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A Review of Hybrid Electric Architectures in Construction, Handling and Agriculture Machines

Francesco Mocera and Aurelio Somà

Abstract

Recent regulations on pollutant emissions have pushed working machines manufacturers towards research and development efforts to meet the strict limits imposed. For a long time, the use of gas aftertreatment systems have been the most widely accepted solution to reduce the amount of pollutants produced per unit of work done. However, lower emissions limits lead to larger systems and consequently higher difficulties in vehicle integration. Thus, alternative solutions have been studied in the last years to solve the emissions problem using wisely the on-board space. Hybrid electric technologies represent a valuable alternative in this direction. In this work, a review of the current state of the art in the adoption of hybrid and electric technologies on working vehicles is proposed. Due to the high amount of application fields and concepts for special applications, the analysis focused on the three major fields which however includes most of the working machines: Construction, Handling and Agriculture. This work highlights how the requirements of each specific field, strongly affects the design of an optimal hybrid electric architectures.

Keywords: Construction machinery, Handling machinery, Agriculture machinery, Hybrid electric systems, Energy saving

1. Introduction

Worldwide, air quality is now recognized to be affected at different levels by each human activity field [1–4]. The transportation field is generally addressed as one of the major contributors to air pollution. However, residential and commercial heating as well as industrial processes [5, 6], play an important role when it comes to CO₂, NO_x and particulate matter production.

Transportation covers a wide range of vehicles categories, from light/heavy duty road transport up to railway, maritime or aviation transport of people or goods. Each of them affects in a different way the total production of some pollutant elements. This is the reason why regulations have been imposed in the last years to force vehicle manufacturers to satisfy certain quality standards in terms of pollutants production. Passenger cars and light duty vehicles have now emissions levels way lower than two decades ago [7] but there is still room for further improvements. New technologies have been developed to properly treat exhaust gas and to

increase the overall vehicle efficiency. In this direction, hybrid and electric vehicles have demonstrated to be a realistic alternative solution for the near future. Lower footprints on CO₂ emissions have been measured in Real Driving Scenarios with Portable Emissions Measurement Systems (PEMSs) [8] but still open is the discussion on the production of other pollutants like NO_x and Particulate Matter (PM) [9]. However, proper control strategies of a hybrid power unit can reduce the overall emissions with respect to traditional thermal engine powered architectures [10].

If on one hand the electrification process is a well-established trend in automotive, there are also other fields of application where this technology is demonstrating its capabilities as alternative propulsion system for traditional powertrains. This is the case of Non-Road Mobile Machineries (NRMM), vehicles which can be used both for transportation and for heavy industrial works. According to the definition given by the EU regulations [11–15], machines can be classified as NRMMs if they are used in construction, handling, agriculture and farming, forestry and gardening. However, also railcars, locomotives and inland waterway vessels fall within the given definition, although they represent a totally different segment of vehicles. Several studies have shown that due to the high level of resources invested to improve road transports' emissions, NRMM are becoming a not negligible source of pollutants [16–18]. Historically, these machines have been equipped with high power Diesel engines known for their high efficiency, durability and reliability. However, despite of the high performance over total cost of ownership (TCO) ratio for this type of propulsion technology, diesel engines have been addressed by many researchers and non-academic authorities as one of the greatest contributors to air pollution [19, 20]. Exhaust gas aftertreatment systems have been widely used by OEM engine manufacturers to meet international emissions regulations and adopted by NRMMs' companies which use these systems to power their machines. However, the stricter regulations have become, the higher the volume required by aftertreatment systems to properly filter the exhaust gas stream from dangerous pollutant elements [21, 22]. The on-board volume required to install these filters is space dedicated only to exhaust gas elaboration. This space can be considered as a dead volume from the productivity point of view, in terms of space used to add functionalities to the machine. This is one of the reasons why several NRMM manufacturers are looking for proper alternatives to standard Diesel-based propulsion systems. Hybrid electric architectures represent a viable solution to increase the overall efficiency of the machine [23]. The hybridization level of the architecture [24, 25] optimized to the specific working cycle helps in reducing the amount of pollutant produced per Unit of Work performed [26, 27]. At the same time, the more sophisticated technology involved in these architectures allows to add extra functionalities to the machine, opening new working scenarios to the same machines.

This work aims to give an overview about the electrification process that is involving the field of working off road machines. Starting from the definition of the basic architectural topologies and their comparison within the scope of off-road heavy-duty applications, an analysis of the proposed concepts and products during the last two decades is shown. Since the NRMM classification cover a wide range of working fields, this review focused the attention on the three major working fields: Construction, Handling and Agriculture. All the considerations developed for these fields of application can be extended to other specific projects.

2. Basic hybrid and electric architectures

Vehicle electrification involves the adoption of electric and electronic components within a mechanical system to provide power as a primary source or together

with other power units [28–32]. Combining properly these components, many powertrain topologies can be obtained allowing for a high level of performance optimization. This characteristic is crucial when it comes to NRMMS, where each field of application requires special custom solutions. Thus, the knowledge of the load characteristics and of the working cycle of each type of machine is mandatory to design an optimal architectural solution [33, 34]. Looking closer at the structure of all the possible electric topologies, three basic functional schemes can be identified: full electric, series hybrid and parallel hybrid [35–39].

2.1 Battery electric vehicles

From a system point of view, a full electric architecture is the simplest solution when it comes to powertrain electrification. As shown in **Figure 1**, a full electric architecture consists of a single power source used to drive all the possible mechanical loads applied to the vehicle: the driveline, the hydraulic system and all the PTOs (Power Take-Offs) are electrically driven. By means of an electronic converter, the electric energy previously stored in a battery pack (DC voltage and current) is regulated to provide alternate voltage and current (AC) to the installed electric motor (EM) [40, 41]. One or more electric machines can be used to optimize performance of the specific machine [42, 43].

The lower number of moving parts involved in electric machines increases the powertrain mechanical reliability when compared to Internal Combustion Engines (ICE) [44, 45]. Nowadays, power converters represent a well consolidated technology. If temperatures are well managed with proper cooling solutions, aging mechanisms related to thermal cycles can be mitigated leading to good reliability over the entire life of the vehicle [46–48]. Full electric architectures would probably replace all modern powertrains solutions if the available energy storage systems (ESSs) would perform better under different aspects [49, 50]. The most developed and promising ESSs for vehicle applications are based on Lithium-Ion Batteries (LiB) [51–54]. In terms of energy density, the ratio between 1 liter of Diesel fuel (≈ 10.9 kWh) and 1 liter of LiB (≈ 0.25 kWh) is currently 44. Considering an average conversion efficiency of an ICE ($\approx 30\%$) and of an electric system composed by an electric motor and its power converter ($\approx 85\%$), the gap reduces to 15 times, still too shifted in favor of thermal engines. If a proper battery pack design can satisfy the energy needs of a machine typical working cycle, still precautions are required to safely use the stored electric energy. LiB manufacturers prescribe a Safe operating Area (SoA) [55–58] in terms of temperature ranges and power limits where the chemical stability of each single cell is usually guaranteed. To operate in the SoA, a proper cooling system must be considered to avoid undesired thermal runaway phenomena which could damage permanently the entire battery pack [59–64]. Moreover, a proper Battery Management System must be designed to continuously monitor cells behavior, to avoid them to work outside their voltage limits both during charging and discharging [65–67]. This approach is necessary both for short and

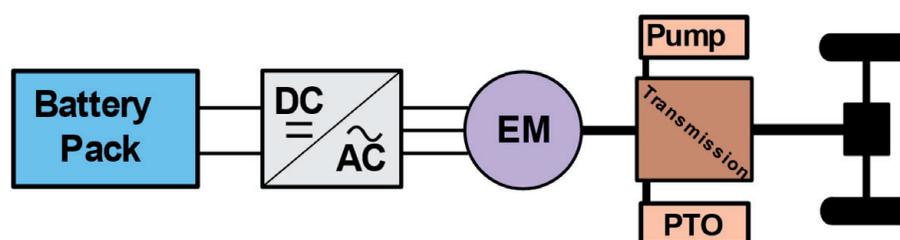


Figure 1.
Full electric architecture for a working vehicle.

long term performance analysis based on the State of Charge (SoC) [68–72] and State of Health [73–77] estimation using different modeling technique and specific testing activities [78–81]. If proper care of the battery pack working conditions is guaranteed, chemical aging mechanisms can be stemmed achieving a total life of thousands of cycles depending on the specific battery chemistry [82–84].

Battery electric vehicles represent today a promising alternative to traditional thermal powertrains. The actual state of the art LiB technology suggests that with proper design strategies this solution could be a suitable choice to propel also NRMMs. However, the actual cost [85–88] of the commercially available LiB solutions prevent from the widespread adoption of this type of architecture. New battery chemistries promise to increase the average LiB energy and power densities which could place this architectural solution closer to traditional powertrains.

2.2 Parallel hybrid electric vehicles

In a parallel hybrid electric vehicle, the power coming from an ICE and from an EM is mechanically combined to satisfy the power demand from all the different mechanical loads. This architectural solution allows to satisfy the same peak power demand of a traditional powertrain with a smaller ICE. This is called engine downsizing [89, 90] and is particularly useful when the average power demand is consistently lower than the peak power capability of the thermal engine. This is a very common problem especially in NRMMs where their multipurpose nature prescribes high power engines to satisfy all the possible loading scenario the machine might face during its operating life. Thus, the oversized engines usually work far from their nominal working conditions leading to higher fuel consumption. Using an electric machine coupled to a smaller engine, it is possible to cover the average power demand with the thermal unit and the peak power with the boost given by the electric system (**Figure 2**).

The parallel hybrid topology increases the overall efficiency of the vehicle requiring less amount of fuel per unit of work performed [91–93]. Moreover, the use of an EM and the fast response of the electronic units allow to quickly accommodate rapid variations in the external mechanical load. On the other hand, the topology intrinsically reduces the level of optimization on the ICE operating point. The mechanical connection between the engine and the external load does not allow it to work in the most efficient conditions. The rotational speed required by the application is intrinsically related to the actual engine speed so if the load requires a specific operating speed due to the limited amount of gear ratios of the transmission, the engine will rotate at a speed different from the optimal one. Thus, on this type of architecture, at least one clutch and a gearbox are required. The presence of these components increases the efforts required to integrate an external electric system on an existing vehicle layout.

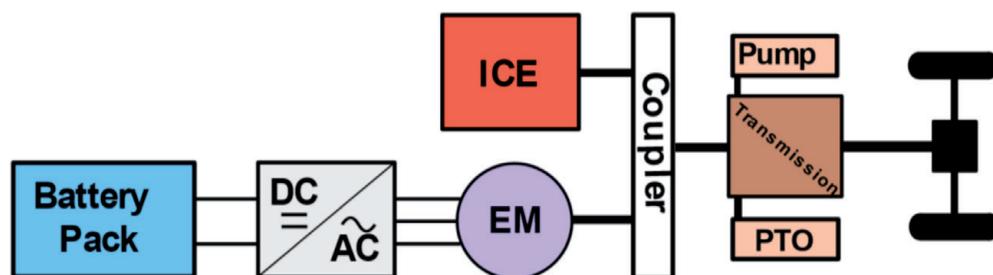


Figure 2.
Parallel hybrid architecture for a working vehicle.

2.3 Series hybrid electric vehicles

Most of the drawbacks of a parallel hybrid architecture are related to the mechanical connection between the ICE and the mechanical loads. The series hybrid topology shown in **Figure 3** addresses this problem, decoupling the ICE from the driveline. An electric generator (EG) attached to the engine is used to convert its mechanical power into electricity which can be used to charge the battery pack, to propel the vehicle using the electric motor attached to the driveline or both [94, 95]. Being mechanically free to rotate at its own speed, the engine can deliver power in its most efficient working points, most of the time in steady state conditions. This allows a high level of optimization in terms of fuel consumption depending on the specific working cycle [96–99]. A series hybrid configuration can work in different operating modes: full hybrid if all the power produced by the ICE is used to propel the vehicle (the presence of a battery pack may not be necessary); full electric if the engine is shut down and the installed battery pack is the only source of energy going into the driveline or other services (hydraulic systems, PTOs, etc.); mixed modes when both the ICE and the battery pack are involved. The last case is particularly interesting because the engine can be used both to propel the vehicle and to charge the battery pack when the power demand is lower than the current production. At the same time, the combined use of both the engine and the battery pack increases the power availability. This is the reason why the proper design of this architecture allows a higher level of engine downsizing compared to a parallel hybrid topology. As in the NRMM case, most of the time engines are oversized with respect of their standard working cycles. Thus, the availability of another source of energy allows to size the ICE for the average power demand covering the peaks with the electric system. The greater flexibility of this hybrid configuration comes at the price of a higher number of components, thus more on-board space is required. As shown in the following sections, this architecture well fit to machines where the power produced by the engine cannot be mechanically transferred by a shaft to the driveline because of the engine location inside the vehicle. Traditionally, this problem was faced using hydrostatic transmissions, which however are not very efficient if compared to electric power transmission [100–102].

2.4 Power split

Electric systems well perform when it comes to power transfer between machines that are not mechanically coupled together. This characteristic can be used to design power-split drivelines where power can be taken from a point of the transmission and used in another point with a different combination of torque and speed using combining mechanisms like planetary gear sets [103–105]. As

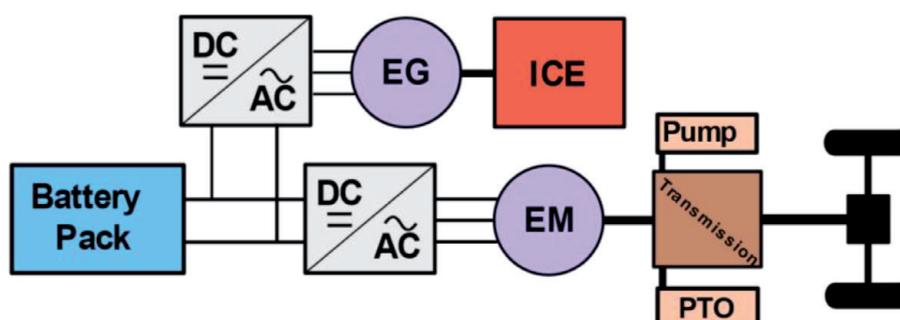


Figure 3.
Series hybrid architecture for a working vehicle.

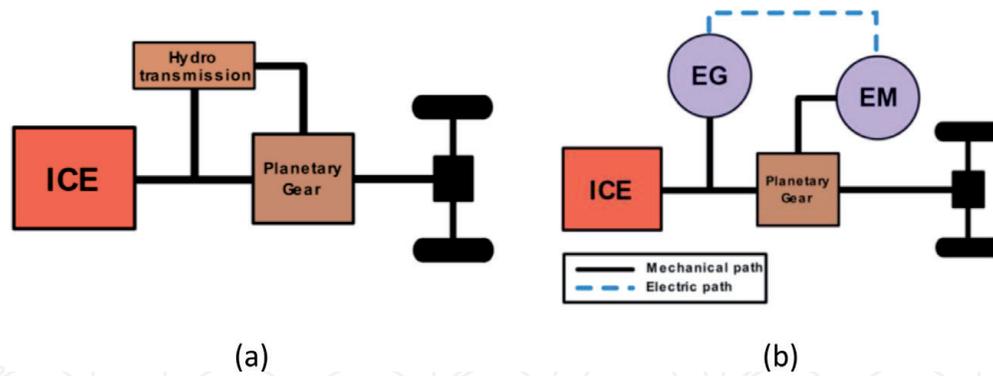


Figure 4. Hydraulic (a) and hybrid electric (b) power split configuration.

shown in **Figure 4**, this approach is not an exclusive feature of electric systems. Hydraulic power-split configurations have been widely used in the past on NRMMs achieving good performance in terms of controllability and power density. The main drawback is related to the low efficiency (60–70%) which characterize power transfer by mean of a hydraulic path. Depending on the vehicle layout thus on the distance between the pump and the hydraulic motor, the energy loss can increase consistently requiring a high-power engine to achieve the desired performance at the wheel or PTO. The same power-split capabilities can be achieved using an “Electric transmission”. An electric machine actuated as a generator (EG) can take power from a certain point of the transmission (usually directly from the ICE) and transfer it by means of a DC Bus to the electric motor (EM). The higher transmission efficiency (>85%) and its stability over time allows to consider highly optimized ICE, thus better performance of the overall driveline in terms of liters of fuel per unit of work.

2.5 Hybridization factor for NRMM

The high number of possible configurations achievable with the combination of an ICE and one or more electric machines makes it difficult to classify them. Several years ago [26, 106], the definition of a Hybridization Factor (HF) given in Eq. 1 was thought to classify different hybrid solution in automotive applications.

$$HF = \frac{P_{em}}{P_{ICE} + P_{em}} \quad (1)$$

Where:

P_{em} represents the power delivered by the electric motor/motors to propel the vehicle

P_{ICE} is the nominal power of the thermal unit.

With this definition, the lower the HF value, the lower is the contribution of the electric system to the overall power output of the driveline. In **Table 1**, the typical HF classification proposed for hybrid powertrains is shown. The lower and upper bound of this classification are of course the traditional thermal powered architecture (HF = 0) where the power demand is covered by the ICE and the full electric powertrain (HF = 1) where electricity is the only on-board source of power. In between, there are all the possible combination. Micro hybrid indicates those vehicles with small electric systems (usually 12–48 V) used to help the ICE mainly

Electrification class	HF
Micro Hybrid	< 5%
Mild Hybrid	5–10%
Full Hybrid	10–50%
Parallel	50–75%
Series	
Full Electric	100%

Table 1.
 Typical HF classification for automotive powertrains.

in start/stop conditions. Mild hybrid are systems with high voltage battery systems (200 V) with the aim to help the engine mainly during transient working conditions. Full hybrid configurations have high voltage electric systems (>400 V) to power the vehicle together with downsized ICE. Some battery packs have enough stored energy to propel the vehicle in full electric mode for small periods if the driveline is designed to allow it.

In the field of NRMMs, the classification problem is a more challenging task due to the large differences among the categories included in the same class. The very first problem to face when dealing with the classification of these machines is the presence of different power path and users inside the same vehicles. In a car, the power coming from the engine will be mainly used to propel the vehicle. The power required by the auxiliaries is usually a very small fraction of the engine delivery. Thus, the hybridization level of the main power user (the driveline) coincides with the one of the entire vehicle. On the other hand, in NRMMs different power path and users can usually coexists with similar power needs. Thus, the Hybridization Factor definition must consider the level of hybridization of each power user within the same machine. This is the reason why Somà et al. proposed in [24, 107] a new formulation of the Hybridization Factor (Eq. 2) specifically defined for working machines. In this definition, there is a clear distinction between the two main functions of this class of vehicles: the driving (HF_{Drive}) and working ($HF_{Loading}$) paths. Considering telescopic handlers as main case study, the authors proposed an equal distribution of the overall power demand scenario which translated into a weight factor of 0.5 to be applied to each path.

$$HF_{WM} = \frac{1}{2} (HF_{Drive} + HF_{Loading}) \quad (2)$$

This definition overcomes the standard approach proposed in the automotive field introducing a clear distinction between what can be described as the wheel path and the other ones (hydraulic tools, implements, etc.) which instead characterize and distinguish each NRMM. If no specific information about the machine working cycle are available, it is possible to assume that on average both the driveline and the other mechanical loads have the same weight in terms of power demand for the engine.

3. Overview on powertrain electrification for NRMM

International regulations about vehicle emissions are pushing the industry and the scientific community into the investigation of new alternative powertrain

solutions for NRMM. Requirements are clearly stated in those documents and the main outcome is the same in all the categories grouped under the NRMM definition: more efficient and less pollutant machines are mandatory. Manufacturers from the construction field were already the pioneers in the electrification process back in the early 2000s. Later on, several other segments started to consider electric powertrains in all their different topologies to improve their products performance. In the following sections an overview on the actual state of the art of hybrid and electric NRMM is presented, considering both prototype concepts and production machines where available. Due to the wide range of machines falling within the EU definition, the authors propose an analysis focused on the three main categories of industrial working machines: Construction, Handling and Agriculture. These three fields will be explored in this order also because of the historical evolution that involved the electrification process. As already stated, in the construction field the first movements started back in the early 2000s. Then, several solutions were proposed in the handling field which can be considered also in between the needs that come both from the construction and agriculture field. Nowadays, also several manufacturers from the agriculture field are experiencing new electric solution which both allow to meet emissions regulations and to increase the overall productivity with the adoption of a higher level of automation.

3.1 Construction

The first scouting attempts on the real capabilities of electric powertrains in industrial vehicles were performed in the construction field as discussed in [108, 109]. First excavators [110–112], then wheel loaders and bulldozers were electrified with different hybridization levels [113–115]. Nowadays, several manufacturers are already at a mature development stage and propose to the market electrified version of their top line products. In the following sections, a review of the most mature hybrid technologies in the construction field is given.

3.1.1 Excavator

Nowadays, the most relevant excavators' manufacturers propose to the market electric and hybrid solution as alternative solution to traditional powertrains demonstrating the maturity of this technology on this specific segment. The most widely adopted architecture for this type of machines consists in a series-parallel configuration like the one shown in **Figure 5**. The ICE is coupled with an electric motor/generator machine which can supply/take power to/from the mechanical path depending on the actual working condition. The electric system usually consists also of an ESS in charge of exchanging electric power with the electric machine which actuate the swing mechanism of the machine. During the acceleration phase of the swing movement, both the ESS and the motor generator attached to the ICE can provide power to improve performance. Vice versa, during deceleration the ESS can recover the electric energy coming from the swing machine actuated as a braking element.

If on one hand the architecture is more or less the same among different players as shown in **Table 2**, the structure of the ESS is a strategic point and several solutions are available today. Manufacturers like Komatsu [115] and Hitachi [117] use Ultracapacitor based ESS in favor of a higher power capability. Other manufacturers like Kobelco [118] prefer to use LiB based ESS in favor of their higher energy density. These two solutions affect the ICE sizing at the design stage as well as the control strategy which is in charge of optimizing power delivery and fuel consumption. Currently, the tracks, the arm, the boom and the bucket are still hydraulically actuated using the fluid coming from the pump mechanically coupled to the hybrid

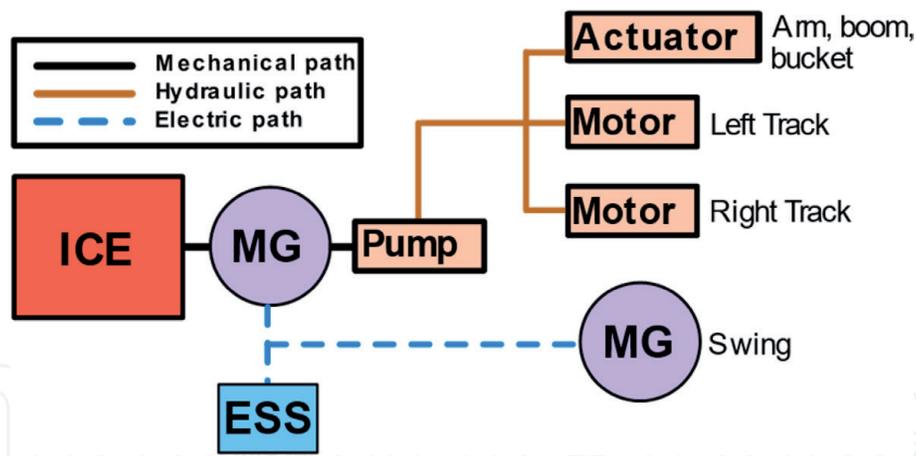


Figure 5.
 Common hybrid architecture for hybrid excavators.

Manufacturer	Model	Year	Operative weight (t)	Architecture Drive-Load	ESS
Bobcat	E10e	2019	1.2	Full Electric	Li-Ion
Caterpillar	323F ZLine	2019	25.7	Full Electric	Li-Ion
Hitachi [116]	ZH210 5	2014	22	Parallel-Series	Supercapacitor
	ZH210 6	2017	22	Parallel-Series	Li-Ion
	ZE85	2019	8.5	Full Electric	Li-Ion
	ZE19	2019	1.9	Full Electric	Li-Ion
Kobelco [117]	SK210 H	2017	21	Parallel-Series	Li-Ion
	SK17SR-3E	2019	1.7	Full Electric	Li-Ion
Komatsu [115]	HB215LC-3	2018	21.5	Parallel-Series	Supercapacitor
	HB365LC-3	2016	36.5	Parallel-Series	Supercapacitor
	Mini Excavator	2019	4.7	Full Electric	Li-Ion
Volvo	EX2	2017	2.5	Full Electric	Li-Ion
	ECR25	2019	2.5	Full Electric	Li-Ion
Wacker Neuson	EZ17e	2019	1.7	Full Electric	Li-Ion
	EZ26e	2019	2.6	Full Electric	Li-Ion

Table 2.
 Hybrid electric excavators.

power unit. Since no mechanical connection is present between the ICE and the mechanical loads, this architecture allows the design of energy optimization strategies focused on finding the most efficient engine working point to meet the actual power demand. It is also interesting to note how several manufacturers proposed full electric solutions for small excavators in the last years (**Table 2**). One of the main reasons for this trend is the possibility to use these full electric machines in urban area with low emission restrictions for public health reasons.

3.1.2 Wheel loaders

Among wheel loaders manufacturers, Caterpillar, Hitachi, John Deere and Volvo have demonstrated to be fully involved in the electrification process of their products (**Table 3**). Compared to excavators, the different vehicle architecture of these

Manufacturer	Model	Year	Operative weight (t)	Architecture Drive-Load	ESS
Atlas Weyhausen	AR65	2010	6.5	Parallel-Parallel	Li-Ion
Caterpillar	988 K XE	2017	52.7	Series-N/A	N/A
	906	2019	5.6	Full Electric	Li-Ion
Hitachi [119]	ZW220HYB-5B	2015	18.8	Series-Parallel	Supercapacitor
John Deere [120]	944 K	2013	54.2	Series-N/A	N/A
Kramer [121]	5055e	2016	4.1	Full Electric	Lead Acid
Mecalac	12MTX	2009	11.4	Parallel-Parallel	Li-Ion
	e12	2018	11.4	Full Electric	Li-Ion
Volvo [122–124]	L220F	2008	31	Parallel-Parallel	Li-Ion
	LX1	2017	21	Series-Parallel	Li-Ion
	LX2	2017	4.9	Full Electric	Li-Ion
	L25	2019	5	Full Electric	Li-Ion

Table 3.
Hybrid electric wheel loaders.

machines well fit with different hybrid electric solutions. As the example shown in **Figure 6a**, Hitachi used a series architecture for its ZW220HYB-5 [119]. In this architectural solution, the hybrid power unit obtained by the mechanical coupling between an ICE and an electric generator is responsible of the electric energy production that is transferred to the two electric motors installed on the front and rear axle to propel the vehicle. The adoption of two independent electric machine for the driveline allows for better traction management and energy recovery during braking. An ultra-capacitor based ESS is in charge of providing a power boost to the two electric machines attached to the driveline as well as of recovering the energy during regenerative braking. Moreover, the extra power can help the ICE during transient conditions and in case of stationary operations.

Other interesting solution have been developed by Volvo in the last years. The Volvo L220F Hybrid was the first result of the electrification research and development program of this company [122]. The architecture developed for this machine is shown in **Figure 6b**. It was a parallel hybrid configuration with an electric motor/generator mechanically coupled to the engine shaft. The main goal of this structure was to help the engine during transient operations providing the required extra power and to allow frequent and responsive start & stop operations thanks to the higher power capabilities of the installed electric motor compared to usual engine starters. The adoption of an ultra-capacitors based ESS allowed for fast power boost during transient operations as well as for energy recovery during braking. In this case, the power unit was mechanically connected to the driveline by mean of a gearbox which split the mechanical power between the front and rear axle. Thus, the engine working point was intrinsically related to the load characteristics, limiting the degrees of freedom in energy management and optimization.

Two hybrid and electric vehicle derived from L220F Hybrid project: the LX1 (**Figure 6c**) [123] and the LX2 [124]. The former is a series hybrid configuration with no mechanical driveline. Four electric motor/generators are directly connected

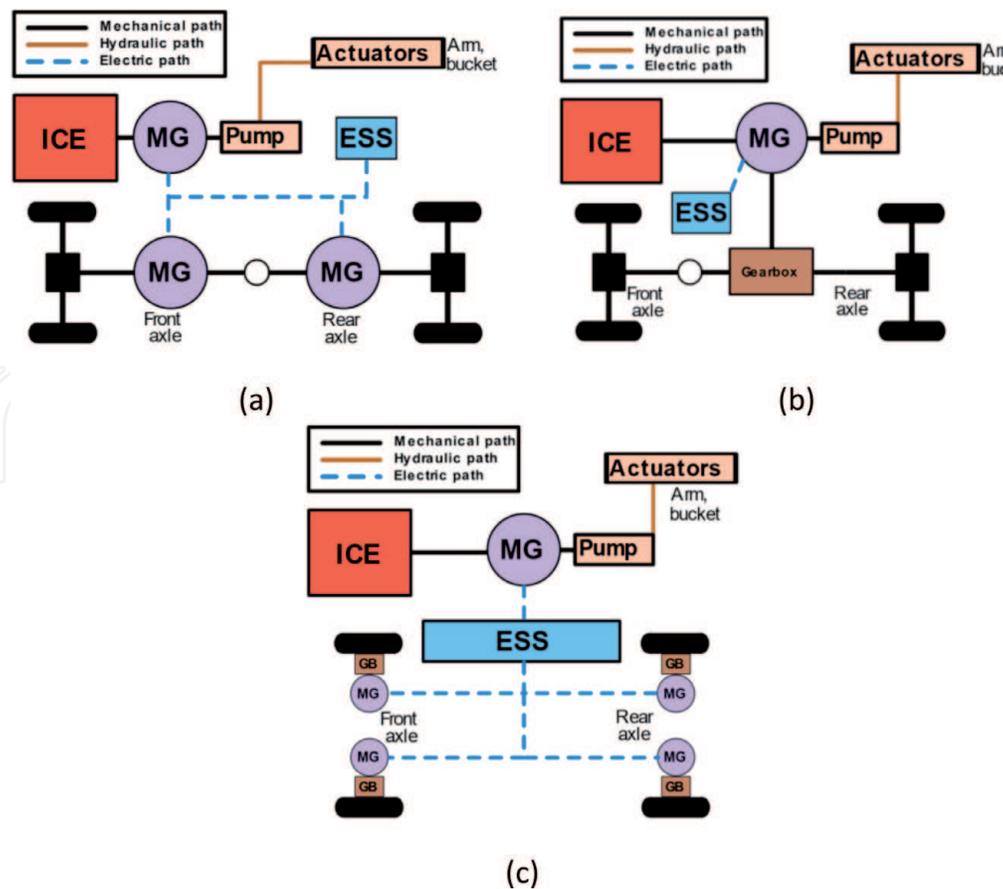


Figure 6.
 Common hybrid architecture for hybrid wheel loaders: a) Hitachi ZW220HYB-5, b) Volvo L220F, c) Volvo LX1.

to each wheel and use the power coming from the hybrid power unit with the ICE coupled to an electric motor/generator. The system can rely also on a battery based ESS which guarantees a certain full electric capability to this machine. This configuration comes with a downsized Diesel engine to cover the average power demand of the working cycle using the electric system to supply extra power for the instantaneous peaks. The combination of a smaller Diesel engine and an overall higher efficiency of the driveline allows to achieve lower fuel consumption as demonstrated by the field tests performed by Volvo. On the other side, the LX2 project is a small full electric autonomous dumper designed to work for a full day without any local emission.

Another interesting solution was proposed by John Deere with the 944 K Hybrid Wheel Loader [120]. The loader proposed by John Deere is a series hybrid configuration with four electric drives, one for each wheel and a motor/generator mechanically coupled with the ICE. The main difference between this architecture and the one proposed by Volvo (LX1) is the absence of an ESS on board. The hybrid power unit (ICE+MG) is responsible for the overall electric energy production, thus for the power going to the wheels to propel the vehicle. The use of high-power brake resistors is mandatory to preserve the high voltage DC bus when the four motors must provide braking power. To regulate the overall vehicle speed during downhill, the four electric machines must provide braking torque, thus must work as generators. The electric energy coming from the vehicle kinetic energy can be dissipated as heat into the brake resistors without permanently damaging the High Voltage Bus. A controlled braking torque allows to achieve constant speed during downhill increasing productivity and reducing the operator efforts (Figure 7).

Other manufacturers developed hybrid wheel loaders prototypes as shown in Table 3. However, as demonstrated also in other NRMM segments, the

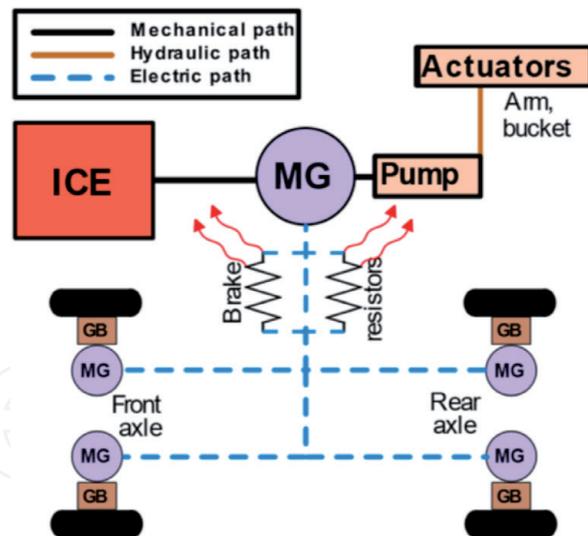


Figure 7.
Hybrid architecture: John Deere 944 K wheel loader.

improvements in LiB ESS and their lower costs are pushing manufacturers towards full electric architectures, especially for small loaders used primary in closed environments (Low Emissions Zone). Kramer, with its 5055e [121] wheel loader is the perfect example of this trend.

3.2 Handling

Handling machines can be found in several fields of application, from construction to agriculture and more in general in all freight movements between different places. These machines are characterized by a high level of versatility thanks also to the use of proper external tools. Several studies focused in finding the best way to electrify this class of machines, focusing their attention on the lifting/handling systems as well as on the driveline [24, 25, 125].

Among the manufacturers involved in the development of hybrid electric solutions for telehandlers, the Italian manufacturer Merlo was the first in proposing a hybrid electric architecture. In 2010 at Bauma (one of the most worldwide known fairs about construction machines) the company presented their first hybrid electric prototype of a telescopic handler, the P25.5. However, the project grew both technologically and architecturally leading to the gold medal received at the Agritechnica fair in 2013 thanks to the hybrid electric turbo-farmer TF40.7 [24]–[25]. As shown in **Figure 8**, a series–parallel configuration was chosen to provide power both to the driveline and to the hydraulic system which actuates the telescopic boom. Looking closely the architecture, the driveline is a traditional series hybrid topology, with an electric motor/generator directly connected to the input of the gearbox which then split the power between the front and rear axles. This electric machine can receive power from the hybrid power unit (ICE+MG) designed with a smaller diesel engine or from a LiB based ESS which could also allow for some full electric operations in Low Emissions Zones. The hydraulic path is supplied by the hybrid power unit to which the pump is mechanically connected. Moreover, a specific design of the mechanical architecture allows to move the telescopic in full electric operations without the need to power on the ICE [126].

In 2018, two different manufacturers proposed two hybrid electric telescopic handlers projects: the Liebherr TL 432–7 and the Manitou MT1135. A common denominator can be found between these two projects. Both are powered by the E-Deutz power unit [127]. Deutz is an OEM manufacturer focused on diesel engines

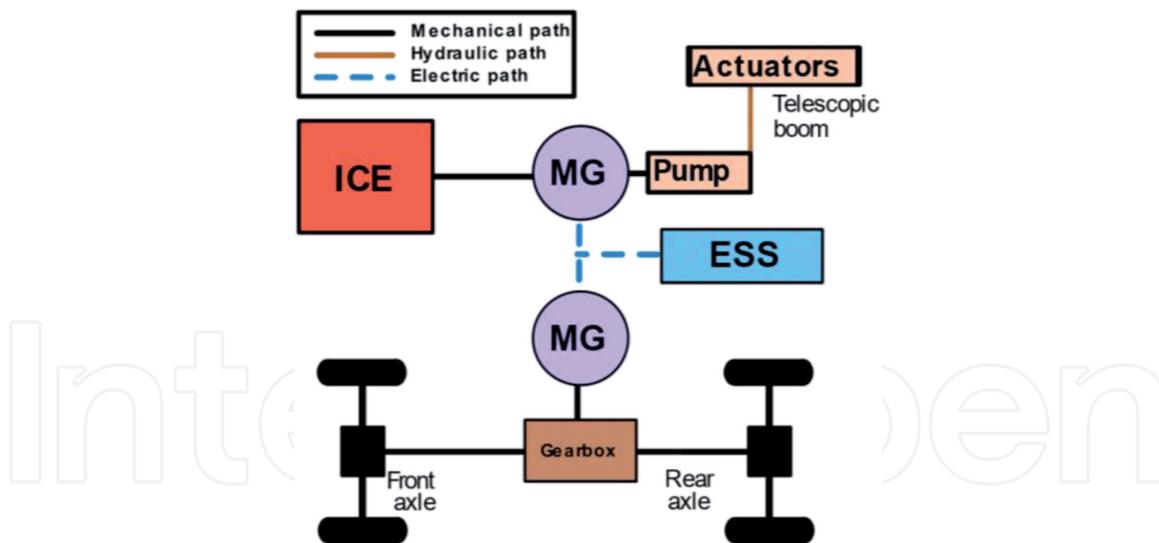


Figure 8.
 Hybrid architecture: Merlo TF 40.7 telescopic handler.

for off-road applications. The E-Deutz system consists of an electric drive mechanically coupled to a diesel engine through a mechanical transmission able to disengage the connection when necessary. Like in a traditional parallel hybrid power unit, the electric motor can provide extra power to the engine during transient heavy operations using the energy stored in a LiB based ESS. The key point of this solution is the electric characteristics of the system. The ESS and the DC bus of the power line has a nominal voltage of 48 Volt. Despite the high current required to provide the nominal power of the electric machine (≈ 20 kW for a total of 400 A), the low voltage electric system is something which also other manufacturers are looking for. Although not explicitly declared, low voltage electric systems may represent a clear trend for the near future. To the authors opinion, the higher safety level against electric shock of a low voltage system could be the key to disrupt the skepticism of the final user against the adoption of electrified technologies. However, it is clear that low voltage systems are possible only in low power application due to the high currents that could be involved in heavy duty tasks.

As shown in **Table 4**, several other interesting applications can be found in the literature as well as in some commercial product. The trend is to move towards full electric configurations which greatly simplify an architecture which is already very complex due to the high number of tasks these machines can be called to perform. Within the E-Deutz project, Liebherr and Manitou recently presented two full electric prototypes characterized by a high voltage battery pack (about 400 V). On the other hand, Manitou is developing another electrification project called Oxygen [128], a series of electric and hybrid handlers presented at Bauma fair in 2019. Small telescopic handlers have a real possibility to be fully electrified thanks to their relatively less demanding use. These machines usually operate in limited areas where the availability of charging point can reduce the range anxiety regarding full electric solutions.

Talking about small machines, the Italian manufacturer Galizia proposed a small telescopic handler the Multi 636 electric several years ago. This machine was powered by a 48 V system demonstrating that the limited amount of power which characterizes its typical workload could be satisfied by a low voltage system. Recently, also another Italian manufacturer Faresin proposed the 6.26 [129], a small full electric telehandler.

Other interesting application of electric technologies in the handling field can be found in port container handlers. Konecranes is the pioneer manufacturer in this

Manufacturer	Model	Year	Operative weight (t)	Architecture Drive-Load	ESS
Merlo [24, 25]	P41.7	2010	6.7	Series-Parallel	Li-Ion
	TF40.7	2013	7.5	Series-Parallel	Li-Ion
	Roto 45.35 S	2016	15.4	Series-Parallel	Li-Ion
Liebherr (E-Deutz) [127]	TL 432-7	2018	7	Parallel-Parallel	Li-Ion
	TL 432-7	2018	7	Full Electric	Li-Ion
Manitou (E-Deutz) [127]	MT1135	2018	8.9	Parallel-Parallel	Li-Ion
	MT1135	2018	8.9	Full Electric	Li-Ion
Manitou Oxygen [128]	MRT 2550 h	2019	18.9	Series-Parallel	Li-Ion
	MT 625 e	2019	4.7	Full Electric	Li-Ion
Faresin [129]	6.26	2018	2.6	Full Electric	Li-Ion
Galizia [130]	Multi 636	2014	6.4	Full Electric	Lead Acid
Konecranes [131]	SMV 4531 TB5 HLT	2013	45	Series-Parallel	Supercapacitor
CSV Ferrari [132]	HY-LIFT	2017	38.5	Series-Electric	Supercapacitor
XCMG	XCS45-EV	2018	45	Full Electric	Li-Ion

Table 4.
Hybrid electric handlers.

sector. The company presented in 2013 the SMV 4531 TB5 HLT reach stacker [131]. This machine consists of a series-parallel configuration where the hybrid power unit provide power both to electric driveline and to the electro-hydraulic lifting system. The adoption of an ultra-capacitors based ESS well fit to the application due to the frequent lifting operation from which is possible to recover a good amount of energy. Similarly to Konecranes, the Italian manufacturer CSV-Ferrari developed a hybrid ultra-capacitor based container handler called HY-Lift [132] which uses two electric motors to power the driveline.

3.3 Agriculture

There is a large number of machines designed to increase the mechanization level of agricultural or farming tasks. However, this variety can be simplified if the analysis is performed looking at the common needs of a farmer. The most used machines to pull and move objects as well as to transfer power to external devices are tractors. In few cases, depending on the size of the machine and on how often it needs to be used, it may be convenient to install a dedicated power unit which can be used for self-propulsion. There are several machines which can be identified in this category but the number of electric or hybrid configuration is still very small. Thus, for the purpose of this analysis agricultural machines will be divided in tractors and other agriculture machines.

3.3.1 Tractors

In a farm, tractors can be seen as a multipurpose machine able to pull trailers or external tools (properly called implements) and/or provide power to other machines or implements which do not have their own power unit. As shown in **Table 5**, the electrification process in agriculture started in the early 2000s [140–142] but, for a long time, nothing more than sporadic projects can be found. The first official concept was presented by Belarus at Agritechnica 2009: it was the Belarus/RuselProm 3022e [133, 143]. As shown in **Figure 9**, it was a full series hybrid with no external ESS. Thus, the power required to propel the vehicle and, eventually, external auxiliaries came always from the ICE. There are pros and cons to this architectural solution. The series configuration allows to disconnect the ICE from the driveline, giving higher freedom in energy management. Moreover, the adoption of an electric drive which can operate also at low rpm (down to 0) without the need of external gear reductions allows to reduce and simplify the overall layout of the gearbox. This is a big advantage especially for tractors which are well known

Manufacturer	Model	Year	Operative weight (t)	Architecture Drive-Load	ESS
Belarus/RuselProm [133]	3022e	2009	11	Series–Parallel	N/A
Claas [134]	Arion 650	2015	6.8	N/A-Series	Li-Ion
Carraro [135]	Ibrido	2018	2.7	Parallel–Parallel	Li-Ion
Fendt [136]	e100 Vario	2017	3	Full Electric	Li-Ion
John Deere [137, 138]	6210 RE	2013	7.3	N/A-Series	N/A
	6R SESAM	2016	7.3	Full Electric	Li-Ion
RigiTrac [139]	EWD 120	2011	8	Series–Series/ NA	Li-Ion
	SK50	2018	2.4	Full Electric	Li-Ion

Table 5.
Hybrid electric tractor.

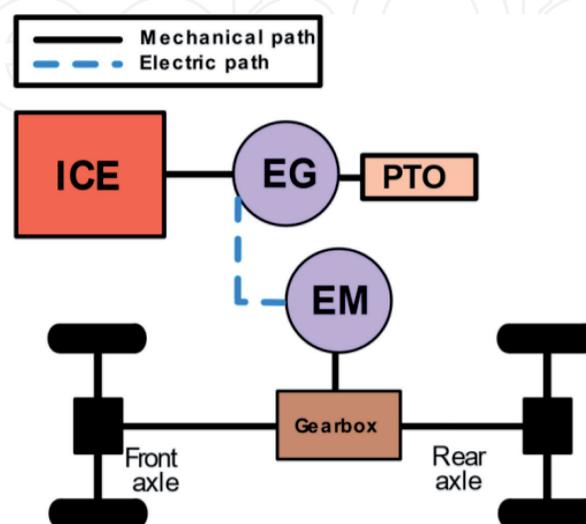


Figure 9.
Hybrid architecture: Belarus 3022e tractor.

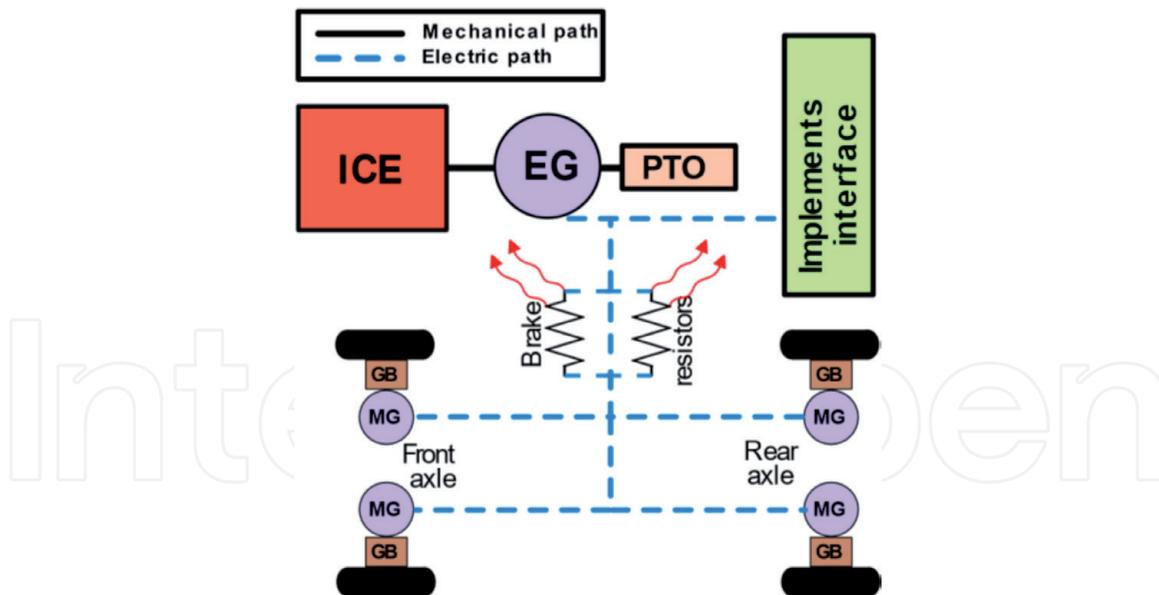


Figure 10.
Hybrid architecture: RigiTrac EWD 120 tractor.

for having a large number of gear ratio to cover all the possible working needs of the user. However, some cons can be identified in this architectural solution. The absence of an external ESS does not allow any engine downsizing in favor of fuel consumption optimization. The ICE must be able to cover the peak power requirements of the traditional power unit. Moreover, the physical connection with the PTO forces the engine to rotate at fixed rotational speeds prescribed for this standard connection (usually 540 and 1000 rpm). Thus, when powering external tools, the energy management strategy cannot pursue the optimal working point for the ICE.

In 2011, the company RigiTrac presented the EWD 120 at Agritechnica 2011 [139]. As shown in **Figure 10**, the architecture proposed by the Swiss company consisted of a full series architecture where the hybrid power unit was in charge of producing the electric energy required to propel the four in-wheel motors. This was the true innovation introduced with respect of the previous concepts. In-wheel electric motors well fit to machines which have to properly transmit torque to the ground to maximize traction. The fine controllability obtainable with this driveline solution allows to achieve better performance in traction force. However, the major innovation introduced with this prototype, which is also in accordance with the most recent trends in this field, is related to the adoption of an electric interface to transfer electric power to external implements [134] – [137, 144]. Implements are usually powered mechanically through the PTO and/or hydraulically using the power taken by a hydraulic pump from the ICE (usually low power applications). The mechanical connection of the load to the PTO shaft, force the engine to rotate to the standard speeds discussed before. Moreover, within the implement the PTO power is split by means of complex mechanisms which convert the rotational motion to the most convenient form for the final implement users. This process is highly inefficient and usually does not guarantee a high precision in the motion transmission, especially in the long term due to wear of mechanical components. This is becoming a strong drawback now more than ever because of the need for highly accurate implements required in the framework of precision farming. The availability of an electric power source (the hybrid unit) and the possibility to easily transfer this power to electrically driven devices on the implements were the major breakthroughs of this prototype.

Following the RigiTrac example, John Deere (2013) and Claas (2015) presented two implement oriented electrified tractors. The John Deere 6210 RE [137] and the Claas Arion 650 Hybrid [134] tractor architectures can be schematically described as shown in **Figure 11a** and **b**. They consist of an electric generator connected to the ICE which convert its mechanical energy into electric energy for the high voltage implement interface. Thus, this configuration can be thought as a series configuration from the implement point of view and a traditional mechanical architecture for the driveline which is powered by the ICE.

In this architecture, the role of the energy management controllers is crucial. It is clear that an intelligent controller must be developed also on the implement side to evaluate what is the actual power demand which must be provided by the control unit on the tractor side. However, the adoption of advanced controllers on the implement is an already started process which will bring high precision tools in the next years.

More recently, full electric tractors have been presented by several manufacturers. In 2016 John Deere presented at SIMA a full electric prototype of the 6R SESAM [138], the first modern battery powered tractor. It is equipped with two electric machines which propel the transmission and the PTO. The on-board battery pack is claimed to reach 4 hours of mixed work or 55 km of transportation.

On year later, in 2017 Fendt presented the e100 Vario [136] at Agritechnica 2017, the first full electric specialized tractor. A single electric motor is used to propel both the rear and front axle (when the 4WD is required). The system is powered by a 100 kWh battery pack claimed by the manufacturer to accomplish an entire working day with a single charge.

In 2018, Carraro presented the first hybrid electric orchard tractor “Carraro Ibrido” [135] at EIMA fair. This interesting concept considered a pure parallel architecture with a motor generator coupled to a downsized ICE to provide extra power when needed. A small battery pack was considered to store the required electric energy.

At the end of 2018, John Deere presented another electric project: A full electric, cable powered, autonomous tractor [145]. There are traces of similar solutions designed in the Soviet Union when the tractor was directly connected to the grid. At that time the benefits of the technological solution were not enough to justify it. Now, with the increasing need of more efficient vehicles and with the possibility to fully automatize some field operations thanks to autonomous technologies, this idea

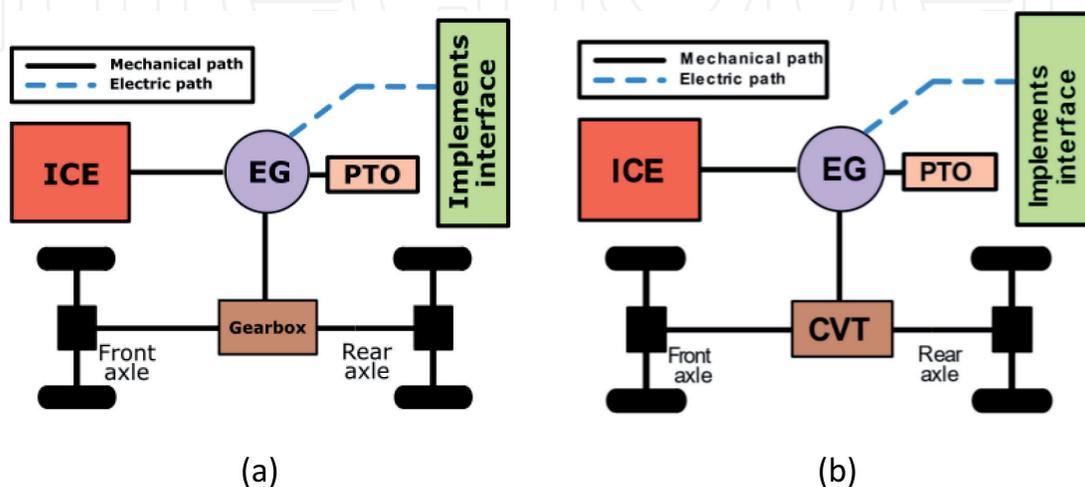


Figure 11.
 Hybrid architecture: (a) John Deere 6210 RE, (b) Claas Arion 650 hybrid tractor.

Manufacturer	Model	Year	Operative weight (t)	Architecture Drive-Load	ESS
Supertino [33]	Electra 21	2017	11.9	Full Electric	Li-Ion
Siloking [147]	TruckLine e.0	2016	3.5	Full Electric	—
Kremer [150]	T4E	2013	—	Full Electric	Li-Ion
Schaeffer [148]	23-e	2017	2.3	Full Electric	Li-Ion

Table 6.
Other electric machines in agriculture.

could regain interest. The solution could increase productivity, allowing for 24/7 operations without the need of refuel the tank nor recharge the battery pack.

3.3.2 Others

Although electrification is a well-established trend on the tractor side, there are some relevant applications also on other fields of application too. Generally speaking, these machines are self-propelled machines which have been electrified to reduce emissions with respect to their traditional Diesel engine powered versions. One example is surely the vertical feed mixer by the Italian manufacturer Supertino [33, 146]. In this case, the analysis of the working cycle of these types of machines clearly demonstrates the feasibility of a full electric architecture. The limited area where usually these machines operate reduce the range anxiety because the installed power can be used mainly to conclude the cow feeding. Other manufactures have proposed similar machines. One example can be found in the German manufacturer Siloking [147], which proposes a smaller size full electric feed mixer as well.

Other electric examples can be found when looking at all the handling machines used in agriculture. Surely the Merlo TurboFarmer hybrid presented in the previous section falls also into this category. However, there is a large group of manufacturers that are electrifying small handlers and forklifts, traditionally powered by small Diesel engines. Examples in this direction are the Schaeffer 23-e and 24-e [148]–[149] small, full electric loaders mainly used in farming and green maintenance applications.

Finally, it is also worth to mention the first full electric straddle tractor from the French company Kremer: the T4E [150], which aim was to reduce as much as possible the vines contamination level related to exhaust emissions and oil losses from hydraulic tools. This aspect is also an interesting point for those who wants to dedicate to biological agriculture since no contaminants will deposit on plants if full electric solutions are adopted (**Table 6**).

4. Discussion and conclusions

Nowadays, the scientific community and NRMMS manufacturers are investing time and efforts to bring electric technologies into several working field to achieve better performance in a more efficient and less pollutant way. The actual state of the art in terms of technology level is compliant with the working scenarios if the hybrid/electric architecture is properly designed according to the specific need of each application. The successful application of electric technology in Construction, Handling and Agriculture, has proved two major aspects: the suitability of electric technologies also for heavy duty tasks as well as for harsh environments and the overall lower Total Cost of Ownership (TCO) of those electrified machines

compared to their equivalent Diesel-powered versions. In the last decade, the agriculture field has demonstrated to be the most conservative and skeptic field of application. However, the advantages deriving from the electrification of traditional powertrain, the robustness of the new technologies and the strict emissions regulations are pushing manufacturers towards these new technologies. During all the fairs where these new prototypes and/or products were presented, the feedback from the respective community of interest has always been positive. This is demonstrated by all the prizes these machines have won as innovation awards. However, the technology still has difficulties when it comes to the widespread acceptance from the market. There is a mismatch between what the new machines offers and what the final user searches to satisfy their need. To the authors opinion, there are two major elements that are preventing the market acknowledgement for these machines:

- The variety of working scenario that each machine can face during its life makes it difficult to design the perfect architecture to fulfill all the requirements.
- The influences deriving from the automotive field which represent a major concern against the adoption of electric technologies in the NRMM field.

Today's design methodologies derive from standard approaches focused on Diesel technologies which do not have the problem of not having enough energy to accomplish the workday. Diesel powered machines usually comes with oversized engines to cover the peak power demands that can be faced during the whole operating life. Depending on the specific machine, these situations may happen very few times during their entire life thus the average fuel consumption would be higher just to have the capability of doing something instead of really doing it. An oversized power unit can be accepted when the re-fueling time is negligible, but it becomes a real concern for those machines where the recharging time is high and must be well programmed during the working day to minimize the costs. Moreover, an oversized electric architecture can increase a lot the final cost of the machine, thus a more optimized design must be pursued. A proper design of the electrified architecture must identify which applications can benefit from a full electric solution from those where hybrid powertrains still represent the best compromise in terms of costs/benefits between the past and the future. It is not a case that all the major manufacturers choose hybrid solution for high power machines. They offer several advantages but with a faster way to recharge the on-board energy reservoir. Although the advantages of a full electric solution from the architectural point of view, very few cases can now fit with the current limitation of the actual state of the art of battery technologies. Moreover, the diffusion of electric vehicles in the automotive fields is showing both the advantages and the weaknesses of the actual level of technology. The common term range anxiety which addresses the not comfortable feel of the user to accomplish a certain trip with the on-board charge, is inevitably affecting also the use of electric technology in the NRMM field. Not being able to close a working task may translates in additional costs related to cumulative delays and this is not acceptable for companies which will use these new machines. However, the proper design of the HF and of the ESS can solve this problem. The higher the HF, the more the machine will rely on the installed ESS. Thus, for heavy-duty machines the best solution is to pursue a hybrid solution with a downsized Diesel engine supported by an ESS based electric system. For small machines and other special cases (depending on the specific working cycle) Full Electric solutions are perfectly possible as also demonstrated in **Figure 12**, where the trend in the last years is clearly

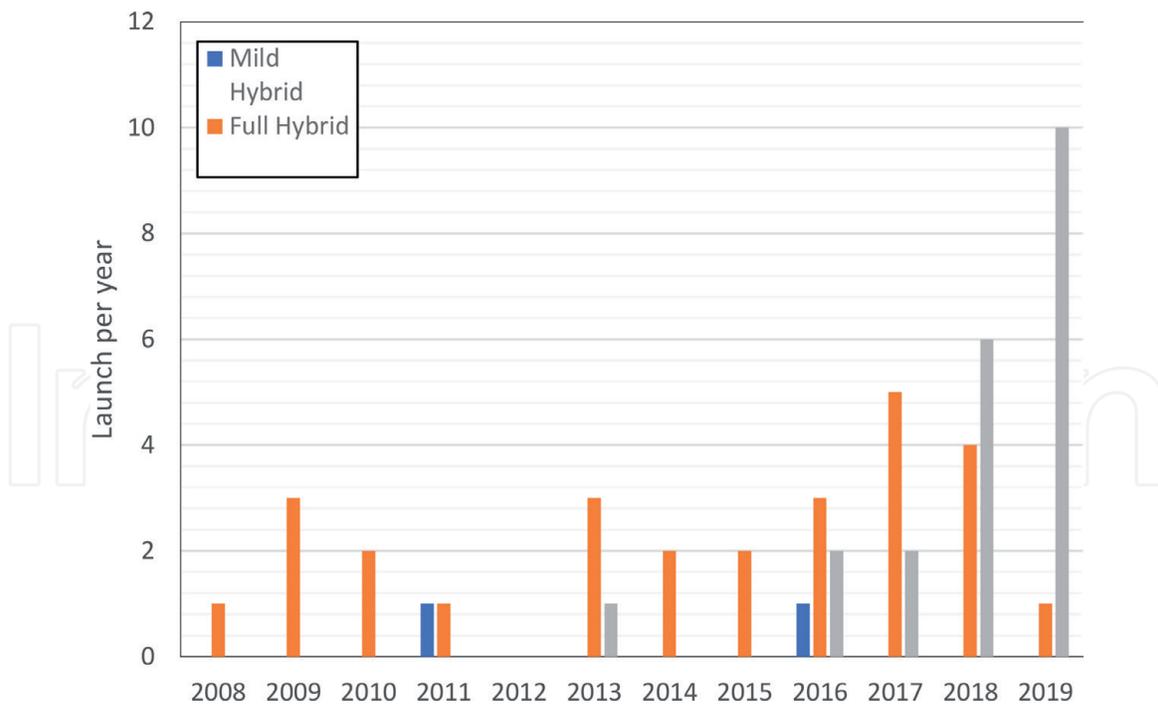


Figure 12.
Overview hybrid electric NRMM launched between 2008 and 2019.

in their favor. Moreover, new LiB technologies with higher energy density or faster charge time are approaching the market and this will solve most of the problem related to the on-board ESS. However, the future of working machines will be more and more closely related to electric technologies and at a some point the final user will have the possibility to choose between electric and non-electric powertrains with no major compromises compared to old traditional ones.

In conclusion, the proposed research review highlighted a clear trend in the scientific and industry community. Electrification is entering, at different growth rates, in different fields of working vehicles, because of the possibility to approach a common problem (reduce emission maintaining the power requirements) with the possibility to improve the technical features of the machine itself. Clearly, electric systems allow to introduce more precise control in any working feature that can translate to productivity increase. Thus, new concepts and solutions can be expected in the next years together with mass production of some consolidated technologies.

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