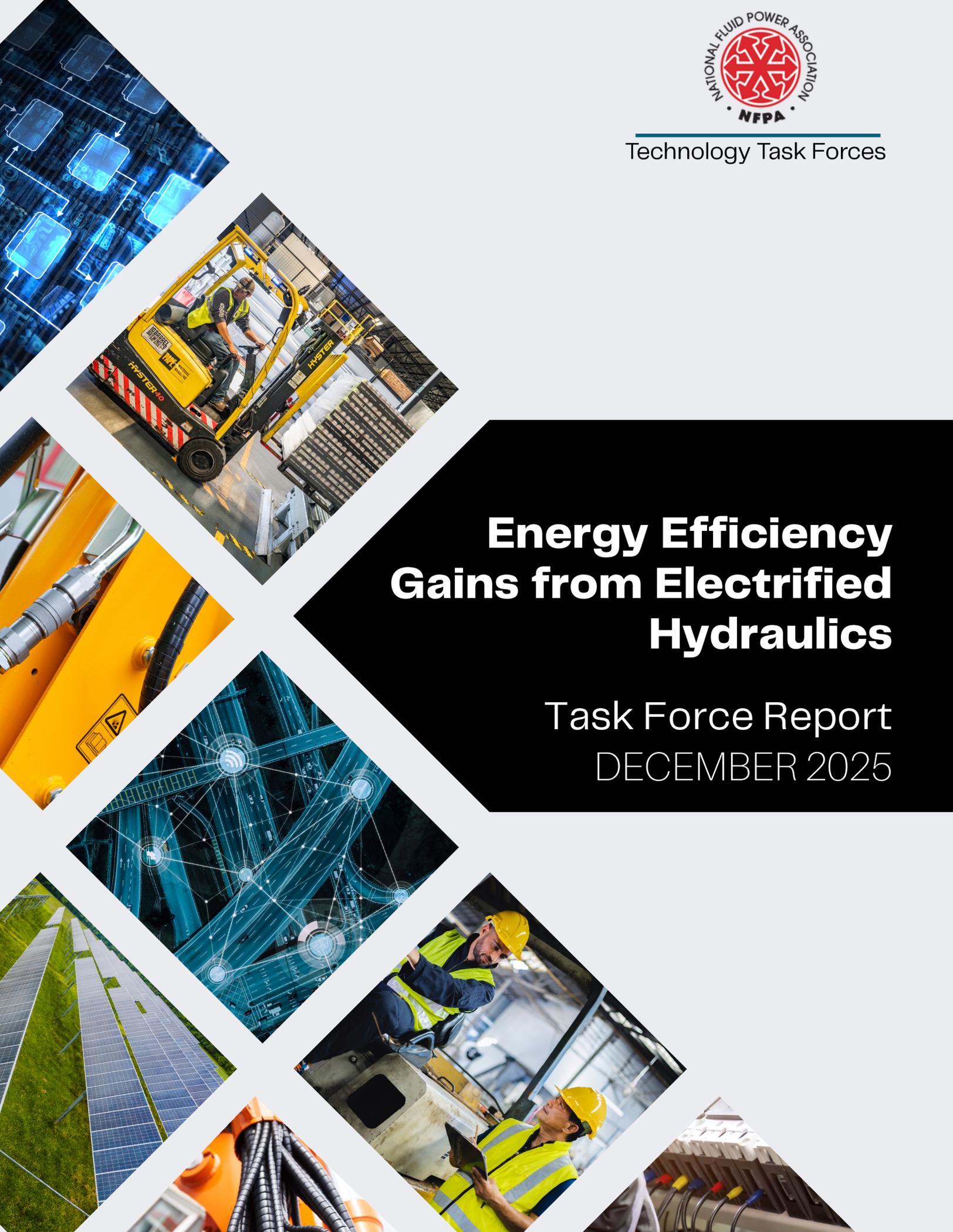




Technology Task Forces

A collage of images related to industrial technology and energy efficiency. It includes a blue digital network diagram, a yellow Hyster forklift in a warehouse, a close-up of a yellow hydraulic hose, a blue digital network diagram, a solar panel array, two workers in yellow safety vests and hard hats reviewing a tablet, and a close-up of a hydraulic hose.

Energy Efficiency Gains from Electrified Hydraulics

Task Force Report
DECEMBER 2025



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BACKGROUND

As defined in the 2023 NFPA Technology Roadmap, many machine-level technology trends are actively shaping the future of the fluid power industry. These trends include the increasing electrification, connectivity, and autonomous functionality of mobile and industrial machines that use fluid power in their power or control systems.

In September 2023, NFPA launched two Technology Task Force teams, one focused on Mobile machinery and the other on Industrial machinery. Their task was to better understand these trends and engage stakeholders across the supply chain in developing the resources and connections needed to keep fluid power positioned as an actuation technology of choice on mobile and industrial platforms.

The Mobile Task Force identified several projects that would help it fulfill this mission, including:

- **Energy Efficiency Gains from Electrified Hydraulics.** Produce a white paper that summarizes the ways in which hydraulic systems and/or components can return gains in energy efficiency to mobile equipment with electrified power sources. Collect and present case studies showing applications of these methods.

The Task Force met multiple times to discuss this project, to share information and resources, and to develop a set of responses and recommendations. This report concludes the Task Force's final consensus, published in December 2025.

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INTRODUCTION

In 2024, the hydraulic industry witnessed a significant shift toward electrification in the off-highway market, presenting an exciting and complex challenge for manufacturers and suppliers alike. Over the past year, a wide range of electrified mobile machines were introduced: skid steers, street sweepers, excavators, forklifts, and wheel loaders, among others. These newly electrified machines featured various power source configurations, such as fuel cells, plug-in electric systems, hybrid electric systems, and fully battery-electric designs.

As with any emerging technology or market transition, there are early adopters eager to lead with innovative solutions and others who prefer to observe how the market responds before committing resources. Common reservations about electrification include concerns about whether it can match the performance of traditional internal combustion engine machines in the market, the limited availability of proven suppliers for electrification components, consideration of the environment where your machine is operating, uncertainty about market willingness to absorb higher total machine costs, and the current lack of robust infrastructure needed to support widespread adoption.

This white paper is not intended to convince readers to pursue electrification, but rather to support those who have already chosen to explore this path. Electrification is becoming part of the portfolio of energy options to choose from in the market today, and the NFPA's primary goal with this white paper is to provide a clear overview of the current state of the market, highlight key benefits associated with electrification, and offer best practices and considerations for those preparing to implement or expand electrified solutions within the off-highway market.



THE NEED AND DRIVERS FOR EFFICIENCY GAINS

Over the past two years, numerous government incentives have been introduced to encourage investment in electrification. These include federal and state tax credits for buyers of electric machines, as well as carbon credit programs that allow companies investing in electric vehicles to offset higher carbon emissions in other areas of their operations.

These regulations are not just policy shifts - they are reshaping where and how electrified machines are being deployed. One area seeing the most immediate impact is urban construction, where electrification offers several practical advantages:

- Compact equipment size required for maneuverability in tight spaces around buildings lends itself well to the machine size best suited for electrification.
- Health and safety benefits, as electrified machines eliminate harmful diesel exhaust noise and fumes in enclosed or populated areas, improving conditions for nearby residents and workers.
- Favorable duty cycles, with frequent idle periods between tasks reducing energy use.
- Access to electricity, with most urban sites having grid connections or generators for mid-shift charging or plug-in operation.



Figure 1. Cities Embrace Low Emission Zones to Fight Air Pollution (Source: <https://brightorder.com/blog/low-emission-zones/>)



Addressing Inefficiencies of Internal Combustion Engines

One of the primary drivers behind electrification lies in addressing the inherent inefficiencies of internal combustion engines. To illustrate, consider a diesel fuel tank filled to 100% capacity. Once the fuel passes through the engine, approximately 65% of the available energy from the fuel is lost as heat and exhaust, leaving only 35% available for actual work. After you consider the average hydraulic pump efficiency of 85% and the average hydraulic system efficiency of 60%, you are left with only 18% of the original energy available from the diesel fuel to do work.

**see 'conventional power source' section of the image below*

In contrast, let us now consider an electrified power source that contains a fully charged battery. The typical electric motors and inverters on the market today can operate at efficiencies between 85% and 90%. Now, when we assume the same 60% hydraulic efficiency as with the diesel-powered system example, eliminating the inefficiencies of an internal combustion engine results in approximately 46% of the battery's original energy being available for productive work—significantly improving overall system efficiency. We can therefore conclude that when using an electric power source over a conventional diesel engine, you can utilize the available energy on board the machine in a more efficient manner, with fewer losses due to friction and heat.

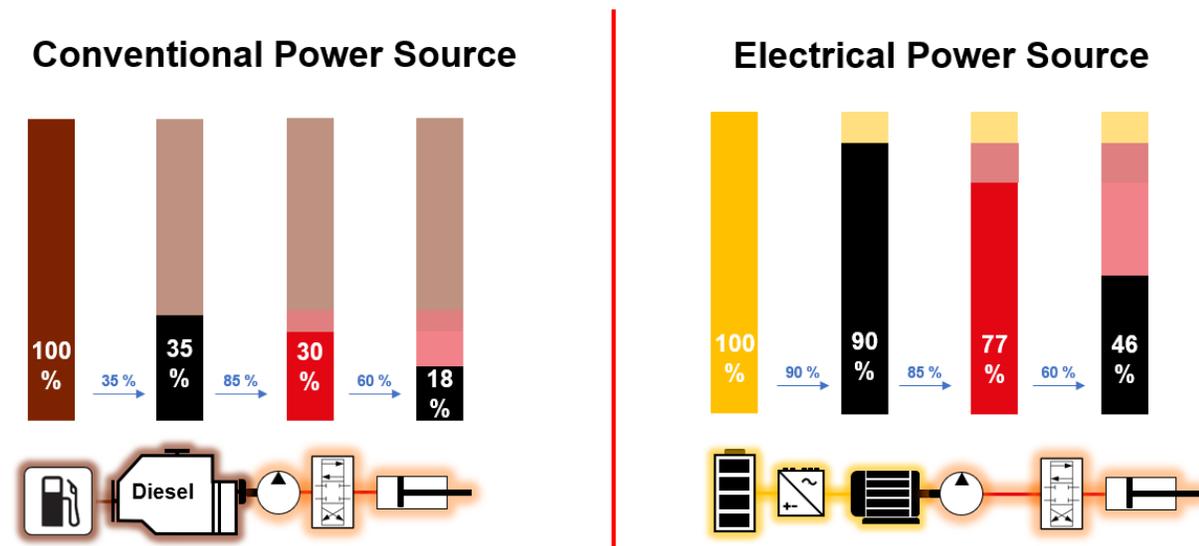


Figure 2. Energy Efficiency Visualization (Source: HYDAC)

MOTOR SELECTION AND SIZING FOR SYSTEM OPTIMIZATION

Conventional Method for Component Selection

One of the more complex challenges in machine electrification is the difference in motor sizing methodology compared to traditional internal combustion engine (ICE) systems. Conventional machines are often sized based on a concept known as *corner power*, where the engine is selected to handle the simultaneous peak requirements for both hydraulic flow and pressure. This approach is commonly used throughout the mobile hydraulic industry, particularly when relying on theoretical models or datasheets in the early stages of development, such as when creating a new machine from scratch. A prime mover is chosen based on this corner power scenario because they do not want the engine to be a limiting factor in the machine's ability to meet its performance targets. However, in practice, it is exceedingly rare for a machine to operate at maximum flow and maximum pressure simultaneously, making this method overly conservative and often inefficient.

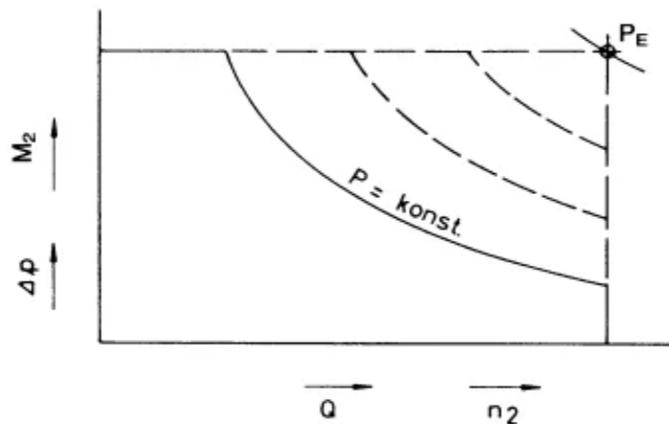


Figure 3. Corner Power P_e of a Transmission (Source: <https://www.hawe.com/fluid-lexicon/corner-power/>)

Duty Cycle Energy Mapping for Component Selection

A more accurate and effective strategy involves instrumenting an existing machine, if it is available, with sensors and data acquisition systems to collect data during a standard operating range. This performance data is what is referred to as duty cycle, or an understanding of the ratio of time under load vs idle. While this test is conducted, with the instrumentation on the machine, you will also be able to read the maximum conditions that the machine will see under operating conditions. It is essential, however, that baseline testing reflects the machine's true



ENERGY EFFICIENCY GAINS FROM ELECTRIFIED HYDRAULICS

operating conditions. Field usage can at times diverge from design assumptions, as operators may use equipment in unconventional or unpredictable ways. Real-world performance data enables engineers to make informed decisions regarding system sizing, potentially reducing component cost, weight, and energy consumption without compromising performance.

Duty Cycle Energy Mapping is particularly valuable when selecting electric motors, which offer unique advantages over internal combustion engines since they do not need to be sized in the traditional corner power methodology, and instead greatly benefit from having this data when selecting a motor. Electric motors are defined by standardized duty types, most notably S1 (continuous duty) and S2 (short-time duty) as described in IEC 60034-1.

Continuous Duty (S1) represents operation under constant load until thermal equilibrium is reached.

Short-Time Duty (S2) allows for operation above continuous duty over short durations before requiring a lower duty cycle to allow for cooling in the system.

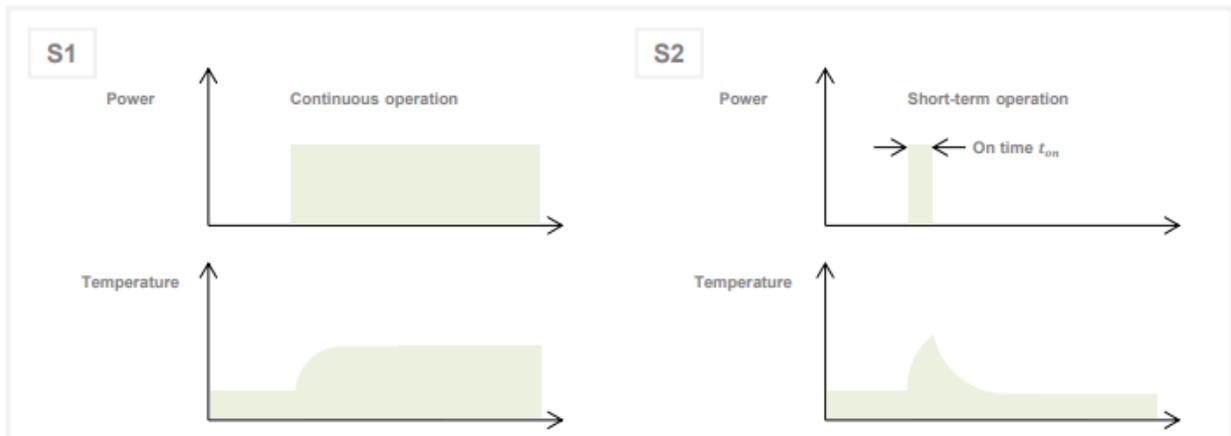


Figure 4. Motors and Generators (Source: <https://www.engiro.com/products/motors-and-generators>)

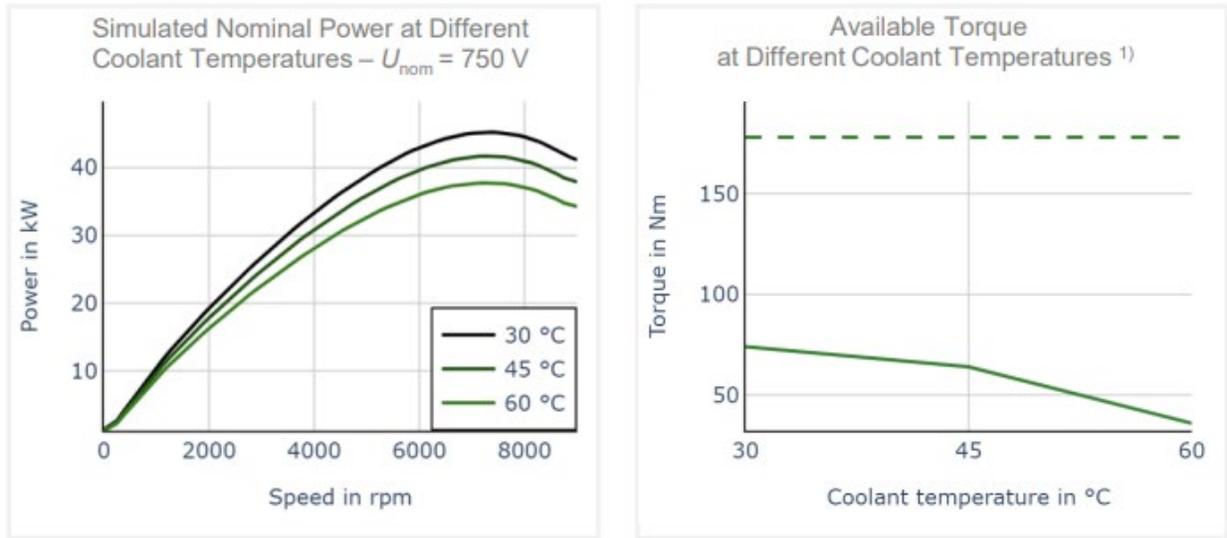


Figure 5. Motors and Generators (Source: <https://www.engiro.com/products/motors-and-generators>)

Thermal Considerations

Most electrification components, such as motors, inverters, and batteries, have an optimal thermal operating range, often thought of as their “thermal sweet spot.” When operating temperatures move outside this preferred range, these components are typically designed to *intelligently derate*—reducing performance to allow the cooling system to catch up to prevent conditions that could lead to thermal runaway or accelerated component degradation.

While this self-protective behavior is beneficial from a system reliability and engineering perspective, it can become a significant operational burden if the components are not properly sized. Frequent performance derating can hinder machine productivity and lead to operator frustration. The IEC 60034-1 standard classifies this type of operation as *S9: Non-periodic duty with load and speed variations*, which accounts for fluctuating loads and the influence of thermal constraints over time.

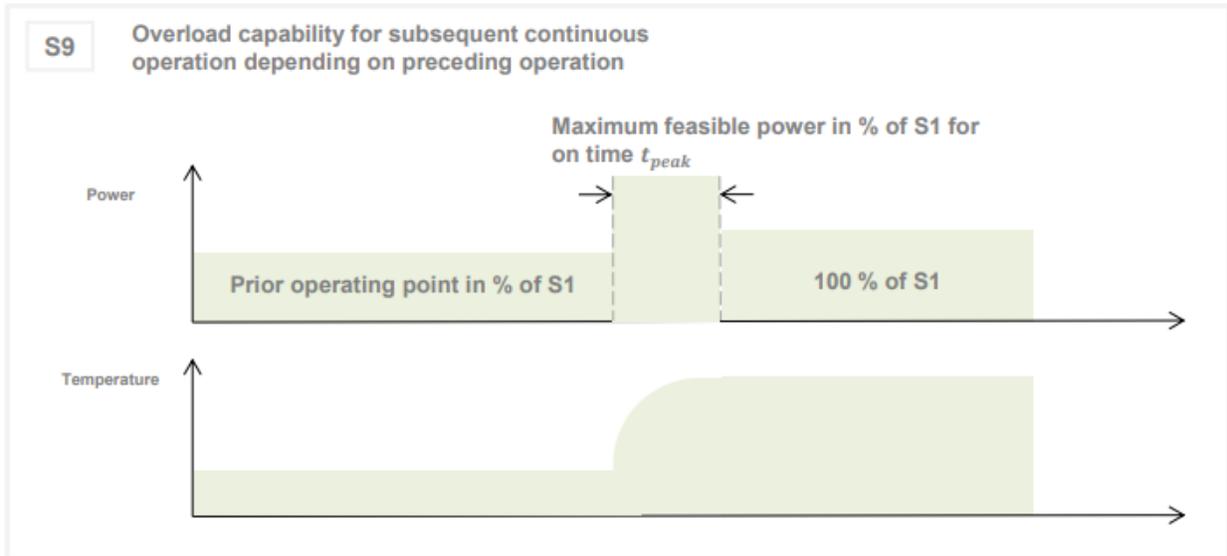


Figure 6. Motors and Generators (Source: <https://www.engiro.com/products/motors-and-generators>)

Ultimately, electric motor failures are rarely the result of torque or speed limitations, and more commonly, they stem from excessive heat which leads to the degradation of the components within the motor. Therefore, just as it is important to ensure that the duty cycle of the application fits within the capability of the motor, it is also just as important to ensure that the cooling system is properly sized to handle the heat rejection for the system. Depending on the heat rejection requirements, you can find air cooled motors or liquid cooled motors on the market to help meet your machine requirements and ambient conditions.

INCREASING HYDRAULIC EFFICIENCY FOR SYSTEM OPTIMIZATION

Back in the Addressing Inefficiencies of Internal Combustion Engines section, we talked about the efficiency differences when utilizing energy on-board the machine between a conventional and electrical power source. Now, consider the impact of increasing only the hydraulic efficiency in both scenarios by 20%. In a conventional diesel power source, this improvement would recover an additional 6% of the system’s energy—a notable but modest gain. However, in an electric power source, the same efficiency increase results in a 15% energy gain, highlighting the significant role that energy-efficient hydraulics play in optimizing the performance and viability of electrified machines. This disparity emphasizes why improving hydraulic efficiency is a critical focus, and generally why it is almost always a consideration when electrifying a new vehicle.

In practical terms, by increasing the hydraulic efficiency on electrified equipment we can directly see this translate to either an increase in machine operating time if the battery stays the same, or an ability to save cost and weight by reducing the battery size. Such an improvement could mean the difference between a six-hour and an eight-hour working shift or a significant reduction in battery size and cost—both of which are critical factors in the adoption and viability of electrified machinery.

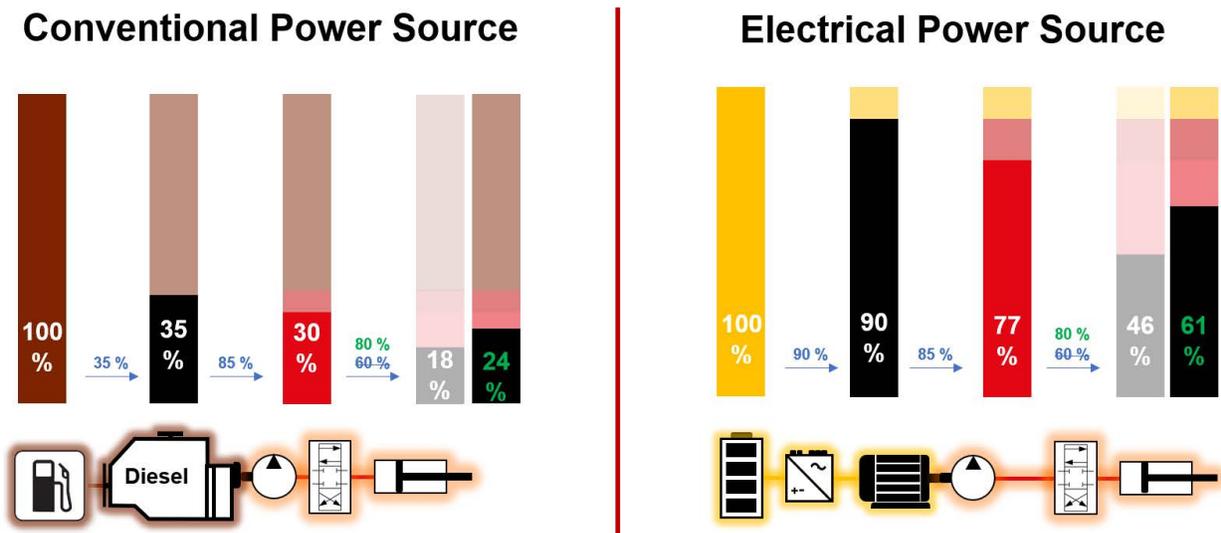


Figure 7. Energy Efficiency Visualization with Efficient Hydraulics (Source: HYDAC)

Areas to Focus for Hydraulic Efficiency Gains

Using the tools and examples earlier in the paper we learned how to increase the efficiency of the electric motor (through duty cycle energy mapping and product selection), but now we want to start focusing on increasing the efficiencies of the hydraulic circuit. A good place to start is looking at the metering losses in the circuit. It is estimated that over 50 percent of the energy loss in a traditional hydraulic system come from metering loss.

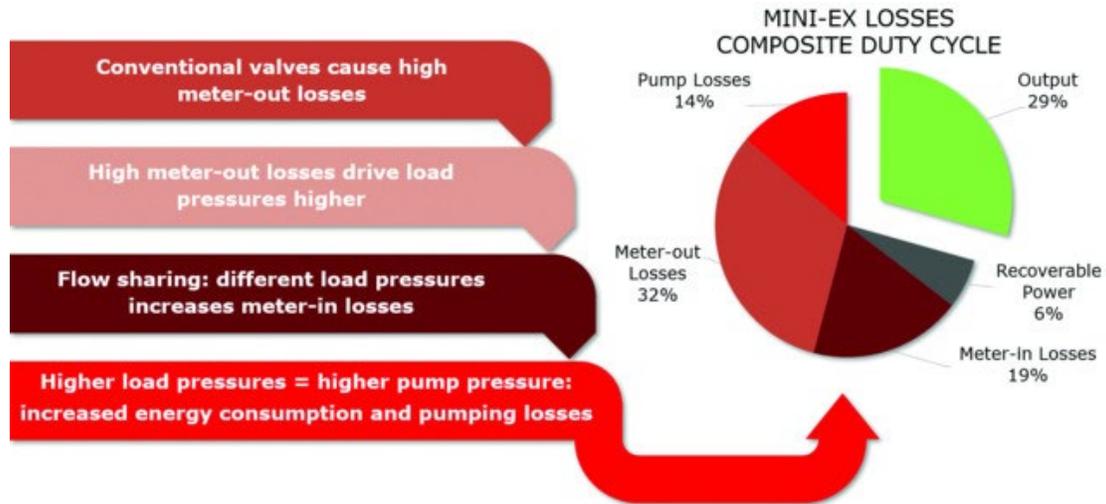


Figure 8. Hydraulic Optimization for Electric machines (Source: <https://www.oemoffhighway.com/fluid-power/article/22894946/danfoss-danfoss-power-solutions-hydraulic-optimization-for-electric-machines>)

Metering-Out Losses

Metering-out losses occur when energy is consumed during the controlled release of hydraulic fluid from an actuator, typically as a result of added resistance in the return path. One of the most common sources of metering-out losses in mobile machinery is the load-holding valve: a critical component used to improve control, stability, and safety in systems with suspended loads, such as mini-excavators or telehandlers.

At its core, a load-holding valve is a spring-biased check valve installed on the rod or bottom side cylinder which experiences load due to gravity. These valves offer several key benefits:

- Prevent unintended motion or drift
- Reduce internal leakage and cavitation risk
- Improve fine control and boom stability
- Provide safety in the event of hose rupture or pump failure



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These functions are achieved by requiring the system pump to generate sufficient pressure to overcome the valve's spring force before fluid can exit the cylinder. This added pressure demand increases the energy required for movement—an inefficiency referred to as metering-out loss.

The spring force within a load-holding valve is sized according to the machine's anticipated maximum suspended load. For instance, a mini excavator may use a spring rated for 10–25 tons, while a larger mining excavator may require springs rated for load-holding weight over 50 tons.



Figure 9. Unloaded excavator bucket (Source: [Excavators for Beginners: 5 Things to Know About Operating](#))

Example: Lowering an Unloaded Bucket

Consider the scenario of lowering an unloaded bucket. Although the bucket weight is minimal, the load-holding valve prevents gravity from lowering the arm without active hydraulic input. Because the spring is designed to resist downward motion and is sized for holding the weight of a full bucket, the hydraulic pump must deliver enough pressure to "crack" the valve and allow



fluid to flow—resulting in unnecessary energy expenditure even under low-load conditions. The fluid which flows through the crack will also most likely increase the temperature in the fluid because of the restriction.

While load-holding valves are essential for maintaining safe and precise machine control, selecting the right valve can reduce energy penalties:

- Pilot-operated load-holding valves use a portion of the system’s control pressure to assist valve opening, reducing the pump's pressure requirement to crack open the valve.
- Electrohydraulic load-holding valves respond directly to operator input (e.g., joystick signals), enabling more efficient and responsive system behavior without excessive energy demand.



Figure 10. The Best Attachments for Telehandlers (Source: <https://www.boomandbucket.com/blog/the-best-attachments-for-telehandlers>)



Metering-In Losses

If metering-out losses are associated with restricting flow as fluid exits a cylinder, metering-in losses arise from controlling the flow entering a cylinder or actuator—often during slow or fine movements.

These losses are especially prevalent in systems where precise speed control is required, such as:

- Gently raising a boom
- Coordinating the movement of multiple actuators at varying speeds

In most mobile hydraulic designs, pumps are sized using the corner power methodology—i.e., selecting a pump that can meet the system’s maximum pressure and flow requirements. While this ensures adequate power for peak demands, it creates challenges at lower speeds or partial loads. Controlling fine movements often requires reducing flow or pressure, typically achieved using in-line flow restrictions like:

- Orifices
- Pressure relief valves
- Bypass compensators
- Proportional or pilot-operated flow controls

These components regulate actuator speed but do so by converting excess energy into heat, contributing to overall system inefficiency. This conversion of hydraulic energy into thermal energy is classified as metering-in loss.

Example: Simultaneous Cylinder Movements

In a telehandler, for instance, if multiple cylinders are actuated simultaneously—but require different speeds or forces—the shared pump must distribute flow unevenly. Matching flow to each function often requires introducing resistance in the lines, which leads to inefficiencies and increased heat generation.

The Ideal—but Impractical—Solution



ENERGY EFFICIENCY GAINS FROM ELECTRIFIED HYDRAULICS

In an ideal scenario, each actuator would be paired with its own pump, sized specifically for its task. This would allow direct, efficient control of both flow and pressure without the need for in-line restrictions. However, due to space, cost, and complexity constraints, this approach is rarely feasible.

As a result, system designers should aim to reduce metering-in losses by choosing high-efficiency flow control strategies, such as:

- Pilot-operated valves - which reduce pressure loss across the valve
- Proportional control valves - which dynamically adjust to match the load and flow requirements more precisely than fixed orifices

By adopting smarter, more adaptable control technologies, engineers can significantly reduce hydraulic inefficiencies and improve the overall energy efficiency of mobile machines.

ADVANCED LOOK AT SOFTWARE, ELECTRONIC CONTROLS, AND SENSING

The transition to electrified hydraulics is not simply a matter of replacing the engine with an electric prime mover—it requires a fundamental rethinking of how systems are controlled and optimized. Traditional hydraulic architectures, while proven to be reliable and cost-effective, were designed around constant engine power and limited mechanical control. These systems often suffer from inherent drawbacks such as throttling losses, pressure mismatches, and wasted energy.

As manufacturers evaluate the feasibility of electrification, many are also taking the opportunity to revisit their existing architectures with a fresh perspective. Increasingly, they are turning to advanced technologies such as electrified proportional controls, high-performance hardware capable of running complex embedded software, and rugged sensors designed for demanding mobile environments. Together, these tools enable a new level of efficiency and machine control—unlocking performance improvements that were previously out of reach.

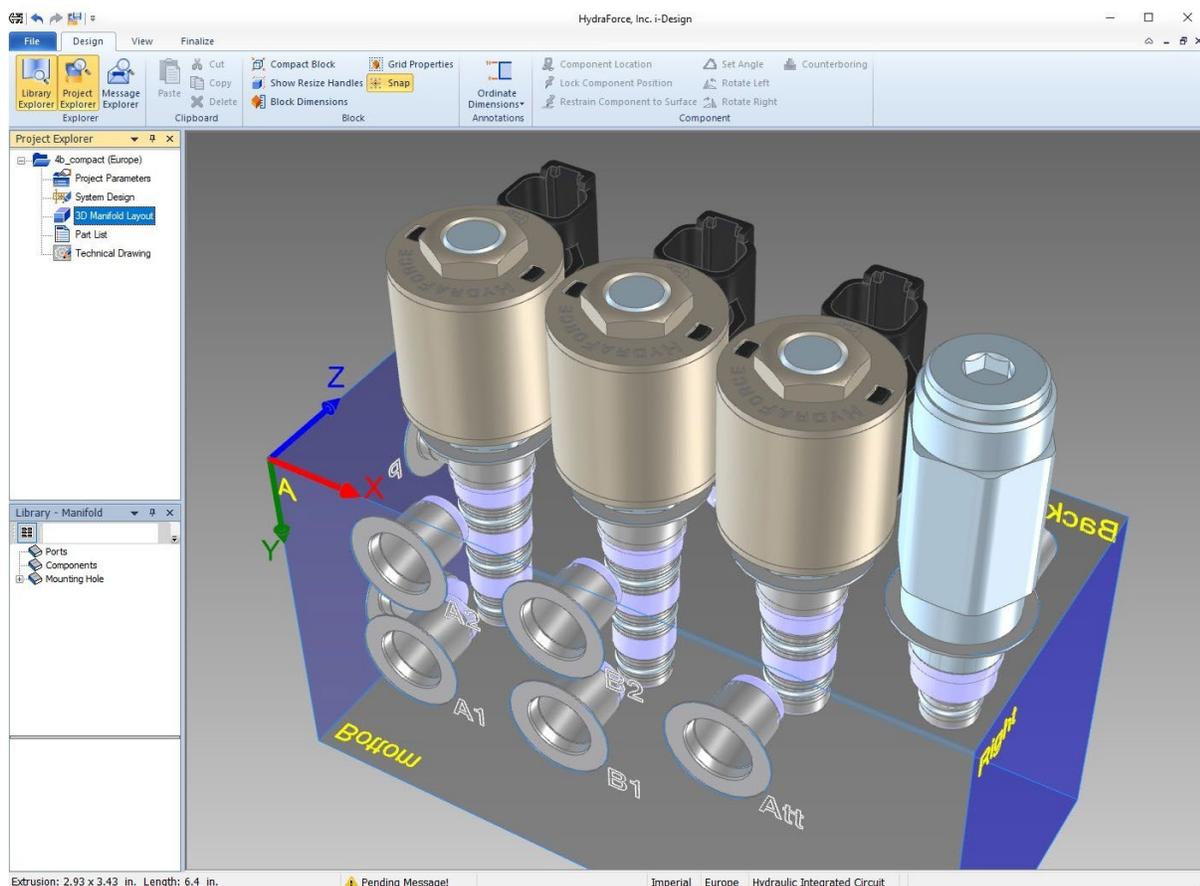


Figure 11. I-Design (Source: <https://www.hydraforce.com/products/custom-manifolds/i-design/>)



Electronic Controls: Dynamic Efficiency in Real Time

When electronic controls were first introduced to mobile hydraulic machines, the focus was less on efficiency and more on expanding capability. Early adopters began by replacing direct mechanical linkages with hydraulic pilot lines driven by electrical signals, allowing operators to control valves through electric joysticks rather than fighting against heavy fluid forces through direct acting levers. This change reduced operator effort and consequently improved operator comfort and provided greater precision in managing machine functions. It also gave designers new flexibility in how cabs and control stations could be arranged, since the controls no longer required hydraulic lines to be routed into the operator space, but reduced it to only a few electrical cables.

Beyond operator comfort and ergonomic improvements, the move to electro-hydraulic controls opened the door to software integration and advanced control strategies that were not possible with purely mechanical systems. Examples include:

- Dynamic load matching - continuously adjusting pump output to match actual load demand, rather than running at a constant setting.
- Electronic flow sharing - replacing mechanical flow compensators with software-managed distribution, minimizing throttling losses and enabling multiple functions to operate efficiently in parallel, with the flexibility to adjust dynamically instead of relying on fixed orifices.
- Closed-loop control - monitoring and adjusting parameters such as pressure, flow, or torque in real time to prevent overshoot of input, reducing wasted energy, and delivering smoother, more precise machine movements.

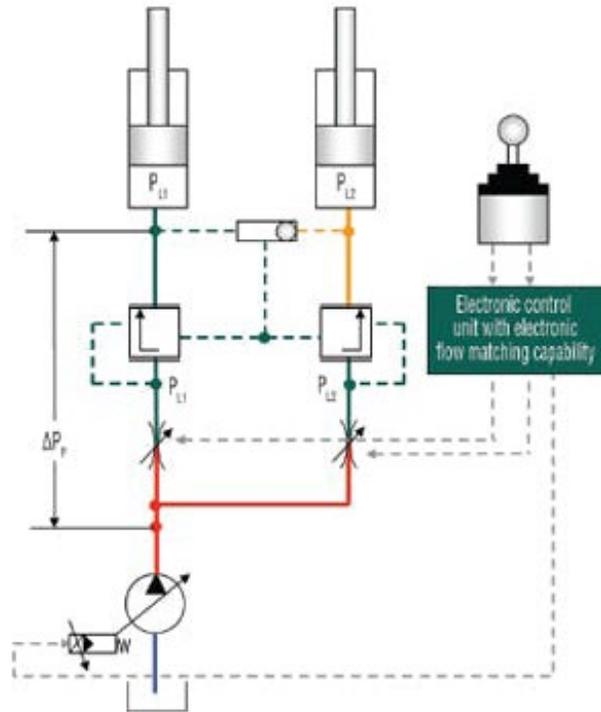


Figure 12. Beyond Load Sensing (Source: <https://www.powermotiontech.com/hydraulics/hydraulic-valves/article/21883058/a-step-beyond-load-sensing>)

These strategies not only reduce wasted energy but also help extend component life by minimizing unnecessary stress on the system. The result is a machine that can accomplish more work with less input power. This efficiency gain has direct implications for electrified architectures: lower power demand can influence battery capacity requirements and, in some cases, could even enable a system to operate at a reduced voltage level by decreasing peak power demands.



Software Solutions: Predictive and Adaptive Control

If hydraulic valves and actuators can be considered the muscles of modern hydraulics, and electronic sensors the nervous system, then software and its controller serve as the brain. As discussed earlier, the first wave of electronic integration allowed machines to move from direct mechanical linkages to pilot-operated controls. Today, continued advances in software have expanded its role far beyond simple automation. With the right architecture, software can now predict, optimize, and adapt machine behavior in real time.

- Predictive algorithms - analyze duty cycles and operator behavior, anticipating load changes before they occur. By proactively adjusting pump displacement or valve settings, these algorithms prevent sudden demand spikes that would otherwise waste energy.
- Digital twins - allow engineers to simulate machine operation virtually, evaluating control strategies and energy-saving concepts before a physical prototype is built. Once deployed, these models can be continuously refined with real-world data, creating a feedback loop that improves performance over time.
- Position feedback and command matching - ensure that operator inputs are translated into only the power required. For example, if an operator commands a cylinder to extend beyond its physical stroke, the controller can interpret the position feedback and prevent unnecessary energy use.
- User assist functions – reduce operator burden by supporting complex or repetitive work functions. This not only increases efficiency and speed but also lowers the skill threshold required for effective machine operation.

A unique advantage of software-enabled solutions is their capacity for continuous improvement. As long as a machine has access to the necessary feedback—through the right data signals and sensors—its performance can be enhanced over time with new algorithms, updates, and customer-driven features. This adaptability ensures that machines not only meet today's requirements but also evolve to address the challenges of tomorrow.



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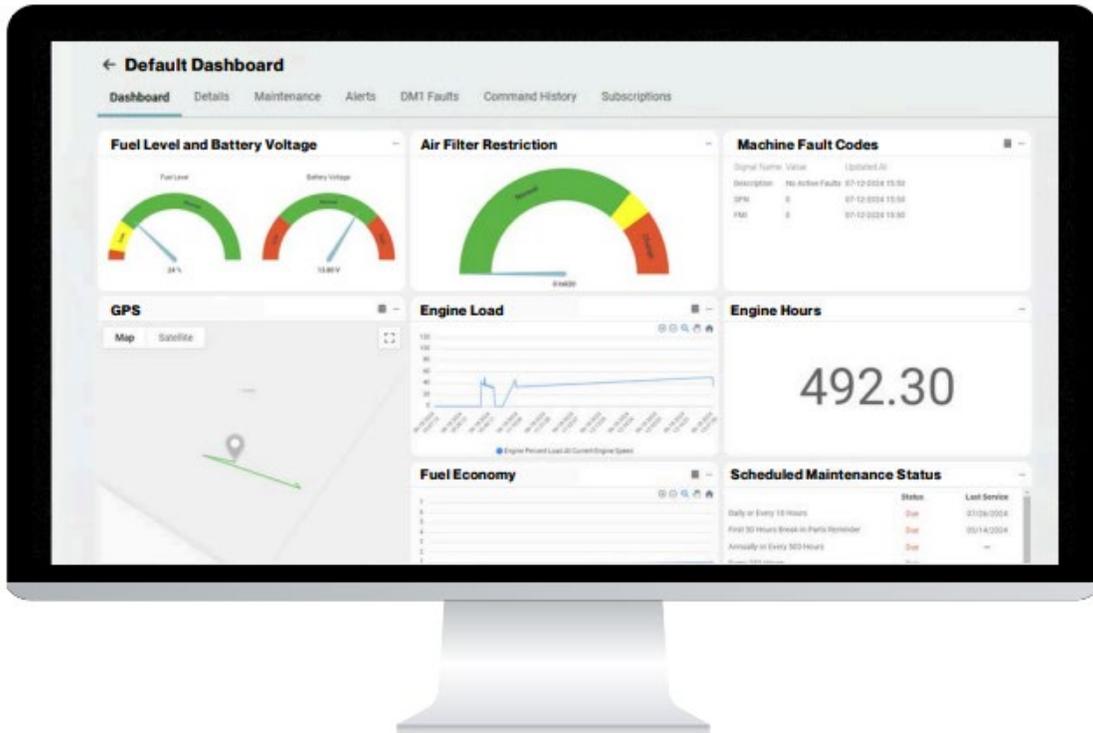


Figure 13. Elevat Case Study (Source: <https://www.elevat-iot.com/wp-content/uploads/2024/08/Elevat-Case-Study-Construction-24.01.pdf>)

Sensing and Data Collection: From Monitoring to Maintenance

Sensors have long played a critical role in mobile hydraulic systems, providing pressure, temperature, flow, and position feedback to enable closed-loop energy management. However, their capabilities extend far beyond basic monitoring. Through sensor fusion—the integration and analysis of multiple sensor data streams—machines can gain a more comprehensive understanding of system health and operating conditions.

By correlating signals from across the machine, sensor fusion can detect subtle changes such as fluid viscosity, identify early signs of leakage, monitor component wear, or even account for environmental influences. This deeper insight enables a shift from time-based to condition-based maintenance, ensuring that service is performed precisely when needed rather than at fixed intervals. The result is optimized machine uptime, reduced unnecessary maintenance costs, and greater flexibility for operators to plan service around actual machine requirements.

Future Directions: Intelligence and Autonomy

The next frontier in mobile hydraulics lies in the integration of artificial intelligence and machine learning, both onboard the machine and through cloud-based analysis of operational data. By continuously learning from real-world performance, these systems can optimize pump and valve behavior in real time, adapting not only to environmental conditions and the machine’s duty cycle but also to individual operator styles, skill levels, and the specific work being performed.

Advanced algorithms could also incorporate geofencing and site-specific data, dynamically adjusting machine performance based on location and task. For example, if a machine moves from one area of a job site to another, its control parameters could automatically shift to optimize for the specific functions being performed or the operator currently controlling the machine.

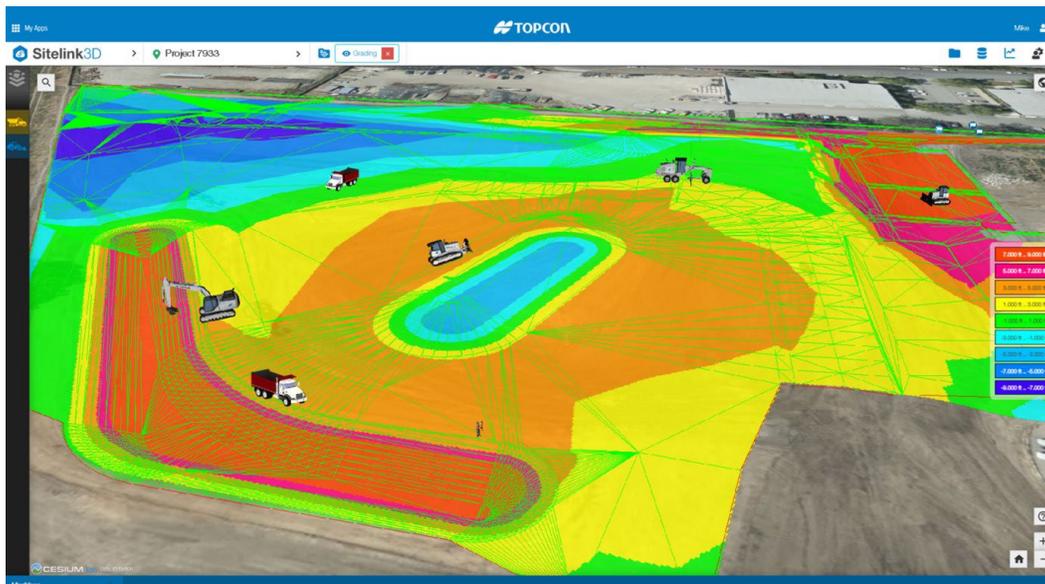


Figure 14. How Geofencing and Virtual Fencing Improve Excavator Safety and Performance (Source: <https://www.machmall.com/content-info/how-geofencing-and-virtual-fencing-improve-excavator-safety-and-performance/757>)

Autonomous and semi-autonomous systems further extend these efficiency gains by minimizing variability introduced by human operators. Semi-autonomous solutions for grading, lifting, or digging are already demonstrating reduced cycle times and decreased unnecessary motion, directly lowering energy consumption and enhancing overall machine efficiency. These intelligent systems represent a significant step toward maximizing productivity, reducing operating costs, and advancing the performance potential of electrified and hybrid mobile machinery.

Energy Efficiency Gains from Electrified Hydraulics

As this paper has illustrated, electrification provides multiple avenues for improving the overall efficiency of mobile machines. We have examined how an electric power source can better utilize available energy compared to a conventional internal combustion engine (ICE) machine, and how proper component sizing and selection can optimize energy use. This includes considerations of corner power and avoiding thermal derating.

We then explored inefficiencies inherent in hydraulic architecture, including metering losses, and discussed strategies for minimizing these losses to enhance overall system performance. Finally, we examined operational efficiency improvements enabled by electronic controls and software, along with the future potential of predictive maintenance and artificial intelligence to further optimize machine operations.

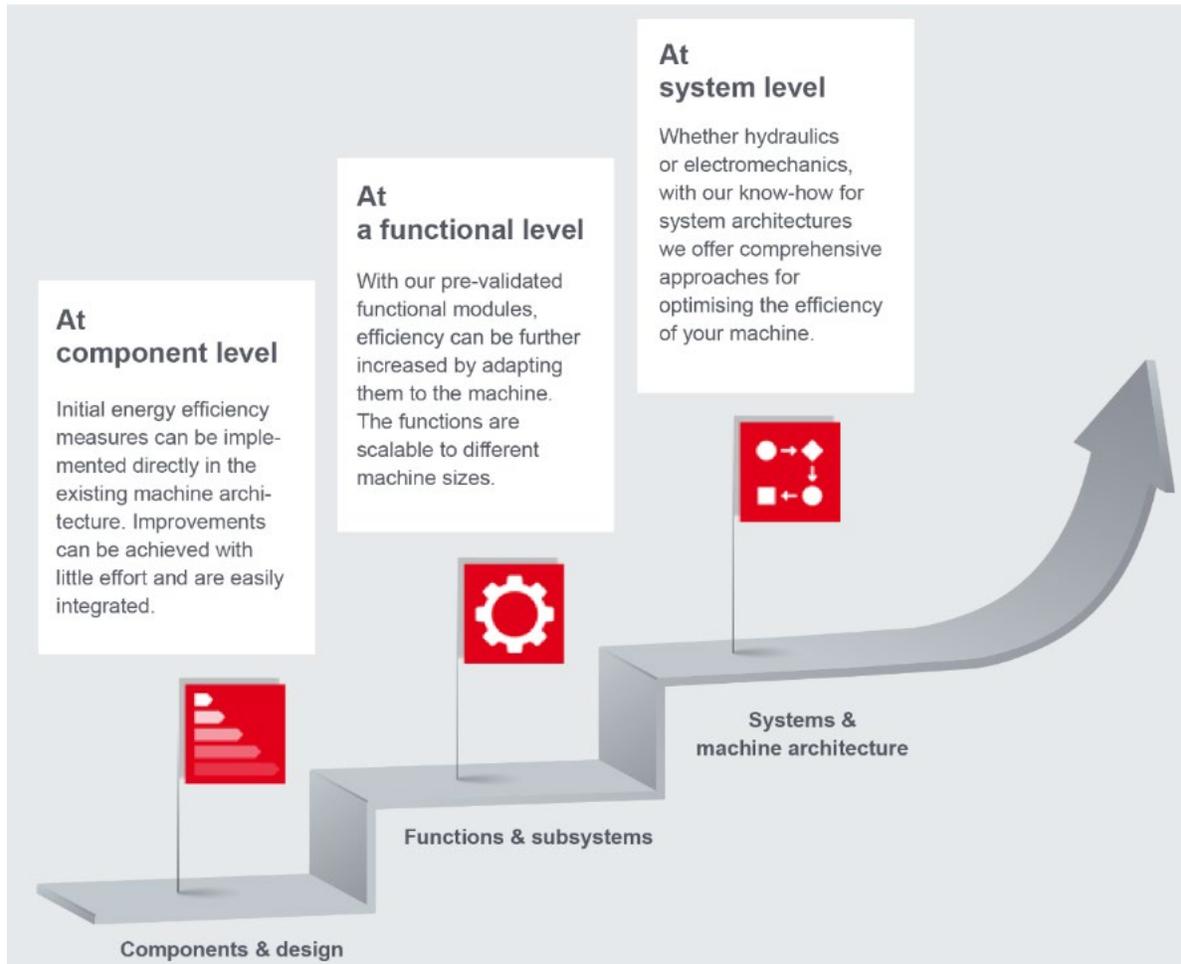


Figure 15. Energy-Efficient Work Functions (Source: <https://www.hydac.com.au/products/emobility/energy-efficient-work-functions.html>)



ENERGY EFFICIENCY GAINS FROM ELECTRIFIED HYDRAULICS

When considering the transition to electrification, it is important to recognize that the greatest efficiency gains arise not from individual technologies alone, but from their integration within the entire machine architecture and site ecosystem. A controller alone can only adjust outputs; software alone can only model behavior; sensors alone can only measure conditions. Together, they form a feedback loop of monitoring, prediction, and optimization that drives meaningful improvements in energy efficiency and machine performance.

While introducing electrification may increase initial system costs, it is essential to communicate the potential return on investment to end customers. The combination of higher efficiency, reduced operating costs, improved performance, and enhanced ease of operation can offset the initial investment when compared to legacy, mechanically dense machines.

Looking forward, embracing electrification, advanced controls, and software-driven optimization are increasingly essential for OEMs. The machines that will succeed in the marketplace are those that demonstrate not only superior performance, but also energy efficiency, operational simplicity, and a reduced total cost of ownership. As suppliers continue to innovate and refine these technologies, the potential for further efficiency gains and cost reductions through electrification will continue to grow.



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TASK FORCE PARTICIPATION

Energy Efficiency Working Group

- Marcus Herrera, HYDAC — Project Lead and Principal Author
- John Tudor, Oilgear — Contributing Author
- Anthony Langeweg, HED (Hydro Electronic Devices) — Contributing Author
- Matt Via, HED (Hydro Electronic Devices) — Contributing Author
- Sara Baldoni, VIS Hydraulics
- Trevor Combs, Trelleborg Sealing Solutions
- Sharvari Divey-Teall, Crown Equipment
- Diego Guidi, VIS Hydraulics
- Narendra Gupta, Hyster-Yale Group
- Ben Holter, Husco
- Jessica Horn, Bucher Hydraulics
- Anant Jain, Danfoss
- Deepak Kadamanahalli, CNH Industrial
- Chris Kolbe, HYDAC
- Pavan Kumar, Ajax Engineering
- Michael Miles, KersTech, Inc.
- Russ Schneidewind, Hydraforce
- Greg Shtrahman, Marzocchi Pumps
- Josh Stevens, Texas Hydraulics
- John Suh, John Suh Innovations
- Edgar Torres, Bucher Hydraulics
- Adam Vogts, IFP Motion Solutions