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Enhancing Energy Efficiency in Drilling: Innovative Pipe Handling with Hydraulic Energy Recovery

Sai Kishore Ayalasomayajula[1,*], Jürgen Binder[2]

[1]Herrenknecht AG, Schwanau, Germany,
[2]Herrenknecht Vertical GmbH, Schwanau, Germany,
E-mail: ayalasos@herrenknecht.com
**Corresponding author*

Abstract.

Geothermal drilling operations involve frequent lifting and lowering of heavy tubulars, making pipe handling one of the most energy-intensive rig subsystems. In conventional designs, the gravitational potential energy released during lowering is dissipated as heat through throttling valves. This paper presents a novel hydraulic energy-recovery concept that integrates a load-compensation cylinder and a gas-charged accumulator to capture and reuse this otherwise wasted energy. The system architecture was modelled in Siemens Amesim, and parametric studies were conducted to optimize accumulator pre-charge and volume. Simulations predict energy-recovery efficiencies up to approximately 70% per lifting cycle, with corresponding reductions in hydraulic-power demand. A prototype was implemented on a Herrenknecht vertical rig and verified during factory acceptance tests, which demonstrated substantial reductions in operating pressure from about 176 bar to 99 bar when compensation was active confirming the predicted load-sharing effect. The concept provides a compact, retrofit-capable solution for improving the energy efficiency of hydraulic pipe-handling systems and offers a practical pathway toward reduced rig-level power consumption and enhanced sustainability in geothermal drilling operations.

Keywords. Hydraulic energy recovery, pipe handling, accumulator, load compensation, tripping, drilling energy efficiency.

NOMENCLATURE

E_{dead}	Mechanical energy required to move the handler's dead load [kJ]
E_{comp}	Mechanical energy contributed by the compensation system [kJ]
E_{uncomp}	Uncompensated residual energy supplied by the HPU [kJ]
$E_{acc,usable}$	Usable accumulator energy (isothermal approximation) [kJ]
$E_{rec,available}$	Available recovered energy after hydraulic losses [kJ]
η_{Comp}	Compensation efficiency = $E_{Compensated} / E_{Required}$

η_{hyd}	Hydraulic round-trip efficiency
p_0	Accumulator pre-charge pressure [bar]
p_1	Accumulator minimum working pressure [bar]
p_{max}, p_{min}	Maximum and minimum accumulator pressures [bar]
V_0	Accumulator effective gas volume [L]
F(h)	Cylinder force as a function of displacement [N]
h	Cylinder stroke displacement [m]
P_{hyd}	Hydraulic power [kW]
Q	Volumetric flow rate [L/min]
η	Overall efficiency factor
N	Number of pipe joints handled per bit change

1. INTRODUCTION

Geothermal and other deep-well applications are gaining renewed importance as global energy policy and security concerns accelerate investment in dispatchable, low-carbon energy sources. Among all drilling activities, the tripping process 'repetitive lifting and lowering of heavy tubulars' remains one of the most energy-intensive operations on a drilling rig. In conventional hydraulic systems, the gravitational potential energy released during lowering is dissipated as heat across throttling valves, resulting in substantial energy loss and increased cooling demand.

To address this inefficiency, the present work investigates a hydraulic energy-recovery subsystem integrated into a horizontal pipe handler. The subsystem captures the energy released during lowering operations and reuses it to assist subsequent lifting cycles. A nitrogen-charged hydraulic accumulator, connected via a dedicated compensation cylinder and control block, temporarily stores hydraulic energy that would otherwise be wasted. This stored energy is then discharged to support the boom cylinder during lifting, thereby reducing the load on the hydraulic power unit (HPU).

The overarching goals of this research are threefold:

1. Quantify the energy requirements of typical pipe-handling cycles and determine the recoverable portion through simulation and testing.
2. Evaluate the effectiveness of the accumulator-based compensation system in reducing mechanical and hydraulic power demand.
3. Validate the simulation results through factory acceptance testing (FAT) and establish a framework for future on-rig performance measurements.

The proposed concept supports broader industry efforts to improve rig-level energy efficiency, reduce emissions, and enable hybridization of hydraulic subsystems with electrical energy-storage technologies. By focusing on a modular retrofit-capable component, the pipe handler this approach provides a practical step toward measurable sustainability gains in geothermal drilling operations.

2. LITERATURE REVIEW

Energy recovery in hydraulic systems is well established in mobile and construction machinery, particularly for applications involving cyclic lifting and lowering motions. In such systems, gravitational potential energy released during lowering is often dissipated as throttling losses. Accumulator-based energy regeneration concepts have been shown to capture this energy and reuse it during subsequent lifting operations, thereby reducing peak actuator loads and instantaneous hydraulic power demand [1]. While high levels of energy recovery can be achieved locally at actuator level through accumulator-assisted regeneration, net system-level energy savings are strongly influenced by hydraulic losses, control strategy, and the proportion of non-compensated operating phases. Experimental and simulation studies show that integration effects limit the direct translation of local recovery ratios into overall reductions in hydraulic power-unit energy demand [2]. In industrial practice, accumulator-based systems are commonly applied for peak shaving and short-term energy buffering, particularly in excavators and cranes, where appropriate control strategies have demonstrated measurable reductions in fuel and electrical energy consumption [3].

For drilling applications, several studies have adapted energy recovery concepts to hoisting and tripping operations. Quan et al. [4] and Zhang [5] demonstrated potential-energy recovery in drilling rigs to reduce motor power demand during lifting; however, these approaches primarily addressed large-scale vertical hoisting systems and did not consider compact, high-cycle pipe-handler mechanisms typical of modern geothermal drilling rigs. More recent research has expanded toward system-level energy management and hybrid drilling-rig architectures. Chupin [6] reported diesel-consumption reductions of 20–30% through integrated energy storage and optimized generator scheduling, highlighting the importance of system-level coordination rather than isolated subsystem optimization. Beyond individual subsystems, improving energy efficiency has become a strategic objective in geothermal drilling operations, driven by operational cost and sustainability considerations [7], [8]. Operational studies further indicate that tripping efficiency and fuel consumption significantly affect overall rig performance and cost structure [9], [10].

3. SYSTEM DESIGN

This section describes the design and functional architecture of the pipe handler equipped with an integrated hydraulic energy-recovery subsystem. The design objective is to minimize the net energy demand on the HPU by recovering gravitational potential energy during lowering and reusing it to assist lifting operations.

3.1. Design Objectives

The main design goals were defined as follows:

- Capture and store gravitational potential energy during the lowering phase of trip-out operations.
- Reuse stored energy to assist lifting during trip in operations, reducing instantaneous HPU demand.

- Maintain full operational safety, controllability, and compatibility with existing pipe-handler geometries.
- Enable compact integration or retrofit within the envelope of standard geothermal pipe-handling systems.

3.2. Functional Description

The horizontal pipe handler is an automated handling system used on geothermal drilling rigs to lift, rotate, and position tubulars such as drill pipes, casing, and tubing between the catwalk and the well centre. A typical handling cycle involves lifting a horizontally positioned drill pipe (up to 13.72 m length and 4500 kg mass), rotating it to a vertical orientation, and handing it over to the top drive within a single operating sequence.

For such operations, Figure 3.1. shows a representative force diagram of compensation relative to the force required to support the pipe handler dead load, with and without an additional pipe weight. The area under the curve corresponds to the potential energy that can be recovered during lowering.

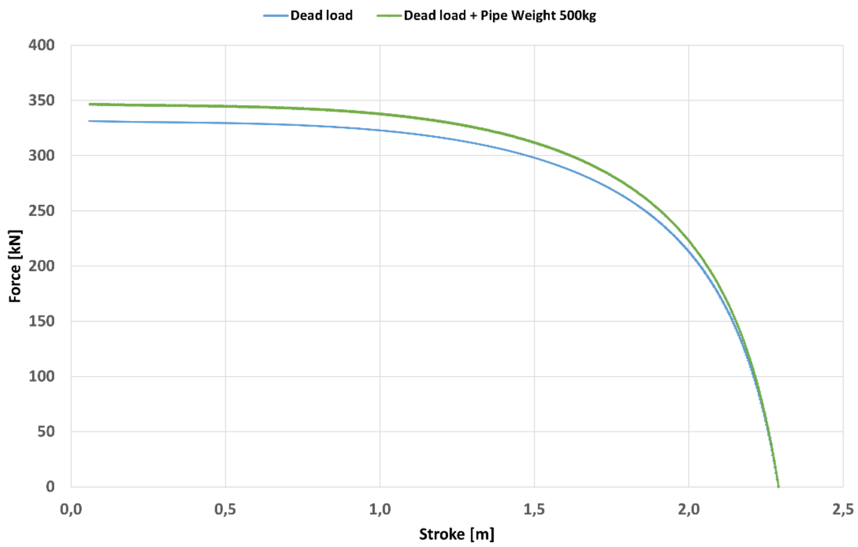

Figure 3.1.: Required Force Diagram of Compensation Cylinder

3.3. Functional Architecture

The pipe-handling system comprises a mechanically coupled boom assembly with hydraulically independent lifting and compensation circuits, as illustrated in Figures 3.2 and 3.3. The primary lifting and lowering motion are provided by the boom cylinder (1), which is driven directly by the hydraulic power unit (HPU, 6) and equipped with load-holding valves to ensure secure positioning in the event of pressure loss. In parallel, two load-compensation cylinders (2) are mechanically coupled to the boom frame but hydraulically decoupled from the HPU and instead connected to a nitrogen-charged accumulator (3) via a dedicated control manifold (4).

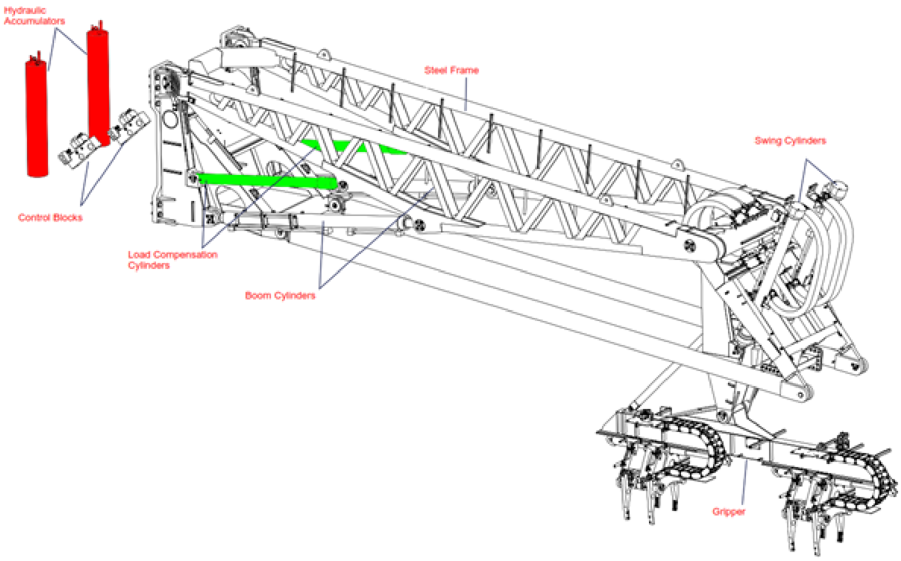

Figure 3.1.: Novel Pipe Handler with load Compensation Cylinder

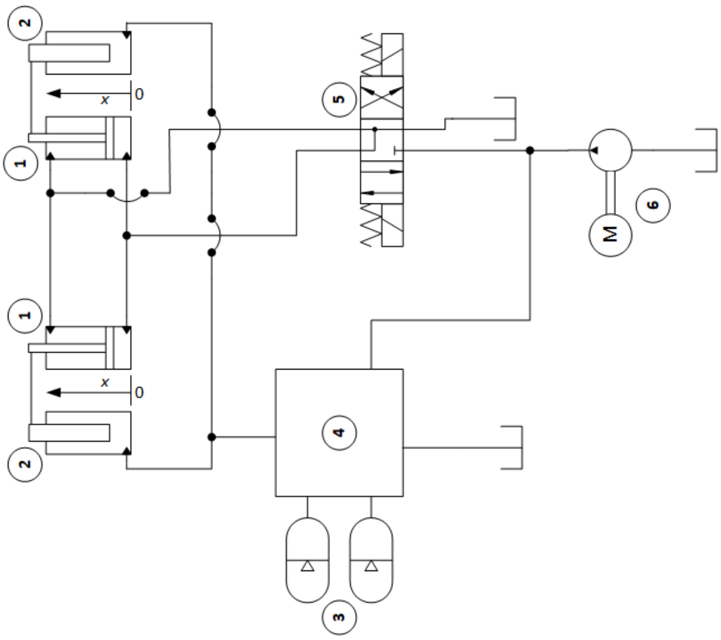

Figure 3.3.: Hydraulic Schematic Novel Pipe Handler

During lowering, hydraulic energy is transferred to the accumulator through compression of the nitrogen gas, while during subsequent lifting this stored energy is released to support the boom cylinder and reduce peak HPU power demand. The control block (5) regulates hydraulic flow between the compensation cylinders and the accumulator and incorporates directional, check, and relief valves to manage energy transfer, provide over-pressure protection, and isolate the compensation circuit when inactive.

3.4. System Coordination and Monitoring

System operation is monitored using standard pressure and position sensors, providing feedback on cylinder and accumulator pressures as well as boom position relative to the well centre. These signals are processed by a programmable logic controller (PLC), which sequences valve operations, coordinates accumulator charging and discharging, and establishes interlocks with external handling systems. This coordinated control enables repeatable motion and controlled energy exchange during cyclic tripping operations, resulting in reduced instantaneous HPU power demand over successive cycles.

4. ENERGY RECOVERY MECHANISM

The proposed hydraulic energy-recovery mechanism operates cyclically through two complementary phases - lowering capture and lift assist - across the two primary operational modes of the pipe handler: Trip In (running pipe into the well) and Trip Out (removing pipe from the well). Each Trip consists of two sub-cycles, one loaded and one unloaded, forming a complete energy-exchange loop between the boom cylinder, the load-compensation cylinder, and the hydraulic accumulator.

4.1. Trip In: Lifting Loaded, Lowering Unloaded

During Trip In, the handler performs two sequential motions:

Cycle part 1 – Lifting loaded: The handler lifts the dead load plus a pipe segment from the catwalk to the well centre. In this motion, the accumulator discharges previously stored hydraulic energy into the compensation cylinder, producing an assisting force that reduces the effective pressure required in the boom cylinder. This lowers the hydraulic power demand from the HPU and results in smoother lifting dynamics.

Cycle part 2 – Lowering unloaded: After transferring the pipe to the well centre, the handler returns to the catwalk carrying only its dead load. During this lowering phase, the compensation cylinder retracts, forcing hydraulic fluid into the accumulator and re-charging it. Gravitational potential energy from the handler’s structure is thus converted into stored hydraulic energy, preparing the system for the next lifting sequence.

4.2. Trip Out: Lowering Loaded, Lifting Unloaded

The Trip Out process follows the inverse energy flow:

Cycle part 1 – Lowering loaded: The handler lowers a pipe segment from the well centre to the catwalk, supporting the combined dead load and pipe mass. The boom cylinder retracts under load while the compensation cylinder directs fluid into the accumulator. The gravitational energy of the pipe and structure is stored as compressed gas energy rather than dissipated as throttling losses.

Cycle part 2 – Lifting unloaded: Once the pipe is placed on the catwalk, the handler returns to the well centre with only the dead load. The accumulator assists this motion by releasing part of its stored energy into the compensation cylinder, thereby reducing the required boom-cylinder pressure and the hydraulic energy drawn from the HPU. This balanced exchange closes the energy loop for the Trip Out sequence. Summary of Trip cycles and energy flow is presented in Table 4.1.

4.3. System-Level Control and Energy Flow

Over consecutive trips, this alternating sequence of accumulator charging (during lowering) and discharging (during lifting) maintains a nearly steady-state energy balance.

The control block governs this exchange by routing hydraulic flow between the compensation cylinder and the accumulator while preventing over-pressurization. Check and relief valves ensure that accumulator charging is smooth, and that stored energy is released only during commanded lift phases. The result is a cyclic reduction of peak HPU power and smoother hydraulic operation with less throttling loss.

Operation	Cycle	Motion	Load Condition	Accumulator Energy Flow
Trip In	Cycle part 1	Lift (Catwalk → Well Centre)	Dead load + pipe	Discharge – assist lift
	Cycle part 2	Lower (Well Centre → Catwalk)	Dead load only	Charge – recover energy
Trip Out	Cycle part 1	Lower (Well Centre → Catwalk)	Dead load + pipe	Charge – recover energy
	Cycle part 2	Lift (Catwalk → Well Centre)	Dead load only	Discharge – assist lift

Table 4.1.: Summary of operational cycles and corresponding energy flow in the pipe handler

4.4. Interpretation

In this sequence, each complete Trip In or Trip Out operation alternates between an energy-storage and an energy-release phase. The oil level in accumulator is maintained within the designed range (p_0 to p_1) by the control block & PLC, ensuring consistent assistance during loaded lifts and safe capture during lowering phases. Over multiple trips, this results in lower HPU energy demand, smoother motion, and measurable reductions in overall hydraulic consumption compared with conventional systems.

5. MODELING, SIMULATION, AND VALIDATION

5.1. Simulation Model

A detailed component-level model was implemented in Siemens Amesim to analyze the dynamic behaviour of the hydraulic load-compensation subsystem. The model incorporated nonlinearities of the accumulator gas law, valve pressure drops, and cylinder dynamics. Parametric sweeps were carried out to optimize accumulator pre-charge, volume, and valve sizing.

Representative input parameters used in the simulations are:

Parameter	**Value**
Boom-cylinder effective area	0.012 [m²]
Boom-cylinder stroke	3.2 [m]
Compensation-cylinder effective area	0.012 [m²]
Compensation-cylinder stroke	2.2 [m]
Typical handled joint mass	500 [kg]
Structural dead load (self-weight)	18,000 [kg]
Accumulator nominal volume	120 [L]
Ambient temperatures tested	–5 [°C], +20 [°C] , +40 [°C]

Table 5.1.: Simulation Parameters

The performance indicator was the compensated-energy fraction, defined as the ratio between energy supplied by the compensation subsystem and the total mechanical energy required by the handler.

The mechanical work during one pipe-handling cycle is obtained by integrating the measured or simulated force–displacement curve:

$$E_{work} = \int_{h_0}^{h_1} F(h)dh \qquad (5.1)$$

For discrete data, the trapezoidal approximation was applied:

$$E_{work} \approx \Sigma_{i=1}^{n-1} \left(\frac{h_{i+1} - h_i}{2}\right)(F_i + F_{i+1}) \qquad (5.2)$$

The accumulator's usable isothermal energy between minimum and maximum pressures is expressed as:

$$E_{acc,usable} = p_0 V_0 \, ln\left(\frac{p_{max}}{p_{min}}\right) \qquad (5.3)$$

Accounting for hydraulic round-trip efficiency η_{hyd}:

$$E_{rec,available} = \eta_{hyd} \cdot E_{acc,usable} \qquad (5.4)$$

The compensation efficiency is then:

$$\eta_{Comp} = \frac{E_{Compensated}}{E_{Required}} \qquad (5.5)$$

5.2. Simulation Results

The total energy required for pipe handling was computed by numerical integration of simulated force-displacement curves (Equation 5.1). All results are expressed in SI units (N, m, J, kJ).

Dead-Load Work

From the measured boom-cylinder dead-load curve:

$$E_{dead} = \int_{h_0}^{h_1} F_{dead}(h)dh = 625.2\ kJ$$

This value represents the total mechanical work per cycle that must be supplied by the HPU when the compensation system is inactive.

Compensation Simulation and Temperature Dependence

Parametric simulations with optimized accumulator pre-charge p_0 generated compensation-cylinder force profiles for several ambient temperatures (Figure 5.1.).

The variation in compensation force with ambient temperature arises from the thermodynamic behaviour of the nitrogen-charged accumulator. For a given pre-charge pressure and volume, higher temperatures lead to higher gas pressure levels, resulting in increased compensation forces, while lower temperatures reduce the available force accordingly. The observed hysteresis between the lifting and lowering curves is primarily caused by heat transfer between the gas and the ambient air. The small discrete force steps near the end positions of the stroke originate from valve cracking pressures, numerical switching of control elements in the simulation model, and damping effects at the mechanical stroke limits. These effects are inherent to realistic hydraulic systems and are intentionally retained in the model to reflect non-ideal operating behaviour.

For the selected operating point at +20 °C, the integrated work areas under these curves (Figure 5.2., Figure 5.3.) yield the remaining uncompensated energy E_{uncomp} that the HPU must supply when compensation is active.

In these simulations, the integrated energy segments $E_A+E_B+E_C$ correspond to the mechanical work that remains to be supplied by the HPU after the compensation system has acted.

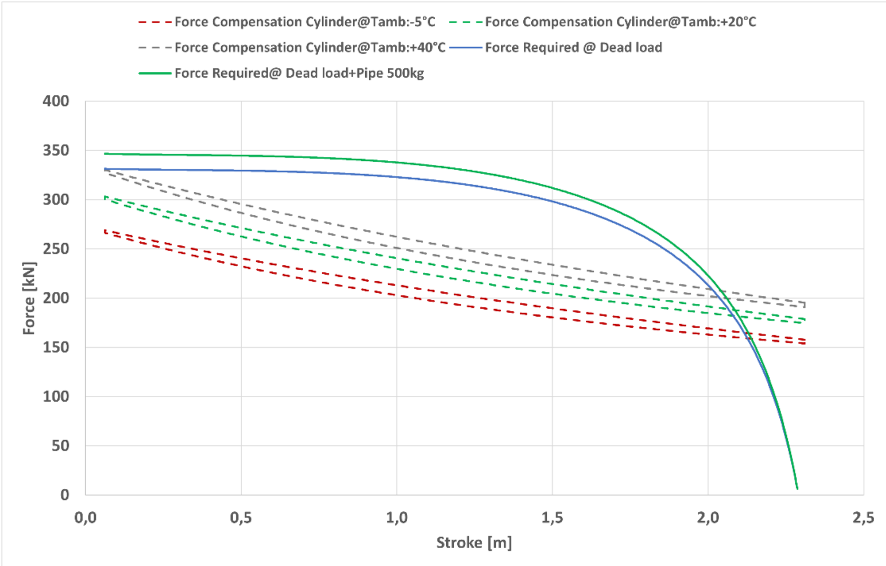

Figure 5.1.: Simulated compensation cylinder Force vs Stroke for varying ambient temperature

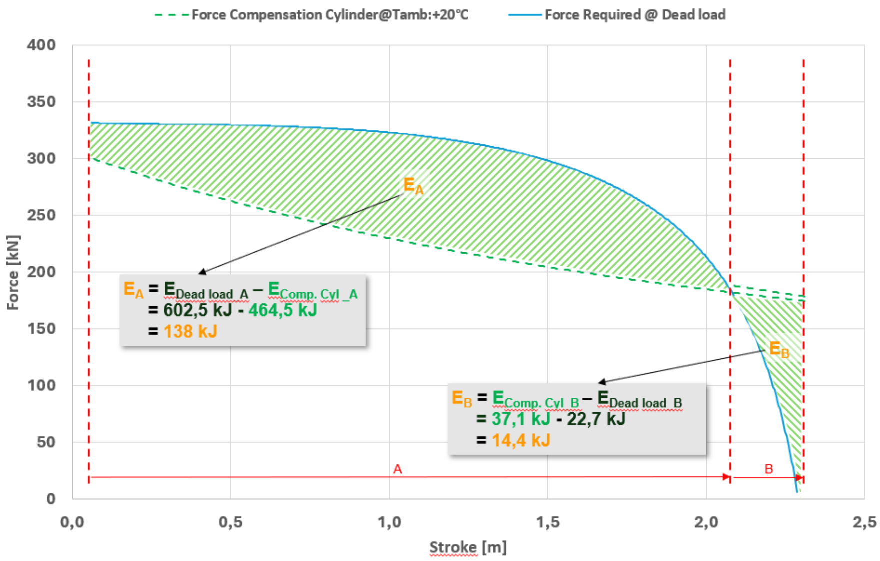

Figure 5.2.: Lift-phase forces and residual (uncompensated) energy segments

Accordingly, this represents the uncompensated energy:

$$E_{uncomp} = E_A + E_B + E_C \qquad (5.6)$$

The effective mechanical energy provided by the compensation system is therefore given by

$$E_{comp} = E_{dead} - E_{uncomp} \qquad (5.7)$$

Hence, when the compensation subsystem is active, the HPU needs only to provide E_{uncomp} while the balance E_{comp} is contributed by the accumulator-assisted compensation circuit. The corresponding fractional reduction in HPU energy demand is E_{comp}/E_{dead}.

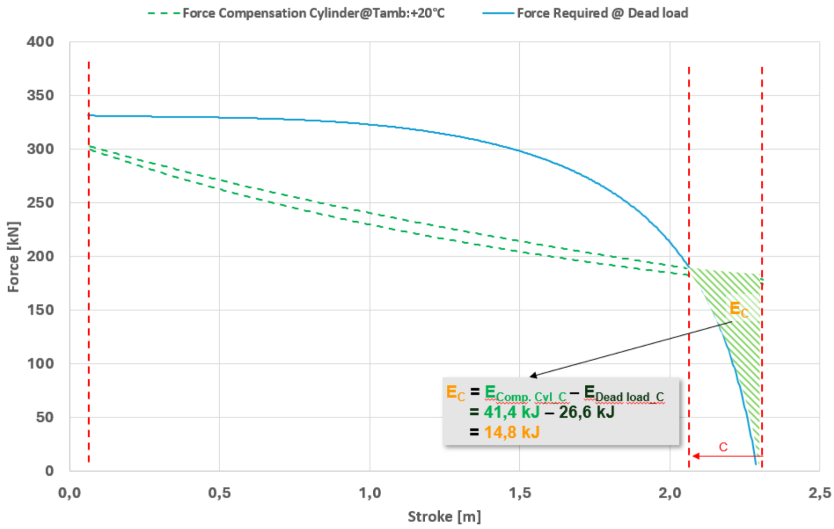

Figure 5.3.: Lowering-phase forces and residual (uncompensated) energy segments

Case 1 – Baseline Dead Load

$$E_A = 138.0\ kJ, E_B = 14.4\ kJ, E_C = 14.8\ kJ$$

Hence Uncompensated work:

$$E_{uncomp} = 167.2\ kJ$$

Compensation contribution:

$$E_{comp} = 625.2 - 167.2 = 458.0\ kJ$$

Energy reduction relative to dead-load energy:

$$\frac{E_{comp}}{E_{dead}} = 0.7326 = 73.26\%$$

Case 2 – Dead Load + 500 kg Pipe

$$E_A = 165.7\ kJ, E_B = 14.4\ kJ, E_C = 14.8\ kJ$$

Hence Uncompensated and compensated work are:

$$E_{uncomp} = 194.9\ kJ$$

$$E_{comp} = 653.9 - 194.9 = 459.0\ kJ$$

And therefore, Energy reduction is :

$$E_{comp}\ /\ E_{dead,new} = 0.7019 = 70.19\%$$

5.3. Results Summary

For the two investigated load cases, the mechanical compensation contribution was 458 kJ and 459 kJ, corresponding to actuator-level energy reductions of 73.3% (dead load) and 70.2% (dead load + 500 kg pipe). It is important to note that the compensation ratios of 70-73% reported here refer to the mechanical load compensation at the actuator level, i.e., the fraction of lifting work provided by the accumulator-assisted compensation cylinder rather than by the boom cylinder. These values therefore describe local energy sharing within a single lifting or lowering cycle and do not yet represent net system-level energy savings at the HPU level.

6. RIG / HPU SCALING FOR FULL DRILL BIT CHANGE

Building on the actuator-level results presented in the previous section, the following analysis scales the pipe-handler energy demand from individual lifting and lowering cycles to a complete drill bit-change operation. In this context, it is essential to distinguish between the local mechanical load compensation achieved within a single cycle and the resulting net hydraulic energy demand at the power-unit level, which is additionally influenced by hydraulic losses, Trip Out operations performed without pipe load, and non-compensated operating phases.

The scaling analysis estimates the HPU energy demand for a full bit-change operation - that is, completely removing a 2,500 m drill string and reinserting it with a new drill bit. Each trip of the pipe handler (PH) corresponds to the movement of one drill pipe joint. A full bit-change therefore consists of successive **Trip Out** and **Trip In** sequences.

Let:

- Dead-load mechanical energy per cycle $E_{dead} = 625.2\ kJ$
- Dead-load + pipe (500 kg) cycle $E_{dead,new} = 653.9\ kJ$
- Compensation energy (dead-load cycle) $E_{comp,1} = 167.2\ kJ$
- Compensation energy (+500 kg cycle) $E_{comp,2} = 194.9\ kJ$
- Pipe joint Length $L_j = 13.72\ m$
- Borehole Depth $d = 2500\ m$
- Number of joints $N = {}^{d}/_{L_j} = 183$

6.1. Per-Cycle and Per-Trip HPU Energy

For hydraulic round-trip efficiency η :

$$E_{C1}(\eta) = E_{dead,new} - \eta E_{comp,2} \quad (6.1)$$

$$E_{C2}(\eta) = E_{dead,new} - \eta E_{comp,1} \quad (6.2)$$

Trip energy (valid for Trip In or Trip Out):

$$E_{Trip}(\eta) = E_{C1}(\eta) + E_{C2}(\eta) \tag{6.3}$$

Here η denotes hydraulic round-trip efficiency (fraction of simulated mechanical compensation that is available hydraulically).

Reference (no-compensation) Trip: $E_{no\_comp,Trip} = E_{dead,new} + E_{dead} = 1279.1\ kJ$

Full Drill bit change total:

$$E_{total}(\eta) = 2 \cdot N \cdot E_{Trip}(\eta) \tag{6.4}$$

Estimated savings:

$$Savings(\eta) = \left(1 - {E_{Trip}(\eta)}\big/{E_{no\ comp,Trip}}\right) \cdot 100 \tag{6.5}$$

6.2. Numerical Results

Hydraulic Efficiency η	**E_{C1} (kJ)**	**E_{C2} (kJ)**	**E_{Trip} (kJ)**	**E_{Trip} (kWh)**	**E_{Total} (kWh)**	**Energy per m (kJ/m)**	**Est. Savings (Mech)**
1.0	459.0	458.0	917.0	0.255	93.23	134.3	**28.3 %**
0.9	478.5	474.7	953.2	0.265	96.91	139.6	**25.5 %**
0.8	498.0	491.4	989.4	0.275	100.59	144.9	**22.7 %**
0.7	517.5	508.2	1025.6	0.285	104.27	150.2	**19.8 %**

Table 6.1.: Simulated mechanical energy per Trip and for full bit-change (2500 m, 183 joints)

The results summarized in Table 6.1. represent the net HPU energy demand for a complete drill bit-change operation when the compensation system is active and Energy per meter refers to total HPU energy normalized by drill-string length. Although actuator-level analysis indicates mechanical load compensation ratios of up to approximately 70-73%, the corresponding system-level HPU energy savings are reduced to approximately 20-30% once hydraulic losses, Trip out operations performed without pipe load, and non-compensated operating phases are considered. These values therefore provide a realistic estimate of the achievable energy reduction under practical operating conditions.

7. PROTOTYPE VALIDATION AND PRELIMINARY RIG TESTS

The hydraulic compensation subsystem and its associated control components were installed on the vertical rig and evaluated during the factory acceptance tests (FAT). These initial tests were performed to confirm basic functionality, safety, and control logic prior to field commissioning. Although limited in duration, they provided valuable insights into system performance under real load conditions.

7.1. Factory and Preliminary Observations

During FAT, a clear difference in boom-cylinder pressure was observed between compensated and uncompensated configurations. The reported pressures represent characteristic average lifting pressures evaluated over the loaded lifting phase used here as a representative measure for estimating instantaneous hydraulic power. The actual pressure varies continuously along the cylinder stroke due to geometry, friction, and dynamic effects.

- **Without compensation (cylinder inactive):** required pressure 176 bar
- **With compensation active:** required pressure: 99 bar

The relative reduction is therefore:

$$Pressure\ reduction = 1 - \left({}^{p_{active}}/_{p_{inactive}}\right) \qquad (7.1)$$

$$Pressure\ reduction = 1 - \left({}^{99}/_{176}\right) = 0.4375 = 43.75\%$$

This reduction corresponds directly to the fraction of lifting force now provided by the compensation circuit rather than by the boom cylinder and hence indicates that the HPU only needed to deliver the residual, or uncompensated, energy E_{uncomp}.

Interpreting pressure reduction as hydraulic power reduction Assuming actuator volumetric flow is approximately unchanged between compensated and uncompensated cases, hydraulic power scales with pressure according to $P_{hyd}(t) = p(t)Q(t)$.

Using the observed pressure change from 176 bar to 99 bar:

$$\frac{p_{active}}{p_{inactive}} = \frac{99}{176} = 0.5625 = 56.25\%$$

i.e. a reduction of 1-0.5625 = 0.4375 or 43.75% in instantaneous hydraulic power. Applied to the analytically estimated, uncompensated reference energy demand for a complete drill-bit change operation energy range varies $P_{inactive} \approx$ 93 to104 kWh, this implies:

$$P_{active} \ = \ 0.5625 \ \cdot P_{inactive} \ = \ 52\ to\ 58.5\ kWh$$

This simplified estimation is directionally consistent with the mechanical load compensation observed at actuator level, while the lower magnitude reflects the net system-level reduction expected once hydraulic losses and non-compensated operating phases are included.

7.2. Comparison with Simulation and FAT Results

Simulation results predict actuator-level mechanical compensation efficiencies of approximately 70-73% under idealized, loss-free hydraulic conditions. In contrast, the 56.25% pressure and corresponding power reduction observed during factory acceptance testing (FAT) represents realistic, loss-inclusive performance, accounting for hydraulic friction, throttling, line pressure losses, and non-ideal accumulator thermodynamics.

The FAT results confirm the fundamental energy-saving principle of the hydraulic compensation system and validate the simulation predictions at actuator level under realistic operating conditions. The observed pressure and power reductions demonstrate effective load sharing by the accumulator-assisted compensation cylinder. It is emphasized that these reductions are derived from characteristic phase-averaged lifting pressures and the resulting instantaneous hydraulic power during specific lifting phases. Net energy savings over a complete drill bit-change operation, however, result from time integration of hydraulic power across all compensated and non-compensated motions and should therefore not be inferred directly from phase-specific reductions.

8. CONCLUSION

This paper investigated the application of accumulator-assisted hydraulic energy recovery to drilling pipe-handling systems, with the objective of reducing hydraulic power-unit (HPU) energy demand during cyclic tripping operations. A combined simulation and experimental approach were employed to quantify both actuator-level mechanical load compensation and resulting system-level energy effects under realistic operating conditions. The study focused on a retrofit-oriented solution compatible with existing geothermal drilling rigs and standard hydraulic architectures

At actuator level, the accumulator-assisted compensation cylinder provided a substantial share of the lifting work during cyclic operation. Simulation results demonstrated mechanical load compensation ratios of approximately 70-73%, indicating that a significant fraction of the required lifting energy can be supplied locally by stored hydraulic energy rather than by the boom cylinder. Experimental force–stroke measurements confirmed the predicted trends and revealed characteristic nonlinearities and hysteresis effects, which were attributed to nitrogen gas compressibility, temperature-dependent pressure variation, and frictional losses within the hydraulic system.

Factory acceptance tests (FAT) further showed pronounced reductions in operating pressure and instantaneous hydraulic power during compensated lifting phases. A pressure decrease of approximately 56% relative to uncompensated reference operation was observed, corresponding to a 43.75% reduction in instantaneous hydraulic power during these phases. It is emphasized that these reductions represent phase-specific, instantaneous effects and should not be directly interpreted as total energy savings without considering the full operating cycle.

To assess rig-level impact, the actuator-level results were scaled to a complete drill bit-change operation, accounting for both compensated and non-compensated motions. The resulting analysis showed that, despite high local compensation ratios, the net HPU energy reduction for a full bit-change operation is limited to approximately 20-30%. This difference arises from hydraulic losses, unloaded return strokes, and operating phases in which compensation is inactive. These findings highlight the importance of system-level integration and time-integrated power analysis when evaluating hydraulic energy recovery concepts.

From a practical perspective, the proposed solution offers a favourable balance between achievable energy savings and implementation effort. The accumulator-based compensation concept can be integrated into existing pipe-handling systems with minimal structural modification and moderate additional component complexity. Under typical geothermal drilling conditions, the resulting reduction in electrical energy demand suggests a payback period on the order of 1-3 years, depending on duty cycle and energy costs.

Overall, the results confirm that accumulator-assisted hydraulic energy recovery represents a technically robust and economically attractive option for improving the energy efficiency of drilling pipe-handling operations. While actuator-level compensation ratios are high, realistic system-level assessments remain essential to avoid overestimation of achievable savings. Future work will focus on extended field trials to validate long-term performance, quantify temperature and aging effects, and refine control strategies for further optimization of rig-level energy efficiency.

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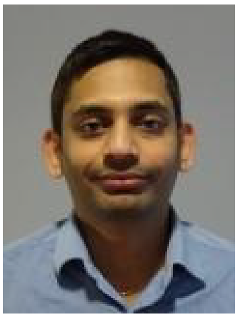
Biographies



Sai Kishore Ayalasomayajula received his Bachelor's degree in Mechanical Engineering from JNTU Kakinada, India in 2009 and his Master's degree in Mechanical/Mechatronics Engineering from Fach Hochschule Kaiserslautern, Germany in 2018. He has over 13 years of professional experience in hydraulic system development and engineering applications. Since 2020, he has been working at Herrenknecht AG, where he currently serves as Group Leader Hydraulics. Prior to this, he worked in various hydraulic development roles at several companies in Germany and India. His professional interests include hydraulic system design, energy recuperation, and rig automation, with a focus on sustainable and efficient drilling technologies.

Jürgen Binder began his career with a three-year apprenticeship as a mechanic before joining Herrenknecht AG in 1982. Over the course of four decades, he has worked across machining, assembly, field service, and engineering functions. Following a degree in Mechanical Engineering, he led engineering of small tunneling systems and later advanced to Project Manager for global tunneling projects. With the establishment of Herrenknecht Vertical GmbH, he became General Manager, responsible for the technical development of advanced deep-drilling systems and currently serves as Technical Director. His key interests include engineering innovation, renewable energy systems, and cost-optimized equipment design for sustainable drilling operations.