Chapter 1

Trends and Hybridization Factor for Heavy-Duty Working Vehicles

Aurelio Somà

Additional information is available at the end of the chapter

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Abstract

Reducing the environmental impact of ground vehicles is one of the most important issues in modern society. Construction and agricultural vehicles contribute to pollution due to their huge power trains, which consume a large amount of petrol and produce many exhaust emissions. In this study, several recently proposed hybrid electric architectures of heavy-duty working vehicles are presented and described. Producers have recently shown considerable attention to similar research, which, however, are still at the initial stages of development. In addition, despite having some similarities with the automotive field, the working machine sector has technical features that require specific studies and the development of specific solutions. In this work, the advantages and disadvantages of hybrid electric solutions are pointed out, focusing on the greater electromechanical complexity of the machines and their components. A specific hybridization factor for working vehicles is introduced, taking into account both the driving and the loading requirements in order to classify and compare the different hybrid solutions.

Keywords: hybrid, electric driveline, working vehicle, hybridization factor

1. Introduction

Over the past decades, the efficiency of vehicles has become a highly discussed topic due to pollution regulation requirements. Modern internal combustion engines (ICEs) have already reached remarkable performances compared with the engines of the early 1990s. However, they are still unable to consistently reverse the growth trend in pollutant emissions because the number of vehicles is also constantly increasing [1, 2]. The European Union first introduced mandatory CO_2 standards for new passenger cars in 2009 [3] and set a 2020-onward target average emission of 95 g CO_2/km for new car fleets. The automotive industry devotes considerable research efforts toward reducing emissions and fossil fuel dependency without sacrificing vehicle performance. Recently, manufacturers developed technologies to reduce the NOx and particulate emissions of diesel engines, such as selective catalytic reduction and diesel oxidation catalyst [4, 5]. Moreover, common rail fuel injection has led to higher-efficiency diesel engines [6, 7]. Partial substitution of fossil diesel fuel with biodiesel is an appealing option to reduce CO_2 emissions [8, 9]. In the Brazilian transportation sector, the addition of biodiesel to fossil diesel fuel has been increasing since 2012 [10].

Heavy-duty construction and agricultural vehicles also have an environmental impact. In *Agricultural Industry Advanced Vehicle Technology: Benchmark Study for Reduction in Petroleum Use* [11], the current trends in increasing diesel efficiency in the farm sector are explored. **Figure 1** shows the diesel demand in the United States, highlighting that in the agricultural and construction machinery field, the demand has remained relatively constant since 1985, representing a significant portion of the total fuel consumption. Similarly to the automotive sector, considerable efforts have been dedicated in recent years toward reducing the energy consumption of construction and agricultural machines without compromising their functionality and performance, taking into account the restrictions imposed by the recent emission regulations [12, 13]. Engine calibrations have been optimized to reduce exhaust pollutants in accordance with the U.S. Environmental Protection Agency emissions tiers. This was

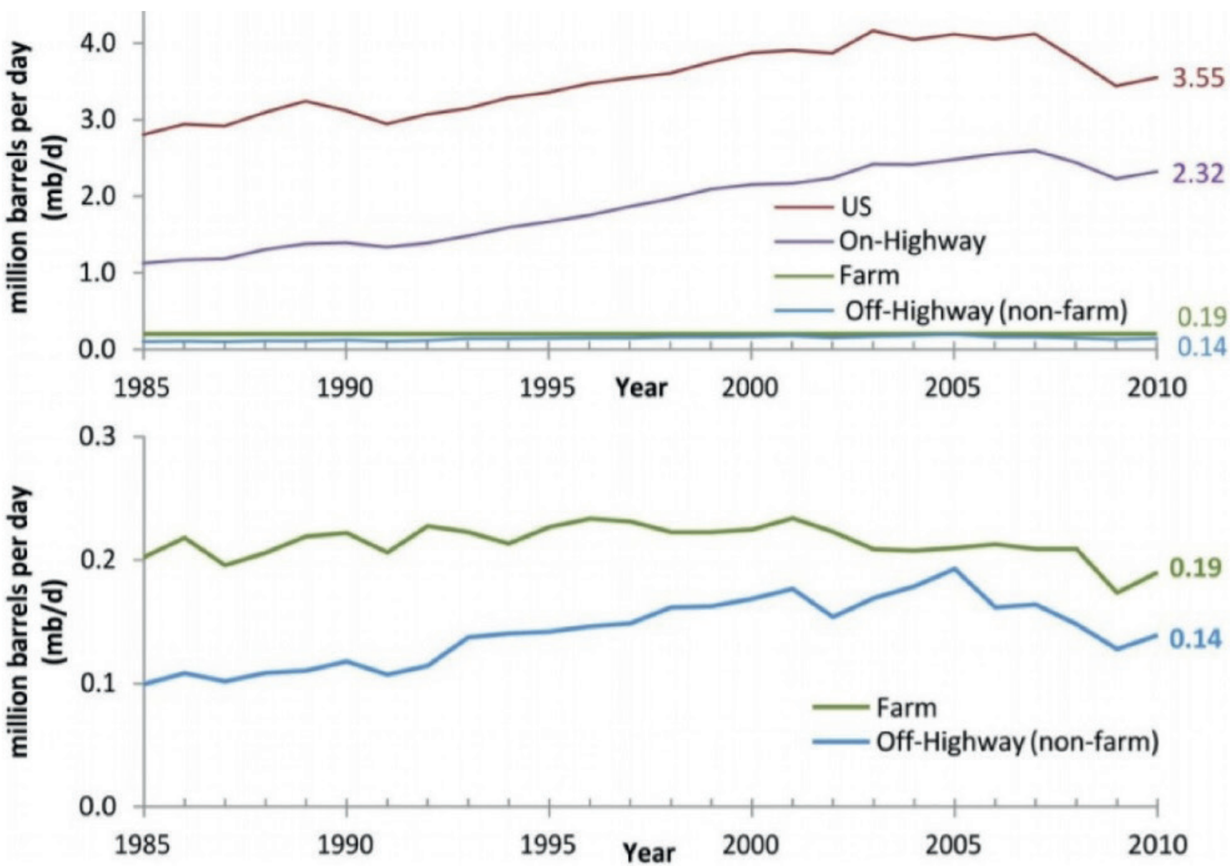

Figure 1. Historical diesel consumption in the United States. "Farm" includes agricultural diesel use; "off-highway" includes forestry, construction, and industrial use [11].

accomplished through several means, including in-cylinder combustion optimization and exhaust gas recirculation, without exhaust after-treatment systems for Tiers 1–3. With the addition of exhaust after-treatment systems for the Tier 4 interim stage, some engines require diesel exhaust fluid to catalyze pollutants in the system (e.g., urea). Some manufacturers claim as much as 5% greater fuel efficiency for their Tier 4 interim engines compared with Tier 3 models [14]; however, these entail increasing complexity, dimensions, and maintenance costs. Although most construction and agricultural vehicles include a driving mode tractor as a primary power unit, most modern models provide power for implementing a power takeoff (PTO) shaft and/or fluid power hydraulics. Moreover, working machine engines can stay idle for a notable amount of time [15]. Advanced engine controls are being introduced to reduce fuel consumption by lowering engine idle speeds and even shutting off the engine during extended idle periods. Examples of these strategies are found in existing patent applications, which indicate intentions of further development of these strategies [16]. Hybrid electric propulsion systems allow the combustion engine to operate at maximum efficiency and ensure both a considerable reduction of pollutant emissions and an appreciable decrease in energy consumption. Over the last few years, many configurations of hybrid propulsion systems have been proposed, some of which are also very complex. The fuel efficiency in this operating mode is greater than in a conventional machine for the following reasons:

- the fuel and energy consumption is limited only to the vehicle work time;
- the electronic control selects the engine speed to minimize fuel consumption depending on the state of charge of the batteries and the vehicle power demand;
- the power transmission from the electric motor to the gearbox ensures greater energy savings compared with hydraulic power transmission;
- the electric motor acts as a power unit to charge the batteries, while the vehicle is slowing down/stopping.

The automotive field has the largest number of studies, published patents, and proposals for hybrid and electric vehicles. Recently, intensive research has been carried out to find solutions that will enable the gradual replacement of the conventional engine with a highly integrated hybrid system. In the construction and agricultural working machines field, the number of concepts is limited and sporadic, and only recently has the market shown great attention to these studies. Thus, hybrid architectures allow the development of work machines characterized by high versatility and new features. Such machines can be used both indoors and outdoors because they can operate in both full electric and hybrid modes. The advantages to end users are reduction of running cost due to greater fuel efficiency and use of electric energy, and better work conditions due to low noise emissions.

From a system engineering point of view, the different solutions are described by introducing a specific hybridization factor suitable for work vehicles that include two main functionalities: driving and loading. The high-voltage electrification of work vehicles is also currently under development [17, 18]. According to Ponomarev et al. [19], in order to be competitive, manufacturers should offer energy-efficient and reliable hybrid vehicles to their customers. Compared with automobiles, the introduction of electric drives in work vehicles would allow expanded functionalities because these machines have a large variety of functional drives [20]. The first part of this report gives an overview of the components of the electrification solution and hybrid/electric architectures, discussing the advantages related to the different solutions. The machines are then schematically described and compared, showing the hybrid architectures of the proposed solutions. Finally, the introduction of a specific hybridization factor is proposed as a first classification of the main hybrid work vehicles [21, 22].

2. HEV power train configurations

The SAE defines a hybrid vehicle as a system with two or more energy storage devices, which must provide propulsion power either together or independently [23]. Moreover, an HEV is defined as a road vehicle that can draw propulsion energy from the following sources of stored energy: a conventional fuel system and a rechargeable energy storage system (RESS) that can be recharged by an electric machine (which can work as a generator), an external electric energy source, or both. The expression "conventional fuel" in the SAE definition constrains the term HEV to vehicles with a spark-ignition or a compression-ignition engine as the primary energy source. However, the United Nations definition of HEV [24] mentions consumable instead of conventional fuel. On this basis, the primary energy source in an HEV is not necessarily the engine hydrocarbon fuel, or biofuels but can also be the hydrogen fuel cell. The term electric-drive vehicle (EDV) is used in Ref. [25] to define any vehicle in which wheels are driven by an electric motor powered either by a RESS alone or by a RESS in combination with an engine or a fuel cell. Some types of EDV belong to the subset of plug-in electric vehicles (PEVs) [25, 26].

Compared with conventional internal combustion engine vehicles, HEVs include more electrical components, such as electric machines, power electronics, electronic continuously variable transmissions, and advanced energy storage devices [27]. The number of possible hybrid topologies is very large, considering the combinations of electric machines, gearboxes, and clutches, among others. The two main solutions, series and parallel hybrid, can be combined to obtain more complex and optimized architectures. There is no standard solution for the optimal size ratio of the internal combustion engine and the electric system, and the best choice includes complex trade-offs between the power as well as between cost and performance [28]. The power train configuration of an HEV can be divided into three types: series, parallel, and a combination of the two [29].

2.1. Series hybrid electric vehicles

Series hybrid electric vehicles (SHEVs) involve an internal combustion engine (ICE), generator, battery packs, capacitors and electric motors as shown in **Figure 2** [30–32]. SHEVs have no mechanical connections between the ICE and the wheels. The ICE is turned off when the battery packs feed the system in urban driving. A significant amount of energy is supplied from the regenerative braking. Therefore, the engine operates at its maximum efficiency point, leading to improved fuel efficiency and lesser carbon emission compared with other vehicle

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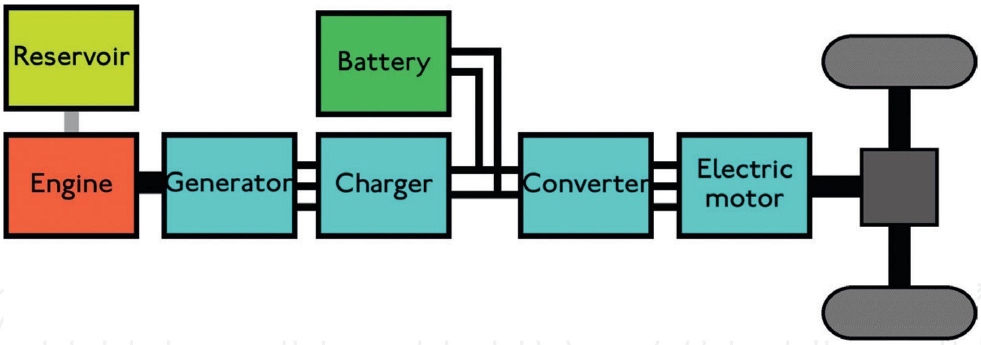

Figure 2. Schematic of series hybrid electric vehicles (SHEV).

configurations [33]. The series hybrid configuration is mostly used in heavy vehicles, military vehicles, and buses [34]. An advantage of this topology is that the ICE can be turned off when the vehicle is driving in a zero-emission zone. Moreover, the ICE and the electric machine are not mechanically coupled; thus, they can be mounted in different positions on the vehicle layout drive system [35].

2.2. Parallel hybrid electric vehicles (PHEV)

In a PHEV, mechanical and electrical powers are both connected to the driveline, as shown in **Figure 3**. In the case of parallel architectures, good performance during acceleration is possible because of the combined power from both engines [35]. Different control strategies are used

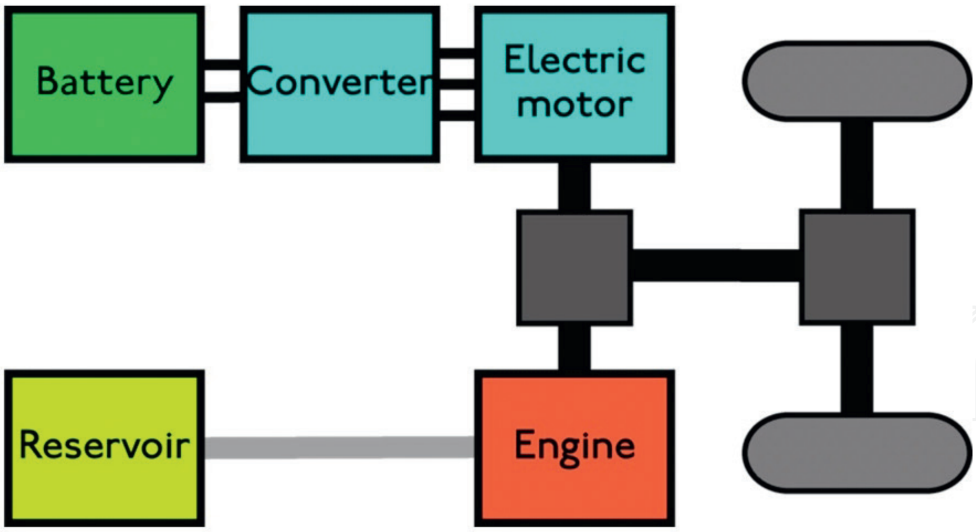

Figure 3. Schematic of parallel hybrid electric vehicles (PHEV).

in a preferred approach. If the power required by the transmission is higher than the output power of the ICE, the electric motor is turned on so that both engines can supply power to the transmission. If the power required by the transmission is less than the output power of the ICE, the remaining power is used to charge the battery packs [36]. Moreover, mechanical and electric power could be decoupled, and the system has a high operating flexibility enabling three modes of operation: purely combustion; purely electric and hybrid. Usually, a PHEVs are managed in purely electric mode at low speeds, until the battery charge state reaches a predetermined low threshold, typically 30%.

2.3. Combination of parallel and series HEVs

In the series-parallel hybrid configuration can be highlighted two main power paths. In mechanical power path, the energy generated by the combustion engine is directly transmitted to the wheels, while the electric path the energy generated by the thermal engine is converted first into electrical energy by means of the generator and then again converted to mechanical energy delivered at the wheels. It is possible therefore to have mixed architectures denominated "power splits" in which the installed power is divided by means of mechanical couplers. Combination of parallel and series hybrid configurations is further divided into subcategories based on how the power is distributed [37]. PHEVs are even more suitable topologies than HEVs for reducing fuel consumption because, unlike HEVs, they may be charged from external electric power sources [38]. In all the configurations, regenerative braking can be used to charge the battery [36]. Moreover to make recharging of batteries easier, some configurations are equipped with an on-board charger and defined Plug-in electric vehicle (PEV) [39].

3. Sub-system components of hybrid vehicles

3.1. Electric motors

The energy efficiency of a vehicle power train depends on, among other features, the size of its components. The optimization problem of sizing the electric motor, engine, and battery pack must consider both performance and cost specifications [40, 41]. Among electric motors, although the permanent magnet synchronous motor is considered as the benchmark, other types of motors are being explored for use in HEVs. Currently, there is some concern on the supply and cost of rare-earth permanent magnets.

Considerable research efforts have been made to find alternative electric motor solutions with the lowest possible use of these materials [42, 43]. For instance, some automotive applications use induction motors or switched reluctance motors [34]. **Figure 4** shows the most conceivable electric motor scenario in forthcoming years. Compared with hydraulics, electric drives provide better controllability and dynamic response and require less maintenance. Similarly to electric power, hydraulic power can be distributed quite easily on the implement; however, hydraulics suffers from poor efficiency in part-load operating conditions [44]. The specific electric drives for agricultural tractors are listed in Refs. [45, 46].

3.2. Continuous variable transmission (CVT)

Working vehicles drive at low speed, and the energy consumed in accelerating and climbing slopes should be partially recovered at decelerating and descending slopes. Compared with urban and on-road vehicles, construction and agricultural are used in a lower range of

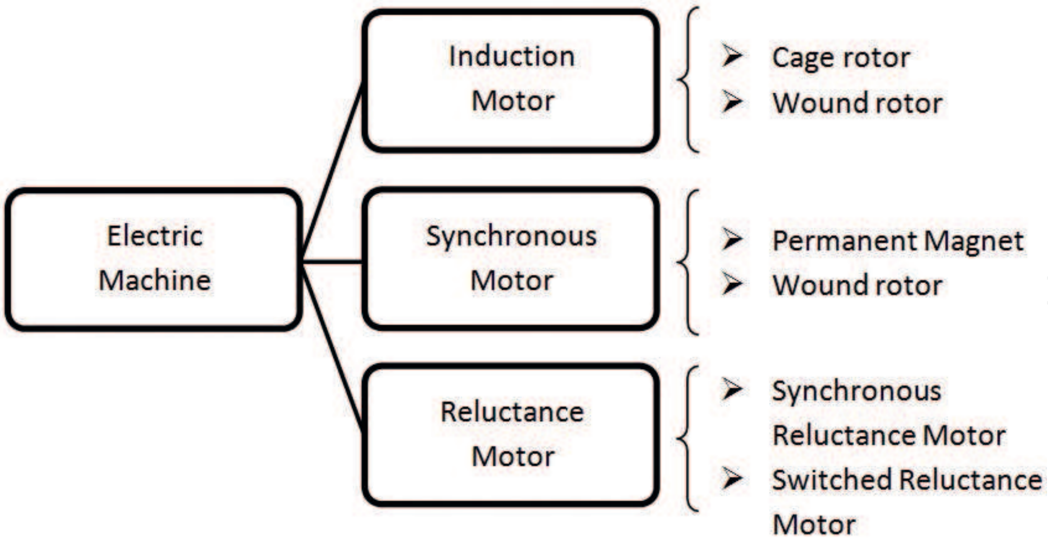

Figure 4. Types of electric motors for HEV applications.

velocity. Rolling requirements in construction and agricultural machines are related to the resistance due to tire deformation combined with resistance due to soil deformation [47, 48]. In the case of work vehicles, continuous variable transmission CVT could be used to determine the energy flow that reaches the transmission from each energy source (engine, generator, and motor battery) [49].

3.3. Energy storage devices

The energy efficiency of construction machinery is generally relatively low, and kinetic or potential energy is lost during operation [50]. Currently, batteries [51], super-capacitors, hydraulic accumulators, and flywheels are mainly used as energy storage devices in hybrid construction and agricultural machinery (HCAM), as schematically described in **Figure 5**.

3.3.1. Batteries

Batteries are the most studied energy storage and are divided into three types: Li-ion [52], nickel-metal hydride [53, 54], and lead-acid [55]. Li-ion batteries are considered as a highly prospective technology for vehicle applications [56, 57] because of their larger storage capacity, wide operating temperature range, better material availability, lesser environmental impact, safety [58–60]. However, despite having the highest energy density, Li-ion batteries a shorter lifetime, higher vulnerability to environmental temperature, and higher cost compared with other energy storage devices. A comprehensive review examined the electrochemical basis for the deterioration of batteries used in HEV applications and carried out tests on xEVs, automotive cells, and battery packs [61, 62] regarding their specific energy, efficiency, self-discharge, charge-discharge cycles, and cost. The results indicated that Li-ion is currently the best battery solution, surpassing the other technologies in all parameters except charge speed, in which Pb-acid batteries showed a better performance. Over the last years, graphene and its applications have become an important factor in improving the performance of batteries [63].

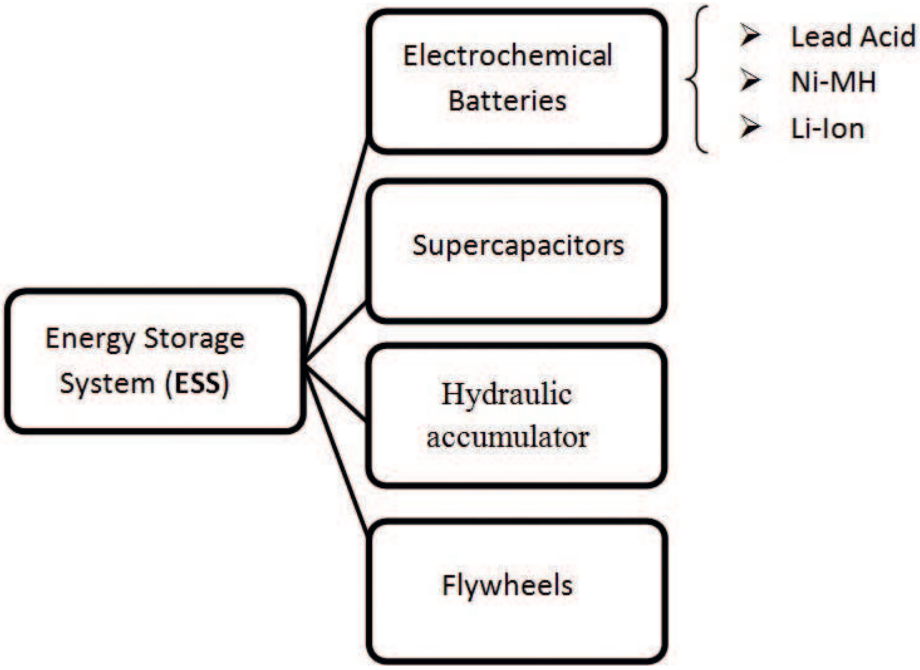

Figure 5. Energy storage for hybrid construction and agricultural machinery.

3.3.2. Supercapacitors

An alternative energy storage device for hybrid power trains could be super-capacitors, which are designed to achieve fast-charging devices of intermediate specific energy [64]. A super-capacitor [65, 66] has the advantage of a fast charge-discharge capacity, allowing a higher regenerative braking energy and supplying power for larger acceleration [67] and can be classified as a double-layer capacitor or a pseudo-capacitor according to the charge storage mode. However, the main drawback of a super-capacitor is that it has low energy density, which leads to a limited energy capacity.

3.3.3. Hydraulic accumulator

The hydraulic storage approach converts the recoverable energy into hydraulic form inside an accumulator and then releases it by using secondary components or auxiliary cylinders [68–70]. Compared with an electric hybrid system composed of a battery or super-capacitor, a hydraulic accumulator device has an advantage in power density over an electric system. Moreover, hydraulic accumulator energy recovery systems are ideal for cases of frequent and short start-stop cycles [71, 72]. However, the application of such systems in work vehicles still presents several defects: The impact of the limited energy density is a design trade-off between the energy storage capacity and volume or weight [73].

3.3.4. Flywheel energy storage system

The flywheel energy storage system (FESS) has improved considerably in recent years because of the development of lightweight carbon fiber materials. This system has become one of the most common mechanical energy storage systems for hybrid vehicles [74, 75]. When in charge mode, the electric motor drives the flywheel to rotate and store a large amount of kinetic energy (mechanical energy); when in discharge mode, the flywheel drives the generator, converting kinetic energy into electric energy [76]. The FESS has the advantages of high energy density and high power density [77] and works best at low speeds and in frequent stop-start work conditions. Producing this system could be cheaper than producing batteries; however, the system has limited storage time, and a significant percentage of the stored capacity is wasted through self-discharge [78].

4. Hybridization factor

In HEV engineering, the integration of engines, mechanical components, and electric power trains leads to increased energy efficiency, that is, a reduction in fuel consumption and a subsequent decrease in CO_2 emissions. In the automotive industry, the basic logic of a hybrid vehicle is to provide a new source of power that intervenes in place of the primary source (ICE) to improve the overall performance of the system. Moreover, there are possible modes of operation that are not provided in a conventional vehicle, such as regenerative braking and electric mode (EV). Below are some of the main advantages of a hybrid configuration over a vehicle equipped with a combustion engine alone.

- Electric motor can act both as an engine and as a generator, allowing a reversible flow of power from the battery to the wheels and vice versa.
- During braking, some of the kinetic energy is recovered (regenerative braking).
- The vehicle can be used only in the electric mode (zero emission vehicle—ZEV).
- When the vehicle has to stop temporarily, the combustion engine can be switched off, therefore ensuring considerable energy saving.

It should first be mentioned that there is actually no real classification for hybrid vehicles, although a first orientation phase can be identified by defining a significant hybridization factor (HF) as the ratio between the power of the installed electric motor and the total amount of power delivered by the combustion engine and electric motor on the vehicle:

$$HF = \frac{P_{em}}{P_{em} + P_{ICE}} \tag{1}$$

where P_{em} is the electric motor drive power, and P_{ICE} is the internal combustion engine power. In the case of conventional vehicles, the hybridization factor is clearly equal to zero, whereas in the case of electric vehicles, the hybridization factor has a unit value. Between these values, all possible solutions can be obtained. In the automotive engineering field, the definition of the hybridization factor has been extensively studied for several applications [49, 79, 80], considering its effect on performance and optimization [81–83]. Furthermore, depending on the degree of hybridization and the capacity of the hybrid propulsion system to store energy, three different levels of hybridization are defined.

- **Full hybrid** is when the electric system alone is able to make the vehicle move on a standard driving cycle ($0.5 < HF < 0.7$).

- **Mild hybrid** is when the purely electric operation mode is not able to follow a full standard driving cycle (0.25 < HF < 0.5).
- **Minimal hybrid** is equipped with a stop and start function, characterized by a decreasing distance in the purely electric mode (0 < HF < 0.1).

HF = 0 is applicable to a conventional engine vehicle, whereas HF = 1 is applicable to a "pure" electric vehicle, such as the BEV [43]. **Table 1** presents the hybridization factors calculated by using Eq. (1), taking into account the electrical driveline for automotive applications.

Compared with cars, the introduction of electric drives in tractors would allow expanded functionalities, considering that agricultural machines have a large variety of functional loading and working drives [20, 84]. The working cycle of a vehicle is strongly correlated with the application. In the case of a car, the comparison can be carried out by evaluating the extra-urban cycle and the urban cycle. For example, in the case of the urban cycle, the vehicle recovers energy due to frequent accelerations and stops. Working machines even with repetitive movements, such as excavators, are able to recover the kinetic energy of the arm. For agricultural tractors and machinery, two tasks [85] have been identified, such as working conditions with steps at which energy recovery is possible: transport and front loading. Telescopic handlers also have a similar duty cycle. Unlike in hybrid cars, the hybrid propulsion system in heavy-duty machinery can supply power to the driveline and loading hydraulic circuit [86]. The mechanical power supplied by the ICE flows to recharge the battery pack, actuate the hydraulic pump, and move the driveline (**Table 2**).

Although there is no classification for hybrid heavy-duty machines in the literature, a first orientation phase can be determined by defining a hybridization factor for a work vehicle HF_{WV} [87].

4.1. Driveline power

Hybrid architecture in series or in parallel has, in both cases, at least one electric motor (EM_1) for moving the vehicle. In order to generalize the different configurations define (EM_1), the electric motor used for the traction of the vehicle. Therefore, according to the hybridization factor described in the automotive field, the first term (μ_1) of the hybridization factor for heavy-duty vehicles (HF_{HDV}) is as follows:

$$\mu_1 = \frac{P_{em_1}}{P_{em_1} + P_{ICE}} \tag{2}$$

Vehicle	Electric motor (kW)	ICE (kW)	HF Eq. (1)
Toyota Prius	31	43	0.42
Toyota Prius 3rd gen.	50	53	0.49
Honda Insight	10	50	0.17
Honda Civic	10	63	0.07

Table 1. HF comparison among automotive vehicles [80].

	Hybrid architecture		
	Series	Parallel	Series-parallel
Driveline powered by ICE	No	Yes	Yes
Driveline powered by EM	Yes	Yes	Yes
Loading devices powered by EM	No	Yes	Yes
Loading devices powered by EG	Yes	No	Yes
Loading devices powered by ICE	No	Yes	Yes

Table 2. Architectures of hybrid construction and agricultural machinery (HCAM).

4.2. Loading power

The driveline architecture in work vehicles can be electrical, hydraulic, and/or mechanical. Moreover, the loading power can be hydraulic or electrohydraulic depending on the vehicle topology architecture. Many work machines have some hydraulic actuators to be controlled, a big difference between a passenger car and a heavy-duty vehicle. In a full hybrid vehicle, for example, the hydraulic power for loading the bucket is supplied by the hydraulic pump, which can be powered by the ICE or an electric motor (EM_2). The second ratio (μ_2) of the hybridization factor for heavy-duty vehicles can therefore be defined as follows:

$$\mu_2 = \frac{P_{em_2}}{P_{em_2} + P_{ICE}} \quad (3)$$

In the automotive industry, the power of the internal combustion engine is mainly used for the handling of the vehicle, and other functions (such as air conditioning) may be neglected in a first order assessment hybridization. In a work machine, the power of the internal combustion engine can be used for both driving operations for loading activities. In particular, it is observed that the power required to move loads or to carry out excavation work is of the same order of magnitude of power required to move the vehicle. So, the design of a hybrid working vehicle must take into account the power requirements of the working cycle with particular reference to the types of equipment that can be connected to the arm or blade of the machine. In the present work, in order to define a hybridization factor that allows comparing the many hybrid applications in the construction and agricultural machinery sector is the hypothesis that the power can be conventionally comparable between driving and loading is used.

According to the previous statement and combining the two ratios expressed in Eqs. (2) and (3), the hybridization factor for heavy-duty work vehicles can be defined as follows:

$$HF_{WV} = \frac{1}{2}\left(\mu_1 + \mu_2\right) \quad (4)$$

5. Architecture review of hybrid construction and agricultural machinery

Manufacturers, governments, and researchers have been paying increasing attention to hybrid power train technology toward decreasing the high fuel consumption rate of construction machinery [17]. Hybrid wheel loaders, excavators, and telehandlers have particularly shown significant progress in this regard [88, 89]. With hybrid work vehicles attracting more attention, power train configurations, energy management strategies, and energy storage devices have also been increasingly reported in the literature [73, 90–92]. Both researchers and manufacturers have approached studies of the hybrid power system applications, energy regeneration systems, and architectural challenges of construction machinery qualitatively but not systematically and quantitatively. A first review of an electric hybrid HCM was presented in 2010 [107]. More recently, a specific review of a wheel loader and an excavator [108] was carried out, and another work in the field of high-voltage hybrid electric tractors [109] was published. Hitachi successfully launched the first hybrid loader in 2003 [90], and Komatsu developed the first commercial hybrid excavator in 2008 [93]. Komatsu developed the HB205-1 and HB215LC-1 hybrid electric excavators, which are capable of recovering energy during the excavator slewing motion and of storing this energy in ultra-capacitors. Earth-moving machinery manufacturers have developed some diesel-electric or even hybrid-electric models . Johnson et al. [96] compared the emissions of a Caterpillar D7E diesel-electric bulldozer with its conventional counterpart [95]. Over the last years, there has been increasing interest in tractor and agricultural machinery electrification [96–99]. A number of tractor and agricultural machinery manufacturers have developed some diesel-electric or even hybrid-electric prototypes [20, 49, 100–102]. Recently, the Agricultural Industry Electronics Foundation started working on a standard for compatible electric power interfacing between agricultural tractors and implements [103], including, among others, the John Deere 7430/7530 E-Premium and 6210RE electric tractors [104] and the Belarus 3023 diesel-electric tractor [105]. Among telehandler vehicles, the TF 40.7 Hybrid telescopic handler proposed by Merlo [106]. Thus, it is necessary to study the various types of power train configurations of hybrid wheel loaders and excavators to better understand their construction features. The power requirement has different working cycles depending on the applications. Many construction machinery manufacturers and researchers have studied hybrid wheel loaders to effectively use the braking energy and operate the engine within its high-efficiency range [110–113]. According to the classification of hybrid vehicles in the automotive field, there are three main design options for hybrid wheel loader power trains: series, parallel, and series-parallel. In the literature review, the proposed architecture is mainly described, but no attempt at classification and comparison is made. It is not easy to find data sheets on the different vehicles because most of them are still at the prototype level. The comparison first outlines the architectures of the hybrid work vehicle solutions developed by the main manufacturers, as shown in **Table 3**.

Figure 6 shows the series hybrid configuration of a wheel loader. As in the configuration of a hybrid vehicle, classic engine series ICE directly drives the electric generator, the electricity so generated is used to control the electric motor connected to the driveline. The advantage of a series hybrid wheel loader is the greater simplicity. In addition the engine ICE, being decoupled from the wheels, it can be used at a fixed point in the conditions of greater efficiency.

Model	Type of vehicle	Driveline	Loading and working system	Energy storage
Caterpillar—D7E	Dozer	Series	Conventional	None
Volvo—L220F Hybrid	Wheel loader	Parallel	Parallel	Battery
Mecalac—12MTX Hybrid	Articulated loader	Paralell	Paralel	Battery
John Deere—644K Hybrid	Wheel loader	Series	Parallel	None
Merlo—TF 40.7 Hybrid	Telehandler	Series	Parallel	Battery
Claas—6030 Hybrid	Telehandler	Parallel	Conventional	Battery
Kobelco SK200H Hybrid	Excavator	Conventional	Series	Battery/capacitors
Komatsu—HB215 LC-1	Excavator	Paralel	Parallel	Supercapacitors

Table 3. Hybrid working vehicles and their architectures.

In the case of hybrid wheel loaders in series from the transformation of mechanical power into electrical and drive of the electric motor can also be done with a battery pack reduced but the generator and the electric motor need to be manufactured in terms of maximum power demand. The presence of the battery pack can allow to better manage the power demand peaks without the need to over-dimension the motor ICE [114, 115]. In literature, the hybrid drive train in the series has been applied mainly in large tonnage hybrid wheel loader.

In 2009, Caterpillar came out with the first electric hybrid bulldozers. The Caterpillar D7E model is within the range of medium dozers and replaced the traditional model D7R [94].

The company claimed an increase of productivity and a reduction in fuel consumption up to 24% over the conventional model [94]. The driveline architecture is of the series electric hybrid type, as described in **Figure 6**, with the electric motors powered directly from the inverter but having the peculiarity to be directly charged from the ICE without any accumulation system.

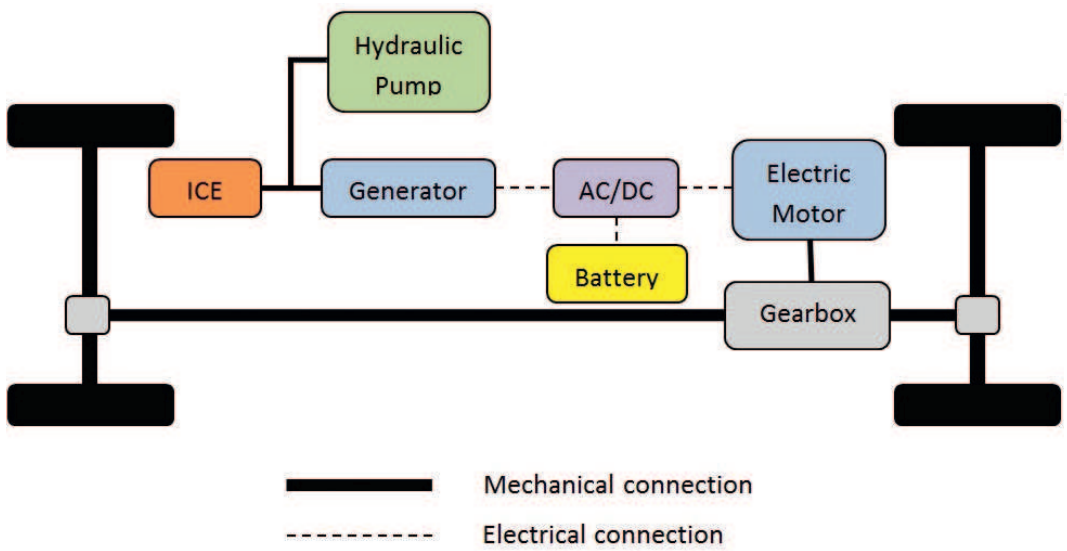

Figure 6. Working vehicle with series hybrid configuration.

The hydraulic system has a conventional architecture. **Table 4** shows the main parameters of this work vehicle. A parallel hybrid power train configuration has two separate power sources that can directly power the loader. The disadvantage of a parallel configuration is that the engine cannot always be controlled in its high-efficiency operating region because it is still mechanically coupled to the wheels with an increased efficiency compared with the conventional model and a fuel consumption reduction of 10%[116]. **Figure 7** shows a schematic of the Volvo L220F parallel hybrid electric wheel loader (HEWL). The vehicle has a parallel hybrid electric architecture for both the driving and the loading system. The basic idea of this parallel hybrid layout is to supply additional electric power when necessary, regenerating the machine during normal operations and minimizing the consumption in idle conditions. The power required by the device can be flexibly provided by using a work pump, which is driven by the pump motor shows the main parameters of the Volvo L220F. Mecalac proposed a similar architecture for the 12 MTX hybrid model and claimed to save up to 20% in fuel consumption [117].

However, the parallel configuration is still on the researching stage, and Liugong has applied a solution with super-capacitors instead of batteries [118] as schematically shown in **Figure 8**.

At the CONEXPO International Trade Fair for Construction Machinery (2011), John Deere presented the first prototype of its hybrid wheel loader, the 944K hybrid. In February 2013, the entry of the first hybrid wheel loader, the 644K hybrid, in the market was announced with a reduction in fuel consumption up to 25% [119]. In this smaller model, a single electric machine provides all the power needed to drive the vehicle. The vehicle driveline has a series electric hybrid architecture, with the electric motor directly powered by the inverter without an energy storage system. **Figure 9** shows a schematic view of John Deere 644K hybrid wheel loader [120]. The installed electrical machines are liquid-cooled brushless permanent magnet motors.

The innovative architecture proposed by Merlo, as shown in **Figures 10** and **11**, is considered as a fully series architecture for vehicle traction and as a parallel architecture for the operation of hydraulic systems. This kind of innovative, patented series-parallel architecture, with a split input for hydraulic lifting, allows both the electrical and the mechanical components to be arranged in a way that is compatible with the current layout and performance of Merlo machines. The main objectives of this hybrid telehandler are an overall improvement in performance, a decrease in daily fuel consumption in ordinary work activities, and a reduction in noise emissions. Moreover, the proposed configuration is capable of working in full electric, zero-emission mode for indoor use, such as in cattle sheds, stables, industrial and food processing warehouses, and buildings. In Ref. [87], it has been demonstrated a fuel consumption reduction of 30% with the same level of dynamic performance compared with the conventional telehandler.

Claas proposed a parallel mild hybrid solution for the Scorpion telehandler. The simulation results reported in Refs. [121, 122] show a reduction in fuel consumption of about 20% and emissions for this parallel hybrid solution compared with the traditional model. The solution proposes the use of the electric motor as a power boost to maintain the performance while using a smaller diesel motor.

Vehicle	Vehicle operative weight (t)	Electric driving motor (P_{EM1}) (kW)	Electric loading motor (P_{EM2}) (kW)	ICE (kW)	HF (Eq. 2)	HF (Eq. 3)	HF_{WV} (Eq. 4)	% of fuel reduc
Caterpillar D7E	26	2*60	0	176	0.40	0	0.20	24
Volvo—L220F Hybrid	32	50	50	259	0.16	0.16	0.16	10
Mecalac—12MTX Hybrid	8.3	20	20	51	0.28	0.28	0.28	20
John Deere—644K Hybrid	19	80	80	171	0.32	0.32	0.32	25
Merlo—TF 40.7 Hybrid	7.5	60	40	56	0.52	0.42	0.47	30
Claas—6030 Hybrid	5.6	15	0	55	0.21	0	0.11	20
Kobelco SK200H Hybrid	20	0	37	114	0	0.24	0.12	40
Komatsu—HB215 LC-1	21	20	90	104	0.16	0.46	0.31	25

Table 4. List of hybrid working vehicles HF and claimed fuel reduction.

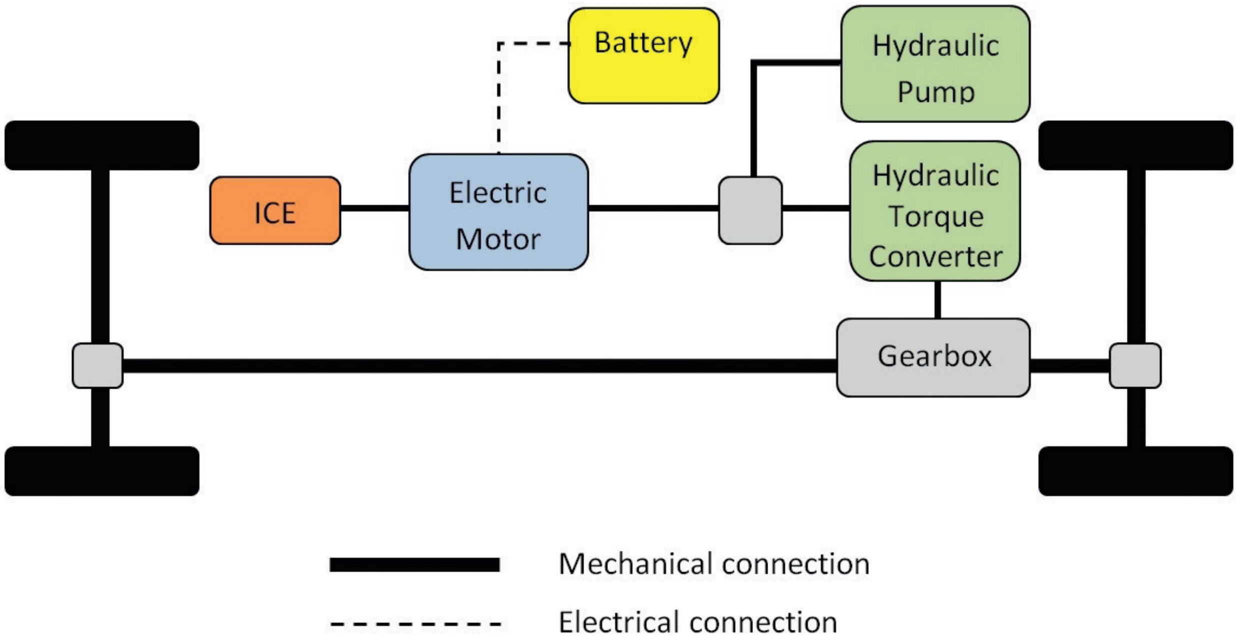

Figure 7. Parallel hybrid configuration of the Volvo L220F hybrid [116].

The excavator is a type of construction machinery with a larger weight and higher energy consumption [107]. A hybrid excavator can typically recycle two energy types, including the braking kinetic energy of the swing and the gravitational potential energy of the booms. In the recent literature, excavators present a wide combination of series, parallel, or series-parallel hybrid architectures. The change in configuration and the additional costs of electrical components make the commercialization of hybrid configurations difficult. **Figure 12** shows the

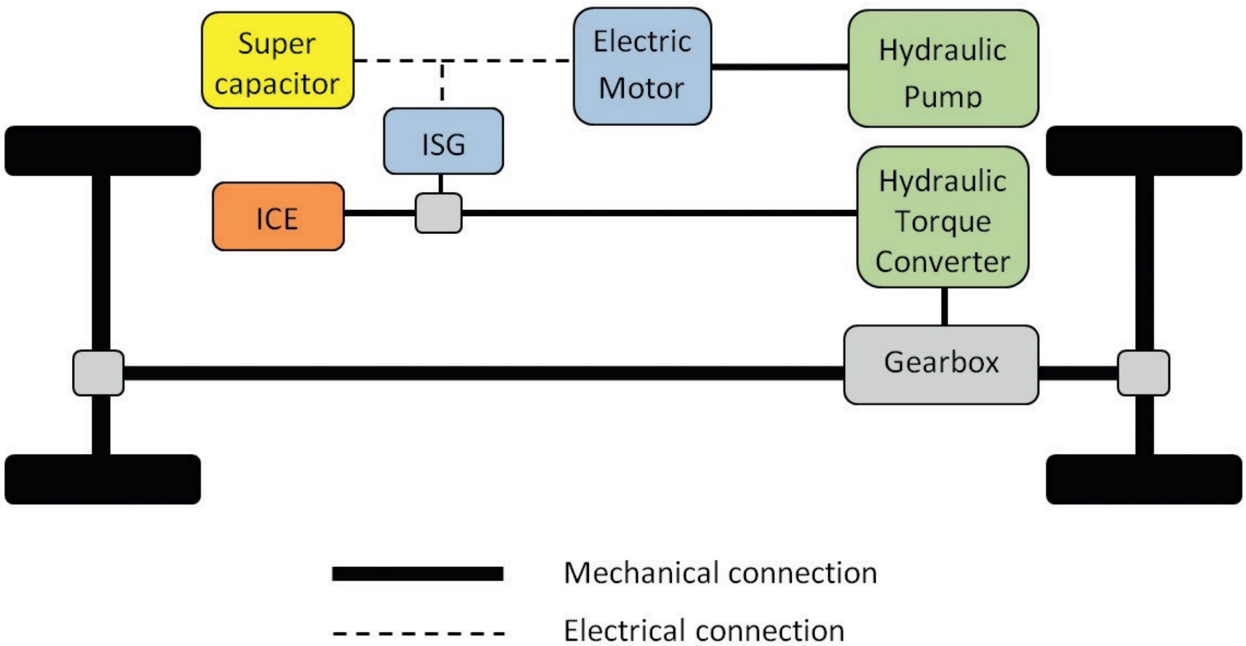

Figure 8. Parallel hybrid configuration with super-capacitors, as applied by Liugong [118].

http://dx.doi.org/10.5772/intechopen.68296

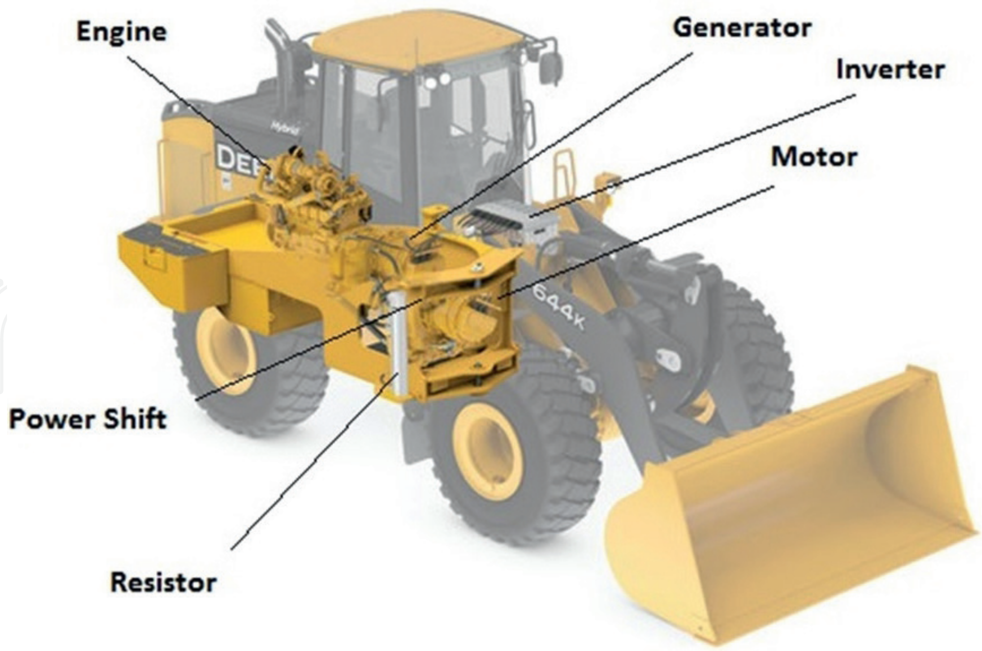

Figure 9. Schematic of the John Deere 644K hybrid wheel loader [120].

schematic of the Kobelco series hybrid excavator; the first prototype of this 6-t configuration was developed in 2007 with a claimed in [123] to cut fuel consumption by 40% or more and reporting results of the verification test on the efficiency of the hybrid excavator in different working cycle operations [124, 125].

As showed in **Figure 12** in the hybrid solution proposed by Kobelco, each hydraulic is driven by an electric motor. This solution increases efficiency but the production cost is higher.

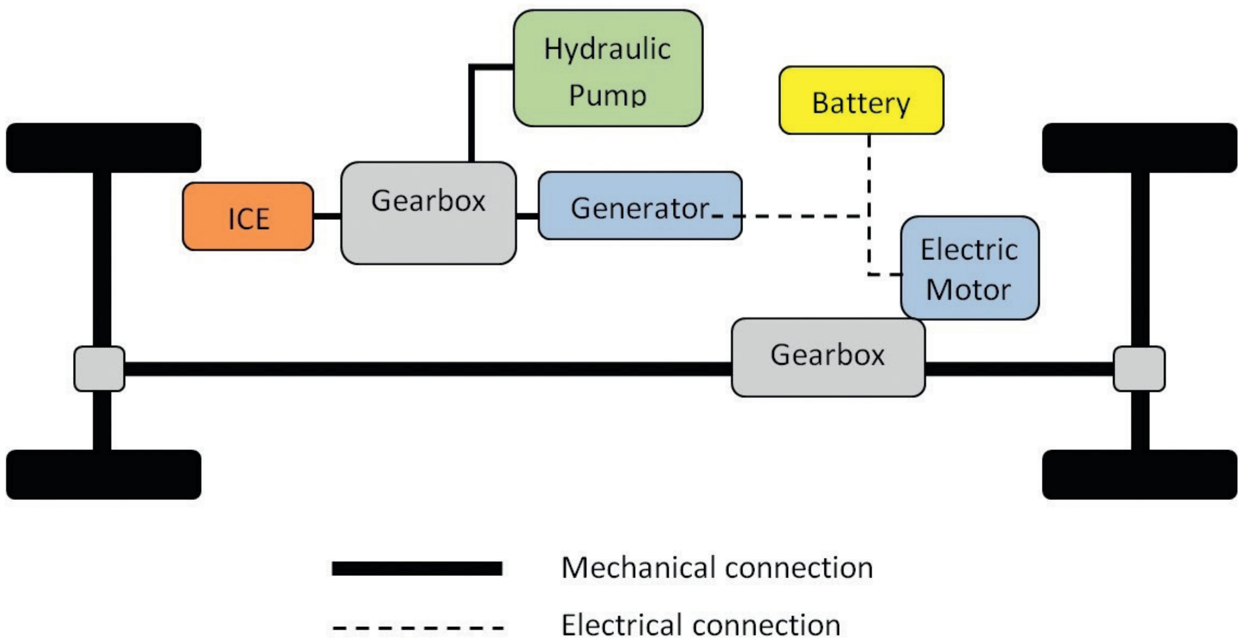

Figure 10. Series-parallel hybrid configuration of a Merlo working vehicle [106].

Figure 11. View of Merlo – TF 40.7 hybrid the hybrid telehandler [106].

In the case of parallel hybrid excavator, the internal combustion engine operates the hydraulic pump and generator. The hydraulic pump drives the hydraulic circuit of the device, in a manner similar to conventional excavators, while the generator transforms the mechanical energy into electrical power and can operate the electric motor of swing rotation. The hybrid solution in parallel is simpler; however, the fuel consumption is higher, and the return time for these working machines is longer [126]. Hitachi, as shown in **Figure 13**, proposed a parallel hybrid excavator with the gravitational potential recovery of the boom [113].

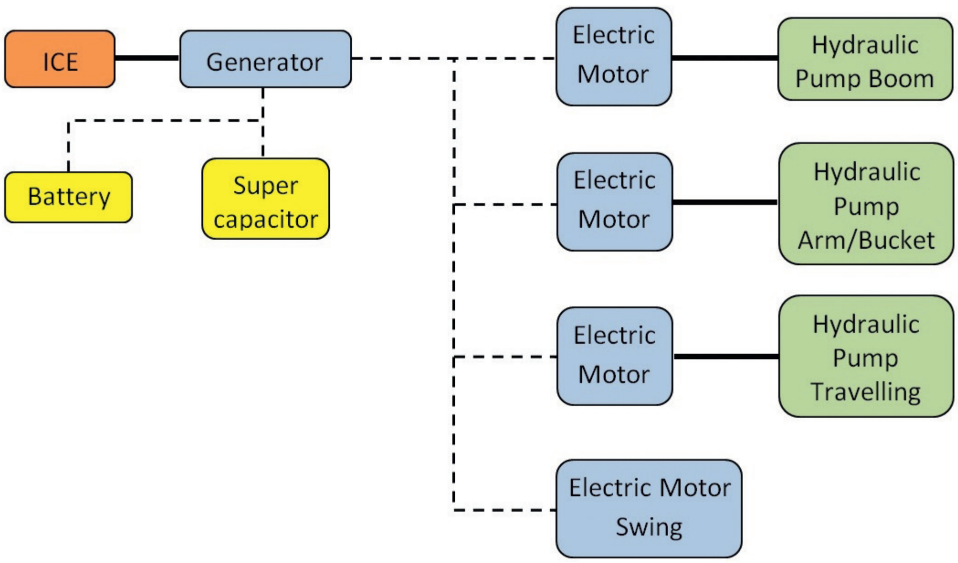

Figure 12. Series hybrid configuration of the Kobelco excavator.

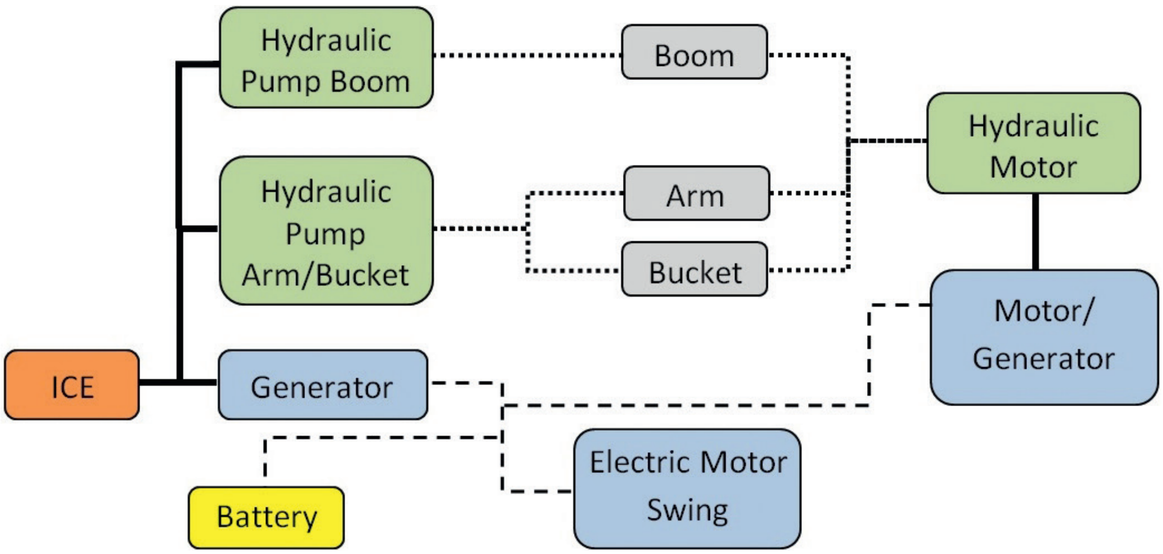

Figure 13. Parallel hybrid configuration for working excavator Hitachi [127].

In the series-parallel hybrid power train configuration of an excavator, the engine drives the generator directly. The hydraulic pumps are driven by the generator in series, and the swing electric motor is powered by the generator and the battery or super-capacitor in parallel. Although series-parallel hybrid excavators have higher production costs compared with parallel and series structures, they offer the shortest cost recovery time and efficiency with a fuel consumption up to 25% [126]. Series-parallel hybrid excavators are regarded as the most promising solutions, and both Komatsu (**Figures 14** and **15**) and Doosan use similar configurations [128, 129].

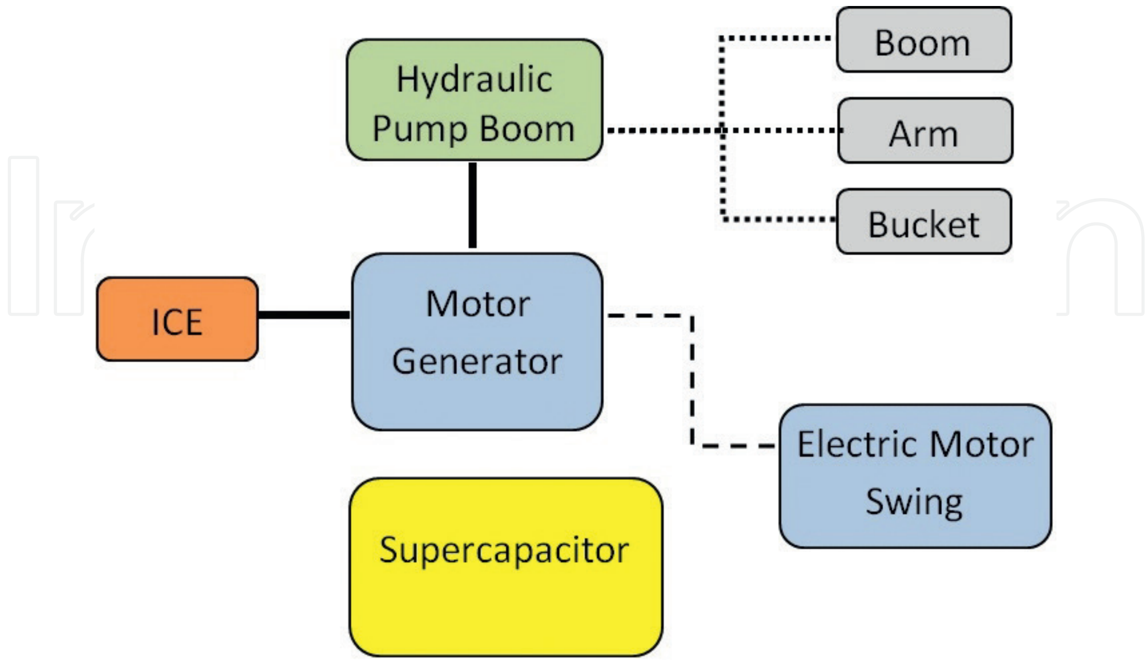

Figure 14. Series-parallel hybrid configuration for working excavator Komatsu [126].

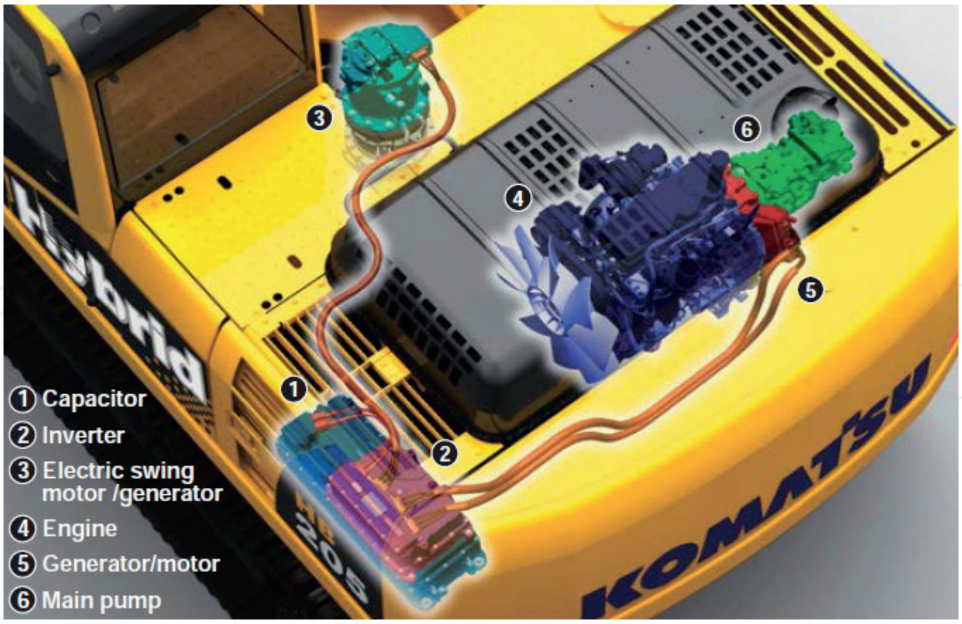

Figure 15. Schematic view of Komatsu—HB215 LC-1 hybrid excavator [126].

The attempt at classification in the present work is based on the specific HF defined in Section 4, taking into account the data sheets of the vehicles. **Table 4** shows the hybridization factors for work machines, calculated by using Eq. (4) [22] and considering the effect of a hybrid electric driveline and hybrid electric loading/working functions.

6. Trends and conclusions

This study focused on the electrification of work vehicles, such as agricultural machineries, which is still in the research and development stage. Similarly to HEVs, the main design issue in HACMs is controlling the energy transfer from the sources to the loads with minimum loss of energy, which is dependent on the driving and working cycles. Compared with automobiles, the introduction of electric drives in tractors would allow expanded functionalities because agricultural machines have a large variety of functional drives.

Main differences in requirements, working cycles, and proposed hybrid architectures between HEV and HACM were determined along the present study, focusing on a specific hybridization factor for working vehicles that consider both the driving and the loading electrification.

The hybridization factor for working vehicles is introduced in order to classify and compare the different hybrid solutions proposed by main manufactures taking into account different architectural choices. Moreover, the claimed increasing of efficiency due to the power train electrification is reported and listed in terms of fuel consumption reduction. Taking into account a large variety of architectural hybrid solution, it has been proven a good correlation between the hybridization factor and the fuel efficiency as a general trend in benefit of hybrid electrification of working machine.

Because charging a battery pack from the grid is more efficient than charging it from a tractor engine, it seems logical to hybridize the tractor with high-voltage batteries and propulsion motors. In this manner, the internal combustion engine could be downsized, and the traction battery pack could be charged from the grid. Fuel consumption costs would thus decrease. However, compared with traditional construction machinery, an additional energy storage device is needed, which increases the initial costs. Moreover, the cost added by high-voltage equipment needs to be considered in the whole turnover of the hybrid vehicle conversion. As indicated by several reports and prototypes, hybrid systems have promising applications in both agricultural and construction machinery, but major drawbacks are related to the increased cost due to electrification. Hybrid technologies, particularly energy storage devices, are still in the early stages of development, and the trends in cost reduction could push researchers and manufacturers toward the optimization of hybrid solutions for HCAM.

Abbreviation

BEV	Battery electric vehicle	CVT	Continuously variable transmission
EDV	Electric-drive vehicle	FCV	Fuel cell vehicle
HEV	Hybrid electric vehicle	SHEV	Series hybrid electric vehicle
PHEV	Parallel hybrid electric vehicle	HF	Hybridization factor
ICE	Internal combustion engine	PEV	Plug-in electric vehicle
ZEV	Zero emission vehicle	ESS	Energy storage system
RESS	Rechargeable energy storage system	BMS	Battery management system
HCAM	Hybrid construction and agricultural machineries		

Author details

Aurelio Somà

Address all correspondence to: aurelio.soma@polito.it

Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy

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