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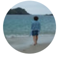

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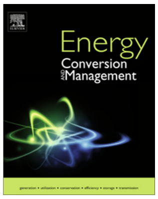

Review

High voltage electrification of tractor and agricultural machinery – A review

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ABSTRACT

Reduction of both pollutant emissions and fossil fuel dependency is an objective of energy policies worldwide. In many countries, governments promote the use of efficient vehicles like the hybrid electric vehicle. Incorporation of electric drives in tractor and agricultural machinery presents advantages in terms of increased energy efficiency and expanded functionalities. Higher efficiency means reduction in fuel consumption and subsequent decrease in CO_2 emission. New functionalities improve work quality and increase operator comfort. Tractor electrification takes advantage of decoupling loads and drives from the engine, which allows operating the latter at its highest efficiency point. Major advantages of machinery electrification are torque and speed control, noise reduction, and a more flexible design. In this paper, a review of the state-of-the-art of agricultural machinery high voltage electrification is presented.

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Contents

1. Introduction

The automotive industry is devoting considerable research efforts to reduce emissions and fossil fuels dependency without sacrificing drivability [1,2]. Likewise, many researchers and manufacturers have worked on reducing the energy consumption of agricultural machines without compromising their functionality and performance [3].

The European Union first introduced mandatory CO_2 standards for new passenger cars in 2009 [4]. This regulation set a 2020-onwards target of 95 g CO_2/km as average emissions for the new car fleet. Emission of NO_x and diesel particulate matter has been regulated since the early 1990 s for passenger cars [5], and since the mid-1990 s for off-road vehicles [6], with emission limits becoming increasingly tighter [7].

To reduce NO_x and particulate matter emissions of diesel engines, manufacturers have developed technologies like selective catalytic reduction, diesel oxidation catalyst, cooled exhaust gas recirculation, and exhaust particulate matter filter [8]. Reitz and Duraisamy [9] stated that innovative in-cylinder combustion strategies and exhaust emission after-treatment systems are required to meet stringent emissions regulations. Du et al. [10] reported on a compound combustion mode featuring lower NO_x

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Nomenclature

Abbreviations

AC	alternating current
A/C	air-conditioning
AEF	Agricultural Industry Electronics Foundation
BEV	battery electric vehicle
CNG	compressed natural gas
CVT	continuously variable transmission
DC	direct current
EDV	electric-drive vehicle
FCV	fuel cell vehicle
HEV	hybrid electric vehicle
HF	hybridization factor
HHV	hybrid hydraulic vehicle
ICE	internal combustion engine
M/G	motor/generator
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PTO	power take-off
PVEV	photovoltaic electric vehicle
RESS	rechargeable energy storage system
SAE	Society of Automotive Engineers
TTW	tank-to-wheel

Symbols

M	torque
P	power
P/W	power/weight (power-to-weight ratio)
r/min	revolutions per minute
1∼	single-phase
3∼	three-phase

and particulate matter emissions than the conventional diesel engine, and higher efficiency than the typical spark-ignition engine. Their system was based on cooperative control of exhaust gas recirculation and combustion phasing of gasoline/diesel blended fuels.

To reduce net CO_2 emission, partial substitution of biodiesel and pure plant oil fuel for fossil diesel-fuel is an appealing option [11,12]. According to Flórez-Orrego et al. [13], the addition of 5–7% v/v of biodiesel to fossil diesel fuel is compulsory in the Brazilian transportation sector since 2012.

Common-rail fuel injection has led to higher efficiency diesel engines [14,15]. More recently, hybrid electric vehicles (HEVs) have gained popularity because they have reduced the fuel consumption and the exhaust gas emission of automobiles [16–18]. Ao et al. [19] proposed a weighted cost function of fuel economy and NO_x emissions for a HEV. Compared with the strategy of maximizing only fuel economy, the combined fuel economy-NO_x optimization strategy yielded a 15.2% reduction in NO_x emission at the cost of increasing fuel consumption by 5.5%. This result is in agreement with Clark [8], who stated that NO_x and particulate matter emissions requirements are not fully aligned with efficiency requirements. Yet analogously Janulevičius et al. [20] reported a NO_x distribution between effective ploughing and headlands maneuvering of 69.4% and 30.6%, respectively; while the CO_2 share was of 84.6% and 15.4%, respectively.

Prior to 1955, automobiles used 6 V batteries [21]. Thereafter, impelled by the ever-increasing demand of electric power, the 12 V battery charged by a 14 V alternator took over.[1] This change was motivated by practical reasons: transmitting high power at low voltage entails high current and subsequent large conductor cross-sectional area. This is expensive, adds weight to the vehicle and occupies more space.

Apart from the conventional safety-extra-low-voltage 12 V direct current (DC) system, HEVs include a higher voltage battery (e.g. 201.6 V in Toyota Prius Hybrid 2010-3rd generation) for vehicle propulsion. Hereinafter the term *high voltage* is used for any wiring system which contains one or more circuits operating above 60 V DC or alternating current (AC) root-mean-squared, as defined by the Society of Automotive Engineers (SAE, [22]). The terms *high voltage battery* and *traction battery* are regarded as synonymous. Analogously, *traction alternator* means a high voltage generator devoted to power propulsion motors.

Demirdöven and Deutch [23] forecasted a swifter pace of adoption for HEV technology compared to fuel cell vehicle (FCV). Since 2004 their previsions have been confirmed, and today most automobile manufacturers offer at least one HEV model in their product palette. Simpson [24], taking the conventional internal combustion engine (ICE)-vehicle as the baseline, reported a fuel economy of 45% for the plug-in hybrid electric vehicle (PHEV), higher than HEV's 30%. Worldwide, there is general agreement in that the following natural step in vehicle electrification is the PHEV.

Walkowicz et al. [25] reported results of 13-month comparative field study between five conventional diesel tractors and five parallel-HEV tractors of the Coca-Cola Refreshments delivery trucks fleet. The five diesels and the five hybrids drove similar cycles with similar kinetic intensity, average speed and stops per mile. The HEV group yielded a 13.7% fuel economy improvement over the diesel group. Barnitt [26] compared in-use performance of hybrid-electric, compressed natural gas (CNG) and diesel buses at New York City Transit. He concluded that second generation hybrids exhibited 43% and 22% better fuel economy than the CNG and diesel buses, respectively. Although on-road vehicles are second to none as to electrification, a bunch of remarkable high voltage applications can be found in the fields of mining, earthmoving, construction, forestry, and agricultural machinery.

In 1974, Terex started marketing their *Titan*, a diesel-electric mining haul dump truck [27]. The term *diesel-electric* is used for those vehicles that have an electrified powertrain but lack high voltage batteries. In 2014 BELAZ started marketing their *75710*, the largest dump truck manufactured to date, with a payload capacity of 450 t. This truck has two *traction alternators*, each one of 1704 kW, and four traction motors, each of 1200 kW. According to Chadwick [28], diesel-electric mining dump trucks outperform their mechanical-drive counterparts, especially on steep grades.

Earthmoving machinery manufacturers have developed some diesel-electric or even hybrid-electric model. Johnson et al. [29] compared emissions of Caterpillar *D7E* diesel-electric bulldozer with its conventional counterpart. They obtained that CO_2 emission of the diesel-electric bulldozer ranged from a 28% lesser to a 2% higher than the conventional, depending on push-distance and push effort. However, NO_x emissions of the diesel-electric were 7–21% higher than the conventional bulldozer. The latter

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[1] Some trucks use a 24 V DC electrical system, powered either by a 24 V off-the-shelf battery or by two batteries of 12 V connected in series. On the other side, the possibility of using a 36 V battery charged by a 42 V alternator on luxury automobiles has been a recurrent topic during the last decades.

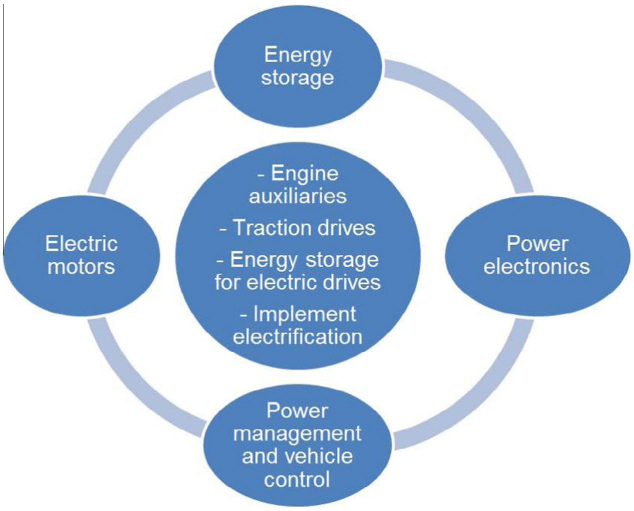

Fig. 1. Areas of tractor and agricultural machinery high voltage electrification, surrounded by key technologies involved.

shortcoming is in accordance with the aforementioned misalignment between NO_x emissions and efficiency requirements [8,19]. Komatsu developed the *HB205-1* and *HB215LC-1* hybrid-electric excavators, which are capable of recovering energy during the excavator slewing motion and store this energy in ultracapacitors. Filla [30] reported a fuel economy of 10% for Volvo *L220F Hybrid* wheeled loader over its conventional counterpart.

In the last years, there is an increasing interest in tractor and agricultural machinery electrification [31–40]. In 2002, the Agricultural Industry Electronics Foundation (AEF) developed the ISO11783 (ISObus) standard to promote compatible communications between tractor and implements of any manufacturer. Nowadays, the AEF is working on a standard for compatible electric power interfacing between agricultural tractor and implements. A number of tractor and agricultural machinery manufacturers have developed some diesel-electric or even hybrid-electric prototype in the last years. To cite a few, we have the hydrogen fuel cell tractor by New Holland, the John Deere *7430/7530 E-Premium* and *6210RE* electrified tractors, the diesel-electric Belarus *3023* tractor, the *X-Concept* tractor by Fendt, the *UX-eSpray* electric sprayer and the *EDX* electric seeder by Amazone, the AXIS-E drive electric fertilizer spreader by RAUCH, the *E-Rogator* diesel-electric self-propelled sprayer by AGCO, the *TF 40.7 Hybrid* telescopic handler by Merlo, etc.

According to Buning [41], the areas of tractor electrification using high voltage can be divided into four groups, namely, engine auxiliaries or non-propulsion loads; traction drives; energy storage for electric drives; and implement electrification (Fig. 1). Sections in the present review follow that order, where tractor-engine-based generation of electric energy for electrified implements has been included in the engine auxiliaries section.

2. High voltage electrification of agricultural tractor

2.1. Hybrid vehicle rationale

A hybrid is defined by SAE as a vehicle with two or more energy storage systems both of which must provide propulsion power – either together or independently. Apart from HEVs, other types of hybrids exist, like the hybrid hydraulic vehicle (HHV). SAE [22] defines a HEV as a road vehicle that can draw propulsion energy from both of the following sources of stored energy: (1) a conventional fuel and (2) a rechargeable energy storage system (RESS) that is recharged by an electric motor-generator system, an external electric energy source, or both. In a strict sense, the expression ‘conventional fuel’ in SAE definition would constraint the term HEV to vehicles with spark-ignition or compression-ignition engine as the primary energy source. However, United Nations definition of HEV [42] speaks of *consumable* instead of *conventional* fuel. On this basis, the primary energy source in a HEV is not necessarily the engine hydrocarbon fuel – or biofuels, but can also be the hydrogen fed to a fuel cell. While the ICE is a generator of mechanical energy, the fuel cell is an electric generator. For the purpose of this review, United Nations definition of HEV is preferred.

Nemry et al. [43] used the term electric-drive vehicle (EDV) for any vehicle in which mechanical power is supplied to the drive wheels by an electric motor that is powered either solely by a RESS or in combination with an engine or a fuel cell. According to those authors, the EDV would encompass five types of vehicle, namely, battery electric vehicles (BEVs), HEVs, PHEVs, FCVs, and photovoltaic electric vehicles (PVEVs). However, three more types of EDV can be considered (Fig. 2). Although intrinsically the fuel cell can deliver power up to important transients, some of its auxiliaries like the air compressor and the hydrogen humidifier cannot follow unlimited load transients [32]. Therefore, for the fuel cell to be practical in a vehicle, it needs to be hybridized with an RESS [44,45]. From the eight types of EDV included in Fig. 2, four of them belong to the subset of the plug-in electric vehicles (PEVs).

In practice, there is an easy way of determining whether a vehicle is a hybrid or not. For example, Technical University of Madrid hosts a straddle over-the-row four-wheel-drive hydraulic tractor. In this tractor, engine mechanical power is converted to hydraulic power through several engine-driven pumps; then the oil is pumped to four hydraulic motors, one per wheel. Since this tractor lacks a hydraulic energy accumulator it is not hybrid-hydraulic, but diesel-hydraulic. Being a diesel-hydraulic, tractor propulsion requires that the engine is spinning, unlike a hybrid. Interestingly, Caterpillar intentionally did not include the label *hybrid* in the bodywork of the diesel-electric bulldozer aforementioned, because that bulldozer does not include energy reservoir other than the diesel fuel [46].

Albeit HEVs are the mainstream in literature and the prevalent object of research projects funding, HHVs have encountered a number of successful applications, like refusal trucks and excavators [47,48]. The main improvement made in hydrostatics during the last years has been the use of proportional solenoid valves and electronic controls. Electric motors on their behalf have made remarkable progress through the increase in their *power/weight* (*P/W*). However, in many cases electric motors are still far from hydraulic motors as to *P/W*. As shown in Table 1, orbital or geroler hydraulic motors have a *P/W* almost eightfold better than the nearest electric motor, *viz.* the synchronous permanent magnet, although the latter greatly outperforms the orbital hydraulic motor as to efficiency (92% *vs.* 71%). On the other hand, Table 1 also shows that there is no much difference in either efficiency or *P/W* between radial piston hydraulic motor and synchronous permanent magnet motor. Fluid motors present the advantage that the own working fluid acts as a coolant. This is not the case for electric motors, which need a dedicated coolant, be it air, water, or oil. Rydberg [48] stated that the only aspect in which electric motor outperforms hydraulic motor is in the integration with control electronics, which is more straightforward for the electric motor.

The HEV engineering philosophy is a holistic one, or ‘1 + 1 > 2’ [49]: Smart integration of engine, mechanic and electric powertrains can lead to increased energy efficiency, i.e. reduction of fuel consumption and subsequent decrease in CO_2 emissions. The integration level of electric drives and power electronics into the mechanical powertrain indicate the degree of hybridization [31]. The hybridization factor (HF) for a vehicle is defined [50] as:

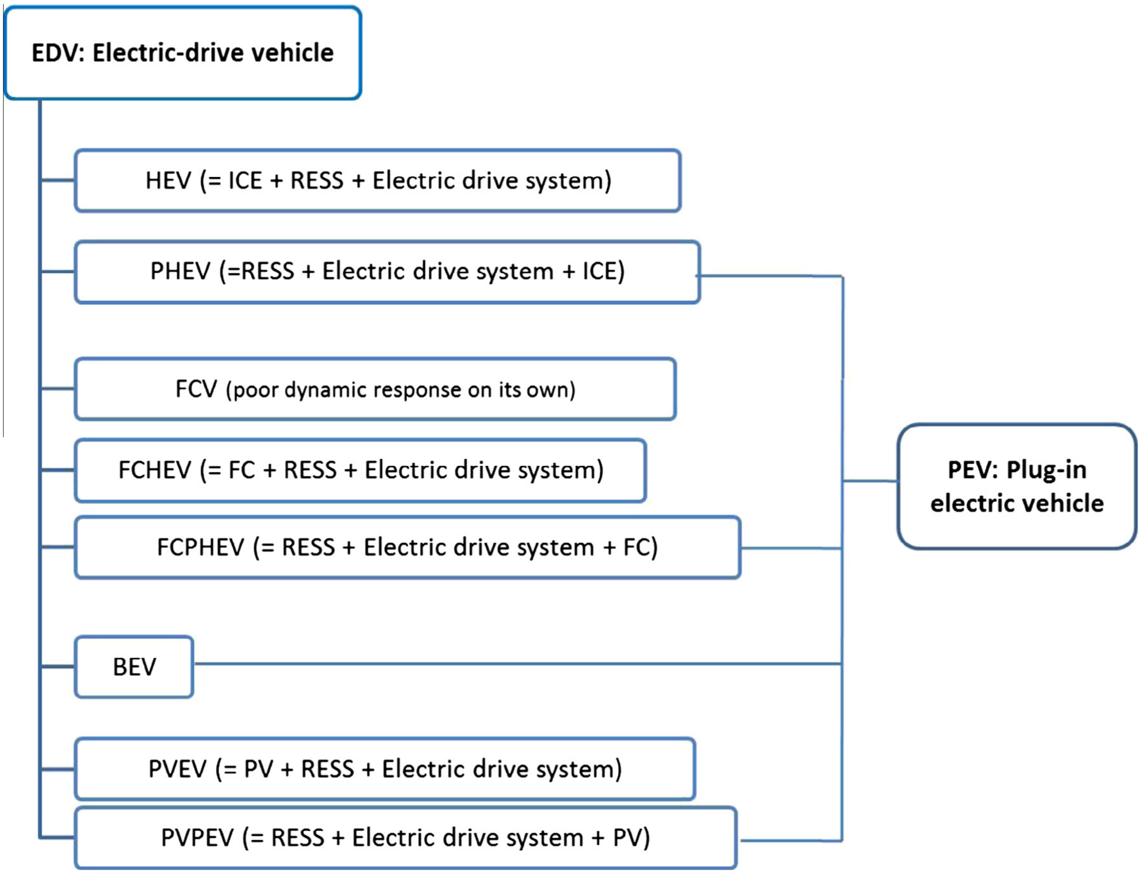

Fig. 2. Types of electric-drive vehicles, and the subset of plug-in electric vehicles.

Table 1
Efficiency and power-to-weight ratio for electric and hydraulic motors of comparable mechanical power. Compiled by the authors from technical catalogues of the companies listed at table footnote.

Type of motor	Efficiency (%)	Output power, *P* (kW)	Weight, *W* (kg)	*P*/*W* (kW/kg)
Synchronous, permanent magnet[a]	92.0	12.0	49.0	0.24
Induction, cage rotor[b]	90.2	11.0	97.0	0.11
Reluctance, synchronous[c]	93.3	11.0	69.0	0.16
Hydraulic, orbital or geroler[d]	71.0	11.0	5.9	1.86
Hydraulic, radial piston[e]	89.0	12.0	40.0	0.30

[a] Emerson (Dyneo®).
[b,c] ABB.
[d] Danfoss.
[e] Rexroth.

$$\mathrm{HF} = P_{electric}/(P_{electric} + P_{ICE}) \tag{1}$$

where $P_{electric}$ is the electric drive power, and P_{ICE} is the engine power.

According to the value of HF, HEVs are classified as microhybrids ($0 < \mathrm{HF} < 0.1$), mild hybrids ($0.1 < \mathrm{HF} < 0.25$), full hybrid ($0.25 < \mathrm{HF} < 0.5$), and PHEVs ($0.5 < \mathrm{HF} < 0.7$). The value $\mathrm{HF} = 0$ is for a conventional engine vehicle, whereas $\mathrm{HF} = 1$ is the case of a 'pure' electric vehicle like the BEV.

Somà et al. [51] proposed a specific hybridization factor for working vehicles like telescopic handlers, which not only demand power for vehicle propulsion but also for acting bucket hydraulic cylinders. The pump of the bucket hydraulic circuit can be powered directly by the ICE or by an electric motor. Focusing on the second case, they proposed a loading hybridization factor, HF2, following Eq. (1). They also calculated the propulsion hybridization factor, which they called HF1. Assuming a duty cycle with equal distribution of time devoted to propulsion and loading work, they calculated the vehicle overall hybridization factor as the arithmetic mean of HF1 and HF2.

2.2. Engine auxiliaries and energy generation for electrified implements

A first milestone in tractor hybridization is to drive diesel engine ancillaries electrically. The aim is to decouple traditional mechanical-driven non-propulsion loads, like the radiator cooling fan, water pump, or air-conditioning (A/C) compressor, from the engine. By decoupling these loads, parasitic losses are reduced and overall efficiency increases. Furthermore new functionalities arise, like the electric fan, which can be easily reversed to clean dust and debris from the radiator. It could seem that converting a mechanical load to electric is inefficient, because of the additional losses associated to generation of electricity and subsequent final conversion to mechanical energy. Nevertheless, those losses are compensated for by the fact that being electric, the loads can be switched on and off, or even better, speed up and down, on demand.[2] Mitchell et al. [52] compared a state-of-the-art cooling system including adjustable-speed electric fan and water pump, with conventional – i.e. less electrified – cooling systems. They concluded that the state-of-the-art cooling system outperformed the others with regards to warm-up time, temperature tracking, and energy consumption.

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[2] In fact, most automobiles replaced mechanical with electric fan many years ago. But the conventional automotive electric fan has only on-off functionality.

John Deere *7430/7530 E-Premium* tractors feature a three-phase (3∼) 480 V-20 kW induction generator mounted directly to the 132 kW engine flywheel. Generator production is partially consumed by two 3∼ 480 V engine auxiliaries [53,54]; these adjustable-speed non-propulsion loads are the radiator fan and the A/C compressor. Moreover, the *7430/7530 E-Premium* includes two power interfaces at the tractor rear side, one of them 230 V AC single-phase (1∼) and the other 3∼ 400 V AC. These power interfaces could be used to power some electrical equipment with the tractor at standstill. For example, one could utilize the 3∼ interface to power an arc-welding machine. Although it would be more efficient to power the welding machine from the machinery-building mains, eventual supply from the tractor may be useful. For example, tractor operator might need to weld a broken part of a plough or other implement in the field. By connecting the welding machine to the tractor power interface, the need for a portable gen-set is circumvented.

Pessina and Facchinetti [55] compared the fuel consumption of *7530 E-Premium* and its conventional counterpart in two working scenarios: field harrowing and on-road towing of a trailer. The *E-Premium* yielded a fuel economy of 4% over the conventional tractor in the harrowing work, while in the trailer road transport work the difference was of 16%. John Deere sequel in relation to high voltage electrification was their *6210-RE* [36], whose topology is of the type depicted in Fig. 3a. The rated voltage of the *6210-RE* DC-link is 700 V, and this tractor equips two implement inverters, each of which is able to provide DC or AC power up to 20 kVA and a current up to 26.5 A [56].

In the last years, *turbocompounding* technology has received considerable attention [57], as a way of increasing vehicle overall efficiency. Turbocompounding consists of harnessing the energy of engine exhaust gases, so that, after leaving the turbine of the turbocharger, they make spin a second turbine which is connected to an electric generator (Fig. 4). Interestingly, another way to harness the energy of exhaust gases is through a thermoelectric generator, based on the Seebeck effect. This presents the advantage over other waste heat recovery systems like the turbocharger, electric turbocompounding, or Rankine cycle, of including no moving parts [58].

2.3. Traction drives

Both HEV and PHEV driveline topology can be of any of three types: Parallel, series (Figs. 5 and 6), and series-parallel. The paths of mechanical and electrical power are parallel and tandem to each other in the parallel and series architecture, respectively. The so-called *complex*, *split-parallel*, and *power-split* (Fig. 7) configurations are variations of the series-parallel topology.

In the parallel architecture, mechanical and electrical powers can drive the transmission together or separately [59]. In this topology, there is one electric machine, which acts both as motor and generator (M/G). One disadvantage of parallel architecture is that when the M/G is powering the wheels, it cannot charge the battery. For agricultural tractors, which not only need to propel themselves but also have to transfer power to implements, a dedicated generator is of paramount importance. Therefore, the parallel architecture will not be further discussed here.

A first drawback attributed to the series architecture is that the engine, the generator and the motor are sized to handle the full power of the vehicle. Therefore, the total weight, cost and size of the powertrain can be excessive. A second shortcoming is that the engine power has to flow through both the generator and motor (Figs. 5 and 6). Total efficiency is therefore affected, due to the several energy conversions. However, series topology has some important advantages. First, since there is no mechanical link between the engine and the wheels, the engine-generator set can be located anywhere. Second, the realization of a continuously variable transmission (CVT) is possible [60,61]. Third, conventional mechanical elements like gearbox or transmission shafts are not necessary; therefore, electric in-wheel motors can be implemented easily[3] (Fig. 6). When all four wheels are driven individually, greater tolerance is afforded with regard to different tire radii as well as reduced tire wear. Furthermore, active traction control for each wheel helps protect the soil and increase traction. For example, the Rigitrac *EWD120* is a diesel-electric tractor featuring four 33 kW motors, one in each wheel, plus an 85 kW generator [63]. Husson et al. [64] patented a design of this type, with the particularity that the PTO could be, partially, driven electrically. Belarus 3023 [65] features a series topology, with one motor combined with mechanical transmission at the final part of the driveline, similar to the design shown in Fig. 5. Individual all-wheel-drive allows for torque vectoring [66].

Florentsev et al. [65] and Puhovoy [67] reported results of comparative test between Belarus *3023* diesel-electric prototype tractor and its conventional under-load shift stepped gearbox drivetrain counterpart. Both tractors mounted tires of the same size and tilled a same depth of soil with the same plough. Specific fuel consumption was 10.8 kg/ha for the diesel-electric prototype and 13.2 kg/ha for the conventional tractor. The difference was therefore 2.4 kg/ha, which divided by 13.2 kg/ha yields an 18% fuel economy for the diesel-electric. Furthermore, the prototype optionally featured a front PTO driven by an adjustable-speed drive electric motor, which provides progressive start functionality.

Farkas [68] developed a testing method for hydrostatic-mechanical power-split CVT simulation. He concluded that experience gathered from the modeling of power-split CVT could be adapted to hybrid-electric powertrains. Comprehensive reviews on power-split CVTs applied to agricultural tractors can be found in Renius and Resch [69], Farkas and Kerényi [70], or Linares et al. [71]. Most literature and commercial developments on power-split CVT applied to tractor deal with the hydraulic pump-motor pair instead of the electric generator-motor pair. Moreover, aforementioned literature does not contemplate energy storage i.e. powertrain hybridization.

Power-split (Fig. 7) combines the advantages of series and parallel topologies. The main principle behind power-split architecture is the decoupling of the power supplied by the engine from the power demanded by the vehicle driver. At lower speeds, the system operates as a series powertrain, while at high speeds, where the latter is less efficient, the engine takes over. In the hydrostatic-mechanical CVTs reviewed e.g. by Linares et al. [71], no hybridization is contemplated: To operate, the engine must be turned on, and at high speeds the mechanical branch – rather than the engine as in a hybridization context – takes over. Rossi [72] designed an electronic-CVT (e-CVT) based on coaxial and concentric arrangement of the two electric machines, viz. the generator and the motor. This e-CVT was proposed as a solution for full hybrid transmission of specialized agricultural tractors in Rossi et al. [39]. Barucki [73] built a test-bench to compare series and input-coupled power-split electric powertrain configurations. Efficiency of the power-split configuration was up to 8% higher than that of the series-hybrid.

Ca. 1960, Allis-Chalmers developed a fuel cell tractor [74]. In 2009, New Holland presented their *NH2*^{TM} fuel cell electric tractor [75]. In 2011, they presented the second version of the hydrogen

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[3] Although in-wheel motors – generally designed as outer-rotor, inner stator – have many advantages, they also have a shortcoming, especially for on-road vehicles: Introducing the motor into the wheel hub increases wheel weight, which is inversely proportional to its ability to follow road profile [62]. Fortunately, this effect is partially compensated for by the fact that friction brake are lighter in HEVs, because a high share of the braking torque is exerted by the motor, via regenerative braking.

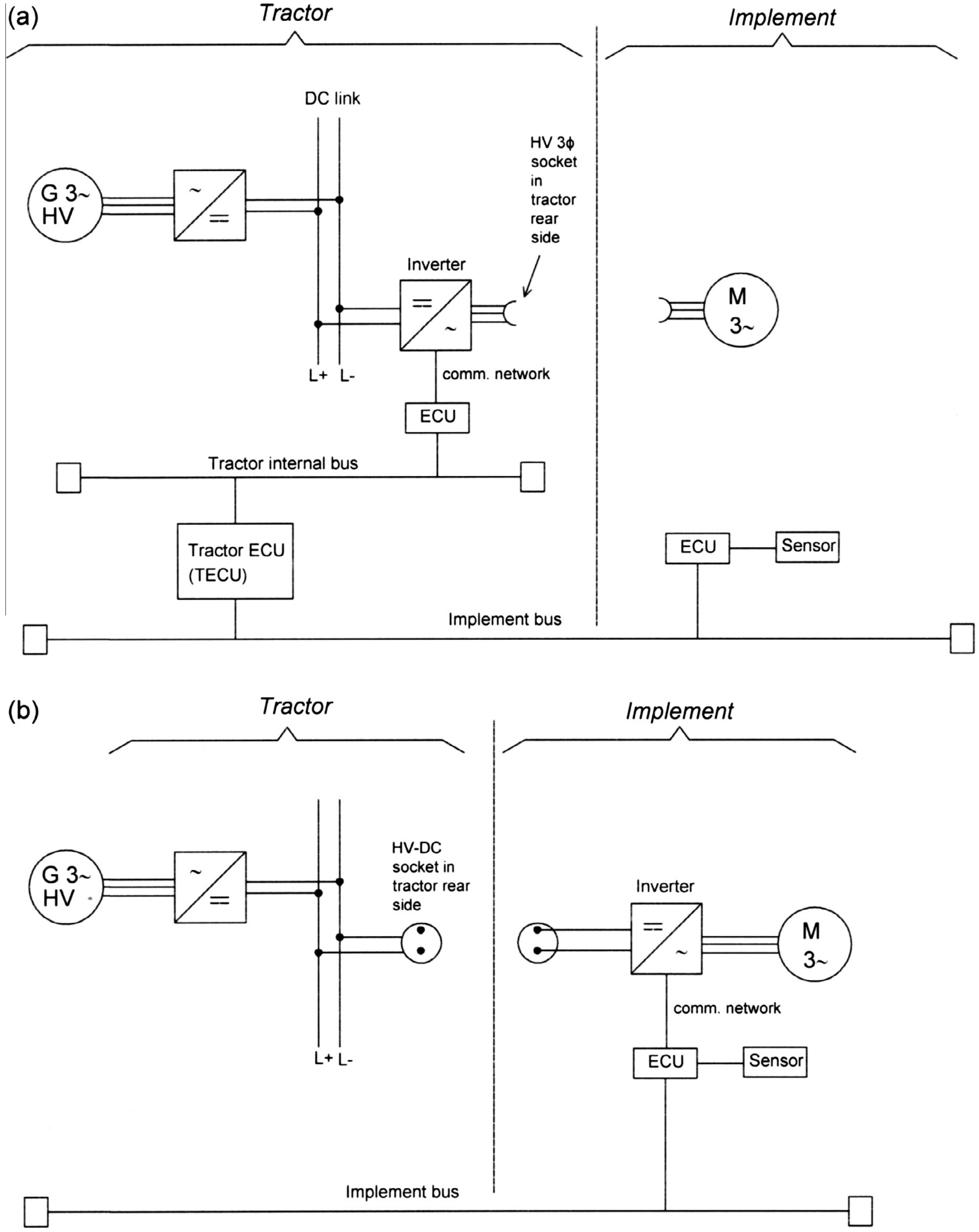

Fig. 3. Basic system architecture with inverters (motor adjustable speed drives) on the tractor (a), which requires AC 3~ high voltage interface at the tractor rear side; and with inverters on the implement (b), which requires DC high voltage interface at the tractor rear side. For the sake of simplicity, only one adjustable speed drive has been represented in either case.

electric tractor. Compared to the first version, the rated power supplied by the fuel cell was increased from 50 kW to 100 kW [76]. The second version *NH2^{TM}* tractor equips two electric motors: one for traction and one to power the PTO and hydraulic circuit pump. Each electric motor features a rated power of 100 kW, with nominal efficiency of 96%. The tank can hold 8.2 kg of H_2 at a pressure of 350 bar. This tractor also equips a 300 V–12 kW h Li-ion battery (12,000 W h/300 V = 40 A h) with a peak power output of 50 kW. Gallmeier and Auernhammer [77] compared overall efficiency i.e. tank-to wheel (TTW) efficiency of different drivelines based on different primary energy sources. When the primary energy converter is a fuel cell, TTW efficiency can reach 50%, which is rather higher than 32%, the maximum TTW efficiency corresponding to a diesel engine. Tritschler et al. [32] investigated the

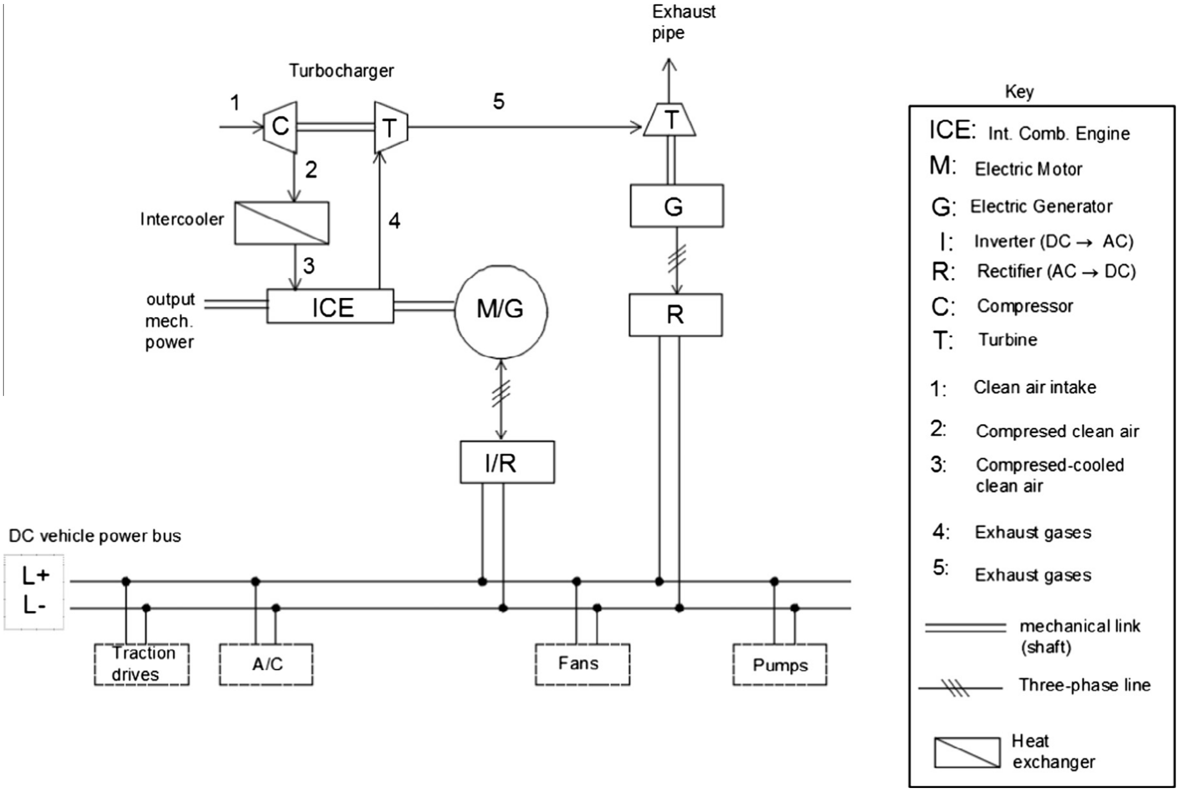

Fig. 4. Scheme of turbocompounding system. The electric loads/drives connected to the DC power bus can be either DC motors or AC motors powered by inverters (adjustable speed drives).

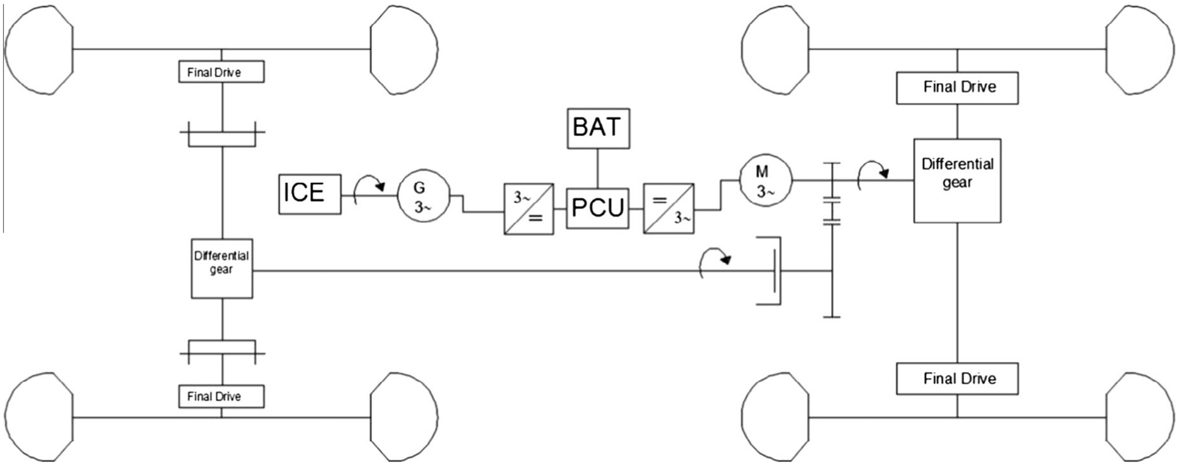

Fig. 5. Series continuously variable transmission with one traction motor, for hybrid-electric and plug-in hybrid electric tractors. PCU stands for power control unit.

potential of a fuel cell hybrid drive train for agricultural tractors. They addressed optimization of energy flux in order to increase the efficiency and to reduce the stress on the fuel cell.

Table 2 includes a comparison among four of the diesel-electric and hybrid-electric agricultural tractors abovementioned.

2.4. Energy storage

Both from economic and environmental point of view, the only energy that a ground vehicle should waste is that required for overcoming frictions. Energy consumed in accelerating and climbing slopes should be recovered at decelerating and descending slopes. Friction occurs against air and ground; the latter is called *rolling resistance*. Compared to on-road vehicles, apart from the *internal rolling resistance* due to tire deformation, agricultural tractors are subjected to an *external rolling resistance* due to soil deformation [78].

On urban cycle, full hybrid-electric powertrains based on power-split CVT have demonstrated their ability to reach 40% and higher fuel economy compared to conventional driveline based on engine and gearbox [39]. HEVs recover energy by means of *regenerative braking*, a consequence of Faraday–Lenz law.[4] Regenerative braking relies upon rotary electric machines being reversible. When the electric machine consumes electricity, it operates as a motor, thereby generating positive torque. Conversely, when it produces

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[4] Which in turn is an expression of the Law of Conservation of Energy.

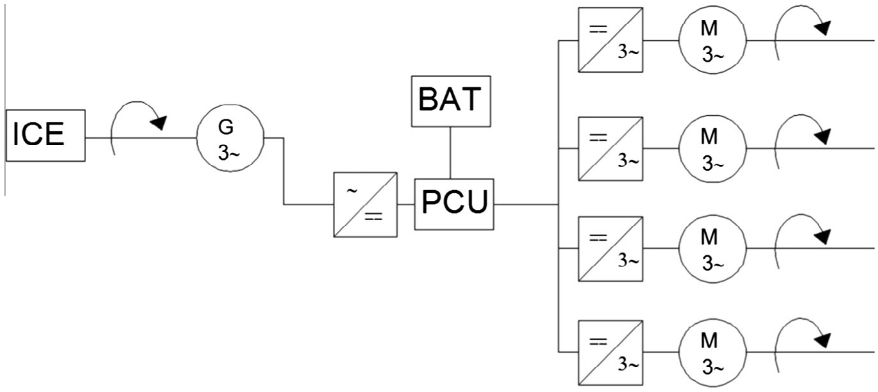

Fig. 6. Series continuosly variable transmission with four traction motors, one per wheel, for hybrid-electric and plug-in hybrid electric tractors.

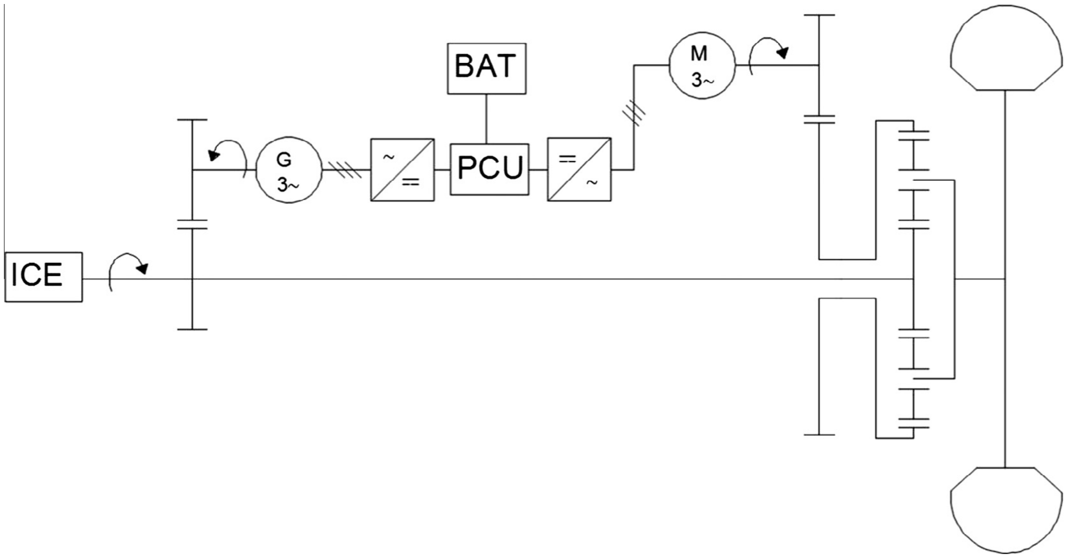

Fig. 7. Input-coupled power-split continuously variable transmission, for hybrid-electric and plug-in hybrid electric tractors.

Table 2
Diesel-electric and hybrid electric tractors.

Tractor	Primary power source	High voltage battery	Powertrain architecture	Degree of hybridization	Reference
Belarus *3023*	Diesel engine	No	Series CVT with one traction motor		[65,67]
John Deere *7430/7530 E-Premium*	Diesel engine	No	Conventional	Micro hybrid (480 V AC engine auxiliaries)[a]	[36]
Rigitrac *EWD 120-Diesel Electric*	Diesel engine	No	Series CVT with four traction motors, one per wheel		[63]
New Holland *NH2*™	Hydrogen fuel cell	Yes (300 V, Li-ion)	CVT with one traction motor	Fuel cell hybrid electric vehicle	[76]

[a] Namely, the radiator fan and the A/C compressor (while the water pump is driven by a 12 V DC motor).

negative – braking – torque is because it is generating electricity. The electric machine operating as a generator charges battery by regenerative braking or absorbing engine power when engine output is greater than that required to drive the wheels [79].

Hoy et al. [80] discussed the possibility of adding GPS information to the powertrain management system. With respect to hybrid tractor energy storage, this would allow to draw energy from the batteries before start climbing a slope, taking into account that when descending the slope regenerative braking would recharge the batteries.

Apart from fuels (hydrocarbons, biofuels, hydrogen), there are several ways to store energy on-board a HEV, namely electrochemical batteries, ultracapacitors or supercapacitors, and flywheel (Fig. 8). The Ragone chart plots power density against energy density for different energy buffers. In this chart, supercapacitors and batteries plot in different regions; while supercapacitors feature high power density and low energy density, the opposite is true for batteries.

Within electrochemical batteries, Pb-acid, Ni-metal hydride (Ni-MH), and Li-ion must be mentioned as proven technologies. Mousazadeh et al. [81] compared these technologies with regard to their specific energy, efficiency, self-discharge, charge-discharge cycles, and cost. From their work it follows that Li-ion is the best battery to date, surpassing the remainder technologies in all parameters – except as to charge speed where the Pb-acid battery proved superior. In the last years, graphene and its applications

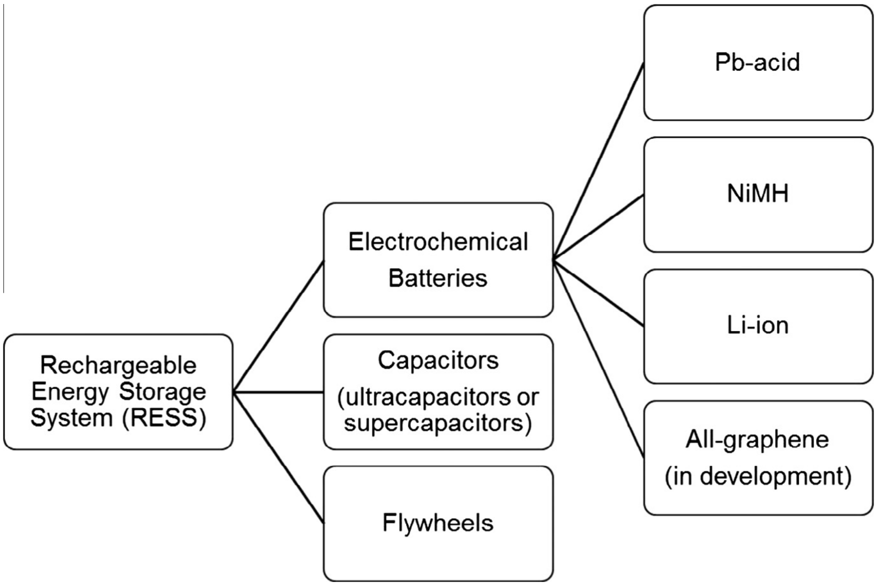

Fig. 8. Energy storage technologies for electric-drive vehicles. MH stands for metal hydride.

has become a hot topic of research. One important application of graphene is in improving batteries performance. Kucinskis et al. [82] highlighted that graphene improves electron conductivity of Li-ion battery cathode materials. Kim et al. [83] proposed the *all-graphene* battery, made with graphene in both the anode and the cathode, as a promising advanced energy storage system.

Hydrogen has been identified as an energy vector that can help to reduce greenhouse gas emissions when used for electrical propulsion [17]. For successful commercialization of hydrogen-powered vehicles, hydrogen storage is a critical enabling technology [84]. There are several candidate technologies to store H_2 on-board a vehicle. According to Durbin and Malardier-Jugroot [85] they can be classified into mechanical storage (compression, cryogenic cooling and cryo-compression), chemical hydrides, and adsorption materials. Noteworthy, hydrogen fueled to the fuel cell must be of very high purity, otherwise the fuel cell can be 'poisoned'.

The most straightforward way of obtaining H_2 for on-board fuel cell is by direct refueling. However, until enough H_2 refueling stations are available, a provisional trade-off exists, *viz.* the installation of on-board *reformers*. A *reformer* generates H_2 from a conventional hydrocarbon fuel, namely diesel-fuel or gasoline. Nevertheless, *reformation* cannot be considered a sustainable technology, because a vehicle equipped with a reformer produces CO_2 emissions, unlike a FCV directly refueling H_2, which only emits water vapor. According to Thounthong et al. [86], the gas produced from a reformer contains about 70–75% H_2, 20–25% CO_2, and 10–100 ppm CO.

The fuel cell provides more electricity per mass of fuel than any other non-nuclear method of power generation [87]. Although fuel cell systems still suffer certain drawbacks as their limited lifetime, high cost and the hydrogen storage and distribution infrastructure, they are able, compared to a diesel-engine vehicle with a conventional transmission to reduce fuel consumption by almost one-third [32].

3. High voltage electrification of implements and self-propelled harvesters

Incorporation of low voltage electric drives in agricultural implements has increased in the last years. For example, planter manufacturer Kinze offers electric drive option in their *4900* series. The major functionality of this electric drive is that allows maintaining consistent seed spacing from the inside row of the planter to the outside when planting on curves. Furthermore, noise associated to mechanical elements like hexagonal shafts, chains, sprockets, gears or clutches is eliminated.

Electrification of agricultural machinery can save energy through more efficient power transfer and through accurate control of seed and chemicals application [80]. For example, in the *UX eSpray* trailed sprayer by Amazone, the decoupling of implement drives from the tractor engine allows for their precise individual control. As a result, the spray liquid circuit can be separated from the fresh water circuit to a large extent [88]. Karner et al. [89] conducted a survey among Austrian manufacturers of agricultural machinery, to inquire about their interest in electric-driven machinery. About one-third of them could develop a prototype within the following five years, another one-third would remain expectant to competitor's activities, and the remainder one-third did not show interest on the subject. From the one-third manufacturers that would develop a prototype, 47% of them were interested in electric drives due to efficiency reasons, while the remainder 53% was interested due to increased functionality reasons.

There are several manners to provide a portable high voltage grid whereto connect a high voltage agricultural implement. One is equipping the tractor with a high voltage engine-driven generator and electric power interfaces at the tractor rear side. Another is to equip the implement with its own high voltage generator, powering it from the tractor PTO. A third one would be to mount a portable generator on the three-point front hitch of the tractor. Nonetheless the latter option is inconvenient, as it makes the front hitch unavailable for an eventual front implement. Furthermore, in the third case a long power cable would have to be installed from the front- hitch-mounted generator to the rear hitch-mounted implement.

Götz et al. [90] and Rahe et al. [91] reported on field tests of electrified tractor and implement. The framework was a research project which main objectives were to supply electric energy for engine auxiliaries and for an electrified implement, by means of a 50 kW permanent magnet synchronous generator powered by the tractor 164 kW engine. The engine auxiliary was the radiator fan, powered by a 400 V–15 kW motor. The implement was an Amazone single-grain *EDX eSeed* pneumatic-planter equipped with two 3$\sim$ 400 V–11 kW motors. The implement motors drove two fans, one for the fertilizer application system and the other for the seed. Due to reduction of fan speed at headlands, energy consumption was 30% lower than in the conventional machine i.e. when the fans are powered by hydraulic motors.

Rauch [92] compared the efficiency of four fertilizer spreading disc drive systems, namely mechanical, hydraulic connected to tractor remote control valves, the hydraulic so-called ‘power-beyond’, and electric. The latter consisted of two 3∼ 480 V–13 kW motors, spinning at 5000 r/min. He concluded that electric drive equaled efficiency of mechanical drive at maximum disc torque, whereas it surpassed efficiency of mechanical and the two types of hydraulic drive at any lower value of disc torque. Another advantage of electric drive is that the spreading discs could be shut down more quickly, thanks to the electrical braking of disc electric motors.

Küpfer and Leu [93] addressed the shortcoming of film tearing in the wrapping unit of a round baler. They stated that film viscosity changes with ambient temperature, and that suitable torque should be exerted during bale wrapping to avoid film tearing. They argued that electric drive can be more finely controlled than hydraulic drive. For example, if torque changes the baler could be halted within 450 ms, avoiding film tears. Biziorek [94] patented a round baler with electrically driven roller, and with the motor inside the roller. Motor speed was adjustable and direction of rotation could be reversed. The different rotation directions of the roller and thus of the bale during baling and wrapping would avoid the risk of unwinding the twine or other wrapping material during bale unloading, since the latter would roll out off the machine in the same direction as it rotates during wrapping. Another advantage is that the roller and the bale could be smoothly accelerated in a start phase after ejection of the previous bale.

Productivity improvement in combine harvesters relies upon increase of maximum feed rate at given grain quality parameters and improving functionality in order to decrease specific power requirements. Feed rate increase based upon an increase of the threshing unit width is limited by road traffic legal restrictions. Favache [95] designed a drive with the motor inside the threshing roller. With this design, the throughput of the machine was maximized for a given width, since the lateral space required for conventional mechanical transmission is saved.

Combine harvesters require a large amount of main and ancillary drives. The number of transmission elements, which can be a measure of the machine complexity, can be reduced by 60% by using electrical drives [96]. According to Bernhard and Schlotter [97], if combine harvester drives were electrified the weight and cost of the machine will rise. Weight increase is undesirable in agricultural machines because it increases soil compaction. On the positive side drives could be controlled separately and fuel consumption could be reduced.

Scheidler et al. [98] argued on the benefits of driving electrically the combine harvester unloading auger. For example, it might be possible upon engagement of the motor to rock the shaft back and forth slightly to initiate movement of the grain. Further, current feedback from inverter to motor could be used as an indicator of grain unloading rate to increase auger speed as the tank empties. Bernhard and Schreiber [99] argued that considering P/W average value for electric motors, the mass of the components of the electric drive train is six times higher than the mass of the hydraulic components. But compared to the total mass of the combine harvester, this additional mass only represents a 3%.

Bernhard and Kutzbach [100] installed an electronic-controlled hydrostatic series CVT wheel-drive train and an electric series CVT wheel-drive train in the same combine harvester. The objective was to do comparative performance field tests between the two CVTs possible. The hydrostatic powertrain was comprised of a variable displacement pump and a variable displacement hydraulic motor. With regard to the electric powertrain, the generator was a permanent magnet synchronous machine, and the motor was an induction machine. Aumer et al. [101] estimated overall combine harvester efficiency of 72–82% for electrical propulsion and 40–68% for hydrostatic propulsion, respectively. Scheidler and Pine [38] patented a mild-hybrid electric powertrain to propel a combine harvester. Whenever engine speed would drop, the M/G would support the engine, drawing electric energy from a battery pack.

Gallmeier [102] developed a hybrid-electric driveline for powering the header and intake of a self-propelled forage harvester. He compared fuel consumption of the hydraulic baseline harvester with the hybrid-electric prototype. He obtained that energy efficiency of the electric driveline was 23.3% better than hydraulic powertrain during the typical load cycle.

AGCO developed a diesel-electric self-propelled sprayer [103]. This prototype featured four electric in-wheel motors, each one of 84 kW. The water-cooled electric generator produced 200 kW at 1500 r/min, or 240 kW at 1900 r/min. The 650 V DC output from the generator was converted to 3∼ supply for the in-wheel motors. The prototype included a high power resistor to drop system voltage to zero in 4 s after engine switching-off. In 2010, AGCO compared the performance of this prototype with its conventional counterpart at a research farm in USA. Both sprayers worked at 19 km/h and 29 km/h on level fields and on slopes of up to 10%. Each machine sprayed 36 ha four times. Fuel consumption was measured via CANbus and by refuelling at the end of each test. In early summer 2010 the diesel-electric sprayer consumed 20–30% less fuel than the conventional sprayer, whereas in autumn it consumed about 25–30% less. In spite of aforementioned benefits, the diesel-electric prototype had a shortcoming: it weighed approximately 800 kg more than its conventional counterpart.

Breu [104] compared the cost of the *inverters on the tractor* (Fig. 3a) and *inverters on the implement* (Fig. 3b) topologies, for an electric-driven implement featuring two 10 kW motors. Assuming an inverter unit cost of 300–600 € for the two inverters, ascribable to the *inverters on the implement* configuration, and being 0 € the cost ascribable for this entry to the *inverters on the tractor* topology, he nonetheless estimated a slightly lower overall cost for the *inverters on the implement* architecture. Thus, the overall cost was of 850 € for the latter case, whereas for the *inverters on the tractor* topology the cost was of 900 €. The reason is that the latter configuration carries higher costs in the cable harness and interfaces entries.

4. Potential applications and future trends

High voltage electrification of ground vehicles like agricultural machinery is in the focus of current research and development [105]. Ponomarev et al. [106] stated that to be competitive, manufactures should offer energy efficient hybrid vehicles to customers. Compared to automobiles, introduction of electric drives in tractors would allow expanded functionalities, since agricultural machines have a large variety of functional drives [35]. Fig. 9, partially based on Pohlandt and Geimer [107], sums-up some *pros* and *cons* of electric and hydraulic powertrains.

The duty cycle of a vehicle is highly correlated with its ability to recover energy [108]. Urban driving adapts very well to energy recovery, due to frequent acceleration and stops. Construction machines with repetitive movements, like excavators, are able to recover kinetic energy too. For agricultural tractor and machinery, two tasks have been identified to date [109] wherein energy recovery is possible: Transportation and front loading [110,111]. Furthermore, self-propelled tree-trunk-shakers have a duty cycle somehow similar to telescopic handlers. Therefore it seems reasonable to think that self-propelled trunk-shakers have potential to be hybridized.

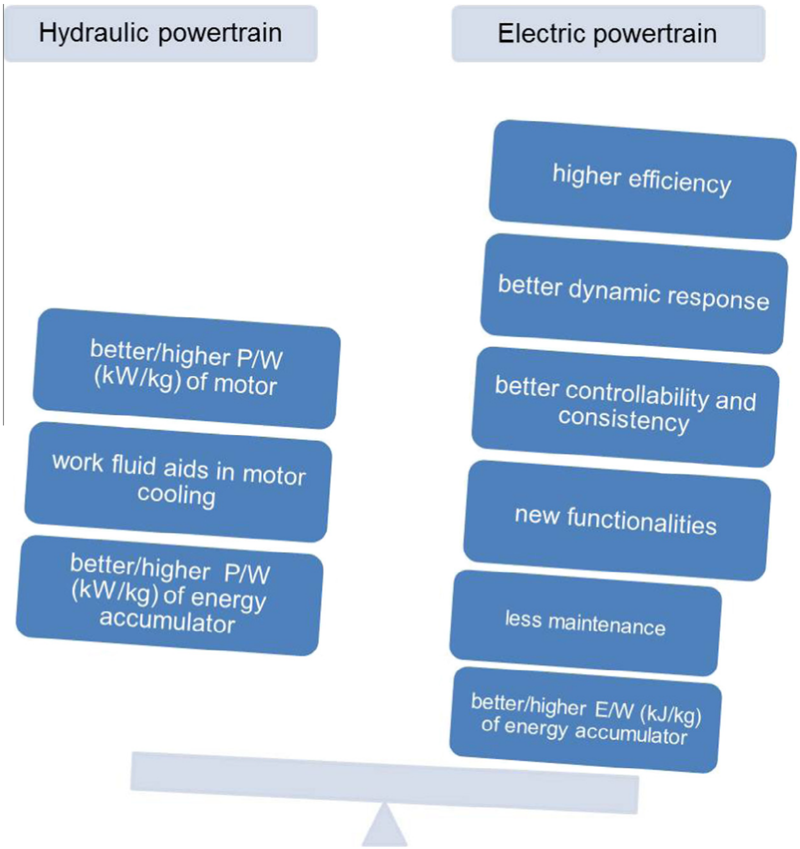

Fig. 9. Merit points of both hydraulic and electric powertrains.

The energy efficiency of a vehicle powertrain depends, amongst other features, on the size of its components. For example, the rated efficiency of a four-pole 0.37 kW induction motor fed with 400 V AC–50 Hz is 72%, whereas for a 37 kW motor of the same type and similarly fed the rated efficiency is 92.5%. Likewise, reciprocating engine efficiency increases with increasing cylinder displacement. Hence, it is sound to study the optimal dimensions of the components that minimize fuel consumption for a given duty cycle [112]. For instance, Ebbesen et al. [113] addressed the optimization problem of sizing the electric motor, engine and battery, such that fuel consumption is minimized while performance and cost specifications are met.

Motors, power control electronics, energy storage devices and energy management are key technologies for successful design of HEVs (Fig. 1). Although the permanent magnet synchronous motor[5] is considered the benchmark, other types of motors are being explored for their use in HEVs. Nowadays there is some concern on the supply and cost of rare-earth permanent magnet, and research is being conducted on electric motors with zero or with little of that material [16,50,114]. For instance, Tesla electric vehicles use induction motor, while electric Land Rover *Defender 110* uses switched reluctance motor. According to Ehsani et al. [115] one shortcoming of the latter motor type is its acoustic noise. Fig. 10 shows the electric motors that presumably will prevail in the forthcoming years,[6] whereas Table 1 includes their efficiency and power-to-weight ratio. Compared to hydraulics, electric drives provide better controllability and dynamic response, less maintenance and easier implementation of safety measures like quick stop [90]. Hydraulic power, like electric power, can be distributed quite easily on the implement, but hydraulics suffers from poor efficiency in part-load operating conditions [116].

According to Bernhard [117], for agricultural tractors, which need not to be accelerated very fast or have to change driving speed permanently, the use of traction batteries is not reasonable since their weight has to be transported all the time, while they can be used to recover braking energy quite seldom. One exception would be transportation with a loaded trailer on a hilly road. In this case, to maximize energy recovery, the use of engine braking is unadvisable [118] because it competes with regenerative braking. On the other hand, some kinetic energy could be recovered from implements PTO drivelines and from hydrostatic cylinders work load [89].

PHEVs are even more suitable topologies than HEVs for reducing fuel consumption in that, unlike HEVs, they may be charged from external electric power sources [119]. This offers the opportunity to use different high conversion efficiency technologies and/or renewable energy sources [120]. Generally, the simplest way to manage the energy distribution between the battery and the engine for a PHEV is to first use electricity to drive the vehicle, until the battery state-of-charge drops to a preset low-threshold, typically 30% [121]. To make recharging of automobiles easier, PHEVs are usually equipped with an on-board charger [122]. Charging vehicle batteries from the utility grid is straightforward, as the user only needs to connect a cable to the mains.

Several works in literature deal with optimization of HEV architecture and energy management [39,123,124]. In power-split CVT, planetary gear set kinematics ultimately affects to fuel economy, by determining the energy flow that reaches the planetary gear from each energy source (engine, generator, motor-battery). Because charging a battery from the machinery-building mains is

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[5] The propulsion motor equipped by the paradigmatic Toyota *Prius* HEV.

[6] The brushed DC motor is not considered because of its high maintenance requirements.

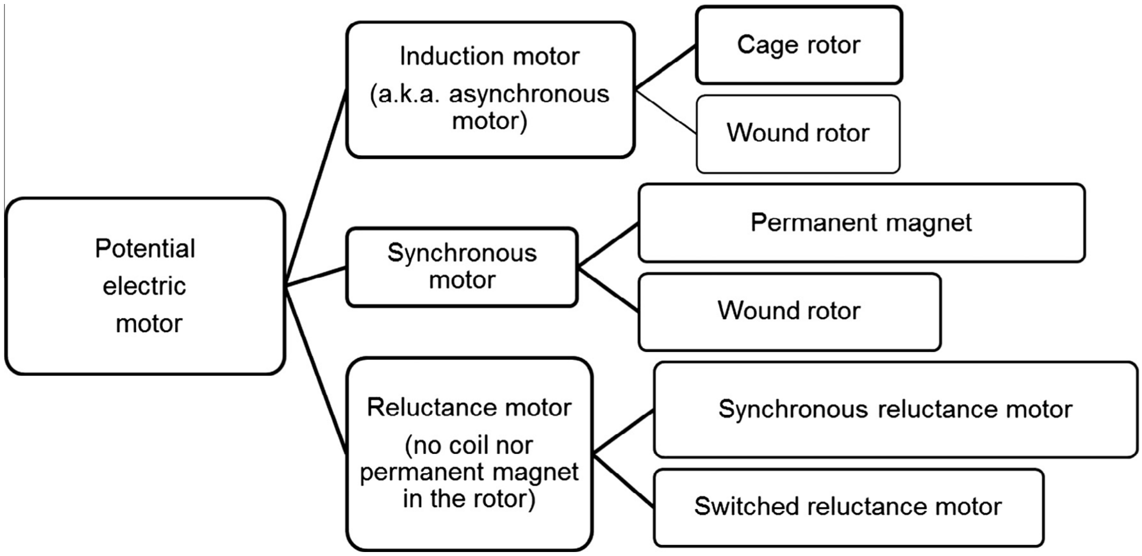

Fig. 10. Potential electric motors for use in tractor and agricultural machinery high voltage electrification.

more efficient than charging *via* tractor engine, it seems logical to hybridize the tractor with high voltage battery and propulsion motor. In this manner, the engine could be downsized, while the traction battery would be charged in the machinery-building during night. The following morning, the energy required for field operation would be drawn both from the engine and the battery. Fuel consumption costs would decrease, but the cost of high voltage equipment also play a role, what ultimately leads to machinery cost analysis.

Agricultural tractor needs to span a wide range of torque and speed. High torque is demanded in low speed heavy tasks like ploughing, while high speed is required for road transportation. To generate the required torque for a high drag force without using additional gears, electric propulsion motors would have to be of excessive diameter [125].[7] Montonen et al. [126] presented a space-saving concept based on the integration of a permanent-magnet-synchronous-motor and a two-step planetery gearbox. In this design, the planetary ring, sun and planets gears were inside the electrical machine rotor.

One of the main drawbacks of electric drives, namely their poor P/W compared to hydraulic drives, could be circumvented by adopting a controlled-traffic farming strategy. If a heavy electrified tractor-implement moves on tramlines, soil compaction would not be an issue. According to Karner et al. [35], the diesel-fuel will remain as the primary energy source for tractors and self-propelled agricultural machinery, thanks to its high energy density. On the other hand, the foregoing authors forecasted that the broad introduction of electric driven agricultural machinery could happen in the next five to 10 years.

Revision 2 of UNECE Regulation No. 100 [127] details safety requirements for the electric powertrain of road vehicles. While in a conventional diesel vehicle with a 12 V DC electrical system the main electrical hazard is arcing between the battery poles, in a high voltage system a new hazard arises, namely electrical shock.

The X-Concept prototype tractor by Fendt [128] includes safety measures analogous to those of the paradigmatic HEV Toyota Prius. In the latter, when the vehicle is shut-off, two 12 V-controlled relays – one for the positive and the other for the negative high voltage cable – prevent current from leaving the high voltage battery pack. Unlike the negative cable in conventional automobile electrical system, both positive and negative high voltage cables are insulated from the vehicle metal chassis. Moreover, a ground fault monitor continuously monitors for high voltage leakage to the metal chassis while the vehicle is in operation [129].

5. Conclusions

In this paper, the main concepts and technologies related to high voltage electrification of tractor and agricultural machinery have been reviewed. The following conclusions can be drawn:

- Both hydraulic and electric powertrains allow for more flexible design than mechanical driveline. Hybridization, i.e. incorporation of an on-board high voltage battery, adds an extra degree of freedom, since propulsive power in a hybrid vehicle can be drawn either from the fuel or from the battery.
- A number of works in the literature report higher efficiency of electric powertrains over hydraulics in agricultural machinery.
- Tractor and agricultural machinery have the opportunity of following the path opened by automobiles and construction machinery with regard to energy recovery and vehicle hybridization. Detailed analyses are required to identify potential operations where energy recovery is possible within agricultural machinery.
- A plug-in hybrid electric tractor with power-split or series CVT operating in a controlled traffic farming strategy seems promising. Tractor high voltage batteries could be charged from machinery-building mains at night. The following morning, energy required for the field task would be drawn both from fuel and battery. Analyses of the cost of owning and operating agricultural machinery should be conducted to compare various conventional *vs.* electrified tractor-implement combinations.
- Although it is difficult to foresee the pace of introduction of high voltage drives in agricultural machinery, 'something is moving'. In the past, introduction of hydraulic power transmission from tractor to implements did not supersede PTO. Similarly, incorporation of high voltage powertrains will co-exist with PTO and hydraulics.

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[7] For example, the torque of induction motor varies quadratically with motor diameter and linearly with motor length.

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References

[1] Faria R, Moura P, Delgado J, de Almeida AT. A sustainability assessment of electric vehicles as a personal mobility system. Energy Convers Manage 2012;61:19–30.

[2] Willems F, Foster D. Integrated powertrain control to meet future CO$_2$ and Euro-6 emissions targets for a diesel hybrid with SCR-deNOx system. In: 2009 American control conf St. Louis, Mo., USA, June 10–12, 2009; 2009. p. 3944–9. Paper No. FrA01.2.

[3] Borgui M, Zardin B, Pintore F, Belluzi F. Energy savings in the hydraulic circuit of agricultural tractors. Energy Proc 2014;45:352–61.

[4] Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO$_2$ emissions from light-duty vehicles. Off J Eur Union L140/1. 5/6/2009.

[5] Council Directive 91/441/EEC of 26 June 1991 amending Directive 70/220/EEC on the approximation of the laws of the Member States relating to measures to be taken against air pollution by emissions from motor vehicles. Off J Eur Communities L242. 30/8/1991.

[6] Moya A, Barreiro P. Recortar emisiones en vehículos agrícolas-Introducción del Tier 4: camino hacia las cero emisiones en vehículos todoterreno. Tierras 2011;176:88–94.

[7] Fiebig M, Wiartalla A, Holderbaum B, Kiesow S. Particulate emissions from diesel engines: correlation between engine technology and emissions. J Occup Med Toxicol 2014;9:6.

[8] Clark NN. NO$_x$/fuel tradeoff for powertrain technologies. In: Heavy-duty vehicle efficiency technical workshop. San Francisco, Caifl., USA. October 22, 2013. Available at: <http://www.theicct.org/sites/default/files/Nigel%20Clark%20-%20NOx%20Fuel%20Tradeoff.pdf>; 2013 [accessed: 8/1/2016].

[9] Reitz RD, Duraisamy G. Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. Prog Energy Combust 2015;46:12–71.

[10] Du J, Sun W, Guo L, Xiao S, Tan M, Li G, et al. Experimental study on fuel economies and emissions of direct-injection premixed combustion engine fueled with gasoline/diesel blends. Energy Convers Manage 2015;100:300–9.

[11] Pali HS, Kumar N, Alhasan Y. Performance and emission characteristics of an agricultural diesel engine fueled with blends of Sal methyl esters and diesel. Energy Convers Manage 2015;90(146):153.

[12] Ettl J, Thuneke K, Remmele E, Emberger P, Widmann B. Future biofuels and driving concepts for agricultural tractors. In: 22nd European biomass conf & exhib. Hamburg, Germany; 2014.

[13] Flórez-Orrego D, Silva JAM, de Oliveira Jr S. Exergy and environmental comparison of the end use of vehicle fuels: the Brazilian case. Energy Convers Manage 2015;100:220–31.

[14] Xu-Guang T, Hai-Lang S, Tao Q, Zhi-Qiang F, Wen-Hui Y. The impact of common rail system's control parameters on the performance of high power diesel. Energy Proc 2012;16:2067–72.

[15] Cwikowski P, Teodrorcyck A. The latest achievements in gasoline and diesel injection technology for the internal combustion engines. J KONES Powertrain Transp 2009;16(2):79–90.

[16] Kiyota K, Kakishima T, Chiba A. Comparison of test result and design stage prediction of switched reluctance motor competitive with 60-kW rare-earth permanent magnet motor. IEEE Trans Ind Electron 2014;61(10):5712–21.

[17] Kelouwani S, Agbossov K, Dubé Y, Boulon L. Fuel cell plug-in hybrid electric vehicle anticipatory and real-time blended-mode energy management for battery life preservation. J Power Sources 2013;221:406–18.

[18] Lv C, Zhang J, Li Y, Yuan Y. Novel control algorithm of braking energy regeneration system for an electric vehicle during safety-critical driving maneuvers. Energy Convers Manage 2015;106:520–9.

[19] Ao GQ, Qiang JX, Zhong H, Mao XJ, Yang L, Zhuo B. Fuel economy and NO$_x$ emission potential investigation and trade-off of a hybrid electric vehicle based on dynamic programming. Proc Inst Mech Eng Part D: J Automob Eng 2008;222(10):1851–64.

[20] Janulevičius A, Juostas A, Pupinis G. Tractor's engine performance and emission characteristic in the process of ploughing. Energy Convers Manage 2013;75:498–508.

[21] Miller JM, Goel D, Kaminski D, Shöner HP, Jahns TM. Making the case for a next generation automotive electrical system. In: Proc intl conf on transportation electronics. SAE; 1998. p. 41–51.

[22] SAE Intl. SAE J1715. Information report, hybrid vehicle (HEV) and electric vehicle (EV) terminology; October 2014.

[23] Demirdöven N, Deutch J. Hybrid cars now, fuel cell cars later. Science 2004;305:974–6.

[24] Simpson A. Cost-benefit analysis of plug-in hybrid electric vehicle technology. NREL/CP-540-40485. Presented at the 22nd intl battery, hybrid & fuel cell electric vehicle symp & exhib (EVS-22). Yokohama, Japan; October 23–28, 2006.

[25] Walkowicz K, Lammert M, Curran P. Coca-Cola refreshments class 8 diesel electric hybrid tractor evaluation: 13-month final report. Technical report NREL/TP-5400-53502; 2012.

[26] Barnitt RA. In-use performance comparison of hybrid electric, CNG, and diesel buses at New York City Transit. NREL/CP 540-42534. In: 2008 SAE intl powertrains, fuels & lubricants conf. Shanghai, China; 2008.

[27] Shea T. Terex 33-19 Titan. Hemmings Motor News; 2012 [May 2012].

[28] Chadwick J. Surface haul trucks: picking the best truck options. Int Min 2010 [June 2010].

[29] Johnson KC, Burnette A, Cao T, Russell RL, Scora G. Hybrid off-road equipment in-use emissions evaluation. FY 2010-11 air quality improvement project. Hybrid off-road equipment pilot project. California Air Resources Board; 2013.

[30] Filla R. Alternative system solutions for wheel loaders and other construction equipment. In: First intl CTI forum alternative & hybrid drive trains. Berlin, Germany; 2008.

[31] Aumer W, Lindner M, Geiβler M, Herlitzius T. Electric tractor: vision or future? Landtechnik 2008;63(1):14–5.

[32] Tritschler PJ, Bacha S, Rullière E, Husson G. Energy management strategies for an embedded fuel cell system on agricultural vehicles. In: XIX intl conf on electrical machines, ICEM 2010. Rome: IEEE; 2010.

[33] Prankl H, Nadlinger M, Demmelmayr F, Schrödl M, Colle T, Kalteis G. Multi-functional PTO generator for mobile electric power supply of agricultural machinery. In: Intl conf on agricultural engineering, AgEng. 2011 Hannover. VDI Berichte 2124; 2011.

[34] Wuebbels R. Machine for harvesting stalk-like plants with an electrically driven cutting mechanism. US Patent 0174552 A1; 2012.

[35] Karner J, Baldinger M, Schober P, Reichl B, Prankl H. Hybrid systems for agricultural engineering. LandTechnik 2013;68(1):22–5.

[36] Stoss KD, Sobotzik J, Shi B, Kreis ER. Tractor power for implement operation – mechanical, hydraulic and electrical: an overview. In: Agricultural equipment technology conf. ASABE distinguished lectures series, vol. 37. p. 1–25; 28–30 January, 2013. ASABE Publ. no. 913C0113.

[37] Laguens M. Potential for energy savings through hybridization of agricultural tractors. Engineering degree dissertation, Madrid: Tech. Univ.; 2014.

[38] Scheidler AD, Pine SR. Battery electric hybrid drive for a combine harvester. EP 2 778 003 A1. European Patent; 2014.

[39] Rossi C, Pontara D, Casadei D. E-CVT power split transmission for off-road hybrid electric vehicles. Vehicle power & propulsion conf (VPPC) Coimbra, Portugal. IEEE; 2014.

[40] Zhitkova S, Felden M, Franck D, Hameyer K. Design of an electrical motor with wide speed range for the in-wheel drive in a heavy duty off-road vehicle. In: Intl conf electrical machines (ICEM), 2–5 September. Berlin, Germany; 2014. p. 1076–82.

[41] Buning EA. Electric drives in agricultural machinery – approach from the tractor side. In: Key note report. 21st Ann meeting of the club of Bologna. Bologna, EIMA Intl, November 13–14; 2010.

[42] UNECE. Working party on transport statistics. Definitions of vehicle energy types. ECE/Trans/WP.6/2011/5; 2011.

[43] Nemry F, Leduc G, Muñoz A. Plug-in hybrid and battery electric vehicles: state of the research and development and comparative analysis of energy and cost efficiency. JRC tech notes. European Commission JRC-IPTS; 2009.

[44] Lee SC, Kwon O, Thomas S, Park S, Choi GH. Graphical and mathematical analysis of fuel cell/battery passive hybridization with K factors. Appl Energy 2014;114:135–45.

[45] Zhao H, Burke A, Miller M. Comparison of hybrid fuel cell vehicle technology and fuel efficiency. Institute of Transportation Studies. UC Davis. Research Report UCD-ITS-RR-11-10; 2011.

[46] Vanderwerp D. Caterpillar D7E – feature test. Car&Driver August 2010. Available at: <http://www.caranddriver.com/reviews/caterpillar-d7e-feature-test>; 2010.

[47] Achten PAJ. A serial hydraulic hybrid drive train for off-road vehicles. In: Intl exposition for fluid power, IFPE 2008 tech conf Las Vegas, Nev., USA; 2008. p. 515–21.

[48] Rydberg KE. Energy efficient hydraulic hybrid drives. In: The 11th Scandinavian intl conf on fluid power, SICFP'09, June 2–4, Linköping, Sweden; 2009. p. 1–14.

[49] Chan CC. The state of the art of electric, hybrid, and fuel cell vehicles. Proc IEEE 2007;95(4):704–18.

[50] Boldea I, Tutelea LN, Parsa L, Dorrell D. Automotive electric propulsion systems with reduced or no permanent magnets: an overview. IEEE Trans Ind Electron 2014;61(10):5696–711.

[51] Somà A, Bruzzese F, Viglietti E. Hybridization factor and performances of hybrid electric telescopic heavy vehicles. In: 10th Intl conf ecological vehicles renewable energies (EVER). March 31 2015–April 2 2015. Monte Carlo, Monaco: IEEE; 2015. 9p.

[52] Mitchell T, Salah M, Wagner J, Dawson D. Automotive thermostat valve configurations: enhanced warm-up performance. J Dyn Syst Meas Contr 2009;131. 044501-1.

[53] Hahn K. High voltage electric tractor-implement interface. SAE Int J Commer Veh 2008;1(1):383–91.

[54] Mohsenimanesh A, Laguë C, Luo C, Habash RWY. Electric multi-motor drives with improved induction machine for agricultural wide-span implement carrier (WSIC). In: ASABE & CSBE/SCGAB ann intl meeting. Montréal, Québec Canada. July 13–16; 2014. Paper no. 141893614.

[55] Pessina D, Facchinetti D. Gemelli diversi. Macchine Agricole luglio 2009;2009:44–51.

[56] Keil R, Shi B, Sobotzik J. JD 6210RE-tractor/implement electrification and automation. Antriebsysteme 2013-Elektrik, Mechanik und Hydraulik in der Anwendung. VDE Verlag; 2013.

[57] Singh BN, Wanner KD, Vilar ZW. Novel and ruggedized power electronics for off-highway vehicles. IEEE Electrification Magazine, June 2014; 2014. p. 31–41.

[58] Yu S, Du Q, Diao H, Shu G, Jiao K. Effect of vehicle driving conditions on the performance of thermoelectric generator. Energy Convers Manage 2015;96:363–76.

[59] Emadi A, Lee YJ, Rajashekara K. Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. IEEE Trans Ind Electron 2008;55(6):2237–45.

[60] Hofman T, Steinbuch M, van Druten R, Serrarens AFA. Design of CVT-based hybrid passenger cars. IEEE Trans Veh Tech 2009;58(2):572–87.

[61] Shabbir W, Evangelou SA. Efficiency analysis of a continuously variable transmission with linear control for a series hybrid electric vehicle. In: 19th World congress. The intl federation of automatic control. Cape Town, South Africa; 2014.

[62] Romero S. Analysis of a light permanent magnet in-wheel motor for an electric vehicle with autonomous corner modules. KTH, School of Electrical Engineering. Master thesis; 2011. 103p.

[63] Herlitzius T. Rigitrac EWD 120-Diesel electric. Tecnische Universität Dresden. Available at: <http://tu-dresden.de/die_tu_dresden/fakultaeten/fakultaet_maschinenwesen/ifvlv/landmaschinen/forschung/files/flyer_rigitrac.pdf>; 2011.

[64] Husson G, Shute M, Menier G. Tractor with hybrid power system. US Patent 0047753 A1; 2013.

[65] Florentsev S, Izosinov D, Makorov L, Baida S, Belousov A. Complete traction electric equipment sets of electro-mechanical drive trains for tractors. In: IEEE region & SIBIRCON. Irkutsk, Russia; 2010.

[66] Geiβler M, Osinenko P, Scholz J. Potentials of vehicle dynamics and slip control for mobile machinery enabled by an electric 4WD. In: Fourth Colloquium on Elektrische Antriebe in der landtechnik. Wieselburg, Austria; June 2013.

[67] Puhovoy AA. Agricultural tractor with pure electromechanical drivetrain. SAE Int J Commer Veh 2011;4(1):275–85.

[68] Farkas ZJ. Analysis and simulation of power split continuously variable transmissions. Ph. D. Dissertation. Budapest University of Technology and Economics; 2013.

[69] Renius KT, Resch R. Continuously variable tractor transmissions. In: ASAE distinguished lecture no. 29; 2005. p. 1–37. ASAE Publ. number 913C0305.

[70] Farkas Z, Kerényi G. Power flows and efficiency analysis of out- and input coupled IVT. Mech Eng 2009;53(2):61–8.

[71] Linares P, Méndez V, Catalán H. Design parameters for continuously variable power-split transmissions using planetaries with 3 active shafts. J Terramech 2010;47:323–35.

[72] Rossi C. E-CVT power split transmission for hybrid-electric vehicles. In: Vehicle power & propulsion conf (VPCC), 2013 IEEE, 15–18 October. Beijing, China: IEEE; 2013. p. 1–8.

[73] Barucki T. Experiences with a test-bench for a diesel-electric tractor drive train. In: AgEng 2000. Warwick, UK; 2000. Paper no. 00-PM-025.

[74] Barucki T. Layout and optimizing of electric drive for tractors. Landtechnik 2001;56(2):436–40.

[75] Fuel Cells Bulletin. Hydrogen-powered tractor unveiled at Paris show. Fuel Cells Bull 2009 [February].

[76] Fuel Cells Bulletin. New Holland NH2 fuel cell powered tractor. Fuel Cells Bull 2012:3 [January].

[77] Gallmeier M, Auernhammer H. Towards electric drive lines in mobile equipment. In: AgEng 2004. Leuven, Belgium; 2004.

[78] Osinenko PV, Geisler M, Herlitzius T. A method of optimal traction control for farm tractors with feedback of drive torque. Biosyst Eng 2015;129:20–33.

[79] Katrasnik T. Hybridization of powertrain and downsizing of IC engine – a way to reduce fuel consumption and pollutant emissions – Part I. Energy Convers Manage 2007;48:1411–23.

[80] Hoy R, Rohrer R, Liska A, Luck J, Isom L, Keshwani D. Agricultural industry advanced vehicle technology: benchmark study for reduction in petroleum use. Idaho National Laboratory; 2014.

[81] Mousazadeh H, Keyhani A, Javadi A, Mobli H, Abrinia K, Sharifi A. Evaluation of alternative battery technologies for a solar assist plug-in hybrid electric tractor. Transport Res Part D 2010;15:507–12.

[82] Kucinskis G, Bajars G, Kleperis J. Graphene in lithium ion battery cathode materials: a review. J Power Sources 2013;240:66–79.

[83] Kim H, Park K-Y, Hong J, Kang K. All-graphene battery: bridging the gap between supercapacitors and lithium ion batteries. Sci Rep 2014;4:5278.

[84] Satyapal S, Petrovic J, Read C, Thomas G, Ordaz G. The U.S. department of energy's national hydrogen storage project: progress towards meeting hydrogen-powered vehicle requirements. Catal Today 2007;120:246–56.

[85] Durbin DJ, Malardier-Jugroot C. Review of hydrogen storage techniques for on board vehicle applications. Int J Hydrogen Energy 2013;38:14595–617.

[86] Thounthong P, Chunkag V, Sethakul P, Davat B, Hinaje M. Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device. IEEE Trans Veh Tech 2009;58(8):3892–904.

[87] Tseng C-J, Tsai B-T, Liu Z-S, Cheng T-C, Chang W-C, Lo S-K. A PEM fuel cell with metal foam as flow distributor. Energy Convers Manage 2012;62:14–21.

[88] Amazone. UX eSpray trailed sprayer. Available at: <http://info.amazone.de/DisplayInfo.aspx?id=14005>; 2009 [accessed 11/1/2016].

[89] Karner J, Prankl H, Kogler F. Electric drives in agricultural machinery. In: CIGR AgEng 2012. Valencia, Spain; 2012.

[90] Götz M, Grad K, Weinmann O. Electrification of agricultural machinery. ATZoffhighway 2012;2:11–20.

[91] Rahe F, Wessels T, Weinmann O, Götz M. Field trials with EDX eSeed and ZF Terra+. In: Fourth Colloquium on Elektrische Antriebe in der landtechnik. Wieselburg, Austria; June 2013.

[92] Rauch N. Experiences and visions of an implement manufacturer. In: Key note report, 21st annual meeting of the club of Bologna. Bologna, EIMA Intl; November 13–14, 2010.

[93] Küpfer E, Leu A. Electric servodrives prove themselves in outdoor use. CAN Newslett 2013;4:38–9.

[94] Biziorek S. Round baler with electrically driven roller. EP 2 382 858 B1; 2012.

[95] Favache S. Harvesting machine with electrically driven material conveyor and/or material processing device. US Patent 0056262 A1; 2002.

[96] Herlitzius T, Aumer W, Lindner M, Bernhardt G, Kuß H, Michalke N, et al. Integration of an electrical drive into a tangential threshing cylinder. VDI-Berichte 2009;2060:495–500.

[97] Bernhard B, Schlotter VR. Electric drives for combine harvesters. In: Proc intl conf on crop harvesting and processing, 9–11 February, 2003. Louisville, Kentucky, USA; 2003.

[98] Sheidler AD, Musser JW, Finamore P. Vehicle with electric hybrid powering of external loads and engine off-capability. US Patent no. 0294191 A1; 2009.

[99] Bernhard B, Schreiber VR. Experimental comparison of ground drives for combine harvesters. Landtechnik 2005;60(2):82–3.

[100] Bernhard B, Kutzbach HD. Serial hybrid electric drive train for a combine harvester. In: AgEng 2002. Budapest, Hungary; 2002. Paper no. 02-PM-023.

[101] Aumer W, Lindner M, Geiβler M, Herlitzius T, Bernhardt G. Conceptual comparison of electrical and hydrostatic propulsion in combine harvesters. Landtechnik 2008;63(2):88–9.

[102] Gallmeier M. Comparative assessment of hydraulic and electric module drives for applicability in agricultural working machines. Ph D. Dissertation. Technische Universität Munchen; 2009.

[103] Neunaber M. Four motors=25% less fuel use. Profi 2011;7–8:24–7.

[104] Breu W. Design of a high voltage system for agricultural machines. In: Fourth Colloquium on Elektrische Antriebe in der landtechnik. Wieselburg, Austria; June 2013.

[105] Heckmann M, Gobor Z, Huber S, Kammerloher T, Bernhardt H. Design of a test bench for traction drive systems in mobile machines. Landtechnik 2013;68(6):415–9.

[106] Ponomarev P, Minav T, Aman R, Luostarinen L. Integrated electro-hydraulic machine with self-cooling possibilities for non-road mobile machinery. J Mech Eng 2015;61(3):207–13.

[107] Pohlandt C, Geimer M. Variable DC-link voltage powertrain for electrified mobile work machines. In: 2015 Intl conf on electrical systems for aircraft, railway, ship propulsion and road vehicles (ESARS), 3–5 March. Aachen: IEEE; 2015. p. 1–5.

[108] O'Keefe M, Simpson A, Kelly K, Pedersen D. Duty cycle characterization and evaluation towards heavy hybrid vehicle applications. SAE tech; 2007. Paper 2007-01-0302.

[109] Barthel J, Gorges D, Bell M, Munch P. Energy management for hybrid electric tractors combining load point shifting, regeneration and boost. In: Vehicle power & propulsion conference (VPCC), 2014 IEEE, 27–30 October. Coimbra, Portugal: IEEE; 2014.

[110] Somà A. Effects of driveline hybridization on fuel economy and dynamic performance of hybrid telescopic heavy vehicles. In: Proc technologies for high efficiency & fuel economy, 29–30 September. Rosemont (Ill USA): SAE; 2013.

[111] Somà A, Boso N, Merlo A. Electrohydraulic hybrid lifting vehicle. US Patent No. 8978800 B2; 2015.

[112] Torres O, Bader B, Romeral JL, Lux G, Ortega JA. Influence of the final drive ratio, electric motor size and battery capacity on fuel consumption of a parallel plug-in hybrid electric vehicle. 19th Intl conf urban transport environment. WIT Press; 2013.

[113] Ebbesen S, Elbert P, Guzzella L. Engine downsizing and electric hybridization under consideration of cost and drivability. Oil Gas Sci Technol – Rev IFP Energ Nouv 2013;68(1):109–16.

[114] Dorrell DG. Are wound-rotor synchronous motors suitable for use in high efficiency torque-dense automotive drives? In: Proc IEEE IECON 38th ann conf; 2012. p. 4880–5.

[115] Ehsani M, Gao Y, Miller JM. Hybrids electric vehicles: architecture and motor drives. Proc IEEE 2007;95(4):719–28.

[116] Karner J, Baldinger M, Reichl B. Prospects of hybrid systems on agricultural machinery. GSTF J Agric Eng 2014;1(1):33–7.

[117] Bernhard B. Hybrid drives for off-road vehicles. In: FISITA World automotive congress. Barcelona, Spain; 2004.

[118] Cikanek SR, Bailey KE. Regenerative braking system for a hybrid electric vehicle. In: Proc American control conference. Anchorage, Alaska, USA; May 8–10, 2002.

[119] He Y, Chowdhury M, Pisu P, Ma Y. An energy optimization strategy for power-split drivetrain plug-in hybrid electric vehicles. Transport Res Part C 2012;22:29–41.

[120] Angrisani G, Canelli M, Roselli C, Sasso M. Integration between electric vehicle charging and micro-cogeneration system. Energy Convers Manage 2015;98:115–26.

[121] Chen Z, Mi CC, Xiong R, Xu J, You C. Energy management of a power-split plug-in hybrid electric vehicle based on genetic algorithm and quadratic programming. J Power Sources 2014;248:416–26.

[122] Murgovski N, Johaneson L, Sjöberg J, Egardt B. Component sizing of a plug-in hybrid electric powertrain via convex optimization. Mechatronics 2012;22:106–20.
[123] Moura SJ, Fathy HK, Callaway DS, Stein JL. A stochastic optimal control approach for power management in plug-in hybrid electric vehicles. IEEE Trans Contr Syst Technol 2011;19(3):545–55.
[124] Li Y, Kar NC. Advanced design approach of power-split device of plug-in hybrid electric vehicles using dynamic programming. In: 2011 IEEE vehicle power & propulsion conf (VPCC), Chicago, Ill, USA; 6–9 September 2011. p. 1–6.
[125] Klimentew L, Krüger J, Meyer HJ. Influencing factors of the gearbox in efficiency of electrical traction drives. Landtechnik 2013;68(2):130–4.
[126] Montonen J, Sinkko S, Lindh P, Pyrhönen J. Design of a traction motor with two-step gearbox for high-torque applications. In: 2014 Intl conf on electrical machines (ICEM). Berlin, Germany; 2014.
[127] UNECE Regulation No. 100-Revision 2. Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train. Agreement 12 August 2013. Addendum 99: Regulation No. 100; 2013 (82p.).
[128] AGCO. Fendt X-Concept. Available at: <http://www.fendt.com/int/7710.asp>; 2014 [accessed: 8/1/2016].
[129] Toyota Motor Corp. Toyota Prius hybrid 2010 model 3rd generation. Emergency response guide. Available at: <https://techinfo.toyota.com/techInfoPortal/staticcontent/en/techinfo/html/prelogin/docs/3rdprius.pdf>; 2009 [accessed: 8/1/2016].

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