Red Diesel Replacement Phase 2

DEPOWER2

Digital Electro-Hydraulic Power module With Energy Recovery – Phase 2

Supported by the Department for Energy Security & Net Zero through the Net Zero Innovation Portfolio

Project Lead Organisation: Danfoss Scotland Ltd.

Project Number: RDR2-01-DFS (con_4308)

Project Duration: 04/07/2023 – 30/06/2025

Total Grant Amount at outset: £4,287,148.98

Contents

Executive Summary

This report presents key findings from a Danfoss product development focused on improving hydraulic efficiency in electric excavators through the Digital Displacement pump/motor (DDP1x0D), enabling energy recovery (Dextreme MAX) and reduction in battery capacity requirement.

The project is led by Danfoss Scotland Ltd., a UK-registered company wholly owned by Danfoss A/S (Denmark) and operating within the Danfoss Power Solutions segment. It is supported under Phase 2 of the Red Diesel Replacement (RDR) Programme, part of the Department for Energy Security and Net Zero's Net Zero Innovation Portfolio (NZIP).

The project delivers a complete end-to-end solution for sustainable heavy machinery, demonstrating how CO_2 neutral electricity from the UK grid can reliably power excavators in demanding environments. By enabling a step change reduction in energy consumption, it supports smaller batteries, lower charging requirements and longer up-time. It is expected to dramatically reduce total cost of ownership of today's 30 tonne electric excavators, achieving lower cost than diesel for the first time.

This project follows on from an initial one-year project (2022/2023) as part of the Red Diesel Replacement (RDR) phase 1 project in which Danfoss, through the completion of 11 dedicated work packages, demonstrated greater than 80% efficiency of energy recovery (hydraulic power to DC power) for the Danfoss pump operating as a motor. The RDR phase 1 project advanced the TRL (Technology Readiness Level) from TRL4 to TRL5. The goal of the RDR phase 2 project which commenced in July of 2023 was to achieve a TRL7 at the project close in June 2025.

Phase 2 focused on real-world integration and validation of the DDP1x0 MAX hydraulic system on a full-scale excavator, culminating in a month long demonstration targeting 80% uptime in construction representative conditions. Rigorous on-site testing verified system performance, durability, and energy recovery, laying the foundation for broader commercial deployment across various off-highway applications. The baseline electric excavator, charged overnight, reduces carbon intensity by over 80% compared to the diesel equivalent with MAX increasing that to 89%.

Product development under this project advanced the solution from TRL5 to TRL7, with most subsystems following suit. The MAX system exceeded its energy reduction target, achieving a 39% reduction in standardised Japan Construction Mechanization Association (JCMAS) test cycles against a goal of 33%. These controlled, repeatable conditions validated performance improvements and highlighted further potential through ongoing hardware and software optimization. During the site trial, the vehicle maintained the target 80% uptime, with highly positive feedback from the expert operator, reinforcing the commercial viability and value proposition of the DDP1x0 MAX system.

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Glossary/Abbreviations/Acronyms

RDR2: Red Diesel Replacement – phase 2
ADC: Application Development Centre
APC: Advanced Propulsion Centre UK
ASME: American Society of Mechanical Engineers
CAE: Computer Aided Engineering
CAN: Controller Area Network (bus)
cc: cubic centimetres, cm^3
CO_2: carbon dioxide
Cynefin: A decision-making model developed at IBM by Dave Snowden in 1999.
DD: Digital Displacement
DDP: Digital Displacement® Pump
DDPM: Digital Displacement® Pump Motor
DDP096: Digital Displacement® Pump with 96cc displacement
DDP096T: Two DDP096 pumps assembled in a tandem configuration
DDP1x0D : Double Digital Displacement® Pump Motor with 2x 110cc..190cc displacement, depending on installed crankshaft
DDP1x0 MAX: Danfoss' pioneering DD Pump Motor system with regeneration capabilities, scalable from 110cc to dual 190cc configurations
DDP180D: Double Digital Displacement® Pump Motor with 2x 180cc displacement
DEPOWER2: Digital Electro-hydraulic Power module With Energy Recovery-phase 2
DESNZ: Department of Energy Security & Net Zero
Dextreme: Danfoss integration pathway for DD into excavators with SWAP, FLEX & MAX system architectures
DMP: Danfoss Motion Platform
DPC30: Digital Displacement® Pump Motor (electronic) controller for DDP1x0D
FLEX: Second Dextreme system architecture: SWAP plus dynamic allocation of pump capacity between services (ganging)
FLEX+: Dextreme system architecture: FLEX plus H-Bridge control of at least one actuator
FMEA: Failure Modes and Effects Analysis
FMI: Functional Mock-up Interface
FMU: Functional Mock-up Unit
FPGA: Field Programmable Gate Array
FPGA/SoC: Field Programmable Gate Array as a System on Chip
FPMC: ASME symposium on fluid power and motion control
FRM: Forth Resource Management Ltd – demonstration partner
HEX: Hydraulic Excavator
HILS: Hardware-In-the-Loop test System
IC: Integrated Circuit
ISO: International Organization for Standardization
ISO/TS: International Technical Specification
JCMAS: Japan Construction Mechanization Association
JFPS: Japan Fluid Power System Society
LS: Load Sense
MAX: Third Dextreme system architecture: FLEX+ plus DDPM capable of recovering energy from at least one H-bridge actuator(s)
MBD: Model-Based Design
MCR: Motion Control Rig

MP:	Member of Parliament
NVH:	Noise, Vibration, and Harshness
NZIP:	Net Zero Innovation Portfolio
OEM:	Original Equipment Manufacturer
PCBA:	Printed Circuit Board Assembly
PVG:	Proportional Valve Group
QPS:	Quantised Part-Stroke
rpm:	revolutions per minute
RTV:	Room Temperature Vulcanising. A silicone-based thermal interface material that cures at room temperature
SBTi:	Science-Based Targets initiative
SoC:	System on Chip. A single-chip solution combining a processor and FPGA logic, used in earlier design DDC15 for compact, high-performance valve control.
SWAP:	First Dextreme system architecture: replace original pump with DDP, may include modification of torque control of hydraulic system
TCO:	Total Cost of Ownership
TRL:	Technology Readiness Level
TRL4:	Technology Readiness Level 4. Technology is validated in a laboratory environment, confirming basic functionality under controlled conditions.
TRL5:	Technology Readiness Level 5. Technology is validated in a relevant environment, transitioning from lab testing to early field trials.
TRL7:	Technology Readiness Level 7. Technology is demonstrated in an operational environment as a functional prototype, proving system maturity and readiness for real-world use.
TS:	Technical Specification
QPS:	Quantised-Part-Stroke
WP:	Work Package
WP1:	WP 1: DDP1x0 Controller DDC15 and DPC30
WP2:	WP 2: DDP1x0D hardware
WP3:	WP 3: MAX DD Model-Based Design system
WP4:	Software on Digital Pump Controller
WP5:	System Application Software
WP6:	System Safety Concept
WP7:	Excavator Conversion Activities
WP8:	System Simulation
WP9:	Excavator Demonstration and Test
WP10:	Project Reporting

Background

Company information

Founded in 1933 by Mads Clausen in Nordborg, Denmark, Danfoss has grown from a solo enterprise into a global leader in energy-efficient and innovative solutions.

Today, Danfoss employs approximately 40,000 people across three core segments:

1. Danfoss Power Solutions: Providing full solutions capabilities in mobile and industrial hydraulics, fluid conveyance, electrification, and software.

2. Danfoss Climate Solutions: Providing energy-efficient heating and cooling solutions for industrial applications, buildings, infrastructure, and the entire food and cold chain.

3. Danfoss Power Electronics and Drives: Providing clean-energy solutions including alternating current drives, power semiconductor modules, and electrification in automotive and various industries.

Danfoss Scotland Ltd., a UK-registered entity wholly owned by Danfoss A/S (Denmark), operates within the Power Solutions segment. The project team was primarily based at the Edinburgh R&D centre, with support from colleagues in the UK, Denmark, Germany, and the USA. Danfoss Scotland Ltd. currently employs 49 staff.

Project background

In Phase 1, a prototype Digital Displacement pump/motor was developed to enable energy recovery and proven at expected efficiency levels in a test rig.

The Phase 2 project integrates this into a large battery/electric excavator with the aim of demonstrating significant reduction in the required battery capacity in an operational environment. We also targeted an increased maturity of sub-components (machine, controller, software and system hardware) and developed simulation tools to accelerate development.

Raising the maturity of the system and components and demonstrating them as a functional prototype within a real-world operational environment (achieving Technology Readiness Level 7, or TRL7) will enable us to win Original Equipment Manufacturer (OEM) commitment to take to market in series production.

Hydraulic systems are commonly used in off-road construction and quarrying vehicles such as excavators. In a traditional system, an engine-driven variable-displacement pump supplies fluid to valves that control hydraulic cylinders (Figure 46.1, Figure 54.1). However, this setup suffers from inherent efficiency limitations (Figure 49, [1]).

Poor component efficiency of the conventional pump results in 18% of the mechanical power delivered by the engine being wasted. Throttling the flow in proportional valves wastes a further 37% (Figure 52, [1]). Energy is wasted which could be recovered, such as from lowering the boom, or slowing the swing, a further loss of 15%. Overall efficiency from engine flywheel to actuator power is only 30% [1].

Typically, battery-electric excavators swap the engine for an electric motor (Figure 46.2) without altering the hydraulic system, resulting in up to 70% energy loss. This inefficiency demands oversized batteries and excessive charging energy [2]. Improving system efficiency is widely recognised as essential for viable electrification [3].

Digital control enables better diagnostics and supports automation, with response times 3–4 times quicker than swashplate systems. Its deterministic behaviour and software-driven architecture allow model-based design and simulation-led development, accelerating time to market for advanced integrated systems (Figure 51).

The DDP096 (Figure 55.2,3) is a 12-cylinder radial piston Digital Displacement pump with a 96 cc maximum displacement. It has been demonstrated in both single and tandem (DDP096T) configurations. In 2016, a JCB 16-tonne excavator "Dexter" (Figure 47) equipped with a DDP096T and conventional architecture (SWAP) showed a 16–21% fuel reduction (Figure 52).

From 2018, Dexter was upgraded to the FLEX architecture (Figure 48, Figure 54.2) which splits the pump into independent units digitally linked to outlets based on demand, reducing throttling losses. This achieved a 33% fuel reduction (Figure 50). The DDP096 was not used as a motor in this configuration.

In 2020, the DDP1x0 development started (Figure 56), a larger machine with 15 cylinders, suitable for excavators >20 tonnes with prime movers around 200kW. It had the potential to act as a motor as well as a pump (pump motor), although it was initially incapable of this due to valve limitations.

In 2021, the FLEX project developed the FLEX system further to reduce throttling losses (Figure 54.3). When combined with the Digital Displacement (DD) Pump Motor (DDPM), this forms the originally proposed MAX architecture for this project (Figure 54.4).

In March 2022, the DEPOWER1 project launched, upgrading the DDP1x0D with a new valve enabling motoring. Test rig results showed an exceptional 96.5% efficiency for a hydraulic machine (Figure 57). The design reached TRL5, with packaging studies confirming excavator compatibility and TCO analysis indicating that MAX could reduce lifetime costs of battery-electric excavators below diesel equivalents (Figure 58, Figure 59)

Project Overview

Project Scope

The project aimed to demonstrate a step-change in energy efficiency by integrating the MAX architecture (Figure 46.3) into a 30-tonne battery-electric excavator. It also sought to cut CO_2 emissions by enabling charging from low-carbon or renewable sources. Testing required new embedded software for dynamic operation and endurance trials to improve reliability. Key developments included the ruggedised DPC30 controller, ganging block, and H-bridge. By the end of the project, the full system (DDP1x0, DPC30, hardware, and software) was to be validated in a real-world setting, achieving TRL7.

Aims at outset

Reduce the energy consumed by >33% (Based on system modelling)

This was to be measured as the average DC power drawn from the battery while operating at a standardised work rate (fixed T/h throughput). Instrumentation was to record cylinder pressure, extension, and DC input (current and voltage) to calculate system energy efficiency.

Gain feedback from operating the system in a realistic environment.

Feedback was to be collected from operators using a scoresheet covering controllability, noise/vibration, productivity, reliability, and practicality. Operational experience with battery swapping was to provide insight into the value of the MAX system by reducing battery handling mass.

Increase the TRL of the core components so that the system can be evaluated as a pre-production sample by major excavator OEMs by the end of the project.

Individual components were to reach pre-production maturity with reliability sufficient for OEM evaluation and potential commercialisation, supported by a detailed simulation model.

Benefits:

- Scalable to the full range of large excavators used in quarry and construction work.
- Manufactured in the UK from common recyclable materials.
- Potential to reduce energy consumption by up to 50%, reducing cost and resource consumption of required batteries and energy consumption during charging.
- Digital control enables rapid development, onboard diagnostics and a pathway to automation.

Schedule

The project was tracked within Microsoft Project under a waterfall methodology with targeted sprints. Code was generated so that the Gantt chart view was colour coded for completed workstreams and deliverables (green); in progress deliverables (yellow) and in progress workstreams (red). The project schedule near completion (Figure 62) is provided in appendix one.

Work packages

The DEPOWER2 project from Danfoss was divided into 10 work packages (WPs):

WP1: Development of an electronic controller to enable control of the DDP1x0D for pumping and motoring.

WP1 focused on designing a new controller with the aim of developing previous designs and concepts. The goal was to provide the correct number of channels for controlling and operating the pump valves, as well as accommodating the required number of sensor inputs.

WP2: DDP1x0D hardware: digital displacement pump/motor

WP2 was concerned with the development of the core DDP1x0D pump motor hardware. The core objectives were delivery of DDP1x0D prototype for the hydraulic excavator (HEX) conversation and TRL advancement of DDP1x0D platform.

WP3: Model-based development of the control for the MAX system

WP3 was dedicated to designing the hydraulic and control systems for DEXTREME MAX, including layout definition and hardware selection for a 30T excavator to be installed during WP7. The control system was developed using a model-based design (MBD) approach and calibration strategies for DDP1x0 pumping/motoring were evaluated.

WP4: Software on Digital Pump Controllers DDC15 and DPC30

WP4 focused on developing embedded software for the digital pump controller, translating high-level flow demands into real-time commands for each valve solenoid. The software was also to monitor pump and system conditions, report to the user, and assess pump health.

WP5: System Application Software for controlling the excavator

WP5 was dedicated to integrating the software components from WP3 into the final machine controller, which would act as a supervisory controller for both the prime mover and hydraulic system developed in WP3.

WP6: System Safety Concept

WP6 was responsible for designing operational and functional safety requirements for both operators and bystanders.

WP7: Excavator Conversion Activities

WP7 focused on the procurement, conversion, start-up, and tuning of a DX300LC-7K electric excavator from baseline to the MAX system. Originally a diesel-powered DEVELON® DX300, the machine was converted to fully electric by STAAD B.V., a Dutch company specialising in electric construction equipment. After benchmarking, a full rebuild was carried out, from prime mover to actuators, including hydraulic and electrical systems. The MAX architecture was compared to the original and fault insertion testing was performed to ensure safety.

WP8: 3D System Simulation

WP8 aimed to develop a high-fidelity 3D system simulation and virtual test environment for control development and Human-in-the-Loop testing. Key objectives included selecting a suitable simulation tool, building a full excavator model (control, hydraulics, terrain), and implementing the Human-in-the-Loop setup on the Danfoss Motion Platform (DMP).

WP9: Excavator Demonstration and Test

WP9 focused on preparing and executing the demonstration, including controlled performance tests and a one-month field trial. The DEPOWER2 excavator was deployed in a real working environment with a professional operator to validate performance, durability and energy efficiency. Controlled tests used repeatable duty cycles, while the field trial assessed operability and uptime. Energy use and runtime improvements were measured and analysed.

WP10: Project Execution and Reporting activities

WP10 managed project execution and reporting for monthly, quarterly, stage gate and steering committee meetings. It included change management and maintenance of Department of Energy Security & Net Zero (DESNZ) reporting templates: the Project Plan and Finance Table, Project Cost Breakdown Form, and risk log. DESNZ Key Performance Indicators (KPIs) were regularly reported to track project success.

Financial information:	Original baseline budgeted cost	£7,677,657.98
	Original baseline grant size awarded	£4,941,809.00
	Actual grant claim	£4,260,521.05

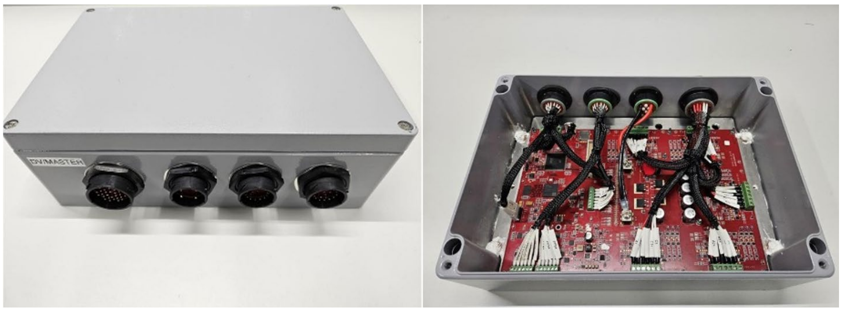
Design Considerations, Technical Development and Challenges

WP1 Development of an electronic controller to enable control of the DDP1x0 for pumping and motoring

WP1 focused on designing a new controller with the aims of providing the requisite number of channels for controlling and operating the pump valves and for the required number of sensor inputs. The DPC30 developed under the DEPOWER2 project is intended to be a single pump controller capable of controlling all 30 DDP1X0D pump valves in a mobile off-highway application and be tolerant to and survive in the off-highway mobile environment. The learnings from previous developments of the DPC12 Mk1, DDC15 and DPC12 Mk2 also provided the opportunity to rationalise the circuit architecture and make a more robust design based on pump controllers.

The DDC15 which was the subject of the RDR phase 1 project (WP5) was used to develop the firmware for the low-pressure valve closing detection and re-opening. Bench top testing verified highly consistent and repeatable current profile allowing accurate valve switching. The DDC15 prototypes were installed on test rigs and on the Danfoss DEPOWER2 Hydraulic Excavator and were validated in both test setups. The onboard improvements of coil driver chips, microcontroller and FPGA were carried forward to the new DPC30 controller, which is purpose designed for mobile equipment.

Figure 1: DDC15 Controller Prototype



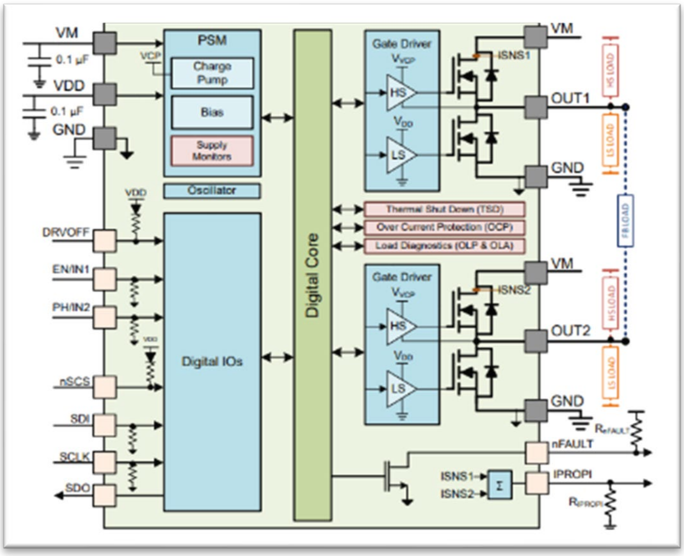
Building on the DDC15 prototype, the DPC30 used the same STM32F765II microcontroller, retaining the processing speed, memory, I/O, and Digital Signal Processor needed for motoring valve control. The FPGA was changed from Xilinx ZYNQ to Artix 7, already used in Danfoss products and offering cost benefits. Future upgrades may require returning to ZYNQ for enhanced valve performance. The firmware was rewritten to match DDC15 valve control and added benefits such as open-source Wishbone bus, Git/Azure DevOps version control, testbench validation, and support for multiple current profiles.

Figure 2: DPC30 Controller Enclosure and PCBA

The FPGA controls the coil driver circuits (Figure 3) and diagnostics through the Serial Peripheral Interface, this protects the driver chips and also allows for current sensing for closed loop feedback current control of the pump valves.

The integrated circuit (IC) coil drivers shown are specified to have high current capacity (32A) to accommodate both pumping and motoring. They have a reduced circuit footprint compared to the DDC15 as the IC incorporates the gate drivers, this allows a much smaller closely arranged printed circuit board as shown in the image above, this has reduced cost and space which are important for mobile off-highway applications.

Figure 3: Coil Driver IC



As a result of the rationalisation of components in the DPC30 and decreasing footprint of the PCBA, the need to dissipate excess heat during high load periods is crucial to functionality and survivability of the controller components. The DPC30 controller uses a thermally conductive silicone layer between the PCBA and the aluminium base plate to conduct heat away from the PCBA. The base plate is used as a heat sink to conduct heat to the mounting fixture.

The enclosure is bonded to the aluminium baseplate, while the cover is laser welded. This assembly method ensures highly reliable environmental sealing to protect the controller internals and is considered more robust for the operating and maintenance environments, exposures, and severities expected in an off-highway mobile application.

Testing in accordance with Danfoss electrical test standard 504H0027 has demonstrated a robust electrical design. The DPC30 has shown to be stable across a range of input voltages from 9-38V and resistant to reversed polarity inputs between -/+36V. It is equally robust against short to ground/ battery; components were shown to be undamaged and operational after testing.

Emissions testing has verified the DPC30 controller is compliant to ISO standard 13766-1 for radiated emissions (Earth-moving and building construction machinery — Electromagnetic compatibility (EMC) of machines with internal electrical power supply). Automotive transient testing was passed in May 2025 after some circuit modification (load shunt and higher rated Field-Effect Transistor), this includes a cold cranking test and load dump test.

Figure 4: Electrical Testing

In conclusion, the development and testing of the DPC30 controller within the DEPOWER2 project successfully met the design goals. These included reducing component count and physical size, while improving functionality and reliability at a lower cost; building on the foundations of the DDC15 prototype and earlier DPC12 controllers.

WP2 DDP1x0D hardware: digital displacement pump/motor

Work Package 2 (WP2) focused on two primary objectives

- The delivery of the DDP180D prototype for HEX conversion and;
- The advancement of the Technology Readiness Level (TRL) of the DDP1x0D platform from TRL5 to TRL7.

Both goals were successfully achieved, with significant technical progress made throughout the project.

Delivery of DDP180D prototype for HEX Conversion

The DDP180D prototype was delivered to Nordborg, Denmark on 28 June 2024 for integration into the HEX system. The pump operated as intended, with the only notable issue post-conversion being sensitivity to cold or high-viscosity oil. This affected valve response times and required recalibration.

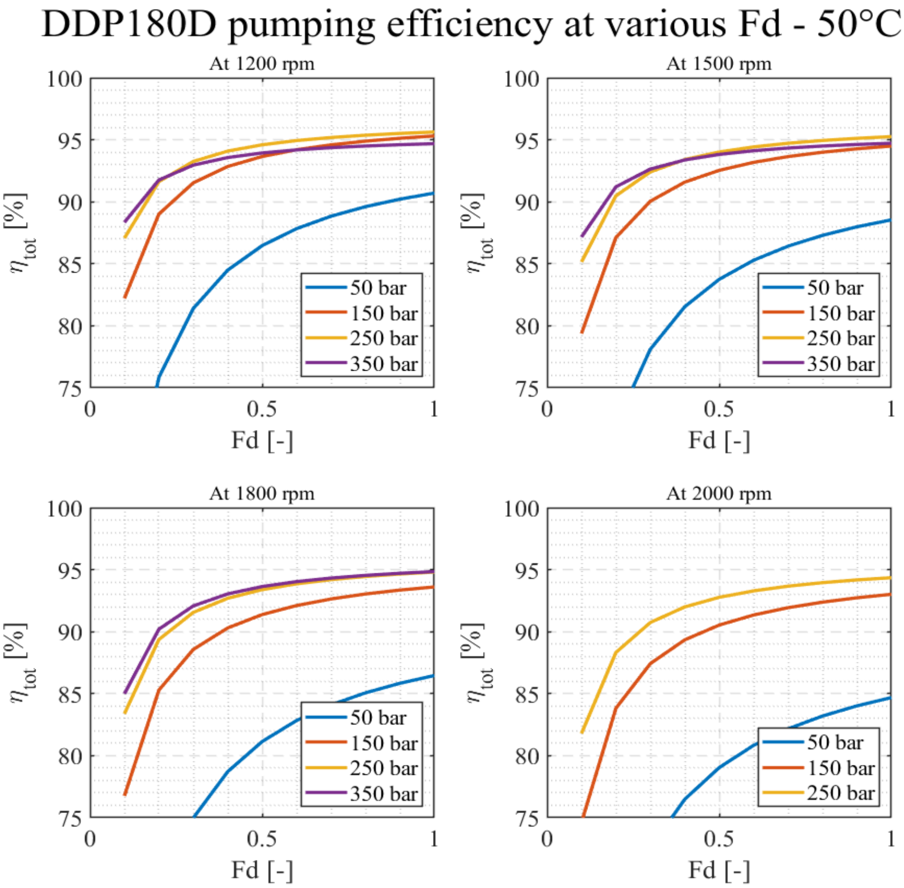
Figure 5: Final hands-on HEX conversion pump prior to shipment (17/06/2024)

Prior to delivery, several challenges were addressed, primarily related to hardware quality. Multiple batches of components were screened to ensure compliance with design specifications. Additionally, a wear issue was identified during early endurance testing. This was resolved for the HEX pump by replacing a key valve component and carefully lapping its sealing surfaces. Subsequently, the issue was addressed in the design phase by selecting improved material combinations that eliminated the need for lapping.

The TRL advancement of the DDP1x0D platform was supported by extensive design validation, combining physical testing with computer-aided engineering (CAE). More than ten prototype pumps were built, including single units representing half of a double pump. These prototypes underwent rigorous performance testing, achieving peak efficiencies of 95% or higher under typical excavator operating conditions—specifically at 1200–1800 rpm and around 250 bar. The DDP technology demonstrated minimal efficiency loss at reduced displacement fractions, a key advantage over traditional swashplate pumps. This is due to the DDP’s selective pressurisation of only active cylinders, reducing idling losses and improving overall energy efficiency.

Figure 6 shows pumping efficiency data for the RDR2 DDP180D installed in the HEX converted in this project. As mentioned above, efficiency peaks at around ~95% when operating at 1200-1800 rpm and at ~250 bar

Figure 6: Efficiency data for the RDR2 HEX machine, as a function of Displacement Fraction (Fd) for different speeds and pressures

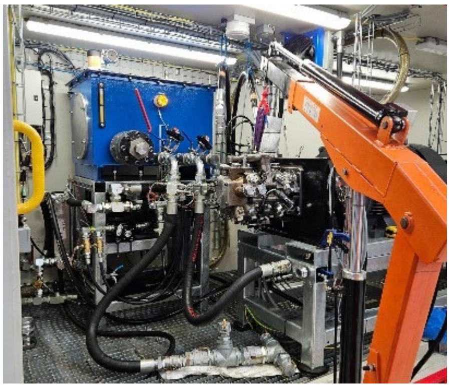


Performance testing confirmed that the pump met a wide range of customer requirements, including fill speed, valve consistency, burst pressure, and operation across temperature extremes. When using components within specification, the pump consistently delivered reliable results. Valve leakage and actuation speed data showed low inter-valve variation, which is critical for precise flow control and maintaining intended noise, vibration, and harshness (NVH) characteristics. Work is ongoing to further improve NVH and to develop control software that can accommodate greater variation in valve behaviour.

Endurance Testing

Endurance testing was a major focus of WP2, with over 5,400 hours of testing completed across 73 separate runs. The pump was subjected to extreme conditions, including 1.5 million pressure cycles at 380 bar, maximum pressures of 535 bar, speeds up to 3000 rpm, and temperatures reaching 100°C. These tests were designed to accelerate wear and expose potential weaknesses. Since the first endurance test in December 2022, numerous design optimisations have been implemented, resulting in a robust pump that now consistently passes endurance testing, even under highly accelerated conditions. Some endurance testing will follow with the bearing assembly stack and customer specific testing following engagement Figure 7 shows a DDP1x0D pump being installed into one of our bespoke test rigs.

Figure 7: DDP150D-X4 being installed in LTS9 test rig for high power endurance test



TRL Development

At the start of the project, the TRL of the DDP1x0D platform was 5, indicating partial validation on our laboratory test rigs. By the end of WP2, the TRL had risen to 7, signifying successful demonstration in operational environments. In addition to the DEPOWER2 project, the technology has been trialled with potential customers on their excavators. Following the successful demonstrator trial, plans are underway to initiate field trials in 2026 involving multiple excavators operating under real-world conditions.

Conclusions

In conclusion, WP2 has delivered a fully functional HEX prototype and significantly advanced the performance, reliability, and readiness of the DDP1x0D platform. The pump now meets stringent performance and endurance requirements, and its TRL progression has positioned the technology for broader customer engagement and field deployment.

WP3 Model-based development of the control for the MAX system

Figure 8: Sankey diagram of excavator losses for a 30T excavator performing dig and dump

WP3 focused on developing DEXTREME MAX, the most advanced hydraulic architecture in the DEXTREME series, aimed at significantly improving excavator efficiency. A model-based design (MBD) approach was adopted to target a 33% energy reduction over typical duty cycles

Crawler excavators consume around 800 kWh daily, with current systems operating at ~30% efficiency. Losses stem from pump inefficiencies, fluid distribution, and unrecovered energy during braking. DEXTREME MAX addresses these through Digital Displacement technology, enabling independent actuator control, reduced throttling losses, and full energy recovery—critical for electric excavators with limited motor down-speeding benefits.

Figure 9: MCR development

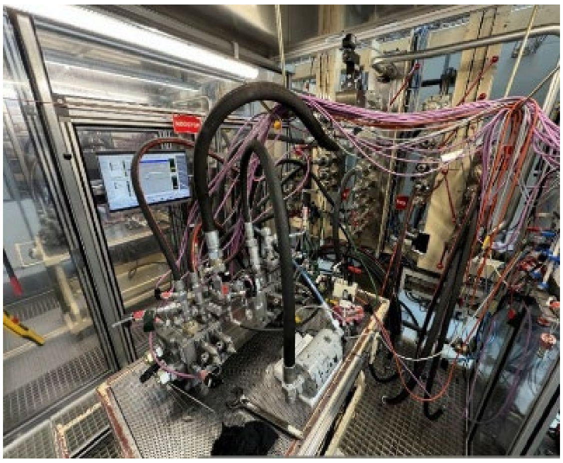
Overview of the technical development

WP3 comprised five interlinked technical workstreams. In the first of these, a **Motion Control Rig (MCR)** was developed to simulate excavator dynamics, featuring a 10-tonne boom structure for realistic testing. This rig supported validation of control algorithms and hardware components, including the H-Bridge and DD motoring control.

Hydraulic System Design: Hydraulic system redesign began with a comprehensive analysis of the existing DX300LC-7K (electric) excavator architecture, revealing challenges such as internally connected pilot lines and reliance on pilot signals for slew lock functions. Solutions included electronic overrides for virtual bleed-off valves, electronic hose burst valves, and pilot shut-off valves. These features allow seamless switching between MAX and SWAP modes while preserving arm and bucket functions.

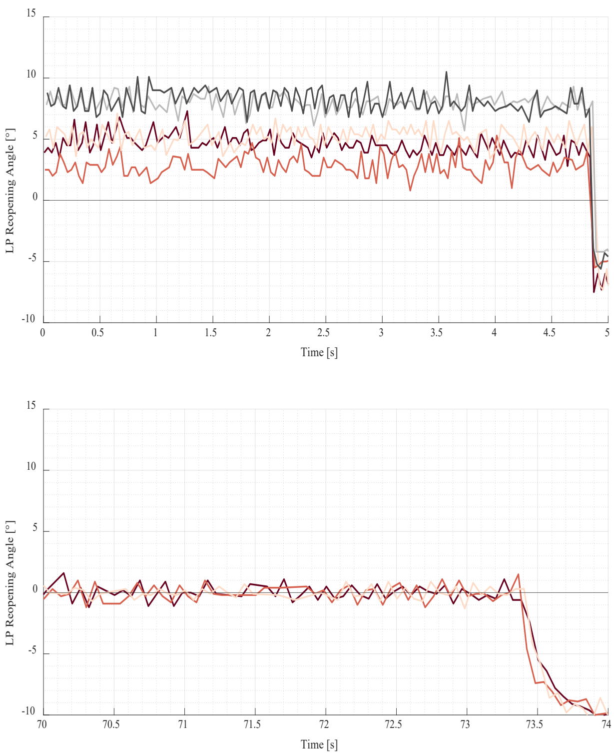
Hardware Design, Component Selection, and Testing: The hardware design prioritised custom components, such as the ganging block, which dynamically allocates pump outputs through specially engineered digital valves to enhance system flexibility. Rigorous testing validated the successful integration and performance of these components. An example of component testing is illustrated in Figure 10.

Figure 10: H-Bridge Boom and Swing PVG® on the test bench



Digital Displacement Pump/Motor Software Calibration Development: Software calibration for Digital Displacement pumps/motors was developed using closed-loop feedback and calibration curves (Figure 11), enabling precise control and advanced motoring functions.

Figure 11: Valve reopening angle in Open (top) and Closed (bottom) loop MStop

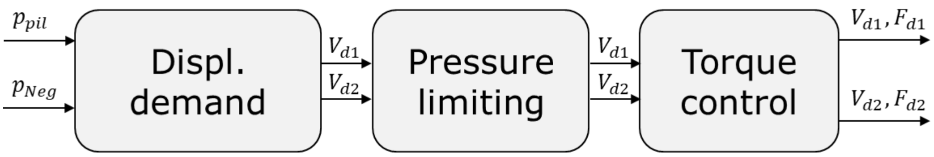


Development of System Controller through MBD

The system controller was built using MBD and simulation, starting with a smaller-scale platform. A validated forward-facing simulation model captured operator inputs, actuator dynamics, and hydraulic behaviour, supporting development of both SWAP and MAX configurations. This approach was critical for development of the MAX system as it features significant hardware and software modifications compared to the baseline excavator.

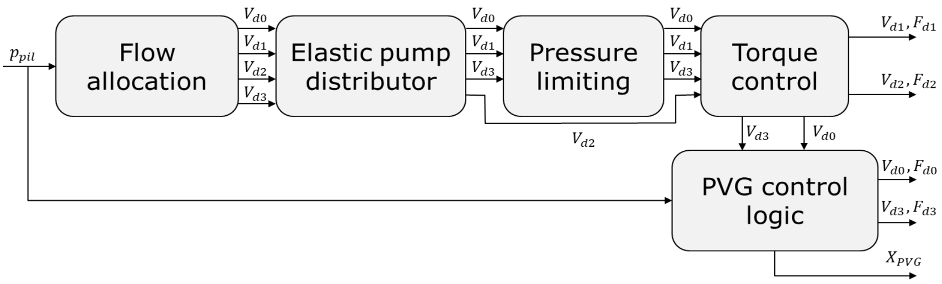
SWAP (Figure 12) integrates an electric motor and DDP, using fractional displacement (Fd) commands based on pilot or service pressures. Key control blocks include displacement demand, pressure limiting, and torque control. MAX (Figure 13) extends this with additional PVG® valves and an elastic pump distributor, enabling dynamic flow allocation and full pressure control per actuator. MAX also supports energy recovery via state-of-charge monitoring, anti-lift-off and advanced torque distribution.

Figure 12: Controller structure SWAP



The MAX solution also includes independent metering valve arrangements, enhancing efficiency and enabling advanced regenerative and differential actuation modes. Cavitation prevention during boom lowering is achieved through differential control or boosted return pressure via a hydraulic integrated circuit.

Figure 13: Controller structure MAX



Control logic combines feed-forward and proportional-integral-derivative strategies, using calibrated lookup tables for smooth response and efficient energy recovery. JCMAS cycles confirmed accurate trajectory tracking and cavitation avoidance. The MAX controller, with its advanced adaptive hydraulic controls and independent metering, significantly reduces energy losses compared to conventional architectures, optimizing excavator productivity and efficiency.

Testing on the MCR

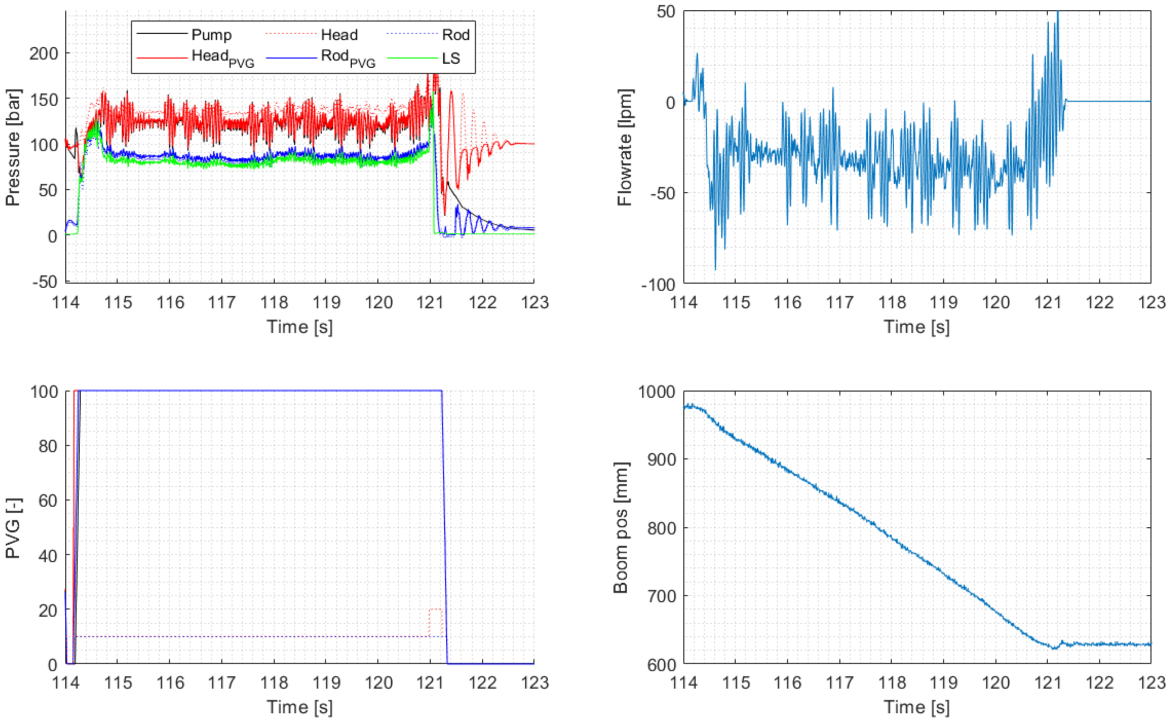
Testing on the MCR validated the complex H-Bridge control, responsible for four-quadrant operation and direct ram control. Initial tests on a scaled PVG32 setup confirmed valve behaviour and control stability across three scenarios:

1. Full Throttling Only (No Motoring):
    - Smooth, easily controllable boom movement.
    - PVG spools managed head pressure effectively through regulated throttling, achieving stable actuator performance.
2. Partial Throttling and Differential Mode (No Motoring):
    - Initial transient drop in actuator position due to sudden pressure changes when entering differential mode requires more control development.
    - The controller maintained stable rod chamber pressure (~60 bar), ensuring controlled boom descent. Optimisation opportunities exist to enhance initial response smoothness.
3. Differential Mode with Motoring
    - Utilised motoring for refined control.
    - Observed quicker convergence and better control, maintaining desired rod pressure (~90 bar).
    - Noted oscillations linked to earlier calibration issues, later resolved through DD180D adjustments in subsequent excavator implementations.

Figure 14 shows data from testing scenario 3; lowering the boom in differential mode with motoring. The pressure plot shows differential mode successfully boosting the head pressure from ~100 bar to ~130 bar, with the rod pressure matching the target of ~90 bar, which corresponds to the Load Sense (LS) pressure. Negative flowrate indicates motoring in the DDPM as the boom was lowered which signified energy recovery, with the position plot showing steady motion. The head pressure and flow plots both show significant pulsation, from calibration issues with the DDPM which were rectified before conversion of the excavator. Overall, this test showed the MAX hardware and control system could work together to recover energy in this key control mode, while maintaining actuator control.

The tests on the MCR successfully demonstrated that the PVG-based H-bridge control approach effectively manages complexity and provides a robust foundation for precise and responsive hydraulic control in various operational scenarios.

Figure 14: Boom down controller validation on MCR platform - differential mode and motoring mode



Conclusions

WP3 successfully delivered a redesigned hydraulic system compatible with DEXTREME MAX and SWAP. It also developed and validated key components and built a robust simulation model to support control development.

The MCR enabled early validation and tuning, reducing final installation risk. The work laid a strong foundation for efficient, responsive, and energy-recuperative excavator control systems. The work carried out during WP3 was essential for building confidence in the system and reducing testing time. It also helped identify potential issues early and supported the development of solutions ahead of final installation.

WP4 Software on Digital Pump Controllers DDC15 and DemsionsPC30

The embedded software in digital pump controllers translates system-level flow demands into real-time commands for pumps and motors, managing valve solenoids, monitoring system conditions, and assessing pump health. Initially, the software supported DDP096 pumps with DPC12 controllers for off-highway applications. WP4 aimed to deliver two new software variants:

- DDP1x0 pump software on the DPC30 controller for excavators.
- DDP1x0 pump-motor energy recovery software on DPC30 for demonstration.

Excavator-compatible software feature maturation

The first work in the project was to adapt the existing production software for excavators using the available DDP096T platform. This required specification of excavator-compatible software features. Working groups, consisting of representatives from software, systems, and customer support teams, developed specifications for the required features. These proposals were then reviewed by the wider Digital Displacement software and systems teams to ensure alignment and completeness.

Following the specification, the identified features were implemented within the Danfoss global software development quality process. This ensured core quality through a structured approach, with all features following a requirements, design, and test cycle. Requirements were specified in a formal requirements tool and thoroughly reviewed. Embedded software for the features was designed and coded, adhering to best practices and coding standards. Testing was undertaken using an existing automated hardware-in-the-loop test system (HILS) to verify the functionality and performance of the implemented features.

Finally, excavator verification was performed. Initial excavator trial tests were repeated on the DDP096T excavator to judge the success of the added features. The software performed well, with NVH and control issues effectively addressed. This resulted in an excavator-compatible Production software base that is available for further work.

DPC30 software feature development, maturation, and support

Software was extended to support the new DPC30 controller, incorporating lessons from prototype trials and Failure Modes and Effects Analysis (FMEA). Key updates included adapting to DPC30 hardware interfaces and enhancing the error system to support service-specific fault responses.

Testing via HILS revealed reliability issues with pogo-pin connectors, prompting a redesign for improved mechanical stability. Excavator trials were repeated with the prototype DPC30 hardware. The software performed well, with NVH and control issues resolved. The software base on DPC30 was successfully made ready for converting to control a DDP1x0 pump.

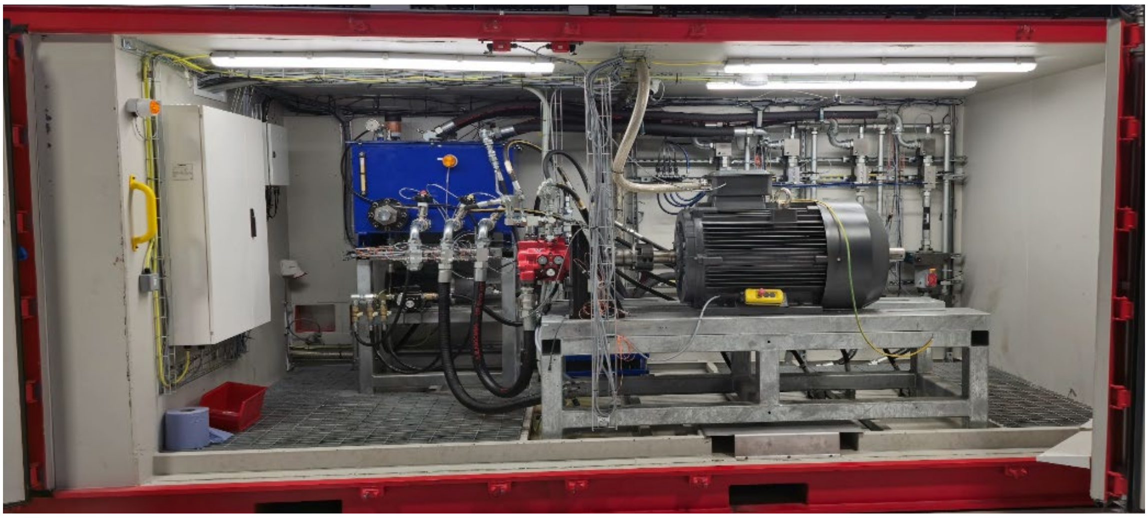
DDP1x0 frame software feature maturation

To complete the customer specific DDP1x0 pumping software, support was added for the DDP150D pump, which was designed for two service SWAP or FLEX excavators. Adapting the existing software was necessary to meet the specific control and performance characteristics of the DDP150D pump. This process involved cross team collaboration, including input from pump design and failure mode and effects analysis, to ensure a robust system design.

A new software test rig was specified to support production-level testing of DDP1x0 software for excavators. The rig’s capabilities and performance requirements were carefully defined. Its design and installation involved sourcing mechanical, hydraulic, and electrical components, and proved more complex than expected. The skills needed for a software-focused test rig differ from those for typical hydraulic performance rigs. Future rig development should be led by engineers experienced in system-level hydraulic testing rather than component-level testing.

After commissioning with a DDP096T pump, the rig was upgraded with a DDP150D pump for full testing. Embedded software was completed and tested using HILS, which was upgraded to replicate DDP150D connections for realistic simulation of pump behaviour.

Figure 15: Complete software test rig during commissioning



Motoring and energy recovery features, R&D and support

A component-level needs assessment identified required low-level components, developed and tested through bench, rig, and excavator trial

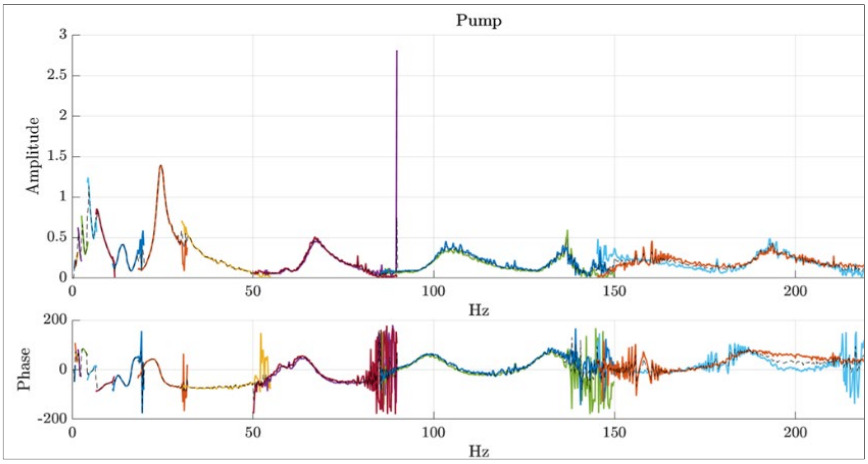
The QPS pumping CAN commands were extended to include motoring, allowing either pumping or motoring to be commanded in the same way. This provided a unified control interface for both operating modes.

Filters were implemented to exclude erroneous shaft sensor readings caused by motor-pump coupling backlash and DDP-induced pressure variation, improving signal robustness. Dynamic ganging and part-stroke awareness were added to miniHILS tools, enhancing bench simulation accuracy.

A system-level assessment defined higher-level functions needed for full deployment, ensuring alignment with overall system requirements. CAN bus support was added to miniHILS to communicate estimated flow to the Simulink target, enabling closed-loop simulation and control.

To address NVH issues, two components were developed: one for current trim control in software and FPGA firmware, and another integrating the chirp tool into standard DDP software for diagnostics and tuning. Valve closing point detection techniques were explored via simulation and bench testing, with firmware added to improve control accuracy.

Figure 16: Chirp tool frequency response analysis from an excavator test



Finally, these components were successfully deployed in the hydraulic excavator demo, requiring minimal support. An outline specification was created for production-intent motoring and energy recovery features, forming a roadmap for future customer-focused software development based on DDP1x0D.

WP5 System Application Software for controlling the excavator

WP5 was designed to bridge developments made across several other work packages. It ensures that the system control architecture derived in WP3 is applied to the final machine configuration defined in WP7. In addition, WP5 incorporates the safety measures developed in WP6 by segmenting the control system into multiple elements. Safety-critical functions are managed by control units and software that are closer to release readiness than those enabling the new system control concept.

Figure 17: Control architecture

In addition to the control work completed in WP3, WP5 ensures seamless interaction with the original system control. This enables the new control system to take over operation of the electric machine (motor and generator), while retaining the original fault handling from Staad for the high voltage system. By maintaining this integration, the DEPOWER2 project can continue to focus on ensuring the safety of the modified machine components.

Overview of the technical development

The deliverables defined at the outset of WP5 were:

- Establish interface between control logic from WP3 and application.
- Adapt control system to accommodate modifications made to the application in WP7.
- Lower the likelihood of risks derived from the risk assessment carried out in WP6.
- Enable the new control system to operate the electric motor without disabling the fault detection and response mechanisms originally integrated by Staad.

Control architecture

The application control developed in WP3 was implemented on a Speedgoat target machine to enable real-time simulation and testing. This approach enabled rapid prototyping by using the same environment for deployment as was used during function exploration. For released solutions, there was a strong requirement for high reliability and optimal hardware cost. The XL104 controllers, used to manage all input and output functions, were developed specifically to meet these demands. The XL104 controllers function as remote input and output handlers and include comprehensive fault detection across all channels. For example, if a critical input such as a pressure sensor fails or returns out of range values, the controller detects the anomaly and automatically transitions the system into a predefined safe state. This involves setting DDP displacement to zero and de energising all system control valves to prevent unsafe operation.

Safety

The most important part of WP5 is to ensure safety. To do so while working with concept development it is important to clearly separate safety from function development as described above.

In addition to separating the application code from the majority of the fault handling logic, placed on the XL104 controllers, the original emergency button has been upgraded. It now includes isolation and shutdown of the DEPOWER2 related components, enhancing overall system safety.

For the XL104 controllers, a Pin FMEA has been carried out to ensure high diagnostic coverage of both the pins used to control the different functions as well as the communication between the different control units.

Faults originating from the application code on the Speedgoat but executed by the XL104 controllers rely on the operator to utilise the emergency button for limiting the risks of harm. This fact also projects additional safety precautions onto worksite management for the final’s application demonstration.

High-voltage systems demand substantial effort to ensure safe operation, which falls outside the scope of the DEPOWER2 project's primary objective of hydraulic system control. Consequently, DEPOWER2 relies on Staad's implementation to manage electrical fault handling. This includes tasks such as insulation testing and enforcing safe operational limits across all high-voltage components to ensure the battery system operates safely.

To ensure the correct implementation of fault handling on the XL104 controllers, a virtual validation of the code was performed. This approach aligns with standard practices in projects that follow the verification and validation (V-model) development methodology. The virtual validation confirms that the fault detection mechanisms identified as necessary in the pin-level FMEA function as intended.

WP6 System Safety Concept

The system safety concept was comprehensively documented in the Functional Safety Management Plan, which outlined the project's specific approach to functional safety management, aligning with established Danfoss internal processes and guidelines.

Following this foundational step, a detailed state-of-the-art analysis was conducted, as mandated by relevant industry standards such as ISO 12100 and the ISO 19014 series. This analysis aimed to identify the most pertinent technologies, safety requirements, and applicable standards specifically for earth-moving machinery, ensuring the project leveraged current best practices.

The insights gained from the state-of-the-art analysis directly informed the creation of the boundary diagram, which precisely defined the scope of functional safety implementation in accordance with ISO/TS 19014-5:2021 (Earth-moving machinery — Functional safety), clearly delineating the system boundaries and interfaces. Simultaneously, the ideal function definition was developed, specifying the machine's intended functions and operational parameters, all while adhering to core functional safety principles.

Building upon these elements, a thorough risk assessment and functional safety standard referral were then performed, systematically evaluating potential hazards and identifying appropriate safety standards. This process culminated in the Definition of the Safety Concept, the establishment of clear safety goals, and the specification of detailed safety functions, all meticulously designed to prevent un-commanded movements and ensure the overall safe operation of the machinery.

Finally, the Fault Insertion Test Requirement Specification was meticulously completed, outlining the necessary procedures to ensure the rigorous verification of functional safety aspects at the machine level. This specification detailed specific test procedures and defined the expected system responses to a range of potential error conditions, ensuring a comprehensive validation process.

The established process will serve as a foundation for future OEM projects. While hardware modifications specified by the OEM will require revisiting the process, this presents an opportunity to reaffirm safety requirements and enhance system robustness from the outset.

WP7 Excavator Conversion Activities

This work package focused on selecting and procuring a base machine, conducting baseline testing, and rebuilding it to the Dextreme MAX architecture. A benchmark test specification was created to track energy and performance changes.

After benchmarking, the machine was fully rebuilt from prime mover to actuators, including hydraulic and electrical systems. Following the rebuild, commissioning and tuning were carried out to optimise system behaviour.

Purchase of the base machine

A 30t electric excavator was selected based on market relevance, energy recovery potential, the advantages of Digital Displacement® technology, and the flexibility offered by removable battery packs, ideal for demonstration site logistics. The decision was further supported by a strong working relationship with the equipment supplier, STAAD.

While the initial plan was to deploy a new machine, high demand driven by a Dutch subsidy program extended lead times. In response, STAAD provided a professionally refurbished DX300LC-7K, which was successfully delivered to Nordborg on March 11, 2024, ensuring the project remained on track without technical compromise.

Though prior use introduced typical integration challenges, these were effectively resolved through close collaboration with STAAD, whose proactive support was vital. Similarly, WEBASTO, the battery system supplier, provided expert assistance that was critical to successful commissioning of the demonstrator.

Baseline testing

In order to quantify performance before and after conversion, comprehensive characterisation of the original configuration was undertaken. The tests have been designed with multiple motivating factors

- Single function behaviour and characterisation
    - With and without load in excavator bucket

        - Step and ramp response, speed, pressure loss, max pressure, hysteresis, cavitation
- Function prioritisation characterisation
    - With and without load
        - Commanding different combinations of functions simultaneously
- Noise, vibrations and harshness characterisation
- Simulated duty cycle testing
    - JCMAS air grading testing cf. testing standard
    - JCMAS air dig and dump testing cf. testing standard
    - Dig and dump with granite gravel cf. OEM testing specification

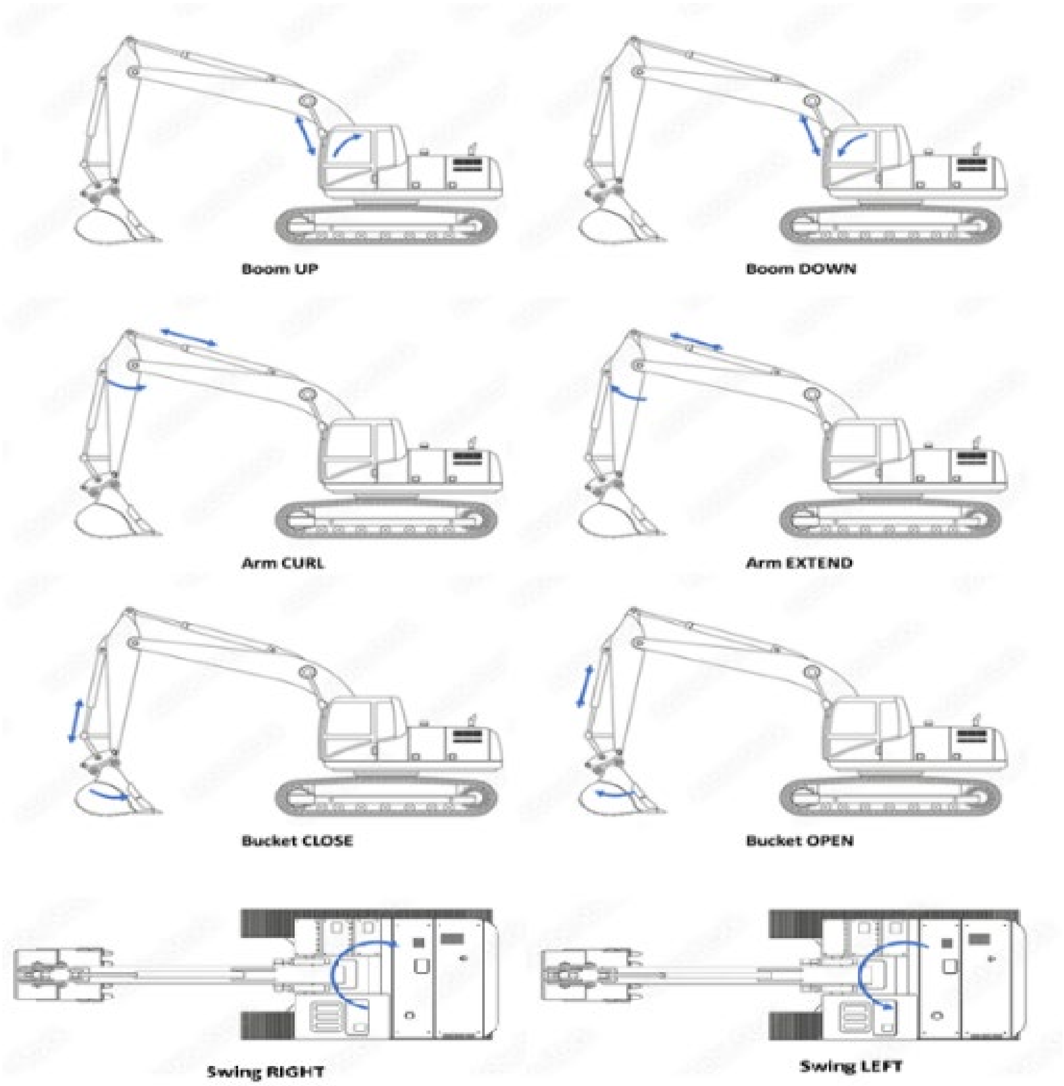
Data acquisition setup

- A comprehensive data acquisition setup was installed to capture key machine parameters—arm, swing, bucket, track, etc.—using DEWESOFT® housed in a cabinet (Figure 61).

Single function testing and characterisation

In order to specify the single function testing and characterisation it is necessary to define the functional movement. This is shown in Figure 18.

Figure 18: Function movement definition



Simulated duty cycle testing

Three different types of simulated duty cycle testing were performed:

1. JCMAS air grading (Equivalent of ISO11152-2)
2. JCMAS air dig and dump (Equivalent of ISO11152-2)
3. Real dig and dump with gravel

All tests are repeatable and can be performed before and after conversion. Operators are generally instructed to work as fast as possible, as this tends to yield the most consistent results.

Figure 19 and Figure 20 provide an overview of the movements that can be found for air dig and dump and air grading. The full description of the testing can be found in ISO 11152-2 which is still in development as of time of writing .

Figure 19: Air digging cycle cf. ISO 11152-2 and JCMAS. [ISO11152-3]

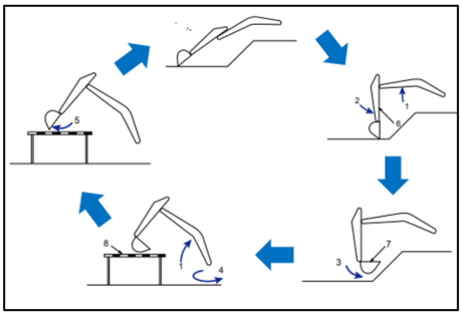
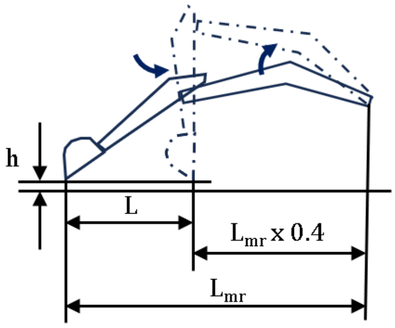


Figure 20: Air grading cycle cf. ISO 11152-2



To simulate real dig-and-dump operations, the test mirrored the motion of air-based trials but used actual granite gravel. The setup enabled repeatable testing by moving ten buckets of material before reestablishing the gravel pile (Figure 21).

Figure 21: Real dig and dump set-up with granite gravel.

Figure 22: JCMAS air dig and dump cycle test set-up.

In order to coach and ensure repeatability a 3D kinematic model with tracking of the bucket motion was developed.

Figure 23: 3D kinematic model with motion tracking of bucket.

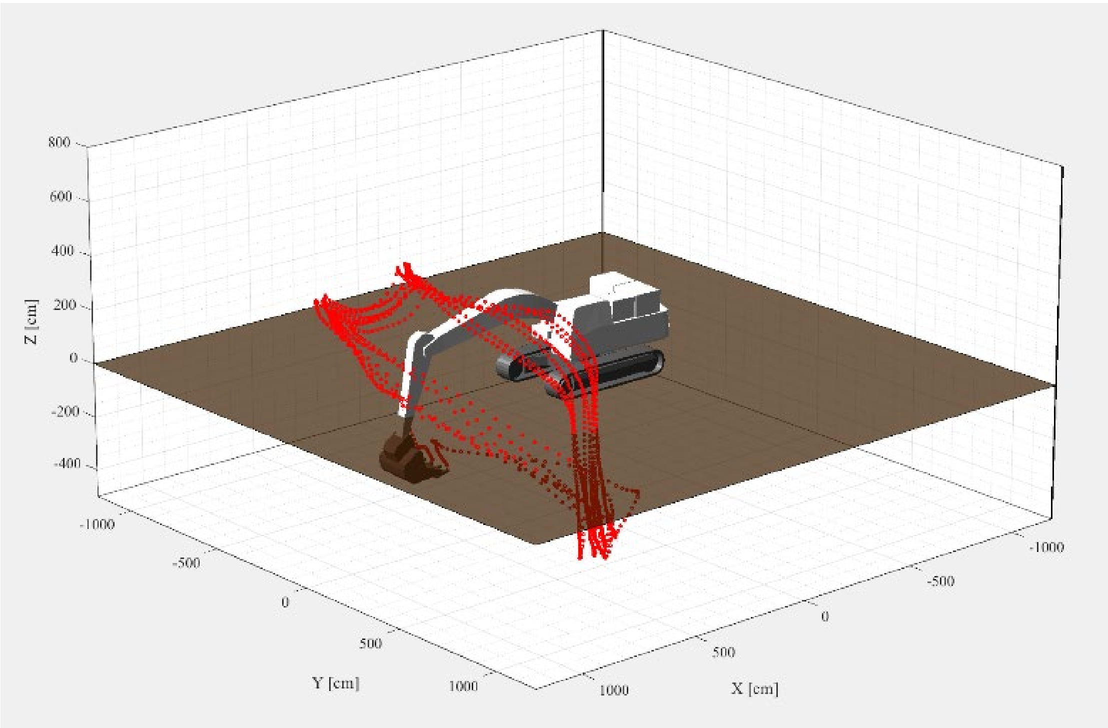
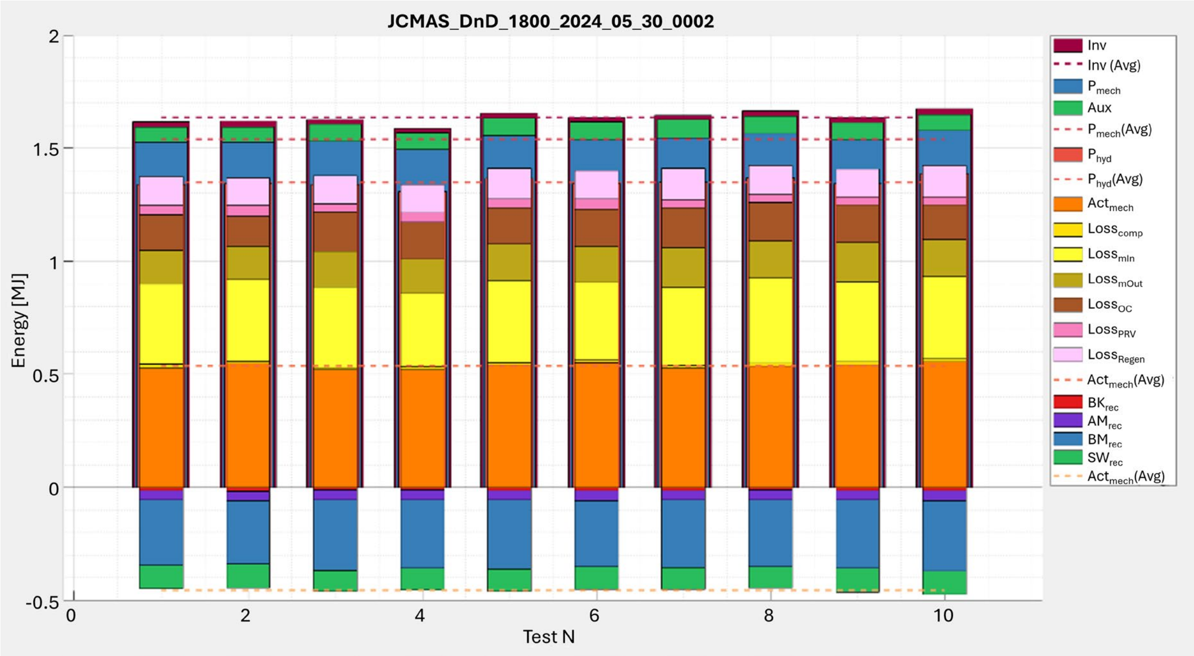


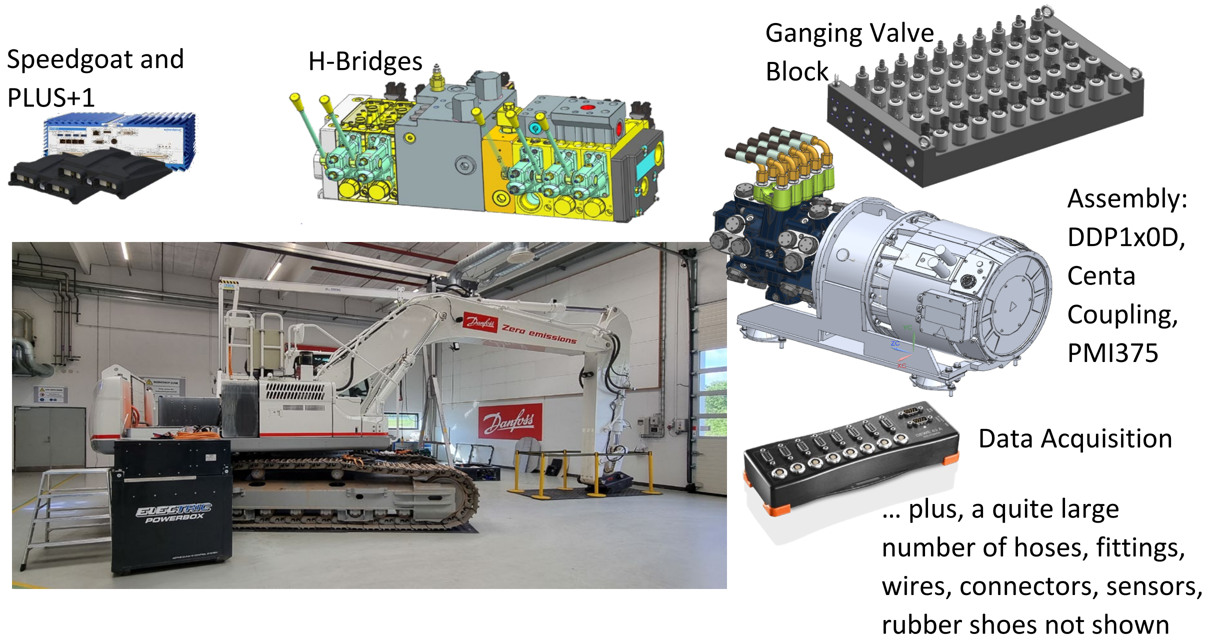
Figure 24 shows an example of the resulting energy analysis plots from in this case, the 10 consecutive JCMAS dig and dump cycles.

Figure 24: Energy break-down for 10 consecutive JCMAS dig and dump cycles.



After successful completion of the baseline testing, the vehicle conversion was initiated. The major components installed during this phase are illustrated in Figure 25 and summarised below:

Figure 25: Major new components installed



- DDP1x0D Pump Motor + PM375 Electric Motor + Centa Coupling:
  These three components were installed as a single mechanical assembly. The Centa Coupling connects the PM375 electric motor to the DDP1x0D tandem pump.
- DPC30 Controller: A ruggedised digital controller responsible for real-time valve actuation and system diagnostics.

- H-Bridge Valve Assembly: Enables four-quadrant control of actuators, allowing for advanced functions like differential actuation and energy recovery.
- Ganging Valve Block: Dynamically allocates flow between services to minimise throttling losses and improve efficiency.
- Battery System: Modular battery packs that supply power to the electric motor and control systems.
- Electrical Control Cabinets: Houses the control electronics, power distribution, and safety systems for the 24V architecture. A second cabinet houses data acquisition modules.
- Speedgoat Mobile Machine: Used for rapid prototyping and deployment of control logic, hosting the application control software. Utilises Danfoss PLUS+1® XL104 Controllers as remote I/O units.

These components collectively form the DEXTREME MAX system architecture, enabling the MAX configuration with full energy recovery and advanced hydraulic control.

Hydraulic and mechanical modification

Prior to mechanical and hydraulic upgrades, the machine was prepared by removing obsolete components and clearing space for new installations. Figure 26 and Figure 27 illustrate the preparatory work.

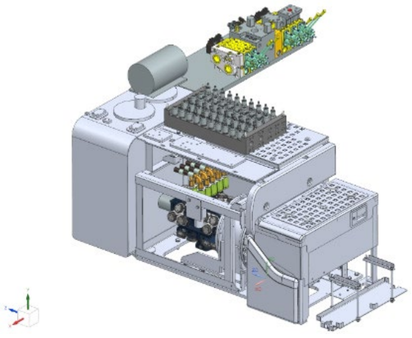
Figure 26: Batteries and battery container removed.

Figure 27: High voltage and pumping compartment removed

T

The mechanical modification included installation of the new DDP1x0 pump. In order to do so, 3D modelling (Figure 28) was utilised to make sure coupling, flanges and brackets could be manufactured.

Figure 28: 3D modelling of the installation

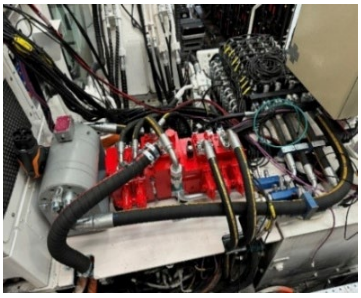


A critical challenge during assembly involved the coupling between the PM375 electric motor and the DDP1x0 tandem pump. The originally sourced component failed to meet procurement specifications. Leveraging the capabilities of the Danfoss workshop, the team successfully modified the coupling without significant delay. Figure 29 shows the completed assembly.

Figure 29: Coupling the pump and electric motor assembly.

Significant new fluid conveyance was installed to support the ganging valve and H-bridge for boom and swing control. This included new flow meters and a redesigned hydraulic layout to enable accurate data acquisition and system monitoring. Figure 30 shows the H-bridge setup with the updated hydraulic layout.

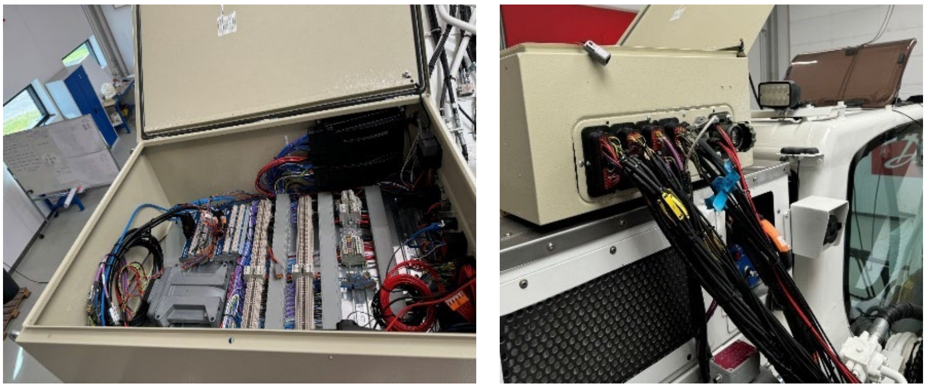
Figure 30: H-bridge valve setup for post-conversion data acquisition



Electrical modification

Extensive work was carried out on the 24V electrical system, which includes control for the Dextreme MAX architecture. Much of the installation was housed in a control cabinet (Figure 31).

Figure 31: Electrical control cabinet



Commissioning, Testing and tuning

Following installation of new components, the DEPOWER2 excavator was successfully commissioned and transitioned to the DEXTREME MAX system. Hydraulic startup was conducted in SWAP mode, confirming stable DD180D/Motor operation and validating key MAX system elements.

Testing verified flow accuracy across motor speeds using fixed displacement methods, while Negative and Positive Flow Control strategies enhanced fluid control and efficiency. MAX trials demonstrated dynamic ganging, H-Bridge boom control, and energy recovery via DD motoring during boom descent.

Outstanding issues include high-speed tracking limits, uncertain valve configurations affecting efficiency, low-voltage startup challenges, and inconsistent boom-down behaviour. Following on from this WP, the next steps involved tuning in Edinburgh to refine controllability, NVH characteristics, and motor control under corner conditions.

WP8 3D System Simulation

WP8 aimed to develop a high-fidelity system simulation model of the DEPOWER2 excavator, enabling human-in-the-loop control development and virtual testing within Danfoss's Virtual Application Development Centre (ADC) framework. Key objectives included selecting a suitable simulation tool for excavator dynamics, integrating it into Danfoss's FMI 2.0-based toolchain and building a real-time capable system simulation setup for the DEPOWER2 excavator.

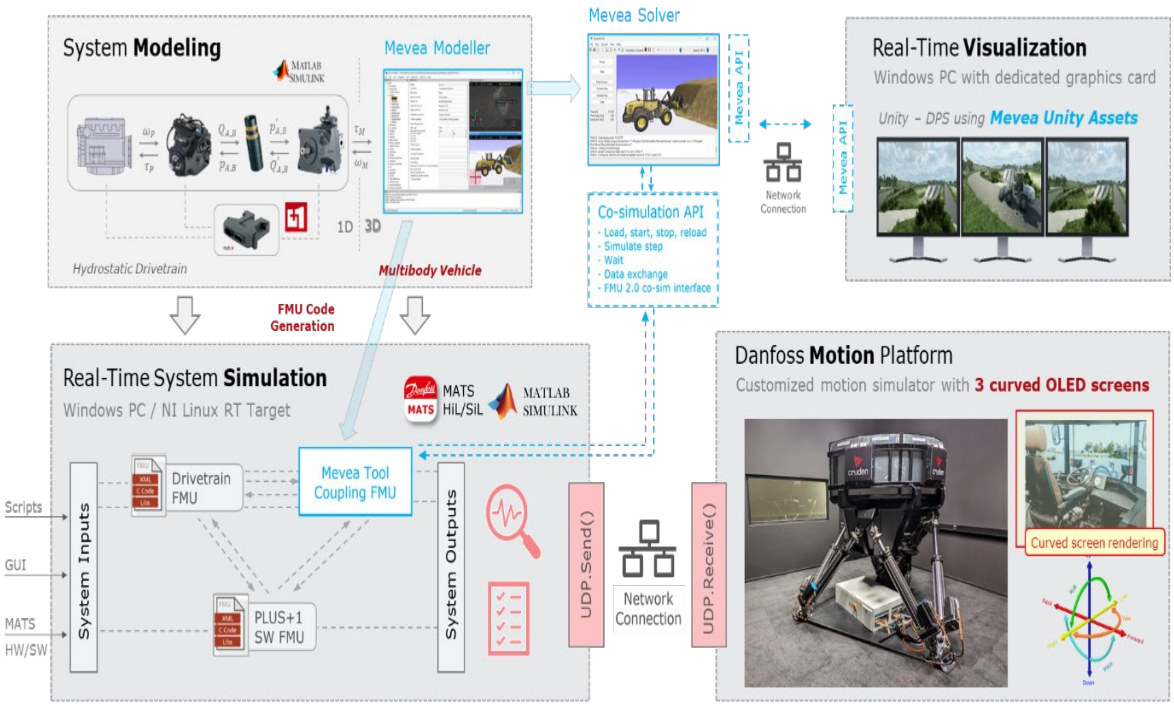
A virtual human-in-the-loop setup was implemented on the DMP simulator, with enhancements to the existing environment. All deliverables were successfully completed, and both the simulation model and improved virtual ADC toolchain are now operational.

Simulation Tool Identification & Integration

Prior simulation models used in WPs 4 and 7 lacked realistic excavator kinematics and terrain interaction. To address this, a vendor analysis identified Mevea Simulation Solutions [4] as the ideal partner due to their expertise in off-highway and earthmoving simulation. Mevea collaborated with Danfoss to develop a new FMI 2.0-compatible co-simulation interface.

The Mevea toolchain supports tracked vehicles, deformable terrain, and bucket-soil interaction, along with Unity-based 3D visualisation. A novel Functional Mock-up Unit (FMU) interface was successfully implemented and is now part of Mevea's official release. The resulting virtual testing toolchain, shown in Figure 32, was presented as a success story at the 2024 Mevea Seminar [5].

Figure 32: Danfoss Power Solution system simulation toolchain topology using Mevea tools with the Tool-Coupling FMU approach.



System Model Development

A critical enabler for the virtual human-in-the-loop test environment was the development of a realistic, real-time system simulation for the DEPOWER2 excavator. This setup combined Simulink-based control and electro-hydraulic models with multibody excavator and terrain simulations using Mevea tools. Key results from this integration are summarised below.

Excavator Modelling.

The excavator modelling process began with collecting data on machine dimensions, joint locations, masses, inertias, and preparing 3D meshes and textures for visualisation. This was achieved using a combination of spec sheets, physical measurements, CAD calculations and a full 3D scan of the test machine. The collected data formed the foundation for building the multibody model in Mevea Modeller. This included defining the excavator as a system of rigid bodies, constraints, force components, and graphical elements.

Model parameters, inputs, and outputs were exposed through a dedicated FMU socket interface, enabling seamless integration with the broader simulation toolchain.

System Modelling. In the system modelling phase, existing 1D models for control algorithms and electro-hydraulic actuation (DEXTREME MAX) were integrated with a newly developed 3D multibody excavator and terrain model. This model enables testing of overall system performance under varying user inputs, dynamic conditions, and scenarios—including interactive digging and earthmoving. A major challenge was ensuring numerical stability, particularly during digging or when hydraulic cylinders reached end-stops, to avoid speed-pressure oscillations and instability.

Model Validation. The system simulation model was tested across typical scenarios and validated against real-world data from the DEPOWER2 excavator.

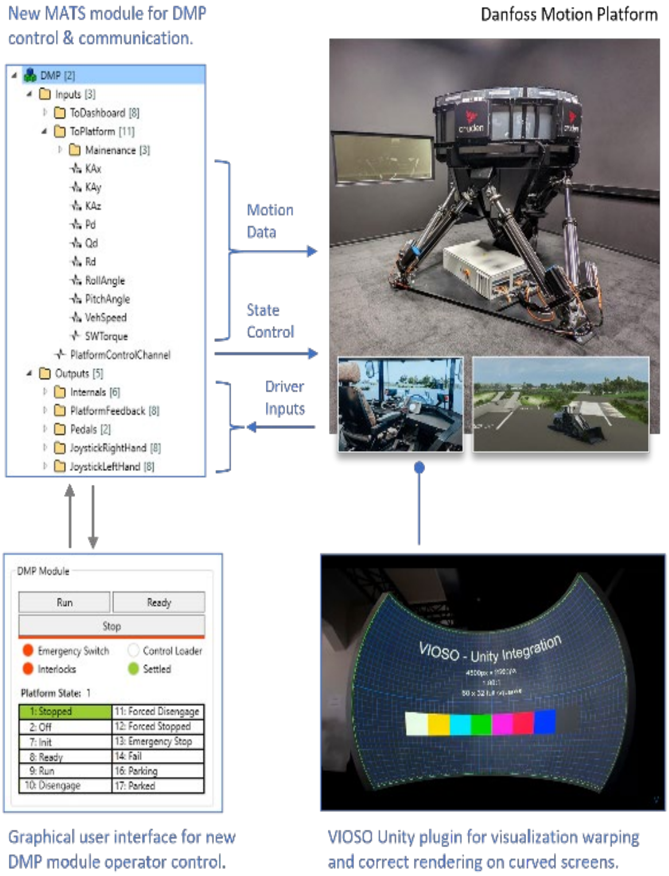
While direct comparison was limited by differing test conditions (even ground vs. gravel hill), the model demonstrated realistic, stable behaviour and accurately predicted pressure dynamics and digging forces.

Overall, the simulation showed strong qualitative agreement with measured data, confirming its predictive accuracy. Key findings were presented at the 2024 Mevea Semina [5]

DMP Simulator Setup

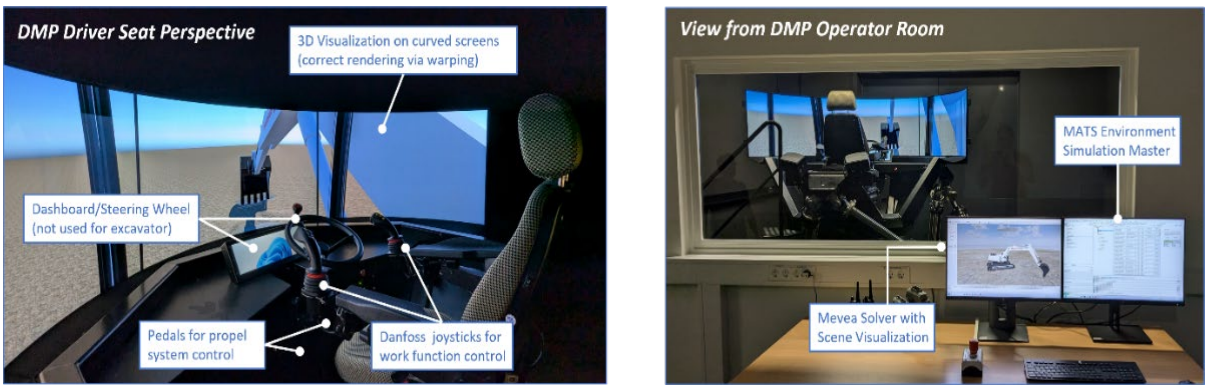
The DMP is a state-of-the-art motion simulator with six degrees of freedom, integrated within Danfoss's Virtual ADC toolchain and used for interactive simulation-based testing. As it had previously only supported standard vehicle propel simulations, several adaptations were needed to support the DEPOWER2 human-in-the-loop setup. A graphical overview on how the individual developments play together to enable an improved driver experience on the DMP is given in Figure 33. Some impressions of the developed final Human-in-the-loop setup can be found in Figure 34.

Figure 33: Overview on technical developments for the overall DMP simulator environment.



DMP Module. A new communication module was developed to integrate data exchange between the DMP motion controller and the test environment. It streams simulated machine data to the DMP and allows the operator to manage simulator states (Run/Ready/Stop) via a dedicated graphical interface.

Figure 34: Overview on the final Human-in-the-loop setup on the DMP



Unity Visualisation. A high-quality 3D Unity visualisation of the DEPOWER2 excavator and its environment was developed and linked to the real-time simulation via the Mevea Unity programming interface. Using Mevea Unity Assets, the visualisation supports dynamic particle effects to represent digging and earthmoving processes.

Operator Interface Hardware. A second Danfoss JS1-H joystick was ordered and installed on the DMP simulator to allow for a more realistic machine operation for excavators or other work function applications.

Screen Warping.

To enhance driver immersion, the DMP simulator uses three curved screens with a custom warping transformation integrated into the Unity visualisation. The VIOSO® "Warping & Blending" plugin was selected, calibrated to the DMP's geometry, and added to the DEPOWER2 Unity project; significantly improving rendering quality. This solution is reusable across future DMP projects, adding lasting value to the Danfoss Virtual ADC toolchain.

WP9 Demonstration Study

Overview of demonstration plan

The demonstration comprised two phases: controlled performance testing by Danfoss and a one-month field trial in a real operating environment with a regular operator.

Post-conversion testing was conducted at a dedicated site near Danfoss' Edinburgh facility, focusing on JCMAS air grading and dig-and-dump cycles, chosen for their repeatability. The controlled setting allowed safe testing of MAX mode mitigating any safety risk from prototype system behaviour.

The field trial took place at Forth Resource Management's East Fenton site, where the DEPOWER2 excavator was used in a large groundworks project. For safety, the machine operated primarily in SWAP mode, with two days in MAX, when the machine was well isolated.

Measuring efficiency in real-world conditions is challenging due to variable factors like task complexity and material properties. JCMAS air cycles offer a repeatable alternative by removing material variability and prescribing motion.

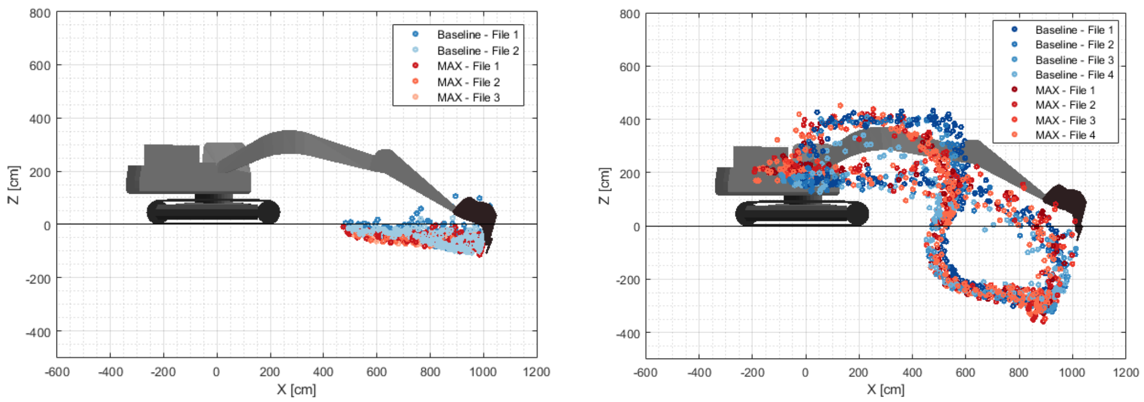
With no baseline machine available on-site, DDP system efficiency was evaluated using JCMAS tests, referencing Nordborg baseline data. The trial primarily focused on reliability validation.

Performance Testing

Considerations and challenges

Ensuring consistency across test cycles was challenging, as baseline tests were conducted by a different operator at a separate site nearly a year earlier. The bucket tracking tool (Figure 23) played a key role in verifying repeatability. helped verify repeatability, and outlier cycles were excluded from energy analysis using plotting tools. A sample dataset is shown in Figure 35.

Figure 35: Comparison of bucket traces for JCMAS tests, left – Grading, right – Dig & Dump



Cycle time affected test repeatability as the DDP180D's 30% larger displacement enabled faster operation than the baseline pump. To match cycle durations, motor speed was adjusted during DDP tests to match the baseline as closely as possible ().

Table 1: Motor speed setpoints for JCMAS Testing

Test Configuration	Motor speed setpoint (rpm)	
	Air Grading	Air Dig & Dump
Baseline	1800	1800
MAX	1350	1600 - 1800

JCMAS Results

Assuming a duty cycle of 30% air grading and 70% air digging, the MAX system would reduce battery power consumption by 39% without compromising work rate. Average results for each valid cycle are presented in Table 2 and Table 3 for air grading and dig-and-dump operations, respectively.

Table 2: Air Grading results

Configuration	Cycle Time (s)	Avg. Input Power (kW)	Input Power Reduction (%)
Baseline	6.78	120.5	-
MAX	7.29	56.9	49.2

Table 3: Air Dig & Dump results

Configuration	Cycle Time (s)	Avg. Active Power (kW)	Avg. Input Power (kW)	Input Power Reduction (%)
Baseline	14.44	41.3	99.9	-

MAX	14.59	40.1	68.2	31.0

Active power reflects the fluid energy reaching the actuators and is included in the analysis, as cycle time alone is insufficient for comparing performance due to the cycle's complexity.

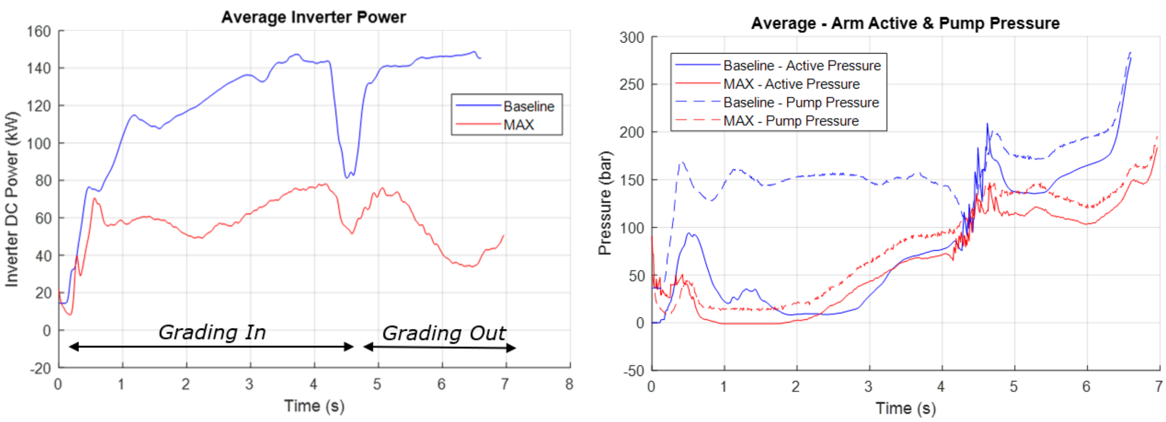
JCMAS Analysis

Test data was analysed to identify where the DDP system improved efficiency. The air grading cycle includes Grading In and Return phases, highlighted in the inverter input power timeseries (Figure 36), alongside arm circuit pressures. In SWAP mode, DDP's lower motor speed and higher efficiency reduced power demand. The flat inverter power curve indicates operation at the motor's torque limit. Although the baseline shared this torque limit, its higher speed led to greater peak power.

Dextreme MAX significantly reduces input power in both phases. During grading in, conventional systems connect both pump outputs to the boom and arm actuators, requiring both pumps to operate at the higher actuator pressure. Since the arm falls under its own weight, minimal pressure is needed (see the arm active pressures in the right-hand plot), but high flow is still required. Meanwhile, the boom lifts at around 130 bar, causing all flow to the arm to be throttled—resulting in over 33 kW of loss. MAX's dynamic ganging separates boom and arm services, eliminating this throttling loss, as shown by the lower pump pressure in the right-hand plot.

In the return phase, the boom lowers and the arm extends. Conventional systems dissipate the boom's potential energy as heat. The DDPM captures this energy through hydraulic motoring and redirects it to the arm service, reducing battery power demand.

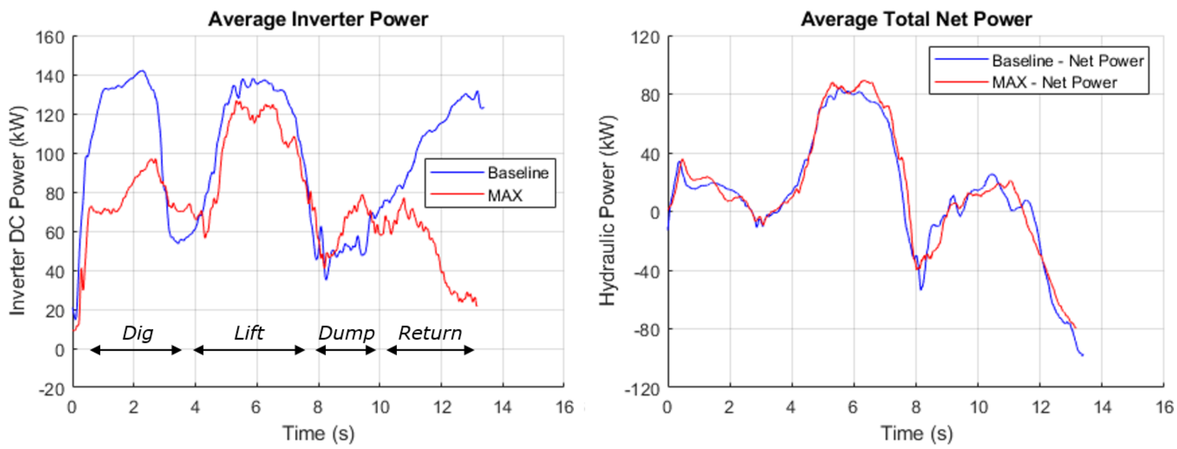
Figure 36: Air Grading inverter power and arm pressures



The dig and dump cycle includes four phases: dig, lift and swing, dump, and return. Figure 37 shows inverter input power and total net actuator power. Both configurations performed similar work overall. MAX improved efficiency during the dig phase, similar to grading in. Its impact was limited during lift and swing due to similar boom and swing pressures, and minimal gains were seen in the dump phase.

In the return phase, MAX recovered boom energy and redistributed it to the arm and swing. With three active services, the DDPM reached saturation and couldn't meet flow demand. To compensate, motor speed was increased to 1800 rpm, maintaining cycle time while reducing battery input power in the second half of the return.

Figure 37: Air Dig and Dump inverter power and actuator net power



Performance Testing Conclusions

JCMAS testing proved that several key aspects of the MAX system performed as expected:

- Dynamic ganging system reduced throttling losses
- DDP180D operated as a pump, motor and hydraulic transformer, enabling energy recovery and redistribution from the boom
- Dynamic control of the motor speed prevented pump saturation slowing down the dig and dump cycle

The energy reduction demonstrated with MAX is very encouraging, with the combined cycle reduction of 39% exceeding the project goal of 1/3. With continued optimisation of system hardware and control software, there should be further efficiency gains to be made in the future.

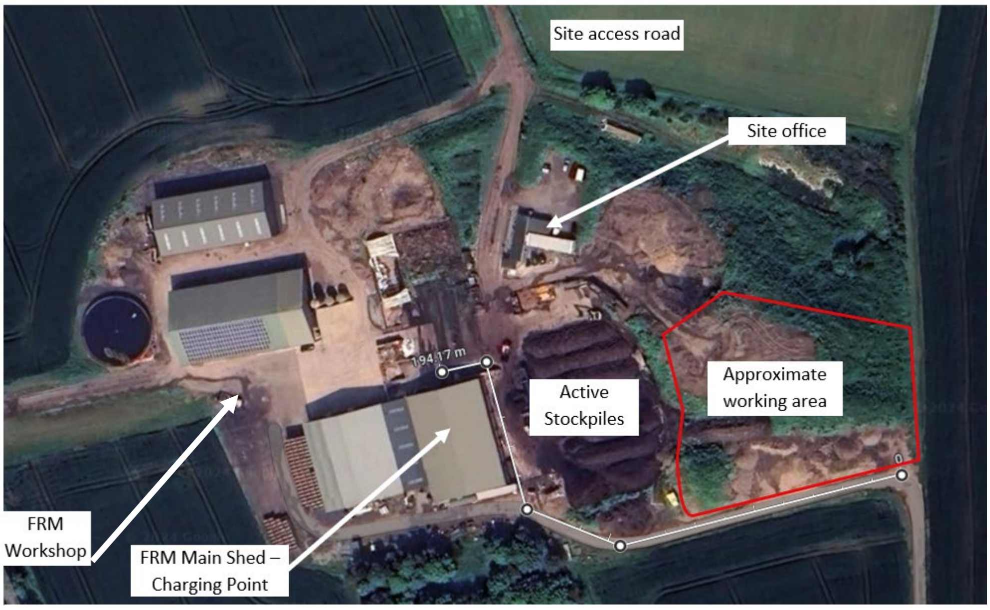
Field Trial

Main considerations and challenges

Planning addressed machine charging, operating conditions, and task provision. The DEPOWER2 excavator supports charging via a 415V 3-phase supply or external DC charging using removable battery modules. The swap system enables mid-shift battery replacement in ~10 minutes but requires an extra vehicle and operator. Where feasible, direct end-of-shift charging is more efficient.

Danfoss testing confirmed SWAP mode operates comparably to conventional machines, posing no added safety risks. The FRM East Fenton site (Figure 38).

Figure 38: FRM East Fenton demonstration site plan



Field Trial Result

The field trial was successful in completing 23 days working days of operation over the course of one month with an average uptime of 85%. Figure 39 shows the DEPOWER2 excavator scraping out the rock pile (left) and shifting earth from the old stockpile (right) during the trial period.

Figure 39: DEPOWER2 excavator working at FRM East Fenton

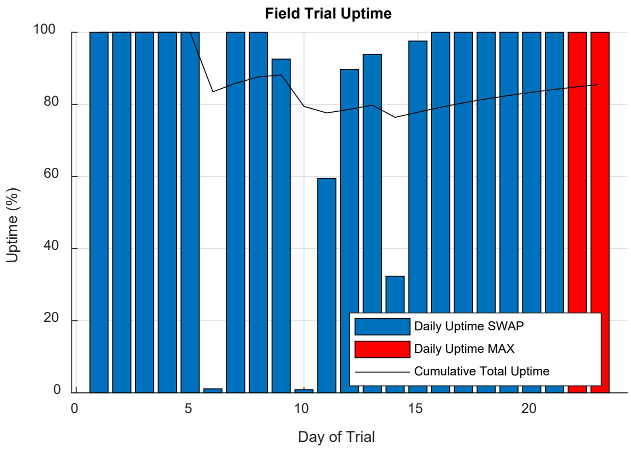
The excavator was charged outside FRM's main shed and tracked to the work area, returning when batteries ran low. Operators were instructed to discharge each module to 15–20% before swapping or recharging, preserving battery health and reserve capacity. This provided ~350 kWh of usable energy, enabling 2–2.5 hours of operation near the

165 kW power limit in SWAP mode. Figure 40 shows a location trace from 23rd May, illustrating typical movement and charging patterns.

Figure 40: location trace of excavator over one working day

Battery life varied and didn't cover a full day, making time-based uptime tracking difficult. Instead, daily battery discharge was used as a proxy: a full "working discharge" was defined as 80% usage of all three modules, equating to 100% uptime. Lower usage was scaled accordingly. For example, ending the day at 60% charge indicated 50% uptime. Unless noted otherwise, incomplete discharge signalled downtime due to breakdowns. Using this method, Figure 41 shows daily uptime as bars and cumulative average uptime as a line. Note: day 23 was not fully completed in MAX.

Figure 41: Daily and cumulative uptime during the field trial



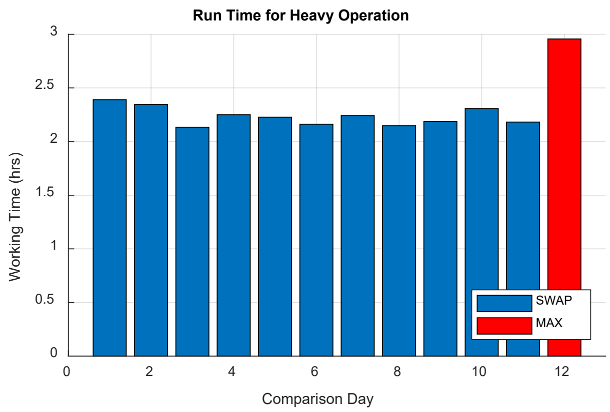
The operator praised the machine's performance in SWAP mode, describing it as a "fantastic bit of equipment" that "easily matched to other (diesel) machines of this size" and even exceeded them in certain motions. Initial concerns about the lack of engine feedback (e.g. no diesel sound under load) proved unfounded, and he found the electric excavator easy to adapt to. Battery life was the only noted limitation.

Dextreme MAX Demo

The final two trial days focused on MAX mode, with a Danfoss engineer present on the first. All MAX features (motoring and transforming in the DDPM, dynamic ganging, and H-bridge control) operated reliably, improving hydraulic efficiency and extending runtime. On the penultimate day, the machine ran for 2:56 during heavy digging. Comparable SWAP-mode days averaged 2:14, suggesting a 32% runtime increase or 24% power reduction (Figure 42). Controlled testing is needed to validate these early results.

The operator found MAX harder to use than SWAP, noting unpredictable boom motions and altered actuator priorities. Danfoss were aware of the control issues prior to the demo, which stem from prototype H-bridge hardware and system control software and are addressing these control challenges in future developments.

Figure 42: Field trial run time for heavy digging work



Field Trial Analysis and Conclusions

A key insight from the trial was the limited battery life during intensive SWAP-mode use, highlighting the challenge of electrifying medium-to-large excavators. Based on JCMAS data, a baseline DX300LC-7K electric would offer similar runtime, while MAX mode could extend this by over 50%. For lighter duty cycles, this improvement could eliminate the need for spare batteries (reducing downtime by eliminating battery swap) and support equipment, or allow for reduced battery capacity; lowering capital costs without sacrificing performance.

Carbon Intensity

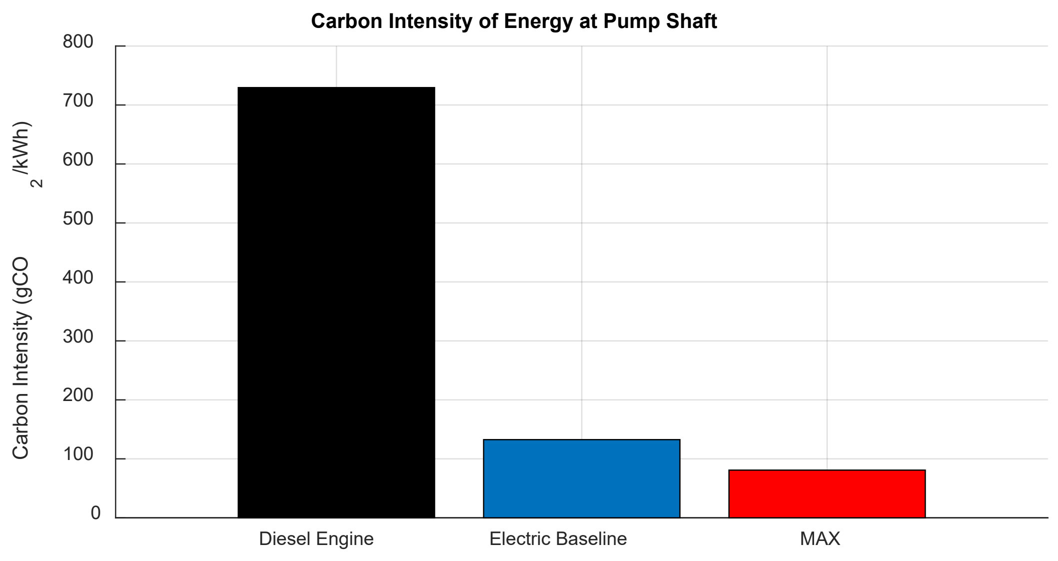
One of the key reasons a machinery operator might move to an electric machine is to reduce or remove emissions at the worksite, but an electric excavator will still create CO_2 emissions if it is not charged from 100% renewable resources. In 2024, the UK electricity grid had an average carbon intensity of 124 g/kWh, dropping to 113 g/kWh between 10 pm

& 8 am [6]. A rough comparison of the carbon intensity of a grid-charged electric excavator and a diesel equivalent can be made with some basic assumptions:

- Diesel carbon intensity is based on a single point for a 202 kW engine at rated power [7] and does not include any carbon emissions from producing or transporting the diesel
- Battery charging efficiency is assumed to be 90% [8] and combined electric motor and inverter efficiency is assumed to be 95% [9]
- The energy consumed by the pump in the diesel and baseline cases is the same and for MAX, it is 39% less – from the combined JCMAS results

Figure 43 below shows that the baseline electric excavator, charged overnight, reduces carbon intensity by over 80% with MAX increasing that to 89%. These numbers should increase in the future as more renewables are brought into the UK grid. The batteries were charged from the national grid but it is worth noting that the FRM site generates electricity through both solar and wind power installations and there is a case to be made that the energy used by the excavator will be somewhat offset by this generation which feeds back to the grid. Ultimately, when charging can be supported on a site with 100% renewables, the carbon intensity would be reduced to zero.

Figure 43: Carbon intensity of energy into an excavator pump to do the same work



Lessons learned from the demonstration

- DDP core hardware and software operated as expected in all operating modes and proved to be robust over the trial period
- MAX gives a clear improvement in efficiency, albeit in an uncontrolled test environment

- In SWAP mode, a regular operator can quickly adapt to the electric DDP machine
- Further work is required to improve the controllability of MAX
- More care should be taken in the specification and installation of appropriate wiring components for off-highway vehicles
- Battery capacity for this size of excavator will continue to be a challenge but DDP can make a significant improvement

Consents and permitting applications and other regulatory approvals /considerations

This project has not required any of the following during its execution:

- Planning Permissions
- Environmental Permits
- Development Consents
- Licenses or Certifications

The activity of the demonstration was limited to temporary movement and removal of stockpiles for an existing organics recycling facility and was not concerned with the construction of either temporary or permanent structures.

Project Metrics

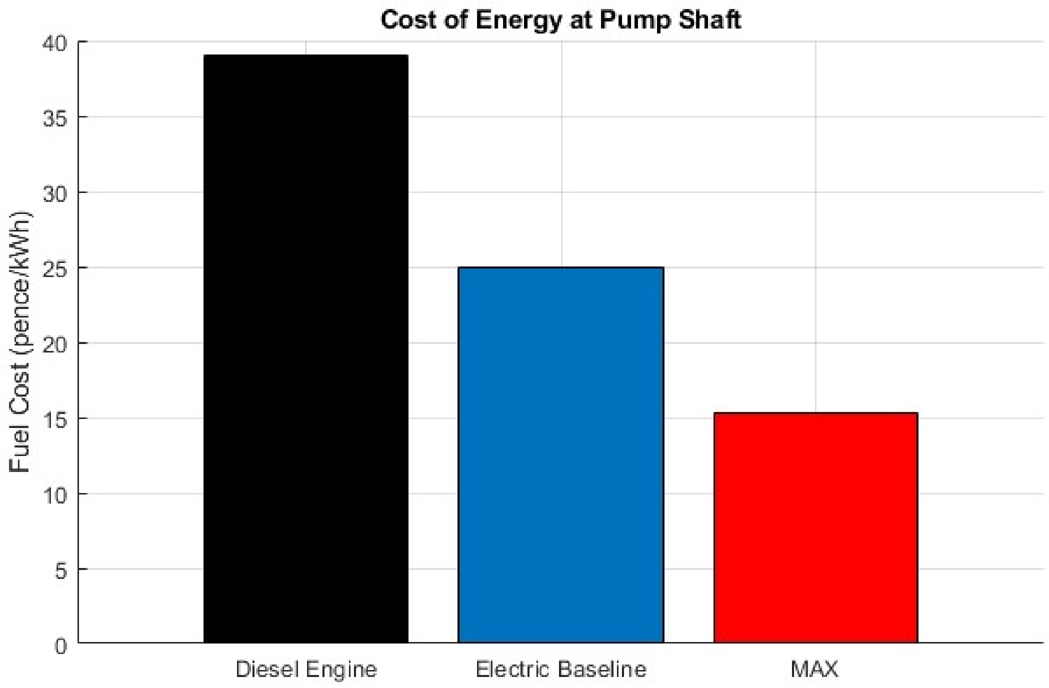
Technology Readiness Level

All the sub-system components were matured throughout the project from TRL5 to TRL7 level in MAX. In addition, we conducted the JCMAS efficiency testing in MAX mode to demonstrate performance and efficiency. A supervised one-day third-party expert operator demonstration trial in MAX was also carried out. Overall, the system was shown to have potential to reduce carbon intensity of excavator operation by up to 89% based on average UK grid mix in 2024 [6].

Table 4: RDR2 Developmental Maturity

Development Maturity	Complete
DDP1x0D ready for MAX	Yes
Controller HW ready for MAX	Yes
Controller SW ready for MAX	Yes
System HW ready for MAX	Yes
Overall DEXTREME performance demonstrated at MAX	Yes
Overall DEXTREME (all of the above) TRL7 real life reliability evidence, operator feedback at MAX	One day operator feedback but needs more time in the field for proven reliability
Overall DEXTREME (all of the above) TRL7 real life reliability evidence, operator feedback at SWAP	Yes

Figure 44: Cost of Energy at Pump Shaft



In terms of cost, the electric baseline provides an approximate saving of 35% against the diesel counterfactual and MAX provides an additional 40% cost saving compared to the electric baseline.

Secondary Project Benefits

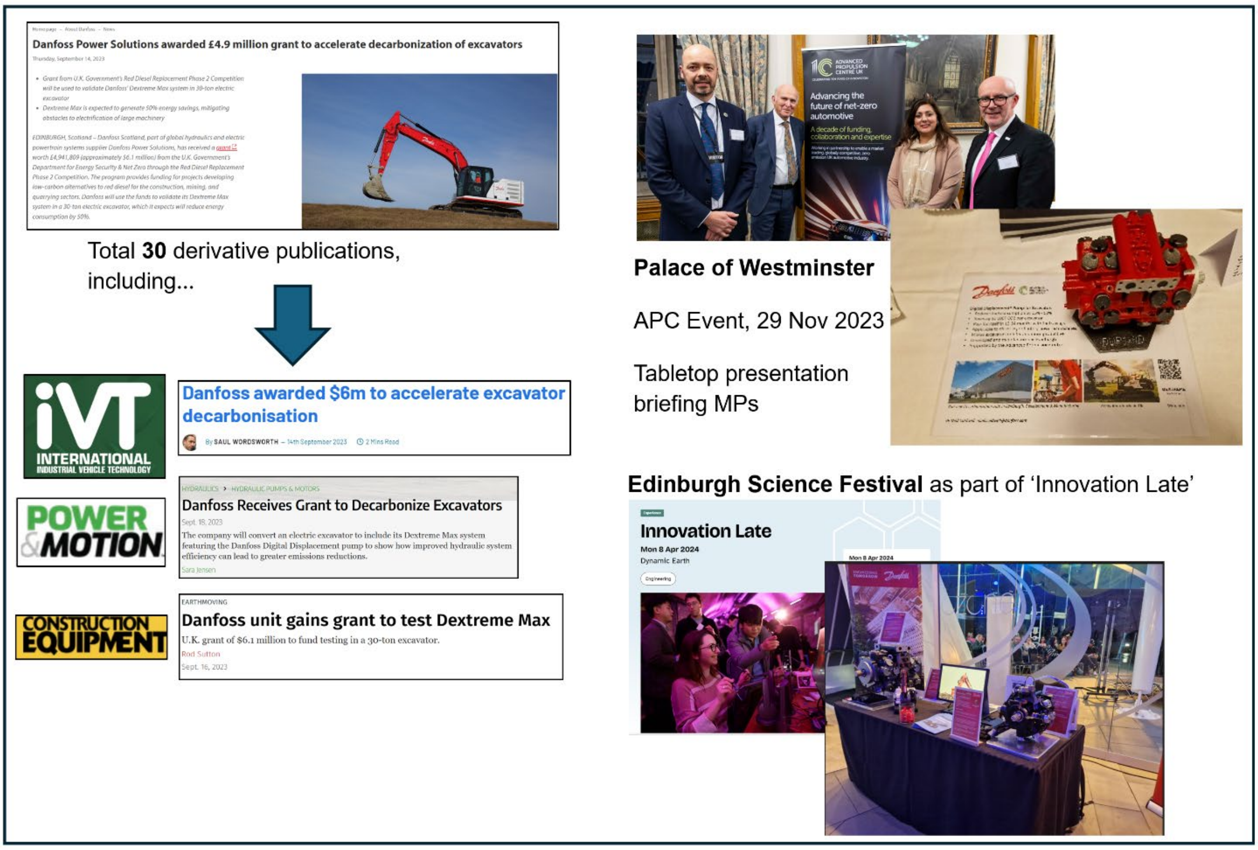
Dissemination activities undertaken

The dissemination activities for the DEPOWER2 project began soon after award in September 2023 with a series of press releases announcing the project and the £4.9 million grant provided through the Red Diesel Replacement Phase 2 Programme.

The press releases led by Danfoss Public Relations appeared in a variety of publications, including Danfoss.com, New Power Progress, Fluid Power Journal, and Industrial Vehicle Technology International. The announcement, "Danfoss Power Solutions awarded £4.9 million grant to accelerate decarbonization of excavators" went on to be publicised in 30 derivative publications (Figure 45).

In November 2023, a conference paper titled "Digital Displacement Motoring Characteristics of Dynamic Energy Recovery and Hydraulic Transformation" was presented at FPMC2023, featuring DDP1x0 test results. Niall Caldwell presented the DEPOWER2 project and DDP1x0D technology during the Advanced Propulsion Centre UK (APC) 10-year anniversary event. Taking place in the House of Commons, the event featured speeches from former Business Secretary, Sir Vince Cable, the Minister for Industry and Economic Security, Nusrat Ghani, Member of Parliament (MP), and host Matt Western,

Figure 45: Dissemination activity



MP, who all shared their thoughts on the past, present, and future of zero-emission automotive. Danfoss was highlighted in the speech by Ian Constance of the APC.

In April 2024, DDP1x0 was presented at the Edinburgh Science Festival as part of 'Innovation Late'. 2024 also saw conference papers presented at the FPMC2024 conference in Bath, with topics including NVH improvements. In October, as part of our global dissemination, a paper was submitted to the 12th JFPS2024 conference in Hiroshima, Japan, focusing on improving the energy efficiency of excavators. A final press release is planned for June 2025 to publicise the results of the DEPOWER2 project upon completion.

Intellectual Property generated from project

- **Saturating bulkhead across high pressure body**

A solo Danfoss Scotland case (PA17981EP01) with European patent application number 24170860.1. Filed on April 17, 2024, and is currently unpublished.

- **Multi pump control considering proximity:**

  A solo Danfoss Power Solutions Inc. case (PA18148US01) with US patent application number 63/570537. It was filed on March 27, 2024, and is currently unpublished.

- **Load balancing design of 1x0 valve assembly:**

  A solo Danfoss Scotland case (PA18968EP01) with a European patent application currently being drafted. It is expected to be filed soon.

Supply chain development

We have undergone extensive supply chain activity for the DDP1x0 and controller. The procurement and engineering teams have worked closely together using comprehensive Danfoss supply chain processes for the selection of final suppliers for the DDP1x0 parts.

During the period of the DEPOWER2 project, we have obtained accurate volume price break points on all parts and significantly reduced our total cost of material.

Project Management

This section summarises the project management approach, key risks, and lessons learned during the DEPOWER2 project.

Structuring and Scheduling

The project followed a Waterfall methodology, with targeted sprints. The project's inherent complexity placed some aspects of it within the chaotic domain of the Cynefin model, requiring a flexible and adaptive approach.

The project was divided into ten WPs, each with distinct deliverables (totalling 59) and strong interdependencies. Key WPs included:

- WP2: Development of a first-of-a-kind DDP1x0D pump motor
- WP1: Development of new electronic hardware to control the DDP1x0D.
- WP4: Modification of the existing kernel and addition of new features for the electronic hardware.
- WP3: Development of optimised control strategies and controls for the new pump motor multi-service system MAX, utilizing Model Based Development.
- WP6: Development of the system safety concept.
- WP5: Development of the System application software.

- WP8: Development of a new 3D simulation utilizing particle systems.
- WP7: Purchase of the base vehicle, instrumentation and running of baseline tests, conversion of the vehicle to the new system MAX, delivery of the machine to Edinburgh.
- WP9: Excavator field demonstration.

Microsoft Project was used for overall project scheduling, with other tools employed within work packages for detailed task tracking. Key milestones included the project start date 04 July 2023 and the revised end date 30 June 2025, extended from the original 31 March 2025.

Progress was tracked through regular work package status meetings, interdependency meetings, a monthly Danfoss internal steering committee meeting and monthly/quarterly progress meetings with the Department for Energy Security & Net Zero.

Significant deviations from the original schedule occurred due to:

- Delayed excavator acquisition: A subsidy program in the Netherlands caused order book overflow, delaying the delivery of a new electric excavator. A used excavator was sourced as an alternative, resulting in a 15-week delay.
- Core excavator controller failures: Two failures of the core controller added a further 6-week delay. The root cause was identified as an overvoltage event during machine startup.

Resourcing of activities

The project was primarily executed by Danfoss Scotland Ltd. in Edinburgh, with support from Danfoss Power Solutions ApS in Nordborg (Denmark), test rig capacity in Minneapolis (US), and simulation expertise in Neumünster (Germany). The activity of WP7 and WP6 was carried out in Nordborg with that of WP8 in Neumünster. Project management was supported by a project leader from the global Innovation and Development Project Management Office.

Coordination of resources across the global Innovation and Development organisation was well-established, facilitating the efficient allocation of necessary capacity.

Key Risks and Mitigations

The top risks identified at the project's outset were:

1. **Proposed system fails to demonstrate sufficient efficiency**
2. **Supply of electrified excavator is late / Excavator not ready in time:** Mitigation strategies included pursuing alternative excavator acquisition options (used OEM

electric excavator, purchase another OEM electric excavator, Danfoss converts Diesel Excavator to Electric Excavator).

3. **Task and milestone deliverables not completed to schedule**: Mitigation strategies included leveraging experienced personnel, implementing robust project management procedures, creating backup hardware procurement plans, engaging the Sponsor team, and escalating barriers.
4. **Motoring controllability may need further improvement**: Mitigation strategies included utilising the demonstration test rig developed in RDR phase 1 and conducting dynamic tests to map out the dynamic performance of the DDP1x0.

The following risks materialised into issues:

- Delayed excavator acquisition: The subsidy program in the Netherlands prevented the timely acquisition of a new electric excavator. The linked activities were managed to coincide to the new delivery date.

Any issues were managed using standard project management practices, including:

- Issue identification and documentation
- Prioritisation of tasks
- Assignment of action plans
- Monitoring and tracking of progress
- Communication of status and updates
- Review and learning from the experience

The outcomes of these efforts included the acquisition of a second-hand excavator, prioritisation of critical activities, and a request for a project extension to ensure successful project completion.

Project Management Lessons Learned

Several key lessons were learned during the project:

- What went well:
    - The dedication and expertise of the project team, particularly given some aspects of the project within the chaotic domain of the Cynefin Model, were critical to success.
    - The co-location of the majority of the work package teams facilitated communication and collaboration.
    - The active engagement and support of the Danfoss Steering Committee enabled timely escalation and prioritisation of activities.

- The opportunity to demonstrate the project's outcomes in a publicly visible competition (1-month demonstration) fostered strong support from external partners, including WEBASTO (battery supplier), Speedgoat (rapid prototyping hardware), and STAAD (base vehicle manufacturer).
    - Contingency made for alternative site for the demonstration which in was ultimately required
- What could have been done better:
    - Make more accurate allowances for relocating facilities during high-priority programs: Moving office space, test rigs, and production areas during the project created greater than expected delays and reduced deliverable performance.
    - Address procurement constraints: The inability to order the excavator before the official project start (due to cost restrictions) resulted in a significant delay.
    - Clarify deadlines: The initial understanding that the project duration was fixed led to premature relocation of the excavator. Knowing that there was some flexibility would have allowed for a longer period of startup and tuning activities at the ADC in Nordborg.
- General Lessons:
    - The dedication and adaptability of the project team were essential to overcoming challenges and finding alternative solutions.

This project demonstrated the importance of a skilled and adaptable team, effective communication, and proactive risk management in navigating complex and uncertain environments.

Commercialisation Plans

Over the next 40 years, the world is expected to build 230 billion square meters in new construction adding the equivalent of Paris to the planet every single week [10]. Excavators, central to this expansion, are notoriously inefficient, consuming large amounts of diesel with much of the energy lost as heat in hydraulic systems. In 2020, building construction accounted for 5% of global energy use [11].

The DDP1x0 targets excavators, a key vehicle in construction, mining, and quarrying. The global excavator market, valued at $85 billion in 2025, is expected to grow to nearly $130 billion by 2035, driven by rising infrastructure demand [12].

To meet the energy challenges of this growth, it is essential to adopt more efficient technologies in excavator systems, reducing waste and improving sustainability across the industry.

The DDP1x0 targets the medium to large excavator segment (20–90 tons), a market slow to adopt electrification due to five major challenges: limited space for bulky batteries, lack of on-site power infrastructure, short operating times, high production costs and supply chain risks. These factors, combined with a higher total cost of ownership (TCO), have restricted electric excavators to niche applications.

DDP1x0 addresses these barriers by delivering exceptional energy efficiency. For OEMs, this means smaller battery packs and reduced cost. For end-users, it enables longer duty cycles and less reliance on site infrastructure.

As the next-generation Digital Displacement pump from Danfoss, DDP1x0 integrates with the DPC30 controller and supports DEXTREME systems—SWAP, FLEX, and MAX. These technologies can cut energy consumption in off-highway vehicles regardless of power source.

Danfoss brings deep expertise in construction, mining, and quarrying, with strong OEM and distributor relationships. Our supply chain strategy emphasises sustainability and resilience, while our leadership in environmental, social, and governance practices and commitment to the Science Based Targets initiative align with the growing decarbonization goals of the construction industry.

Though our current excavator market share is small, our reputation and access to OEM decision-makers position us for growth. Our goal is to reach 10% market share in medium/large excavators within 10 years—equivalent to 13,000 units and a 5% reduction in energy use across the segment.

We maintain a robust Intellectual Property portfolio with over 700 patents and a dedicated team to protect our innovations. While the market is conservative and lacks strong regulatory drivers, DDP1x0 offers a compelling performance leap in control, productivity, and efficiency; making it a strategic differentiator for forward-thinking OEMs.

Next Steps

- Carry out further testing and more detailed data analysis to identify areas where further efficiency improvements can be made – this work will be presented at the International Fluid Power Conference in 2026
- Continue technical development of the MAX system hardware and software on the DX300 to improve efficiency and operability, such as:
    - Further development of the dynamic ganging algorithms
    - Improving the combined motoring and throttling control for boom down and reducing pressure drop for improved energy recovery
    - Improving the swing control or changing to an electric swing system

- Demonstrate the machine to OEMs with the goal of starting a development project to utilise the MAX system

Conclusion

The DEPOWER2 project has demonstrated a transformative step toward decarbonizing heavy-duty construction equipment by proving the viability of Digital Displacement® technology in a full-scale 30-ton electric excavator. The project achieved a 39% reduction in energy consumption during standardised JCMAS duty cycle, surpassing the original 33% target. This efficiency will translate into smaller battery requirements, reduced charging infrastructure demands, and lower total cost of ownership helping to position electric excavators as a competitive alternative to diesel.

Beyond the immediate technical achievements, these results carry significant implications for the broader off-highway sector. Construction and mining equipment account for a substantial share of global energy use and emissions, and electrification has been hindered by the limitations of conventional hydraulic systems. By addressing these inefficiencies, the DEPOWER2 solution removes a critical barrier to adoption which can enable OEMs to deliver machines that are not only cleaner but also more productive and cost-effective. Recovering and reusing energy in hydraulic systems has the potential for benefits within other industrial vehicles, not just excavators

From a sustainability standpoint, the impact is notable. When charged from the UK grid, the MAX system reduces carbon intensity by up to 89% compared to diesel, with the potential for zero emissions when paired with renewable energy sources.

Commercially, the technology supports new opportunities for OEM collaboration and market positioning. The DEPOWER2 project has demonstrated the technical maturity of Digital Displacement® systems at TRL7 and provides a foundation for future developments, including automation and advanced control

In summary, DEPOWER2 has successfully demonstrated the potential of sustainable heavy machinery. By integrating energy efficiency, reliability, and digital control, it offers a practical model for future development and potential to contribute to broader decarbonisation efforts.

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Figure 46: System Architecture Comparison

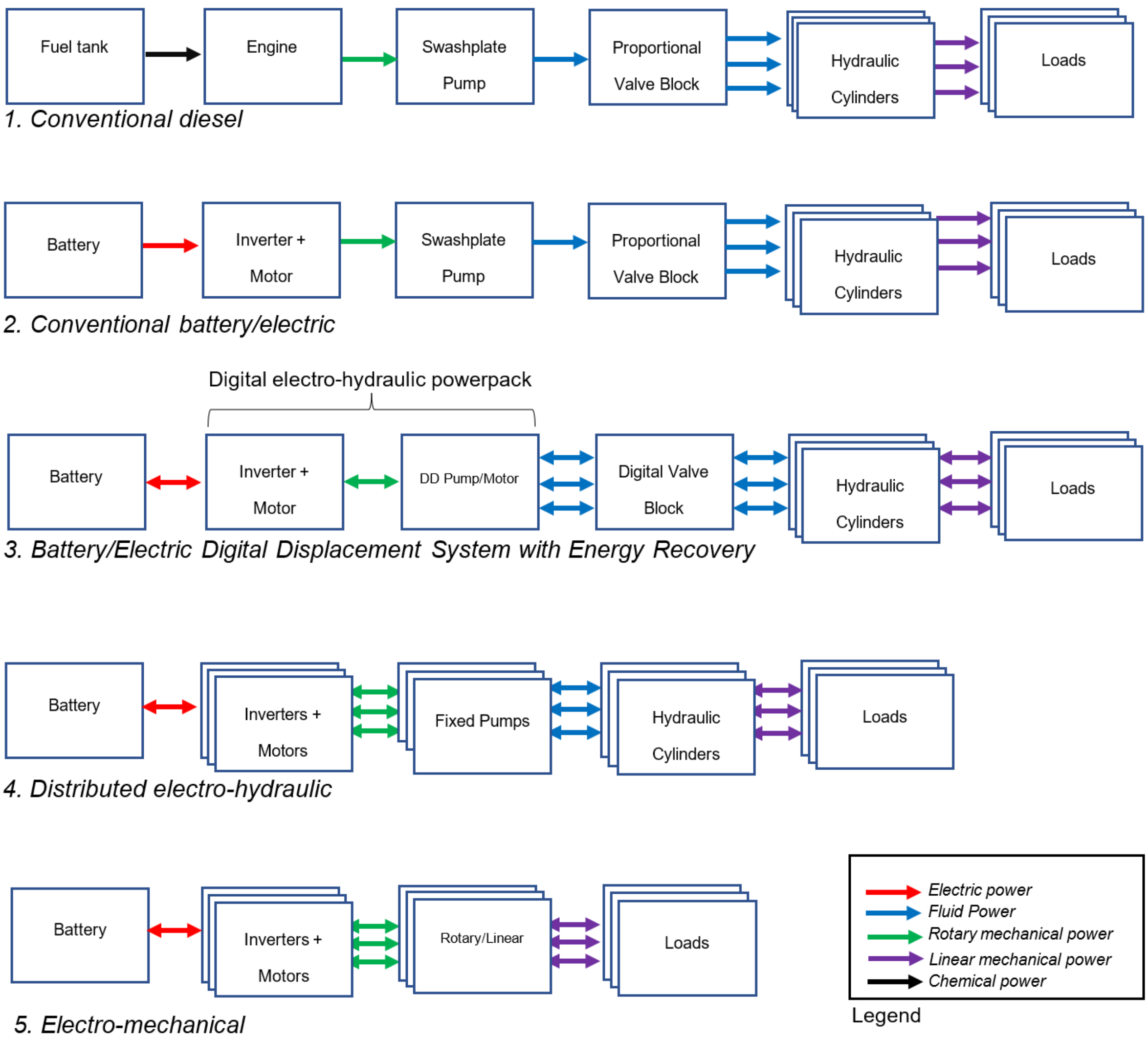


Figure 48: Dextreme FLEX demonstration

Figure 47: Dextreme SWAP demonstration

Figure 49: Levels of application of Digital Displacement excavator (SWAP, FLEX, MAX)

SA level (scope of supply)	Benefits	Validation Status
1 (pump)	15-20% less fuel 10-20% more productivity	Proven in UK and USA
2 (pump + some valves)	30% less fuel	Indicated by lab tests, UK
3 (pump + all valves)	>50% less fuel	Expectation by simulation

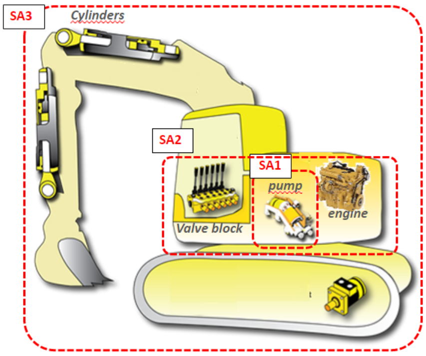


Figure 50: Results of FLEX on Dexter

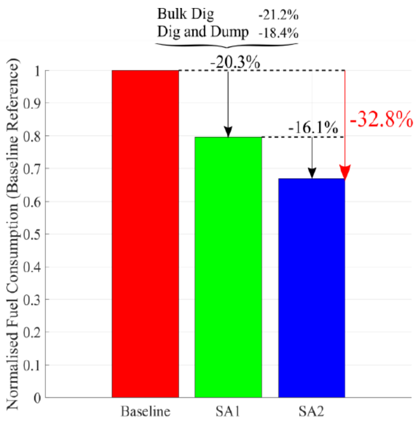


Figure 10: Fuel saving prediction for SA2 system with respect to the baseline machine.

Figure 51: Danfoss' Digital Design Process

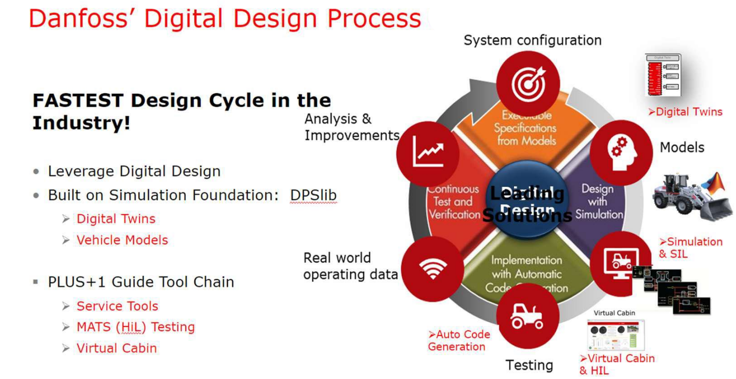


Figure 52: Measurement results for 16T excavator with DDP SWAP [1]

Cycle	Baseline RPM	DDP RPM	Fuel saving per cycle	Cycle rate increase
Trenching	2050	1450	21.2%	10.4%
Bulk dig	2050	1450	21.2%	10.6%
Lorry load 90°	2050	1450	18.4%	-0.4%
Lorry load 180°	2050	1450	16.1%	1.9%
Tracking	2050	1650	16.1%	-
Idling	950	950	27.1%	-

Figure 53: Measurement results for baseline conventional 16T excavator

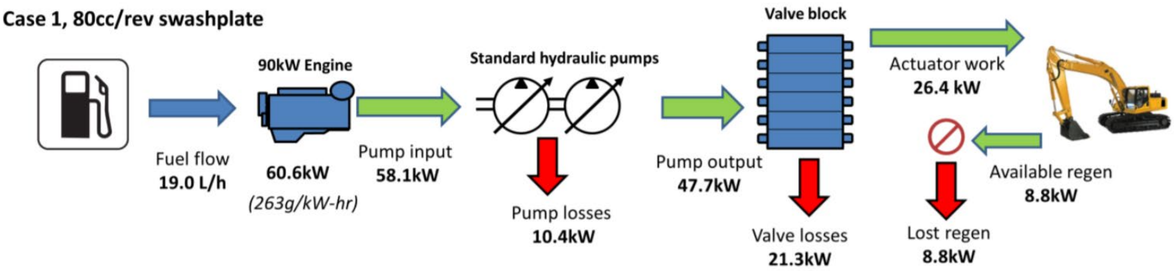
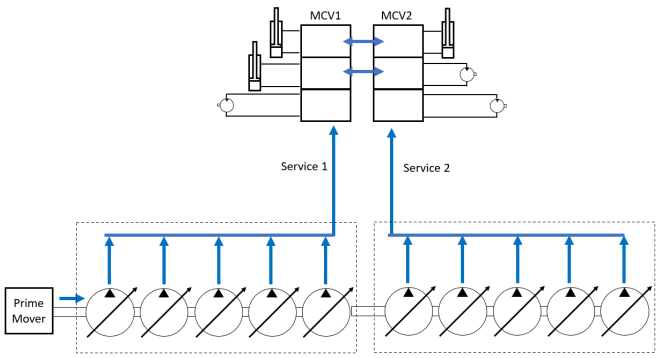
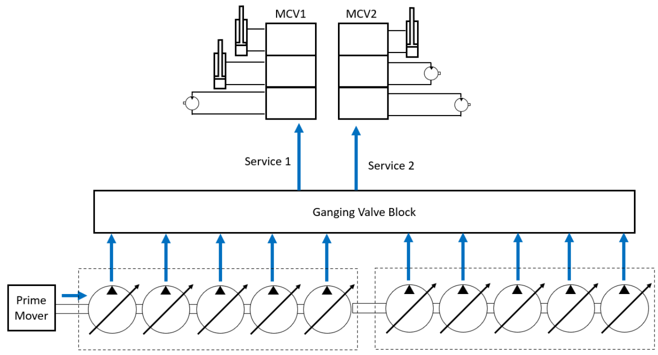


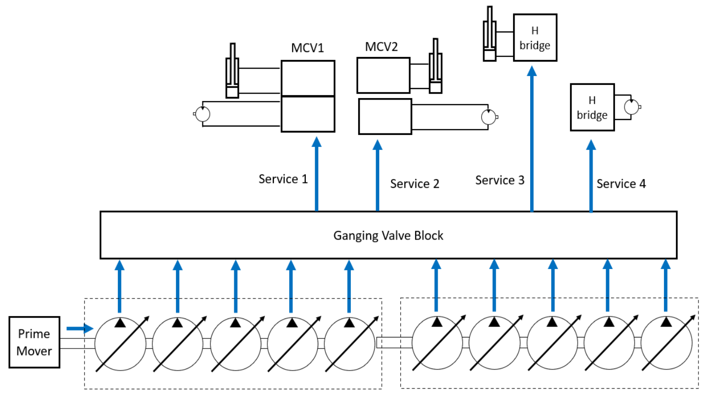
Figure 54: System Architectures



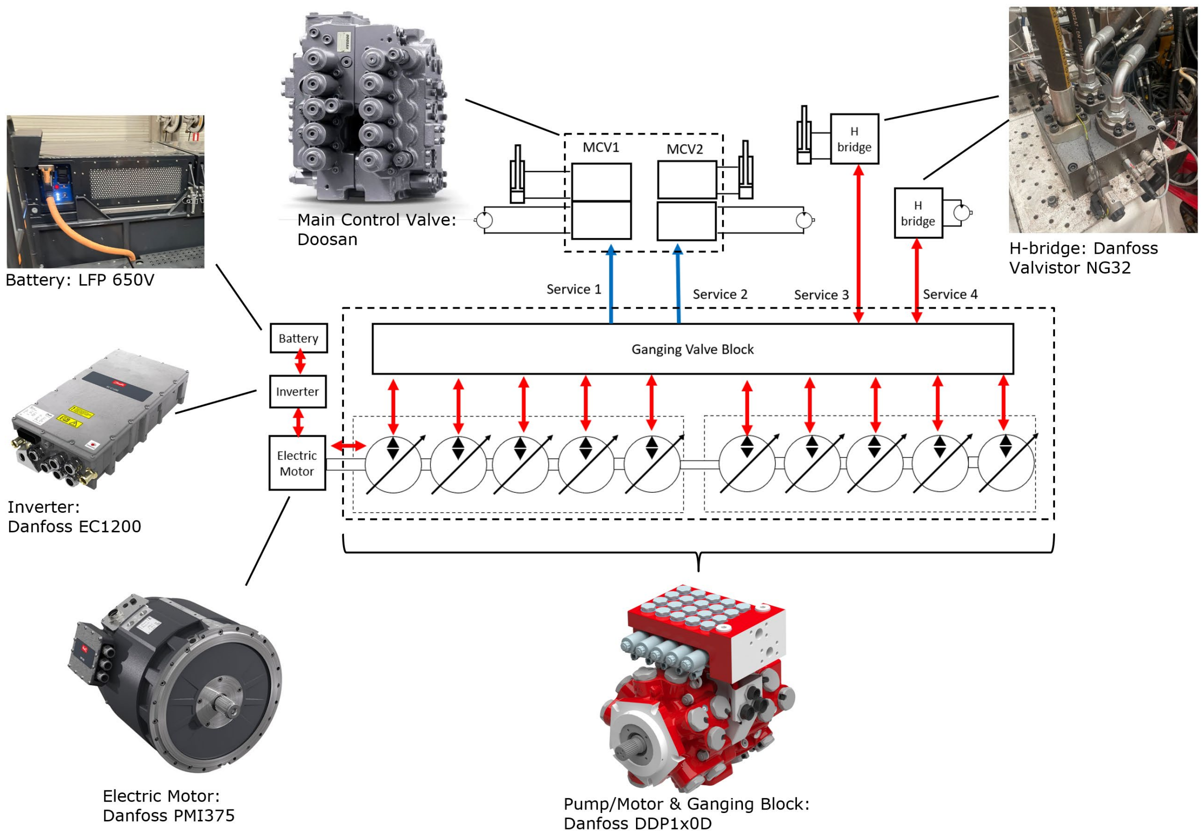
1. Conventional excavator hydraulic system (SWAP)



2. Dextreme FLEX System

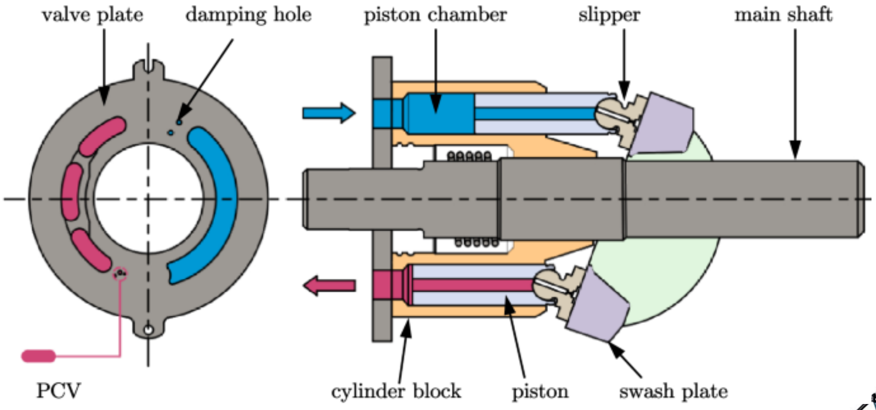


3. Dextreme FLEX+ System



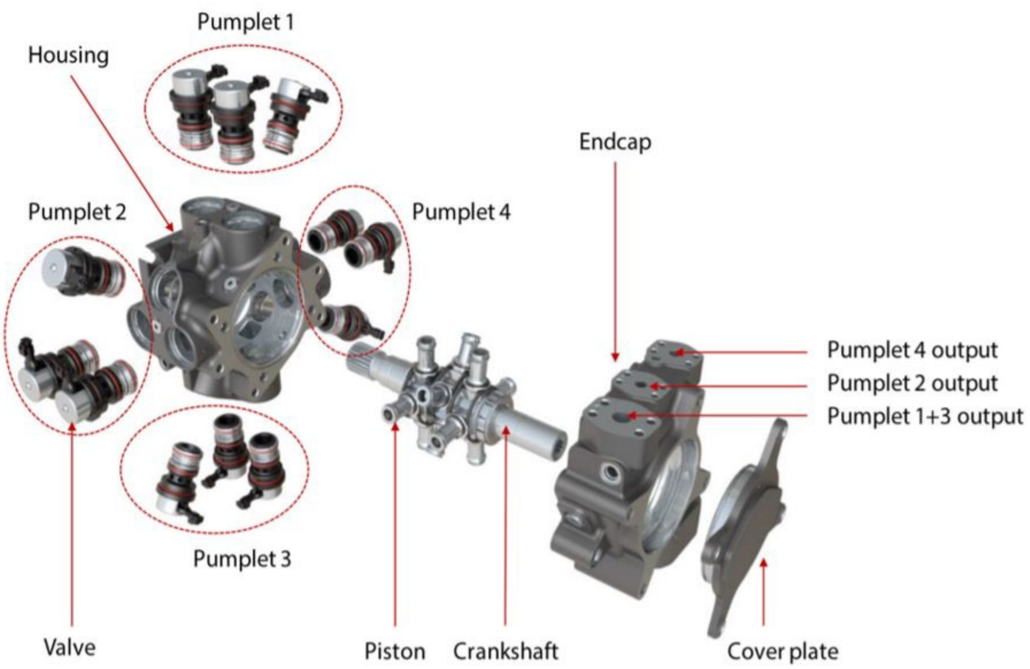
4. Dextreme MAX System for DEPOWER2 HEX

Figure 55: Swashplate vs DDP096



1. Swashplate pump

2. DDP096 Pump

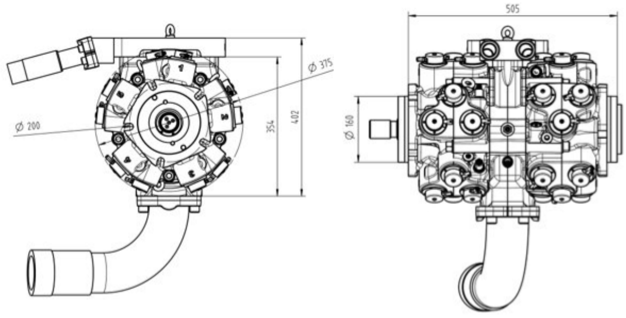


3. DDP096 exploded view

4. DPC12 Pump Controller

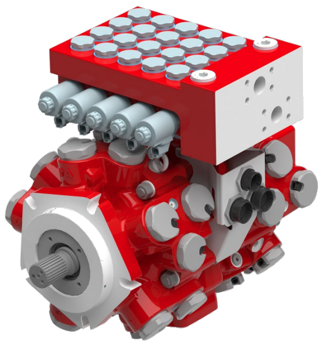
Figure 56: DDP1x0D

	Target
Total displacement	2x 120 - 180cc/rev
Pressure (bar)	350 [420]
RPM range	600 – 2500 [3200]
Max fluid temp (C)	90 [100]
Min viscosity (cSt)	10 [8]
Weight	~180 kg (SA1)
Dimensions	(see drawings)
Suggested thru-shaft options	SAE A 2 bolt (82-2) SAE B 2 bolt (101-2) SAE C 4 bolt

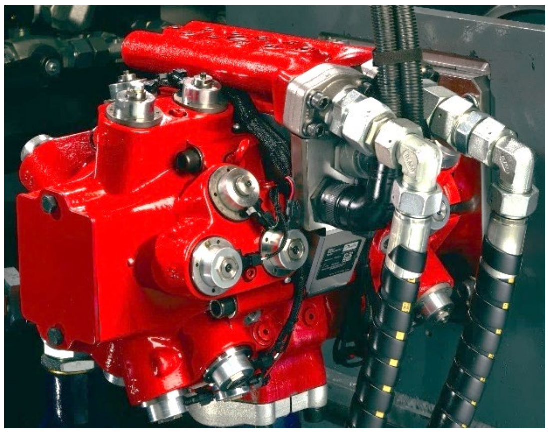


1. Outline specifications and dimensions of DDP1x0D

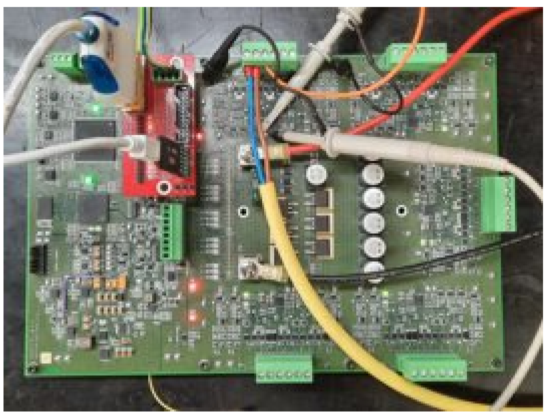
2. Dextreme SWAP *configuration*



3. Dextreme FLEX *configuration*



4. DDP1x0D working prototype



5. DDC15 controller prototype board

Figure 57: DDP1x0D motoring efficiency results

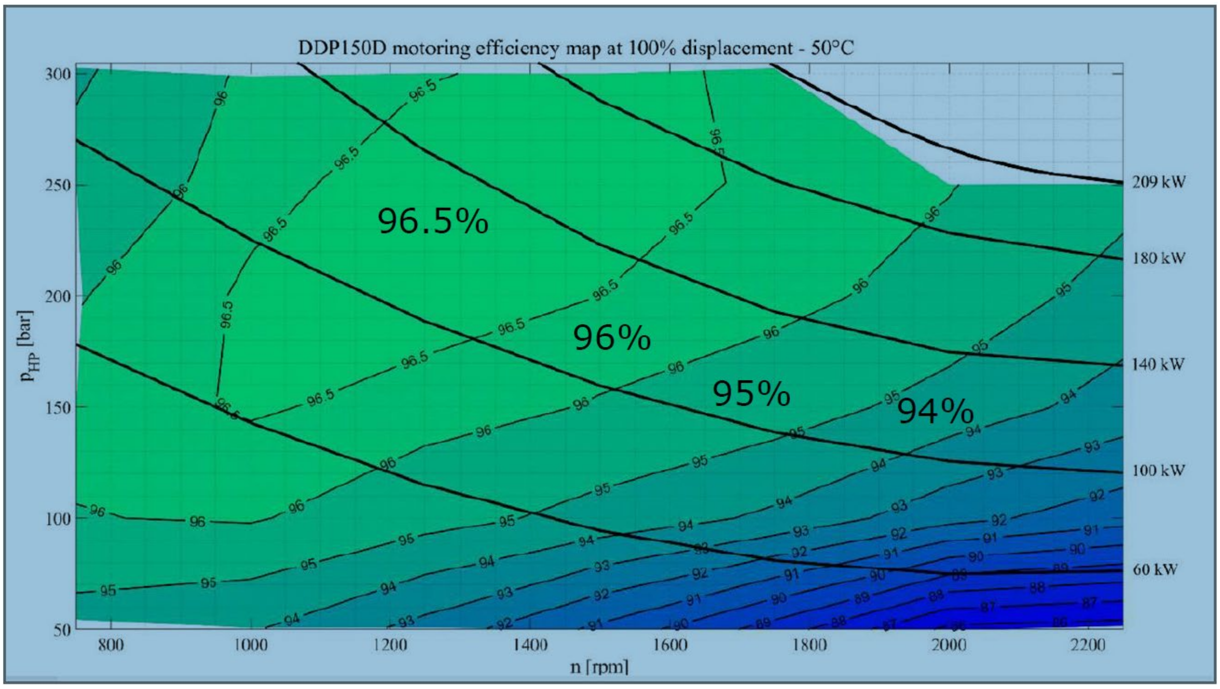


Figure 58:Total Cost of Ownership (TCO) assumptions

TCO – Key assumptions

Parameter – **General**	**Value**
HEX economic life	7 years
HEX operation per day	8 hours
Engine cost	€10,000
Diesel fuel cost	€1.9/L
Electric drive and on-vehicle power distribution	€6,000
Electricity cost	€119/MWh
Battery capacity cost	$200/kWh
H_2 fuel cost (grid production)	€174/MWh HHV
Fuel cell system cost	€432/kW
On-board storage tank cost	€447/kg H_2

Parameter – **16T HEX**	**Value**
16T HEX operation per year	1,000 hours
16T HEX purchase cost	€123,500
Average fuel consumption	11L/hour
Average electricity consumption	74kWh/hour

Parameter – **30T HEX**	**Value**
30T HEX operation per year	1,500 hours
30T HEX purchase cost	€213,750
Average fuel consumption	20L/hour
Average electricity consumption	138kWh/hour

Figure 59: TCO results

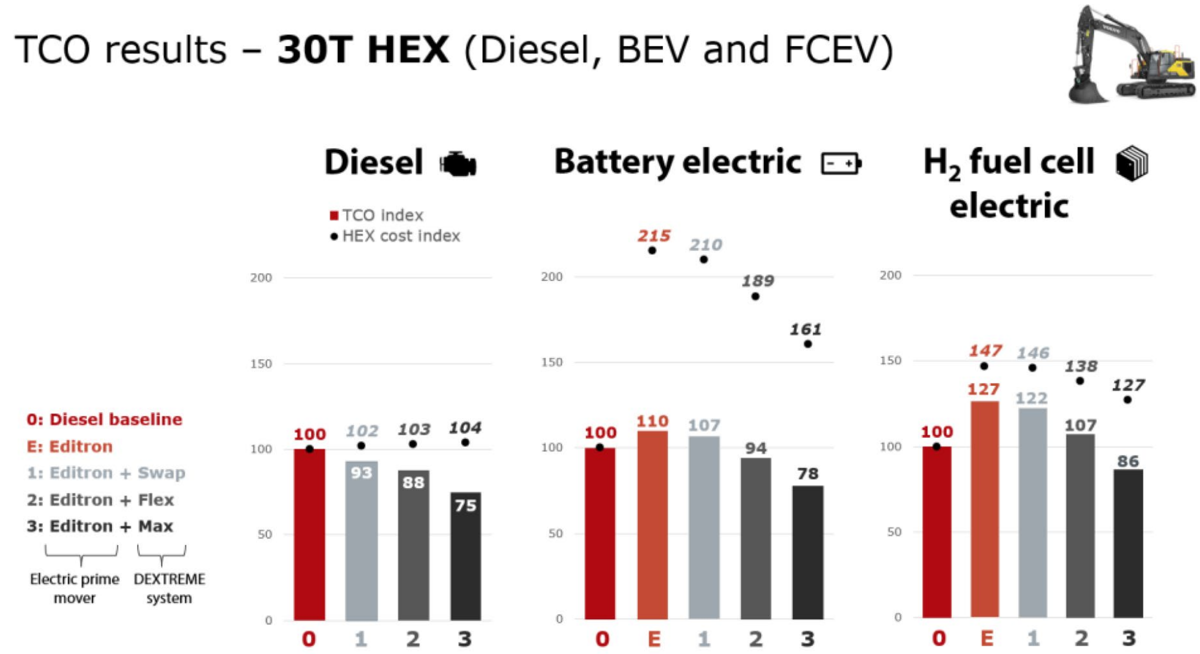
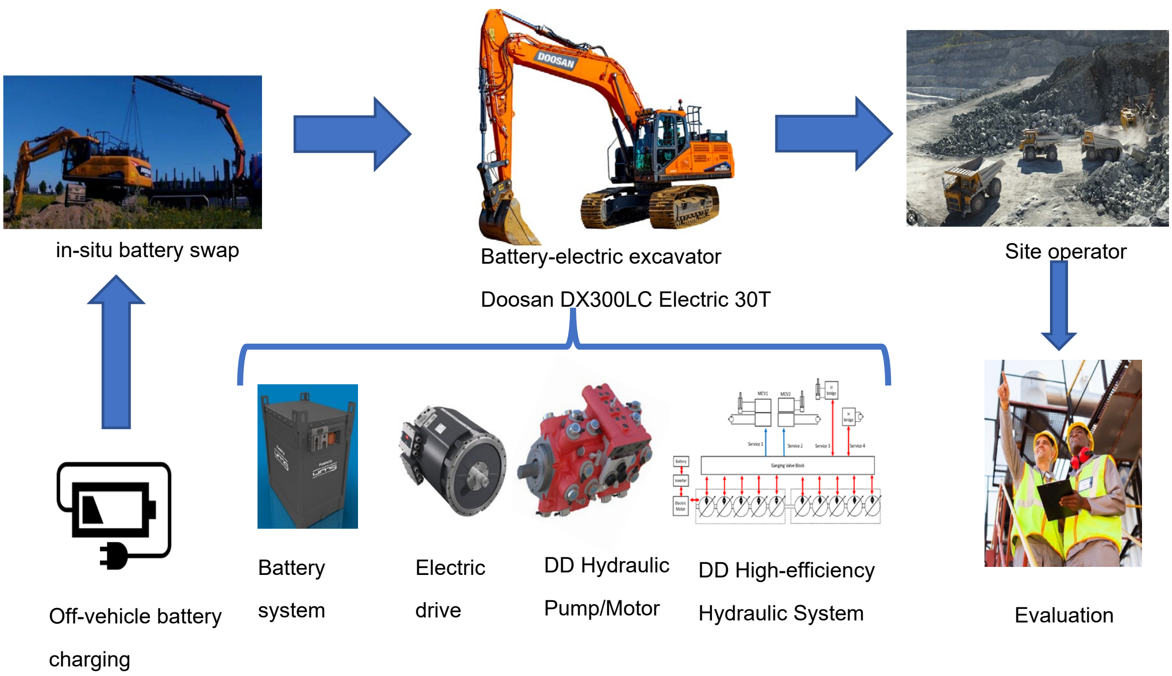


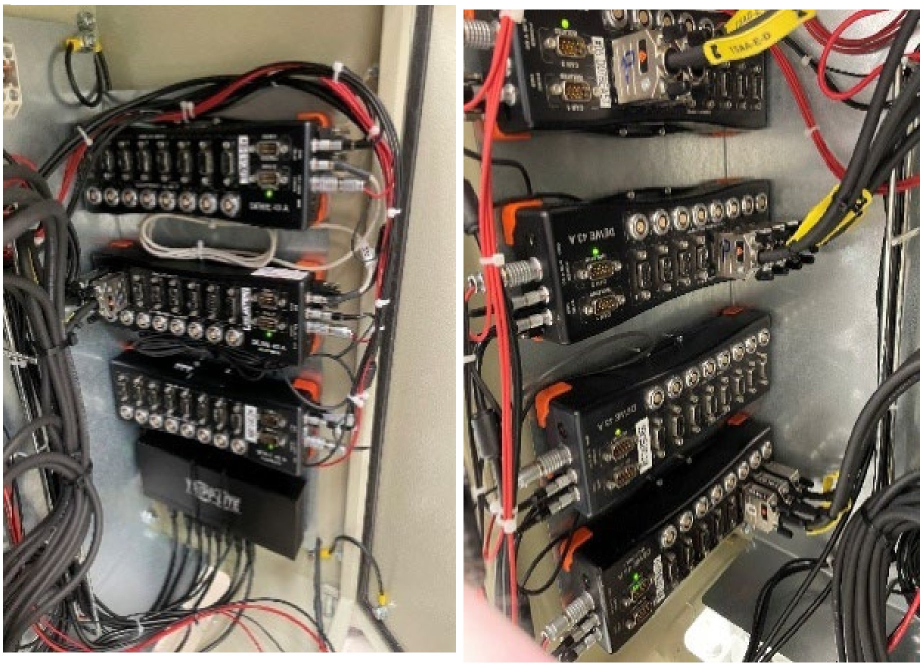
Figure 60: Overall DEPOWER2 system concept



Goals: By improving system efficiency…

- reduce battery capacity requirement from 3 packs to 2 packs
- reduce electrical load on charging infrastructure
- lower overall CAPEX and OPEX than baseline electric machine
- lower TCO than diesel equivalent
- with same/better productivity and run time

Figure 61: Dewesoft setup with 7 DEWE43



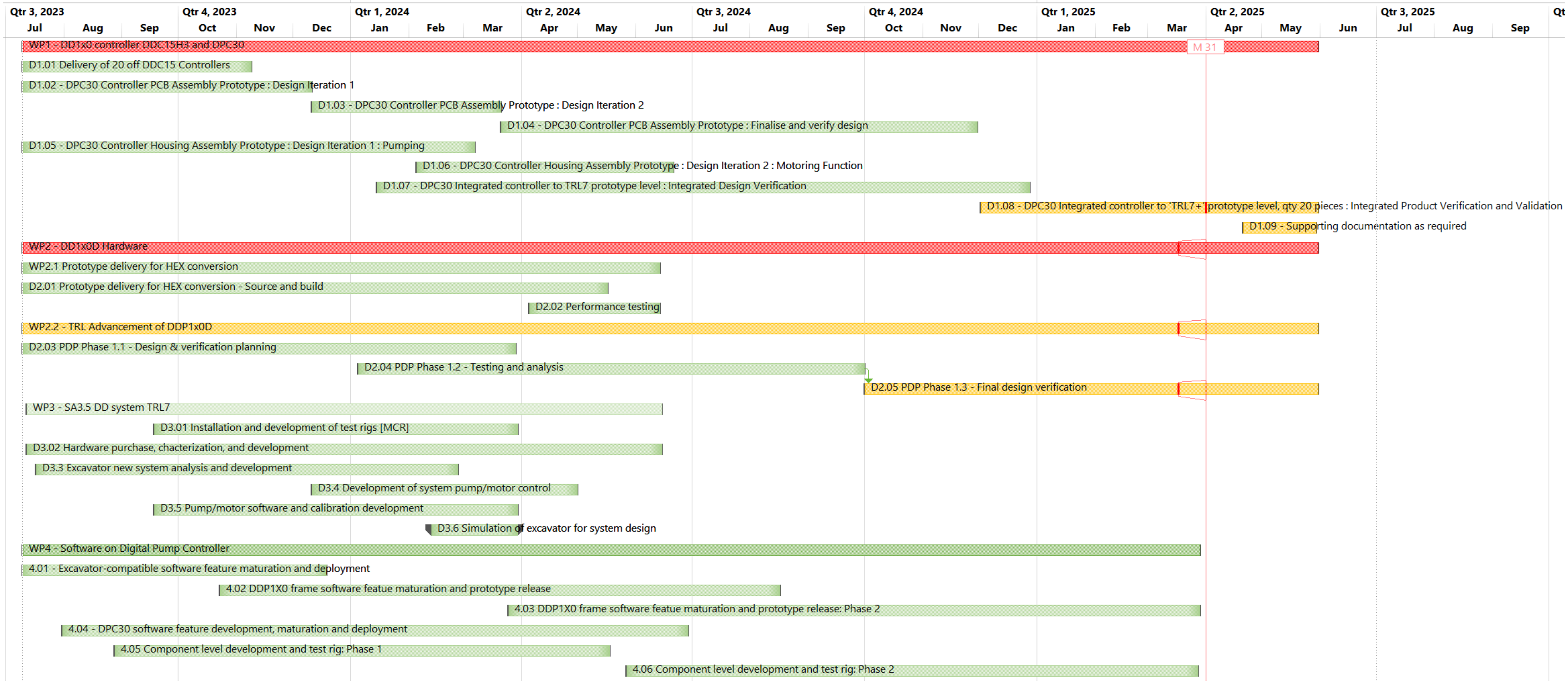
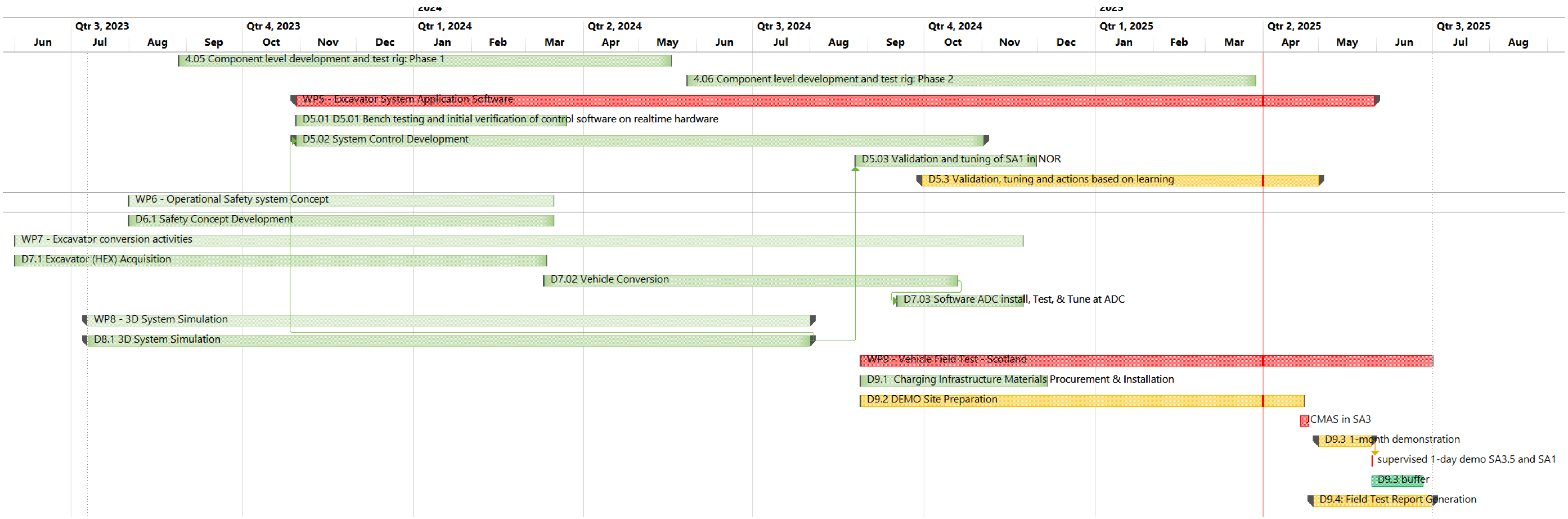


Figure 62: Project Schedule


2024
2025
Qtr 3, 2023
Qtr 4, 2023
Qtr 1, 2024
Qtr 2, 2024
Qtr 3, 2024
Qtr 4, 2024
Qtr 1, 2025
Qtr 2, 2025
Qtr 3, 2025
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May
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Jul
Aug
4.05 Component level development and test rig: Phase 1
4.06 Component level development and test rig: Phase 2
WP5 - Excavator System Application Software
D5.01 D5.01 Bench testing and initial verification of control software on realtime hardware
D5.02 System Control Development
D5.03 Validation and tuning of SA1 in NOR
D5.3 Validation, tuning and actions based on learning
WP6 - Operational Safety system Concept
D6.1 Safety Concept Development
WP7 - Excavator conversion activities
D7.1 Excavator (HEX) Acquisition
D7.02 Vehicle Conversion
D7.03 Software ADC install, Test, & Tune at ADC
WP8 - 3D System Simulation
D8.1 3D System Simulation
WP9 - Vehicle Field Test - Scotland
D9.1 Charging Infrastructure Materials Procurement & Installation
D9.2 DEMO Site Preparation
CMAS in SA3
D9.3 1-month demonstration
supervised 1-day demo SA3.5 and SA1
D9.3 buffer
D9.4: Field Test Report Generation

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