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Electrification of Agricultural Machinery: A Review

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ABSTRACT Today, agriculture industry has a significant impact in global greenhouse gas emissions. A large amount of pollutants come from diesel internal combustion engines, widely used in agricultural machinery. Since mechanization in agriculture is fundamental to achieve a proper food production for a growing human population, changes are needed in common agriculture engineering thinking in order to develop new farming machinery that could outperform conventional ones in terms of environmental impact, as well as performance, productivity and safety. Electrification is a feasible solution. A comprehensive review about agricultural machinery electrification is reported in this paper, with a particular focus on hybrid electric tractors and their implements. The introduction of electric drives in farming tractors is discussed in detail by looking at the main findings in literature and considering state-of-the-art technology. Proposals and prototypes from manufacturers are covered too, as well as economic assessments and future trends.

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 emissions, with a contribution of more than 20% of equivalent carbon dioxide, 42% of methane and 75% of nitrogen oxides (NO_x) [1], [2]. Furthermore, farm-gate emissions are expected to grow in the next decades [3]. The larger part of these pollutants is related to intensive animal farming and ground working, but a considerable amount comes also from internal combustion engines (ICEs), which are the most widespread power sources in the agriculture and forestry industries. Among them, diesel engines are the most common worldwide, both for moving self-propelled machinery, like tractors, harvesters and combines, and for stationary stand-alone power units.

Diesel engines exhaust emissions are carcinogenic to humans [4], which makes them a hazard not only for the environment if not also for the operators of these machines. Besides, particulate matter (PM) produced by ICEs can deplete soil and damage some type of crops [5], causing a reduction of crop production and food quality in a long-term perspective [6]. Exhaust gas emissions are particularly critical when diesel engines are operated outside a certain range [7]. The maximum power region at high speed is one of the worst conditions in terms of exhaust emissions, but unfortunately it also represents a typical working point in agriculture operations [8]. Up to 5% reduction in fuel consumption can be obtained by using an improved ICE control, with a benefit also on the total emissions [9]. Moreover, due to tractors usual working cycles, idling condition has a relevant contribution in terms of environmental impact and engine life [10], [11]. So, idling reduction strategies and idling stop devices are very important in this application [12].

The number of agricultural tractors and machines have increased in the last years [13], and a continuous growth is

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expected in different regions around the world [14]. Therefore, similar increases in terms of fuel consumption and emissions could be foreseen. For these reasons, several treaties and agreements have been signed worldwide to impose new tighter emissions limits for ICEs of Non-Road Mobile Machinery (NRMM) category, to which agricultural vehicles belong. Among these new standards there is the Stage V European regulation [15], which is particularly strict for machinery with diesel engines above 56 kW. Another example are Tiers 3-4 emission standards adopted by the Environmental Protection Agency (EPA) in the United States [16], which also introduced substantial reductions in NO_x and PM for diesel engines above 56 kW [17]. In order to meet these new limits on emissions, manufacturers are forced to equip new generation engines with selective catalytic reducers, diesel exhaust gas treatment, fluid tanks and particulate filters. Such components, in addition to an increased cost, make the diesel units bulkier, causing a reduction in the power density. 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 on the vehicle chassis.

All these reasons encourage the manufacturers to introduce modification in the current powertrains of agricultural machinery and to push forward the industrial and academic research on this topic. Among various proposals, one feasible solution is the electrification of conventional drivetrains, following the trend in the automotive industry toward the development of hybrid electric and full-electric on-road vehicles. The introduction of electric drives in agricultural machinery can have many other relevant advantages in addition to fuel savings, emissions reduction and significant improvement in tank-to-wheel efficiency. The operating costs of the tractor could be substantially reduced not only because of a lower fuel consumption, but also thanks to a reduced maintenance, due to a decreased mechanical complexity. Moreover, a further decrease in operating costs could be achieved with a better economic exploitation of in-site renewable energy sources, like photovoltaic or bio-gas power plants, that could be used to recharge the on-board batteries of electrified tractors. The safety and driveability of the vehicle could be highly improved thanks to the possibility to use a lower number of gears, or to develop drive-by-wire systems and automatic controls of the vehicle stability in a more effective way. Furthermore, electric drives could improve the performances of tractors and allow new functionalities, thus improving crop production. This is particularly true when they are implemented for autonomous and precision farming purposes [18]. Indeed, electric actuators are more compatible with automatic systems than their hydraulic counterparts, due to their ease of control and accuracy. Despite the above presented advantages, several challenges still need to be addressed in the electrification of agricultural machinery.

This paper reviews the proposals and results of various studies presented in literature about electrification of farming tractors and their implements. Moreover, a portrait of the state-of-the-art technology is given by looking at the prototypes and commercial models developed by manufacturers. The article is structured as follows: Section II describes the conventional powertrain of farming tractors and highlights the most relevant challenges in electrification; Section III reports studies and industrial solutions about the introduction of electrically-driven ICE auxiliaries; Section IV presents the hybrid electric and full-electric configurations proposed in literature for tractors powertrain electrification and some industrial concepts developed by manufacturers; Section V introduces main components for tractors' electric drivetrains; Section VI describes different proposals for the electrification of various tractor implements; Section VII reports feasible solutions for waste heat recovery techniques in heavy-duty vehicles; Section VIII presents market analysis, economic assessments and future trends in tractors electrification; finally Section IX summarizes the conclusions of this paper.

II. CONVENTIONAL POWERTRAIN AND CHALLENGES IN ELECTRIFICATION

Fig. 1 shows the conventional powertrain of a mechanical front-wheel drive (MFWD) tractor, which is the most widely adopted structure. In particular, it can be seen that the diesel ICE is the only source of power and it supplies all the main loads through mechanical transmissions. The power flows through a mechanical gearbox to the differential on the rear axle, where the traction wheels are connected. The MFWD configuration is the most widespread layout because it allows a 4-wheel drive (4WD) when high traction efforts are required, even in tractors that have different size between front and rear wheels. Indeed, the front axle differential (not shown in Fig. 1) can be engaged at driver command.

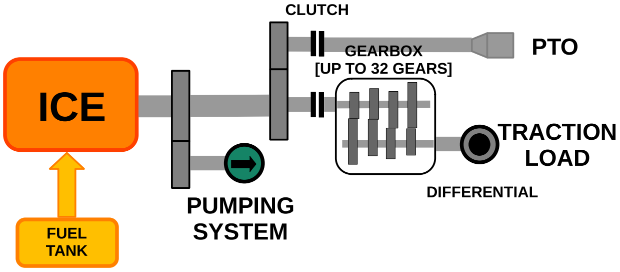


FIGURE 1. **Conventional powertrain of a mechanical front-wheel drive (MFWD) tractor.**

The ICE can be disengaged by a clutch in order to allow a gear change at driver command, with the same principle used in conventional cars. However, differently from on-road vehicles, the main load is not only the traction effort, i.e. the power that needs to be transferred to the wheels, but a large amount of power demand comes from external-connected or self-equipped implements that are needed to perform particular tasks (e.g.: power arrows, atomizers, tillers, reapers, seeders, etc...). Tractors make available at least a mechanical power-take-off (PTO) and a hydraulic power supply for external-connected implements. The PTO is usually placed on the rear side of the vehicle and it is connected to the engine shaft through a speed reducer. The hydraulic power is available in form of pressurized oil, thanks to the use of one or more pumps, which are also mechanically coupled to the engine shaft with speed reducers. The pumping system supplies not only the hydraulic actuators that move the mechanical brakes and the steering mechanisms, as it happens commonly in on-road vehicles, but, when needed, it powers hydraulic actuators that drive on-board equipment, such as lifting mechanisms, and external implements. Moreover, the differences with on-road vehicles are not limited to the presence of additional main loads, but they include a significant diversity in the common power demands too. Indeed, farming vehicles usually do not operate in paved roads. Instead, they often drag particular plowing tools or trailers on non-compact soils. So, the traction effort, as well as the braking and steering power demands of a tractor are very different from a car or a truck.

In terms of powertrain structure, farming tractors are more similar to construction and forestry machinery, such as loaders and excavators. Indeed, all these working vehicles belong to the NRMM category. Nevertheless, agricultural machinery have particular features that distinguish them from all the other NRMM and make their electrification very challenging. As first instance, farming vehicles cover a very 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. Moreover, the conventional powertrain presents a relevant amount of different arrangements, especially because of different mechanical transmissions and hydraulic systems. In addition, some tractors could be equipped with an additional front PTO, or they could have crawlers instead of wheels. Besides, they operate on different types of soil and they perform a great variety of operations, which demand different power flows and a large variability in load levels. Therefore, a very complex gearbox with a high number of gears is needed to adapt the mechanical characteristic of the ICE to these highly varying working conditions. To improve vehicle functionality and reduce operator workload, sometimes high-technology tractors are equipped with hydromechanic continuously variable transmissions (CVT) instead of the conventional stepped gearbox, which enable to decouple vehicle speed and engine speed [19].

Anyway, the main issue in tractors electrification is the definition of standard driving cycles, which is not as easy as for on-road vehicles or other NRMM, and it may be unfeasible. EPA, in cooperation with European Union authorities, has defined a standard Non-Road Transient Cycle (NRTC) to test diesel engines for NRMM and evaluate their conformity with the regulations on emissions limits [20], [21]. However, for farming tractors, the cycle has been defined taking into account only heavy-duty row crop vehicles, and its speed and torque profiles are referred to the engine shaft, so that information about the contribution of different types of loads are not given. Therefore, NRTC cannot be considered fully representative of a tractor working cycle. The German Agriculture Society has made a step forward in this direction with the definition of 14 working cycles for different operations, grouped in the DLG-PowerMix [22]. However, these cycles are far to be widely approved.

The lack of standard driving cycles is probably the major challenge in tractors electrification: it makes not straightforward the choice of proper specifications for the design of electric drives and energy storage systems (ESSs). Furthermore, it limits a lot the identification of optimal energy management strategies (EMSs). For these reasons a large amount of studies presented in literature and summarized in this paper take advantage of in-field measurements performed on specific tractors.

III. AUXILIARIES ELECTRIFICATION

A first step in tractors electrification is to electrically drive ICE auxiliaries in order to reduce parasitic losses. Indeed, these loads can be switched on and off, and their speed can be controlled independently from the ICE speed. This easier and less constrained control, if it is well exploited, could compensates the losses arising from the additional energy conversion, i.e. from mechanical to electrical and then back to mechanical, finally improving fuel economy. This point has been demonstrated by several studies discussed in this section. Moreover, the decoupling of speed of each auxiliary from the crankshaft speed, in addition to efficiency improvements, enables new functionalities.

The most demanding auxiliaries are the cooling fan and the HVAC compressor (heating, ventilation and air-conditioning): both are responsible of up to 32% and 13% of engine rated output power when the tractor is idling and operating on field, respectively [23]. An independent fan speed enables an higher air flow when ICE supplies a high load at low speed, improving cooling, and a lower air flow when ICE operates in low-load high-speed conditions, reducing fuel consumption. Furthermore, fan rotation can be easily reversed to clean the radiator. Some of these functionalities can be achieved even with ICE-driven cooling fans, but in this way the use of variable pitch fans or variable speed transmissions is needed, thus increasing the machine overall dimensions, the mechanical complexity and the maintenance requirements.

Coolant temperature control is definitely improved with an electrically-driven fan, but also an electric pump and an electrically-actuated radiator bypass valve can be implemented for this purpose. A better control allows to adopt a higher reference temperature, improving efficiency. A further advantage provided by the adoption of an electric coolant pump is the possibility to run it after engine power off, avoiding over-temperatures both in the engine block and in the turbocharger [24], [25].

Several examples of cooling system electrification are reported in literature, although many are not in the agricultural sector. In [26] an advanced cooling system was studied on a heavy-duty truck. The designer adopted a 20 kW electric motor driving a newly designed fan, an electric coolant pump, an electrically-actuated bypass valve and a reworked heat exchanger. The study shows that such cooling system is able to reduce fuel consumption by 2.7% during typical steady-state conditions, as well as increasing the ambient capability of the truck by more than 6°C. In [27] various cooling system configurations were analyzed for a heavy-duty diesel vehicle and for a micro-hybrid truck:

1) a full-electric configuration with several electric fans, an electric pump and a controllable bypass valve;
2) a configuration with electric fans but with mechanical pump and a wax valve;
3) a system with a single mechanical fan and a mechanical pump, but with a controllable valve.

On the standard diesel vehicle the best results were obtained adopting only the electric fans, with a 5% fuel saving, while on the micro-hybrid vehicle the highest saving of 5.8% was obtained with the full-electric configuration. In [28] the performance of an electric fan on a 31 kW 2WD agricultural tractor was evaluated. The absence of a mechanical linkage between ICE and fan allowed for a better positioning of the fan toward the radiator, improving the airflow. Fuel consumption was improved from 2.2% up to 8.1% depending on the operation, with an overall 5.1% estimated saving. Moreover, a 4% torque increase was observed at the PTO. It should be pointed out that the above described studies are not completely fair, as state-of-the-art mechanical drives for variable speed fans on some high-technology tractors were not considered during the comparisons.

Farming tractors manufacturers early moved to electrify ICE auxiliaries and on-board cooling systems. Two tractors with electrified auxiliaries were launched by John Deere in 2007: the 7430 and 7530 E-Premium. Instead of a standard 2.4 kW alternator, they were equipped with a 20 kW electric generator (EG) directly connected to the engine flywheel, which was able to supply several auxiliaries driven by electric motors (EMs), such as brake compressor, fan, coolant pump and air-conditioning compressor, allowing for maximum cabin cooling even with ICE at idle. In the 7530 E-Premium an AC power socket was also included to supply external portable working equipment, such as welding, drilling and cutting tools, at a line-to-line rated voltage of 380 V (both one-phase and three-phase supply available), and up to 5 kW power. This power socket was the first example of electrical PTO (e-PTO) ever implemented in a tractor, at least in the authors knowledge. The diesel unit of the John Deere E-Premium platform with its electrified auxiliaries is outlined in Fig. 2. According to a test conducted in [29] on the 7530 conventional and electrified variants, a 4% and 16% fuel consumption reduction was achieved, respectively in harrowing and road transport. Nevertheless, the electrified versions were discontinued, perhaps due to an unsuccessful market demand.

IV. POWERTRAIN ELECTRIFICATION

The powertrain electrification regards the introduction of electric drives in those drivetrains which are functional to supply the main loads of a vehicle. As explained in Section II, in the case of agricultural tractors the main load is not only the traction effort, as it happens in on-road vehicles, but a large amount of power demand comes from implements and on-board working tools that are needed to perform particular tasks. Therefore, also the drivetrains that transfer power to mechanical PTOs, hydraulic remotes and hydraulic actuators of three point linkages are significant. On the contrary, the driving systems, such as steering and braking actuators, the engine auxiliaries mentioned in Section III, the cabin air-conditioning and all the other systems that are functional to the driver comfort and the vehicle driveability are not considered as main loads, even though some of them could have a relevant power demand. Thus, studies about their electrification are not included in this section.

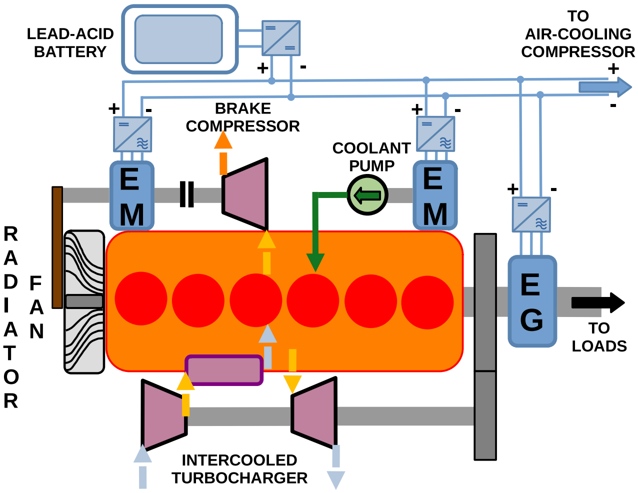


FIGURE 2. Outline of John Deere E-Premium diesel unit with electrified auxiliaries.

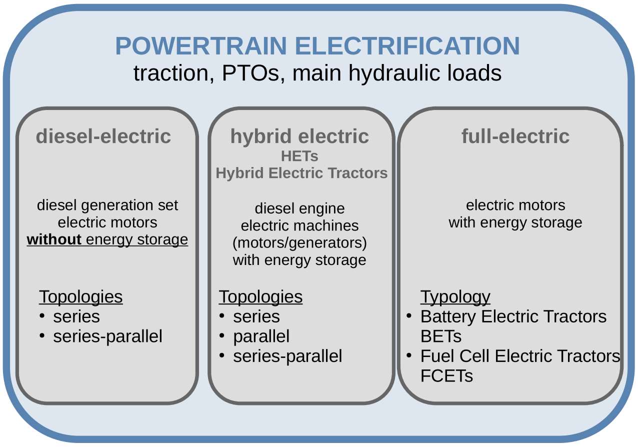


FIGURE 3. Classification of tractors drivetrain electrification.

The powertrain electrification of a farming tractor can result in a diesel-electric, hybrid electric, or full-electric drivetrain, as described by Fig. 3. The classification that will be used hereafter follows what has been done in other recent reviews of agricultural machinery electrification [30]–[32], although, unlike them, proposals about all the powertrain configurations will be covered in this work.

A. DIESEL-ELECTRIC AND HYBRID ELECTRIC POWERTRAINS

In diesel-electric drivetrains all the power comes from an engine-driven generator, while in hybrid electric drivetrains there are at least two power sources, one of which is able to store electrical energy (ESS: Energy Storage System), while the other is an ICE [33]. In agricultural machinery, ICE is usually fueled with diesel, although some bio-fuel blends have been proposed in literature to reduce emissions [34]. The key difference between a diesel-electric powertrain and a hybrid electric one consists exactly in the presence of a bidirectional electrical storage device, i.e. a battery pack or a supercapacitors bank, that provides a significant amount of power, and it is functional for the specific purpose of the drivetrain. Hybrid electric and diesel-electric powertrains can be classified together according to their architecture, also called power flow topology. Three basic architectures can be identified: series, parallel and series-parallel [35]. Series and series-parallel structures can be diesel-electric or hybrid electric, thanks to the presence of an electric machine working mainly as generator (EG) and mechanically connected to a diesel unit, whereas parallel architectures can be only hybrid electric, because in this topology an ESS, usually a battery pack, is fundamental. Hybrid electric tractors (HETs) are defined as "plug-in" (PHETs: Plug-in Hybrid Electric Tractors) when the ESS is a battery pack that can be recharged through an external power supply.

In literature, and by now also in the commercial habit for passenger cars, hybrid electric powertrains are often classified looking at the so-called Degree of Hybridization (DoH), or hybridization factor H. The conventional DoH, widely approved for on-road vehicles, is defined as represented in (1) [35]:

$$H = \frac{P_{EM_T}}{P_{EM_T} + P_{ICE}} \tag{1}$$

where P_{EM_T} is the rated power of the traction electric motor and P_{ICE} is the rated power of the engine. From (1) it is clear that if a powertrain has a conventional structure, then $H = 0\%$ ($P_{EM_T} = 0$), whereas if a drivetrain is completely electric, then $H = 100\%$ ($P_{ICE} = 0$). For increasing value of H from 0 to 1 the vehicle is classified as micro-hybrid, mild-hybrid or full-hybrid, but the ranges that define each class are still not well agreed.

However, the above presented definition is not completely representative of the powertrain electrification in the case of working vehicles, agricultural machinery included, where the drivetrains related to mechanical PTOs, hydraulic PTOs and hydraulic actuators can be electrified too, in addition to the traction drive. Thus, Somá [36] proposed a new hybridization factor specifically defined for hybrid electric and diesel-electric NRMM (H_{NRMM}). The novel approach takes into account not only the traction drive, but also the electrification of those drivetrains that are functional to working tasks. The total hybridization factor H_{NRMM} is the arithmetic mean between the conventional DoH H_T for the traction drive and another DoH H_L for the working loads drivetrains, as expressed in (2):

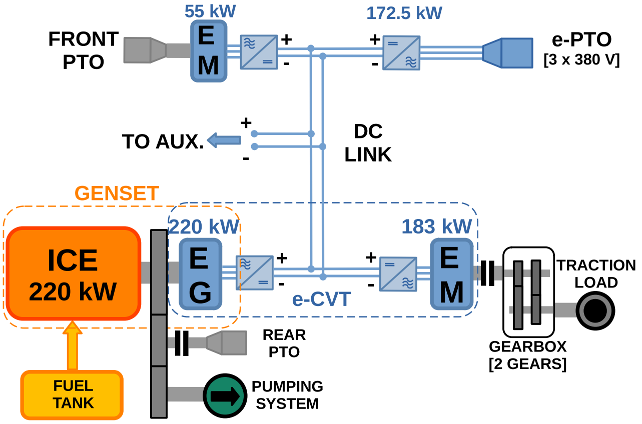


FIGURE 4. Series diesel-electric powertrain of Belarus 3023.

$$\begin{cases} H_T = \frac{P_{EM_T}}{P_{EM_T}+P_{ICE}} \\ H_L = \frac{P_{EM_L}}{P_{EM_L}+P_{ICE}} \end{cases} \Longrightarrow H_{NRMM} = \frac{H_T+H_L}{2} \tag{2}$$

where P_{EM_L} is the total rated power of the electric drives on the working loads drivetrains. This index will be used later (Fig. 13) to compare the industrial concepts of electrified tractors developed by manufacturers until now.

1) SERIES ARCHITECTURES

Fig. 4 and 5 represent the series configuration of a diesel-electric and of a hybrid electric drivetrain, respectively. As already mentioned, the key difference is the presence of a bidirectional electric ESS. A generator is mechanically connected to the diesel engine shaft, resulting in a diesel generation set (GENSET). The GENSET supplies all the power converters of the electric motors through a DC link at high or low voltage level. The coupling of a generator with an electric motor (EM) is called electro-mechanical continuously variable transmission (e-CVT), because the speed of the final drive can be adjusted continuously, and its control is independent on the ICE speed, thanks to the flexibility of electric drives and the lack of a mechanical linkage between ICE shaft and load.

In the series architecture the ICE can be completely decoupled from the loads, i.e. wheels or tracks in case of traction, hydraulic actuators and PTOs shafts in case of working loads. Thus, the engine can operate always in its lowest brake specific fuel consumption (BSFC) region. Moreover, in off-road working vehicles such configuration makes possible to decoupled all the loads from each others, with feasible additional gains in fuel economy and new functionalities for increasing performance. As an example, in farming tractors

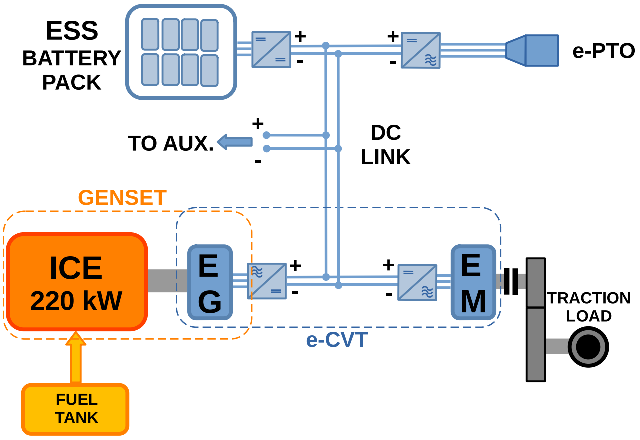


FIGURE 5. Series hybrid electric powertrain.

the PTO shaft speed, which affect the implement performance, could be independent on the wheels speed.

The major disadvantage in the series architecture concerns the weight, the volume and the cost of the main components, especially regarding electric machines, which must be sized according to the entire power demand of each electrified drivetrain. Furthermore, during the powertrain design, a particular care must be given to minimize the losses due to double energy conversions (from mechanical to electric, and then back to mechanical), so that the overall efficiency gain and fuel consumption reduction will be effective.

Fig. 4 outlines specifically the powertrain of the 300 Hp tractor Belarus 3023, whose main features are described in [37]. This tractor was developed by Minsk Tractor Work in partnership with RUSELPROM-ElectricDrive. The pre-series model was launched on the market at the international agricultural exhibition Agritechnica, that took place at Hannover in 2009. It has a series diesel-electric architecture, where the mechanical transmission on the original platform 3022DV has been replaced by an e-CVT made by two liquid-cooled asynchronous machines. The engine cooling fan and the front PTO could be driven by other induction motors as upgraded options. In addition, as a further upgrade, the tractor could be equipped with a power socket (e-PTO) able to supply a rated power of 172.5 kW at standard 50 Hz three-phase or one-phase industrial low voltage (380 V line-to-line). The micro-controllers related to each power electronic converter are networked together through a CAN-bus communication system.

Some comparative plowing tests were performed between the Belarus 3023 and the conventional variant Belarus 3022DV. Trials have shown that the productivity of plowing aggregate of the Belarus 3023 is 2% higher than its conventional variant, while fuel consumption is lower by 18%.

Fig. 5, instead, outlines the series hybrid electric structure investigated in [38], where a forward vehicle model was developed for a series HET with an e-PTO. The model was used to compare the following rule-based energy management strategies (EMSs):

1) a thermostat-like control (TC), where the GENSET is turned on and off according to battery State-of-Charge (SoC) value through an hysteresis controller;
2) a power follower control (PFC), where the GENSET is designated as the primary source to meet the power demand in almost all working conditions.

The performance of the two EMSs were compared during repeated plowing and harvesting cycles through numerical simulations. The results show that PFC outperforms TC in terms of equivalent fuel consumption. As regards emissions, the NO_x production of PFC is less than that of TC. However, PFC produces more PM. This is because the operating points of GENSET are optimal for fuel consumption rather than emissions. In addition, transitions of the GENSET between OFF and ON are a source of considerable exhaust emissions.

The same forward model was used in [39] to develop three different optimization-based EMSs with the main goal to minimize fuel consumption. Dynamic programming, an indirect method and a direct method were used to solve a specifically-formulated optimization control problem, and three different optimal EMSs were obtained. These EMSs show improvements in fuel efficiency up to 5%, when compared to PFC rule-based strategy.

In [40] a prototype of series hybrid electric crawler tractor for logging in forests was designed. Anyway, the proposed hybrid powertrain could be attractive to improve the traction drive of crawler tractors for agriculture applications too, as suggested by the authors. The prototype was realized converting a small crawler (2100 kg weight, 3 m length, 1.35 m width). The original 38 kW diesel engine was replaced by a downsized 14 kW ICE. The traction motors are two 6.3 kW induction machines. The battery pack consists of twelve 12 V rechargeable lead-acid batteries connected in series. As a result, although lead-acid batteries were used, the weight of the vehicle did not increased, because the original engine and double hydrostatic transmission were replaced by a lighter diesel engine and electric machines. Moreover, according to preliminary estimations, the series hybrid crawler reached a 30% increase in fuel economy.

In [41] the technical feasibility of a hybrid electric tractor backhoe loader was investigated. The authors adopted a series architecture to electrify only the hydraulic systems that move the rear and front loaders and the steering mechanisms. In the proposed hybrid electric configuration each hydraulic actuator belongs to a separated fluid circuit, which is powered by an electrically-driven pump. So, the hydraulic actuators are not replaced by electric ones, but they are controlled independently from each other and from the engine operating point. Moreover, fluid losses due to a large hydraulic circuit with a single pump and multiple valves are significantly reduced by using separated circuits with their related pumps and no valves. The mean electrical demand is supplied by the GENSET, while the high variable transients energy flows are compensated by a supercapacitors bank, which has been chosen as ESS due to the high frequency charge and discharge

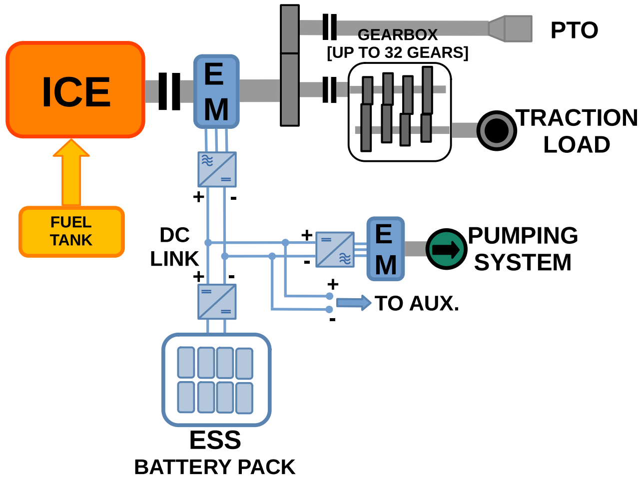


FIGURE 6. Parallel hybrid electric powertrain.

cycles needed for this application. Traction drive was not considered electrified in this project.

Simulation results show that the adoption of supercapacitors reduces the torque and power oscillations, with a gain of at least 6-7% in fuel efficiency. Finally, the hybrid model saves about 49-63% of fuel during a reference duty cycle for backhoe loaders when compared with the conventional vehicle.

2) PARALLEL ARCHITECTURES

A hybrid electric parallel architecture is represented in Fig. 6. A diesel-electric powertrain is not possible with this configuration, due to the lack of an electric machine that works mainly as generator, so at least one electric ESS becomes mandatory. An electric machine (EM) is mechanically connected to the ICE shaft, which is linked to the final drive usually through a gear transmission. The mechanical coupling between the ICE and the EM can be made with a direct flange connection between the engine shaft and the EM shaft, or by means of a speed reducer. In this configuration the EM works mainly as a motor: it can provide the starting torque, and it can boost the ICE during high power-demanding duty cycles. Operating as a generator, it can recharge the ESS by kinetic energy recovery, or when the engine provides surplus power. The layout depicted in Fig. 6 is a particular parallel structure: the clutch inserted between the engine shaft and the EM shaft allows the decoupling between the two devices and a full-electric operation during low power-demanding duty cycles.

This is the cheapest hybrid architecture, and in many cases the easiest to implement to electrify an existing vehicle, because only one electric machine is needed, and the engine can be significantly downsized, thanks to the possibility of EM torque boosting. On the other hand, battery recharging through ICE surplus power is very inefficient, and it should be avoided as much as possible. Then, the ESS should be able to store a large amount of energy to guarantee a sufficient autonomy. Thus, expensive Li-ion modules are usually chosen. However, the major drawback is that the engine is still mechanically connected to the load, thus it cannot work always in its lowest BSFC point. Furthermore, the final drive speed depends on the ICE speed, so that new functionalities are strongly limited. Nevertheless, with a suitable control of the EM, it is possible to maintain the ICE near its optimal operating line, i.e. the highest efficient working point for each speed value. This control strategy is known as load point shifting.

It is interesting to mention that in some recent reviews about agricultural machinery electrification [30], [31], studies about parallel layouts have not been covered, even though already presented in literature. Indeed, many authors stated that a generator is of paramount importance to get a more electric agricultural tractor, in order to supply electrified implements.

Fig. 6 shows specifically the parallel powertrain investigated in [42] and [43]. In both papers, the electrification of a compact agricultural tractor for orchards and vineyards was faced. The pre-existing ICE-based platform was converted to the parallel hybrid architecture by downsizing the original diesel engine from 4-cylinder 77 kW (100 Hp) to a 3-cylinder 55 kW unit, the basic step to meet the Stage V European regulation. The additional room that was obtained through the cylinder removal was exploited to insert a permanent magnet EM, so that the vehicle wheelbase did not need to be increased. A 25 kWh battery pack composed with $LiFePo_4$ cells was chosen because it was considered suitable for this application due to the high thermal stability and safety in case of perforation or crash.

The feasibility of the hybrid tractor was assessed through simulated fuel consumption comparisons with its conventional counterpart, using different duty cycles identified from real working scenarios and in-field measurements [44]. The results show that a consumption benefit is always achieved in hybrid mode, but the advantage is very limited for those duty cycles that require a large amount of power. Moreover, the full-electric mode seems to be detrimental in heavy operating conditions due to the repeated energy switches and to the high battery current. On the contrary, significant benefits connected to the electrification can be obtained during those cycles that, on average, need a lower amount of energy, both in hybrid and full-electric mode. A further benefit related to low-power operations is a slow battery discharge, allowing to keep the engine off for a long period. These outcomes prove that the development of an effective hybrid agricultural tractor can be performed with a relatively limited effort through a conversion of a pre-existing platform.

The electrification of medium-size narrow tractors was proposed also in [45], where the basic structure and control method of a 66 kW HET with a parallel architecture were conceived. The engine was designed to provide the load power in steady-state conditions, whereas the electric machine was intended to fulfill the transients in hybrid mode and the entire load in pure electric mode. Two different EMSs were implemented for transportation tasks and field operations, with a different management between hybrid and pure electric mode. The efficiency of the hybrid tractor was compared with the conventional one assuming an 8 hour working day with 15% road transport and 85% plowing. A conventional DoH of 23% was chosen, which results in an engine rated power of 51 kW and an electric motor rated power of 15 kW. With such design and the above mentioned EMSs, simulations show that the fuel economy is improved by 19.2% with the battery SoC kept between 40% and 70%.

A detailed performance analysis between a conventional 75 kW tractor and a parallel hybrid electric architecture with a downsized diesel engine was presented in [46] too. The comparison shows that the hybrid powertrain is able to achieve the same performances of the conventional one, but with an equivalent fuel consumption reduced by 15-18%, depending on the operating conditions.

Barthel *et al.* [47] developed an enhanced EMS that combines load point shifting (LPS) based on a suboptimal optimization approach, with regeneration and boost based on heuristics. The control strategy of the powertrain is switched between LPS, regeneration and boost by an automatic supervisor, according to the vehicle operating state, i.e. required speed, torque and current SoC of the battery pack. The system has been simulated considering the powertrain of the LIB-Off-Road concept, a hybrid electric tractor with a parallel architecture conceived by John Deere as a feasible upgrade of the 7530 E-Premium. Four different EMSs have been compared:

1) no control strategy;
2) LPS only (without regeneration and boost);
3) LPS with regeneration an boost;
4) LPS with regeneration, boost and SoC set point shifting (enhanced strategy).

The results show that for a tested transportation cycle the fuel efficiency is improved by 1.9% and 4.7%, with the introduction of the third and fourth EMSs, respectively. Instead, with the second EMS no improvements in fuel efficiency could be achieved, because of the additional losses in the electric drive. Simulations show that potential for fuel saving is given when transportation tasks are considered. However, in this application, it is not as high as in full-electric or hybrid electric on-road vehicles.

3) SERIES-PARALLEL ARCHITECTURES

Series-parallel architectures try to overcome the drawbacks of series and parallel structures. The basic idea is to avoid double energy conversions and bulky electric machines, but at the same time to keep the engine speed decoupled from the load. This result is achieved by using a planetary gear [48], a mechanical device outlined in Fig. 7. A lot of different configurations can be obtained, depending on where the planetary gear is inserted and on how it is connected to the other devices. The main disadvantages of these architectures are an increase overall mechanical complexity and the presence of at least two electric machines, a generator (EG) and a motor (EM). Moreover, in the EMS design a particular care must be taken to avoid circular power flows in the electric branch, that cause useless double energy conversions.

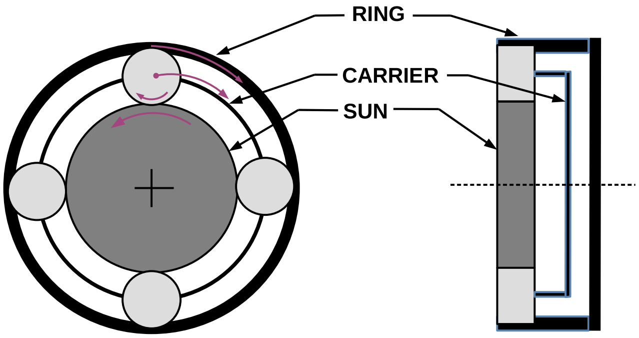


FIGURE 7. Planetary gear outline.

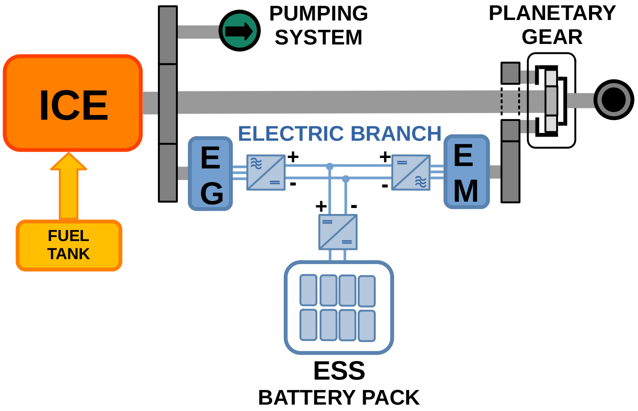


FIGURE 8. Input-coupled output-split series-parallel powertrain for a wheel loader.

Fig. 8 outlines the input-coupled output-split layout proposed in [49] for a heavy-duty wheel loader. This topology could be implemented in farming tractors too. The mechanical coupling between the ICE and the EG is connected to the sun shaft of the planetary gear, while the EM is linked to the ring shaft. The carrier shaft is connected to the differential, which is placed in the traction wheels' axle. This powertrain exploits the benefits of a series architecture at low traction requirements and progressively takes advantage from the coupling of a parallel drivetrain at increasing power demands, according to the ordinary employment of a loader. The simulations were performed using a dynamic drivetrain model on standard duty cycles for wheel loaders. The EMS consists in a power distribution between ICE and the electrical subsystem, depending on the battery SoC. The EM and EG torque are controlled by the EMS, while the ICE working point is derived as a consequence of the mechanical bonds given by the chosen architecture. Results show that ICE always works near the maximum efficiency area, while the battery SoC remains inside the 40-60% range. Simulation comparisons between the proposed hybrid electric powertrain and the conventional hydrostatic CVT point out that

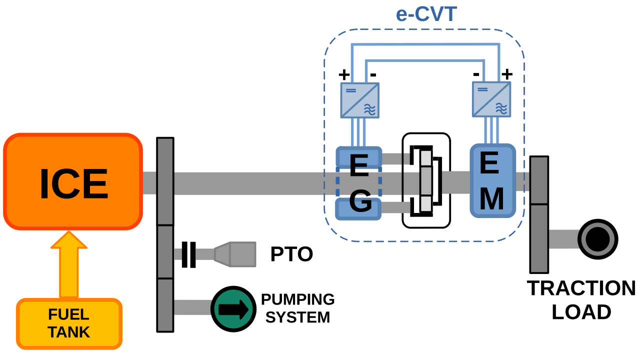


FIGURE 9. Power-split powertrain for a specialized tractor.

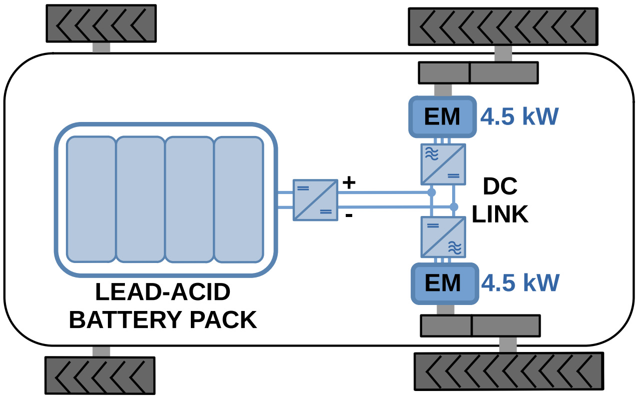


FIGURE 10. Full-electric powertrain for a small family farming tractor.

the hybrid electric solution reduces the fuel consumption by about 12%.

Fig. 9 represents the prototype power-split e-CVT designed in [50] for a 75 kW specialized tractor. The proposed layout is based on a coaxial and concentric arrangement of the electric machines connected to the planetary gear, which allows a significant reduction of transmission displacement at the same power rate, thus improving e-CVT power density. A permanent magnet generator and an induction motor are connected on the sun shaft and ring shaft, respectively, while the ICE flywheel is connected to the carrier shaft. This configuration can refer to a hybrid electric or diesel-electric powertrain, depending on the presence of an ESS on the DC link.

B. FULL-ELECTRIC POWERTRAINS

In a full-electric powertrain all the power sources provide electric power. The most common and successful configurations, also proposed for farming tractors, consist in a vehicle completely powered by a rechargeable battery pack (BETs: Battery Electric Tractors), or in a hydrogen-propelled powertrain (FCETs: Fuel Cell Electric Tractors), where a fuel cell stack is usually electrically coupled with a battery module or a supercapacitors bank to increase the performances during highly varying duty cycles.

It is worthwhile to point out that in previous reviews about agricultural machinery electrification [30]–[32], works on BETs have not been covered, whereas FCETs have been reported, thanks to the commercial interest of New Holland about this technology. Furthermore, in [32] BETs are considered unfeasible and it is assumed that diesel engines will be remain the fundamental power source in agricultural machinery during the next decades, because the energy density of diesel fuel is at least 50 times higher than state-of-the-art Li-ion modules.

1) BETs: BATTERY ELECTRIC TRACTORS

Studies about the technical and economical feasibility of BETs have been presented in literature mainly for small family farming tractors [51]–[56], but there were few analysis on heavy-duty row crop tractors too [57]–[59].

Fig. 10 outlines the full-electric powertrain of a 9 kW prototype conceived and manufactured in [51] for testing purposes. The drivetrain has a rear-wheel traction configuration, featuring two 4.5 kW induction motors, where each motor is dedicated to drive a distinct traction wheel. The transmission system consists in a simple dual chain with a total transmission ratio of 34.6, in order to adapt the high-speed low-torque motors characteristics to the vehicle traction requirements. The motors are fed by two independent inverters, so that the speed and torque of each traction wheel can be controlled independently. Thanks to this feature, the authors were able to tune properly a wheel-slip control. A lead-acid battery bank composed of four units was chosen as ESS. Each module is rated at 12 V and has an energy capacity of 217 Wh. The series connection of the modules provides an input voltage of 48 V to the two inverters.

In drawbar tests the electric prototype outperforms a similar diesel-fueled tractor both in terms of drawbar force stability (oscillations minimization) and maximum mean value. The adopted wheel-slip control provides a greater stability with a more uniform speed, despite there is a small reduction in the average speed. Furthermore, the energy consumption is significantly reduced, with a saving of 46%.

Ueka *et al.* [53] obtained even more optimistic results in terms of fuel savings and emissions reduction in an experimental comparison between a BET and its conventional counterpart during in-field traveling and tillage operations. The study was based on an existing 10 kW tractor that was modified to become full-electric. A reduction of around 70% was obtained for both fuel consumption and CO_2 emissions.

Full-electric small family farming tractors were investigated in [54] too, through a simple design method and plowing trials on a prototype, and in [55], by means of analytical modeling and numerical simulations. A single permanent magnet motor and a lead-acid battery were adopted in both papers. The authors report that the tractor is able to plow with furrow depth of about 5-6 cm at a constant speed of 5 km/h for more than 6 hours.

Moreover, an innovative electrically-driven traction equipment for small family farming is proposed in [56]. The solution consists in a four-wheel-drive chassis with flexible mountings that allow to vary the track width and to change the ground clearance, in order to adapt effectively to narrow row plantations, which are a very common practice in small scale agriculture. The equipment is suitable only for in-field operations, but the authors claim many advantages: a fuel cost reduction up to 81%; a great adaptability thanks to the innovative mechanical layout; the possibility to make autonomous the machinery without a great effort.

Regarding high-power machinery, Brenna *et al.* [57] made a preliminary sizing of the main components of a full-electric 157 kW row crop tractor. The design was focused in particular on the choice of the electric traction motor and the capacity of the battery pack. A water-cooled direct drive torque motor was chosen. The capacity of the battery pack was selected by estimating the total energy required by soil tillage throughout a whole day work. The resulting capacity is 662.2 kWh.

The feasibility of autonomous BETs was investigated in [58] through computational simulations and tractors fleet optimization in an organic dairy farm of 200 ha with five crops in the crop rotation cycle and a conventional plow among the used implements. The results show that it could be possible to replace a 160 kW conventional tractor with two autonomous BETs, each one with a 36 kW electric motor and a 113 kWh battery pack. The total cost of operations results 15% lower, while the energy consumption and the greenhouse gas emissions would be reduced of 58% and 92%, respectively, if compared to conventional diesel, when energy consumption and emissions from battery manufacturing were included too.

2) FCETs: FUEL CELL ELECTRIC TRACTORS

Fig. 11 outlines the powertrain of New Holland NH2 fuel cell electric tractor [60], presented at Agritechnica in 2011. It is equipped with a 100 kW-rated PEM (Proton Exchange Membrane) fuel cell stack, fueled by a tank that can hold 8.2 kg of hydrogen gas at a pressure of 350 bar. The fuel cell stack supplies two 100 kW electric motors driven by two independent inverters, one for traction and one to power the PTO and the hydraulic pump. A 300 V Li-ion battery pack with a capacity of 12 kWh and a peak power of 50 kW is connected to the DC link to improve the dynamic performances of the tractor, while preserving the fuel cell stack life.

Tritschler *et al.* [61] investigated the potential of a fuel cell drivetrain for agricultural tractors. They considered a commercial 85 kW PEM fuel cell and a Li-ion battery module connected to a 700 V DC link by DC/DC step-up converters. The powertrain structure is the same of Fig. 11, except that another electric motor was inserted to drive independently the hydraulic pump. A dynamic model of the entire drivetrain was implemented to evaluate the tank-to-wheel efficiency and compare the results with the conventional tractor. DLG-PowerMix duty cycles were used to simulate in-field working conditions. The simulations were performed using three different EMSs, with a different balance of the power flow between the fuel cell and the battery pack. The energy consumption results reduced by almost a third.

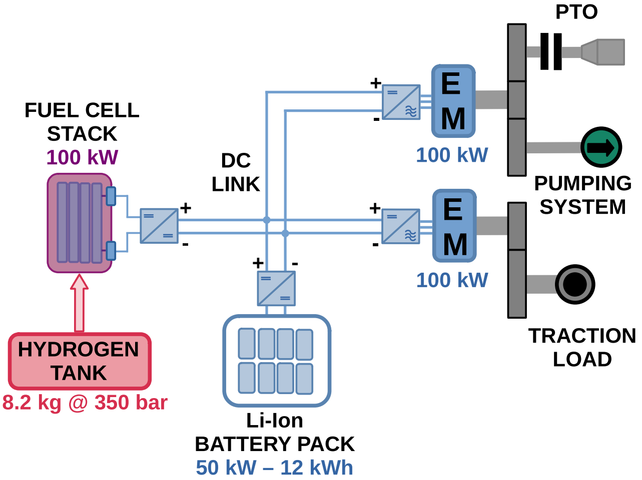


FIGURE 11. Full-electric powertrain of the hydrogen-propelled tractor New Holland NH2.

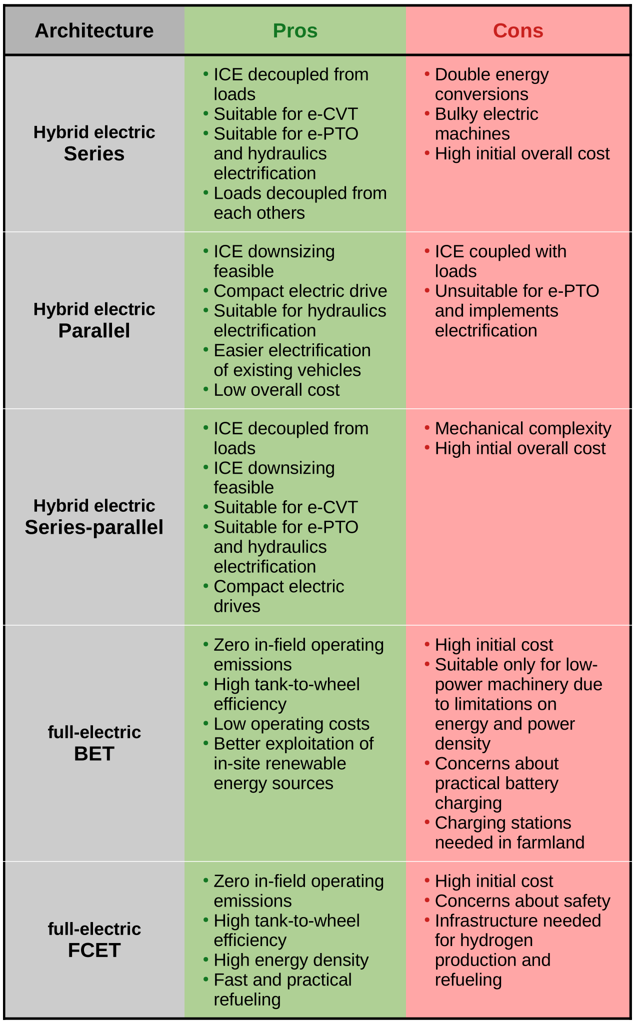
A prototype of hybrid electric fuel cell unmanned tractor for precision agriculture was designed and tested in [18]. The autonomous robot featured a 33.6 kW diesel engine, a 5 kW PEM fuel cell and two 12 V lead-acid battery modules. The prototype shows significant reduction in fuel consumption during operations with three different electrified implements, namely a row crop cultivator, a patch sprayer and a canopy sprayer. Moreover, reductions in pesticides and chemicals use are observed.

C. INDUSTRIAL PROTOTYPES

Fig. 12 summarizes the main advantages and disadvantages of each architecture for farming tractors electrification previously discussed.

Fig. 13 reports and compares the main features of some prototype tractors with electrified auxiliaries and/or electrified drivetrains presented by agricultural machinery manufacturers until now [62]– [65]. Tractors powertrains are featured with the hybridization factors expressed in (2). Some of them have been discussed in details in previous sections. Few of these vehicles went to pre-series production and then were launched onto the market. However, all the trials made until now failed due to lack of market demand. So, their production were dismissed.

From Fig. 13 it can be seen that interest toward electrification in agriculture arise at the beginning of this century, as proved by many early prototypes developed in 2007-2011. Then, the topic lose interest for almost ten years, maybe due to the market failure of some of the first trials. Nevertheless, now manufacturers interest toward electrification is increasing again, as demonstrated by the last prototypes presented in recent years (2018-2020). Among them, in addition to the concepts reported in Fig. 13, Carraro electrified solutions deserve a mention too [66].



Architecture	Pros	Cons
Hybrid electric **Series**	• ICE decoupled from loads • Suitable for e-CVT • Suitable for e-PTO and hydraulics electrification • Loads decoupled from each others	• Double energy conversions • Bulky electric machines • High initial overall cost
Hybrid electric **Parallel**	• ICE downsizing feasible • Compact electric drive • Suitable for hydraulics electrification • Easier electrification of existing vehicles • Low overall cost	• ICE coupled with loads • Unsuitable for e-PTO and implements electrification
Hybrid electric **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
full-electric **BET**	• Zero in-field operating emissions • High tank-to-wheel efficiency • Low operating costs • Better exploitation of in-site renewable energy sources	• High initial cost • Suitable only for low-power machinery due to limitations on energy and power density • Concerns about practical battery charging • Charging stations needed in farmland
full-electric **FCET**	• Zero in-field operating emissions • High tank-to-wheel efficiency • High energy density • Fast and practical refueling	• High initial cost • Concerns about safety • Infrastructure needed for hydrogen production and refueling

FIGURE 12. Summary of advantages and disadvantages of each type of electrified powertrain for agricultural tractors.

V. MAIN COMPONENTS FOR TRACTORS ELECTRIC DRIVETRAINS

The design and manufacturing of the main components for electric drivetrains of heavy-duty off-highway vehicles is still an open issue. In particular, the definition of proper design specifications is challenging, as well as a fair choice of devices types and system settings. In this section, feasible proposals about the design and specifications of electric drivetrain components for agricultural tractors will be covered.

A. DC BUS VOLTAGE LEVEL

The electric power system should be rated to a target voltage level to get a fair trade off between the following requirements and constrains:

1) the average and peak power demand of the loads;
2) the maximum allowable volume and weight for the components, especially regarding the storage device, the electric machines and the power converter units;
3) safety requirements on insulation and costs.

According to the SAE definition reported in [30], the term "high voltage" in automotive electric power systems indicates a DC bus rated voltage higher than 60 V. Below this threshold, the systems are classified as low voltage. In vehicles, standard low voltage levels are 12 V, 24 V and 48 V, mainly because these values can be easily obtained with lead-acid battery modules. On the contrary, standard high voltage levels have not been defined yet, even for on-road vehicles, due to the great flexibility of lithium-ion (Li-ion) cells in terms of electrical layout.

B. ELECTRIC ENERGY STORAGE SYSTEMS

In HETs and BETs the electric ESS could be a battery pack, a supercapacitors bank or a mix of these two. According to Ragone plot reported in Fig. 14, supercapacitors have the highest specific power and a specific energy higher than common electrolytic capacitors, but yet smaller than any battery type [67]. On the other hand, the batteries have a greater specific energy, especially the Li-ion type, but a lower specific power. Among them, lead-acid modules are commonly implemented in low voltage systems, usually up to 48 V, while Li-ion cells are gaining an increasing popularity for high voltage systems in automotive applications. Li-ion type is expected to become the dominating battery technology in the next few years, thanks to its energy-density and power-density capability. So, supercapacitors are used mainly to balance high-varying transient power requirements and to recover more effectively braking kinetic energy, whereas battery packs work as energy storage devices as first instance. Systems that combines batteries and supercapacitors can be implemented in order to exploit the advantages of both technologies at the same time [68], [69]. From some of the studies presented in previous sections, it emerges that hybrid battery-supercapacitors systems could be mandatory to fulfill harsh discharges during heavy in-field operations. Moreover, for the same reason, power-oriented Li-ion modules should be preferred to energy-oriented ones, especially in HETs, where electric drives are used to fulfill peak power demands.

The same charging techniques adopted for on-road vehicles can be suitable for agricultural machinery too [70], obviously in a perspective of sufficient power supply available in the farmland, or very close to it. As regards conductive wired charging, fast high-voltage DC charging seems to be more convenient than low industrial voltage charging for agricultural machinery [71], [72], not only because to the high charging power needed to supply large capacity batteries in an acceptable working time, but also thanks to some peculiarities of farmland. Indeed, high voltage levels could be available taking advantages of in-site renewable energy power plants, such as photovoltaic and bio-gas plants [73], and the DC/DC charger could be installed inside the farm instead of being on tractors. Fast battery exchange seems also more competitive than direct wired charging for agricultural applications [52], [59], and even innovative wireless systems could be promising in a future perspective [74].

Company	Model and year	Type and Architecture	Primary power source	Electric engine auxiliaries	Electrified loads	H_T (%)	H_L (%)	H_{NRMM} (%)
John Deere	7430 E-Premium 2007	Conventional	ICE 6TI* 147 kW	• Radiator fan • Coolant pump • AC compressor • Brake compressor	• Conventional traction • Conventional rear and front PTOs	0	0	0
	7530 E-Premium 2007	Conventional	ICE 6TI 156 kW	• Radiator fan • Coolant pump • AC compressor • Brake compressor	• Conventional traction • Conventional rear and front PTOs • E-PTO (5 kW – 380 V AC)	0	0	0
Minsk Tractor Work	Belarus 3023 2009	Diesel-electric Series	ICE 6TI 220 kW	• Radiator fan	• Electric traction (motor on rear axle) • Conventional rear PTO • Electrically-driven front PTO (55 kW) • E-PTO (172 kW –380 V AC)	45.4	20.0	32.7
New Holland	NH2 2011	Full-electric FCET	Fuel cell stack 100 kW	- No engine	• Full-electric traction • Electrically-driven rear PTO	1	1	1
Fendt	e100 Vario 2018	Full-electric BET	Li-ion battery 70 kW rated 150 kW peak 6 h autonomy	- No engine	• Full-electric traction • Electrically-driven rear and front PTOs • E-PTO (up to 150 kW boost – 700 V DC)	1	1	1
	X-Concept 2019	Diesel-electric Series	ICE 4TI 147 kW	• Radiator fan • Coolant pumps • AC compressor	• Conventional traction • Conventional rear and front PTOs • E-PTO (130 kW rated – 700 V DC)	0	46	23
FPT Industrial Steyr (CNH Brands)	Steyr Konzept 2019	Hybrid electric Series	ICE 4TI 150 kW	• Radiator fan • Coolant pumps • AC compressor	• Electric traction (four wheel motors) • Electrically-driven rear and front PTOs • E-PTO (48 V – 700 V DC)	40	30	35
Argo Tractors Landini	Rex4 Electra 2020	Hybrid electric Series-parallel	ICE 4TI 82 kW	• Radiator fan • Coolant pumps • AC compressor	• Electric assisted traction (two motors on front axle) • Conventional rear and front PTOs	Data not found	0	Data not found

*6TI means 6-cylinders Turbocharged Intercooled engine

FIGURE 13. **Summary of prototype electrified tractors presented by manufacturers.**

C. FUEL CELLS AND HYDROGEN STORAGE

Despite only few studies have investigated such technology in agriculture until now, fuel cell powertrains seems to be more promising than batteries-powered drivetrains for off-road heavy vehicles electrification [75], thanks to their higher energy density, and to the faster refueling if compared to battery charging. Among present technology, PEM and SO (Solid Oxide) fuel cells are the most suitable solutions for mobile high-power applications [76]. Methanol fuel cells have been also proposed for automotive applications, even though they have lower efficiency than PEM and SO fuel cells. However, state-of-the-art fuel cells have poor dynamic performances due to the slowness of their chemical reactions. Thus, in automotive applications auxiliary batteries or super-capacitors banks are mandatory to fulfill power peaks and fast transients, causing an increase in the overall system cost.

Moreover, safety issues in hydrogen storage on vehicles are major concerns due to extreme flammability of hydrogen, even though some studies have proved that both pressurized gas hydrogen [77] and liquid hydrogen storage [78] have an

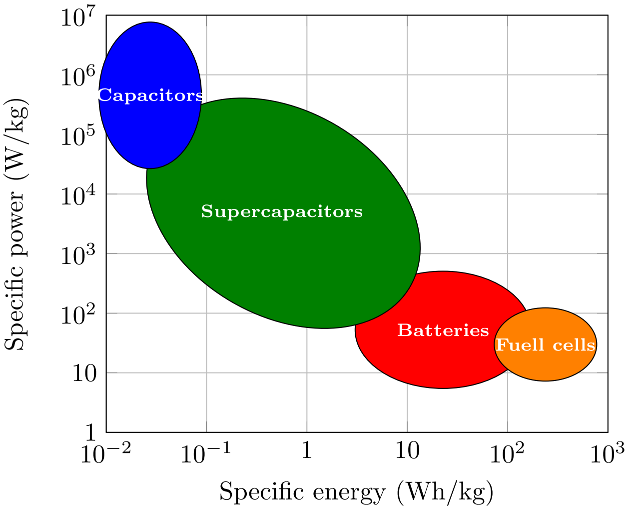


FIGURE 14. **Ragone plot. Comparison between different power generation devices and storage technologies widely used in electric and hybrid electric vehicles.**

explosion risk comparable to that of gasoline fueled vehicles, thanks to hydrogen lightness in the former case, and when proper tanks are used in the latter option. An even safer solution is metal hydride storage, which allows an energy density comparable to pressurized storage with no risk either of inflammability nor explosions [79]. Such system can be very suitable for off-road applications because its major drawback, i.e. an increased weight, is not of great concern in off-road vehicles, if not a benefit.

Nevertheless, an effective introduction of hydrogen propulsion in off-road applications is strictly related to the development of reliable and widespread infrastructures for hydrogen production, transportation and refueling.

D. ELECTRIC MACHINES

The design of electric machines seems particularly challenging for hybrid electric tractors rather than for full-electric ones, due to the coexistence of high-power electric systems and diesel units in a limited space, even though some issues are shared by both configurations.

Many works presented so far prove that the development of an effective HET can be performed through a conversion of existing platforms. Yet, at these conditions, there are strict size constrains for the EMs, which must fit in the volume cleared by the ICE displacement reduction, or by the removal of mechanical components. Therefore, EMs for agricultural tractors must have a high power density. This requirement is quite important also to make electric drives more competitive with their hydraulic counterparts, widely used in tractors [80]. Indeed, state-of-the-art electric motors have lower power densities than hydraulic actuators, although they allow an easier and more accurate control. So, the higher efficiency of electric drives is not exploited due to an increased weight of the machinery, which may lead to an insufficient overall efficiency to justify the higher initial costs.

The electric load, i.e. the current density in the armature winding, should be maximized to achieve high power densities. However, in this way, a higher thermal load must be dissipated to avoid over-temperatures in slot insulation. Therefore, an air-cooling may not be enough. Indeed, in all the concepts reported in this paper, liquid-cooled machines have been adopted, mostly with an external water-jacket. Even the use of hair-pins instead of wounded winding could be beneficial to improve the power density [81], [82].

Low losses is a key requirement as well. This may not seem a critical problem for electric machines, since they can easily exhibit efficiency over 90%. But the highest efficiency region is usually placed at high speed and low torque, whereas farming tractors often work at high torque and low speed during in-field operations [83].

The major challenge in the EM design is the lack of representative duty cycles, due to the great variety of tractors operations. In particular, the choice of proper torque requirements is not straightforward. The maximum power demand may not be a cost-effective option for the rated specification, or even it may lead easily out of the size constraints. Instead, since in many working conditions the machines are subjected to a varying torque demand, it could be a proper choice to set a lower rated torque, while the peaks could be fulfilled with an overload torque. Yet, in this way, the EM must be designed to have a proper overload capability, in order to supply the peaks for enough time, without electromagnetic or thermal damages.

To do this, in [84] the thermal equivalent torque method was adopted. Then, the authors designed a six-pole liquid-cooled SPM with 10 kW rated power (40 Nm @ 2600 rpm). The performance, efficiency and thermal behavior of the motor were deeply analyzed through finite element analysis and equivalent lumped-parameters circuits. The motor is able to withstand an up-to 150 Nm overload torque at 2600 rpm for a maximum time of 200 s without incurring in demagnetization or thermal damages to slot insulation.

The choice of the electric machines type is not straightforward too. In the concepts presented so far in this paper, all the three state-of-the-art EM types for automotive applications are tried [85], namely SPMs, IPMs and IMs. Generally, permanent magnet synchronous motors, both with surface mounted (SPM) and interior magnets (IPM), have the highest power densities. The former ones are used mainly for medium-low speed applications, where the machine can be controlled always in MTPA. Instead, the latter ones are preferred when a wide speed range is needed, thanks to their good flux-weakening capabilities. The use of rare-earth magnets (NdFeB and SmCo) seems to be mandatory to fulfill the power density requirement of agricultural application. So, both SPM and IPM are more expensive than asynchronous induction motors (IMs). Nevertheless, automotive industry is now greatly interested in the reduction of rare-earth magnets, especially in high-grade ones, due to unreliable supply chains and price instability [86], [87]. Furthermore, high temperature class magnets must be used to achieve the needed overload capability, and a particular care must be given not to demagnetize them. On the contrary, IMs do not suffer from demagnetization problems, and the thermal issues are limited only to the slot insulation. So, they are cheaper, and they could exhibit better overload capabilities. However, their power density is lower.

The choice of the machine type is strongly related to the powertrain architecture, especially on how the EM is mechanically connected to the load. When the EM is installed on the engine crankshaft, as the motor in parallel configuration of Fig. 6 or the generator in series-architecture of Fig. 5, or it is in direct drive with low-speed loads, as traction wheel motors, then high speed is not required (speed values not overcome 2600 rpm). Therefore, SPMs could be proper choices. On the other hand, when the EM is mechanically coupled through speed reducers or gears trains, as in power-split configurations of Fig. 8-9 or in full-electric powertrains of Fig. 10-11, then a wide speed range is needed, thus IPMs or IMs could be better choices.

Some studies have already dealt with the design of IPMs for agricultural applications, mainly regarding courtyard BETs [88], [89]. Zhitkova *et al.* [90] presented in detail the design and analysis of a 20 kW liquid-cooled IPM for a full-electric agricultural tractor, standing out the significant challenges given by this particular application.

When some strict size constraints occur, it may be possible that a very low machine aspect ratio is needed. In those cases, axial flux machines should be considered as well [91], [92], and they could be preferred to their radial flux counterparts in many cases [93], [94]. Other special machines could be suitable for this challenging application too, with several advantages if compared to traditional machines [95]–[98]. For instance, double-rotor radial flux machines can make integrated power-split e-CVTs [100], while double-stator machines can be used as wheel motors or additional generators [101]. As another significant example, hybrid excitation permanent magnet motors, both radial flux [102] and axial flux types [103], [104], have great potentials for heavy-duty off-highway vehicles, thanks to their increased torque capability in their entire speed range, even at high speed values.

E. POWER CONVERTERS

The choice of power electronics converters (PE) for electric drivetrains of tractors is mainly driven by the same demanding requirements already described for EMs, although some considerations should be drawn as there are peculiarities which applies specifically to this drive component.

As happens for EMs, there is a need to minimize volume and weight of the electric power unit too, which again results in challenging requests in term of power density and efficiency. However, differently from EMs, where working cycle can be used to properly design the machine and avoid oversizing, inverters are usually sized considering the maximum current supplying at full load to the electric machine, being their thermal responsiveness much greater than the EM one (i.e. they heat up more quickly).

Liquid cooling is preferred to convection or forced air cooling also for PE. Moreover, in hybrid solutions where the level of integration is high, there is a tendency in using the same coolant for the engine and the electric drive. As the optimal coolant temperature for ICE is around 90 Celsius degrees, this results in demanding requirements for the EM and very challenging design constraints for the PE [105].

At the moment, the most used switching power device for automotive systems, in the range of power and voltage relevant for the application under analysis, is the Silicon IGBT, which, however, is known for rapidly decreasing its performance when operating at high temperature [106]. Requirements of demanding temperature environment are usually fulfilled by selecting devices with superior current rating, or by oversizing the converter heatsink. Nevertheless, the recent advent into the market of the so-called wide-bandgap devices (WGB), Silicon Carbide (SiC) and Gallium Nitride (GaN), can pave the way for lighter and more efficient power converters [80]. WBG-based converters are characterized by lower switching losses and higher switching frequencies. Furthermore, they can operate efficiently at higher temperatures than their silicon counterpart. In addition, their are suitable in case of partial load operation, with working cycles subjected to frequent current variations.

As farming tractors often work at high torque and low speed, conduction losses are expected to be the prominent source of power losses for PE. Therefore, converter architectures that minimize the number of switching devices in series are preferred. So, voltage source inverters (VSIs) are advantaged compared to other options. An interleaved parallel solution is proposed in [107], where both high current handling and low ripple are pursued with a modular approach.

Nevertheless, as the requirements are becoming more and more demanding, it is expected that power electronics and electric machines will be no longer designed separately, but a cooperative design process will be preferred [108], which involves a high level of integration. In case of high efficiency required in the low speed high torque region, multi-phase segmented integrated architectures represent a promising solution [109].

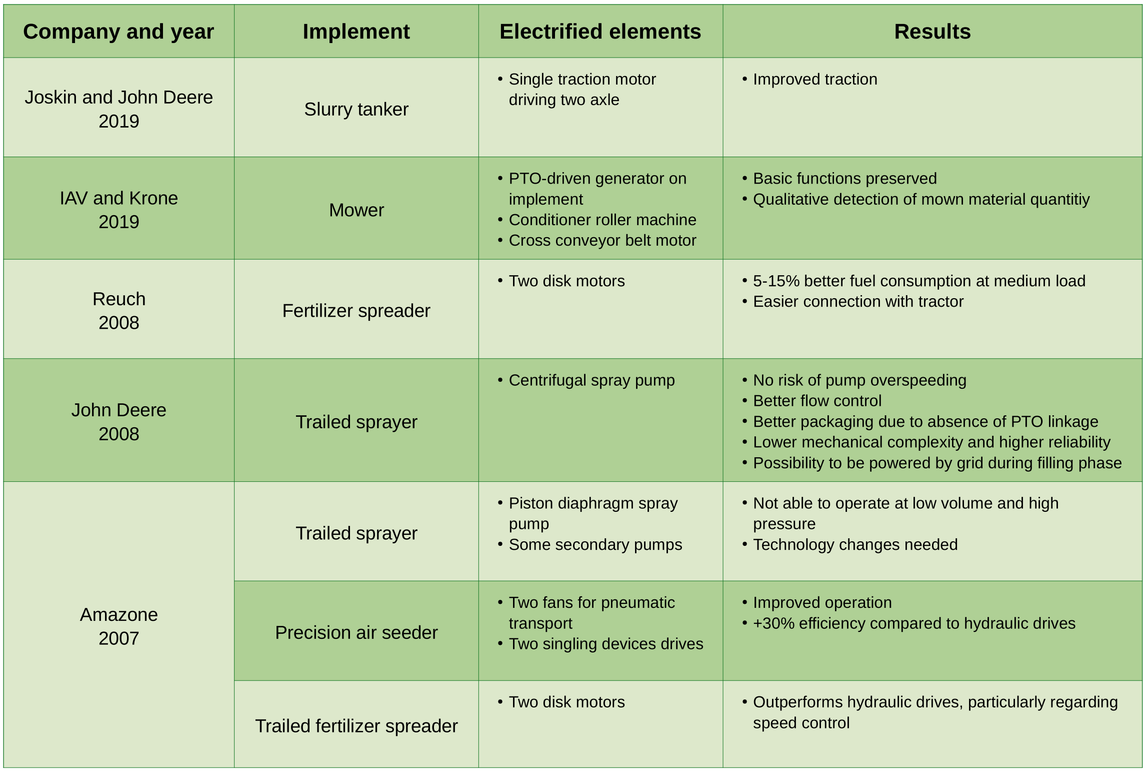
VI. IMPLEMENTS ELECTRIFICATION

Implements electrification can lead to fuel savings in two different ways:

1) thanks to a more efficient power transfer, substituting hydraulic drives with electric ones, as they could offer an up to 30% higher efficiency [110];
2) thanks to a more accurate control of seed and chemicals application [111].

Over the years several studies and prototypes of electrified implements were made. The main features of prototypes and commercial solutions presented by implements manufacturers until now are summarized and compared in Fig. 15.

In their study, Rahe and Resch [110] analyzed three different electrified implements: a trailed sprayer, a precision air seeder and a trailed fertilizer spreader. The fluid circuit of



Company and year	Implement	Electrified elements	Results
Joskin and John Deere 2019	Slurry tanker	• Single traction motor driving two axle	• Improved traction
IAV and Krone 2019	Mower	• PTO-driven generator on implement • Conditioner roller machine • Cross conveyor belt motor	• Basic functions preserved • Qualitative detection of mown material quantitiy
Reuch 2008	Fertilizer spreader	• Two disk motors	• 5-15% better fuel consumption at medium load • Easier connection with tractor
John Deere 2008	Trailed sprayer	• Centrifugal spray pump	• No risk of pump overspeeding • Better flow control • Better packaging due to absence of PTO linkage • Lower mechanical complexity and higher reliability • Possibility to be powered by grid during filling phase
Amazone 2007	Trailed sprayer	• Piston diaphragm spray pump • Some secondary pumps	• Not able to operate at low volume and high pressure • Technology changes needed
	Precision air seeder	• Two fans for pneumatic transport • Two singling devices drives	• Improved operation • +30% efficiency compared to hydraulic drives
	Trailed fertilizer spreader	• Two disk motors	• Outperforms hydraulic drives, particularly regarding speed control

FIGURE 15. **Summary of prototype electrified implements presented by manufacturers.**

the sprayer was simplified adopting several electrically driven pumps. However, the developed solution was not able to reach high pressures, as the adopted setup, i.e. diaphragm piston pumps, was not suitable for electric drives. For this reason, they concluded that electrification would lead to changes in specific sprayer components. On the air seeder four electric drives were installed: two 11 kW motors used to drive the fans for the pneumatic transport of fertilizer and seeds and two 400 W electric actuators for other components. The system shows a 30% efficiency increase over conventional hydraulic circuits during field tests. On the analyzed fertilizer spreader, water-cooled motors were used to drive the disks. The system outperforms hydraulic solutions as regarding disk-speed control, but it suffers the humidity inside electrical components.

Despite the higher efficiency shown by the electric drives, Rahe and Resch, through an analysis of several studies available in literature, report fairly low fuel savings, from 1% to 13%, with the higher values achieved with traction drives. However, to obtain these savings in the overall farming process all the machinery used throughout the year need to exhibit these levels of improvement. This fact, combined with the limited fuel savings, means that electrified solutions, and the associated costs, are justified only by increased functionality or by lower maintenance requirements.

Regarding the former reason, Joskin and John Deere [112] developed a slurry tanker equipped with an electric motor that drives two of the three axles. The motor is fed by an up-to 100 kW generator integrated in the tractor powertrain. An improved traction effort is achieved enabling operation with bigger tankers using the same tractor or, equivalently, using a lighter tractor in combination with an equally sized tanker. Moreover, in past years John Deere studied some electrified implement prototypes: a fertilizer spreader and a trailed sprayer, driven by two inverters installed on a John Deere 7530 E-Premium [113]. The fertilizer spreader, developed by Rauch, is equipped with two 5 kW rated power permanent magnet motors that drives the disks through a reduction gearbox. Both simulations and field tests showed a decreased fuel consumption compared to hydraulic and mechanical spreaders, with particularly good results at partial load. The best fuel consumption values are 11 l/h for the hydraulic spreader at selective control valve (SCV), 10.25 l/h for the mechanical, 9.5 l/h for the hydraulic at Power Beyond, and 9 l/h for the electrical one. SCVs are valves installed on the tractor that are used to control the implement operation: they are a significant source of losses. On the other hand, a direct connection between pump and implement, the so-called Power Beyond, allows to improve efficiency, although in this way some sort of control valve is needed on the implement. At rated power, efficiency is comparable with the mechanical spreader, outperforming both the SCV and Power Beyond hydraulic versions, while at low disk power the electric version shows a considerably higher efficiency than all the other solutions, outperforming the second best (i.e. mechanical) with a 65% vs 45% efficiency. Moreover, the electric spreader is easier to couple with the tractor. As regarding the electrified sprayer, the piston diaphragm pump found on the traditional implement was replaced with a centrifugal pump, which better fits to the electric motor characteristics. The author did not mention any possible fuel saving, but report several advantages: no risk of pump overspeeding; no PTO linkage, enabling better positioning of the various components; an improved safety for the operators and a tighter turning radius for the vehicle; no relief valves needed; high reliability due to the low number of moving parts; easy flow control. Moreover, during the filling phase, the implement could be powered by the grid, keeping the ICE off.

To investigate the potential advantages of implement electrification IAV and Krone developed a partially electrified mower prototype [114]. It is equipped with three 48 V electric machines, one of which is driven via PTO shaft and acts as a generator. The basic functions of the implement were preserved and, in addition, it was possible to qualitatively detect the quantity of mown crop material. The costs of these electric drives are still greater than those of equally powered hydraulic drives. The use of electric drives is dependent on the need of an accurate control, as a justification for the higher costs.

The common aspect emerging from all these studies is the focus on the increased functionalities along with precision agriculture principles, because the eventual fuel savings do not, themselves, justify the higher costs of the electric drives. However, implements electrification is gaining interest and an international standard (ISO/CD 23316) is now under development to define a proper high voltage electrical connection with the tractor.

VII. WASTE HEAT RECOVERY IN HEAVY DUTY VEHICLES

In recent years exhaust gas energy recovery has been the topic of several studies, although few of them have investigated applications in agricultural machinery [115]. Energy can be harnessed in various ways: adding a low pressure turbine (LPT) after the turbocharger; extracting excess power from the turbocharger; using Rankine or air-Brayton cycles to drive a turbine (Fig. 16). The harvested power can be used to drive an electric generator or can be fed to the crankshaft through a gear train, with the former case being relevant for this paper.

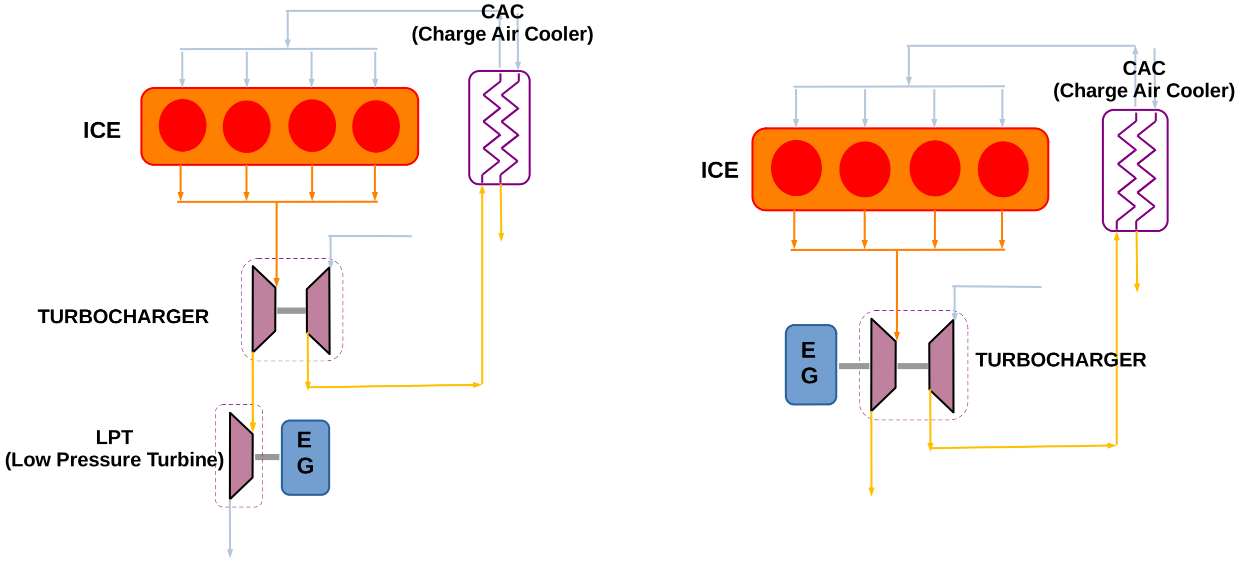
Andwari *et al.* [116] compared the use of a LPT and an Organic Rankine Cycle (ORC) as waste heat recovery systems on a 316 kW diesel truck engine. At low speed and low load both methods are able to extract 2–4 kW; at medium speed and medium and high load the ORC produces 5–8 kW, while the LPT 6–14 kW; in proximity of the maximum power point the ORC produces 12–16 kW, while the LPT around 30 kW. The BSFC improvement, however, presents a different behavior: the ORC is able to provide a 2–3% improvement at low speed and 3–5% from medium to high speed, while the LPT allows for a 2–5% improvement at medium speed and 5–8% at high speeds. Nevertheless, at low speed, the LPT showed even a negative, although limited, effect on BSFC, as the generated power was not sufficient to overcome the power losses due to the increased back-pressure.

Teo *et al.* [117] analyzed three heat recovery methods on a 90 kW 5.9 l turbocharged diesel engine used in power generation and marine applications. The three methods consisted in:

- driving an electric generator with a LPT;
- driving an electric generator directly with the turbocharger;
- using an air-Brayton cycle, taking compressed air from the charge air compressor, heating it up using the exhaust gases and expanding it in a turbine.

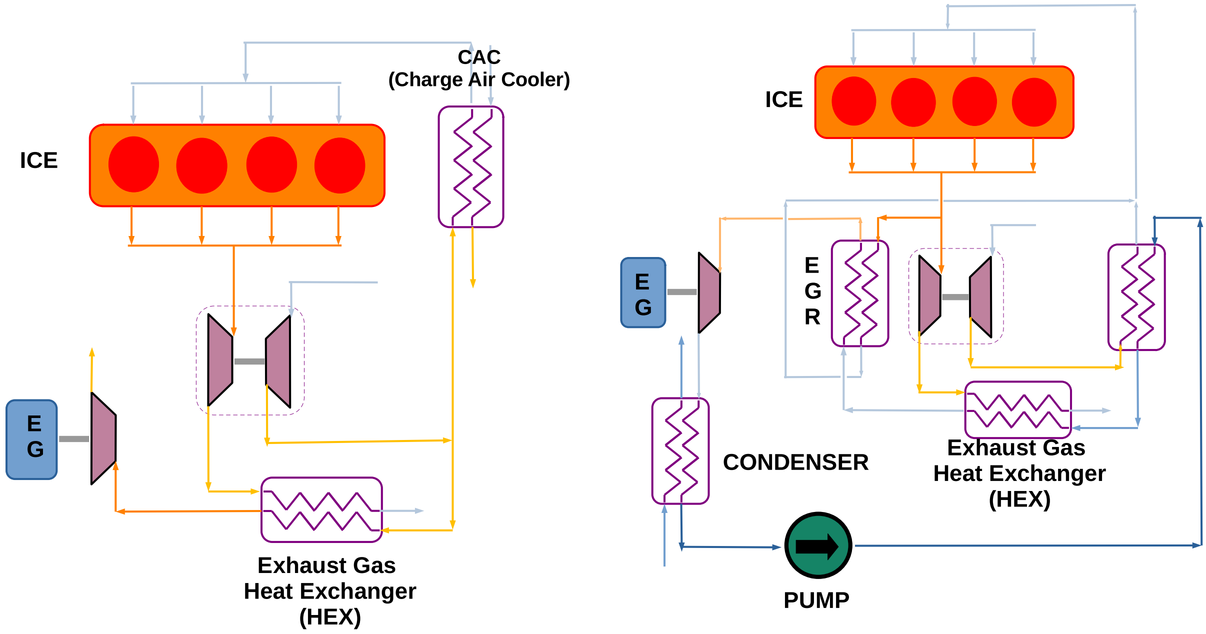
None of these methods were able to work properly using the original engine configuration, as they resulted in a lower power output. However, this problem can be solved with modifications on the turbocharger, by the adoption of a turbine volute with a smaller area over radius ratio. The LPT resulted the best recovery method, being able to recover up to 4–5.5 kW, although is sensitive on LPT sizing, which must be properly done to avoid undesired back-pressure. The generator on the turbocharger is able to recover up to 1.75 kW, with its limiting factor being the magnitude of pressure at which the turbine operates (to avoid excessively high back-pressure), and the fact that the whole expansion takes place in a single stage. The air-Brayton cycle is not able to harvest more than 0.64 kW, as it shares the same compressor with the ICE, so its mass flow rate is limited. All the analyses were made at 100% load, so there is no information on partial load performance. However, all the methods showed an increase in recovered power with engine speed.

Hountalas *et al.* [118], [119] analyzed the effect of different configurations on a diesel truck engine: mechanical turbo-compounding with a LPT; electric turbo-compounding on the turbocharger; steam and organic Rankine cycles absorbing heat from an exhaust gas heat exchanger, from the EGR cooler (Exhaust Gas Recirculation) and from the charge air cooler (CAC). As stated by the authors, the LPT can be used also to drive an electric generator, so it remains relevant for this work. At 100% load, they were able to recover up to approximately 60 kW with the LPT. Total system power at full load was increased from 371 kW to 388 kW, with an approximately 4.5% BSFC decrease, considering the ICE power reduction due to the added turbine, whereas at 25% load there is no significant variation in both total system power and BSFC. Regarding the electric generator connected to the turbocharger, at full load a 2% BSFC reduction was observed with the standard efficiency turbocharger, and it goes up to 6.5% with a highly efficient turbocharger, while the recovered power is 20 kW and 40 kW, respectively. Whereas the recovered power is lower compared to the LPT, the negative effect on ICE power is lower, thus total system power is similar: 378 kW for the standard turbocharger and 393 kW for the higher efficient one. The results also highlights the need of an increased turbocharger efficiency when adopting electric turbo-compounding, as it increases the available surplus power. Adopting the Rankine cycle, at 100%



(a) Generator on LPT

(b) Generator on turbocharger



(c) Air-Brayton cycle.

(d) Organic or steam Rankine cycle

FIGURE 16. **Proposals for waste heat recovery from engine exhaust gases.**

load, recovered power reaches 32 kW and 42 kW, using steam or organic fluid respectively, while BSFC improvement reaches 9% and 11%. The authors provide some interesting considerations on the various energy recovery systems too: adopting the Rankine cycle there is higher reduction in BSFC, but the volume, weight and cost are considerably higher than turbo-compounding, making the latest the preferred solution for truck applications. Those conclusions could be valid also for agricultural tractors, due to similar size and packaging limitations.

From all the discussed studies, it emerges that recovered power is low at low load and low speed. As stated in [120], for heavy-duty off-highway vehicles with engine power greater than 150 kW, once a DC bus is available, it could be worthwhile to recover waste heat from the exhaust gases. The power range analyzed correspond to the power of a row crop tractor, which usually do not perform as many low-duty operations as specialized tractors (for example precision operations in vineyards, as shoot tipping), so a high amount of exhaust energy is often available, and it could be beneficial to adopt some sort of waste heat recovery.

VIII. ECONOMIC ASSESSMENTS, MARKET ANALYSIS AND FUTURE TRENDS

An increasing number of technical papers have dealt with economic assessments, costs estimations and market analysis about the electrification of tractors and their implements, thanks to the raising interest from manufacturers, that want to push forward a technology application still in the research stage. Feasible prospects about the introduction of more electrified agricultural machinery are of paramount importance to drive effectively the technical research, especially when it is at the beginning.

As regards hybrid technology, in [121] a survey was administrated with 101 participants from the agricultural communities in California and Texas in order to analyze potential market acceptance for a HET and to identify those factors that could have a greater influence on the purchase decision. The preliminary results suggest that reliability is a deterministic factor and farmers are willing to pay more for a reliable unit, rather than for a cleaner or more efficient vehicle. The primary benefit of hybrid technology, namely fuel efficiency and reduced exhaust emissions, are not major factors that affect purchase decisions. Then, the authors state that farmers age has a strong impact on purchase decision: experienced old farmers are much less willing to buy an HET than young farmers or new agricultural entrepreneurs. Finally, the authors declare that a relevant part of the survey respondents has a lack of knowledge regarding hybrid electric technology and very few confidence with it. So, they suggest that a successful marketing strategy for an HET should rely on customer education, to help them understand the farm-level benefits in the adoption of hybrid electric technology.

As regards BETs, Gao and Xue [122] made an economic assessment of full-electric transformation of farming tractors fueled with diesel in the Chinese agricultural market. The economic assessment was carried out by evaluating the life cycle cost and the payback period of incremental investment (IPBP: Incremental PayBack Period), which refers to the time needed to recover the difference investment required for electrification. Various battery technologies and farming tractor types were considered by the authors, as well as a wide range of tractors power. Results show that the cost of electric transformation increases significantly with the increase of tractor power, but it is limited by the weight and volume of the chosen battery pack, as well as the driving time. The authors state that it is not suitable for a Chinese farmer to transform a conventional tractor with a power greater than 22.6 kW. In general, the results shows that the full-electric transformation of high-power farming tractors is unsuitable. The operating cost of the transformed electric tractor is about 60% of the conventional vehicle, although the cost of electric transformation is 2–5 times higher. The price of agricultural electricity and the unit cost of battery pack have a significant impact on the life cycle cost. The minimum IPBP is 2.053 years and it is more economical to electrify farming tractors when the price of agricultural electricity remains unchanged and, at the same time, the unit cost of the battery pack falls down.

The development of more electric tractors, including both hybrid and full-electric technologies, and their related market penetration is expected within 15 years [123]. Scenarios analysis foresee at first instance an early development phase, when the new technology will be still in the research stage and it will be far from the conventional one both in terms of performance and costs. Then, in a second transitory period, it will gradually become competitive with the old technology. During this period, electric drives in tractors will not replace completely hydraulic actuators and mechanical PTO, but they will be probably coexist with them. Moreover, the costs of electrified tractors will be still higher than traditional ones, so the market demand could be slowed by a low customer acceptance, if not supported by public policy. Finally, in a long-term period, electrified tractors will be the dominant technology in agricultural industry, pushed by shortage of fossil fuels reservoir and thanks to the spread of autonomous and precision agriculture. In [124] automation is addressed as a key driver for the introduction of more electric drives in agricultural machinery.

IX. CONCLUSION

A complete review about the electrification of agricultural machinery has been developed and presented in this paper. After the description of the peculiarities of this kind of vehicles, the electrification challenges have been introduced. Various electrified layouts proposed in literature and selected by manufacturers have been described and analyzed. Several examples have been reported along as their pros and cons.

Besides the traction requirements, also additional loads such as implements and auxiliaries are considered: in agricultural vehicles such loads are a considerable part of the vehicle total power demand. Peculiar solutions for energy efficiency and losses recovery have been included as well.

Beyond the state of the art from the literature and from agricultural machinery manufacturers, the paper highlights also that the electrification in this area is in its initial stage of development. In comparison with road-vehicles, agricultural machinery electrification is more challenging. For this reason, attention of the research community toward this topic is increasing and a strong development is expected in the incoming years.

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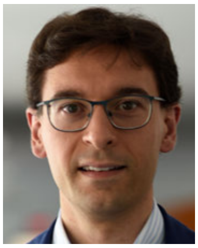

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