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Challenges and solutions for designing Energy-Efficient and Low-Pollutant Machines in Off-Road hydraulics

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ABSTRACT

Increasing energy efficiency in off-road hydraulics is an essential requirement mainly achieved by removing functional flow throttling in control valves and enabling energy recovery in hybrid mobile machines. Focusing on hydraulic excavators and wheel loaders gives the greatest benefit due to their widespread use. Thus, we propose a structured survey and a critical review of their energy-efficient systems, including the combustion engine. We address solutions based on proportional valve control that can recover energy, digital valves, displacement control, electro-hydraulic control, and hydraulic transformers. We recall the operating principles and stress both the design challenges and potential of the proposed approaches. Readers get an up-to-date overview of these techniques and their impact on productivity. Our analysis suggests that future trends will typically enable energy efficiency and low-pollution via machine hybridization and strong integration between hydraulics and combustion engines.

1. Introduction

Pressing environmental and economic arguments ask for much higher energy efficiency and lower exhaust emissions in off-road hydraulics, in addition to ensuring productivity. These mobile machines are the backbone for an essential field such as construction, where hydraulic excavators (EXs) and wheel loaders (WLs) are mainstream equipment with large market volumes [1]. These machines usually leverage a hydraulic system driven by a compression ignition (diesel) engine, where more than 95 % of the engine power is used by the hydraulics [1]. The resulting quantities of burnt diesel fuel are remarkable (*e.g.*, more than 1 million liters per year for a 250-ton mining shovel [2]) and sum up to massive amounts of consumed energy and production of pollutants. For instance, 1.8 Quadrillion British Thermal Units (Quads) per year is the energy's upper estimate for the American off-road sector alone [1]. The poor average energy efficiency[1] of the hydraulic system in state-of-the-art machines plays a major role. It was estimated as 21 % across all mobile applications in the early 2010s [3], or up to about 30 % in some specific cases [1], varying notably between equipment types and duty cycles. Predictions point out that these machines will rise in number in the coming years, increasing the energy demand even more [2].

The main consequences of low-energy efficiency are two-fold. Many tons of carbon dioxide (CO_2) and pollutants of concern are released into the atmosphere, such as nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and hydrocarbon (HC). Significant examples are the 2,700 tons of annual equivalent CO_2 for a single shovel [2] or the average 59–69 g/h for a conventional 20-ton EX [4]. A white paper [5] elaborated on data collected in 2011 by the American Environmental Protection Agency [6], showing that the off-road sector is responsible for the 18 % of NO_x and 39 % of $PM_{2.5}$ emitted in the U.S. by all mobile sources, including on-road vehicles, locomotives, aircraft, and marine vessels. Similar trends for NO_x and $PM_{2.5}$ were traced in Europe [5], where the construction sector characterized by EXs and WLs contributes largely.

Moreover, there are excessive operating costs due to the high diesel price. It increased roughly three times in the U.S. compared to the early 2000 s [7] when many popular hydraulic systems were conceived. All mobile fluid power in the U.S. consumes at least 0.362 Quads yearly,

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[1] In off-road hydraulic machines, energy efficiency often refers to the hydraulic system (the ratio of the actuators' work and the mechanical energy entering through the pump shaft). Energy efficiency can, however, take different meanings, for instance, if the combustion engine's losses are included in the calculation (*i.e.*, overall machine's efficiency), or the focus is only on a specific component (*e.g.*, the engine or the pump alone). The correct sense of the definition in the paper will emerge from the context when not explicitly stated.

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Nomenclature

List of symbols

A	Hydro-pneumatic accumulator
C	Hydraulic cylinder
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Displacement control
DCV	Directional control valve (nonproportional)
EGR	Exhaust gas recirculation
EHA	Electro-hydrostatic actuator
EM	Electric motor
ESD	Energy storage device
EX	Excavator
HC	Hydrocarbon
HP	High-pressure line / Hydraulic common rail
HCCI	Homogeneous charge compression ignition
HT	Hydraulic transformer (3-port hydraulic unit)
ICE	Internal combustion engine / Prime mover
LP	Low-pressure line / Charge line
LS	Load-sensing
LPC	Local pressure compensator
LTC	Low-temperature combustion
MT	Mechanical transmission
NO_x	Nitrogen oxides
P	Hydraulic pump/motor
PS	Power supply (centralized)
PCCI	Partially premixed combustion
PDCV	Proportional directional control valve
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter
RPM	Revolutions per minute
VGT	Variable geometry turbocharger
WL	Wheel loader

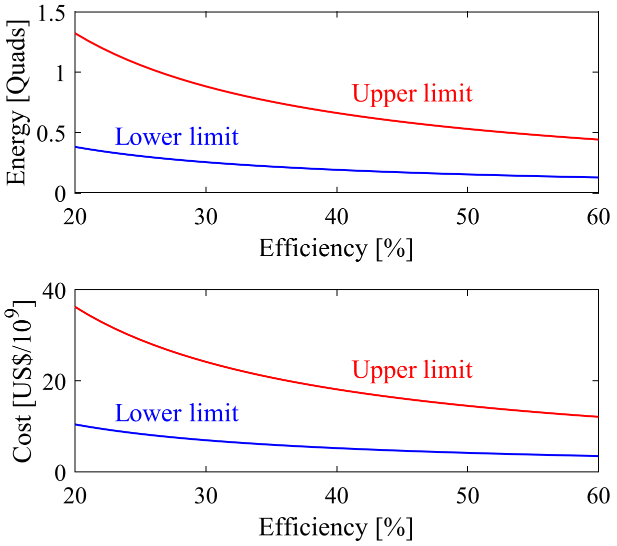

Fig. 1. Prediction of the yearly consumed energy and diesel cost for the mobile fluid power in the U.S. based on the average energy efficiency of the hydraulic system (data elaborated from ref. [3] and reference diesel price of 3.80 US $/gallon). Lower limit: produced work 0.076 Quads/yr. Upper limit: produced work 0.265 Quads/yr.

while 1.26 Quads is the predicted upper limit [3]. Recalling the estimated average efficiency of 21 %, about 0.076 Quads of work are produced, assuming the lower energy request of 0.362 Quads. If the average efficiency of the hydraulic system were 37 % (long-term goal [3]), the same amount of work could be delivered by saving 0.157 Quads. Regarding yearly costs in the U.S. alone, US$ 4.29B could be saved (diesel's energy density of 138,700 BTU/gallon and price of 3.80 US $/gallon [7] were adopted). Fig. 1 illustrates this scenario for different values of the average energy efficiency.

While operating costs impact the end-users, emissions have broader effects. Many countries introduced, therefore, stringent regulations for combustion engines (*e.g.*, EPA Tier 4 Final in the U.S., Stage V in Europe, or China IV) and took initiatives to lower CO_2 emissions or reach "carbon neutrality" in the mid-term future (*e.g.*, China's climate pledge sets this target before 2060). This firm approach helps but does not largely curb down the greenhouse gases being released because state-of-the-art hydraulics is still not sufficiently energy-efficient. This technical gap remains chronically unbridged despite the many system architectures studied since the 1980 s [8]. These solutions usually share cost-effective designs based on hydraulic valves that leverage functional energy dissipations to control the machine. So, alternatives have been considered more recently, and previous publications have tried to collect these outcomes. Existing review articles address valve-controlled EXs [8–11], energy recovery alone [12], large-scale machinery [2], and electro-hydraulic systems with a predominant focus on the electric domain [13,14]. However, a void in the literature prevents readers from obtaining a complete and up-to-date overview of hydraulic throttleless systems and combustion engines that favor energy efficiency and low-pollution in off-road machines. Concentrating on these aspects is vital for the sector's sustainability because a substantial increase in energy efficiency cuts down exhaust emissions (an obligation of many governments) and boosts machine productivity (a key demand of end users).

The purpose of our paper is, hence, to close the said gap by proposing a critical review of the existing energy-efficient systems for hydraulic EXs and WLs (focusing on these key applications gives the most significant benefit because they consume the most energy worldwide). We also emphasize combustion engines, which are often neglected or marginally addressed in articles about hydraulic machines. Thus, according to the meaning of "energy-efficient" chosen here, these systems should ensure (1) actuation without flow throttling or, at least, with reduced metering losses and (2) capabilities for energy recovery or, at least, limited energy absorption by the prime mover when operating overrunning loads. The resulting options are based on valve control (Section 3), displacement control (**Section 4**), electro-hydraulic control (Section 5), and hydraulic transformers (**Section 6**), depending on the control method. Then, we also discuss system requirements (**Section 2**), methods to improve combustion engines (**Section 7**), and future trends (**Section 8**).

2. Off-road machines used in construction

Off-road machines can be seen as the operator's arm extensions controlled by hydraulic systems. They include the hydraulic actuators of the working functions (implements), the propulsion, and the steering or braking subsystems when needed. A few machines are designed differently but do not reflect the primary trend (*e.g.*, electro-mechanical solutions or fully mechanical propulsion drives). From the end-users standpoint, the top priority is maximizing performance in terms of controllability and productivity. Central factors are cost-effectiveness (especially for the initial machine purchase) and robustness (minimum downtime and low-complexity maintenance). Moreover, the machine size and the application field call for special demands that are analyzed separately for EXs and WLs.

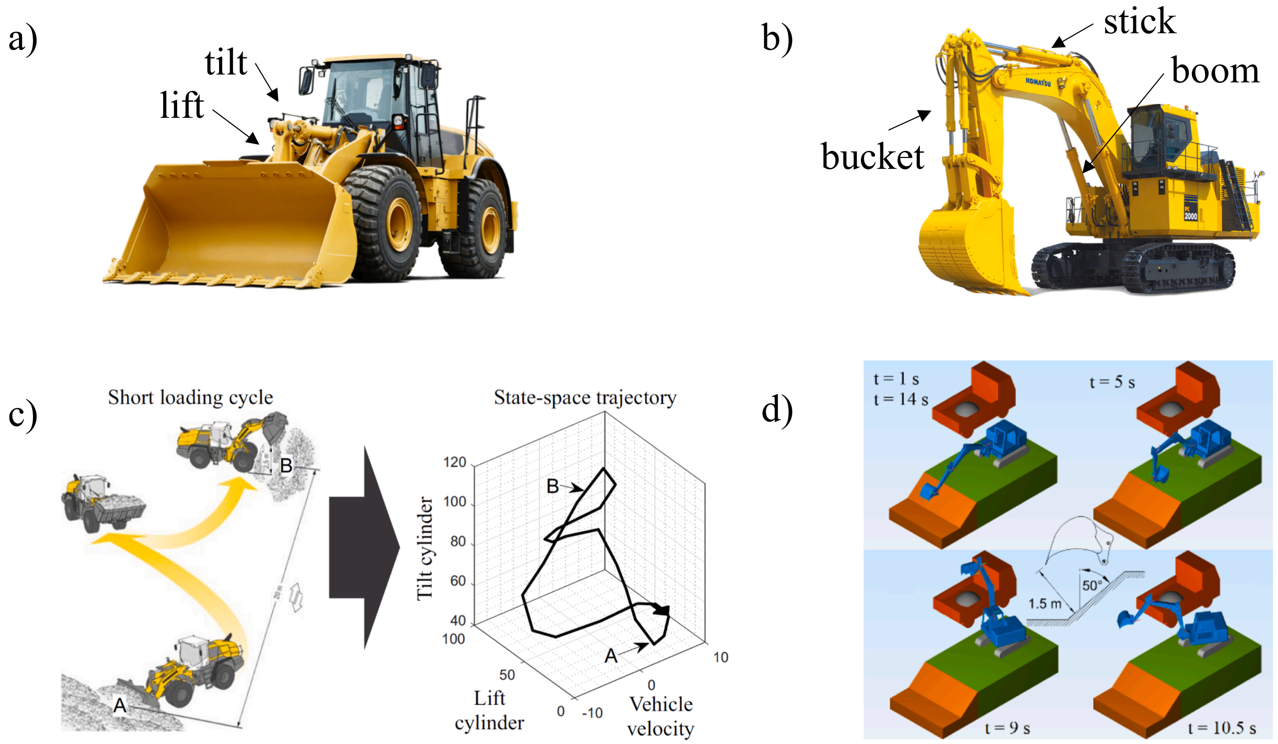

Fig. 2. Pictures not to scale of a) a wheel loader and b) an excavator. Representative working cycles of c) a wheel loader [15] and d) an excavator [16].

2.1. System's operational requirements

Hydraulic EXs come in various sizes (curb weights ranging from about 1 to 1,000 metric tons) and configurations (standard, long-reach, backhoe, or hydraulic shovels). The standard version comprises at least a boom, stick, and bucket actuator attached to the front of the machine, a rotating upper structure driven by the swing actuator, and propulsion motors moving two crawlers (Fig. 2). Compact EXs also have a blade, a boom-swing cylinder, and, often, wheels instead of crawlers or additional attachments such as hammers or thumbs.

The bucket moves soil or other materials, and the cabin rotates while the lower carriage remains stationary. Typical operations are dig-and-dump, trenching, and grading cycles that dictate different power demands for each actuator [17]. EXs also spend considerable time idling (the actuators remain at rest) or traveling within the worksite. Routine maneuvers involve repetitive cycles with opportunities for energy recovery, predominantly potential energy for the boom and kinetic energy for the swing [18]. If not recovered, the available energy must be dissipated into heat by throttling flow in control valves; additional energy is wasted to cool down the working fluid.

The application field sets diverse requirements for the working functions. Machines below 20 tons tend to guarantee the independent velocity control of each actuator. Perceiving the load is preferable instead for bigger EXs. More general needs exist, such as ensuring sufficient system damping to reduce oscillations and guarantee the user's comfort and accuracy (this characteristic defines the "personality" of the machine [19]), controlling overrunning loads (*e.g.*, when lowering the boom), avoiding the stall of the prime mover, offering passive load-holding for safety reasons, and managing actuation priorities (*e.g.*, prioritize to the swing motor over the stick actuator [20]). Auxiliary drives ensure the machine functions (*e.g.*, a fan for the cooler, an alternator for the 24 V electrical system, *etc.*). They are smaller subsystems that do not generate useful work on the actuators but continuously draw energy from the prime mover.

The power demand of the hydraulic system varies abruptly in response to unpredictable operator commands. If additional energy sources do not support the engine, its delivered power can change within seconds from almost zero up to the rated value (Fig. 3). The resulting engine's operating points of popular (nonhybrid) EXs end up being in regions with very low-energy efficiency, a situation aggravated by abrupt transients. These characteristics, combined with the poor energy efficiency of hydraulic systems, are the current weakness of EXs.

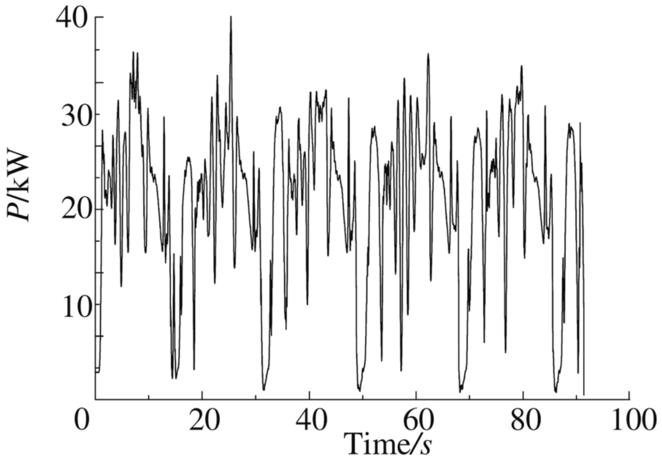

Fig. 3. Measured engine power during a typical excavator cycle taken from ref. [21]. Each cycle duration for this 7-ton machine is almost 20 s, the peak power is approximately 35 kW, and the average power is about 15 kW.

WLs are the other primary type of construction equipment. They are available in sizes ranging roughly from 1 to 160 metric tons, where larger machines are employed primarily in mining. They lift/lower their bucket that is tilted by a linkage. These actuators (boom-lift and bucket tilt) are part of the working functions, including the steering and an optional attachment (*e.g.*, a sweeper brush or a grapple clamp). Moreover, the propulsion subsystem is a crucial element of WLs since they are designed to move forward and backward very often. Based on the

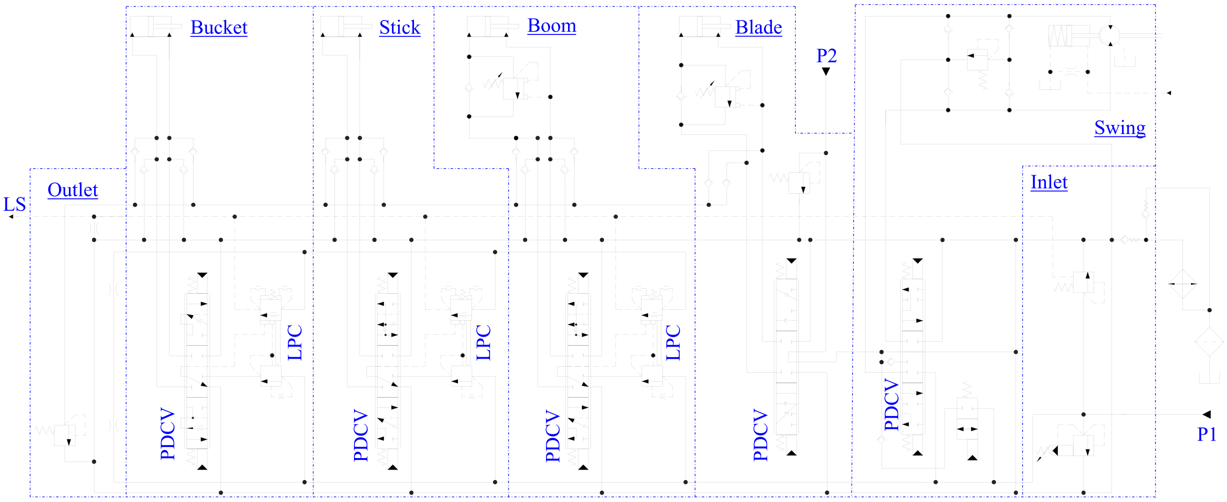

Fig. 4. Simplified schematics of a load-sensing excavator adapted from ref. [30].

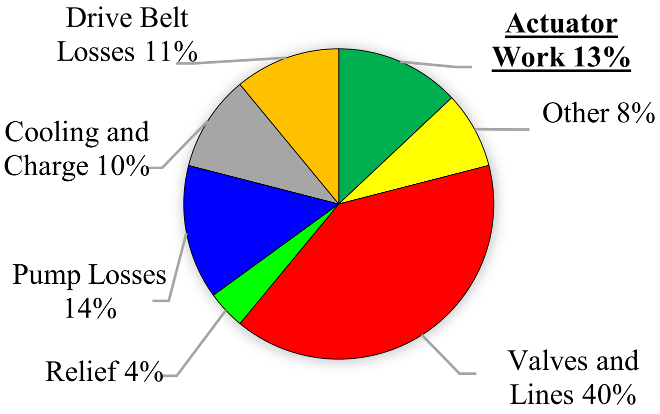

Fig. 5. Energy distribution in a 5-ton, load-sensing excavator adapted from ref. [31].

machine's curb weight, standard options are hydrodynamic transmissions with gearboxes and torque converters (large equipment) or hydrostatic transmissions (small equipment) that can ensure a stepless increase in the traveling speed [22].

Representative operations for WLs are Y-pattern cycles to transport material or truck loading cycles (Fig. 2). They involve lifting/dumping a load and traveling with frequent accelerations and decelerations from/to a standstill. Specific requirements are, therefore, traction control to reduce tire slip and increase the machine's pushing force [23], steering actuation with priority [24], and active ride control [25]. Opportunities for energy recovery are given by the prolusion system (kinetic energy) during decelerations [26] and by the boom-lift actuator (potential energy) when lowering the arm structure [27]. For instance, about 10 % of the total energy used in loading cycles is available for regeneration in a 24-ton machine [28]. It is also worth noticing that the engine's power demand of WLs is similar to that of EXs with sudden and extreme changes [29], as shown in Fig. 3.

2.2. Conventional hydraulic systems (nonhybrid valve control)

The hydraulics of EXs and WLs handles the operational requirements described in the previous section. Standard machines use inefficient and nonhybrid valve control. "Inefficient" means that flow throttling is functional for control purposes and energy recovery is not feasible (the hydrostatic propulsion drive of WLs is the only exception). In detail, multiple layouts have been developed over the past decades [8]. They primarily address motion control (*i.e.*, issues such as load interactions, system damping, or actuation priorities) involving very often pure mechanical-hydraulic devices. Load-sensing (LS) systems are typical for small-to-medium EXs, while positive or negative flow control is preferred for bigger applications above 20 tons. Fig. 4 depicts the LS system of a compact EX [30] and highlights the proportional directional control valves (PDCVs) and their local pressure compensators (LPCs) that throttle fluid. The main pump, a variable-displacement unit, delivers flowrate at a pressure equal to the highest actuator pressure plus the constant LS margin. A fixed-displacement pump is dedicated to the swing and blade actuators to avoid flow saturation in the swing.

As already hinted, flow throttling in such a system strongly limits the machine's energy efficiency. A clear example refers to a digging cycle of a 5-ton LS EX [31], where only 12.5 % of the mechanical energy entering the system through the pump shaft is converted into actual work by the actuators (Fig. 5). About 40 % of the input energy is dissipated by control valves and hydraulic lines, 10 % by the cooling and charging subsystems, 11 % by the mechanical transmission driving the pumps, and 4 % by pressure-relief valves. A suitable system design could avoid almost all these losses (up to 65 % of the input energy). A similar analysis for an 18-ton EX, supported by a Sankey diagram showing the energy flow, gives similar results [17].

Because of this inadequate energy utilization, upgraded versions of these mechanical-hydraulic solutions involved electronics. Relevant outcomes are electronegative flow control [32], electropositive flow control [33], and LS with pump margin adjusted electronically [34]. The corresponding (partial) reduction of metering losses favors higher efficiency (*e.g.*, almost 12 % more in a 22-ton EX completing a dig-and-dump cycle [33]), even if enormous quantities of energy are still wasted due to functional dissipations and unideal control. Additionally, the concept of digital displacement offered interesting opportunities for efficiency improvements via individual control of the pistons within hydraulic pumps [35]. The pump's energy efficiency and dynamic response benefit the entire machine, even if dissipative flow throttling remains. For instance, a 20-ton EX showed 13 % more meters of trench dug per liter of fuel than a traditional tandem pump [36].

Despite these efforts, it was argued that the design and development of mobile machines are not optimal yet. This process can be improved by using virtual prototypes that contain a detailed operator model for EXs [37] and WLs [38] or by developing standardized working cycles to fairly compare the performance of alternative solutions for EXs [39]. Finally, the operator's behavior can play a leading role in fuel consumption and productivity (*e.g.*, differences up to 150 % and 300 %, respectively, can take place in WLs [40]). Therefore, real-time classification of working cycles could detect the best template and assist the

Table 1
Obstacles that prevent from achieving high-energy efficiency in construction machines.

Subsystem (Topic)	Current obstacles
Hydraulics (Layout)	Inefficient system architectures based on functional flow throttling.
Machine (Performance)	Operations of hydraulics and engines in inefficient regions.
Machine (Control)	Lack of coordination engine/hydraulics causing abrupt transients.
Hydraulics (Control)	Suboptimal control of the hydraulics or lack of electronic devices.
Machine (Performance)	Significant energy losses in critical components (*e.g.*, pumps).
Machine (Layout)	Energy-intensive auxiliary drives.
Machine (Simulation)	Lack of design and modeling tools for system optimization.
Machine (Analysis)	Lack of standard duty cycles for fair comparisons of alternatives.
Machine (Sensors)	Need for real-time detection of operations for assisting the driver.

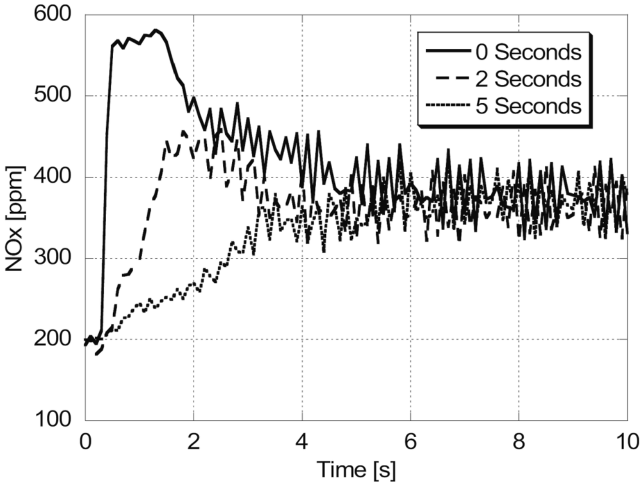

Fig. 6. An example of NO_x emissions during tip-in transients under different load ramp-up durations taken from ref. [43].

driver in operating the machine more efficiently; such an approach was recently studied for WLs [15] and EXs [41]. Table 1 summarizes these barriers that limit energy efficiency in today's off-road hydraulics.

2.3. Prime movers

It is worth stressing again that most hydraulic EXs and WLs available on the market use internal combustion engines (ICEs) as prime movers. There are a few examples of electrically-powered, off-road machines (**Section 5.1** digs into that), but they are limited to compact applications or mining equipment. As a result, ICEs are the most realistic option for many heavy-duty machines because they are powerful, accessible, and well-known.

In terms of the engine's dynamic behavior, machine manufacturers must consider all operating scenarios, including peak power demands. This approach often leads to the selection of larger, more powerful engines. For instance, standard EXs are usually operated at a constant engine speed where peak power is achieved, eliminating the need to adjust the engine speed throughout a working cycle. However, in most engines, this specific value is considerably higher than the speed at which optimum efficiency is attained [17,42]. As a result, the engines of off-road machines often operate at suboptimal efficiency levels under highly transient conditions (Fig. 3). The impact of these pulsating loads on emissions and fuel efficiency has been well-documented in literature [43–46]. Studies have shown that NO_x, unburned HC, and PM emissions increase significantly during load tip-in events, which is more pronounced as the tip-in event becomes shorter (Fig. 6). NO_x emissions can be almost twice as high, and peak PM emissions can be an order of magnitude greater than steady-state values [43]. Consequently, the resulting fuel consumption due to transients can account for up to 50 % of the total emissions [47,48].

Thus, it is possible to improve the engine performance by leveraging specific techniques discussed in Section 7. These solutions alone are, however, not sufficient because leveling off the engine load through hybrid systems is a necessary aspect.

2.4. Hybrid systems

It was highlighted that EXs and WLs offer the possibility of recovering energy due to their "cyclic" operations. This energy can be reused immediately and/or stored to support the combustion engine's potential downsizing and, even more importantly, stabilize its functioning (*i.e.*, "peak shaving" removes abrupt transients, cuts emissions, and reduces fuel consumption). Thus, the resulting hybrid systems include at least one energy storage device (ESD) other than the ICE. The following options are feasible: hydro-pneumatic (bladder- or piston-type),[2] electric (batteries[3] or supercapacitors), and kinetic (flywheels) ESDs. Crucial characteristics vary significantly with the nature of these ESDs (Table 2), namely the power density, energy density, self-discharging rate, and cost.

Power density is more critical than energy density in construction machines if the ESD is intended to meet high-power peaks lasting up to a few seconds. Hydro-pneumatic accumulators are the natural choice due to their high-power density, remarkable round-trip efficiency, cost-effectiveness, and simple integration into existing systems. Batteries or supercapacitors are characterized by notable energy density, even if they require other electric components (at least, a motor/generator and its power converter). Using flywheels is also possible, but they are only suitable for short-term energy storage due to their pronounced self-discharging rate.

2.5. Challenges and opportunities

Combining key elements from above, off-road construction machines are typically powered by diesel engines, require a performant hydraulic system, and give a chance to recover energy. Therefore, designing energy-efficient systems poses the challenges listed in Table 3 on top of ensuring the expected power output and controllability.

There are opportunities in terms of system layout to overcome these obstacles. The engine power can be distributed to the hydraulic actuators using the three primary arrangements shown in Fig. 7, where this classification refers to the control elements and not the entire system: (1) full hydraulic distribution via valves or transformers connected to a high-pressure power supply driven by a prime mover (PS); (2) mechanical-hydraulic distribution using pumps driven by the prime mover; and (3) electro-hydraulic distribution with pumps driven by electric power packs. Pure electro-mechanical distribution also exists for battery-powered machines meant for low-power operations [55]. Such drives cannot keep up with hydraulic cylinders in heavy-duty machines [56] unless combined with a passive hydraulic drive [57]. Thus, electro-

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[2] Membrane-type accumulators are also indicated for energy storage, but only other types are reported here due to their suitability for heavy-duty operations [49].

[3] Lithium-ion batteries are emphasized due to their higher power density and charging/discharging efficiency [9], but redox flow, lead-acid, and nickel metal hydride (Ni-MH) batteries are also viable.

Table 2
Illustrative values of standard energy storage devices for construction machines.

Characteristic	Bladder-type[a] accumulators	Piston-type accumulators	Lithium-ion battery	Supercapacitors	Flywheels
Power density [kW/kg]	30–1300 [49]	46.5 [49]	0.6–2 [9]	≤5 [50]	1–5.5 [51]
Energy density [Wh/kg]	2.4–6.5 [49]	0.2–1.4 [49]	100–120 [9]	4–15 [50]	20–200 [51]
Energy efficiency [%]	60 [49] 89 [52]	90–96 [49]	90 [9]	95 [51]	90–95 [51]
Lifetime [No. of cycles]	$>3.6\cdot10^{4}$ [52] 3–5 years [53]	3–5 years [53]	$>10^{3}$ [9]	10^{4}-10^{5} [54]	10^{4}-10^{7} [54]

[a] Components with and without insulating foam are reported (the lower numbers in the energy efficiency and lifetime cells refer to nonstandard, insulated accumulators).

Table 3
Challenges to achieving high-energy efficiency in off-road construction machines.

Subsystem (Area)	Challenges
Hydraulics (Architecture)	Minimize/Avoid functional losses due to flow throttling in control valves.
Hydraulics (Sizing)	Match efficiently the required pressure level for each actuator.
Hydraulics (Sizing)	Ensure performance in unconventional scenarios (*e.g.*, when using attachments or when the bucket hits an obstacle).
Machine (Architecture)	Enable and maximize the use of energy recovery in duty cycles.
Energy storage (Architecture)	Store efficiently or reuse the available extra energy immediately.
Machine (Architecture)	Minimize the parasitic losses of auxiliary drives during idling.
Machine (Control)	Avoid fluctuating and/or abrupt power demands on the engine.
Engine (Sizing)	Size the engine correctly to get high-power output most of the time.
Hydraulics (Sizing)	Avoid poor design practices by using oversized/undersized hydraulic parts.
Hydraulics (Architecture)	Match the machine's system design to the application.

mechanical distribution is not discussed further.

The approaches (1) to (3), used independently or in combination, lead to the systems presented hereinafter, where Fig. 8 gives an overview of these technologies. Finally, other aspects for maximizing energy efficiency include suitable control strategies, more efficient components, machine connectivity, and advanced working site planning. Since these elements are not strictly related to the design of system architectures, we omit their discussion.

3. Hydraulic valve control

When leveraging fully hydraulic power distribution to actuators, valve control is, by far, the most common technology. It is helpful to distinguish three subcategories: (1) conventional architectures with proportional valves (*i.e.*, the nonhybrid systems without energy recovery capability described in **Section 2.2**); (2) more recent alternatives with proportional valves, typically hybrid systems, that do enable energy recovery; and (3) digital hydraulics with on/off valves. The inefficient first class is not of interest in this article (an extensive review is already available [8]), while the other two subcategories deserve further examination.

3.1. Proportional (hybrid) valve control

This section addresses solutions based on proportional valve control that recover energy. Two reviews of these systems were recently published [10,11], so we only recall the most promising ideas and stress examples of working prototypes (Table 4). These approaches can represent a temporary replacement for a transition toward future (efficient) machines.

In alternatives that store energy in hydro-pneumatic accumulators, the charge pump reuses the boom's recovered energy in a 9-ton EX. It operates as a motor to reduce the load on the combustion engine, so about 9 % of the input energy in trench digging cycles can be supplemented by the ESD [58]. A machine with a 3-chamber boom cylinder was also studied [59]; the peak power of the prime mover can be reduced by almost 65 % due to one chamber always being connected to an accumulator. A newer approach combined multiple hydraulic cylinders for the boom with a hydro-pneumatic accumulator to store energy locally in both large-scale [60] and mid-scale [61] EXs. Energy savings of close to 41 % and recovery efficiency of 65.9 % were shown for the latter case. A more drastic modification uses multi-chamber cylinders [62], as illustrated in Fig. 9. The high-pressure, common-rail supplies the boom, stick, and bucket actuators and the secondary-controlled motors for the swing, traction, and fan. Measurements confirmed 34–50 % higher fuel efficiency (ton/liter) due to less metering losses and greater power availability, increasing the productivity of a 30-ton crawler EX.

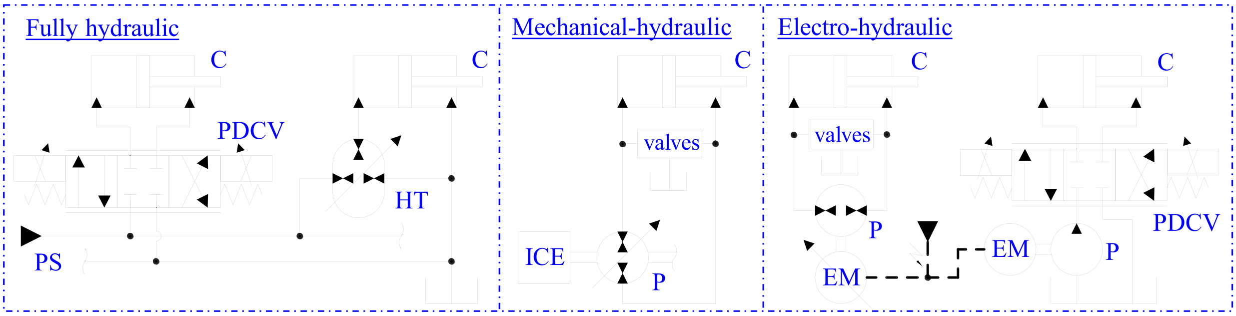

Fig. 7. Illustrative diagram of the main approaches for distributing the prime mover's power to the working hydraulics with focus on the control elements of the actuators.

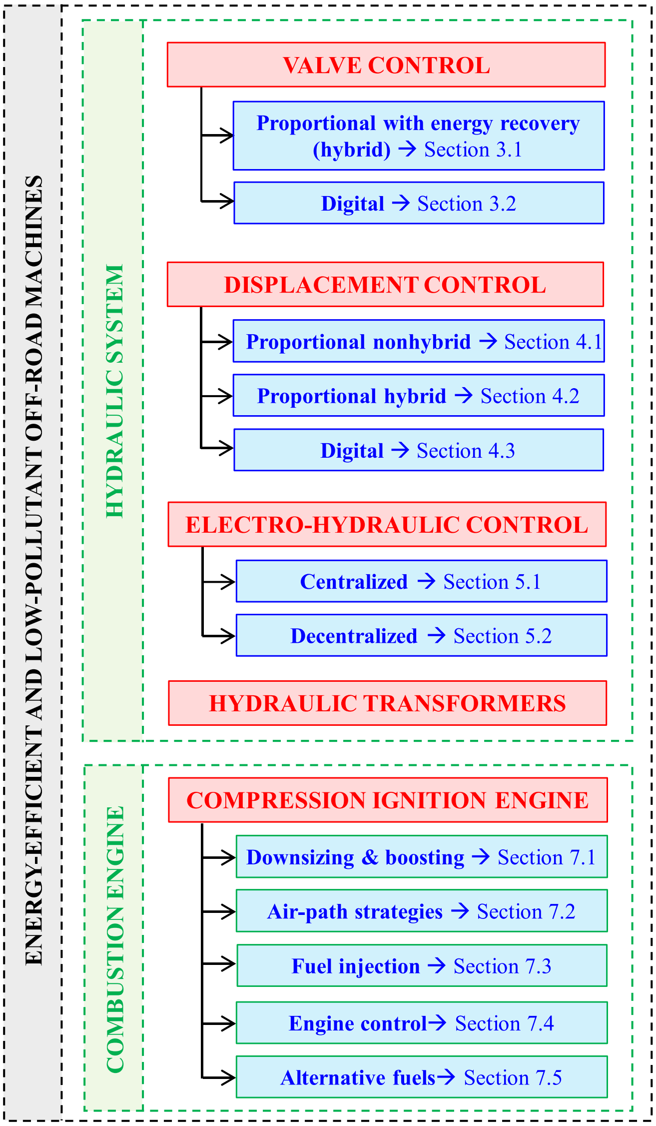

Fig. 8. Opportunities for energy-efficient and low-pollutant off-road machines powered by combustion engines (battery-powered machines or applications without an ICE are not included in this schematic).

Leaving aside hydro-pneumatic energy storage, several hybrid layouts relying on batteries and/or supercapacitors were introduced in the 2010 s. One trend converts the hydraulic motor of the swing into an electric one, so its dedicated motor/generator coupled to the engine can also assist the prime mover during acceleration. Such a commercialized solution enables, on average, a 25 % decrease in fuel consumption [63]. Another tendency is to install a hydraulic motor in the boom actuator's return line to the reservoir; it drives an electric generator connected to a supercapacitor that supplies a motor driving the main pump. The total energy recovery efficiency is between 26 % and 33 % [64]. Similarly, a hydraulic motor in the boom actuator's return line can assist an auxiliary pump that supplies a common rail; almost 18 % of the input energy is saved compared to standard valve control, but the boom actuation is slightly slower [65]. Another alternative combines hydro-pneumatic and electric ESDs to make the system more compact and comparable to pure valve control in terms of dynamic response; approximately 40 % of the available potential energy can be regenerated [21].

Changing ESD typology again, applying flywheels to off-road hydraulics is uncommon. Only a 17-ton EX prototype was traced [66]; Ricardo claimed it could save about half of its available potential energy in a material handling cycle using a flywheel with a storage capacity of 200 kJ. Simulation studies explored this concept for the boom of a 4-ton EX, where the flywheel is driven by an additional hydraulic unit connected to the boom actuator via valves [67]. A similar system reduces energy consumption by up to almost 49 % in an unloaded cycle of a LS machine [68]. In general, an in-depth analysis indicated flywheels could be competitive with other ESDs when leveraging their main advantages (almost unlimited service life and energy storage capacity independent of time or depth of discharge). Other authors suggested combining flywheels with another ESD [69] and proposed a hydraulic flywheel accumulator that grasps complimentary characteristics of each domain [70].

Table 4
Synthesis of significant prototypes using proportional valve control with energy recovery.

ESD	Machine	Key design features
N/A	14-ton WL [77]	Variable LS margins and flow regeneration for overrunning loads.
Hydro-pneumatic accumulator	9-ton EX [58]	Recovery from boom and charge pump used as a motor to support the engine.
	6-ton EX [59]	3-chamber boom cylinder.
	76-ton EX [60]	Multiple hydraulic cylinders for the boom combined with an accumulator.
	33-ton EX [61]	
	30-ton EX [62]	Common rail: multi-chamber cylinders and secondary-controlled motors.
	17-ton WL [72]	Overcenter pump of the stand-alone hybrid system coupled to the engine.
	6.5-ton WL [73]	
Battery and/or supercapacitor	20-ton EX [63]	Electric swing actuator.
	Small EX [64]	Hydraulic motor in the boom's return line driving an electric generator.
	23-ton EX [65]	Hydraulic motor in the boom's return line assisting an auxiliary pump.
	12-ton WL [71]	Hydraulic working functions and full-electric propulsion subsystem.
*	7-ton EX [21]	Hydraulic accumulator in the boom's return line together with hydraulic motor driving an electric generator.
**	17-ton EX [66]	Carbon-fiber composite flywheel with magnetic coupling.

* Hydro-pneumatic and electric; ** Flywheel

Focusing on WLs relying on proportional valve control, the most common trend embraces hybrid and propulsion subsystems linked together to support the engine. Examples of working prototypes involve batteries [71] or hydro-pneumatic accumulators [72,73]. The latter case uses an overcenter pump for the hybrid subsystem, which gives a 29.5 % reduction of emissions (NO_x and PM) due to smoother engine transients. Then, some recent outcomes are worth mentioning, even if they are limited to simulations. Several configurations were discussed at a principle level [74], concluding that hybrids also increase the machine's operability (they help to find a better compromise among conflicting demands such as productivity, efficiency, and cost). Another alternative combines the propulsion and hybrid subsystems, leading to a tunable hybridization degree by using a secondary-controlled motor [22]; fuel savings of 18.3 % (mild hybrid) and 18.9 % (full hybrid) are achievable compared to a conventional hydrostatic drive. A more drastic approach is based on a common rail to supply the power-split propulsion and the implements equipped with 4-chamber cylinders controlled individually by 2/2 proportional valves [75]; this machine enables energy recuperation and sharing between actuators but keeping the rail pressure as low as possible presents some control challenges that might require predictive algorithms.

Concerning the latest findings about using batteries in WLs, a simulated degradation model showed that battery life could be enhanced without deteriorating fuel economy when applying a trade-off

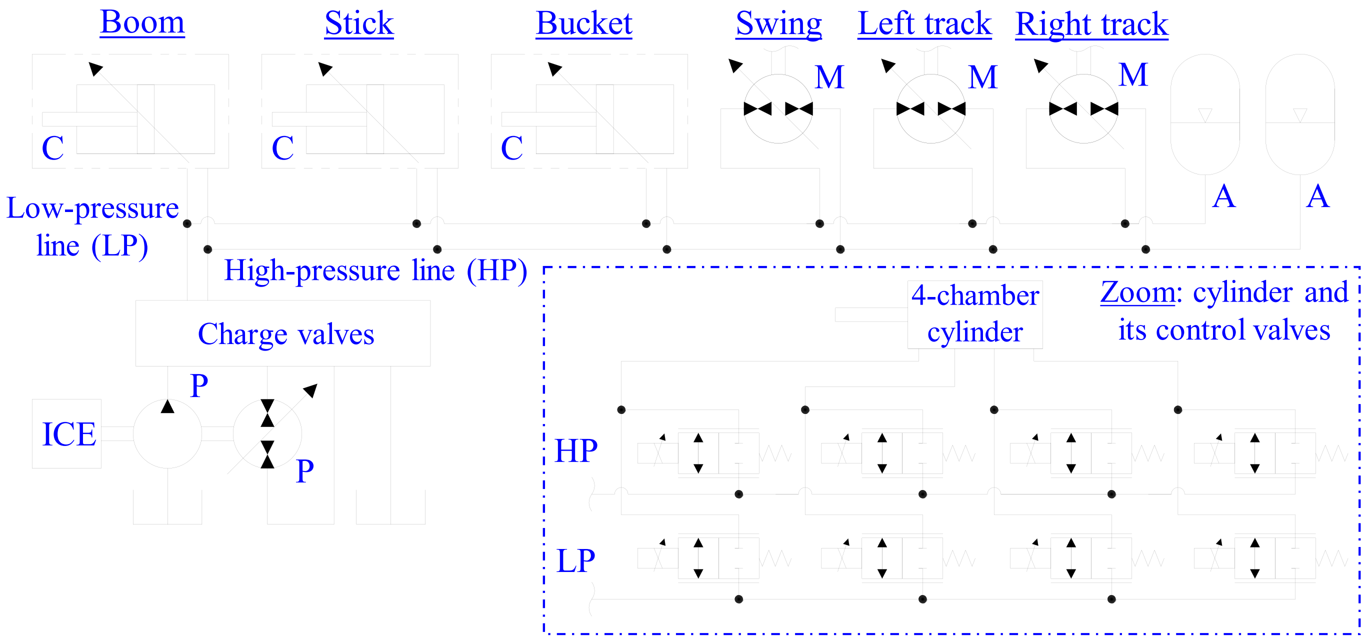

Fig. 9. Simplified schematics adapted from ref. [62] of an excavator based on proportional valve control with multi-chamber cylinders.

between fuel economy and loss minimization of the battery capacity [29]. A hybrid subsystem was developed to charge/discharge the battery using a dedicated hydraulic unit linked to the constant-pressure propulsion subsystem [76]. The resulting ESD has a much higher energy density (165.6 kJ/kg) compared to a hydro-pneumatic accumulator (4.5 kJ/kg) and constant power density (1.1 kW/kg), even if the latter parameter is sometimes lower than the one of the hydraulic counterparts. The benefit is about giving active control of the ESD, allowing multiple pressure profiles to reduce fuel consumption (*e.g.*, 5.9 % reduction when shifting from 330 to 270 bar). Lastly, a possibility without hybridization relays on variable LS margins and flow regeneration for overrunning loads [77]; it was tested that throttling losses can be mitigated, turning into 45 % power savings for medium-to-low speed of the actuators and about 20–30 % in other speed ranges.

Despite the energy recovery capabilities discussed in this section, the system complexity increases to different extents, and most importantly, functional flow throttling is still present. Such a scenario suggests exploring a different approach built on digital valves.

3.2. Digital valve control

The control elements in digital hydraulics are on/off valves. Flow paths are opened/closed by switching one valve at high-frequency or by enabling, at lower frequencies, parallel connections of multiple valves. Benefits include simple components, fast valve dynamics, and enhanced system flexibility (the controller defines characteristics typically realized by components such as flow regeneration). There is also the opportunity for increased energy efficiency when driving an actuator [78], even if throttling losses are not entirely removed (adding orifices to the valves is a widespread practice to ensure smooth flow characteristics [79]). Then, the digital displacement concept to individually control the chambers within pumps/motors improves their energy efficiency and offers control advantages [35,80]. It benefits conventional valve-controlled systems and can directly control actuators (Section 4.3). Some drawbacks are, however, still not completely solved, mainly pressure pulsations induced by valve switching, lifetime of digital components (more than one billion switching cycles are expected), physical size, and the need for complex control techniques [81].

An initial attempt applied digital valve control on the boom of a stationary EX using a power supply with 3 pressure levels, 27 on/off valves, and a 4-chamber cylinder [82]. The experiments exhibited relatively smooth operations, but the system's energy efficiency was not studied. Then, a distinctive digital pump/motor [83] was tested to drive 2 actuators of a backhoe boom [84]; 2 separate sets of valves (digital and proportional) realized the actuator position control. Energy savings slightly above 40 % took place because separating the supply pressures and applying independent metering minimizes throttling losses. Another study proposed a hybrid solution integrating the ESDs and cylinder [85]. Only a limited amount of power is continuously transferred from the centralized power supply to the actuator, while high-power peaks are handled locally. Its potential application to a 21-ton EX was only suggested, but this principle also has general validity for electro-hydraulic control (**Section 5.2**).

A more organic investigation proposed 4 independent metering edges per actuator in the main functions of an EX (Fig. 10), where the controller ensures an electronic LS behavior of the pump. Comparisons against a 21-ton LS EX simulated 28–42 % savings of the input hydraulic energy [86]. Considering the minimum system modifications, lower metering losses almost entirely justify these savings. This idea was then implemented with 7 valves per actuator for a total of 112 digital valves installed on an EX [87]. Experiments on a grading cycle confirmed a 36 % reduction of the hydraulic input energy, even if some control challenges are still pending (*e.g.*, the operator can feel undesired pressure fluctuations). Furthermore, a digital boom-swing actuator replaced the original LS set-up in a 1.1-ton EX [88]. It uses the digital actuator originated by integrating the ESD and the actuator [85] that was developed further [89]. Swinging maneuvers gave 72–74 % reductions in electric energy consumption due to efficient and power-on-demand functioning.

Moving to WLs, a first attempt replaced LS proportional valves with 5 parallel-connected, on/off-valves per edge in the lift and tilt functions [90]. Depending on the scenario, the automatic selection of control modes, including flow regeneration, was simulated for a 5-ton WL, giving between 33 % and 63 % less losses. An implementation of this system was realized with 6 on/off-valves per edge [91], but its energy efficiency was not mentioned since the focus was on redesigning the control algorithm to deal with industrial controllers. Then, the same authors simulated alternative hybrid systems using hydro-pneumatic accumulators, one of them being mainly digital. It gives fuel savings of up to 26 % compared to the LS WL, but additional analyses of the

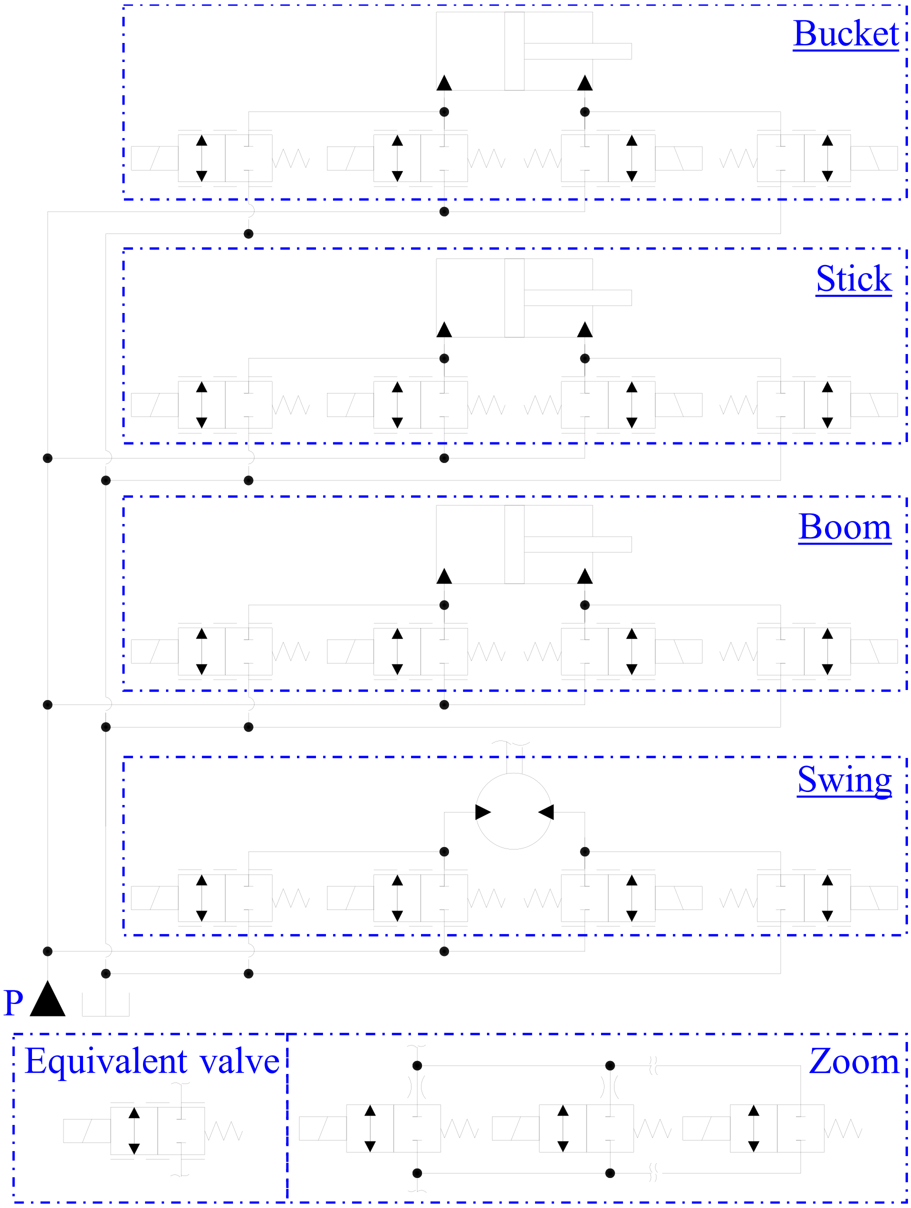

Fig. 10. Simplified schematics adapted from ref. [87] of an excavator based on digital valve control.

Table 5
Synthesis of significant off-road prototypes using digital valve control.

Machine	Key design features
Only EX arm [82]	Supply with 3 pressure levels, 27 on/off valves, a 4-chamber cylinder.
Backhoe arm [84]	Supply with 2 pressure levels, 2 sets of valves (digital and proportional).
21-ton EX [87]	4 metering edges per actuator (7 on/off valves each), electro-LS pump.
1.1-ton EX [88]	Digital multi-pressure boom-swing actuator [85] with power-on-demand.
5-ton WL [91]	4 metering edges per actuator (6 on/off valves each), electro-LS pump.

system's dynamic response were recommended [92]. Table 5 summarizes these results.

4. Displacement control

Displacement control (DC) relies on adjusting the pump's displacement setting to control the actuator motion while removing functional losses and allowing for energy recovery. This technology is mainly implemented using swash-plate pumps leading to proportional DC (**Section 4.1** and **Section 4.2**), but it can also be realized with digital pumps (**Section 4.3**).

4.1. Nonhybrid proportional displacement control

Proportional DC is applicable in two main ways. Each actuator port is permanently coupled to the corresponding pump port in a closed-circuit configuration [93]. Additional devices, typically pilot-operated check valves, balance the differential flow of the cylinder by enabling a connection with the (low-pressure) charge line. Conversely, a

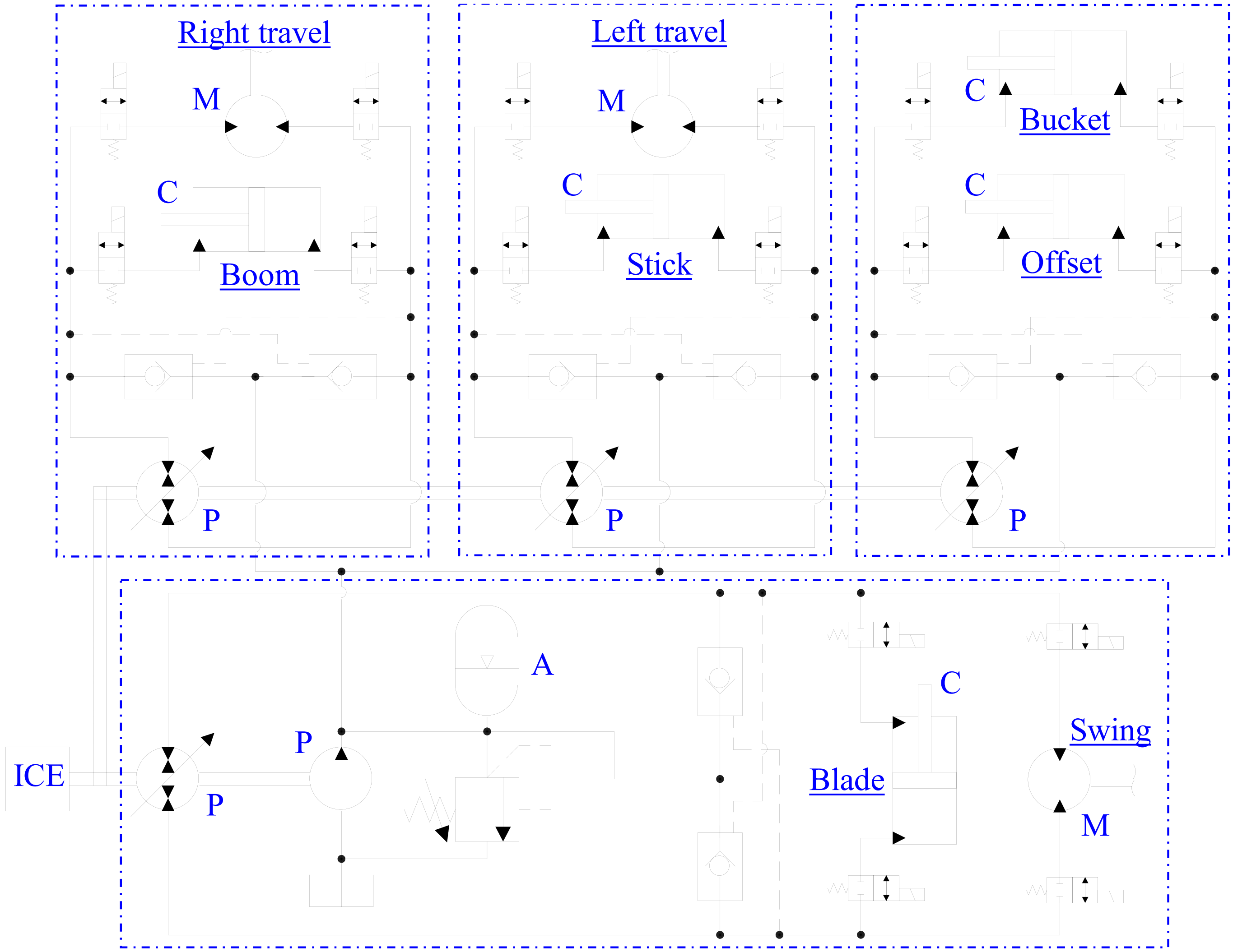

Fig. 11. Simplified schematic adapted from ref. [97] of a nonhybrid, displacement-controlled excavator.

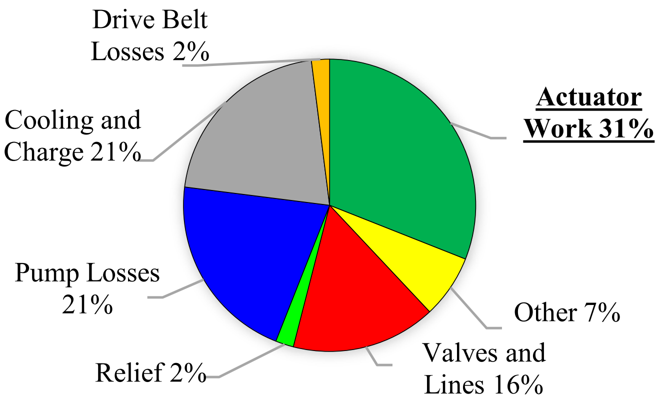

Fig. 12. Energy distribution adapted from ref. [31] in a nonhybrid, displacement-controlled excavator.

directional control valve connects the pump, actuator, and reservoir in open-circuit arrangements, where this nonproportional valve ensures negligible flow throttling [94]. Despite 100 % energy efficiency of the hydraulic system is theoretically achievable, the parasitic losses of the pump become critical at partial displacement settings [95]. Then, pumps' churning losses introduce additional dissipations when the actuators are inactive but the engine is running. Another drawback is the costly set-up due to the one-pump-per-actuator requirement for simultaneous movements; such a condition calls for at least 4 units on an excavator because the boom, stick, bucket, and swing are involved in common operations. Each pump needs a high-bandwidth PDCV to ensure sufficient dynamic response [96].

The first displacement-controlled EX was developed for a 5-ton machine comprising 4 pumps that control 8 hydraulic actuators (Fig. 11). Digital valves enable/disable the connections between pumps and actuators so that a minimum number of units is installed [97]. A comparison against the commercialized LS EX demanded only 50 % input energy in a measured digging cycle [31]. The energy distribution shows that the hydraulic system's efficiency of the DC EX is 30.9 % (Fig. 12), while the one of the LS machine is only 12.5 % (Fig. 5). Similar trends were highlighted for a 20-ton DC EX, even if only in simulations [98]. These improvements are almost entirely justified by eliminating flow throttling in control valves that dissipate approximately 35–40 % of the input mechanical energy in standard LS systems (see **Section 2.2**). Significantly, enhancing energy efficiency improves the EX performance; loading the same amount of soil on a truck took 13 % less time and about 40 % less fuel than the LS machine [99].

Displacement control was also simulated for a 30-ton EX [100]. The first alternative resembles the system in Fig. 11 with DC for the 4 main actuators. It requires only 70 % of the mechanical energy entering the LS baseline machine in a truck-loading cycle, so the overall energy

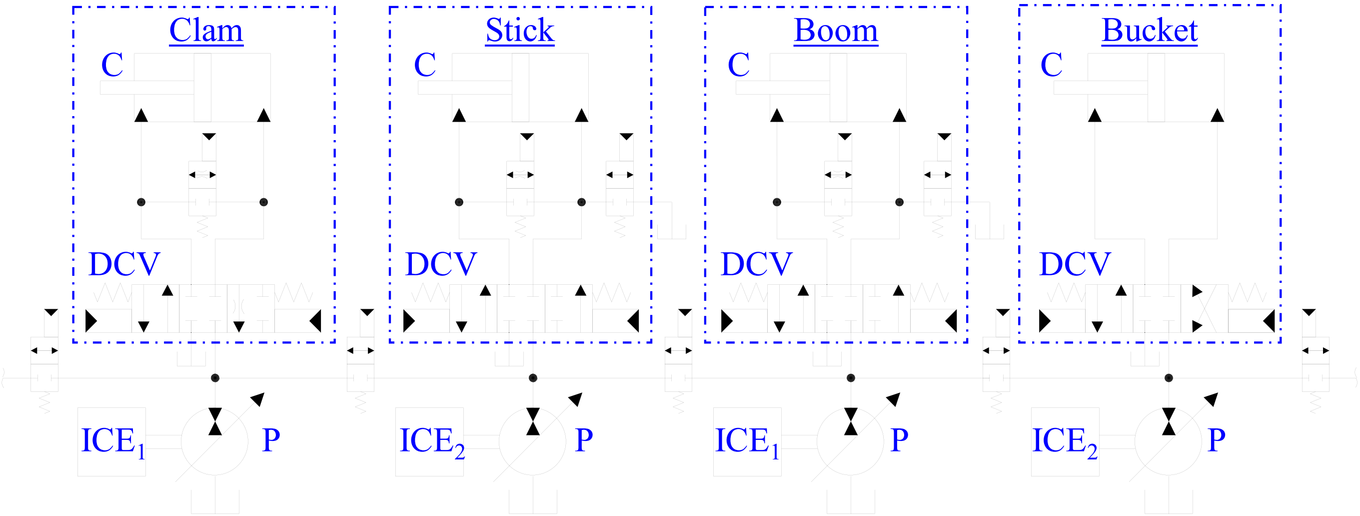

Fig. 13. Simplified schematic adapted from ref. [107] of a nonhybrid, displacement-controlled hydraulic shovel.

efficiency jumps to 57 % compared to 40 % of the LS baseline. Mixing DC (boom and swing cylinders) with valve control (stick and bucket actuators with dedicated LS pumps) is a second possibility, resulting in 48 % energy efficiency.

Additional analyses highlighted that there was more room for improvement. First, power management can give an optimal balance between efficiency and performance. Simulations showed a 17 % reduction in fuel consumption in a digging cycle [101]. The cooling capacity could be reduced up to 50 % [31] since higher system efficiency means less heat is generated and transferred to the hydraulic fluid. Moreover, the critical “mode switching” was highlighted for the boom actuator (unstable transitions between operating quadrants can show up when the net force acting on the hydraulic cylinder changes direction during motion); these instabilities are amplified by low system damping that is typical for throttleless actuation [102]. Mode switching can lead to large load oscillations that undermine performance and safety. Including pressure feedback stabilizes the response [103], but this method might not be completely resolutive since ongoing investigations suggest more complex alternatives [104,105]. Furthermore, pump switching via on/off valves was implemented on the boom actuator [106]. The proposed algorithm ensures smooth enough transitions between flow summing and single unit operations opening to redundant actuation.

A conceptually different DC system was studied for a 300-ton shovel with 4 main linear actuators [107]. The original open-center system dissipates almost 35 % of the engines’ mechanical energy in control valves. The proposed DC alternative is arranged in an open-circuit configuration for faster lowering of the boom and stick actuators and easier flow sharing among pumps (Fig. 13). Each actuator has a dedicated pump, 4 in total, that are divided evenly between the 2 diesel ICEs. Experiments demonstrated energy savings of 59 % in the boom alone and 67 % in a digging cycle [108]. Since they were conducted in a facility with different soil hardness from a real mine, a simulated ideal cycle showed 28 % fuel savings, an enormous amount for a machine of this size.

Concerning nonhybrid WLs, a 13-ton machine was converted from LS into DC with dedicated pumps for the boom-lift and tilt functions. Consumption reductions of 15 % were demonstrated with the recovered energy being reused by the propulsion subsystem [109]. Simulations indicated that pump efficiency considerably impacts energy consumption [95]. The same system can also enable active oscillation damping of the boom structure; it improved the original behavior (about 40–60 % energy savings based on the load scenario) while ensuring similar damping capabilities [110]. Finally, the steering system alone of a 4.5-ton WL was converted to DC. Experiments showed 14.5 % fuel savings and 22.6 % productivity gain due to eliminating the steering’s priority and control valves [24].

4.2. Hybrid proportional displacement control

The power demand of nonhybrid equipment is highly variable, like in the 5-ton EX recalled in the previous section [31]. This scenario is ideal for introducing hybrid systems that can downsize the engine’s rated power and give some freedom in managing its operating points. Thus, three hybrid versions of the identical 5-ton DC EX were proposed [111]: a parallel hybrid and a series–parallel hybrid with a closed- and open-circuit swing motor (the first and second options are depicted in Fig. 14).

The parallel hybrid modifies the system in Fig. 11 by adding a hydro-pneumatic accumulator and a dedicated overcenter pump to transfer power between the ESD and the engine. Conversely, the series–parallel hybrid includes the accumulator inside the swing subsystem since the swing motor becomes a secondary-controlled unit. Experiments showed acceptable closed-loop velocity control of the swing motion [112]. Adaptive robust control is, however, preferable to manage the nonlinearities in the cabin rotation [113]. Simulations addressing all actuators were also done by applying a rule-based strategy derived from optimal control [114]. Fuel savings of 17 % were predicted in a digging cycle compared to the nonhybrid DC machine discussed above. Two developed control algorithms were proposed [115] and implemented [116], namely a suboptimal strategy (it maintains the engine at rated speed and constant torque) and a near-optimal strategy (it always commands the minimum ICE speed, ensuring the actuators’ flow requirements). Further improvements adjusted the engine speed to minimize fuel consumption while considering the power management of the entire system at a supervisory level [117]. Measurements during a digging cycle proved that the engine power never increases above 55 % of the maximum value (*i.e.*, almost 50 % of engine downsizing is feasible for that cycle). The final upgrade of this 5-ton EX shown in Fig. 15 leverages a planetary gear train to couple the engine and the pumps [118]. Decoupling the actuators’ flow from the ICE speed allows engine operations in efficient regions. It leads to important fuel savings when simulating a 90-deg digging cycle (almost 12 % against the series–parallel hybrid EX and about 60 % compared to the LS machine).

Hybrid DC was also applied to the boom and swing actuators of a 40-ton EX [119]. The peculiarity was about connecting 2 pumps to the bore-side chambers of the boom cylinders, the other port of one pump to the rod-side chambers, and the other port of the second unit to an

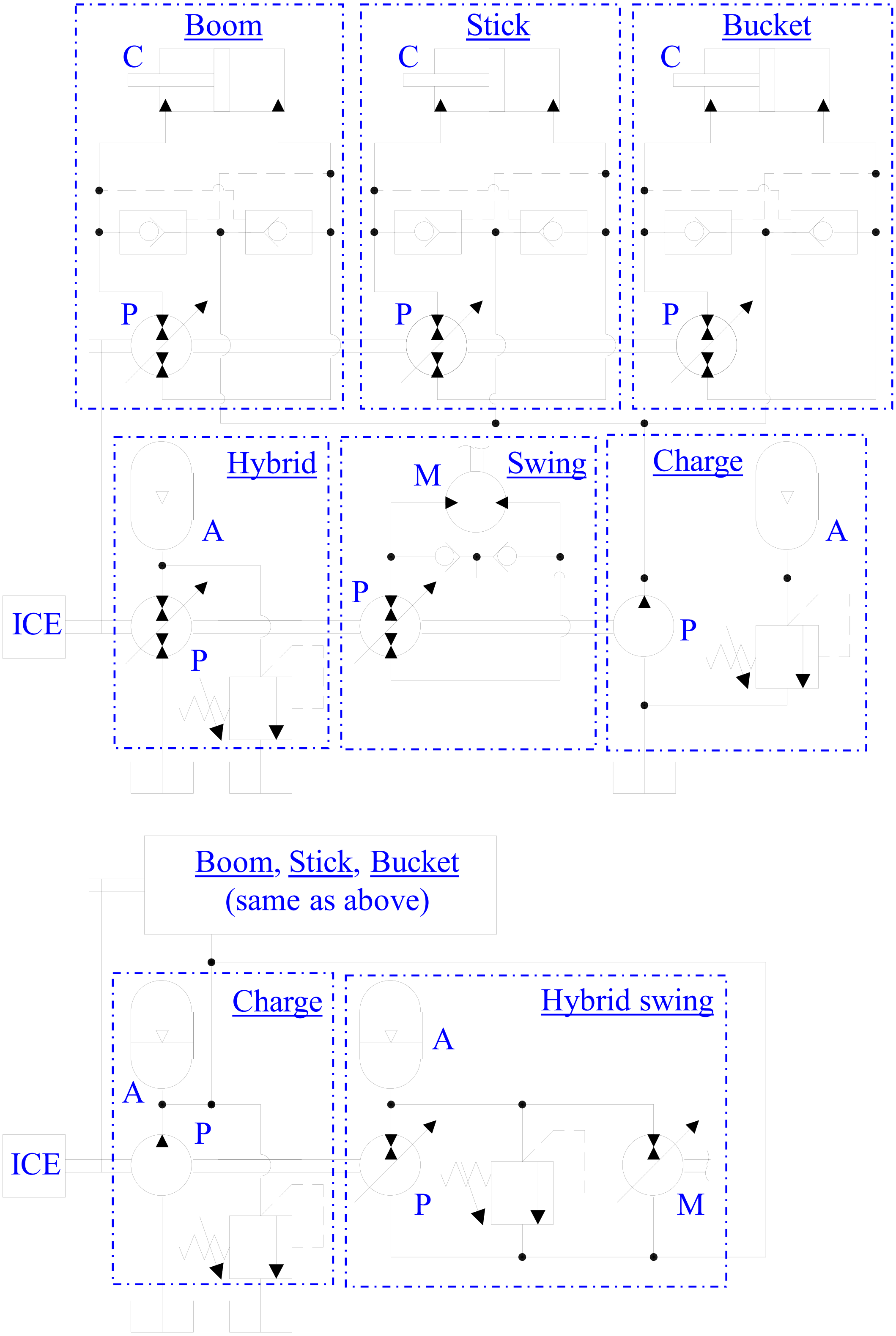

Fig. 14. Simplified schematics adapted from ref. [111] of hybrid, displacement-controlled excavators: parallel hybrid (upper) and series–parallel hybrid (lower).

accumulator. About 25 % engine downsizing was claimed, and a prototype was mentioned, but published results were not traced. Lastly, DC was simulated for the swing function of a 15-ton EX using a separate secondary-controlled motor [120]. It was arranged in both open- and closed-circuit configurations. About 25 % of the input energy can be recovered, but estimations of the overall efficiency are missing.

Considering WLs, a 24-ton hybrid machine uses a diesel ICE optimized for low-speed operations with a nominal value of 1,400 RPM [28,121]. Its propulsion subsystem includes a power-split transmission with a purely hydrostatic drive. The boom-lift and tilt functions are displacement-controlled, and there is also a hydrostatic hybrid subsystem with a double-piston accumulator. This WL achieved 10–15 % fuel

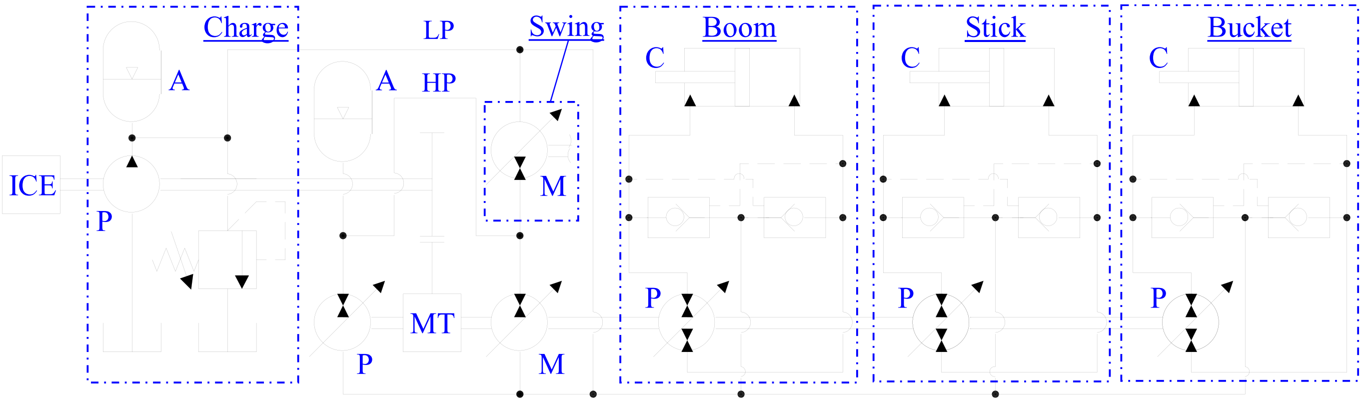

Fig. 15. Simplified schematics adapted from ref. [118] of a hybrid excavator with power-split transmission and displacement-controlled actuators.

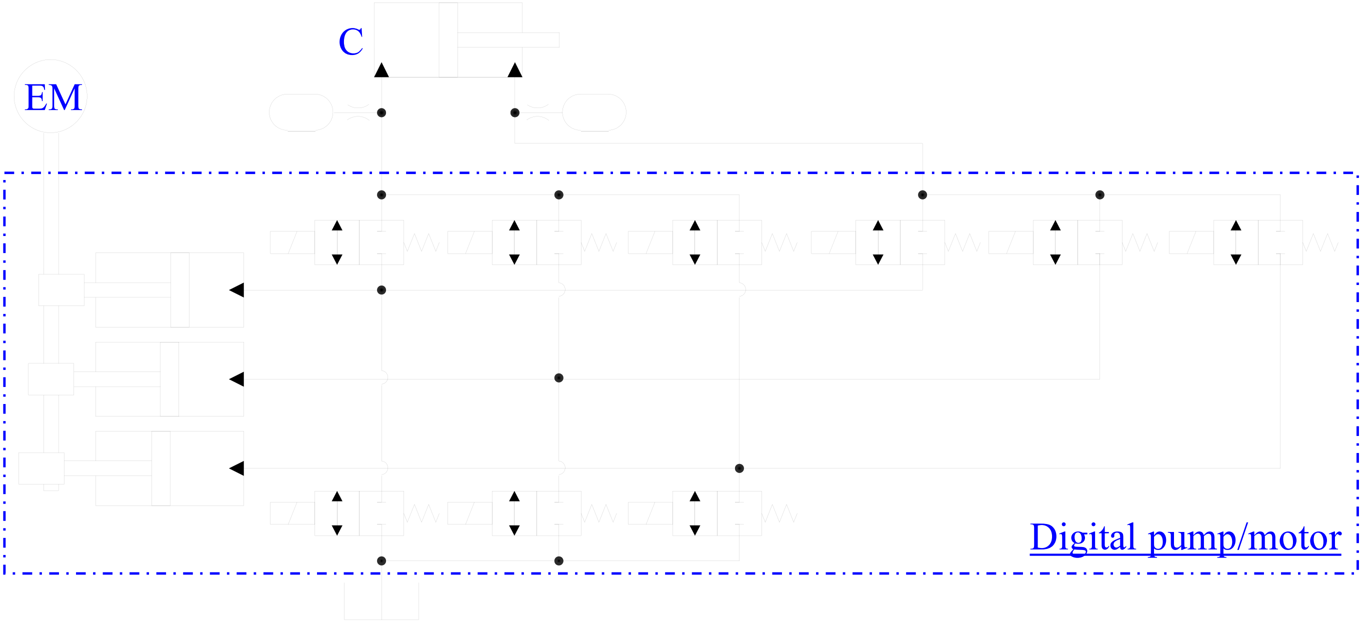

Fig. 16. Simplified schematics adapted from ref. [124] of digital displacement control.

savings compared to the valve-controlled counterpart [122]. It is worth noticing that, in practice, no recovered energy can be stored in the accumulator (other drives instantly consume most of it). Even if the stored energy must be supplied directly by the engine, the ESD can boost the machine's productivity; this superior performance required a 7 % additional fuel consumption compared to measurements with the hybrid subsystem being disengaged.

4.3. *Digital displacement control*

Leaving aside proportional control of the pump's displacement setting, the idea of controlling the actuator motion directly with a digital pump/motor was patented in 2010 [123]. A digital power supply with independent outlets can drive multiple actuators by adjusting the pressure level of each outlet to the corresponding load (throttling losses are essentially removed). An array of digital valves enables/disables the proper fluid paths to achieve the desired operations, and a hydro-pneumatic accumulator can also be added to level out the load on the

Table 6
Synthesis of significant off-road prototypes using displacement control.

Machine	Key design features
5-ton EX [97]	Nonhybrid system with 4 pumps for 8 actuators (closed-circuit).
300-ton EX [108]	Nonhybrid system with 4 pumps for 4 actuators (open-circuit).
13-ton WL [109]	Nonhybrid system with 2 pumps for 2 actuators (closed-circuit).
4.5-ton WL [24]	Nonhybrid system with 1 pump for steering actuator (closed-circuit).
5-ton EX [112]	Hybrid system with 4 pumps and secondary-controlled swing motor.
24-ton WL [121]	Hybrid system with DC for boom-lift and tilt and hydrostatic transmission.
Static EX [124]	Digital DC using a pump/motor with 3 outlets (actuator ports and reservoir).

prime mover. Published studies applying this method are not available to the best authors' knowledge, even if control of a stationary excavator arm was recalled in a public presentation.[4]

A similar approach relies on a digital pump/motor that can act as a hydraulic transformer [83]. It was tested on the boom of a stationary EX's arm (Fig. 16), showing good control performance except for some ripples in the piston velocity despite the addition of damping orifices [124]. Specific values of the hydraulic system's energy efficiency were not given explicitly, but it can be roughly estimated to be as high as 50 % [125]. Another application was then simulated involving the boom and stick actuators of a stationary excavator arm [126]. The digital power supply was configured with 5 outlets (the 4 actuator ports and an accumulator). Using the accumulator comes at the expense of higher energy consumption (more pressure losses in the digital valves), but the power demand to the prime mover remains smooth. The prototypes that emerged from the entire discussion about DC are listed in Table 6.

5. Electro-hydraulic control

Electro-hydraulic, or electro-hydrostatic, control favors the electrification of off-road machines [14]. Variable-speed EMs are key figures used to drive hydraulic pumps. Special demands, therefore, exist at both component and system levels.

As already stated recently, EMs are often not sufficiently addressed when dealing with this emerging technology [14]. More research is needed to combine EMs and hydraulics better, especially when EMs become control elements. Counter-intuitive situations might happen, such as utilizing wide-bandwidth EMs [127], which may not necessarily be beneficial for feedback control in some cases [128]. In detail, permanent-magnet synchronous machines are a popular choice due to their excellent efficiency and high-power density compared to other electric machines [14]. EMs usually operate with closed-loop speed control, even if a novel approach suggests replacing it with torque control using the inverter's high-bandwidth capability (400 Hz) [129]. This technique gives superior dynamic response when pursuing position tracking, but it is affected by measurement noise that requires attenuation methods such as an extended Kalman filter [130]. Finally, EMs exhibit favorable characteristics at high speeds (their efficiency improves with speed, and their output power per unit volume is directly proportional to speed).

Coupling pumps to EMs directly is desired due to gearbox inefficiencies. Thus, specific pump/motor designs are needed to achieve much higher speeds than standard units optimized for direct coupling to ICEs. This feature enables reduced pump displacements that, in turn, benefit the sizing of EMs that depends on the rated torque. Preliminary studies were presented for high-speed units up to 10,000 RPM, but they cannot switch their high- and low-pressure ports [131], or they show a pressure-dependent, speed-flow relation due to their hydrodynamic operating principle [132]. Then, dedicated pumps should also ensure wear-free and efficient operations at very low speeds (<250 RPM) for fine adjustments of the actuators when directly coupled.

Additionally, providing electric energy to off-road machines is essential. The supply methods are mainly based on lithium-ion batteries, engine-driven generators, fuel-cells, or power cables. All these sources have faults (*e.g.*, energy and power density for batteries, local emissions for generators, infrastructures for supplying hydrogen to fuel-cell, or portability for cables). Thus, no single solution fits all (ref. [14] fully develops this topic). While considering all these aspects, we divide electro-hydraulic control into two main branches.

5.1. Centralized electro-hydraulic control

We talk about centralized, electro-hydraulic control when hydraulic valves generating functional dissipations are still present, similar to those systems in **Section 2.1**, but the pump is now driven by an EM instead of an ICE. Conventional, valve-controlled hydraulic systems are maintained, making this option easily implementable. The main advantages are the machine hybridization to support the ICE when present, a more independent and efficient power distribution (*e.g.*, separate EMs and pumps for propulsion and implements), the possible use of fixed-displacement pumps that avoid pump's control losses, a reduction of pump speed to diminish idling losses when needed, and a potential restraint of noise emissions even if some declared values still recommend use of hearing protection (*e.g.*, up to 87 dB [133]).

Several compact machines following this line are commercially available: a 1.9-ton EX with a Li-Fe battery and 20 kW of peak power [134], another 1.9-ton EX with a 7-kW EM in continuous [133], and a 5-ton WL with a 22-kW EM and a 40-kWh battery [135] to mention a few cases that are sometimes referred as "full-electric" or "all-electric". Enabling indoor use is the main reason for completely removing the ICE in these small-size machines, given their zero (local) emissions of exhaust gases. Then, prototypes of EXs powered by fuel cells [136,137] and of bigger machines were also announced, for instance, a 26-ton EX with a 300-kWh battery pack [138], a 24-ton EX with a 123-kW EM [139], and a WL with an EM of at least 78 kW [140]. The same approach was also considered for huge-scale equipment such as a 270-ton shovel to recover braking energy [141] and a 120-ton shovel to support its ICE [142].

Another opportunity, even if not strictly defined as electro-hydraulic control, concerns using electric drives in the swing of EXs. It can be done with a hydraulic motor [143] or an EM alone [144]. The latter approach greatly improves energy efficiency, for instance, up to 21 % in a compact EX [145]. Similarly, the propulsion of WLs can be purely electrical, such as in a 17-ton WL that was tested with 1 or 2 EMs for the propulsion and another EM to drive the hydraulic pump for the implements. The dual-EM drive resulted in the best solution for changing adhesion coefficients with the ground of the two axles [146].

It is, therefore, clear that this technology (*i.e.*, valve-controlled hydraulics supplied by pumps that are driven by electric motors) has a sufficient maturity level for series production. Nevertheless, there are considerable downsides when valve control is kept that call for improvements (*i.e.*, functional flow throttling and the missed opportunity of leveraging the fast dynamics of EMs for control purposes).

5.2. Decentralized electro-hydraulic control

Decentralized, electro-hydraulic control achieves motion by adjusting the speed of pumps directly coupled to hydraulic actuators without control valves in between. The resulting standalone devices are also known as EHAs, namely electro-hydrostatic actuators [147] or zonal hydraulics [148]. Widespread energy-efficient architectures are single- or dual-pump systems [149], but other arrangements are also possible [150] since the challenge is balancing the differential flow of asymmetric cylinders in closed-circuit configuration. These drives can also include passive load-holding [151], oil cooling and filtering [152,153], or self-contained design [154,155]. Further studies on oil conditioning are still needed for closed-circuit configurations [153], especially for high-power drives (more heat generation) and for limited actuator motion (minimum oil replacement). Nevertheless, EHAs outperform conventional (low-bandwidth) valve control in terms of both dynamic response [156] and energy efficiency [157]. Extremely high-energy efficiencies up to about 85 % are feasible, with some advantages for the open-circuit configuration [158,159]. Recent research results integrated an EM and an external gear pump in a 9-kW prototype, giving an overall energy efficiency up to 69 % [160]. Such a device was tested on the boom of a 4.5-ton machine, showing an efficiency of the electro-

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[4] Link to a presentation given by Dr. N. Caldwell at Purdue University (West Lafayette, USA) in 2019.

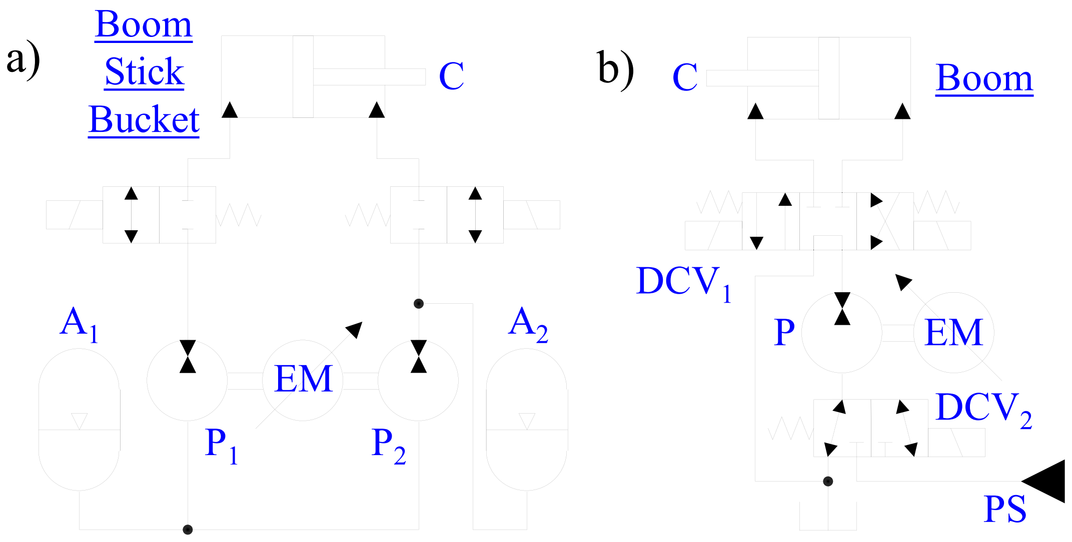

Fig. 17. Decentralized electro-hydraulic control: a) an individual drive adapted from ref. [164]; and b) a hydraulically-supported drive adapted from ref. [16].

hydraulic system of up to 60 % [161].

When applying this decentralized concept to off-road machines, partial electrification can be chosen by leaving standard valve control for some actuators. For instance, fuel savings close to 25 % were predicted for a 21-ton EX that combines a single-pump EHA for the boom with a full-electric swing [162]. A different EHA with a 3-port pump can recover about 83 % of the boom's potential energy in a 6-ton EX [163]. Conversely, the system modifications can be more relevant if complete electrification is considered. Simulations showed up to 73 % overall efficiency in a digging cycle of a 1-ton EX equipped with single-EM/dual-pump EHAs in the boom, stick, and bucket functions according to Fig. 17 **a)** and a pure electric swing [164]. The installation of these EHAs is also possible directly on the arm of the EX; the added mass maintains the mechanical stress within safety margins but increases the energy consumption by about 15 % [148]. Sufficient position tracking is achievable for this machine [165], where a PID controller with an actuator's velocity feedforward ensures higher energy efficiency [166]. The same system design was also simulated for a 9-ton hybrid EX, concluding that the pumps should be located as close as possible to the actuators to remove significant losses in the transmission lines [167]. Major dissipations might also occur in the actuators if cushioned for these decentralized systems, while pumps and EMs might contribute to a lesser extent [168].

Dealing with high-power actuators is demanding because substantial quantities of electricity must be available onboard. Then, the EMs of independent EHAs must manage all the power, leading to costly electric setups in motors, drives, onboard generators, and ESDs. Design strategies that reduce the EM sizing torques are one choice [169]. Choosing hybrid EHAs is technically feasible because they use smaller EMs, but system complexity increases [170]. Nonetheless, EHAs in multi-actuator machines can share power between domains to enable EM downsizing. An initial concept leverages 3 pressure rails, supplied by a centralized pump, that are connected by nonproportional valves to one port of the EHA's pump [171]; power is transferred both electrically and hydraulically to/from the actuator, even if both system design and control complexity increase dramatically [172]. A similar idea was developed and simulated for the 3 main actuators of a 7-ton EX, transferring almost 60 % of the energy hydraulically and saving about 28 % fuel compared to the LS machine [173]. A less drastic modification for the same EX, where only the boom's EHA is supported hydraulically according to Fig. 17 **b)**, achieved 61 % downsizing of the EM without affecting motion control [16]. It is worth noting that this power sharing is also feasible by networking multiple EHAs [174], even if this original approach was not traced in off-road machines.

Table 7
Examples of off-road prototypes using electro-hydraulic control (commercialized machines are not reported here).

	Machine	Key design features
Centralized	26-ton EX [138]	A 3.4-ton, 300 kWh battery powers a 122- kW EM (expected duration 5–7 h).
	24-ton EX [139]	A 123-kW EM is installed. EX expected to be launched on the market.
	Mid-size WL [140]	An EM (SRPM technology) of at least 78 kW with a 650 V battery.
	270-ton shovel [141]	2 hydrostatic transmissions for the swing to recover braking energy.
	120-ton shovel [142]	2.25 MW ultracapacitor system levels off the power demand of the 8,000 hp ICE.
Decentralized	6-ton EX [163]	Boom with an EHA (3-port pump).
	1-ton EX [164]	Indirect validation of the dual-pump EHA in closed-circuit.
	Compact WL [27]	Boom-lift with EHA (multi-chamber cylinders for gravity self-balancing).
	1.6-ton WL [175]	Steering system with single-pump and EHA installed externally.

Focusing on WLs, an EHA was used in the boom-lift equipped with 2 multi-chamber cylinders, where almost 60 % of energy savings are expected for the hydraulic pump [27]. Using an EHA for the steering system is also possible, even if details of the other functions are not shared [175]. Results showed efficiency values up to 81.6 % from the 63 % of the conventional system with a priority valve for zero-load conditions in a 1.6-ton WL. Finally, a different interpretation of decentralized electro-hydraulic control was proposed in simulation. The implements are electrically decoupled from the ICE, where each function has a dedicated EM, but valve control is kept [176]; the reduced metering losses cut about 43 % fuel consumption compared to standard valve control.

Table 7 collects the existing prototypes based on electro-hydraulic control to show the more recent research directions in this area.

6. Hydraulic transformers

Hydraulic transformers can recover energy and, most importantly, adapt the pressure level of a given flowrate without introducing throttling losses. A prototype with good energy efficiency was presented in 1997 by modifying conventional axial-piston units [177]. Further improvements resulted in the "floating cup" principle with a much larger number of pistons [178]. This design reduces pressure pulsations and

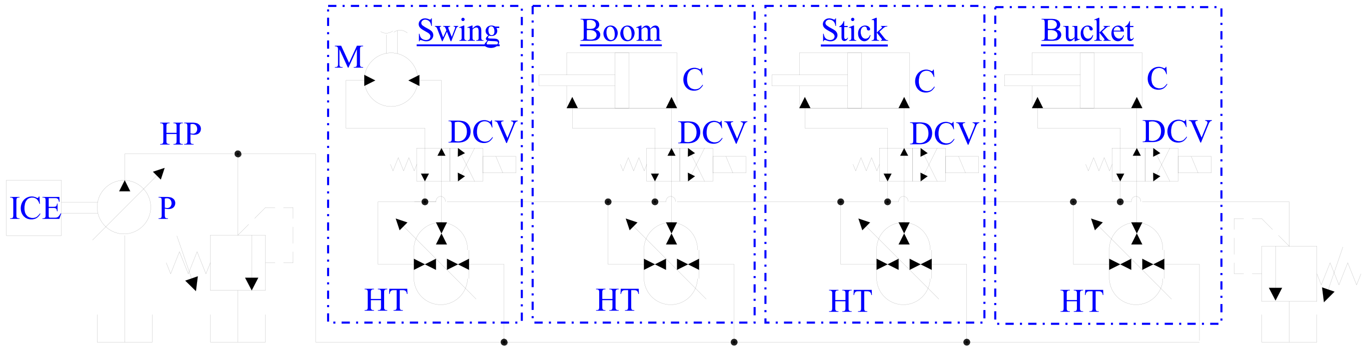

Fig. 18. Simplified schematic adapted from ref. [100] of an excavator based on hydraulic transformers.

Table 8
Major trends for improving performance and emissions of diesel combustion engines suitable for off-road machines.

Trend	Key features
Engine downsizing (smaller ICEs with less rated power)	Lower idle and steady-state fuel consumption [185] but less torque at low speeds requires boosting.
Engine boosting (more air forced into the engine)	Substantial power increase due to energy recovery and turbo-lag elimination (VTG [186], turbo-compound [187–190]).
Downspeeding (operating ICEs at lower RPM in the most efficient zone)	Reducing friction and other parasitic losses improves fuel efficiency and lowers the greenhouse gas emissions output [191].
Air-path strategies (control the air intake)	Methods to reduce NO_x formation, but none of them is resolutive (EGR [194–196], variable valve timing [197], cylinder deactivation [198], compression ratio changes [199]).
Fuel injection strategies (control the injected fuel)	Tools for controlling NO_x, HC, PM, and CO emissions that still need research (injection pulses [204–207], PCCI and HCCI [210,211]).
Engine control (optimize/minimize transient conditions)	Predictive, fuzzy logic, deep learning control [212–215]. Coordinated control with hybrid hydraulic systems will be needed.
Alternative fuels (biofuels, hydrogen and its carriers)	Achieve decarbonization (hydrogen engines for off-road machines have already been reported [229,230]).

improves low-speed performance (a crucial characteristic for direct control of actuators) while enabling accessible manufacturing costs. These 3-port devices are connected to the high-pressure power supply, the low-pressure line, and the linear actuator (digital valves allow piston extension or retraction). Transformers can, therefore, efficiently reduce the power supply's pressure down to the load-induced value of the actuator.

Such a hydraulic transformer was proposed to replace the control valves of a LS EX, an idea presented without further analyses [179]. Simulations were done for a 30-ton EX [100] with 4 dedicated transformers for the main actuators (Fig. 18). The comparison against the LS EX resulted in 31 % less energy consumption (this result is comparable to the DC version of the same machine described in **Section 4.1**). Additionally, the same reference included an alternative system architecture where a transformer was only applied to the boom actuator (the other subsystems maintain the original LS design), improving the overall efficiency by up to 10 %.

A similar approach was also used for a compact LS EX to control the linear actuators of the arm and by adding a high-pressure accumulator on the common rail [180]. Simulations of a digging cycle predicted fuel savings of 20 % with respect to the valve-controlled system. Since this hybrid system maintains the engine's operating point relatively steady, ICE downsizing is possible (from 35 to 25 kW), leading to additional fuel savings (32 % compared to the LS machine). Then, another simulation study considered hydraulic transformers in a 32-ton hybrid WL to control all main functions [181]. The results suggested reduced fuel consumption by up to 50 % in the selected Y-cycle, but supplementary analyses should be conducted on other duty cycles. Diverse transformers relying on digital hydraulics were also developed [83]. They were addressed in **Section 3.2** even if transformers generally were not applied to working prototypes of off-road machines.

7. Internal combustion engines

After discussing energy-efficient solutions for the hydraulic working functions, we focus on the other machine domain, namely the ICE. The effort is toward improving fuel consumption, exhaust emissions, and dynamic response. These objectives can be reached by optimizing the engine's design and operating characteristics and by integrating external technologies such as energy recovery and after-treatment solutions, as explained below and condensed in Table 8. Diesel after-treatment technologies (*e.g.*, oxidation catalysts or particulate filters) are critical for fulfilling rigorous emission rules for medium- and heavy-duty ICEs. This topic is beyond our scope, so readers should refer to refs. [182–184], while we focus on ICE design and operations.

7.1. Downsizing, boosting and downspeeding

Engine downsizing uses smaller ICEs with several advantages, including less frictional and heat losses, lower weight, reduced cost, and significantly lower idle and steady-state fuel consumption [185]. The latter aspect is relevant because idle and steady-state operations can account for a significant portion of the engine's working cycle in off-road hydraulics (steady-state functioning is especially significant for hybrid machines). Another key benefit of downsizing is that engines with lower power outputs often face less stringent emissions regulations. This aspect can lead to the need for smaller after-treatment systems like Selective Catalytic Reduction (SCR) or even eliminate the need altogether, offering both cost and complexity advantages. However, some obstacles remain to the widespread adoption of downsized engines. They may have reduced torque at low engine speeds and poor transient response. Thus, downsized ICEs are often equipped with boosting devices such as turbochargers. Turbochargers boost power at higher engine speeds without significantly rising parasitic, frictional, and pumping losses. Still, they can lag behind at lower speeds (turbo-lag delays the turbocharger's response because the exhaust gas flow is insufficient to spool the turbine quickly). This lag can lead to poor transient performance and increased NO_x emissions as the boosted air–fuel mixture burns at higher temperatures.

Various solutions have been investigated to overcome turbo-lag (Fig. 19). Reducing the turbocharger size can help at low speeds, but it restricts airflow at higher loads unless a wastegate is used, or it may not meet the high-power demands of a downsized engine. Thus, variable geometry turbochargers (VGTs) can provide optimized transient

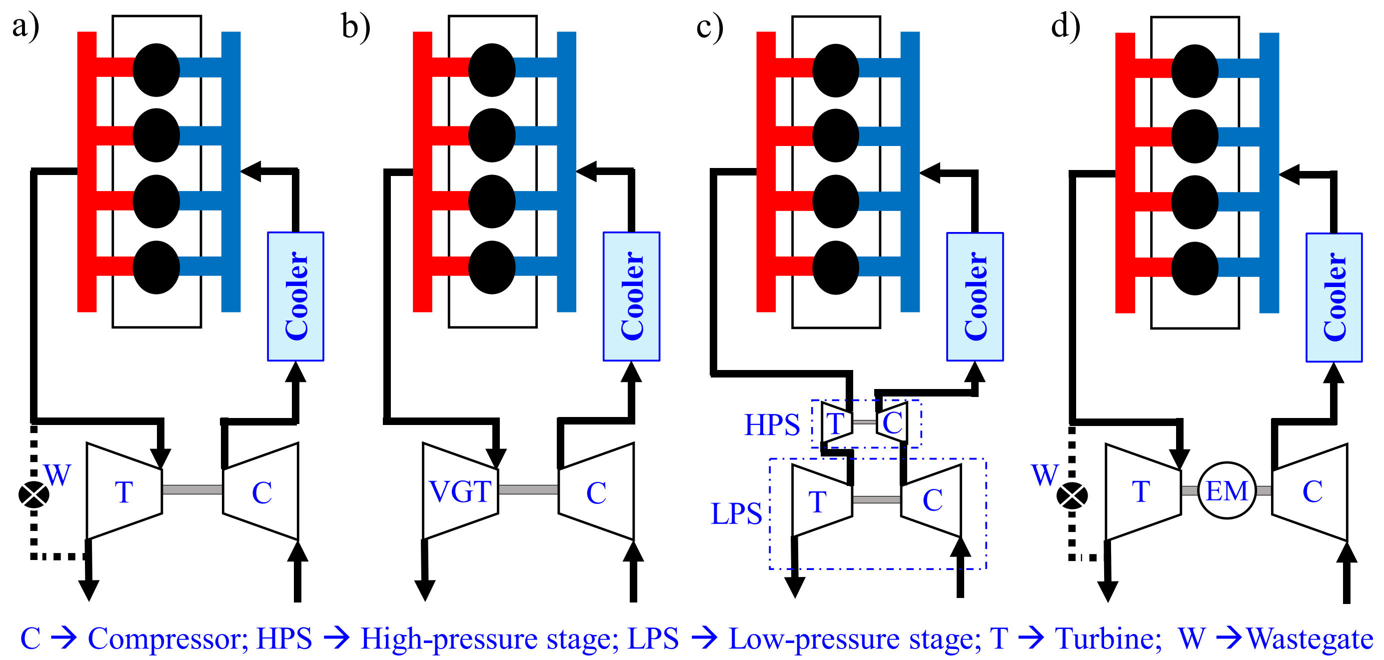

Fig. 19. Solutions for engine boosting: a) wastegate turbocharger, b) variable geometry turbocharger, c) two-stage turbocharger, and d) electric turbocharger.e.

performance with reduced turbo-lag by altering the angle of the turbocharger vanes [186]. By adjusting the flow, VGTs can meet the engine's maximum power requirements under low- and high-load conditions. VGT turbochargers generally offer superior efficiency compared to wastegated turbos, particularly at low RPMs and in terms of fuel economy and emissions. However, their complexity and cost make them less suitable for some applications. Wastegated turbos, on the other hand, remain a viable option due to their simplicity, reliability, and lower cost, but they may compromise on efficiency and performance, especially at low and high RPMs.

Another solution is two-stage turbocharging, which increases costs and complexity. This layout combines a small turbocharger for fast transient response at low engine speeds with a larger one for maximum power demands. Moving to the next step, electric turbocharging integrates an electric motor/generator. The resulting device can also recover kinetic energy from the exhaust gas and store energy in a turbo-compounding configuration; this energy can then increase power by accelerating the system's rotor. Turbo-compounding has been shown to reduce transient response by up to 90 % [187], extract up to 25.7 % more exhaust energy than a non-compounded system [188], and increase both average power and average brake-specific fuel consumption by 3.3–6.5 % [189,190]. Overall, engine downsizing with state-of-the-art boosting devices is a promising technology for improving fuel efficiency and fits within hybrid machines.

Downspeeding is another effective operating strategy that delivers fuel savings of 1–2 % or even higher [191] by running engines at lower revolutions per minute (RPM). This slower speed at the engine's most efficient RPM reduces friction and other parasitic losses, improving fuel efficiency and greenhouse gas emissions output. The reduced heat and friction can potentially extend the engine's overall lifecycle. However, the need to meet the same power outputs at lower engine speeds increases torque demand. This request, conversely, places a higher strain on the drivetrain system, potentially affecting the engine's longevity and performance.

7.2. Air-path strategies

As mentioned, engine downsizing often comes at the cost of increased NO_x emissions. The most direct way to control NO_x and other pollutants is to change the air and fuel injection strategies, which alters the combustion conditions. One option is exhaust gas recirculation (EGR) into the intake manifold, which dilutes the intake charge's oxygen concentration and increases its heat capacity. This method lowers combustion temperatures and NO_x formation. While low EGR rates (around 5 %) can provide marginal thermal efficiency gains (around 1.5 %) and reduce combustion noise, as observed by Selim [192], higher rates tend to decrease efficiency due to the dilution effect. This decrease is caused by the reduced oxygen content in the combustion chamber, diluting the air–fuel mixture and hindering complete combustion. Paykani *et al.* [193] attributed the initial efficiency increase at low EGR to the rising intake charge temperature, facilitating better fuel combustion. For compression ignition engines, EGR rates of up to 50 % or more of the intake charge can reduce NO_x emissions to negligible levels without affecting combustion stability. However, high EGR rates can also increase PM, HC, and CO emissions while reducing brake-specific fuel consumption [194–196]. Other alternative air-path techniques include variable valve timing [197], cylinder deactivation [198], and engine's compression ratio changes [199]. Unfortunately, none of these approaches can be the "silver bullet" to controlling all pollutant emissions to a minimum level.

In addition to EGR, other dilution techniques have been investigated, even if they are more challenging to implement. The supply of noble gases, such as helium and argon, can support oxygen dilution within the cylinder and significantly reduce NO_x emissions [200,201]. Then, water fumigation (*i.e.*, injecting water into the cylinder) cools down the combustion process by reducing peak temperatures and controlling the NO_x formation [202]. Water can be stored onboard or extracted from the exhaust gases using a water recapture system [203].

7.3. Fuel injection strategies

Focusing on the other direct way to control NO_x and other pollutants, fuel injection strategies influence fuel atomization and its mixing with air. Modern diesel injection systems, such as common rail systems, provide fuel to the cylinder at high pressures of over 2,000 bar, which helps combustion. Additionally, rapid injection events allow for multiple injection pulses per cycle, enabling early injections for better mixing and post-injections for improved soot oxidation. These multiple injections effectively control NO_x, HC, PM, and CO emissions from engines [204–207]. Experimental studies have demonstrated that combining multiple injections with high EGR rates can improve diesel engine fuel consumption by about 3 % [208]. This reduction results from an optimized spatial flame distribution close to the wall and a reduced flame temperature that yields lower heat losses.

Furthermore, new combustion concepts have been developed using modern injection systems. Low-temperature combustion (LTC) strategies avoid high NO_x formation zones at elevated temperatures while reducing PM emissions. The homogeneous mixture characteristic of LTC facilitates complete combustion, often leading to thermal efficiencies exceeding those of conventional diesel engines with lower emissions and up to a remarkable 25 % fuel economy improvement compared to spark-ignited engines [209]. Partially premixed combustion (PCCI) and homogeneous charge compression ignition (HCCI) are two of the most well-known LTC concepts. PCCI involves early fuel injection for improved air–fuel mixing and a final injection near the top dead center to ignite the mixture. HCCI, on the other hand, faces a major challenge in controlling ignition and combustion phasing without a late fuel injection [210,211]. Even though these technologies can potentially limit engine pollutants, continued research is needed.

7.4. Engine control

Considering engines from a broader point of view, common control techniques use predefined lookup tables derived from steady-state mapping. ICEs are, therefore, not optimized for operation under transient conditions, a phase responsible for most fuel consumption and pollutant emissions. Due to the multiple degrees of freedom involved, engine control is complex and time-consuming. Several approaches have been tested, such as model-based predictive control design, fuzzy logic control, and, more recently, deep reinforcement learning [212]. Their development can assist in running ICEs cleaner under transient operating conditions [213–215]. Engine control is critical for reducing fuel consumption and pollutant emissions in ICEs for mobile hydraulics, which experience extended transient loads. Coordinated control of the engine with the (hybrid) hydraulic system will be paramount in upcoming off-road equipment since one of the most significant challenges is meeting future transient emissions standards without sacrificing dynamic response.

7.5. Alternative fuels

Concerning the energy carriers, modern engines are designed to operate with conventional fossil fuels like diesel and natural gas. These ICEs can now reach thermal efficiencies of over 50 % in ideal conditions due to advanced waste heat recovery and electrification [216,217]. However, accelerating decarbonization by selecting alternative fuels is more important than ever. This effort requires a new systematic co-development of fuels and engines to deliver significantly lower pollutant emissions and reach carbon neutrality [218,219].

Initial approaches to defossilizing ICEs focused on biofuels. First- and second-generation biofuels (*e.g.*, biodiesel) have combustion characteristics similar to fossil fuels, making them a relatively easy transition without major engine modifications [220]. Although these low-carbon alternatives can help reduce greenhouse gas emissions, the excessive use of food-based biofuels has raised concerns about food prices and insecurity. Third- and fourth-generation biofuels produced from marine organisms (*i.e.*, natural algae and genetically modified algae, respectively) may be a better long-term solution. However, the advancements needed for energy-efficient preparation and sufficient production capacity are not yet at a level that can meet the global fuel demand [221,222].

For these reasons, hydrogen and its carriers like ammonia and methanol have emerged as promising alternatives due to their favorable properties [223–225]. Hydrogen's combustion properties, notably its high flame speed, wide flammability range, and low quenching distance make it particularly well-suited for engine applications. Research by Welch *et al.* [226] suggests that hydrogen spark-ignited engines can achieve brake thermal efficiencies of up to 45 % under specific operating conditions. However, the extremely low volumetric density makes hydrogen's high-pressure storage or liquefaction at low temperatures (-253 °C) difficult to adopt due to safety risks and increased infrastructure costs. Ammonia and methanol, on the other hand, are easier to store and are widely investigated as replacements. Considering their high auto-ignition temperature, these fuels can only be ignited at nominal compression ratios (without intake heating) with diesel or a similar low auto-ignition temperature fuel such as biodiesel.

Previous research has shown that heavy-duty compression ignition engines can run up to 98 % hydrogen energy share ratio under relatively low load conditions, requiring only 2 % of the energy input from the secondary fuel [227]. Under normal operating conditions and to avoid combustion instabilities, a hydrogen energy share ratio of 40–60 % is recommended, which can still achieve significant greenhouse gas emission savings of over 50 % [228]. There are ongoing studies, either in dual-fuel operation or single spark-ignition mode, and initial attempts at operating off-road hydraulics with hydrogen engines have already been reported [229,230].

Finally, along with biofuels, hydrogen, and hydrogen carriers, recent research has focused on developing synthetically produced fuels from hydrogen and captured carbon [231,232]. This technology is not yet mature enough for widespread application, so developments are needed to increase production efficiency and capacity, reduce costs, and make it a practical alternative for powering off-road hydraulics.

8. Discussion and future trends

In this paper, we have analyzed the challenges of designing energy-efficient and low-pollutant off-road machines. We have also reviewed and classified viable solutions considering both areas of these machines, namely the hydraulics and the combustion engine (it is, in fact, apparent that many off-road machines cannot simply eliminate the engine). Therefore, the following generally applicable conclusions to off-road hydraulics have emerged:

- Conventional nonhybrid machines based on proportional valve control without energy recovery represent the state-of-the-art. They are incompatible with the climate pledges of reaching “carbon neutrality” in many countries due to their poor average energy efficiency and high pollutant emissions.
- Hybrid machines powered by engines and based on proportional valve control with energy recovery provide a temporary replacement for a transition toward optimal solutions. Even if system complexity rises to different extents (15 working prototypes were traced), functional flow throttling is present, and the engine load is often pulsating.
- Digital valve control is viable (5 prototypes were traced). Energy efficiency can improve significantly (an excavator uses 36 % less hydraulic energy than the load-sensing counterpart), but flow throttling is not entirely removed. Critical challenges are the pressure pulsations induced by valve switching (the operator can feel them), the need for complex control techniques, and the demanding valve design (extended lifetime and minimal physical size).
- Displacement control is applicable with proportional, swash-plate pumps (5 prototypes were traced). Substantial savings are possible compared to the valve-controlled counterparts, such as 50 % less input energy in a nonhybrid excavator or 10–15 % less fuel in a hybrid wheel loader. Eliminating flow throttling comes at the expense of high churning losses during idle, complex set-ups to ensure simultaneous movements of actuators, and high parasitic losses at pump's partial displacement settings (digital pumps/motors can improve this drawback but bring other issues).

Table 9
Major trends for enabling energy-efficient and low-pollutant off-road machines.

Target	Promising trends
Eliminate functional throttling losses and recover energy.	Valveless design for energy-intensive actuators (decentralized electro-hydraulic control is key).
Level off the load on the combustion engine, if any.	Hybrid systems with hydro-pneumatic accumulators and/or supercapacitors.
Optimize machine performance.	Coordinated control of hydraulics, energy storage, and engine, if any.
Introduce carbon-free off-road machines.	Replacement of fossil fuels with renewable hydrogen and/or electric energy from renewable sources.

- Electro-hydraulic control enables machine electrification and engine elimination for some small equipment. The centralized approach (*i.e.*, an electrically-driven pump with valve control) is already used in series production of compact machines, and 5 prototypes of bigger equipment exist. The decentralized alternative (*i.e.*, electrically-driven pumps directly coupled to hydraulic actuators) can enhance further energy savings but requires more research (4 prototypes were identified). In any case, some challenges arise to integrate these drives into off-road machines since dedicated pumps are needed, and using electric energy (mainly) from renewable sources is expected.
- Machines based on hydraulic transformers were not found even if they can achieve promising energy savings in simulation and stabilize the engine load. Transformers, in fact, still need acceptance since they are typically ignored for mass production.
- A key challenge for future machines is ensuring proper behavior in particular conditions. The prototype functionality is typically demonstrated in repetitive operations, such as conventional digging or leveling cycles. The capabilities of traditional architectures should also be proven if high forces or flowrates are required (*e.g.*, when encountering a large rock or using attachments like a hammer).
- Modern combustion engines can provide high operating efficiencies and low-pollutant emissions with the help of auxiliary systems (*e.g.*, exhaust after-treatment) and machine hybridization to level off the engine load. Despite these advances, meeting net-zero carbon targets requires drastic measures, namely replacing fossil fuels with clean alternatives such as synthetically produced fuels, hydrogen, or hydrogen carriers.

Considering the outcomes of our discussion, the major future trends for off-road hydraulics will involve valveless actuation, at least for large energy consumers, replacement of fossil fuels, machine hybridization, and strong integration of engine and hydraulics (Table 9). This roadmap addresses all the most severe weaknesses of state-of-the-art equipment (*i.e.*, environmental pollution and operating costs) by (1) reducing the amount of fossil fuel being burned, (2) decreasing the quantity of carbon dioxide and other pollutants released into the atmosphere, and (3) lowering the running costs of off-road machines.

Such an approach leverages components and sensors with embedded electronics that allow designing of advanced control algorithms. This method can also optimize the machine's controllability (*e.g.*, the addition of artificial damping) and productivity (*e.g.*, connectivity among machines and less downtime due to health monitoring). The critical productivity requirement is also enhanced by the higher energy efficiency that improves machine performance indirectly. Therefore, it becomes apparent that energy-hungry and widespread equipment, such as excavators and wheel loaders, deserves further developments in this direction.

CRediT authorship contribution statement

Damiano Padovani: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Pavlos Dimitriou:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Tatiana Minav:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] Lynch LA, Zigler BT. Estimating Energy Consumption of Mobile Fluid Power in the United States. CO, USA: Golden; 2017.

[2] Z. Quan, L. Ge, Z. Wei, Y. W. Li, and L. Quan, "A Survey of Powertrain Technologies for Energy-Efficient Heavy-Duty Machinery," *Proc. IEEE*, vol. 109, no. 3, 2021, doi: 10.1109/JPROC.2021.3051555.

[3] L. Love E. Lanke P. Alles Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry 2012 Oak Ridge, TN, USA 10.2172/1061537.

[4] Cao T, et al. Characterization of the emissions impacts of hybrid excavators with a portable emissions measurement system (PEMS)-based methodology. Sci Total Environ 2018;635. https://doi.org/10.1016/j.scitotenv.2018.04.011.

[5] T. Dallmann A. Menon "Technology Pathways for Diesel Engines Used in Non-Road Vehicles and Equipment", White paper 2016 The Int Council on Clean Transportation.

[6] The United States Environmental Protection Agency, "2011 National Emissions Inventory (NEI) Data," 2011. https://www.epa.gov/air-emissions-inventories/2011-national-emissions-inventory-nei-data (accessed Nov. 11, 2022).

[7] U.S. Energy Information Administration, "Gasoline and Diesel Fuel Update," 2022. https://www.eia.gov/petroleum/gasdiesel (accessed Nov. 11, 2022).

[8] D. Padovani, M. Rundo, and G. Altare, "The Working Hydraulics of Valve-Controlled Mobile Machines: Classification and Review," *ASME J. Dyn. Syst. Meas. Control*, vol. 142, no. 7, 2020.

[9] Wang H, Wang Q, Hu B. A review of developments in energy storage systems for hybrid excavators. Autom Constr Aug. 2017;80. https://doi.org/10.1016/j.autcon.2017.03.010.

[10] Lin T, Chen Q, Ren H, Huang W, Chen Q, Fu S. Review of boom potential energy regeneration technology for hydraulic construction machinery. Renew Sustain Energy Rev 2017;79. https://doi.org/10.1016/j.rser.2017.05.131.

[11] Do TC, Dang TD, Dinh TQ, Ahn KK. Developments in energy regeneration technologies for hydraulic excavators: a review. Renew Sustain Energy Rev 2021;145. https://doi.org/10.1016/j.rser.2021.111076.

[12] He X, et al. The applications of energy regeneration and conversion technologies based on hydraulic transmission systems: a review. Energy Convers Manag 2020;205. https://doi.org/10.1016/j.enconman.2019.112413.

[13] He X, Jiang Y. Review of hybrid electric systems for construction machinery. Autom Constr 2018;92. https://doi.org/10.1016/j.autcon.2018.04.005.

[14] Fassbender D, Zakharov V, Minav T. Utilization of electric prime movers in hydraulic heavy-duty-mobile-machine implement systems. Autom Constr 2021;132. https://doi.org/10.1016/j.autcon.2021.103964.

[15] Zauner M, Altenberger F, Knapp H, Kozek M. Phase independent finding and classification of wheel-loader work-cycles. Autom Constr 2020;109. https://doi.org/10.1016/j.autcon.2019.102962.

[16] D. Padovani P. Fresia M. Rundo G. Altare "Downsizing the Electric Machines of Energy-Efficient Electro-Hydraulic Drives for Mobile Hydraulics", in Journal of Physics: Conf. Series 2385, 012028 Bari, Italy 2022 2022 10.1088/1742-6596/2385/1/012028.

[17] M. Vukovic, R. Leifeld, and H. Murrenhoff, "Reducing Fuel Consumption in Hydraulic Excavators—A Comprehensive Analysis," *Energies*, vol. 10, no. 5, 2017, doi: 10.3390/en10050687.

[18] A. Hießl and R. Scheidl, "Energy Consumption and Efficiency Measurements of Different Excavators: Does Hybridization Pay?," in *ASME/BATH Symposium on Fluid Power and Motion Control*, Chicago, IL, USA, 2015.

[19] B. R. Andersson, "Valves Contribution to System Damping," in *5th Scandinavian Int.* Conf. *on Fluid Power (SICFP)*, Linköping, Sweden, 1997.

[20] L. J. Devier, J. J. Krone, and S. V Lunzman, "Hydraulic Flow Priority System," US5,560,387, 1994.

[21] Lin T, Huang W, Ren H, Fu S, Liu Q. New compound energy regeneration system and control strategy for hybrid hydraulic excavators. Autom Constr 2016;68. https://doi.org/10.1016/j.autcon.2016.03.016.

[22] Q. Wen, F. Wang, B. Xu, and Z. Sun, "Improving the Fuel Efficiency of Compact Wheel Loader with a Series Hydraulic Hybrid Powertrain," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, 2020, doi: 10.1109/TVT.2020.3006155.

[23] A. Alexander and A. Vacca, "Traction Control Development for Heavy-Duty Off-Road Vehicles Using Sliding Mode Control," *Int. J. Fluid Power*, vol. 20, no. 3, 2020, doi: 10.13052/ijfp1439-9776.2035.

[24] Daher N, Ivantysynova M. Energy analysis of an original steering technology that saves fuel and boosts efficiency. Energy Convers Manag 2014;86. https://doi.org/10.1016/j.enconman.2014.06.073.

[25] Madau R, Vacca A. “Active Ride Control for Construction Machines Based on Pressure Feedback”, in ASME/BATH Symposium on Fluid Power & Motion Control, Longboat Key, FL. USA 2019. https://doi.org/10.1115/FPMC2019-1649.

[26] R. Kumar, M. Ivantysynova, and K. Williams, “Study of Energetic Characteristics in Power Split Drives for on Highway Trucks and Wheel Loaders,” *SAE Trans.*, vol. 116, no. 2, 2007, doi: 10.4271/2007-01-4193.

[27] Wang X, Zhang H, Zhang X, Quan L. “Design and Efficiency Analysis of Closed Loop Pump Controlled Circuit Hydraulic Lifting System of Wheel Loaders Based on Gravity Self-Balancing Hydraulic Cylinder”, in ASME/BATH Symposium on Fluid Power and Motion Control. UK: Bath; 2021.

[28] Schneider M, Koch O, Weber J. “Green Wheel Loader - Operating Strategy of an Energy Efficient Hybrid Drive Train”, in SAE Technical Papers, Rosemont, IL. USA 2014. https://doi.org/10.4271/2014-01-2400.

[29] I. Shafikhani and J. Åslund, “Energy Management of Hybrid Electric Vehicles with Battery Aging Considerations: Wheel Loader Case Study,” *Control Eng. Pract.*, vol. 110, no. February, 2021, doi: 10.1016/j.conengprac.2021.104759.

[30] G. Altare, D. Padovani, and N. Nervegna, “A Commercial Excavator: Analysis, Modelling and Simulation of the Hydraulic Circuit,” in *SAE COMVEC*, Rosemont, IL, USA, 2012, doi: 10.4271/2012-01-2040.

[31] Zimmerman J, Ivantysynova M. “Reduction of Engine and Cooling Power by Displacement Control”, in 6th FPNI-PhD Symposium. IN, USA: West Lafayette; 2010.

[32] T. Yasuda and Y. Aoyagi, “Hydraulic Drive System for Construction Machines,” US 5,295,795, 1992.

[33] Cho Y, Kim K, Jang D-S. “Development of the Energy Efficient Electro-Hydraulic System for Excavator”, in 7th Int. Fluid Power Conf 2010.

[34] Lettini A, Havermann M, Guidetti M, Fornaciari A. “Improved Functionalities and Energy Saving Potential on Mobile Machines Combining Electronics with Flow Sharing Valve and Variable Displacement Pump”, in 7th Int. Fluid Power Conf 2010.

[35] Rampen WHS. The Digital Displacement Hydraulic Piston Pump. Edinburgh, United Kingdom: University of Edinburgh; 1992.

[36] Budden JJ, Williamson C. “Danfoss Digital Displacement ® Excavator: Test Results and Analysis”, in ASME/BATH Symposium on Fluid Power and Motion Control. FL, USA: Longboat Key; 2019.

[37] Bender FA, Mitschke M, Bräunl T, Sawodny O. Predictive Operator Modeling for Virtual Prototyping of Hydraulic Excavators. Autom Constr 2017;84. https://doi.org/10.1016/j.autcon.2017.08.008.

[38] Oh K, Kim H, Ko K, Kim P, Yi K. Integrated wheel loader simulation model for improving performance and energy flow. Autom Constr 2015;58. https://doi.org/10.1016/j.autcon.2015.07.021.

[39] Hu P, et al. Development of a comprehensive driving cycle for construction machinery used for energy recovery system evaluation: a case study of medium hydraulic excavators. Math Probl Eng 2021. https://doi.org/10.1155/2021/8132878.

[40] Frank B, Skogh L, Alaküla M. “On Wheel Loader Fuel Efficiency Difference due to Operator Behaviour Distribution”, in 2nd Commercial Vehicle Technology Symposium. Germany: Kaiserslautern; 2012. Available: http://www.iea.lth.se/publications/Papers/Frank_2012.pdf.

[41] Shi Y, Xia Y, Luo L, Xiong Z, Wang C, Lin L. Working stage identification of excavators based on control signals of operating handles. Autom Constr 2021;130. https://doi.org/10.1016/j.autcon.2021.103873.

[42] Liebl J, Lederer M, Rohde-Brandenburger K, Biermann J-W, Roth M, Schäfer H. Energiemanagement im Kraftfahrzeug. Springer; 2014.

[43] Hagena JR, Filipi ZS, Assanis DN. Transient diesel emissions: analysis of engine operation during a tip-in. SAE Technical Papers 2006. https://doi.org/10.4271/2006-01-1151.

[44] Z. Filipi, J. Hagena, and H. Fathy, “Investigating the impact of in-vehicle transients on diesel soot emissions,” *Therm. Sci.*, vol. 12, no. 1, 2008, doi: 10.2298/TSCI0801053F.

[45] S. Yu, G. Dong, and L. Li, “Transient characteristics of emissions during engine start/stop operation employing a conventional gasoline engine for HEV application,” *Int. J. Automot. Technol.*, vol. 9, no. 5, 2008, doi: 10.1007/s12239-008-0064-z.

[46] Hagena JR, Assanis DN, Filipi ZS. Cycle-resolved measurements of in-cylinder constituents during diesel engine transients and insight into their impact on emissions. Proceedings of the Institution of Mechanical Engineers, Part d: Journal of Automobile Engineering 2011;vol. 225, no. 9. https://doi.org/10.1177/0954407011414997.

[47] P. A. Hansson, M. Lindgren, M. Nordin, and O. Pettersson, “A methodology for measuring the effects of transient loads on the fuel efficiency of agricultural tractors,” *Appl. Eng. Agric.*, vol. 19, no. 3, 2003, doi: 10.13031/2013.13657.

[48] M. Lindgren and P. A. Hansson, “Effects of Transient Conditions on Exhaust Emissions from two Non-road Diesel Engines,” *Biosyst. Eng.*, vol. 87, no. 1, 2004, doi: 10.1016/j.biosystemseng.2003.10.001.

[49] Minav T, Virtanen A, Laurila L, Pyrhönen J. Storage of Energy Recovered From an Industrial Forklift. Autom Constr 2012;22. https://doi.org/10.1016/j.autcon.2011.11.010.

[50] P. Simon and Y. Gogotsi, “Materials for Electrochemical Capacitors,” *Nanosci. Technol. A Collect. Rev. from Nat. Journals*, vol. 7, 2009, doi: 10.1142/9789814287005_0033.

[51] Puddu P, Paderi M. Hydro-pneumatic accumulators for vehicles kinetic energy storage: influence of gas compressibility and thermal losses on storage capability. Energy 2013;57. https://doi.org/10.1016/j.energy.2013.04.072.

[52] Pourmovahed A. Durability Testing of an Elastomeric Foam for Use in Hydraulic Accumulators. ASME J Sol Energy Eng 1990;112(3). https://doi.org/10.1115/1.2930483.

[53] Li J, Zhao J. Energy recovery for hybrid hydraulic excavators: flywheel-based solutions. Autom Constr May 2021;125. https://doi.org/10.1016/j.autcon.2021.103648.

[54] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. Appl Energy 2014;137. https://doi.org/10.1016/j.apenergy.2014.04.103.

[55] Volvo Construction Equipment, “Volvo CE Unveils 100% Electric Compact Excavator Prototype,” 2017. https://www.volvoce.com/global/en/news-and-events/press-releases/2017/volvo-ce-unveils-100-percent-electric-compact-excavator-prototype/.

[56] D. Hagen D. Padovani M. Choux Guidelines to Select Between Self-Contained Electro-Hydraulic and Electro-Mechanical Cylinders in 15th IEEE Conf. on Industrial Electronics and Applications 2020 Kristiansand, Norway 10.1109/ICIEA48937.2020.9248373.

[57] Li Z, Wang C, Quan L, Hao Y, Ge L, Xia L. Study on energy efficiency characteristics of the heavy-duty manipulator driven by electro-hydraulic hybrid active-passive system. Autom Constr 2021;125. https://doi.org/10.1016/j.autcon.2021.103646.

[58] Casoli P, Riccò L, Campanini F, Bedotti A. Hydraulic hybrid excavator - mathematical model validation and energy analysis. Energies 2016;9(12). https://doi.org/10.3390/en9121002.

[59] Xia L, Quan L, Ge L, Hao Y. Energy efficiency analysis of integrated drive and energy recuperation system for hydraulic excavator boom. Energy Convers Manag 2018;156. https://doi.org/10.1016/j.enconman.2017.11.074.

[60] L. Ge, Z. Dong, L. Quan, and Y. Li, “Potential Energy Regeneration Method and its Engineering Applications in Large-Scale Excavators,” *Energy Convers. Manag.*, vol. 195, no. October 2018, pp. 1309–1318, 2019, doi: 10.1016/j.enconman.2019.05.079.

[61] Jun G, et al. Potential energy recovery method based on alternate recovery and utilization of multiple hydraulic cylinders. Autom Constr 2020;112. https://doi.org/10.1016/j.autcon.2020.103105.

[62] Heybroek K, Sahlman M. A hydraulic hybrid excavator based on multi-chamber cylinders and secondary control-design and experimental validation. Int J Fluid Power 2018;19(2). https://doi.org/10.1080/14399776.2018.1447065.

[63] H. Inoue Development of Hybrid Hydraulic Excavators in 9th JFPS Int. Symposium on Fluid Power 2014 Matsue, Japan 10.20965/ijat.2012.p0516.

[64] Wang T, Wang Q. Efficiency analysis and evaluation of energy-saving pressure-compensated circuit for hybrid hydraulic excavator. Autom Constr 2014;47. https://doi.org/10.1016/j.autcon.2014.07.012.

[65] Gong J, et al. Power control strategy and performance evaluation of a novel electro-hydraulic energy-saving system. Appl Energy 2019;233–234. https://doi.org/10.1016/j.apenergy.2018.10.066.

[66] Ricardo, “Ricardo to Showcase ‘TorqStor’ High Efficiency Flywheel Energy Storage at CONEXPO,” 2014. https://ricardo.com/news-and-media/news-and-press/ricardo-to-showcase-‘torqstor’-high-efficiency-fly (accessed Nov. 10, 2022).

[67] Li J, Zhao J, Zhang X. A novel energy recovery system integrating flywheel and flow regeneration for a hydraulic excavator boom system. Energies 2020;13(315). https://doi.org/10.3390/en13020315.

[68] Li J, Han Y, Li S. Flywheel-based boom energy recovery system for hydraulic excavators with load sensing system. Actuators 2021;10(126). https://doi.org/10.3390/act10060126.

[69] Cronk PM, Van de Ven J. A review of hydro-pneumatic and flywheel energy storage for hydraulic systems. Int J Fluid Power 2018;19(2). https://doi.org/10.1080/14399776.2017.1386061.

[70] Cronk P, Van de Ven J, Strohmaier K. Design optimization, construction, and testing of a hydraulic flywheel accumulator. J Energy Storage 2021;44. https://doi.org/10.1016/j.est.2021.103281.

[71] M. Ochiai S. Ryu Hybrid in Construction Machinery in 7th JFPS Int. Symposium on Fluid Power 2008 Toyama, Japan 10.5739/isfp.2008.41.

[72] Hui S, Junqing J. Research on the system configuration and energy control strategy for parallel hydraulic hybrid loader. Autom Constr 2010;19(2). https://doi.org/10.1016/j.autcon.2009.10.006.

[73] L. Brinkschulte and M. Geimer, “The Use of a Holistic Machine Simulation for the Development of Hydraulic Hybrid Modules to Reduce Transient Engine-Out Emissions,” in *12th Int. Fluid Power Conf.*, Dresden, Germany, 2020.

[74] R. Filla, “Hybrid Power Systems for Construction Machinery: Aspects of System Design and Operability of Wheel Loaders,” in *ASME Int. Mechanical Engineering Congress & Exposition*, Lake Buena Vista, FL, USA, 2009.

[75] Pettersson K, Heybroek K, Mattsson P, Krus P. A novel hydromechanical hybrid motion system for construction machines. Int J Fluid Power 2017;18(1). https://doi.org/10.1080/14399776.2016.1210423.

[76] Wang F, Lin Z, Xu B, Fiebig W. An electric-hydrostatic energy storage system for hydraulic hybrid wheel loader. IEEE Trans Veh Technol 2022;71(7). https://doi.org/10.1109/TVT.2022.3167519.

[77] Madau R, Vacca A, Pintore F. Energy saving on a full-size wheel loader through variable load sense margin control. J Dyn Syst Meas Control 2022;144(3). https://doi.org/10.1115/1.4052821.

[78] M. Linjama M. Vilenius Energy-Efficient Motion Control of a Digital Hydraulic Joint Actuator in 6th JFPS Int. Symposium on Fluid Power 2005 Tsukuba, Japan 10.5739/isfp.2005.640.

[79] A. Laamanen M. Linjama Is it Time for Digital Hydraulics? in 8th Scandinavian Int. Conf. on Fluid Power 2003 Tampere, Finland 10.1016/j.tree.2009.04.004.

[80] M. Heikkilä, J. Tammisto, M. Huova, A. K. Huhtala, and M. Linjama, “Experimental Evaluation of a Digital Hydraulic Power Management System,” in *3rd Workshop on Digital Fluid Power*, Tampere, Finland, 2010.

[81] Winkler B. “Recent Advances in Digital Hydraulic Components and Applications”, in 9th Workshop on Digital Fluid Power. Denmark: Aalborg; 2017. Available: https://www.et.aau.dk/digitalAssets/377/377525_id117-recent-advances-in-digital-hydraulic-components-and-applications.pdf.

[82] A. Dell’Amico, M. Carlsson, E. Norlin, and M. Sethson, “Investigation of a Digital Hydraulic Actuation System on an Excavator Arm,” in *13th Scandinavian Int. Conf. on Fluid Power*, Linköping, Sweden, 2013.

[83] M. Linjama and K. Huhtala, “Digital Pump-Motor with Independent Outlets,” in *11th Scandinavian Int. Conf. on Fluid Power*, Linköping, Sweden, 2009.

[84] M. Karvonen, M. Heikkilä, S. Tikkanen, M. Linjama, and K. Huhtala, “Aspects of the Energy Consumption of a Digital Hydraulic Power Management System Supplying a Digital a Proportional Valve Controlled Multi Actuator System,” in *ASME/BATH Symposium on Fluid Power & Motion Control*, Bath, UK, 2014.

[85] M. Linjama, M. Huova, M. Pietola, J. Juhala, and K. Huhtala, “Hydraulic Hybrid Actuator: Theoretical Aspects and Solution Alternatives,” in *14th Scandinavian Int. Conf. on Fluid Power*, Tampere, Finland, 2015.

[86] Ketonen M, Linjama M. “Simulation Study of a Digital Hydraulic Independent Metering Valve System on an Excavator”, in 15th Scandinavian Int. Linköping, Sweden: Conf. on Fluid Power; 2017.

[87] Ketonen M, Linjama M. “Digital Hydraulic IMV System in an Excavator - First Results”, in 16th Scandinavian Int. Tampere, Finland: Conf. on Fluid Power; 2019.

[88] Ahmed H, et al. “Multi-Pressure Actuator in Enhancing the Energy Balance of Micro-Excavator”, in 16th Scandinavian Int. Tampere, Finland: Conf. on Fluid Power; 2019.

[89] Huova M, Aalto A, Linjama M, Huhtala K, Lantela T, Pietola M. Digital hydraulic multi-pressure actuator – the concept, simulation study and first experimental results. Int J Fluid Power 2017;18(3). https://doi.org/10.1080/14399776.2017.1302775.

[90] M. Huova M. Karvonen V. Ahola M. Linjama M. Vilenius Energy Efficient Control of Multiactuator Digital Hydraulic Mobile Machine in 7th Int. Fluid Power Conference 2010 Aachen, Germany.

[91] Huova M, Ahopelto M, Ketonen M, Ahola V, Linjama M, Huhtala K. “Characteristics of Digital Hydraulics With Commercial Controllers”, in 7th Workshop on Digital Fluid Power. Austria: Linz; 2015.

[92] M. Huova J. Tammisto M. Linjama J. Tervonen “Fuel Efficiency Analysis of Selected Hydraulic Hybrids on a Wheel Loader Application”, in BATH, ASME, Symposium on Fluid Power and Motion Control Bath, UK 2018 2018 10.1115/FPMC2018-8869.

[93] Rahmfeld R, Ivantysynova M. “Energy Saving Hydraulic Actuators for Mobile Machines”, in 1st Bratislavian Fluid Power Symposium. Slovakia: Bratislava; 1998.

[94] Heybroek K, Larsson J, Palmberg J-O, Larsson J. “Open Circuit Solution for Pump Controlled Actuators”, in 4th FPNI - PhD Symposium. FL, USA: Sarasota; 2006.

[95] Williamson C, Ivantysynova M. “The Effect of Pump Efficiency on Displacement-Controlled Actuator Systems”, in 10th Scandinavian Int. Tampere, Finland: Conf. on Fluid Power; 2007.

[96] Grabbel J, Ivantysynova M. An investigation of swash plate control concepts for displacement controlled actuators. Int J Fluid Power 2005;6(2). https://doi.org/10.1080/14399776.2005.10781217.

[97] C. Williamson, J. Zimmerman, and M. Ivantysynova, “Efficiency Study of an Excavator Hydraulic System Based on Displacement-Controlled Actuators,” in *ASME/BATH Symposium on Fluid Power and Motion Control*, 2008.

[98] Zimmerman J. Toward Optimal Multi-Actuator Displacement Controlled Mobile Hydraulic Systems. West Lafayette, IN, USA: Purdue University; 2012.

[99] J. Zimmerman E. Busquets M. Ivantysynova 40% Fuel Savings by Displacement Control Leads to Lower Working Temperatures - A Simulation Study and Measurements in 52nd National Conf. on Fluid Power 2011 Las Vegas, NV, USA.

[100] M. Inderelst S. Losse S. Sgro H. Murrenhoff Energy Efficient System Layout for Work Hydraulics of Excavators in 12th Scandinavian Int. Conf. on Fluid Power, SICFP’11 2011 Tampere, Finland.

[101] Williamson C. Power Management for Multi-Actuator Mobile Machines with Displacement Controlled Hydraulic Actuators. West Lafayette, IN, USA: Purdue University; 2010.

[102] D. Padovani Adding Active Damping to Energy-Efficient Electro-Hydraulic Systems for Robotic Manipulators — Comparing Pressure and Acceleration Feedback in 5th Int. Conf. on Robotics and Automation Engineering 2020 Singapore 10.1109/icrae50850.2020.9310881.

[103] Williamson C, Ivantysynova M. “Stability and Motion Control of Inertial Loads with Displacement Controlled Hydraulic Actuators”, in 6th FPNI - PhD Symposium. IN, USA: West Lafayette; 2010.

[104] Costa GK, Sepehri N. Four-quadrant analysis and system design for single-rod hydrostatic actuators. J Dyn Syst Meas Control 2019;141(2). https://doi.org/10.1115/1.4041382.

[105] Gøytil P, Padovani D, Hansen M. A novel solution for the elimination of mode switching in pump-controlled single-rod cylinders. Actuators 2020;9(20).

[106] Busquets E, Ivantysynova M. A multi-actuator displacement-controlled system with pump switching – a study of the architecture and actuator-level control. JFPS Int J Fluid Power Syst 2015;8(2).

[107] R. Ivantysyn J. Weber Novel Open Circuit Displacement Control Architecture in Heavy Machinery in 8th FPNI Ph.D. Symposium on Fluid Power 2014 Lappeenranta, Finland.

[108] Ivantysyn, and, J., Weber,. Verdrängersteuerung im Offenen Kreis für Einen 300-t-Tagebaubagger. Atzoffhighway 2017;10(2).

[109] R. Rahmfeld M. Ivantysynova J. Weber Displacement Controlled Wheel Loader – A Simple and Clever Solution in 4th Int. Fluid Power Conference 2004 Dresden, Germany.

[110] B. Eggers R. Rahmfeld M. Ivantysynova An Energetic Comparison Between Valveless and Valve Controlled Active Vibration Damping for Off-Road Vehicles JFPS Int. Symposium on Fluid Power 2005 Tsukuba, Japan 10.5739/isfp.2005.275.

[111] J. Zimmerman M. Ivantysynova “Hybrid Displacement Controlled Multi-Actuator Hydraulic Systems”, in 12th Scandinavian Int 2011 Conf. on Fluid Power Tampere, Finland.

[112] Hippalgaonkar R, Ivantysynova M. “A Series-Parallel Hydraulic Hybrid Mini-Excavator with Displacement Controlled Actuators”, in 13th Scandinavian Int. Linköping, Sweden: Conf. on Fluid Power; 2013.

[113] Busquets E, Ivantysynova M. Adaptive robust motion control of an excavator hydraulic hybrid swing drive. SAE Int J Commer Veh 2015;8(2). https://doi.org/10.4271/2015-01-2853.

[114] R. Hippalgaonkar M. Ivantysynova J. Zimmerman Fuel Savings of a Mini-Excavator Through a Hydraulic Hybrid Displacement Controlled System in 8th Int. Fluid Power Conference 2012 Dresden, Germany.

[115] Hippalgaonkar R, Ivantysynova M. Optimal power management of hydraulic hybrid mobile machines - Part I: theoretical studies, modeling and simulation. J Dyn Syst Meas Control Trans ASME 2016;138(5). https://doi.org/10.1115/1.4032742.

[116] Hippalgaonkar R, Ivantysynova M. Optimal power management of hydraulic hybrid mobile machines - Part II: machine implementation and measurements. J Dyn Syst Meas Control Trans ASME 2016;138(5). https://doi.org/10.1115/1.4032743.

[117] E. Busquets M. Ivantysynova Toward Supervisory-Level Control for the Energy Consumption and Performance Optimization of Displacement-Controlled Hydraulic Hybrid Machines in 10th Int. Fluid Power Conference 2016 Dresden, Germany.

[118] Bertolin M, Vacca A. An energy efficient power-split hybrid transmission system to drive hydraulic implements in construction machines. J Dyn Syst Meas Control Trans ASME 2021;143(10). https://doi.org/10.1115/1.4051035.

[119] Boehm D, Hollander C, Landmann T. “Hybrid-Antriebe bei Raupenbaggern – Konzepte und Losungen”, in 3rd Hybridantriebe fur Mobile Arbeitsmaschinen Fachtagung. Germany: Karlsruhe; 2011.

[120] Pettersson K, Tikkanen S. “Secondary Control in Construction Machinery - Design and Evaluation of an Excavator Swing Drive”, in 11th Scandinavian Int. Linköping, Sweden: Conf. on Fluid Power; 2009.

[121] M. Schneider O. Koch J. Weber M. Bach G. Jacobs Green Wheel Loader –Development of an Energy Efficient Drive and Control System in 9th Int. Fluid Power Conference 2014 Aachen, Germany.

[122] M. Schneider O. Koch J. Weber Green Wheel Loader – Improving Fuel Economy Through Energy Efficient Drive and Control Concepts in 10th Int. Fluid Power Conference 2016 Dresden, Germany.

[123] W.H.S. Rampen N.J. Caldwell U.B.P. Stein P. Joly M.R. Fielding Fluid Power Distribution and Control System US 2010/0037604 A1, 2010.

[124] Heikkilä M, Linjama M. Displacement control of a mobile crane using a digital hydraulic power management system. Mechatronics 2013;23. https://doi.org/10.1016/j.mechatronics.2013.03.009.

[125] Heikkilä M, Karvonen M, Linjama M, Tikkanen S, Huhtala K. “Comparison of Proportional Control and Displacement Control Using Digital Hydraulic Power Management System”, in ASME/BATH Symposium on Fluid Power & Motion Control. UK: Bath; 2014.

[126] M. Heikkilä M. Linjama K. Huhtala Digital Hydraulic Power Management System with Five Independent Outlets – Simulation Study of Displacement Controlled Excavator Crane in 9th Int. Fluid Power Conference 2014 Aachen, Germany.

[127] Lee W, Li S, Han D, Sarlioglu B, Minav TA, Pietola M. A Review of integrated motor drive and wide-bandgap power electronics for high-performance electro-hydrostatic actuators. IEEE Trans Transp Electrif 2018;4(3):684–93. https://doi.org/10.1109/TTE.2018.2853994.

[128] P. Gøytil D. Padovani M.R. Hansen Linear Time-Invariant Modelling of Electrohydraulic Cylinders in 2nd Int. Conf. on Electrical, Computer, Communications and Mechatronics Engineering 2022 Maldives 10.1109/ICECCME55909.2022.9988490.

[129] L. Schmidt S. Ketelsen N. Grønkær K.V. Hansen On Secondary Control Principles in Pump Controlled Electro-Hydraulic Linear Actuators BATH/ASME Symposium on Fluid Power and Motion Control 2020 Bath, UK.

[130] N. Simonsen, E. M. Sørensen, M. van Binsbergen-Galan, S. F. H. Kleine, M. H. Nielsen, and L. Schmidt, “Noise Attenuation in a Secondary Controlled Electro-Hydraulic Actuator Using an Extended Kalman Filter,” in *ASME/BATH Symposium on Fluid Power & Motion Control*, Online, 2021.

[131] T. Pietrzyk D. Roth K. Schmitz G. Jacobs Design Study of a High Speed Power Unit for Electro Hydraulic Actuators (EHA) in Mobile Applications in 11th Int. Fluid Power Conference 2018 Aachen, Germany doi.org/10.18154/RWTH-2018-224632 Available.

[132] S.-R. Lee, F. Schoemacker, C. Stammen, and K. Schmitz, “Numerical and Experimental Study on Novel Hydraulic Pump Concept,” in *12th Int. Fluid Power* Conference, Dresden, Germany, 2020. Available: doi.org/10.25368/2020.47.

[133] JBC, “19C-1E Choose JCB E-TECH,” 2021. https://www.jcb.com/en-us/products/compact-excavators/19c-1e (accessed Nov. 04, 2023).

[134] J. Nevrly *et al.*, “Battery Electric Drive of Excavator Designed with Support of Computer Modeling and Simulation,” *Proceedings*, vol. 58, no. 25, 2020, doi: 10.3390/wef-06927.

[135] Volvo, “Electric Compact Wheel Loader Volvo L25 Electric,” 2022. https://www.volvoce.com/europe/en/products/electric-machines/l25-electric/ (accessed Nov. 11, 2022).

[136] Li T, Huang L, Liu H. Energy management and economic analysis for a fuel cell supercapacitor excavator. Energy 2019;172. https://doi.org/10.1016/j.energy.2019.02.016.

[137] Truong HVA, et al. Mapping fuzzy energy management strategy for PEM fuel cell-battery-supercapacitor hybrid excavator. Energies 2020;13(3387). https://doi.org/10.3390/en13133387.

[138] “Unveils an All-Electric 26-Ton Excavator with a Gia-Nt 300 kWh Battery Pack,” *Caterpillar Inc.*, 2019. https://electrek.co/2019/01/29/caterpillar-electric-excavator-giant-battery-pack (accessed Nov. 07, 2022).

[139] Komatsu, “Komatsu PC210 Electric,” 2022. https://www.komatsu.eu/en/bauma-electric (accessed Nov. 04, 2023).

[140] “Danfoss Editron Boosts its Product Portfolio by Developing a Fully-Electric Wheel Loader System,” 2020. https://www.danfoss.com/en-us/about-danfoss/news/dps/danfoss-editron-boosts-its-product-portfolio-by-developing-a-fully-electric-wheel-loader-system/ (accessed Nov. 04, 2023).

[141] Huang J, Dong Z, Quan L, Jin Z, Lan Y, Wang Y. Development of a dual displacement controlled circuit for hydraulic shovel swing motion. Autom Constr 2015;57. https://doi.org/10.1016/j.autcon.2015.06.006.

[142] Abdel-Baqi OJ, Nasiri A, Miller PJ. Energy management for an 8000 hp hybrid hydraulic mining shovel. IEEE Trans Ind Appl 2016;52(6):5041–50. https://doi.org/10.1109/TIA.2016.2599857.

[143] Edamura M, Ishida S, Imura S, Izumi S. Adoption of electrification and hybrid drive for more energy-efficient construction machinery. Hitachi Review 2013;62 (2).

[144] Komatsu, “Komatsu HB215LC-2 Hybrid,” *2014*. https://www.komatsu.eu/en/product-archive/hybrid-crawler-excavators/hb215lc-2-hybrid (accessed Nov. 04, 2023).

[145] A. Opgenoorth S. Quabeck R.W. De Doncker K. Schmitz Challenges and Possibilities of the Integration of Electric Drives in Mobile Machinery Int. Fluid Power Conference 2020 Dresden, Germany 471 480 10.25368/2020.55.

[146] Fei X, Han Y, Wong SV, Azman MA. Efficiency comparison of electric wheel loader powertrains with dual motor input in distributed driving modes. World Electr Veh J 2023;14(10). https://doi.org/10.3390/wevj14100298.

[147] Frischemeier S. Electrohydrostatic actuators for aircraft primary flight control-types, modelling and evaluation. Proc Fifth Scand Int Conf Fluid Power 1997. https://doi.org/10.15480/882.236.

[148] Niraula A, Zhang S, Minav T, Pietola M. Effect of zonal hydraulics on energy consumption and boom structure of a micro-excavator. Energies 2018;11(8). https://doi.org/10.3390/en11082088.

[149] Gøytil P, Padovani D, Hansen M. On the energy efficiency of dual prime mover pump-controlled hydraulic cylinders. ASME/BATH Symposium on Fluid Power and Motion Control 2019. https://doi.org/10.1115/FPMC2019-1642.

[150] Ketelsen S, Padovani D, Andersen TO, Ebbesen MK, Schmidt L. Classification and review of pump-controlled differential cylinder drives. Energies 2019;12(7). https://doi.org/10.3390/en12071293.

[151] Padovani D, Ketelsen S, Hagen D, Schmidt L. A self-contained electro-hydraulic cylinder with passive load-holding capability. Energies 2019;12(2):292. https://doi.org/10.3390/en12020292.

[152] Michel S, Weber J. “Investigation of Self-Contamination of Electrohydraulic Compact Drives”, in 10th JFPS Int. Fukuoka< Japan: Symposium on Fluid Power; 2017.

[153] Han X, Välimaa J, Orifjonov A, Padovani D, Minav T. “Investigating the Filtration Characteristics of Direct Driven Hydraulics”, in ASME/BATH Symposium on Fluid Power & Motion Control, Bath. UK 2021. https://doi.org/10.1115/FPMC2021-70614.

[154] Minav T, Panu S, Matti P. Direct-Driven Hydraulic Drive Without Conventional Oil Tank. ASME/BATH Symposium on Fluid Power and Motion Control 2014. https://doi.org/10.1115/FPMC2014-7834.

[155] Hagen D, Padovani D, Ebbesen MK. “Study of a Self-Contained Electro-Hydraulic Cylinder Drive”, in Global Fluid Power Society PhD Symposium. Russia: Samara; 2018.

[156] D. Hagen, D. Padovani, and M. Choux, “A Comparison Study of a Novel Self-Contained Electro-Hydraulic Cylinder versus a Conventional Valve-Controlled Actuator — Part 1 : Motion Control,” *Actuators*, vol. 8, no. 79, 2019.

[157] D. Hagen, D. Padovani, and M. Choux, “A Comparison Study of a Novel Self-Contained Electro-Hydraulic Cylinder versus a Conventional Valve-Controlled Actuator — Part 2: Energy Efficiency,” *Actuators*, vol. 8, no. 78, 2019.

[158] Minav TA, Heikkinen JE, Pietola M. Direct driven hydraulic drive for new powertrain topologies for non-road mobile machinery. Electr Power Syst Res 2017;152:390–400. https://doi.org/10.1016/j.epsr.2017.08.003.

[159] Qu S, Fassbender D, Vacca A, Busquets E. A high-efficient solution for electro-hydraulic actuators with energy regeneration capability. Energy 2021;216. https://doi.org/10.1016/j.energy.2020.119291.

[160] F. Zappaterra, A. Vacca, and S. D. Sudhoff, “A Compact Design for an Electric Driven Hydraulic Gear Machine Capable of Multiple Quadrant Operation,” *Mech. Mach. Theory*, vol. 177, no. July, 2022.

[161] S. Qu, F. Zappaterra, A. Vacca, and E. Busquets, “An Electrified Boom Actuation System with Energy Regeneration Capability Driven by a Novel Electro-Hydraulic Unit,” *Energy Convers. Manag.*, vol. 293, no. May, 2023.

[162] M. Inderelst D. Prust M. Siegmund Electro-Hydraulic SWOT-Analysis on Electro-Hydraulic Drives in Construction Machinery Int. Fluid Power Conference 2020 Dresden, Germany 225 237 10.25368/2020.111.

[163] Ge L, Quan L, Li Y, Zhang X, Yang J. A novel hydraulic excavator boom driving system with high efficiency and potential energy regeneration capability. Energy Convers Manag 2018;166:308–17. https://doi.org/10.1016/j.enconman.2018.04.046.

[164] S. Zhang, T. Minav, and M. Pietola, “Decentralized Hydraulics for Micro Excavator,” in *15th Scandinavian Int. Conf. on Fluid Power*, , Linköping, Sweden 2017, pp. 187–195, doi: 10.3384/ecp17144187.

[165] S. Danaee, J. Nurmi, T. Minav, J. Mattila, and M. Pietola, “Direct Position Control of Electro-Hydraulic Excavator,” in *Bath/ASME Symposium on Fluid Power and Motion Control*, Bath, UK, 2018, doi: 10.1115/FPMC2018-8896.

[166] Zhang S, Minav T, Pietola M, Kauranne H, Kajaste J. The effects of control methods on energy efficiency and position tracking of an electro-hydraulic excavator equipped with zonal hydraulics. Autom Constr 2019;100:129–44. https://doi.org/10.1016/j.autcon.2019.01.003.

[167] P. Casoli, F. Scolari, T. Minav, and M. Rundo, “Comparative Energy Analysis of a Load Sensing System and a Zonal Hydraulics for a 9-Tonne Excavator,” *Actuators*, vol. 9, no. 39, Jun. 2020, doi: 10.3390/ACT9020039.

[168] D. Padovani, M. Rundo, P. Fresia, and G. Altare, “Energy Analysis of a Hybrid Electro-Hydraulic System for Efficient Mobile Hydraulics,” in *Journal of Physics: Conf. Series*, Carpi, Italy, 2023.

[169] Sarode S, Assaf H, Shang L, Vacca A, Sudhoff S. “Optimizing Electric Machines for Off-Road Mobile Applications”, in 18th Scandinavian Int. Tampere, Finland: Conf. on Fluid Power; 2023.

[170] D. Padovani S. Ketelsen L. Schmidt Downsizing the Electric Motors of Energy-Efficient Self-Contained Electro-Hydraulic Systems by Using Hybrid Technologies in BATH/ASME 2020 Symposium on Fluid Power and Motion Control 2020 10.1201/b18114-63.

[171] Li PY, Siefert J, Bigelow D. “A Hybrid Hydraulic-Electric Architecture (HHEA) for High Power Off-Road Mobile Machines”, in ASME/BATH Symposium on Fluid Power & Motion Control. FL, USA: Longboat Key; 2019.

[172] J. Siefert and P. Y. Li, “Optimal Control of the Energy-Saving Hybrid Hydraulic-Electric Architecture (HHEA) for Off-Highway Mobile Machines,” *IEEE Trans. Control Syst. Technol.*, vol. 30, no. 5, 2021, doi: 10.1109/TCST.2021.3131435.

[173] P. Fresia, M. Rundo, D. Padovani, and G. Altare, “Combined Speed Control and Centralized Power Supply for Hybrid Energy-Eefficient Mobile Hydraulics,” *Autom. Constr.*, vol. 140, no. February, 2022, doi: 10.1016/j.autcon.2022.104337.

[174] L. Schmidt and K. V. Hansen, “Electro-Hydraulic Variable-Speed Drive Networks—Idea, Perspectives, and Energy Saving Potentials,” *Energies*, vol. 15, no. 3, 2022, doi: 10.3390/en15031228.

[175] T. Guo, B. Wu, T. Lin, H. Chen, and Q. Chen, “Closed-Circuit Pump-Controlled Electro-Hydraulic Steering System for Pure Electric Wheel Loader,” *Appl. Sci.*, vol. 12, no. 11, 2022, doi: 10.3390/app12115740.

[176] Lin Z, Wang F, Xu B. Improving Wheel Loader Energy Efficiency With a Series Electric Hybrid Powertrain. BATH/ASME Symposium on Fluid Power and Motion Control 2022. https://doi.org/10.1115/FPMC2022-89099.

[177] Achten PAJ, Fu Z, Vael GEM. “Transforming Future Hydraulics: a New Design of a Hydraulic Transformer”, in 5th Scandinavian Int. Linköping, Sweden: Conf. on Fluid Power; 1997.

[178] P. A. J. Achten *et al.*, “Design and Testing of an Axial Piston Pump Based on the Floating Cup Principle,” in *8th Scandinavian Int. Conf. on Fluid Power*, Tampere, Finland, 2003.

[179] G. E. Vael, P. A. J. Achten, and Z. Fu, “The Innas Hydraulic Transformer the Key to the Hydrostatic Common Pressure Rail,” in *Int. Off-Highway & Powerplant Congress & Exposition*, Milwaukee, WI, USA, 2000, doi: 10.4271/2000-01-2561.

[180] Shen W, Jiang J, Su X, Karimi HR. Energy-saving analysis of hydraulic hybrid excavator based on common pressure rail. Sci World J 2013. https://doi.org/10.1155/2013/560694.

[181] K. Heybroek G.E.M. Vael J.-O. Palmberg Towards Resistance-Free Hydraulics in Construction Machinery 2012 Dresden, Germany.

[182] Tripathi G, Dhar A, Sadiki A. Recent advancements in after-treatment technology for internal combustion engines—an overview. Energy, Environment, and Sustainability 2018.

[183] Ayodhya AS, Narayanappa KG. An overview of after-treatment systems for diesel engines. Environ Sci Pollut Res 2018;25:35034–47.

[184] Martinovic F, Castoldi L, Deorsola FA. Aftertreatment technologies for diesel engines: an overview of the combined systems. Catalysts 2021;11(6):653.

[185] D. Mufaddel, J. Satyum, K. Hari, K. Erik W., and F. Michael, “Evaluation of System Configurations for Downsizing a Heavy-Duty Diesel Engine for Non-Road Applications,” *SAE Int. J. Engines*, vol. 9, no. December, pp. 2272–2285, 2016.

[186] Feneley AJ, Pesiridis A, Andwari AM. Variable geometry turbocharger technologies for exhaust energy recovery and boosting-a review. Renew Sustain Energy Rev 2017;71:959–75. https://doi.org/10.1016/j.rser.2016.12.125.

[187] P. Dimitriou, R. Burke, Q. Zhang, C. Copeland, and H. Stoffels, “Electric Turbocharging for Energy Regeneration and Increased Efficiency at Real Driving Conditions,” *Appl. Sci.*, vol. 7, no. 4, 2017, doi: 10.3390/app7040350.

[188] A. E. Teo Sheng Jye, A. Pesiridis, and S. Rajoo, “Effects of Mechanical Turbo Compounding on a Turbocharged Diesel Engine,” in *SAE Technical Papers*, 2013, vol. 1, doi: 10.4271/2013-01-0103.

[189] Hountalas DT, Katsanos CO, Lamaris VT. Recovering energy from the diesel engine exhaust using mechanical and electrical turbocompounding. SAE Technical Papers 2007. https://doi.org/10.4271/2007-01-1563.

[190] Q. Zhang *et al.*, “Implementing Full Electric Turbocharging Systems on Highly Boosted Gasoline Engines,” in *Proceedings of the ASME Turbo Expo*, 2017, vol. 8, doi: 10.1115/GT2017-64960.

[191] T. E. Reinhart, “Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study-Report #1,” Washington DC, USA, 2015. Available: www.ntis.gov.

[192] M. Y. E. Selim, “Effect of Exhaust Gas Recirculation on some Combustion Characteristics of Dual Fuel Engine,” Energy Convers Manag, vol. 44, pp. 707–721, 2003, [Online]. Available: www.elsevier.com/locate/enconman.

[193] Paykani A, Saray K, Shervani-Tabar M, Mohammadi-Kousha A. Effect of exhaust gas recirculation and intake pre-heating on performance and emission characteristics of dual fuel engines at part loads. Journal of Central South University of Technology (english Edition) May 2012;19(5):1346–52. https://doi.org/10.1007/s11771-012-1148-5.

[194] Boyarski NJ, Reitz RD. Premixed compression ignition (PCI) combustion with modeling-generated piston bowl geometry in a diesel engine. SAE Trans 2006: 133–43.

[195] Thangaraja J, Kannan C. Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels-a review. Appl Energy 2016;180:169–84.

[196] Qi D, Ma L, Chen R, Jin X, Xie M. Effects of EGR rate on the combustion and emission characteristics of diesel-palm oil-ethanol ternary blends used in a CRDI diesel engine with double injection strategy. Appl Therm Eng 2021;199:117530.

[197] Satyanarayana K, Padala VK, Rao TH, Umamaheswararao SV. Variable compression ratio diesel engine performance analysis. Int J Eng Trends Technol 2015;28:1–12.

[198] Fridrichová K, Drápal L, Vopařil J, Dlugoš J. Overview of the potential and limitations of cylinder deactivation. Renew Sustain Energy Rev 2021;146: 111196.

[199] Lou Z, Zhu G. Review of advancement in variable valve actuation of internal combustion engines. Appl Sci 2020;10(4):1216.

[200] El Ela AMA, Eldrainy YA, Elkasaby MM, Nour AM. Effect of replacing nitrogen with helium on a closed cycle diesel engine performance. Alexandria Eng J 2016; 55(3):2251–6.

[201] Prashanth K, Shaik A. Experimental investigation of argon gas induction on diesel engine performance and emission characteristics: a comprehensive study on De-NOx techniques. Process Saf Environ Prot 2021;152:471–81.

[202] Zhu S, et al. A review of water injection applied on the internal combustion engine. Energy Convers Manag 2019;184:139–58.

[203] S. Barros, W. Atkinson, and N. Piduru, “Extraction of Liquid Water from the Exhaust of a Diesel Engine,” *SAE Technical Paper*, 2015.

[204] Tanaka T, Ando A, Ishizaka K. Study on pilot injection of DI diesel engine using common-rail injection system. JSAE Rev 2002;23(3):297–302.

[205] Dimitriou P, Wang W, Peng J, Cheng L, Wellers M, Gao B. Analysis of diesel engine in-cylinder air-fuel mixing with homogeneity factor: combined effects of pilot injection strategies and air motion. SAE Int J Engines 2014;7(4):2045–60. https://doi.org/10.4271/2014-01-9052.

[206] Dimitriou P, Peng Z, Wang W, Gao B, Wellers M. Effects of advanced injection strategies on the in-cylinder air-fuel homogeneity of diesel engines. Proc Inst Mech Eng Part D J Automob Eng 2015;229(3). https://doi.org/10.1177/0954407014540900.

[207] Farhan SM, Wang P. Post-injection strategies for performance improvement and emissions reduction in DI diesel engines—a review. Fuel Process Technol 2022; 228.

[208] Osada H, Uchida N, Shimada K, Aoyagi Y. Reexamination of multiple fuel injections for improving the thermal efficiency of a heavy-duty diesel engine. SAE Technical Papers 2013. https://doi.org/10.4271/2013-01-0909.

[209] M. Elkelawy et al., “Influence of Lean Premixed Ratio of PCCI-DI Engine Fueled by Diesel/Biodiesel Blends on Combustion, Performance, and Emission Attributes; a Comparison Study,” *Energy Conversion and Management: X*, vol. 10, Jun. 2021, doi: 10.1016/j.ecmx.2020.100066.

[210] Paykani A, Kakaee A-H, Rahnama P, Reitz RD. Progress and recent trends in reactivity-controlled compression ignition engines. Int J Engine Res 2016;17(5): 481–524.

[211] Chauhan BVS, Sayyed I, Vedrantam A, Garg A, Bharti S, Shukla M. State of the art in low-temperature combustion technologies: HCCI, PCCI, and RCCI. Adv Combust Sustain Transp 2022:95–139.

[212] Norouzi A, Shahpouri S, Gordon D, Shahbakhti M, Koch CR. Safe deep reinforcement learning in diesel engine emission control. Proc Inst Mech Eng Part I J Syst Control Eng 2023;237(8):1440–53. https://doi.org/10.1177/09596518231153445.

[213] Nikzadfar K, Shamekhi AH. An extended mean value model (EMVM) for control-oriented modeling of diesel engines transient performance and emissions. Fuel 2015;154. https://doi.org/10.1016/j.fuel.2015.03.070.

[214] Cheng L, Dimitriou P, Wang W, Peng J, Aitouche A. A novel fuzzy logic variable geometry turbocharger and exhaust gas recirculation control scheme for optimizing the performance and emissions of a diesel engine. Int J Engine Res 2018. https://doi.org/10.1016/j.semarthrit.2010.10.003.

[215] Ahire V, Shewale M, Razban A. A review of the state-of-the-art emission control strategies in modern diesel engines. Arch Comput Methods Eng 2021.

[216] Weichai Power, “Weichai Group Launches the World’s First Commercialized Diesel Engine with a Brake Thermal Efficiency Over 50%,” Sep. 16, 2020. https://en.weichai.com/wmdgs/wmdls/jtdwc/202009/t20200921_65942.htm (accessed Jul. 07, 2023).

[217] Nissan Motor Corporation, “e-POWER’s Internal Combustion Engine Achieves 50% Thermal Efficiency.” https://www.nissan-global.com/EN/INNOVATION/TECHNOLOGY/ARCHIVE/E_POWER50/ (accessed Jul. 07, 2023).

[218] Johnson T, Joshi A. Review of vehicle engine efficiency and emissions. SAE Int J Engines 2018;11(6). https://doi.org/10.4271/2018-01-0329.

[219] Ou L, et al. Co-optimization of heavy-duty fuels and engines: cost benefit analysis and implications. Environ Sci Technol 2019;53(21). https://doi.org/10.1021/acs.est.9b03690.

[220] Tamilselvan P, Nallusamy N, Rajkumar S. A comprehensive review on performance, combustion and emission characteristics of biodiesel fuelled diesel engines. Renew Sustain Energy Rev 2017;79. https://doi.org/10.1016/j.rser.2017.05.176.

[221] Mat Aron NS, Khoo KS, Chew KW, Show PL, Chen WH, Nguyen THP. Sustainability of the four generations of biofuels – a review. Int J Energy Res 2020;44(12). https://doi.org/10.1002/er.5557.

[222] Malode SJ, Prabhu K, Mascarenhas RJ, Shetti NP, Aminabhavi TM. Recent advances and viability in biofuel production. *Energy Convers Manage*: X Jun. 2021; 10. https://doi.org/10.1016/j.ecmx.2020.100070.

[223] Dimitriou P, Tsujimura T. A review of hydrogen as a compression ignition engine fuel. Int Journal of Hydrogen Energy 2017;42(38). https://doi.org/10.1016/j.ijhydene.2017.07.232.

[224] Dimitriou P, Javaid R. A review of ammonia as a compression ignition engine fuel. Int Journal of Hydrogen Energy 2020;vol. 45, no. 11, Feb. 28. https://doi.org/10.1016/j.ijhydene.2019.12.209.

[225] Verhelst S, Turner JW, Sileghem L, Vancoillie J. Methanol as a fuel for internal combustion engines. Prog Energy Combust Sci 2019;70. https://doi.org/10.1016/j.pecs.2018.10.001.

[226] Welch A, et al. “Challenges in Developing Hydrogen Direct Injection Technology for Internal Combustion Engines”, in SAE Technical Papers (Powertrains, Fuels & Lubricants Meeting). IL, USA: Rosemont; 2008.

[227] Dimitriou P, Kumar M, Tsujimura T, Suzuki Y. Combustion and emission characteristics of a hydrogen-diesel dual-fuel engine. Int J Hydrogen Energy 2018. https://doi.org/10.1016/j.ijhydene.2018.05.062.

[228] Dimitriou P, Tsujimura T, Suzuki Y. Hydrogen-diesel dual-fuel engine optimization for CHP systems. Energy 2018;160. https://doi.org/10.1016/j.energy.2018.07.038.

[229] M. Wolfe, “Liebherr Goes All in on Hydrogen Fuel,” *Truck & Off-Highway Engineering Magazine*, Dec. 2022.

[230] Lord Bamford, “JCB Debuts Clean-Sheet Hydrogen Combustion Engine,” Mar. 2023. Accessed: Jul. 07, 2023. [Online]. Available: https://www.jcb.com/en-us/news/2023/01/jcb-hydrogen-world-first-makes-international-debut.

[231] R. Rosa, “The Role of Synthetic Fuels for a Carbon Neutral Economy,” *C*, vol. 3, no. 4, 2017, doi: 10.3390/c3020011.

[232] Ausfelder F, Wagemann K. Power-to-fuels: E-fuels as an important option for a climate-friendly mobility of the future. Chem-Ing-Tech 2020;92(1–2). https://doi.org/10.1002/cite.201900180.