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Analysis of the Development of an Electric Mini Excavator Based on Environmentally Friendly Technology

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Abstract: This paper reports the development and preliminary experimental evaluation of a battery-electric mini-excavator prototype using an electro-hydraulic powertrain. The diesel prime mover was replaced by a 5 kW, 48 V brushless DC (BLDC) motor supplied by a 48 V, 100 Ah lithium-ion battery pack through a 48 V inverter. The motor drives a hydraulic pump rated at 16 L/min, while the original hydraulic actuators are retained for boom, arm, and bucket movement. The available experimental record includes boom motion times under no-load pressure settings of 125 and 250 psi, a 12 kg load condition, and a maximum-load test. Boom extend time decreased from 2.72 s at 125 psi to 1.97 s at 250 psi under the reported no-load condition. Under a 12 kg load, the reported boom extend time was 8.50 s at 125 psi and 3.28 s at 250 psi. At a 50 kg load, the reported extend time was 9.91 s; hydraulic leakage was observed when the applied load reached 57 kg. These results demonstrate preliminary actuation feasibility, but do not establish comparative energy efficiency, noise reduction, operating cost, or performance superiority over a diesel excavator because the corresponding measurements and diesel baseline are not available. The nominal battery energy is 4.8 kWh; actual operating duration requires measured duty-cycle power and battery-management data. The prototype is therefore evaluated as a preliminary low-voltage electric conversion demonstrator, with further instrumentation and repeatability testing required.

Keywords: Electric mini excavator; Electro-hydraulic system; BLDC drive; Hydraulic actuator

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1. Introduction

Electrification of compact construction equipment is being pursued to reduce exhaust emissions at the point of use, enable operation in enclosed or noise-sensitive environments, and improve the controllability of machine power demand. Battery-electric compact excavators are already commercially available. For example, Volvo Construction Equipment lists the ECR25 Electric with a 48 V, 20 kWh battery in its Asia product information [1] and has since upgraded the model to a 40 kWh battery [2], while JCB markets the 19C-1E as a fully electric mini excavator with a 48 V driveline [3]. These products demonstrate that compact excavator electrification is an established engineering direction rather than a new concept in itself.

Research on electric hydraulic excavators has investigated matching electric motor speed and pump displacement, independent metering, and coordinated pump control to reduce throttling and standby losses. He et al. examined the energy consumption characteristics of a pump-control system for electric excavator arms and reported that a compound speed–displacement strategy improved efficiency by approximately 18.9% relative to a conventional variable-speed pump-controlled cylinder system [4]. Ge et al. showed that a speed- and displacement-variable pump with independent metering reduced idle electric power from 2.05 kW to 0.7 kW compared with a displacement-only concept [5], and a later study of a speed-variable power source reported efficiencies of 40%–71%, which were 3%–10% higher than those of a fixed-speed source [6]. Reviews of hydraulic excavator energy-regeneration systems describe hydraulic accumulators and electro-hydraulic approaches for capturing energy that would otherwise be dissipated

through throttling and heat generation [7], [8]. Hybrid hydraulic excavators with electric–hydraulic variable powertrains and regeneration systems have likewise shown test-bench reductions in fuel consumption and emissions [9], [10].

In parallel, the heavy-equipment maintenance literature documents the failure and troubleshooting patterns of conventional diesel-driven excavators. Low-power complaints in excavator hydraulic systems have been investigated through structured troubleshooting, including pressure and cycle-time checks on a 302.5 mini excavator [11] and on other excavator units [12], [13]; cylinder leakage has been treated as a root-cause diagnosis problem [14]; and engine-side topics such as starting failure, wiring-harness maintenance, fuel-pressure faults, and crankcase blow-by recur as case subjects [15]–[19]. This body of work defines the conventional-drive baseline that electrification changes, but it does not address the battery-electric conversion of the hydraulic power unit. The present paper therefore reads the prototype's actuation data alongside these diagnostic practices.

The contribution of this work is a preliminary conversion and test study of a compact excavator prototype using a 48 V battery–inverter–BLDC motor arrangement and locally developed integration. Its scope is limited to describing the architecture and the boom actuation data currently documented. It does not claim novelty in battery-electric excavators generally, nor does it claim measured energy or noise improvements.

2. Materials and Experiment Methods

2.1. Prototype Architecture

The prototype uses a battery-electric electro-hydraulic architecture. A 48 V, 100 Ah lithium-ion battery supplies a 48 V inverter rated at 100 A. The inverter drives a 5 kW BLDC motor coupled to the main hydraulic pump. The pump is reported to deliver up to 16 L/min. The hydraulic cylinders and linkage for the boom, arm, and bucket are retained. A custom electronic control unit (ECU) is identified in the original design as the system coordination and monitoring unit.

Tabel 1. Reported specifications and functions of the main components of the electro-hydraulic prototype.

Component	Reported specification	Function
Electric motor	BLDC, 5 kW, 48 V	Drives hydraulic pump
Battery	Li-ion, 48 V, 100 Ah	Electrical energy storage
Inverter	48 V input, 100 A rated	Motor drive and protection
Hydraulic pump	Variable displacement; reported flow 16 L/min	Hydraulic power supply
Controller	Custom ECU; detailed control law not reported	System coordination and monitoring

The hydraulic power delivered to the fluid can be estimated from $P_h = pQ$, where p is pressure and Q is volumetric flow rate. For the reported maximum flow of 16 L/min (2.667×10^{-4} m³/s) and pressure of 250 psi (1.724 MPa), the ideal hydraulic power is approximately 0.460 kW. This is substantially below the 5 kW motor nameplate rating. The difference does not, by itself, establish the motor's actual operating efficiency: actual pump flow, pressure at the pump outlet, motor input power, transient duty, and losses must be measured simultaneously.

2.2. Testing Procedure

Experimental The original manuscript reports the following conditions: no-load operation at 125 psi and 250 psi; a 12 kg load condition; and a maximum-load condition of 50 kg. It reports boom extend and retract times for the no-load tests, boom extend times for the 12 kg and 50 kg tests, and leakage at 57 kg. The original document states that

electrical power and motor/inverter temperature were measured, but does not provide their values, measurement instruments, or uncertainty. Therefore, those quantities are not treated as available results in this revision.

Tabel 2. Boom extension and retraction times reported in the original manuscript for the no-load and loaded test conditions at system pressures of 125 psi (0.862 MPa) and 250 psi (1.724 MPa).

Test condition	Boom extend (s)	Boom retract (s)	Other recorded observation
No load; 125 psi	2.72	1.77	-
No load; 250 psi	1.97	1.39	-
12 kg; 125 psi	8.50	-	Extend time only
12 kg; 250 psi	3.28	-	Extend time only
50 kg	9.91	-	Hydraulic leakage reported at 57 kg

Noted : The number of repetitions (n) for each condition and the raw observations. Report mean ± standard deviation only after the raw repeated measurements are available.

2.3. Electrical and hydraulic calculations

The nominal stored battery energy is estimated as $E_{nom} = V_{nom} \times C = 48\ V \times 100\ Ah = 4{,}800\ Wh = 4.8\ kWh$. At a continuous electrical demand equal to the 5 kW motor rating, the ideal energy-to-power ratio is $E_{nom}/P = 0.96$ h. This is an ideal upper-bound arithmetic estimate, not a measured runtime. Actual runtime will be lower because usable capacity is limited by the BMS depth-of-discharge window and because conversion, motor, pump, and hydraulic losses and duty-cycle variations are present.

The hydraulic power relation is $P_h = pQ$. At $p = 250$ psi $= 1.724$ MPa and $Q = 16$ L/min $= 2.667 \times 10^{-4}$ m^3/s, $P_h \approx 0.460$ kW. Overall battery-to-hydraulic efficiency can only be calculated when simultaneous electrical input and hydraulic output are measured: $\eta_{total} = (pQ)/(V_{DC} I_{DC})$, with consistent time averaging over the same operating interval. If flow varies during a cycle, the cycle energy should be calculated by integrating power over time rather than multiplying nominal maximum flow by a single pressure value.

The reported pressure settings are interpreted as pressure-limit or relief settings, not as direct flow commands. Actuator speed is primarily related to delivered flow and effective actuator area ($v = Q/A$). Pressure determines available force ($F = pA$) and influences whether the pump flow is bypassed through a relief path or delivered to the loaded actuator.

The cited IEC 62619:2022 standard specifies safety requirements and tests for secondary lithium cells and batteries used in industrial applications [20]. The original manuscript does not document evidence of design verification against individual IEC 62619 clauses. Accordingly, this revision does not claim IEC 62619 compliance.

3. Results and Discussion

3.1. Effect of pressure setting on boom motion

Under the reported no-load condition, increasing the pressure setting from 125 psi to 250 psi was associated with a reduction in boom extend time from 2.72 s to 1.97 s (27.6%) and retract time from 1.77 s to 1.39 s (21.5%). These are descriptive differences from the reported values; no repeat count or variability estimate is available. The result should not be interpreted as evidence that higher pressure directly increases fluid velocity. Actuator velocity is governed mainly by flow rate and actuator area. A higher pressure limit may instead reduce flow diverted through a relief valve or provide sufficient force margin under the tested load, depending on the actual hydraulic circuit and pump-control strategy.

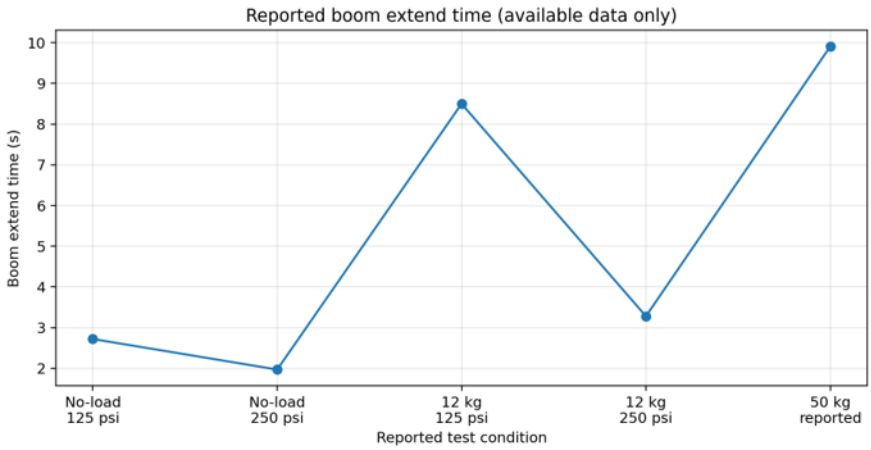


Figure 1. Boom extend times explicitly reported in the source manuscript

3.2. Effect of applied load

For the 12 kg condition, boom extend time was reported as 8.50 s at 125 psi and 3.28 s at 250 psi, a descriptive reduction of approximately 61.4%. The original manuscript attributed this change to torque control. However, the documented test variable is pressure setting, and no controller command, motor-speed trace, torque estimate, pump displacement trace, or pressure-control logic is supplied. The defensible interpretation is therefore limited to an association between the pressure setting and the measured boom extend time.

The 50 kg test produced a reported boom extend time of 9.91 s. Hydraulic leakage was observed when the applied load reached 57 kg. This observation indicates a limitation of the tested prototype configuration, but it does not establish a certified mechanical load limit or safe working load. Further tests should identify the leakage location, pressure at failure, structural stability, and repeatability.

The following table defines the dataset that should be supplied before publication.

Tabel 3. Extension and retraction times (mean ± SD) for each actuator and test condition

Actuator	Condition	Extend time (s), mean ± SD	Retract time (s), mean ± SD
Boom	No load; 125 psi	2.72; n/SD unavailable	1.77; n/SD unavailable
Boom	No load; 250 psi	1.97; n/SD unavailable	1.39; n/SD unavailable
Boom	12 kg; 125 psi	8.50; n/SD unavailable	-
Boom	12 kg; 250 psi	3.28; n/SD unavailable	-
Boom	50 kg	9.91; n/SD unavailable	-
Arm	All conditions	-	-
Bucket	All conditions	-	-

The 5 kW motor rating and the calculated ideal hydraulic power of approximately 0.46 kW at 250 psi and 16 L/min indicate a substantial nominal power mismatch at that operating point. This comparison highlights the need to characterize the actual motor operating point and part-load efficiency. It is not sufficient to infer low efficiency solely from the ratio of hydraulic power to motor nameplate rating; measured DC input power, actual flow, pressure, and motor speed are required.

3.3. Interpretation of the pressure- and load-dependent cycle times

For a cylinder of fixed stroke, mean piston speed is proportional to the flow reaching the actuator, so the ratio of cycle times is an indirect indicator of the ratio of effective flows. The no-load times therefore imply an effective boom extension flow at the 250 psi setting about 1.38 times that at 125 psi (2.72 s/1.97 s) and a retraction flow about 1.27 times higher (1.77 s/1.39 s). Under the 12 kg load the same ratio rises to about 2.59 (8.50 s/3.28 s). Comparing loaded and unloaded extend times at a fixed setting shows the same trend: the 12 kg load lengthened extension by a factor of about 3.1 at 125 psi (8.50 s/2.72 s) but only about 1.7 at 250 psi (3.28 s/1.97 s). These ratios are calculated from single reported values without uncertainty and indicate a trend, not a flow estimate.

Three mechanisms, not mutually exclusive, could produce this behavior, and each is testable. First, if the pressure needed to move the boom linkage and load approaches the 125 psi setting, part of the pump flow would pass over the relief valve and less would reach the cylinder; raising the setting restores margin. Second, if the pump is a variable-displacement unit with a pressure compensator, displacement would be reduced as system pressure approaches the setting, which also slows the actuator. Third, the motor speed may droop under load because of torque or inverter current limits (see Section 3.5), reducing pump flow. The same symptoms, a pressure deviation and a degraded cycle time, were among the hydraulic-system causes identified for low power on a 302.5 mini excavator by Kurniawan et al. [11], and low-power troubleshooting of other excavator units follows a similar approach [12], [13]. Boom cycle time under a fixed load, together with a verified relief pressure, is therefore a suitable commissioning check for the converted machine. Simultaneous logging of pump-outlet pressure, cylinder-port pressures, flow, and motor speed would allow the three mechanisms to be separated.

3.4. Benchmarking against commercial battery-electric compact excavators

The table below places the prototype beside two commercial machines using manufacturer-published nominal data. The prototype has about one quarter of the battery energy (4.8 kWh versus 20 kWh, 24%), motor power (5 kW versus 18 kW peak, 28%), and pump flow (16 L/min versus 58 L/min, 28%) of the Volvo ECR25 Electric [1], while sharing its 48 V bus voltage. This proportionality indicates that the prototype is a scaled-down demonstrator of the same low-voltage architectural class rather than a higher-voltage design.

Table 4. Nominal comparison of the prototype with two commercial battery-electric compact excavators (manufacturer data; prototype values as reported in Section 2).

Parameter	Prototype (this work)	Volvo ECR25 Electric [1], [2]	JCB 19C-1E [3]
Bus voltage	48 V	48 V	48 V driveline
Battery energy	4.8 kWh (nominal)	20 kWh; 40 kWh in updated model	Optional 20 kWh pack
Motor power	5 kW (rated)	18 kW (peak)	Up to 27 hp (≈20 kW), peak
Maximum pump flow	16 L/min	58 L/min	Not stated in cited source
Runtime	Not measured; 0.96 h ideal at 5 kW	Up to 4 h (20 kWh)	Manufacturer states a full shift

The commercial data also indicate what runtime is achievable. Volvo quotes up to 4 h from 20 kWh [1], which implies a mean draw of at least about 5 kW, or roughly 28% of the 18 kW peak. Applying the same ratio to the prototype's 5 kW would give a mean draw near 1.4 kW and at most about 3.5 h from 4.8 kWh before usable-capacity limits. This is a scaling illustration only; it is not a measurement and does not replace a measured duty

cycle. Volvo has since doubled the battery of the updated ECR25 to 40 kWh for up to eight hours of typical operation [2], and JCB offers an optional 20 kWh pack on the 19C-1E [3]. Battery energy is therefore likely to be the primary limit on the prototype's ability to cover a full working shift.

3.5. Electrical–hydraulic power matching

`The nominal electrical data allow a consistency check of the drive. At 48 V, the 5 kW rated motor power corresponds to a DC current of about 104 A (5,000 W/48 V) even at 100% conversion efficiency, which already exceeds the 100 A inverter rating; at an assumed combined motor and inverter efficiency of 90%, the DC current would be near 116 A. The inverter therefore limits sustained DC input power to about 4.8 kW at nominal voltage (48 V × 100 A), and the limit is lower in practice because battery voltage sags under load and with decreasing state of charge. The ratio of rated motor power to nominal battery energy is about 1.04 h^{-1} for the prototype, compared with about 0.9 h^{-1} for the peak motor power of the ECR25 Electric [1], so the prototype battery would be discharged at a comparable or slightly higher relative rate at full power. These limits do not affect the boom motions tested, whose ideal hydraulic power is only about 0.46 kW, but they matter for sizing if the machine is to be operated near the full motor rating.

The ideal hydraulic output of 0.46 kW is about 9% of the 5 kW motor rating, so the motor and inverter would operate at light load during the reported tests. Part-load operation is where fixed-speed drives are known to be inefficient: Ge et al. reported that a speed-variable power source reduced electric power consumption at idle and partial load [5], [6], and He et al. showed that matching motor speed to load power through pump-displacement control improved efficiency in a pump-controlled boom cylinder [4]. Because the ECU control law of the prototype is not documented, it is not known whether the motor runs at a fixed speed or adapts to demand. If it runs at a fixed speed, the idle and part-load losses described in [5], [6] would be expected to apply. This is a hypothesis to be tested by measuring DC input power at idle and during boom cycles. Boom-lowering energy, which is otherwise dissipated as heat, is a further candidate for regeneration through the electric drive [7]–[10].

3.6. Leakage, maintainability, and shifted failure modes

The leakage observed at 57 kg should be converted from a single event into a root-cause finding. Mubarok et al. treated cylinder leakage in a wheel-loader steering cylinder as a diagnosis problem solved by structured inspection [14]; the same approach applies here, recording the pressure at which leakage starts, the leaking component (cylinder seal, hose, fitting, or valve), and the oil condition. The tested pressure limit of 250 psi (1.72 MPa) is well below the working pressures typically used in excavator hydraulics, which are generally of the order of 10–30 MPa. If the retained cylinders, hoses, and seals come from the original machine, leakage at this low pressure would point first to seal or assembly condition rather than to over-pressure. This inference remains to be confirmed by inspection.

Electrification removes the fuel-system, starting, and crankcase failure categories that recur in diesel-machine case studies [15], [17]–[19], but it introduces battery, inverter, and wiring failure categories. Wiring-harness maintenance is already a documented topic on the diesel CAT 302.5 mini excavator [16]. In a 48 V system carrying currents of the order of 100 A, connector resistance and harness integrity become correspondingly more important for heating and voltage drop, so the maintenance plan of the converted machine should include connector torque and temperature checks. Battery safety verification against IEC 62619 [20] and documented BMS limits are prerequisites for any claim of compliance.

3.7. Limitations and directions for further work

Three limitations bound the conclusions. First, no repeat counts or variability are available, so differences between conditions cannot be tested statistically. Second, electrical power and temperature values are not reported, so efficiency, runtime, and thermal margin cannot be calculated. Third, there is no diesel baseline, so no comparison of performance, energy use, noise, or cost can be made. The next test phase should therefore log DC voltage and current, motor speed and torque, pump-outlet pressure, flow, and component temperatures during repeated boom, arm, and bucket cycles, with enough repetitions per condition to report mean ± standard deviation, followed by variable-speed control and boom-energy regeneration studies guided by [4]–[10].

4. Conclusions

A preliminary battery-electric conversion of a mini-excavator hydraulic system was described using a 48 V, 100 Ah lithium-ion battery, a 48 V inverter, a 5 kW BLDC motor, and a hydraulic pump with a reported flow rate of 16 L/min. The available boom measurements show shorter extend and retract times at the 250 psi setting than at 125 psi under the reported no-load condition. For the 12 kg load, the reported boom extend time was 8.50 s at 125 psi and 3.28 s at 250 psi. At 50 kg, the reported extend time was 9.91 s, while leakage was observed at 57 kg.

These findings support only preliminary actuation feasibility under the documented test conditions. They do not establish higher energy efficiency, 80% noise reduction, lower operating cost, or superiority to a diesel excavator. The nominal battery energy is 4.8 kWh, corresponding to an ideal 0.96 h at a continuous 5 kW draw before accounting for usable SOC limits and system losses.

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