Article citation info:
KALOCIŃSKI, T. Modern trends in development of alternative powertrain systems for non-road machinery. *Combustion Engines*. 2022, **188**(1), 42-54. https://doi.org/10.19206/CE-141358

Tomasz KALOCIŃSKI

Combustion Engines
Polish Scientific Society of Combustion Engines

Modern trends in development of alternative powertrain systems for non-road machinery

ARTICLE INFO

Received: 29 July 2021
Revised: 11 August 2021
Accepted: 18 August 2021
Available online: 16 September 2021

The main goal of the paper is to review available alternative powertrain technologies for non-road machinery. Based on that, to propose adequate classification and recognise main trends within this area. The paper presents various powertrain propositions alternative to internal combustion engine and solely mechanical powertrain developed by manufacturers over a course of years. The article explains actual legislative situation regarding environmental challenges connected to the powertrain solutions and reiterates the need for development in that area. Both commercially available and only presented at fairs or at early development stages solutions have been analysed. Depending on the load conditions and work patterns multiple benefits as well as challenges to the reviewed concepts have been discussed. Certain classification of existing powertrain solutions have been proposed taking into account its design and functionality.

Key words: *powertrain technology, alternative drive, hybrid, agricultural, construction*

1. Introduction

Increasingly stringent environmental protection laws and reduction of fossil fuels dependency are the main objectives of modern economies. Development of new powertrain systems faces two major challenges. First is to increase working parameters of the powertrain with simultaneous reduction of fuel consumption and the second to stay compliant with current environmental protection laws. Very often these two conditions are contradictory to each other and are difficult to fulfill [1–4].

Continuous decrease of CO_2 emissions thus reduction of fuel consumption are the main drivers for search of new powertrain solutions. Some countries have introduced specific limits and presented specific laws focused on reduction CO_2 emission. The European Union also have introduced first CO_2 limit standards for example for passenger cars in 2009. In 2015 this limit was set at 130 g/km, and in 2020 at 95 g/km as an average emission calculated for new car fleet [5, 6].

For non-road machinery new Stage V emissions standards have been phased in already in 2018 in European Union. These regulations limit emission of CO, HC, NO_x, PM and PN [7, 8].

Multiple technologies have been put in place over last years to already meet previous limits, especially on NO_x and PM. Namely, high pressure common rail injection, cooled exhaust gas recirculation, diesel oxidation catalyst, selective catalytic reduction and exhaust particulate filter [9, 10].

Use of electric, electrified or hybrid drives can also significantly increase efficiency of powertrains and therefore reduce emissions. Moreover, introduction of mentioned solutions may expand vehicle flexibility and create new functionalities. Together with fast development of machine automatization, precision farming and use of satellite positioning system for farming operation continuously increase interest in alternative drives. Mainly due to ease control of speed and torque and due to system simplification in comparison to mechanical or hydraulic solutions [11, 12].

Starting at mid 1950s manufacturers have already tried alternative powertrain solutions, for instance: IH Farmall 450 with additional electric generator for power output or Allis-Chalmers with fuel cell powered tractor (Fig. 1). Later in 1970s, Terex presented Titan mining dump truck with diesel-electric powertrain. Mentioned examples of alternative solutions have not created significant demand and have been abandoned for next decades [13].

No.	Year	Manufacturer	Model	Alternative drive type	Energy store
1	1954	IH Farmall 450	IH ElectrAll	Electrified components	NO
2	1959	Allis-Chalmers	Fuel cell	FCEV	NO
3	1974	Terex	Titan	Diesel-electric	NO
4	1998	Eltrac/Schmetz GmbH	E135	Diesel-electric	NO
5	2005	IH Case	ProHybrid EECVT	HEV	YES
6	2007	John Deere	7430/7530 E premium	Electrified components	NO
7	2008	Caterpillar	D7E	Diesel-electric	NO
8	2009	Belarus	3023	Diesel-electric	NO
9	2010	Agco	ElectRoGator 1386	Diesel-electric	NO
10	2011	New Holland	NH2	FCEV	YES
11	2011	John Deere	6210 RE	Electrified components	NO
12	2011	Rigitrac	EWD 120	Diesel-electric	NO
13	2012	Komatsu	HB205-1	HEV	YES
14	2013	John Deere	644K	Diesel-electric	NO
15	2013	Merlo	40.7 Hybrid	PHEV	YES
16	2013	Fendt	X Concept	Electrified components	NO
17	2014	Belaz	75710	Diesel-electric	NO
18	2015	Multi Tool Track	N/A	REX	YES
19	2016	Claas	Arion 650 hybrid	HEV/electrified auxiliaries	YES
20	2016	John Deere	SESAM	BEV	YES
21	2016	Kramer	5055e	BEV	YES
22	2016	ZF	Terra +	Electrified components	NO
23	2017	Fendt	e100	BEV	YES
24	2017	Farmtrac	26E	BEV	YES
25	2018	John Deere	GridCON	Electric drive	NO
26	2019	Steyr	Konzept	PHEV	NO
27	2019	Rigitrac	SKE 50	BEV	YES
28	2019	John Deere	1RE	BEV	YES
29	2019	John Deere	Joker	BEV	YES
30	2019	John Deere	8370 eAutoPowr	Electrified components	NO
31	2020	Case	580 EV	BEV	YES
32	2020	JCB	525-60E	BEV	YES
33	2021	John Deere	E-power backhoe	BEV	YES

Fig. 1. List of selected alternative powertrain solutions for non-road machinery

New approach to the alternative powertrain solutions appeared again in early 2000s. In 1998 Schmetz GmbH created test diesel-electric powertrain based on New Holland tractor. Later, with initiative of Universities in Munich and Regensburg, together with AGCO, Wiedemann and Fraunhofer-Geselschaft, project MELA (Mobile Electrische Leistungs- und Antriebstechnik) have started with goal to create high efficiency electric components for diesel-electric powertrains [14].

Similarly, project TEAM (Entwicklung von Technologien fur energiesparende Antriebe mobiler Arbeitmaschinen) created with RWTH University in Aachen and Universities in Karlsruhe and Dresden together with many manufacturers, e.g. AGCO, Claas, Deutz, Wirtgen, CAT, Liebherr, Rexroth and others resulted in works on high speed electric motors and electric components for non-road machinery drives [14].

Since mid 2000s more companies experimented with different types of alternative powertrains, either prototype ones like Belarus with its diesel-electric model 3023, Case with hybrid-electric ProHybrid EECVT or large-scale production like John Deere 7430/7630 E Premium with electrified auxiliaries [13–16].

From 2010s onwards increasingly higher interest in alternative powertrains have been seen. More large companies like John Deere, New Holland or AGGO would create prototypes and large-scale production machines. However, also smaller companies like Rigitrack, Merlo or Farmtrack have started creating its own solutions [12, 13, 17].

Examples of the alternative powertrains selected by author can be seen in Fig. 1. List of selected alternative powertrain solutions for non-road machinery.Fig. 1. List of selected alternative powertrain solutions for non-road machinery

The year of presentation, manufacturer and model as well as type of powertrain have been indicated to present the variety of solutions developed by the manufacturers.

2. Alternative powertrain solutions

Alternative powertrain solutions can vary and encompass different concepts from electrified auxiliary power outputs, diesel-electric and diesel-hydraulic solutions through many hybrid layouts to the battery-electric, fuel cell-electric and many other variations.

Classification and unified definitions of this solutions its needed to understand the differences between them as well as their advantages and challenges for the practical use of them. More in-depth systematization of alternative powertrain solutions for non-road machinery will be presented in this chapter. Proposed classification is author's approach to the subject.

To determine different definitions for alternative powertrain solutions, first definition of the opposite: the conventional drive needs to be clarified. For the non-road machinery traditionally, the conventional powertrain would consist of internal combustion engine and mechanical or hydro-mechanical transmission.

Proposition for non-road machinery classification can be seen on Fig. 2.

2.1. In-series drive

In series drive is the powertrain architecture where prime mover and drive components are connected to each other in a way that one propels the next one and transfers the torque to the driving wheels. For non-road machinery prime mover would typically be diesel internal combustion engine (ICE).

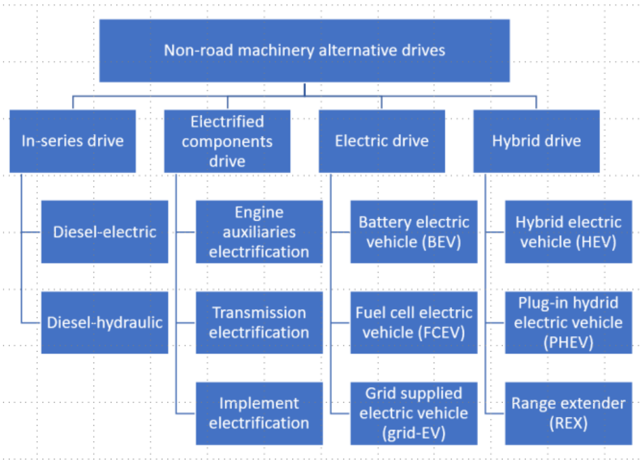

Fig. 2. Non-road machinery alternative drive classification

Fist type of the in-series drive is the diesel-electric drive. In this solution diesel drives the electric generator and sends the electric power straight to the electric motor and further to the transmission or final drive. Alternatively, electric energy can be sent to multiple electric motors mounted on driving axles or even directly on driving wheels. This solution is well known and used within marine, rail and other industries.

The second type of in-series drive used in non-road machinery is the diesel-hydraulic drive. In this solution prime mover supplies torque to the hydraulic pump or pumps and sends the hydraulic power to the hydraulic motors. Similarly, to the previous solution hydraulic motor can drive the gearbox, axles or directly driving wheels. Powertrain of this type is also well known and widely used for instance in agricultural sprayers, telehandlers, harvesting machines and others.

Main advantage of both those solutions is that transmission or gearbox of any type in not required. However, quite often the transmission is used anyway to increase the powertrain possibilities.

It is worth to mention this solution cannot be considered as a hybrid drive. Mainly because it lacks an energy store of any form or source of power other than mainly diesel in this case. In other words, the vehicle cannot be operated if the prime mover is stopped, unlike to a hybrid drives [4].

2.2. Electrified components drive

This alternative powertrain type is sometimes considered to be the first step to the machine hybridization, namely micro-hybridization. Main idea behind the solution is to integrate electric generator within certain areas of the existing, mainly classical powertrain, e.g. on a flywheel. Generated electrical energy can be used to supply components within the machine itself or be sent to the attached implements.

First type of this solution deals with engine auxiliaries electrification. Some systems components within the internal combustion engine (ICE) can be successfully driven by electric motors instead of mechanical or hydraulic drives. This increases ease of control and expands the possibility for new functionalities, e.g. radiator fan reverse for cleaning purposes.

Next type is the transmission electrification. Main objective of this solution is to increase the efficiency and sensitivity of hydraulic or mechanic-hydraulic transmission. Higher efficiency of electric generator and motor successfully increases total efficiency of the transmission in comparison to the use of hydraulic pump and hydraulic motor [3].

The third solution is the implement electrification. Similarly, to the previous two drives, mechanical or hydraulic transmission of energy to the implement can be change for the electric energy. In order to achieve that generator needs to be placed somewhere on a driveline and be able to supply external receivers connected to the machine. Typically, that would be fly wheel or side generator.

In practice, those three solutions can be incorporated within one machine and use common generator to satisfy those three types of needs.

2.3. Electric drive

Purely electric drive cab be another solution for the non-road machinery. In this case power transferred to the driving wheels comes from electric motor and goes either through some sort of transmission or final drive or goes directly to the driving hubs. Electric drive gives wide possibilities for torque and speed control as well as ease of operation.

Electric energy supplied to the electric motor or motors can come from different sources which usually limits the machine range or operational time.

Machine supplying energy to the electric motor from the battery or rechargeable energy storage system (RESS) would be called battery electric vehicle (BEV). Within this powertrain machine uses the energy from the battery which needs to be recharged when minimal state of charge (SOC) is achieved. Therefore, size of the battery simply limits the operational time of the machine.

Other solution offers energy to the electric motor from different source of electricity, namely: fuel cell. Thus: fuel cell electric vehicle (FCEV). This option is based on the idea that electricity is supplied to the electric prime mover through chemical process. Hydrogen stored on a vehicle connects with the oxygen from the ambient air creating: electricity, heat and water. That kind of electric powertrain can be supplied with battery and plug-in option, however not necessarily [1, 2].

The third mentioned type of alternative non-road machinery powertrain supplies electric motor of the machine directly from the electric grid next to the working area. Within presented classification indicated as grid-EV. For machines working mainly stationary or within relatively small radius that solution seems to be rational. For more mobile machinery, e.g. agricultural tractor this solution might be a more of a challenge.

2.4. Hybrid drive

The definition of hybrid drive is a coexistence of primary and secondary drive within a vehicle. Most of the hybrid vehicle solutions consists of internal combustion engine (ICE) as a primary source of drive and electric motor with battery as a secondary drive. Many variants and configurations of the hybrid drives are possible, nevertheless two sources of drive to propel the vehicle is the definition of a hybrid drive [1, 2].

Variety of hybrid drives creates a need for systematization. Different criteria can be taken into account to do so, e.g. architecture or functional.

In terms of architecture hybrid drives can be divided as seen on Fig. 3:

1. Series hybrid drive: drive is supplied by electric motor using energy delivered by internal combustion engine to the battery,
2. Parallel hybrid drive: drive is supplied by internal combustion engine or/and electric motor,
3. Series-parallel hybrid drive: usage of advantages of both, series and parallel drive in order to transmit power and torque.

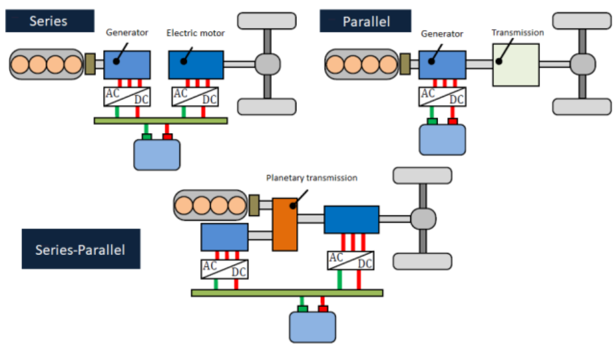

Fig. 3. Hybrid drive architectures [1]

In terms of functional features hybrid drives can be divided into:

1. Micro hybrid drive: the simplest hybrid drive, enables only start and stop of the internal combustion engine when operational parameters are suitable for that, uses only modified engine starting systems,
2. Mild hybrid drive: equipped with electric machine able to support internal combustion engine and recover energy from braking events,
3. Full hybrid drive: drive with full usage of internal combustion engine and electric machine as a motor and generator, simultaneous or separate work of both sources of drive is possible.

Important factor used to describe degree of hybridization of a powertrain is called the hybridization factor (HF) and is defined as a power of electric drives within the powertrain over sum of electric and internal combustion engine drive. According to the description above for micro-hybrid: $0 < HF < 0.1$, mild hybrid: $0.1 < HF < 0.25$, full hybrid: $0.25 < HF < 0.5$, PHEV: $0.5 < HF < 0.7$. The $HF = 1$ refers to pure electric vehicle and $HF = 0$ to conventional non-hybrid powertrain.

One of the most common types of hybrid is hybrid electric vehicle (HEV). This solution is usually referred as internal combustion engine and electric motor with battery designed within one of the architectures mentioned earlier.

Another common solution is plug-in hybrid electric vehicle (PHEV) which is a extension of the HEV by adding possibility of charging a battery from external source (grid).

Specific solution of hybrid drive is range extender (REX). Idea of this drive is a small internal combustion engine with electric generator charging batteries only when needed, otherwise internal combustion engine does not operate. Separate electric motor supplies drive to the wheels [1, 2, 4].

3. Alternative powertrain – selected examples

This paper does not encompass all types of alternative and especially hybrid drives available but just the ones encountered during the study of existing non-road machinery drives and selected as the most significant. Other types of alternative powertrain solutions as hydraulic hybrid vehicle (HHV) or photo-voltaic hybrid vehicle (PVEV) have not been recognized as significant examples in this study [18].

Description of existing examples of powertrain solution within classification in Fig. 2 will be carried out within this chapter.

3.1. In-series drive

Terex in 1974 presented Titan, a 320 tons dump truck. Equipped with 16-cylinder, approx. 2200 kW internal combustion engine and 10-pole AC generator supplying through rectifier DC voltage to the four electric traction motors [19].

Fig. 4. Eltrac E 135 [20]

In 1998, Eltrac E135, first modern agricultural tractor with diesel-electric drive was built by Schmetz GmbH (shown in Fig. 4). Based on New Holland M135 with 6-cylinder, turbocharged Iveco diesel with power of 100 kW and torque of 612 Nm. As shown in Fig. 5, air cooler electric generator supplied power to the electric motor which drive tractor gearbox [20].

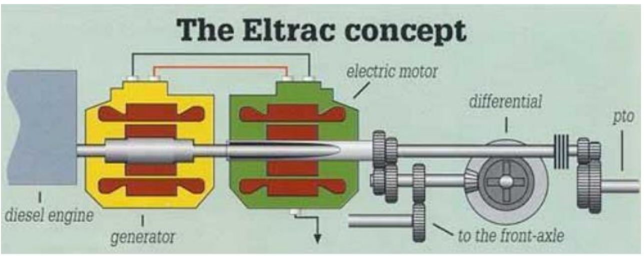

Fig. 5. Eltrac E 135 powertrain diagram [48]

Caterpillar, presented in Fig. 6. have also used diesel-electric drive in 2008 for their D7E bulldozer. Internal combustion engine of 175 kW drives an AC generator sending electric power to two traction motors [21]. Caterpillar claims fuel consumption reduction in this model in compare to its conventional predecessor D7R2 from 10% up to 30% [21].

The emissions of D7E in comparison to the conventional D7R2 appeared to range from 28% lower to 2% higher when it comes to CO_2 and from 7% to 21% higher in terms of NO_x [22].

In 2009 Belarus designed prototype of model 3023 as in Fig. 7. Diesel-electric with 220 kW diesel engine and 172 kW generator supplying power to transmission, electric engine fan drive, front PTO and 380 V power output sockets. Belarus claims 15% to 20% reduction in fuel consumption in comparison to its classical counterpart [23]. Plough field tests showed specific fuel consumption of 10.8 kg/h for the diesel-electric powertrain and 13.2 kg/ha for its conventional version. As result 18% of fuel consumption reduction has been proved [24].

Fig. 6. Caterpillar D7E dozer [21]

Fig. 7. Belarus 3023 with electro-mechanical powertrain [23]

AGCO presented in 2010 self-propelled sprayer ElectRoGator 1386 with 229 kW CAT diesel engine supplying 650 V DC from the 200 kW, water-cooled generator with 1500 rpm. Alternatively, 240 kW with 1900 rpm. Electric motors with 84 kW of power and 700 Nm of torque mounted on each of four wheels (Fig. 8). Lifetime of the electric motors was estimated for 50,000 h which is longer than a lifetime of the traditional sprayer [13, 15].

AGCO claims that electric version o the sprayer featured 36% higher torque, 6% more power. On the prototype of the machine braking energy was dissipated into heat. Development works are conducted to recover this energy as well [23]. In comparison to conventional hydrostatic version, this electrified powertrain reduced fuel consumption in field tests from 20% in a summer up to 30% in autumn [13].

Fig. 8. AGCO ElectRoGator 1386 [23]

Swiss manufacturer Rigitrack together with Technische Universitat Dresden developed diesel-electric tractor EWD 120 (Fig. 9) equipped with 91 kW Deutz engine and 85 kW, 650 V DC liquid-cooled generator came to the public in 2011. Permanent magnet synchronous motors of 33 kW each mounted directly on wheels allowed to control torque transmission on each of axles as shown in Fig. 10. Additional electric output socket was available [17, 23].

Fig. 9. Rigitrac EWD 120 [23]

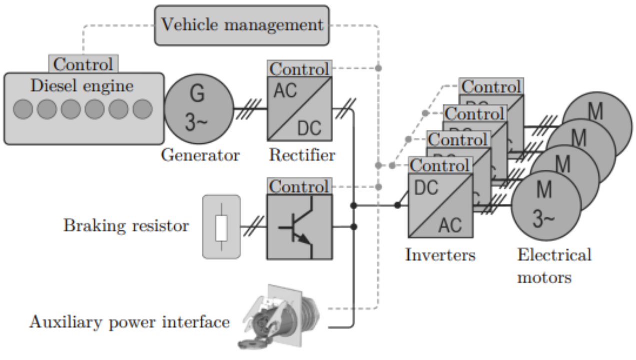

Fig. 10. Rigitrac EWD 120 powertrain architecture [52]

John Deere have introduced in 2013 loader 644K (Fig. 11) with their John Deere 6.8 dm^3, 6-cylinders diesel engine of 167 kW, 985 Nm driving two brushless, oil-cooled AC generators. Electric power is further supplied through solid state, inverters to the four also brushless, oil-cooled AC motors, one for each wheel. Six inverters, one for each of the electric machines are based on insulated gate bipolar transistor (IGBT) technology.

Fig. 11. John Deeer 644K Hybrid loader [27]

Powertrain does not feature energy store, but it is equipped in two water-cooled brake resistors to dissipate brake energy to be used for boom or bucket functions reducing load on the internal combustion engine and reducing fuel consumption (Fig. 12). Larger version of this machine is also available with similar powertrain architecture, model 944K [26]. John Deere claims 25% of fuel consumption reduction in comparison to the conventional powertrain of this machine [23, 27].

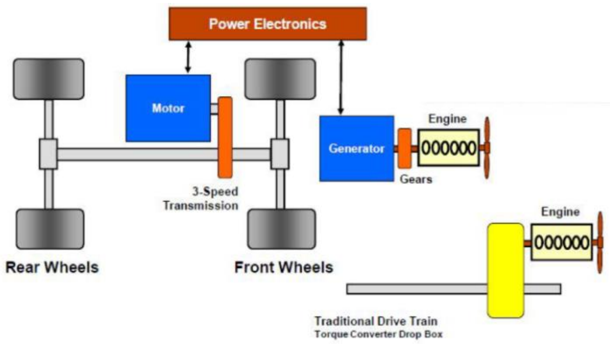

Fig. 12. John Deere 644K loader powertrain diagram, hybrid and traditional [27]

In 2014 Belaz showed their 75710 (Fig. 13) diesel-electric dump truck. This also was the largest dump truck produced with 450 tons of payload prepared to work in difficult conditions and temperatures ranging from –50°C to +50°C. Belaz put two 1704 kW alternators and connected them to four traction motors, 1200 kW each. Alternators driven by two diesel MTU DD 16V4000 engines with rated power of 1715 kW.

Fig. 13. Belaz 75710 [25]

3.2. Electrified components drive

In 1954 IH Farmall presented model IH ElectrAll as in Fig. 14. Regular agriculture tractor based on conventional powertrain architecture but with generator attached in parallel to the internal combustion engine ready to supply external receivers. Generator was a 3-phase, 120/208 V, 10 kW electric machine [14].


Fig. 14. IH Farmall 450 ElectrAll [14]

John Deere introduced in 2007 models 7430 E Premium and 7530 E Premium with standard 121 kW and 132 kW engines respectively. Tractors with conventional architecture featured additional 3-phase, 480 V, 20 kW electric generator mounted on an engine's fly wheel. Part of the electric power from the generator was consumed by electrically driven engine auxiliaries: radiator fan and A/C compressor. This allowed precise control of duty time and speed of these devices. Additionally, electric energy is available on external sockets in a form of 1-phase 230 V, and 3-phase, 400 V (Fig. 15). This power can be used to supply external devices up to 5 kW when tractor is standing still. Mentioned solution resulted in a 5% reduction in a fuel consumption in comparison to the conventional version of those machines [13, 15, 28].

Field tests of electrified and conventional version of 7530 tractor in harrowing and towing a trailer were conducted. Results yielded 4% of fuel consumption reduction in harrowing and 16% in towing a trailer on the road [29].

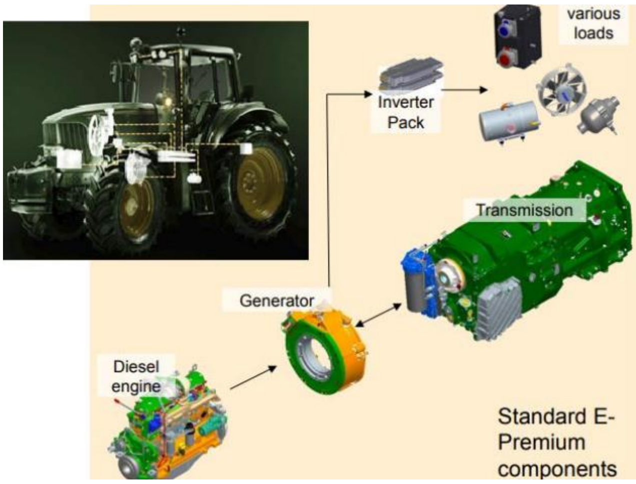

Fig. 15. John Deere 7530 E Premium components [30, 33]

Again, John Deere repeated similar solution and expanded its capabilities in 2011with model 6210 RE. This time architecture was similar to the solutions from 2007 however now 20 kW of electric power was available for driving external machines also when tractor was moving (Fig. 16). Available electric power parameters were 480 V DC and 3-phase, of 750 V AC with max. current of 200 A [13, 15, 30, 31].

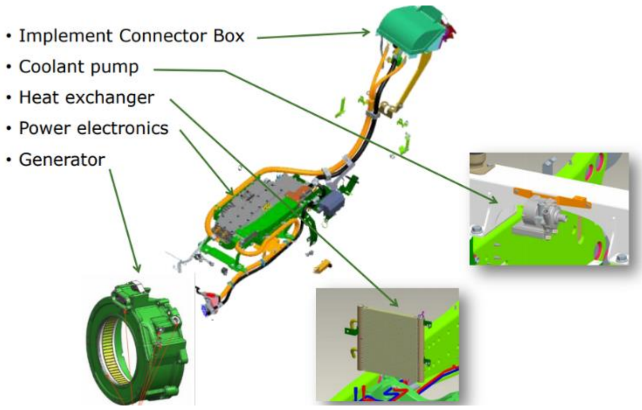

Fig. 16. John Deere 6210 RE powertrain components [30]

Similar solution was presented by Fendt in 2013 with model X Concept (Fig. 17) based on conventional Fendt 722 Vario with 147 kW diesel engine. Fendt has integrated AC generator o 130 kW, 700 V DC on the engine output supplying power to the engine auxiliaries: radiator fan and coolant pump and to the external sockets available to power implements [15, 23].

Fig. 17. Fendt X Concept powertrain components [15]

Other example of similar ready to use technology is a solution prepared by ZF with TERRA + product line ranging from 3-phase, 400 V electric motor hubs through 80 kW generators ready to be integrated between engine and a gearbox of existing machines to full size transmissions with 50 kW and 70 kW generators build in (Fig. 18). Generator is ready to supply energy to implements. Additionally, with deployment of energy store this can create hybrid system with recovery braking capabilities as presented in Fig. 19. The ZF also offers PTO driven generator to be fitted to the existing machine with capacity of supplying energy to two 25 kW electric motors [23, 32].

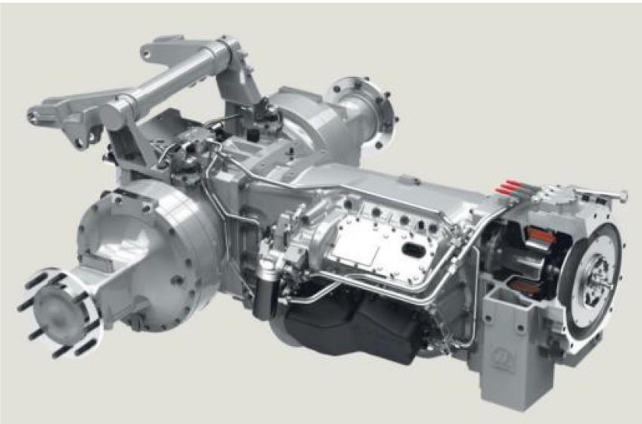

Fig. 18. ZF TERRA+ starter generator with transaxle [23]

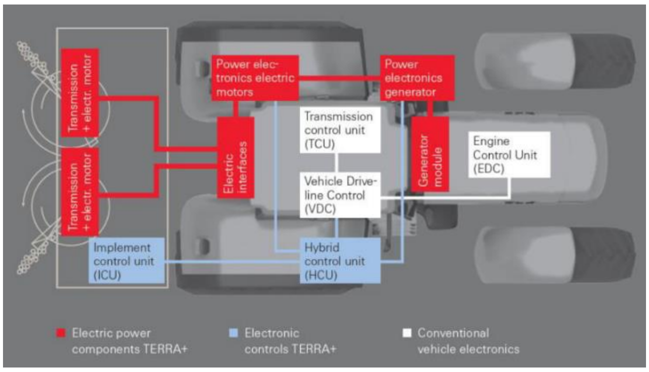

Fig. 19. ZF TERRA+ possible architecture [23]

In 2019 again John Deere presented new solution in their 8370 R eAutoPowr as in Fig. 20. Based on regular tractor architecture with 275 kW, 6-cylinder engine and continuously variable transmission (CVT). However, in this electrified solution hydraulic pump and motor have been changed for electric machines increasing significantly transmission efficiency. Additionally, AC brushless generator capable of supplying 100 kW power to the external implements through sockets on a back of the machine in a form of 700 V DC or 3-phase, 480 V AC. Originally the project was developed together with trailer manufacturer Joskin to support their 100 kW electric motor mounted to the trailer axle [34, 35].

Taking into account that CVT not always supports machine with transmission efficiencies similar to the gear transmission this electrified option seems promising [23].

Fig. 20. John Deere eAutoPowr transmission [34]

3.3. Electric drive

In 1954 Alli-Chalmers presented first fuel cell powered electric tractor (Fig. 21). It featured 1008 cells arranged in 112 units of 9 cells each within 4 banks generating 15 kW of electric energy transferred to the electric drive motor.

Fig. 21. Allis-Chalmers AC D-12 fuel cell tractor [14, 23]

First practical use of fuel cell electric vehicle (FCEV) in terms of tractor was presented by New Holland in 2011 (Fig. 22). Tractor named NH_2 was based on conventional T6.140 model and featured fuel cell module of 100 kW with efficiency of 96% and 2 electric motors, one for PTO drive, other for tractor drive. Each motor performed 100 kW of power and 950 Nm of torque. Quantity of 8.2 kg of hydrogen was stored under 350 bars of pressure. This powertrain solution featured a Li-Ion battery working with 300 V and size of 12 kWh with peak power output of 50 kW [13, 17, 23].

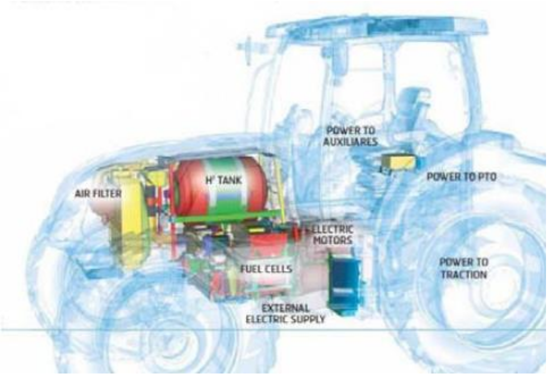

Fig. 22. New Holland NH2 hydrogen-powered tractor [23]

Proposition of prototype battery electric vehicle (BEV) was developed in 2016 by John Deere with a model called SESAM (Sustainable Energy Supply for Agricultural Machinery). Tractor was based on Mannheim's 6R frame and was equipped in 130 kWh, 670 V, Li-Ion battery and 2 electric motors 150 kW each (Fig. 23). One of the motors drives Direct Drive transmission and the second drives PTO. Tractor has capacity of work continuously for approx. 4 h or travel distance of 55 km. Charging of the battery takes about 3 h. Battery is designed for 3100 charging cycles [12, 36].

Fig. 23. Battery pack of John Deere SESAM [36]

Fig. 24. Kramer 5055e loader [17]

In 2016 Kramer presented their first fully electric loader 5055e (BEV). It consists of 2 electric motors, one for the machine drive 15 kW and second for hydraulic drives 22 kW (Fig. 24). Battery works on 80 V and has capacity of 416 Ah. Operational time on one charging depends on load and range between 5 h and 8.5 h [17, 37].

Next fully electric tractor shown by Fendt in 2017, model e100 Vario featured power output of 50 kW with Li-Ion battery of 100 kWh and voltage of 650 V (Fig. 25). Operational time was estimated at 5h under moderate load [12, 38].

Fig. 25. Fendt e100 Vario [38]

Also, in 2017 Indian manufacturer Escorts launched its BEV tractor Farmtrac 26E prepared mainly for vineyards and horticulture presented in Fig. 26. In this solution electric motor of 19 kW drives standard transmission with 21 kWh, Li-Ion battery. This supports 6 h of working time [12].

Fig. 26. Escorts Farmtrac 26E [12]

Very interesting solution for the electric vehicle (EV) have been proposed by John Deere in 2018. Autonomous tractor without the cab called GridCON with constant connection to the electric grid from the site of the field. Tractor is equipped with special spool with 1 km of supply cable mounted in a front of the machine as shown in Fig. 27. Mentioned cable supplies two electric motors, one 100 kW for tractor drive and second 200 kW for power output to the implement. Mass of the tractor is 8.5 t which is an equivalent to the John Deere model 6195R. Max. speed of the machine is 20 km/h. Electric power supply need to be 2.5

kV however tractor power bus is 700 V DC. John Deere claims that running costs of this powertrain solution are reduced by half in comparison to the BEV [39, 40].

Fig. 27. John Deere GridCON [39]

Fig. 28. Rigitrac SKE50 [41]

In 2019 Swiss manufacturer Rigitrac proposed new solution for the fully electric tractor BEV, model SKE 50 (Fig. 28). In this powertrain solution one Li-Ion, 400 V, 80 kWh battery supplies 4 electric motors, one for front axle, second for rear axle, third for front PTO and fourth for rear PTO [12, 41].

John Deere in 2019 shown two fully electric machines, with little information provided. First one, model 1RE, fully electric prototype of small compact tractor with expected operational time of 4.5 h on one charge (Fig. 29).

Fig. 29. John Deere 1 RE [42]

Second one is the John Deere Joker, prototype of fully electric and fully autonomous machine as in Fig. 30. Tractor is featuring no cab and power output of 500 kW. No information about the battery have been provided yet [42].

Fig. 30. John Deere Joker [40]

In 2020 Case and JCB showed their fully electric machines (BEV) for construction industry presented in Fig. 31. For Case that is “Project Zeus” 580 EV backhoe loader powered with 480 V, 90 kW Li-Ion battery pack supplying separately drive and hydraulic components. Single charge will support 8 h of operational time [43].

Fig. 31. Case 580 EV „Project Zeus” [43]

The JCB introduced whole fleet of construction battery electric vehicles. To name one: telehandler 525-60e (Fig. 32). With Li-Ion battery of 24 kWh and 3 charging options: 110 V, 230 V, 415 V. One charge supports entire day of operational time [44].

Fig. 32. JCB 525-60e telehandler [44]

John Deere in January 2021 also presented fully electric backhoe loader called E-power backhoe developed together with National Grid – an electricity and natural gas provider.

The machine it is to perform on the same level as its conventional counterpart, model 310L [45].

In 2021, additionally to described developments, John Deere have already conducted field tests on autonomous machines working in swarm as in Fig. 33. In this particular example John Deere GridCON has supplied power to the single John Deere Joker machine. However, the idea is to supply energy to several machines [46, 47].

Fig. 33. John Deere GridCON and John Deere Joker [47]

3.4. Hybrid drive

First practical full hybrid electric (HEV) powertrain solution for non-road machinery was presented in 2005 Case ProHybrid EECVT (Fig. 34). Tractor based on conventional Case MXM with 120 kW, 800 Nm engine and two electric machines, 50 kW each. One electric machine working as a generator supplies energy to the second one working as a motor. Surplus of energy can be stored in 11.5 kWh, 456 V DC battery. Additionally, energy from braking can be recovered and sent to the battery. In this powertrain solution tractor can work in full electric mode or in a hybrid mode with diesel engine and electric motors together through CVT [14, 48].

Fig. 34. Case ProHybrid EECVT [14]

In 2012, Komatsu introduced full hybrid (HEV) model HB205-1. Because of hybrid architecture diesel engine can be downsized form 6-cylinder to 4-cylinder. Electric generator/motor is placed at the engine output and supplies power to the capacitor as shown in Fig. 35. Electric swing motor/generator moves the upper structure of the machines and recovers energy from when the structure slows down sending it to capacitor. Energy from capacitor can be used to support the diesel engine by the means of motor/ generator placed on the engine output. Komatsu claims fuel consumption reduction between 25–41% [13, 23].

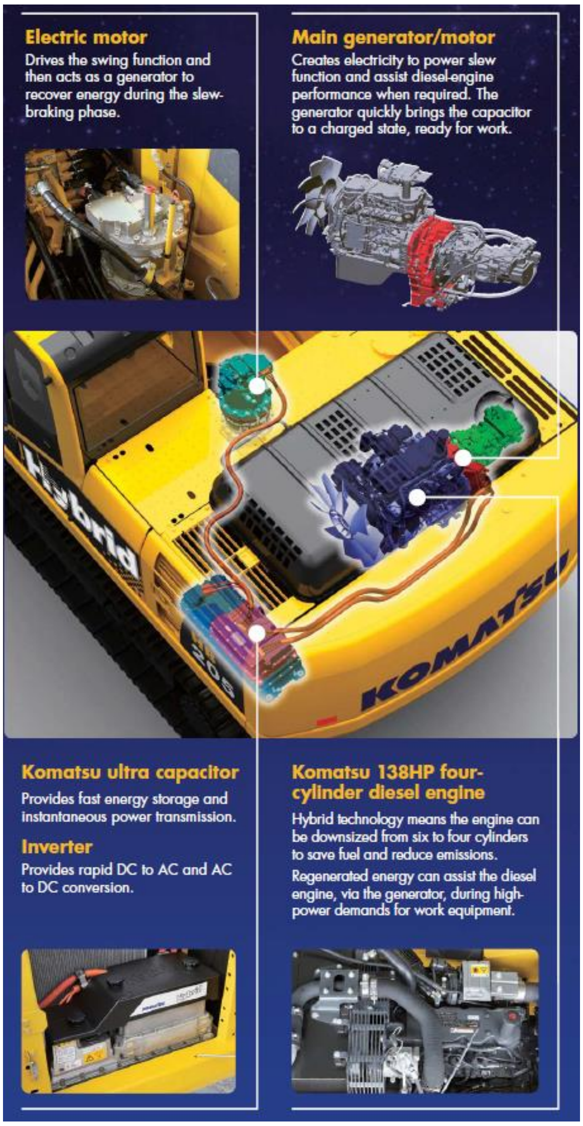

Fig. 35. Komatsu HB205-1 powertrain components [49]

Merlo presented in 2013 their 40.7 plug-in hybrid electric vehicle (PHEV). In fully electric mode the energy is supplied from 30 kWh, Li-Ion battery (Fig. 36). In hybrid mode internal combustion engine working at a constant speed supplies energy to the machine drive and charges the battery. In this architecture diesel output can be reduced in a half without the reduction in machine performance. In case of low-load work or idling, machine can work solely electric and reduce fuel consumption and CO_2 emission up to 30% Merlo claims. Machine can be also charged from the grid as a plug-in hybrid [17, 48].

Fig. 36. Merlo 40.7 hybrid telehandler [48]

Different type of hybrid vehicle (REX) used by Multi Tool trac company from Netherlands as in Fig. 37. This powertrain uses 6-cylinder, 160 kW diesel engine driving 140 kW generator supplying energy to the Li-Ion, 30 kWh battery. This supports 0.5 h of continuous work. Electric energy is supplied from the battery to 4 electric motors at wheels [16].

Fig. 37. Muli Tool Trac [16]

Claas have shown in 2016 full hybrid machine (HEV) based on model Arion 650. The Claas Arion 650 Hybrid. The prime mover in powertrain was a 129 kW, 6.8 dm^3 diesel engine driving 90 kW permanent magnet synchronous generator. The generator was located between engine and EQ200CVT transmission (Fig. 38). Second source of energy in this powertrain was 5.75 kWh, 635 V battery [16, 50].

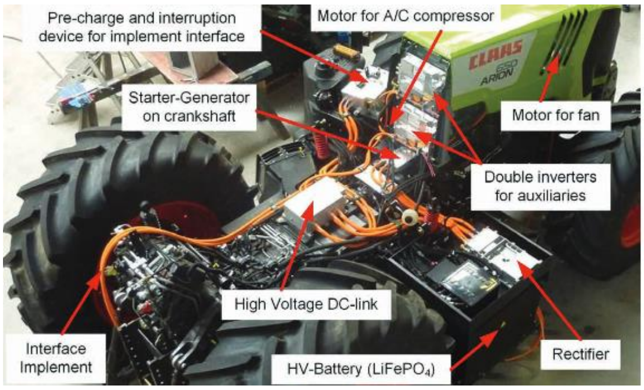

Fig. 38. Class Arion 650 Hybrid powertrain components [16, 50]

In 2019 Steyr presented its Konzept PHEV tractor as shown in Fig. 39. All hydraulics and PTO were electrically driven, external power output socket with 48 V and 700 V available as well. Energy from breaking was recovered and sent to battery. Charging from grid possible. Energy from the battery drives 4 electric motors at wheels [51].

Fig. 39. Steyr Konzept [51]

4. Conclusions

In this paper main known alternative powertrain solutions within non-road machinery area have been presented. Classification for the mentioned examples have been undertaken and described. Together with indication of differences between given solutions. Based on that specific conclusions can be drawn:

1. Alternative powertrain solutions for non-road machinery are getting increasingly more attention, especially electric drives and start to play visible role within market of high tech solutions for this industry segment.
2. Significant rise in development works regarding alternative powertrain solutions started in early 2000s and increased in 2010s.
3. Different structure within development works on alternative powertrain types over course of years is visible with direction moving from experimenting with many solutions to focus on the BEVs.
4. Many alternative powertrain solutions are not limited only to the machine powertrain but also expanded on supplying power to the implement as well.
5. Although pace of development works on alternative powertrains, mainly BEVs seems to be very fast, the limitations to the battery capacity therefore, operational time are still existing.
6. Alternative powertrains for non-road machinery are not making any significant impact on whole industry market now but mentioned pace of development works, also on battery technology puts this kind of solutions into near future perspective.

Nomenclature

AC	alternating current
A/C	air conditioning
BEV	battery electric vehicle
CVT	continuously variable transmission
DC	direct current
EV	electric vehicle
FCEV	fuel cell electric vehicle
HEV	hybrid electric vehicle
HF	hybridization factor
HHV	hybrid hydraulic vehicle
ICE	internal combustion engine
IGBT	insulated gate bipolar transistor
PHEV	plug-in hybrid electric vehicle
PTO	power take-off
PVEV	photovoltaic electric vehicle
RESS	rechargeable energy storage system
REX	range extender
SOC	state of charge

Bibliography

[1] MERKISZ, J., PIELECHA, I. Układy mechaniczne pojazdów hybrydowych. *Wydawnictwo Politechniki Poznańskiej*. Poznań 2015.

[2] MERKISZ, J., PIELECHA, I. Układy elektryczne pojazdów hybrydowych. *Wydawnictwo Politechniki Poznańskiej*. Poznań 2015.

[3] RENIUS, K.T. Fundamentals of tractor design. *Springer*. 2020.

[4] Automotive Handbook. *Robert Bosch GmbH*. 2014.

[5] RYMANIAK, Ł., LIJEWSKI, P., KAMIŃSKA, M. et al. The role of real power output from farm tractor engines in determining their environmental performance in actual operating conditions. *Computers and Electronics in Agriculture*, 2020, **173**, 105405. https://doi.org/10.1016/j.compag.2020.105405

[6] 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. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009R0443

[7] Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R1628&from=LV

[8] European Stage V non-road emission standards. *International Council of Clean transportation*. 2016. http://theicct.org/sites/default/files/publications/EU-Stage-V_policy%20update_ICCT_nov2016.pdf

[9] FEBIG, M., WIARTALLA, A., HOLDERBAUM, B. et al. Particulate emissions from diesel engines: correlation between engine technology and emissions. *Journal of Occupational Medicine and Toxicology*. 2014, **9**(6). https://doi.org/10.1186/1745-6673-9-6

[10] CWIKOWSKI, P., TEODORCZYK, A. The latest achievements in gasoline and diesel injection technology for the internal combustion engines. *Journal of KONES Powertrain and Transport*. 2009, **16**(2), 79-90. http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-article-BUJ5-0032-0016

[11] DZIUBINSKI, M., DROZD, A., ADAMIEC, M. et al. Energy intensity of the electric vehicle. *Advances in Science and Technology Research Journal*. 2017, **11**(4), 27-34. https://doi.org/10.12913/22998624/78516

[12] MALIK, A., KOHLI, S. Electric tractors: survey of challenges and opportunities in India. *Materials Today: Proceedings*. 2020, **28**, 2318-2324. https://doi.org/10.1016/j.matpr.2020.04.585

[13] MOREDA, G.P., MUNOZ-GARCIA, M.A., BARRIEIRO, P. High voltage electrification of tractor and agricultural machinery – a review. *Energy Conversion and Management*. 2016, **115**, 117-131. https://doi.org/10.1016/j.enconman.2016.02.018

[14] WEYMANN, S. Electric drivelines for tractors and agricultural machinery. Part 1. *Agricultural, Horticultural and Forest Engineering*. 2016, **61**(4), 6-8.

[15] WEYMANN, S. Electric drivelines for tractors and agricultural machinery. Part 2. *Agricultural, Horticultural and Forest Engineering*. 2016, **61**(5), 8-10.

[16] WEYMANN, S. Electric drivelines for tractors and agricultural machinery. Part 3. *Agricultural, Horticultural and Forest Engineering*. 2016, **61**(6), 9-11.

[17] WEYMANN, S. Electric drivelines for tractors and agricultural machinery. Part 4. *Agricultural, Horticultural and Forest Engineering*. 2017, **62**(1), 11-14.

[18] MOUSAZADEH, H., KEYHANI, A., JAVADI, A. et al. Optimal power and energy modeling and range evaluation of a solar assist plug-in hybrid electric tractor (SAPHT). *American Society of Agricultural and Biological Engineers*. *Transactions of the ASABE*. 2010, **53**(4), 1025-1035. https://doi.org/10.13031/2013.32586

[19] DREW, D. Terex Titan. It was a big one. *Earthmovers Magazine*. http://www.earthmoversmagazine.co.uk/digger-man/view,terex-titan-it-was-the-big-one-blog-post-revisited_252.htm (accessed on 10.06.2021).

[20] BERNHARD, B. Untersuchungen zur Bewegung Stufenloser Fahrantriebe für Mahdrescher. *Universitat Hochenheim*. 2011. http://opus.uni-hohenheim.de/volltexte/2012/648/pdf/Dissertation_Bjoern_Bernhard.pdf

[21] Caterpillar trade press media representatives. Updated Cat D7E features advanced technology to boost productivity. 2014. http://www.cat.com/en_GB/news/machine-press-releases/updated-cat-d7e-featuresadvancedtechnologytoboostproductivityand.html (accessed on 10.06.2021).

[22] JOHNSON, K.C., BURNETTE, A., CAO, T. et al. Hybrid off-road equipment in-use emission evaluation. FY 2010-11 air quality improvement project. Hybrid off-road equipment pilot project. *California Air Resources Board*. 2013.

[23] HOY, R., ROHRER, R., LISKA, A. et al. Agricultural industry advanced vehicle technology: Benchmark study for reduction in petroleum use. *Idaho National Laboratory*. 2014.

[24] PUHOVOY, A.A. Agricultural tractor with pure electromechanical drivetrain. *SAE International Journal of Commercial Vehicles*. 2011, **4**(1), 275-285. https://doi.org/10.4271/2011-01-2296

[25] Belaz. http://belaz.by/en/products/products-belaz/dumpers/dump-trucks-with-electromechanical-transmission/dumpers-series-7571/ (accessed on 10.06.2021).

[26] Construction Equipment. http://www.constructionequipment.com/john-deere-644k-hybrid-wheel-loader (accessed on 10.06.2021).

[27] SOBOTZIK, J. Electrische Antriebstechnik. Eine neue Chance in Mobile Arbeitmaschinen. *VDI Workshop Electrification*. Wieselburg. 2013.

[28] HAHN, K. High voltage electric tractor-implement interface. *SAE International Journal of Commercial Vehicles*. 2009, **1**(1), 383-391. https://doi.org/10.4271/2008-01-2660

[29] PESSINA, D., FACCHINETTI, D. Gemelli diversi. *Macchine Agricole*. 2009, **7**, 44-51. http://www.researchgate.net/publication/303142160_Gemelli_diversi

[30] KRAH, J.O., SOBOTZIK, J., HAMBLOCH, M. Tractor/implement electrification. Opportunities and challenges. *EtherCat in Mobile Applications*. Frankfurt. 2013.

[31] STOSS, K.J, SHI, B., SOBOTZIK, J. et al. Tractor power for implement operation – mechanical, hydraulic, and electrical: An overview. *Agricultural Equipment Technology Conference*, Kansas City. 2013.

[32] BUNING, E.A. Electric drives in agricultural machinery. An approach from the tractor side. *Bologna, EIMA International*, 2015.

[33] MUNCH, P. Sensorik und Elekrifirizierung bei Landmachinen. *John Deere.* 2013.
[34] Eautopowr Eroffnet neue Traktorbe-triebsweisen. http://flurundfurche.de/eautopowr-eroeffnet-neue-traktorbetriebsweisen/ (accessed on 10.06.2021).
[35] Das Gullefass Arbait mit. http://www.deere.de/de/blog/articles/technik/eautopowr-john-deere-elektrisches-getriebe-power-off-boarding/ (accessed on 10.06.2021).
[36] John Deere SESAM-batterie-traktor. http://www.topagrar.com/technik/news/john-deere-sesam-batterie-traktor-9365391.html (accessed on 10.06.2021).
[37] Into the future with new drive. http://www.kramer-online.com/en/product/model/5055e/ (accessed on 10.06.2021).
[38] Fendt e100 Vario. Unser antrieb fur the zukunft. http://www.fendt.com/at/e100-vario (accessed on 10.06.2021).
[39] An der Langen Leine. http://www.faz.net/aktuell/technik-motor/motor/john-deere-forscht-am-elektrischen-traktor-15961820.html (accessed on 10.06.2021).
[40] PICKEL P. Trends in tractor development. *John Deere ETIC.* Wieselburg. 2020
[41] Rigitrac Traktorenbau AG. http://www.rigitrac.ch/produkte-1/rigitrac-ske-40-electric/ (accessed on 10.06.2021).
[42] Future of farming. http://www.deere.co.uk/en/agriculture/future-of-farming/ (accessed on 10.06.2021).
[43] The industry's first fully electric backhoe loader-The Case 580 EV http://www.casece.com/northamerica/en-us/products/backhoe-loaders/580ev-project-zeus (accessed on 10.06.2021).
[44] The new electric JCB 525-60e compact telehandler. http://www.jcb.com/en-gb/products/telescopic-handlers/525-60e-hi-viz (accessed on 10.06.2021).
[45] John Deere joint its first electric powered backhoe with National Grid. http://www.deere.com/en/our-company/news-and-announcements/news-releases/2021/construction/2021jan06-electric-powered-backhoe/ (accessed on 10.06.2021).
[46] The autonomous swarm tractor from John Deere. http://thefurrow.co.uk/the-autonomous-swarm-tractor-from-john-deere/ (accessed on 10.06.2021).
[47] Farmer.pl http://www.farmer.pl/technika-rolnicza/maszyny-rolnicze/ciagnik-na-prad-z-przewodu-john-deere-zadziwia,108905.html (accessed on 10.06.2021).
[48] CABAN, J., ZARAJCZYJ, J., SZMIGIELSKI, M. et al. Hybrid drive as a future in agricultural technology. *Proceedings of the Institute of Vehicles.* 2018, **3**(177), 19-27.
[49] Komatsu customer support materials. Komatsu hybrid excavator. World-first hybrid technology. http://www.komatsu.com/ (accessed on 10.06.2021).
[50] TETZLAFF, S. System-wide electrification and appropriate functions of tractor and implement. *Landtechnik.* **70**(5), 203-216. 2015. http://doi.org/10.15150/lt.2015.2676
[51] Steyr traktoren. http://www.steyr-traktoren.com/en-distributor/agriculture/technologie/steyr-konzept (accessed on 10.06.2021).
[52] OSINENKO, P. Optimal slip control for tractors with feedback of drive torque. *Technische Universitat Dresden.* 2014.

Tomasz Kalociński MEng. – Manager Training Center & Training Shared Services at John Deere, Faculty of Civil and Transport Engineering, Poznan University of Technology.
e-mail: *tomaszkalocinski@gmail.com*