19 show how PBT varies with ICE and battery price. In order to make these figures clear and easy to read, only three battery price levels are shown: 100, 150, and 200 €/kWh. Shown data already takes into account the best downsizing or hybrid mode (1, 2, mix), respectively for row crop and orchard tractors. PBT trend is consistent with LCC behavior: a low ICE cost combined with a high battery cost, leads to a high purchase cost penalty for the hybrid variant, which is not
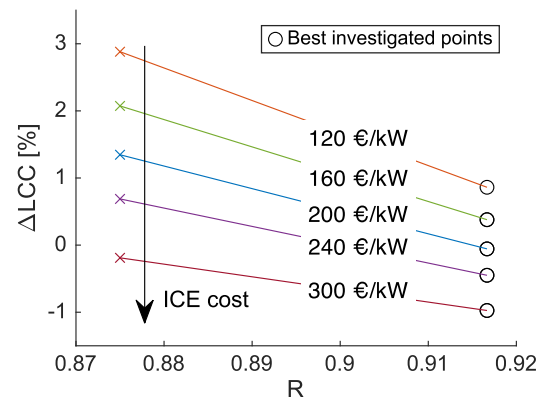

FIGURE 15. Row crop heavy tractor LCC variation due to ICE price.

recoverable during the tractor service life. This phenomenon is exaggerated on the row crop heavy duty tractor, shown in Fig. 19. This is due to the annual savings being very low, meaning that either the hybrid variant is already cheaper from the beginning, or the price penalty will not be recovered during service life, except for very few price combinations. In Fig. 18 small dents are visible, these are due to the optimal R value changing as ICE cost is varied.

C. CO₂ EMISSIONS

Fig. 20 shows CO_2 emissions for the analyzed tractors. CO_2 reductions are consistent with operating cost savings (Table 1), except for the more downsized heavy duty row crop tractor. In this case, the increase of battery production
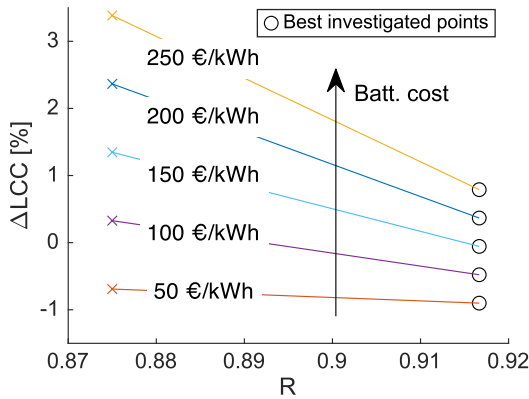
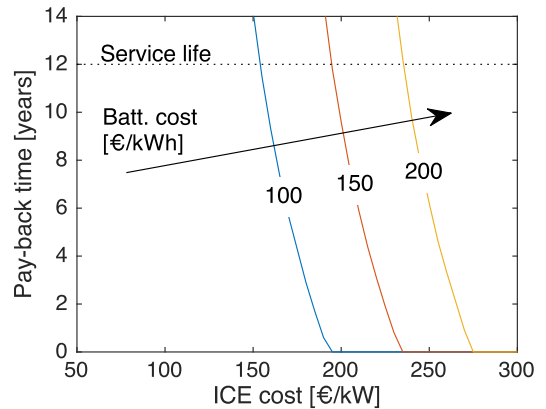**FIGURE 16.** Row crop heavy tractor LCC variation due to battery price.

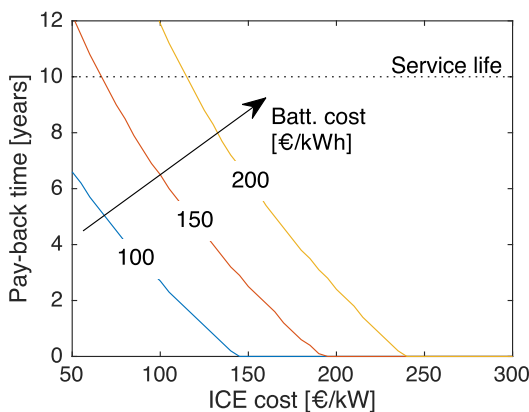**FIGURE 17.** Orchard tractor PBT.

FIGURE 18. Row crop medium tractor PBT.

FIGURE 19. Row crop heavy tractor PBT.

TABLE 4. Main specs and savings, "standard" price combination, best hybrid mode (orchard) or best downsizing R (row crop).

	Orchard (Hyb. mix)	Row crop med. ($R = 0.86$)	Row crop heavy ($R = 0.92$)
EM torque [Nm]			
peak	147	382	471
rated	63	157	118
EM power [kW]			
peak	22	66	51
rated	9	26	14
Batt. cap. [kWh]	21	24	14
Capex [€] Hyb.; non-hyb.	15,233; 15,442 (-1.4%)	36,433; 35,018 (+4.0%)	42,658; 42,022 (+1.4%)
Opex [€/year] Hyb.; non-hyb.	4,574; 4,980 (-8.2%)	1,5747; 16,258 (-3.1%)	16,681; 16,771 (-0.5%)
PBT [years]	0	3.3	9.6

From figures for the orchard tractor, it can be seen, as expected, that low diesel price and high electrical energy price favor less electrical energy intensive hybrid modes (although Hyb. 1 never becomes the most convenient mode, unless electrical energy price is very high), and vice versa. Most importantly, it emerges that the hybrid variants always shows a considerably smaller LCC than the non-hybrid tractor.

Whereas the same LCC trends can be identified on the row crop tractors, the advantage of the hybrid variants is lower or does not even exist. A major aspect that appears from this analysis is that on the heavy duty row crop tractor, the variant with the more downsized engine has a higher LCC than the non-hybrid tractor, even combining the highest diesel price with the lowest electrical energy price (not shown here).

E. SPECS AND SAVINGS SUMMARY

Table 4 summarizes electric system specifications and savings, computed with the "standard" price combination. As expected, the specifications required for the orchard tractor EM and its PE are the least demanding, because the loads are much lower than on the row crop tractors, despite the relatively high downsizing degree. On the contrary, battery size is comparable with the ones of the row crop tractors, probably due the different load cycle (i.e. limited possibility

and electrical energy emissions, compared to $R = 0.92$ variant, overcomes the CO_2 reduction given by the lower fuel consumption.

D. EFFECT OF DIESEL AND ELECTRICAL ENERGY PRICE

Figs. 21, 22 report LCC behavior with varying diesel and electrical energy prices. Prices of ICE and electric elements are set to the "standard" values.
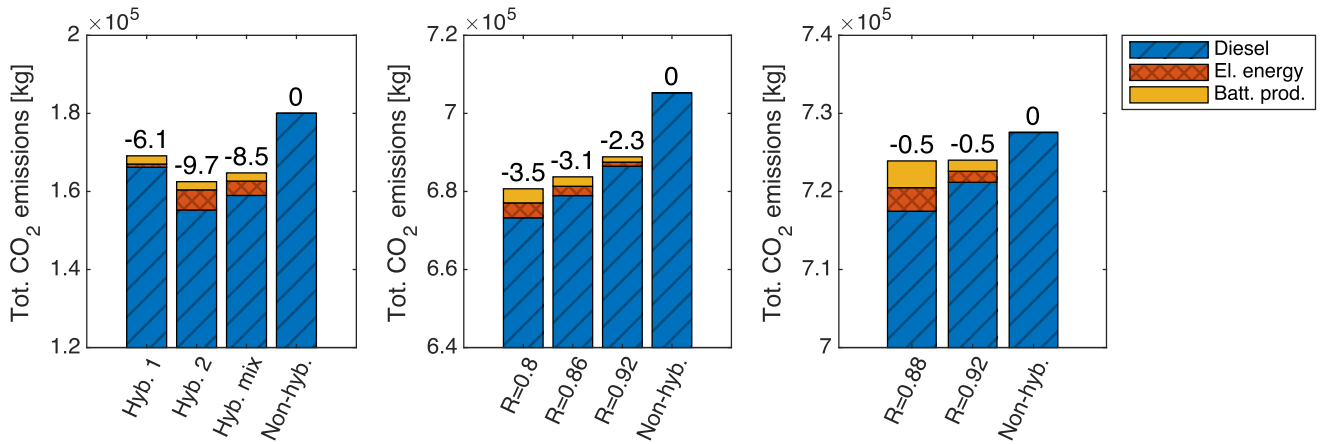
FIGURE 20. Total CO$_2$ emissions - orchard, row crop medium and heavy. Percentage variation is shown above bars.
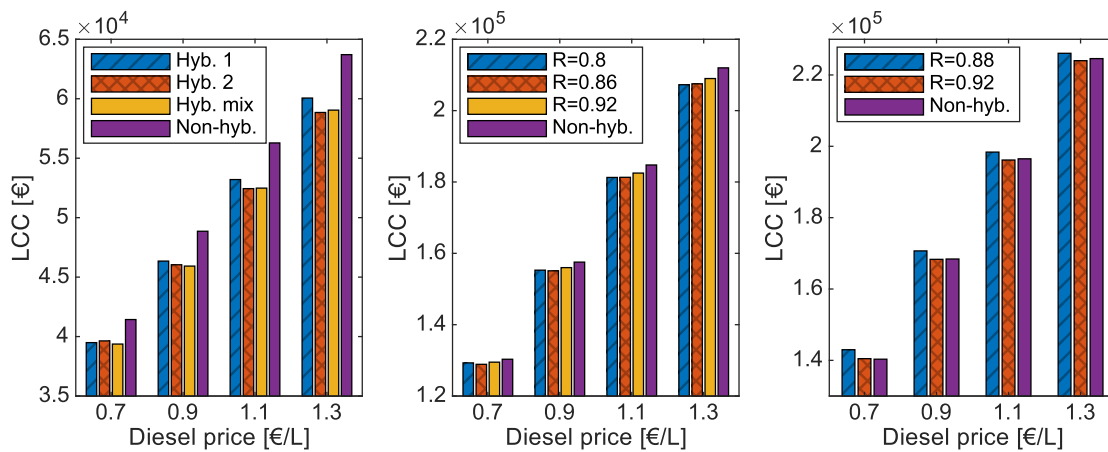

FIGURE 21. LCC behavior with varying diesel price and fixed electrical energy price (0.16 €/kWh). Orchard (left), row crop medium (center) and heavy (right).
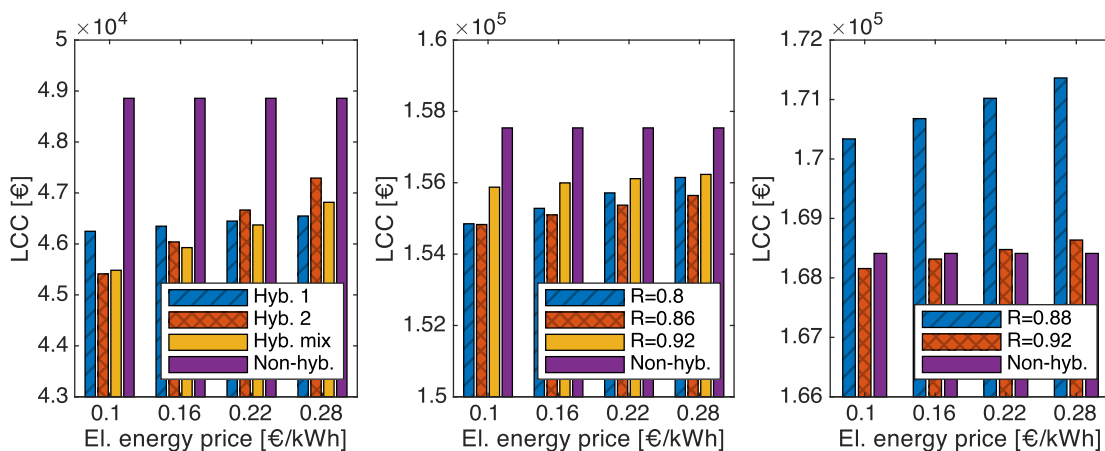

FIGURE 22. LCC behavior with varying electrical energy price and fixed diesel price (0.9 €/L). Orchard (left), row crop medium (center) and heavy (right).

for ICE-powered charging). When comparing the two row crop tractors specs, it emerges that the medium duty one requires higher ratings, except for peak torque. Although this could initially appear counterintuitive, it is consistent with the lower *R* (more downsized ICE).

Initial cost of the orchard tractor results to be lower for the electrified version, this could be explained by the fact that the costs of additional devices needed for powertrain electrification, as well as development costs, were ignored. These aspects have a higher relative

weight on a small tractor. So, this result is probably too optimistic.

As for LCC, savings with the orchard tractor are significant, whereas they are considerably lower with the row crop medium tractor, and negligible with the heavy duty one. This is strictly related to the operational savings decrease moving to tractors with more power intensive cycles.

VIII. CONCLUSION

A method to evaluate the economic feasibility of farming tractors powertrain electrification using LCC analysis was developed. The method was applied to three tractors with different power size and operating cycles. A wide variety of feasible powertrain elements prices was considered on the three different case studies. ICE downsizing or EM exploitation was varied too, depending on the tractor category. It emerged that, for small specialized tractors which perform a lot of low-power operations, significant savings can be obtained from powertrain electrification. On larger size tractors, which perform more power-intensive operations, operating cost savings are very small, leading to limited LCC savings for the most realistic price combinations. Thus, electrification of tractors of these categories should probably regard only auxiliaries and implements.

With the presented method, it is possible to evaluate the safety margin for which a hybrid tractor remains profitable, i.e. how much of a price variation is possible, for a certain cost source, without resulting inconvenient compared to the non-hybrid conventional counterpart.

Although a limited number of ICE downsizing values received an extensive analysis in this paper, the proposed methodology is valid for future more exhaustive economical feasibility studeies, considering also other powertrain topologies, especially when uncertainty occurs on components and energy costs.

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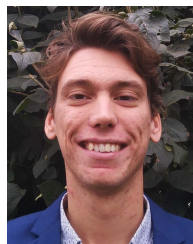
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