JOURNAL OF ADVANCED MULTIDISCIPLINARY STUDIES (JAMS)
JAMS |Volume I Issue II September 2026| DOI: 10.68050/JAMS

Energy-Efficient Hydraulics in Heavy Machinery: A Review of Technologies and Future Directions

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DOI: https://doi.org/10.68050/JAMS.2026.213

Received: 30 Aug 2026; Accepted: 01 Sept 2026; Published: 05 September 2026

ABSTRACT

Heavy earth-moving machinery is essential for construction, mining, and infrastructure development, but its traditional hydraulic systems, powered predominantly by diesel engines, are major contributors to energy losses and inefficiencies. Hydraulic circuits typically account for significant parasitic losses due to throttling, leakage, and limited energy recovery, resulting in high fuel consumption and emissions. This review paper comprehensively examines recent innovations transforming hydraulic technology to improve energy efficiency and sustainability. The paper highlights advancements such as electro-hydraulic actuators, independent metering systems, and digital hydraulics, which enable precise flow control and minimize throttling losses. The integration of energy recovery systems, including hydraulic accumulators and hybrid architectures, is discussed in detail, demonstrating how these technologies capture and reuse energy during braking and lowering operations. Additionally, the adoption of smart sensors, predictive analytics, and advanced control algorithms enables real-time optimization of hydraulic performance, reducing idle losses and improving overall system responsiveness. Emerging trends such as fluid power electrification, compact high-pressure components, and the use of eco-friendly hydraulic fluids are also examined. By synthesizing current research and industrial practices, this paper provides insights into the challenges, opportunities, and future prospects for achieving substantial energy efficiency gains through next-generation hydraulic technologies in heavy earth-moving equipment. This review synthesizes peer-reviewed journal articles, conference proceedings, and industry white papers published between 2000 and 2026. Literature was identified through searches in Scopus, IEEE Xplore, ScienceDirect, and Google Scholar using keywords including "hydraulic energy efficiency," "electro-hydraulic actuators," "digital hydraulics," "energy recovery," and "heavy machinery." Priority was given to experimental and simulation-based studies reporting quantifiable energy savings. Industry sources were included to capture commercial technology readiness and implementation trends.

Keywords: Hydraulic Systems; Energy Efficiency; Electro-Hydraulic Actuators; Digital Hydraulics; Energy Recovery; Heavy Earth-Moving Machinery

INTRODUCTION

Heavy earth-moving equipment such as excavators, loaders, and bulldozers relies extensively on hydraulic systems to convert engine power into mechanical motion. These machines form the backbone of construction, mining, and infrastructure development sectors globally. However, conventional hydraulic architectures are inherently inefficient, with studies indicating that 30–50% of input energy is lost through throttling, leakage, and parasitic flows in hydraulic circuits (Bhola and Wrat, 2026). These inefficiencies not only increase fuel consumption but also elevate greenhouse gas emissions and operating costs, posing significant challenges in meeting stringent environmental regulations (Pate, 2025).

The global heavy equipment industry is under increasing pressure to reduce its environmental footprint while maintaining productivity and performance. According to industry research, fuel costs and regulatory constraints are already impacting large companies, driving the search for more efficient technologies (Pate, 2025). While full electrification of heavy machinery remains a long-term goal, improvements in energy-efficient hydraulic and hybrid technologies will play a pivotal role in the industry's transition towards more sustainable equipment in the medium term (Bhola and Wrat, 2026).

Recent advancements are driving a paradigm shift toward next-generation hydraulic technologies aimed at improving energy efficiency. Key innovations include electro-hydraulic actuation, which combines electric drives with hydraulic power for precise control and reduced throttling losses, and energy recovery systems that capture and reuse energy during braking or lowering operations (Ge et al., 2025). Additionally, digital hydraulics and smart control algorithms enable real-time optimization of flow and pressure, minimizing idle losses and enhancing system responsiveness (Pellegri, 2026). Complementary developments such as advanced hydraulic fluids with low-viscosity variability and high oxidation resistance further reduce mechanical and volumetric losses, improving overall system performance (Zhou, 2025). This review paper aims to provide a comprehensive synthesis of recent system-level technologies developed in both research laboratories and industry, along with the challenges associated with these systems.

INEFFICIENCIES IN TRADITIONAL HYDRAULIC SYSTEMS

Compared with electrical and mechanical systems, hydraulic systems exhibit lower efficiency due to various loss mechanisms. The typical efficiency for a hydraulic motor or pump is up to 85%, whereas it is approximately 98% for a single mechanical gearbox and above 95% for a triple-reduction gearbox (Bhola and Wrat, 2026). For a simple pump-controlled hydraulic system, the overall efficiency is about 70% under ideal operating conditions (Xu et al., 2015). Even with highly efficient electric drivetrains, excavators inherit a major energy challenge from their diesel counterparts, with conventional hydraulic systems wasting up to 70% of the useful power delivered by the prime mover (Ge et al., 2025).

The various losses in hydraulic systems include throttling loss, overflowing loss, and leakage loss, making energy conservation a critical research topic in the hydraulics field to lower energy consumption and emissions (Bhola and Wrat, 2026). Many energy-saving techniques have been proposed and developed by researchers, including load-sensing control, positive and negative flow control systems, high-speed inlet valves, hydraulic capacity speed governing systems, separate controllers for actuator ports, and secondary regulation techniques (Finzel et al., 2010; Vael et al., 2000).

The primary inefficiencies in traditional hydraulic systems can be categorized as follows:

- **Throttling losses:** A major source of energy waste in control valves, where excess flow is throttled to regulate actuator speed, leading to substantial pressure drops and heat generation (Ge et al., 2025). Flow-sharing valves introduce meter-in losses when reconciling differential load pressures across actuators, while meter-out losses are necessary for controlling overrunning conditions (Kim et al., 2020).
- **Leakage:** Internal leakage within pumps, motors, and actuators reduces volumetric efficiency and increases energy demand (Ivantysynova, 2014).
- **Idle losses:** Even during standby or low load conditions, pumps continue to circulate fluid, consuming energy without performing useful work (Bhola and Wrat, 2026).
- **Low energy recovery:** Potential energy during braking or lowering operations is typically dissipated as heat rather than being recovered and reused (Nguyen et al., 2025).
- **Pump inefficiency:** Pumps rarely operate at their optimal displacement and pressure point during real duty cycles, driving further inefficiency (Williamson and Ivantysynova, 2010).

Table 1. Energy loss distribution in traditional hydraulic systems.

Loss Mechanism	Approx. Contribution (%)	Reference
Throttling losses	25–30%	Ge et al., 2025; Kim et al., 2020
Pump/motor inefficiency	15–20%	Williamson and Ivantysynova, 2010; Ivantysynova, 2014

Leakage losses	10–15%	Ivantysynova, 2014; Bhola and Wrat, 2026
Idle losses	20–25%	Bhola and Wrat, 2026; Axin et al., 2012
Other (friction, etc.)	5–10%	Bhola and Wrat, 2026

TECHNOLOGICAL INNOVATIONS TARGETING THROTTLING LOSSES

Technological innovations in hydraulic systems have significantly advanced performance, efficiency, and sustainability. This section examines two key innovations: electro-hydraulic actuators and independent metering systems.

Electro-Hydraulic Actuators (EHAs)

An electro-hydraulic actuator (EHA) is a compact, self-contained actuation system that integrates an electric motor (serving as the prime mover), a hydraulic pump (either fixed or variable displacement), a hydraulic cylinder, and advanced control electronics with sensors (MOOG, 2020). Unlike traditional centralized hydraulic systems, EHAs integrate the electric motor and hydraulic pump into a compact unit, eliminating long hoses and reducing energy losses, leakage, and maintenance (Hagen et al., 2019).

EHAs generate pressure only when needed, minimizing idle losses, and often support energy recovery via accumulators or batteries. With closed-loop servo control, EHAs offer precise positioning and fast dynamic response, making them ideal for high-performance applications (Qu et al., 2018). Research indicates that the natural frequency of EHAs is in the range of 30–50 Hz, sufficient for many industrial applications (MOOG, 2020).

Several studies have demonstrated the energy-saving potential of EHAs. Research on a hydraulic press for deep drawing operations employed four separate EHAs installed at four cushions of the machine. During deep drawing operation, energy was recovered from the die cushion machine to the ram actuator, demonstrating the energy recovery potential of EHAs (Finzel et al., 2010). The system achieved approximately 29% energy savings in hydraulic deep drawing operation (Finzel et al., 2010).

A novel load-prediction-based variable-supply-pressure valve-controlled (VPVC) hydraulic actuation strategy was proposed and developed by Du et al. (2018), in which minimum supply pressure is required for corresponding valve spool displacement for multi-axis hydraulic systems. Using the proposed VPVC controller, less input power was required to accomplish the same motion compared to a fixed-supply pressure-controlled conventional system. Experimental results from two-axis hydraulic robot arms showed 70% hydraulic energy savings compared to the conventional system (Du et al., 2018).

Hagen et al. (2019) presented a novel actuation system for offshore drilling applications consisting of three self-contained electro-hydraulic cylinders capable of sharing and regenerating energy. Simulation studies showed that the proposed self-contained system consumed 83.44% less energy without influencing system performance compared to conventional valve-controlled cylinder systems (Hagen et al., 2019).

An energy-saving control strategy was proposed and developed by Wang and Wang (2016) to enhance the efficiency of an electro-hydraulic servo system. The strategy, based on a load-sensing structure with variable-supply-pressure control, minimized pressure loss across the proportional directional valve. The proposed strategy saved 62.5% of energy supply in harmonic reference tests and 90% energy supply for multi-step reference tests compared to fixed displacement systems (Wang and Wang, 2016).

Yoon et al. (2009) designed and proposed advanced construction machinery to achieve green emission demands and energy saving without affecting performance, safety, or reliability. The proposed construction machine employs electro-hydraulic actuators that consume less system energy than conventional hydraulic valve-controlled actuators (Yoon et al., 2009).

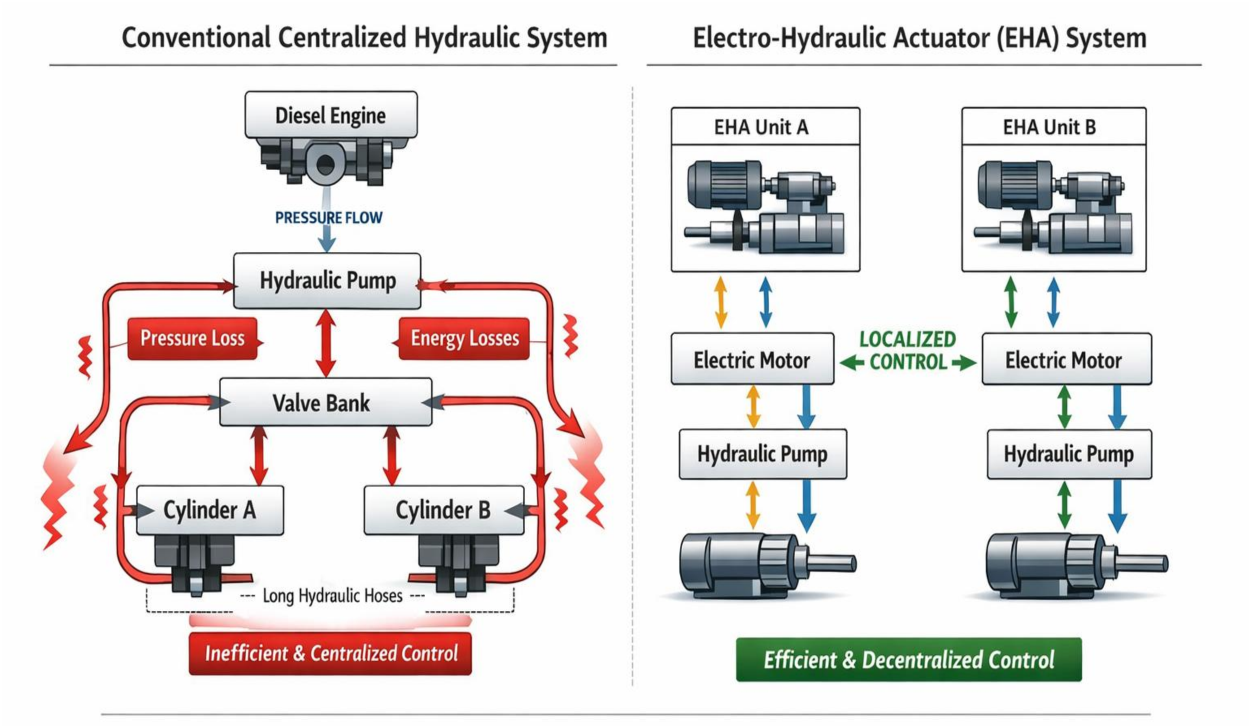

Figure 1: Schematic comparison of conventional vs. electro-hydraulic actuator systems A side-by-side diagram showing the architectural differences.

Independent Metering Systems (IMS):

Independent metering systems (IMS) decouple the meter-in and meter-out functions, allowing precise control of each actuator port. This configuration reduces throttling losses and improves energy efficiency, particularly in heavy-duty mobile machinery (Kim et al., 2020). Traditional hydraulic systems use a single spool valve to simultaneously control both the inflow to and outflow from an actuator, creating inherent coupling that often leads to unnecessary throttling (Shenouda, 2006).

IMS architectures employ multiple proportional valves typically two to four to independently control each actuator port (Eriksson, 2010). This decoupling enables several efficiency-enhancing strategies:

- **Metering mode selection:** The system can select between different metering configurations (e.g., regenerative, power-saving, or high-precision modes) based on operating conditions (Shenouda, 2006).
- **Pressure matching:** Supply pressure can be matched more closely to load requirements, reducing throttling losses (Eriksson, 2010).
- **Energy recovery:** During overrunning loads, IMS can route fluid directly from the actuator outlet to the inlet or to an energy storage device (Kim et al., 2020).

Research has demonstrated that IMS can significantly reduce energy consumption in excavator booms and other applications where loads vary widely during operation. Ding et al. (2018) applied IM technology to a 2-ton excavator, achieving 35.3% lower energy consumption than that of the load-sensing system (Ding et al., 2018). Ge et al. (2017) proposed a pump-and-valve combined principle based on the IM system and a speed and displacement variable power source, thereby increasing the excavator's efficiency to 46.3% (Ge et al., 2017).

The implementation of IMS typically requires more sophisticated control algorithms than conventional systems, but advances in embedded computing have made such control feasible in production machines (Axin, 2013). The swing function in the Danfoss Dextreme Max system utilized an independent metering valve to remove flow-sharing and metering losses, contributing to significant overall efficiency improvements (Pellegri, 2026).

Load-Difference Equilibrium Systems

A novel approach to addressing throttling losses due to load differences in multi-actuator systems has been proposed by researchers (Ge et al., 2025). When multiple actuators are supplied by the same pump, the pump pressure must match the highest load pressure, requiring valves in light-load actuator circuits to compensate through throttling (Ge et al., 2025). This results in what researchers term "throttling losses due to load differences" (TLLD).

To address this, a load-difference equilibrium system using electrohydraulic energy storage (LDES) has been developed (Ge et al., 2025). This system employs a hydraulic pump/motor and electric motor/generator module to regulate the outlet-chamber pressure of light-load actuators, enabling inlet-chamber pressures to reach the level of the highest load pressure. Experimental results show that compared to traditional valve-controlled systems, energy consumption and throttling losses can be reduced by 21.5–37.3% and 79.4–85.8%, respectively, with overall energy-recovery efficiency of approximately 55.8–64.0% (Ge et al., 2025).

ENERGY RECOVERY AND HYBRIDIZATION

The integration of energy recovery systems capture energy that would otherwise be dissipated as heat particularly potential energy during boom lowering and kinetic energy during machine deceleration and store it for later use (Nguyen et al., 2025).

Hydraulic Accumulator-Based Energy Recovery

Hydraulic accumulators are the most common energy storage devices in hydraulic systems due to their high power density, relatively low cost, and direct compatibility with hydraulic fluid (Kumar et al., 2018). Accumulators store energy by compressing a gas (typically nitrogen) or lifting a mass, and they can release this energy rapidly when required (Kumar et al., 2018).

In excavator applications, boom lowering presents the greatest opportunity for energy recovery. Studies have shown that the boom typically offers several times higher recovery potential than other actuators and about two to four times that of the swing function (Bhola and Wrat, 2026). During boom lowering, the potential energy of the boom and attached load can be captured by routing high-pressure fluid from the cylinder into an accumulator rather than across a throttling valve (Nguyen et al., 2025).

Research by Nguyen et al. (2025) presented a hybrid powertrain with dual energy regeneration for boom cylinder movement in hydraulic excavators. The system integrated a hydrostatic transmission to optimize torque and speed between the pump and power sources, with two distinct energy regeneration methods: employing an independent hydraulic motor or utilizing the hydraulic motor mode of the main hydraulic pump/motor to recapture potential energy. Experimental and simulation results showed energy savings of up to 61.64%, with energy regeneration efficiency reaching 73% during cylinder lowering (Nguyen et al., 2025).

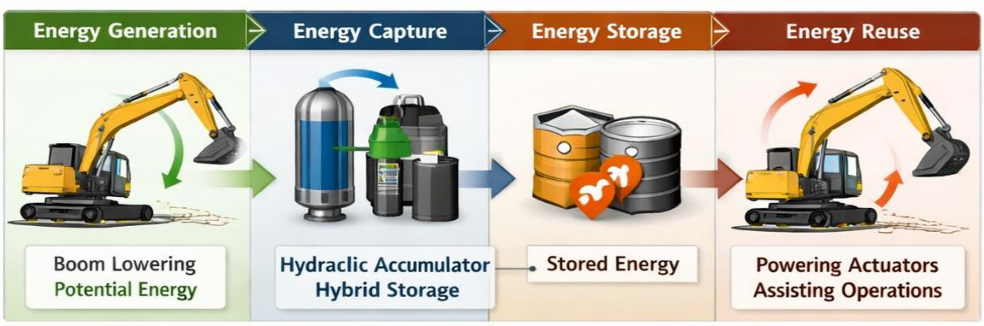

Figure 2: Schematic representation of the energy recovery process in hydraulic systems used in heavy civil engineering machinery.

Three-Chamber Cylinder Systems

An innovative approach to energy recovery involves replacing conventional hydraulic actuators with three-chamber cylinders (Romagnuolo et al., 2024). Romagnuolo et al. (2024) proposed a system in which the third chamber, obtained inside the cylinder rod, is connected to a secondary hydraulic circuit involving a series of accumulators. The compression and subsequent expansion of gas inside the accumulator allows storage of recoverable energy during load lowering and deployment in the next cycle (Romagnuolo et al., 2024).

Simulation results from this proposed system showed that on a working cycle of 20 seconds, only 25% of the hydraulic energy required for the conventional system is needed to operate the boom in the proposed configuration (Romagnuolo et al., 2024). This method can be easily extended to several hydraulic actuators that realize frequent height changes of the load (Romagnuolo et al., 2024). Hao et al. (2020) further investigated three-chamber cylinder performance for boom energy recovery systems, demonstrating significant energy savings potential.

Electric Energy Storage Systems

Electric energy storage systems, particularly batteries and supercapacitors, offer complementary characteristics to hydraulic accumulators (Lin et al., 2010). While accumulators excel at high-power, short-duration storage, electric storage provides higher energy density and more flexible energy management. Hybrid systems combining both storage types can optimize performance across diverse operating conditions (Lin et al., 2010).

Supercapacitors are particularly well-suited for regenerative braking applications due to their ability to accept and deliver high power over short durations (Wang et al., 2019). Gong et al. (as cited in Lin et al., 2010) developed an electrohydraulic hybrid excavator in which the gravitational potential energy of the boom and rotary kinetic energy during swing braking can be recovered into a supercapacitor. Experimental studies showed that approximately 17.6% of energy consumption could be saved by this scheme (Lin et al., 2010).

Yu et al. (2015) studied a scheme using a variable-displacement hydraulic motor and generator to collect boom potential energy. By optimizing the generator working point through control of hydraulic motor displacement, energy regeneration efficiency reached up to 57.4% (Yu and Ahn, 2015).

Hybrid Hydraulic Architectures

Hijikata (2024) explored a hydraulic hybrid architecture combining an open center system with a constant pressure system (STEAM) for excavators. Important features of this system include the ability to operate the internal combustion engine at its most efficient point and recover energy using accumulators (Hijikata, 2024). The research established basic principles and design guidelines for developing a new hydraulic architecture, with simulations and experiments confirming system efficiency improvements (Hijikata, 2024).

Cheng et al. (2016) developed a novel pump displacement controlled system for multi-actuators with energy recovery, demonstrating improved efficiency through advanced control strategies.

Hydrostatic Transmission Systems

Hydrostatic transmissions (HST) offer another approach to improving energy efficiency, particularly in applications requiring variable speed and torque control (Heybroek, 2008). HST systems decouple the prime mover from the driven load, allowing the engine to operate in its most efficient region while the transmission handles varying load demands (Heybroek, 2008).

Recent research has explored integrating HST with energy recovery systems to maximize overall efficiency (Nguyen et al., 2025). The combination allows optimal torque-speed matching while capturing and reusing energy that would otherwise be lost (Nguyen et al., 2025).

Table 2. Comparison of energy recovery technologies for hydraulic excavators.

Technology	Energy Savings	Key Advantages	Primary Limitations	Reference
Hydraulic accumulator	30–50%	High power density, low cost	Low energy density	Kumar et al., 2018; Bhola and Wrat, 2026
Electric (battery/supercapacitor)	40–60%	High energy density, flexible use	Higher cost, power electronics needed	Lin et al., 2010; Wang et al., 2019
Three-chamber cylinder	Up to 75%	Direct energy recovery, simple integration	Requires cylinder redesign	Romagnuolo et al., 2024; Hao et al., 2020
Hybrid (combined)	Up to 61.6%	Optimized performance	Complex control, higher initial cost	Nguyen et al., 2025
Load-difference equilibrium	21.5–37.3%	Addresses multi-actuator inefficiencies	Additional components required	Ge et al., 2025

SMART SYSTEMS AND CONTROL ALGORITHMS

The integration of smart sensors, predictive analytics, and advanced control algorithms enables real-time optimization of hydraulic performance, reducing idle losses and improving overall system responsiveness (Bosch Rexroth, 2026).

Idle Speed Control Systems

Idle losses represent a significant portion of energy waste in many heavy machinery applications (Bhola and Wrat, 2026). During standby periods or between work cycles, conventional systems continue circulating fluid and consuming power. Idle Speed Control (ISC) systems address this inefficiency by automatically reducing engine speed or shutting down the prime mover during extended idle periods (Bhola and Wrat, 2026).

Research indicates that ISC systems eliminate the requirement for additional components and reduce control complexity, making them relatively easy to implement compared to more sophisticated energy recovery systems (Bhola and Wrat, 2026). When the operator demands power, the system rapidly restores operating conditions, minimizing productivity impact while achieving fuel savings.

Advanced ISC systems incorporate predictive algorithms that learn operator behavior patterns and duty cycle characteristics, optimizing the balance between fuel savings and rapid response (Bhola and Wrat, 2026). These systems can achieve significant fuel reductions in applications with frequent idle periods, such as urban construction sites or material handling operations.

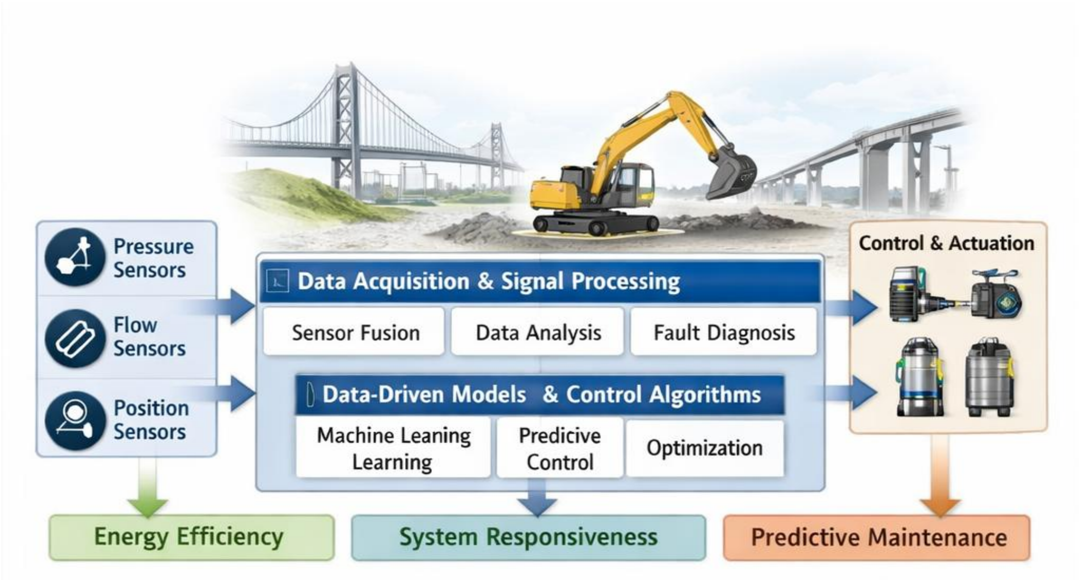

Figure 3: Conceptual architecture of a smart hydraulic system for heavy civil engineering machinery, illustrating the integration of pressure, flow, and position sensors with data acquisition, signal processing, and advanced control algorithms.

Predictive Analytics and Machine Learning:

The application of machine learning and predictive analytics to hydraulic systems represents an emerging frontier in efficiency optimization (Bosch Rexroth, 2026). These technologies enable:

- **Predictive maintenance:** Anticipating component failures before they occur, reducing unplanned downtime and maintaining optimal efficiency (Bosch Rexroth, 2026).
- **Real-time efficiency optimization:** Continuously adjusting system parameters based on current operating conditions and predicted future demands (Zhou et al., 2025).
- **Adaptive control:** Learning from past operation to improve future performance, particularly in applications with repetitive duty cycles (Zhou et al., 2025).

Research has demonstrated that neural network-based controllers can optimize PID parameters in hydraulic systems, reducing oscillations and improving response speed (Zhou et al., 2025). These intelligent control systems adapt to changing conditions and component wear, maintaining optimal performance throughout the machine's lifecycle.

Bosch Rexroth (2026) has developed training programs focused on data-driven connected hydraulics, teaching participants how to use data collected from connected hydraulic systems for performance monitoring and predictive maintenance. Topics covered include smart hydraulic power unit systems, data acquisition with sensors and standardized communication protocols, and applying hydraulic data in the cloud for monitoring, maintenance, and prediction (Bosch Rexroth, 2026).

Digital Hydraulics

Digital hydraulics represents a fundamental shift from traditional analog control to discrete, digital control strategies (Pellegri, 2026). Rather than using proportional valves to continuously modulate flow, digital hydraulic systems employ arrays of on/off valves that are switched rapidly to achieve the desired average flow (Pellegri, 2026).

The Digital Displacement® technology developed by Danfoss exemplifies this approach (Pellegri, 2026). In this system, multiple independently controlled outlets from a single pump/motor enable independent actuator supply, eliminate flow-sharing losses, and facilitate energy recovery (Pellegri, 2026). Each pumping chamber can be selectively enabled or disabled on each revolution, allowing precise matching of displacement to instantaneous demand (Achten et al., 2016).

Recent validation of Danfoss's Dextreme Max digital hydraulic architecture in a 30-tonne electric excavator demonstrated substantial efficiency improvements (Pellegri, 2026). Compared to the baseline electric excavator, the converted machine reduced DC energy use by 49.2% in air grading tests and 31% in air dig and dump tests, with negligible impact on cycle time. For a typical duty cycle mix of 30% grading and 70% digging, the digital hydraulic system would reduce battery power consumption by 35%, resulting in 53% longer operating hours with the same battery capacity (Pellegri, 2026).

The key advantages of digital hydraulics include (Pellegri, 2026; Achten et al., 2016):

- **Elimination of throttling losses:** Flow is controlled by enabling/disabling displacement units rather than throttling across valves.
- **Independent metering:** Multiple outlets can supply different actuators simultaneously with independently controlled flow.
- **Integrated energy recovery**: Digital units can operate as pumps or motors, enabling efficient energy recovery without additional components.

QUANTITATIVE COMPARISON OF TECHNOLOGIES

To provide a practical framework for technology selection, Table 3 presents a quantitative comparison of emerging actuation and transmission technologies based on published research.

Table 3. Quantitative comparison of emerging hydraulic technologies.

Technology	Energy Savings (%)	Complexity (1-5)	Cost Impact (%)	Maturity (TRL)	Key Applications	Reference
Electro-hydraulic actuators	54–90	4	+20–40	8-Jul	Industrial machinery, presses	Du et al., 2018; Hagen et al., 2019; Wang and Wang, 2016
Independent metering	20–40	3	+10–25	9-Aug	Mobile hydraulics, excavators	Ding et al., 2018; Kim et al., 2020; Ge et al., 2017
Digital hydraulics	31–49	4	+15–30	7-Jun	Electric excavators, mobile machines	Pellegri, 2026; Achten et al., 2016
Hydraulic hybrids	30–50	3	+15–25	9-Aug	Excavators, material handlers	Kumar et al., 2018; Hijikata, 2024
Electric hybrids	40–62	4	+30–50	8-Jul	Excavators, wheel loaders	Nguyen et al., 2025; Lin et al., 2010
Load-difference equilibrium	21.5–37.3	3	+15–25	6-May	Multi-actuator systems	Ge et al., 2025
Three-chamber cylinder	70–75	3	+20–30	6-May	Boom cylinders	Romagnuolo et al., 2024; Hao et al., 2020

Note: TRL = Technology Readiness Level (1-9 scale); Cost impact relative to conventional systems

RECENT DEVELOPMENTS AND EMERGING TRENDS

Fluid Power Electrification

The convergence of electrification and hydraulics is creating new opportunities for efficiency improvement (Zhou, 2025). Fluid power electrification encompasses several distinct approaches:

- **Electric prime movers:** Replacing diesel engines with electric motors, enabling zero-emission operation and simplifying energy recovery (Pate, 2025).
- **Hybrid architectures:** Combining electric and hydraulic power trains to leverage the strengths of both technologies (Nguyen et al., 2025; Lin et al., 2010).

The development of battery-electric excavators has accelerated in recent years, driven by tightening emissions regulations and improving battery technology (Pate, 2025). However, machine runtime and cost remain primary barriers to adoption. Batteries must be sized to last a full shift, driving up costs as battery packs are the single most expensive component of battery-electric machines (Pellegri, 2026). Hydraulic efficiency improvements directly address this challenge by reducing the battery capacity required for a given runtime (Pellegri, 2026).

Compact High-Pressure Components

Increasing system operating pressures enables higher power density, allowing smaller, lighter components for a given power rating (Ivantysynova, 2014). This trend supports electrification by reducing the space and weight required for hydraulic systems, accommodating larger batteries within the same machine envelope (Zhou, 2025).

Research is exploring components rated for pressures up to 500 bar or higher, requiring advances in materials, seals, and manufacturing processes (Ivantysynova, 2014). These high-pressure systems also demand improved fluid formulations to maintain performance and durability under more severe operating conditions (Zhou, 2025).

Eco-Friendly Hydraulic Fluids

The transition to electrified systems is placing new design requirements on hydraulic fluids and lubricants (Zhou, 2025). Electrified drive systems and actuators are creating more compact systems with higher heat loads, tighter tolerances, and new demands on every fluid in a machine (Zhou, 2025). As systems shrink and compartmentalize, fluid reservoirs are getting smaller, meaning hydraulic fluids must now withstand higher loads for longer periods without breaking down. Fluids today must demonstrate improved oxidation stability, thermal durability, and resistance to varnish and deposits (Zhou, 2025).

Multi-viscosity fluids, whether mineral, semi-synthetic, or fully synthetic, are designed to perform across a broad temperature range, eliminating the need for seasonal change-outs (Zhou, 2025). These formulations provide shear stability, cold-start protection, and sustained performance even in high-load or high-temperature applications (Zhou, 2025).

Advanced fluid formulations with low-viscosity variability across temperature ranges and high oxidation resistance further reduce mechanical and volumetric losses, improving overall system performance (Zhou, 2025). The selection of appropriate fluids must consider compatibility with system components, particularly seals and hoses, as well as performance under expected operating conditions (Zhou, 2025).

Varnish control is becoming an increasingly urgent priority (Zhou, 2025). Increased thermal and mechanical loads in newer systems make hydraulic fluid more prone to deterioration, leading to varnish formation that can degrade valve performance, increase downtime, and skew sensor readings. To mitigate these issues, fluids should be formulated with varnish-resistant additive technologies (Zhou, 2025).

Future fluid strategies are likely to include increased use of synthetics, biodegradable options, and tailored formulations for specific subsystems (Zhou, 2025). Closer collaboration between OEMs and fluid suppliers will be needed to align fluid specifications with evolving system designs (Zhou, 2025).

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite significant progress in energy-efficient hydraulic technologies, several challenges remain to be addressed before widespread adoption can occur.

Current Limitations

There are some limitations related to the installation of modern hydraulic technologies.

1. **Cost and complexity**: Many energy-efficient technologies increase system cost and complexity, creating barriers to adoption particularly for smaller contractors and in price-sensitive markets (Bhola and Wrat, 2026). Electro-hydraulic actuators and digital hydraulic systems require sophisticated electronics and control software, increasing both initial cost and the technical expertise required for maintenance (Bhola and Wrat, 2026).
2. **Reliability concerns:** The introduction of additional components accumulators, electric machines, power electronics potentially increases the number of failure points in the system (Bhola and Wrat, 2026). Ensuring reliability and durability in harsh operating environments remains a challenge (Ivantysynova, 2014).
3. **Control complexity:** Advanced hydraulic systems require correspondingly advanced control algorithms (Axin, 2013). Developing and validating control software for complex multi-domain systems demands significant engineering effort and rigorous testing. The Danfoss Dextreme Max project required a complete redesign of the control strategy, with the controller managing flow allocation, displacement distribution, pressure regulation, torque sharing, and boom-specific recovery logic (Pellegri, 2026).
4. **Standardization gaps:** The rapid pace of innovation has outpaced standardization efforts, creating challenges for system integration and component interchangeability (Bhola and Wrat, 2026). Industry standards for digital hydraulic interfaces, energy storage integration, and control communication protocols are still evolving.
5. **Market inertia:** The heavy equipment industry is traditionally conservative due to the high cost of machine downtime and long product lifecycles (Pate, 2025). Customers are often reluctant to adopt unproven technologies, slowing the diffusion of innovations (Pate, 2025).
6. **Hydraulic fluid challenges:** Electrification places greater emphasis on fluids enabling cleaner, quieter, longer-lasting systems (Zhou, 2025). Advanced servo valves and electronically controlled actuators demand extremely clean oil to operate reliably, with ISO cleanliness levels down to 18/16/13 or even lower (Zhou, 2025).

FUTURE RESEARCH DIRECTIONS

Based on the current state of the art and identified gaps, several priority areas for future research emerge:

System-level optimization: Most research to date has focused on individual components or subsystems (Bhola and Wrat, 2026). Integrated optimization of complete hydraulic systems considering interactions between prime mover, energy storage, actuation, and control offers potential for further efficiency gains (Bhola and Wrat, 2026; Inderelst et al., 2012).

Advanced control strategies: The development of model predictive control, reinforcement learning, and other advanced algorithms tailored to hydraulic systems could unlock additional efficiency improvements while maintaining or improving performance (Axin, 2013; Zhou et al., 2025).

Digital twin integration: Creating accurate digital representations of physical hydraulic systems enables virtual prototyping, optimization, and predictive maintenance (Bosch Rexroth, 2026). Research into efficient modeling techniques and real-time model updating will support this development.

Standardized architectures: The development of standardized modular architectures for energy-efficient hydraulic systems would reduce development costs, improve component interchangeability, and accelerate technology adoption (Bhola and Wrat, 2026).

Lifecycle assessment: Comprehensive evaluation of the environmental and economic impacts of energy-efficient hydraulic technologies across their full lifecycle including manufacturing, operation, and end-of-life is needed to guide technology development and policy decisions (Pate, 2025).

Human-machine interaction: As hydraulic systems become more automated and intelligent, understanding how operators interact with these systems and designing interfaces that maintain operator trust and situational awareness becomes increasingly important (Pate, 2025).

Refinement of digital hydraulic systems: Opportunities for improvement identified in the Danfoss Dextreme Max project include custom valve design to address meter-out losses, refined control logic to address inefficiencies discovered during post-test analysis, and electrified swing drives to further reduce losses and enable additional recuperation (Pellegri, 2026).

Advanced fluid technologies: Continued development of oxidation-resistant, varnish-mitigating hydraulic fluids; greater adoption of synthetic and multi-viscosity products; and increased demand for biodegradable and environmentally acceptable fluids, especially in applications near sensitive ecosystems (Zhou, 2025).

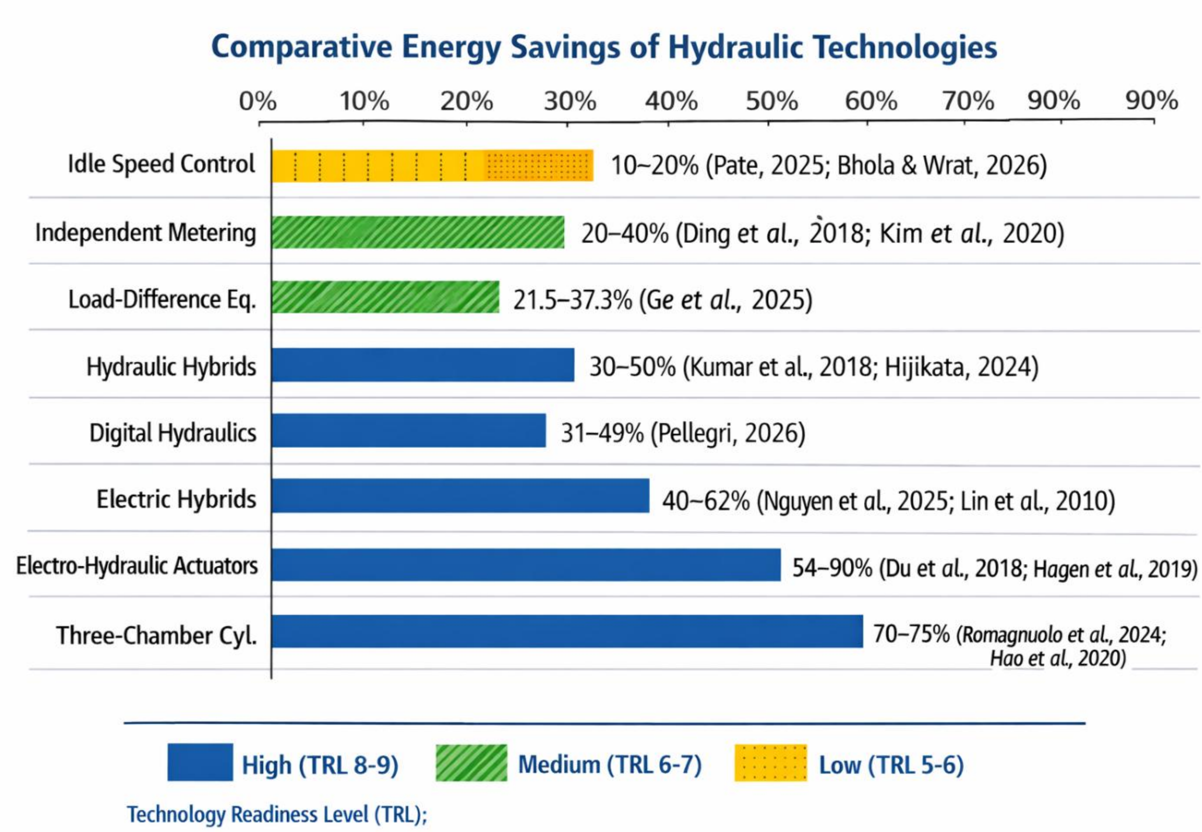

Figure 4: Comparative efficiency and maturity of hydraulic technologies.

CONCLUSION

This review has examined the current state and future directions of energy-efficient hydraulic technologies for heavy machinery. Traditional hydraulic systems suffer from significant inefficiencies, with 30–50% of input energy lost through throttling, leakage, and limited energy recovery. These losses translate directly into increased fuel consumption, higher operating costs, and greater environmental impact. Recent technological innovations offer substantial opportunities for improvement. Smart control systems, including idle speed control and predictive analytics, further optimize performance across varying operating conditions. The convergence of electrification and hydraulics is creating new opportunities for efficiency improvement, with digital hydraulics offering particular promise for electric excavators. The advanced hydraulic fluids formulated for the electrified era provide improved oxidation stability, thermal durability, and resistance to varnish and deposits, enabling cleaner, quieter, longer-lasting systems. However, significant challenges remain. Cost, complexity, reliability concerns, and market inertia slow the adoption of these technologies. Future research must address system-level optimization, advanced control strategies, digital twin integration, and standardization to accelerate the transition toward more sustainable hydraulic systems. The heavy equipment industry stands at a crossroads. While full electrification remains a long-term goal, improvements in energy-efficient hydraulic and hybrid technologies will play a pivotal role in the near- to medium-term transition toward more sustainable equipment. The integration of digital hydraulics with electric prime movers appears particularly promising, offering the potential to combine zero-emission operation with the productivity and runtime required for widespread adoption. As environmental regulations tighten and the economic case for efficiency strengthens, continued innovation in hydraulic technology will be essential. The technologies reviewed in this paper individually and in combination provide a clear path toward substantially reducing the energy consumption and environmental impact of the heavy machinery that underpins modern construction, mining, and infrastructure development.

REFERENCES

1. Achten P, Brink T, van den Oever T, Potma J, Schellekens M. Dedicated design of the hydraulic hybrid excavator. Proceedings of the 10th International Fluid Power Conference; 2016 Mar 8-10; Dresden, Germany. p. 313-328.
2. Axin M. Fluid power systems for mobile applications with a focus on energy efficiency and dynamic performance. Linköping: Linköping University; 2013.
3. Axin M, Eriksson B, Palmberg JO. Energy efficient fluid power systems for mobile machinery – a comparison. Proceedings of the 8th International Fluid Power Conference; 2012 Mar 26-28; Dresden, Germany. p. 423-438.
4. Bhola M, Wrat G. Energy-Efficient Hydraulics in Heavy Machinery: Technologies, Challenges, and Future Directions. Sustainability. 2026;18(1):302.
5. Bosch Rexroth. Data-driven Connected Hydraulics in Advanced Manufacturing [Internet]. Singapore: Bosch Rexroth; 2026 [cited 2026 Mar 19]. Available from: https://www.boschrexroth.com/en/sg/academy/brrtc-trainings/data-driven-connected-hydraulics-in-advanced-manufacturing/
6. Cheng M, Xu B, Zhang J, Yang H. A novel pump displacement controlled system for multi-actuators with energy recovery. Proceedings of the 10th International Fluid Power Conference; 2016 Mar 8-10; Dresden, Germany. p. 449-462.
7. Chiang MH, Chen CC, Kuo CFJ. The high response and high efficiency velocity control of a hydraulic injection molding machine using a variable rotational speed electro-hydraulic pump-controlled system. International Journal of Advanced Manufacturing Technology. 2009;43(9):841-851.
8. Cho SH, Noskievič P. Position tracking control with load-sensing for energy-saving valve-controlled cylinder system. Journal of Mechanical Science and Technology. 2012;26(2):617-625.
9. Ding R, Zhang J, Xu B, Cheng M, Pan M. Energy efficiency improvement of a novel hydraulic system with independent metering control for construction machinery. IEEE Access. 2018;6:67158-67170.
10. Du C, Plummer AR, Johnston DN. A new load-prediction based variable supply pressure control for multi-axis hydraulic systems. Proceedings of the 11th International Fluid Power Conference; 2018 Mar 19-21; Aachen, Germany. p. 476-489.
11. Eriksson B. Mobile fluid power systems design with a focus on energy efficiency. Linköping: Linköping University; 2010.
12. Finzel R, Helduser S, Jang DS. Electro-hydraulic dual-circuit system to improve the energy efficiency of mobile machines. Proceedings of the 7th International Fluid Power Conference; 2010 Mar 22-24; Aachen, Germany. p. 367-380.
13. Ge L, Quan L, Li Y, Zhang X, Yang J. Characteristics of a Novel Electrohydraulic Multi-actuator System with Low Throttling Losses and Energy Regeneration Capability. Chinese Journal of Mechanical Engineering. 2025;38:114.

14. Ge L, Quan L, Zhang X, Zhao B, Yang J. Efficiency improvement and evaluation of electric hydraulic excavator with speed and displacement variable power source. Energy Conversion and Management. 2017;150:720-730.
15. Hagen D, Padovani D, Choux M. Enabling energy sharing and regeneration in hydraulic systems with self-contained actuators. Proceedings of the 16th Scandinavian International Conference on Fluid Power; 2019 May 22-24; Tampere, Finland. p. 1-12.
16. Hao Y, Quan L, Cheng M, Ge L, Zhang X. Research on the performance of three-chamber hydraulic cylinder for boom energy recovery system. Automation in Construction. 2020;116:103233.
17. Heybroek K. Saving energy in construction machinery using displacement control hydraulics. Linköping: Linköping University; 2008.
18. Heybroek K, Larsson J, Palmberg JO. Open circuit solution for pump controlled actuators. Proceedings of the 4th FPNI PhD Symposium; 2006 Jun 13-16; Sarasota, FL, USA. p. 27-40.
19. Hijikata S. Hydraulic Hybrid Architecture combining an Open Center with a Constant Pressure System for Excavators. Aachen: Shaker Verlag; 2024.
20. Huang J, Wang H, Quan L, Ge L. Development of a novel multi-port hydraulic pump/motor for energy recovery systems. IEEE Access. 2019;7:120825-120837.
21. Inderelst M, Losse S, Sgro S, Murrenhoff H. Energy efficient system layout for work hydraulics of excavators. Proceedings of the 8th International Fluid Power Conference; 2012 Mar 26-28; Dresden, Germany. p. 343-356.
22. Ivantysynova M. Innovations in pump design – are there any limits? Proceedings of the 9th International Fluid Power Conference; 2014 Mar 24-26; Aachen, Germany. p. 12-27.
23. Ketelsen S, Padovani D, Andersen TO, Schmidt L, Ebbesen MK. A novel self-contained electro-hydraulic cylinder with series coupling of two fixed displacement machines. Proceedings of the 11th International Fluid Power Conference; 2018 Mar 19-21; Aachen, Germany. p. 490-503.
24. Kim S, Lee J, Kim H. Independent Metering Valve: A Review of Advances in Hydraulic Machinery. Journal of the Korean Society for Precision Engineering. 2020;37(8):567-578.
25. Kumar S, Das S, Ghoshal SK, Das J. Review of Different Energy Saving Strategies Applicable To Hydraulic Hybrid Systems Used In Heavy Vehicles. IOP Conference Series: Materials Science and Engineering. 2018;377:012072.
26. Lantto B. On fluid power control with special reference to load-sensing systems and sliding mode control. Linköping: Linköping University; 1994.
27. Lin T, Wang Q, Hu B, Gong W. Research on the energy regeneration systems for hybrid hydraulic excavators. Automation in Construction. 2010;19(8):1016-1026.
28. Lovrec D, Kastreve M, Ulaga S. Electro-hydraulic load sensing with a speed-controlled hydraulic supply system. Journal of Mechanical Engineering. 2009;55(3):153-162.
29. MOOG. Electrohydrostatic actuators [Internet]. East Aurora: MOOG Inc.; 2020 [cited 2026 Mar 19]. Available from: https://www.moog.com/products/actuation-systems/electrohydrostatic-actuators.html
30. Nguyen VH, Do TC, Ahn KK. Hybrid powertrain with dual energy regeneration for boom cylinder movement in a hydraulic excavator. Automation in Construction. 2025;171:105974.
31. Padovani D, Ketelsen S, Hagen D, Schmidt L. A self-contained electro-hydraulic cylinder with passive load-holding capability. Energies. 2019;12(2):271.
32. Pate KS. Heavy Equipment Industry: Trends, Challenges, and Strategic Outlook. Doctoral dissertation, Purdue University. 2025.
33. Pedersen HC, Schmidt L, Andersen TO, Brask MH. Investigation of new servo drive concept utilizing two fixed displacement units. Proceedings of the 8th International Fluid Power Conference; 2012 Mar 26-28; Dresden, Germany. p. 439-452.
34. Pellegri M. Digital Hydraulics Increase Electric-excavator Runtime. Mobility Engineering Technology. 2026.
35. Qu Z, Zhang J, Xu B, Su Q, Pan M. Energy efficiency analysis of electro-hydrostatic actuator for aerial vehicles. Proceedings of the BATH/ASME 2018 Symposium on Fluid Power and Motion Control; 2018 Sep 12-14; Bath, UK. V001T01A028.
36. Rahmfeld R, Ivantysynova M. Displacement controlled linear actuator with differential cylinder a way to save primary energy in mobile machines. Proceedings of the 5th International Conference on Fluid Power Transmission and Control; 2001 Apr 3-5; Hangzhou, China. p. 296-301.

37. Romagnuolo L, Frosina E, Rozzi de Hieronymis C, Bordini G, Senatore A. Innovative and self-adaptive energy recovery system in hydraulic cylinders for cyclic operations. Journal of Physics: Conference Series. 2024;2893:012059.
38. Schmidt L, Groenkjaer M, Pedersen HC, Andersen TO. Position control of an over-actuated direct hydraulic cylinder drive. Control Engineering Practice. 2017;64:1-14.
39. Shenouda A. Quasi-static hydraulic control systems and energy savings potential using independent metering fluid power valves. Atlanta: Georgia Institute of Technology; 2006.
40. Vael GEM, Achten PAJ, Fu Z. The Innas hydraulic transformer the key to the hydrostatic common pressure rail. SAE Technical Paper 2000-01-2561. 2000.
41. Wang L, Wang Y. Energy-saving control of electro-hydraulic servo system based on variable supply pressure. Proceedings of the 2016 IEEE International Conference on Aircraft Utility Systems; 2016 Oct 10-12; Beijing, China. p. 112-117.
42. Wang T, Wang Q. An energy-saving control strategy for electro-hydraulic servo systems. IEEE Access. 2019;7:123456-123465.
43. Williamson C, Ivantysynova M. Pump efficiency approximation for modeling energy efficient fluid power systems. Proceedings of the 7th International Fluid Power Conference; 2010 Mar 22-24; Aachen, Germany. p. 145-158.
44. Xu B, Cheng M, Yang H, Zhang J, Sun Y. A hybrid displacement/pressure control scheme for an electrohydraulic flow matching system. IEEE/ASME Transactions on Mechatronics. 2015;20(6):2771-2782.
45. Yoon JI, Kwan AK, Truong DQ. A study on an energy saving electro-hydraulic excavator. Proceedings of the ICCAS-SICE International Joint Conference; 2009 Aug 18-21; Fukuoka, Japan. p. 3825-3830.
46. Yu YX, Ahn KK. Improvement of energy regeneration for hydraulic excavator swing system using novel hydraulic-electric hybrid system. Proceedings of the 15th International Conference on Control, Automation and Systems; 2015 Oct 13-16; Busan, Korea. p. 1783-1787.
47. Zhou S, Liu Z, Li M, Liu D, Wang C, Li H. A Study on Fractional-Order Adaptive Super-Twisting Sliding Mode Control for an Excavator Working Device. Applied Sciences. 2025;15(23):12581.
48. Zhou Z. Designing Hydraulic Fluids and Lubricants for the Electrified Era. Power & Motion. 2025 Dec 17.