Final report

1. Project details

Project title	Efficient Cement Handling Systems Based on Electro- Hydraulic Power Regeneration Networks (eCHASPOR)
File no.	J.nr. 64020-2046
Name of the funding scheme	EUDP20-II Energy efficiency
Project managing company / institution	Aalborg University
CVR number (central business register)	29102384
Project partners	Bosch Rexroth A/S
Submission date	5 November 2025

2. Summary

Describe the objectives of the project, the obtained results and how they will be utilized in the future, both in English and in Danish. The summary will be published on www.eudp.dk and www.energiforskning.dk.

Project summary

Cement production is one of the most energy consuming and CO_2 emitting industries. A vision within this industry is to enable such productions with zero CO2 emissions by 2030. This necessitates efficiency improvements at all levels, from material types and usage to processes and material handling. This project will develop an entirely new efficient drive technology for cement handling systems based on the concept of electro-hydraulic power regeneration networks. The proposed technology utilizes variable-speed motor/pump units as its core, and these units share multiple hydraulic lines as well as an electric DC-bus. Combined with multi-objective controls, the technology allows to direct power between different parts of the system, while enabling individual actuation of these parts. The developed cement handling systems will be highly efficient, highly scalable, durable and commercially feasible compared to state-of-the-art. The proposed technology is developed through thorough understanding of physical features, innovative control methods, cement handling applications and commercial aspects. The goal is a green technology that improves average efficiencies with at least 50%, that is scalable up to 250 [kW] output power and that enables an increased turnover and market share by 2030.

The purpose of the project

Facing the climate crisis, a key challenge is excessive energy use and the associated emissions related energy loss in industrial systems. The main purpose of the project was to develop and demonstrate highly energy efficient, integrated electro-hydraulic variable-speed drive network technology (main innovation) for cement cooler transport systems.

Results, conclusions and perspective

The most important results in the project were:

- An electro-hydraulic drive (power regeneration networks) architecture design methodology, considering safety, cooling, filtering and oil-filling functionalities.
- Development of an electro-hydraulic drive network wide control strategy and design approach, enabling individual motion control of all hydraulic actuators as well as the minimum system pressure, with the desired control precision.
- Realization of a physical prototype satisfying all industrial requirements, designed specifically for the demonstration host, including a reduction of necessary hydraulic fluid above 90%.
- Experimental validation in the laboratory of the physical prototype, i.e. at part load as compared to the demonstration partner. Especially, the developed control functionality provides the desired performance.

The results will be useful in many regards. The technology allows to reduce energy losses and emissions broadly in cement handling systems, and the industrial project partners will proceed targeting this objective. During the project the partners recognized a much broader perspective for the technology than “just” cement handling systems. In fact, electro-hydraulic drive networks turn out to have perspectives beyond cement handling. Hence, additional projects were established considering the electro-hydraulic drive networks for heavy-duty mobile machinery, and more projects are in consideration, where the results here serve as a baseline.

Projektresumé

I lyset af klimakrisen er en hovedudfordring den overdrevne anvendelse af energi og de tilhørende udledninger relateret til energitab i industrielle systemer. Hovedformålet med projektet var at udvikle og demonstrere højeffektiv integreret elektro-hydrauliske drevnetværksteknologi (primær innovation) til cementkøler-transportsystemer.

Resultater, konklusioner og perspektiv

De væsentligste resultater I projektet er:

- En designmetode til elektro-hydrauliske drev (effektregenererings-) netværksarkitekturer, indeholdende sikkerheds-, kølings-, filtrerings- og oliepåfyldningsfunktioner.
- Udvikling af en systemniveaubaseret styrings- og reguleringsstrategi og design tilgang til elektro-hydrauliske drevnetværk, som giver mulighed for individuelt at styre bevægelsen af de hydrauliske aktuatorer samtidig med systemets minimumstryk, med den ønskede præcision.
- Realisering af en fysisk prototype som opfylder alle industrielle krav, og som er designet specifikt til demonstrationsværten, inklusiv en reduktion af den nødvendige hydrauliske olie på over 90%.
- Eksperimentel validering af den fysiske prototype i laboratoriet, dvs. ved dellast sammenlignet med demonstrationspartnerens last. Her viste den udviklede styrefunktionalitet sig at give den ønskede performance.

Resultaterne er brugbare I mange henseender. Teknologien kan bruges til at reducere tab og udledninger bredt indenfor cementhåndteringssystemer, og projektets industripartnere vil fortsat søge denne målsætning.

Igennem projektforløbet indså partnerne at teknologien har en meget bredere perspektiv end ”bare” cement-håndtering. Der er derfor blevet iværksat nye projekter vedrørende anvendelsen af elektro-hydrauliske drev-netværk i tunge mobile arbejdsmaskiner, og flere andre overvejes, hvor dette projekt tjener som grundlag.

3. Project objectives

3.1. Technology Developed & Demonstrated

The technology considered is in the subject area of electro-hydraulic drive systems technology, having the focus mainly on energy efficiency. The technology is focused on systems design rather than component design and rely on variable-speed electric motor drives combined with hydraulic pumps/motors as the central component assembly. The idea is to establish systems using several of these assemblies with a common electric supply, relevant hydraulic connections between hydraulic actuators as well as short circuit connections between hydraulic actuators, forming an electro-hydraulic drive network. This approach renders such drive networks highly energy efficient compared to traditional technology as throttle losses are nearly eliminated but also allows to distribute hydraulic energy on a system wide level, i.e. the power of multiple electric machines may be directed to a single cylinder. Consequently, one does not need one electric motor drive for one actuation that must meet max. force and speed requirements, even though not concurrently, as in standalone electro-hydraulic drives. Rather, the power requirement of the actuators is shared by multiple electric motors, why the system level power installation requirement may be reduced in comparison, making such drives more commercially feasible.

3.2. Background

Cement production is related to substantial energy consumption, and the processing of minerals into the final product through heating, but also material cooling, processing and handling etc. The handling of materials during the cooling process is realized by clinker/cement transport systems, exposed to dusty and murky conditions as a result of the bulky nature of the material. Furthermore, these transport systems provide high forces due to the high material density and high production rates, and consequently these systems consume large amounts of energy. These transport systems convey the clinker material from a furnace outlet to a clinker roller breaker system as depicted in figure 3.1., while the clinker material is cooled, and is essential for the process.

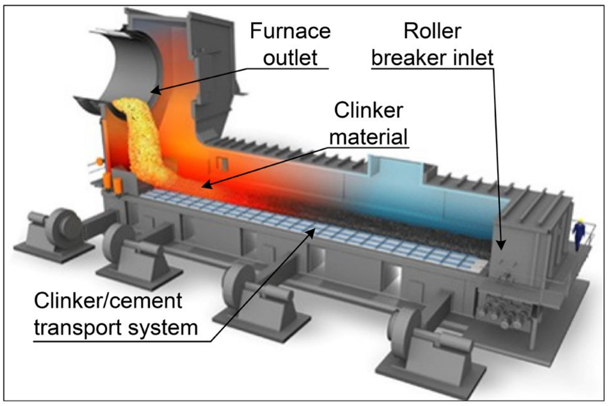

Fig. 3.1. Illustration of clinker/cement transport process.

The clinker transport process is realized by hydraulic cylinders due to their high force and power density, their durability towards fluctuating and impact loads and robustness toward operation in dusty and murky environments. The transport area is comprised of several parallel lanes forming a moving floor, and typically the transport area includes 3-11 lanes, each are actuated by 1-3 hydraulic cylinders per lane. An operation cycle of a clinker/cement transport system is typically conducted in three steps as illustrated in figure 3.2., the cycle rate typically ranges from 3-15 cycles per minute, with average output power levels ranging from 15 [kW] – 250 [kW].

Predominantly, the hydraulic cylinders actuating the lanes are controlled by throttle control valves, with system level energy efficiencies ranging from 40%-47%. Typically, clinker/cement transport systems operate around the clock 330 days a year. Hence for a single machine in the largest power range the energy consumption exceeds 4,2 [GWh/year]. The corresponding CO_2 emissions for such a machine equals ≈ 632 [tonnes/year] based the average emissions per kWh electric energy in DK in 2019[1]. As a result of the low energy efficiencies, ≈ 335 [tonnes/year] is associated with energy losses.

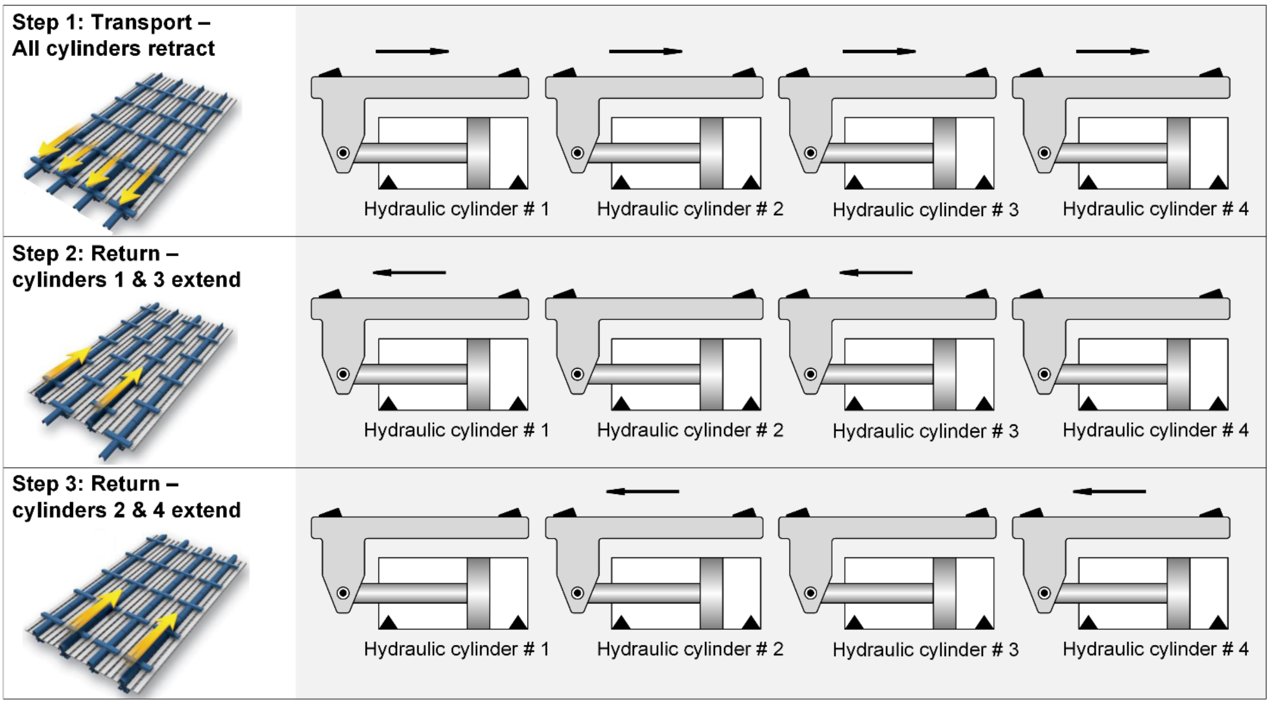

Fig. 3.2. Illustration of an operation cycle for a 4-lane clinker/cooler transport system.

3.3. Project Objective & Energy Technology Developed

The main objective of the project was to develop and demonstrate a technology that enables highly energy **e**fficient **c**ement **ha**ndling **s**ystems based on electro-hydraulic **po**wer **r**egeneration networks (eCHASPOR networks). The key objectives were high energy efficiencies, necessary and reliable functionalities and commercial feasibility. The proposed concept was based on a network of variable-speed hydraulic pump drives, enabling a high degree of energy regeneration between electrical and hydraulic subsystems. A 4-lane example of the eCHASPOR network concept is illustrated in Fig. 3.3.

The eCHASPOR network concept completely avoids inefficient throttle control and minimizes power conversion stages and related losses (electric↔hydraulic) via a simple architecture with few standard components. The functionality of an eCHASPOR network is enabled by 4-quadrant pump/motor/inverter drives interconnected with a common DC-bus, common hydraulic lines and a small fluid reservoir allowing to account for the cylinder differential volumes. Clinker/cement transport systems are only subject to strictly resistive loads, not necessitating any significant electric energy recuperation features, hence only capacitor(s) are included in the DC-bus accounting for electric power transients mainly related to reversing lane motion directions etc. The

[1] https://energinet.dk/Om-nyheder/Nyheder/2020/01/16/Rekord-lav-CO2udledning-fra-danskernes-elforbrug-i-2019

functionality was to be realized by innovative multi-objective controls allowing for individual motion control of the cylinders, lower system pressure control, power regeneration and loss minimization.

A prototype demonstration of the developed eCHASPOR network concept was to be conducted in an operational environment, with the demonstration host facilitated by FLSmidth A/S.

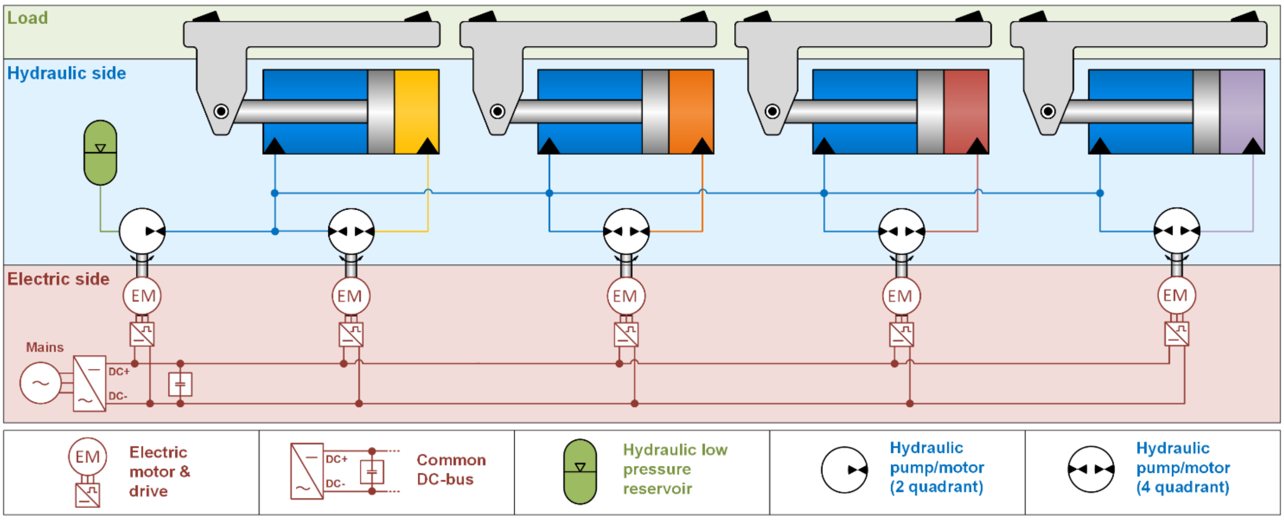

Fig. 3.3. Schematics of an eCHASPOR network actuating a 4-lane clinker/cement transport system.

Finally, the key project objectives related to eCHASPOR network technology was:

- To realize total energy efficiencies above 70%
- To allow a high degree of energy regeneration electrically and hydraulically
- To be scalable from 15 [kW] – 250 [kW] (output power)
- To be realizable at a cost not exceeding 80% of existing solutions, consuming only 20% space
- To be operable without any specialized technical knowledge beyond common operator knowledge

4. Project implementation

4.1 Project Evolvement

The project went to a very high degree according to the plan, with the EUDP funded parties and the self-funded party FLSmidth working well together. From the start of the project, it was planned to bring a cement manufacturer onboard the project, to have a full stakeholder chain involved comprising research institution, over component manufacturer, to OEM and end-user. The idea of this was to be able to consider all relevant features and requirements necessary for developing an industrially viable technology.

Initially, the project group tried to bring a Danish cement manufacturer onboard the project as the end-user. However, due to other research and development obligations, this manufacturer decided not to be involved. For this reason, the project participants approached a Spanish cement manufacturer, which decided to enter the project as a demonstration partner.

4.2 Project Evolvement

Throughout the period from 2022 to 2025, the eCHASPOR project underwent a significant and complex evolution, progressing from the conceptual design phase to the development and validation of a fully functional prototype system. The early stages of the project were characterized by solid technical progress, with the successful completion of the fundamental system design, including vital subsystems for oil cooling and filtration, safety and emergency stop features, and the creation of a specialized oil tank enabling hydrodynamic flow separation. A schematic of the modular architecture is illustrated in figure 4.1.

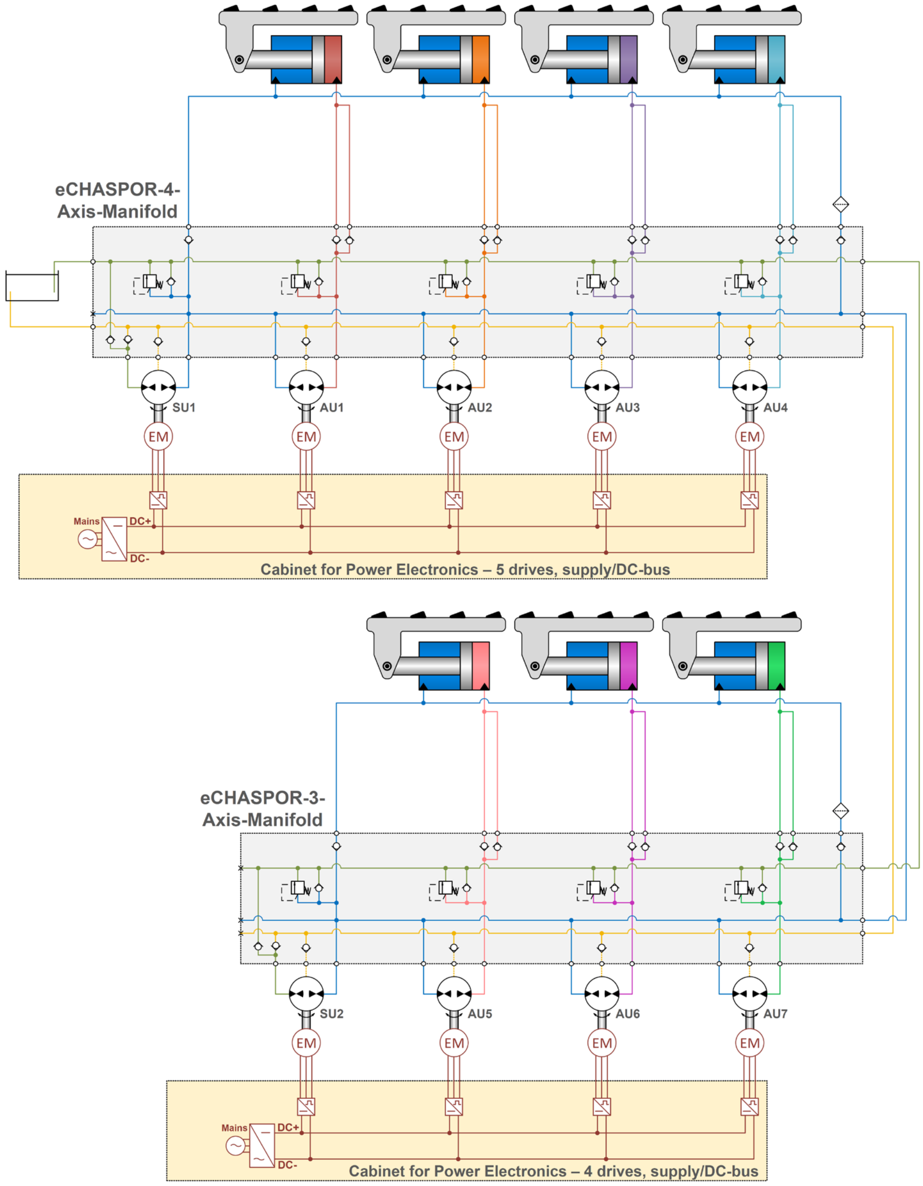

Fig. 4.1. Illustration of modular eCHASPOR networks – here 3 and 4 lane versions coupled into a 7-lane system.

The system's modular architecture was a key innovation, allowing scalability across various clinker/cement transport system sizes, including larger systems than those currently in production. With the modular 3 and 4 axis eCHASPOR networks depicted in figure 4.1. the drive networks for clinker/cement transport systems with 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 lanes etc. may be realized.

These developments in demonstrated strong technical momentum and adherence to the original project plan. However, the project also faced its first major challenge during this phase when the intended demonstration partner, the Danish cement manufacturer, decided not to participate due to resource constraints and internal strategic priorities. This led to the selection of a new partner, the Spanish cement manufacturer, which caused inevitable delays in prototype design and planning as the team adapted the system specifications to the new partner's operational conditions.

In 2023, the project entered its implementation and prototyping phase. Despite the earlier setback, the consortium successfully completed the prototype design and began system assembly. The hydraulic prototype was built at Bosch Rexroth's facilities in Austria, while the electrical subsystem was developed by a Danish partner. After successful factory acceptance tests, the prototype was transported to and installed at Aalborg University's laboratory for validation, as seen in the pictures in figure 4.2.

Fig. 4.2. eCHASPOR prototype about to be installed a laboratory at Aalborg University.

During this period, the project team faced external economic challenges, including substantial component price increases following the COVID-19 pandemic and the war in Ukraine. Additionally, the new demonstration system at the Spanish cement manufacturer had a significantly higher power output requirement than initially planned for the Danish cement manufacturer, necessitating a reconfiguration of the test load system. By leveraging existing components and resources from Bosch Rexroth and FLSmidth, the team managed to develop a cost-effective test setup based on the load concept in figure 4.3, albeit one that limited the system's maximum power validation due to available load cylinders etc. The build-up of one of the load systems is depicted in figure 4.4.

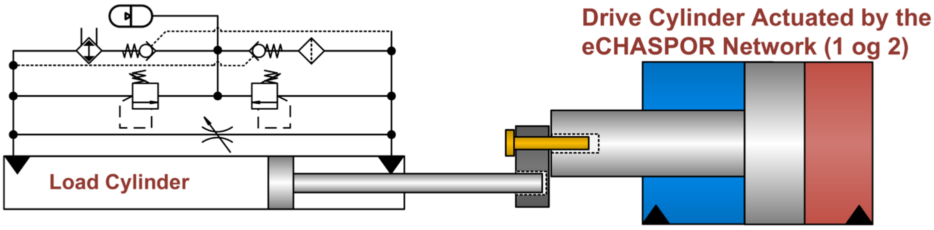

Fig. 4.3. Illustration of load system setup.

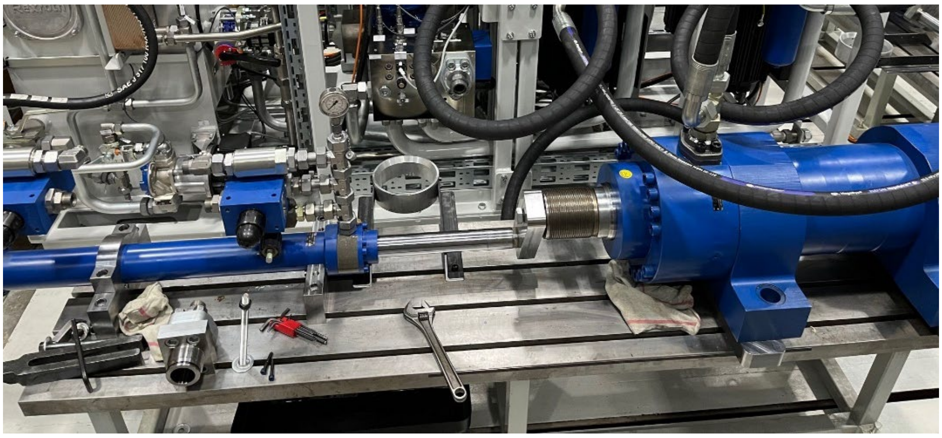

Fig. 4.4. Picture of the build-up of one of the load systems at a laboratory at Aalborg University.

Despite an overall delay of 8–9 months, the partners considered the progress satisfactory, as the system's functionality and control mechanisms were validated through extensive simulations and preliminary laboratory testing via the test setup depicted in figure 4.5.

By the end of 2023, the eCHASPOR system had achieved full functional validation in laboratory conditions. Control algorithms were implemented and optimized on the system hardware, with laboratory tests confirming stable operation and system-level leakage monitoring. A 48-hour endurance test demonstrated robust performance, and although the system's full energy efficiency could not be tested under partial load conditions, simulations estimated an overall efficiency of 65.8–70.1%, indicating strong potential for industrial application. The next critical phase involved installation and commissioning of the prototype system at the production plant at Spanish cement manufacturer conducted in December 2023 and January 2024. However, this milestone did not proceed as planned. During the on-site commissioning in early 2024, the project team discovered multiple leaks in the plant's pipework and deficiencies in the electrical installation. Despite repeated repair attempts, the system could not be pressurized, and the commissioning had to be postponed until the demonstration partner had corrected the installation issues. Although the Spanish cement manufacturer initially agreed to complete the required fixes before the next scheduled maintenance stop, progress was slow and ultimately inadequate.

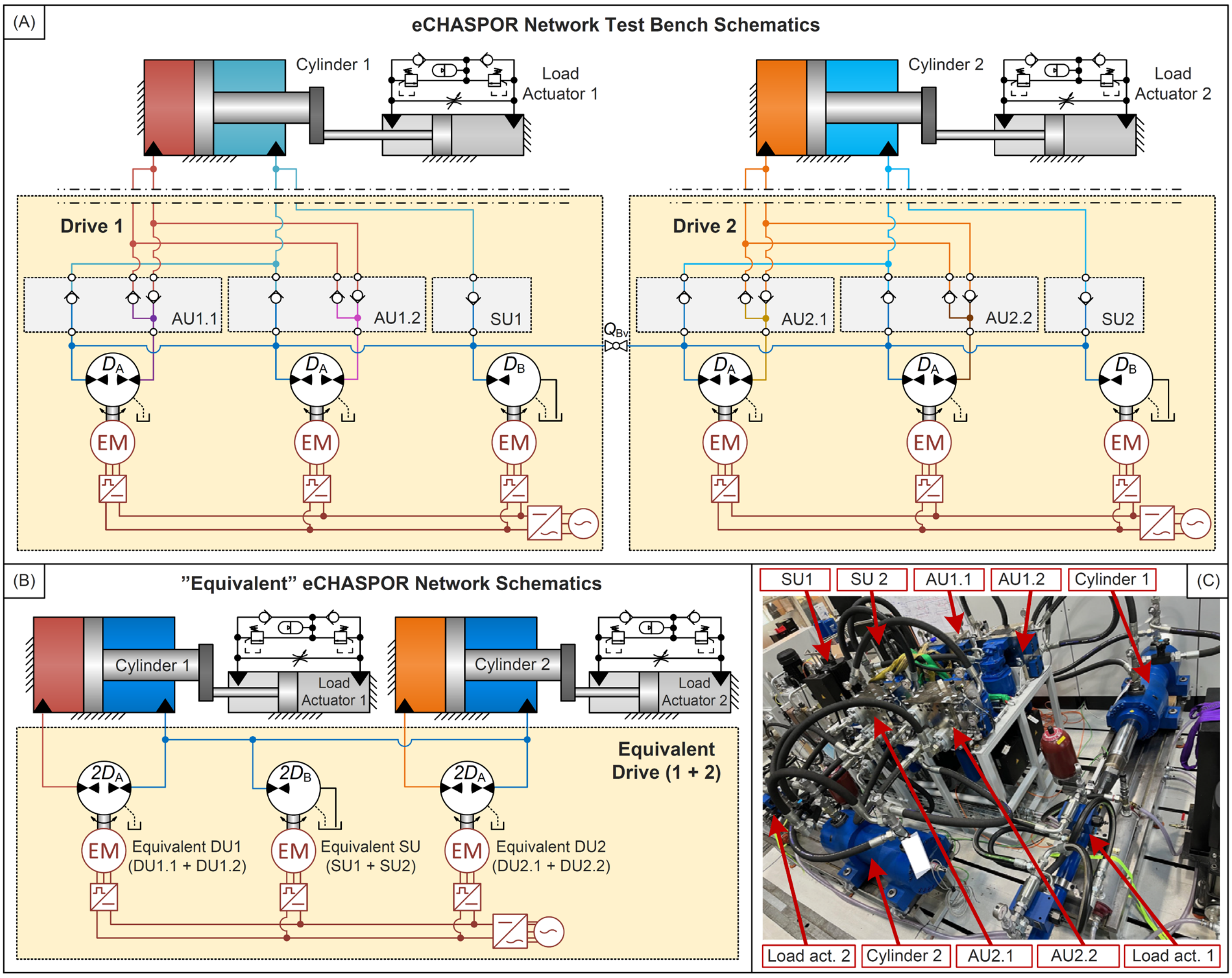

Fig. 4.5. (A) Dual cylinder eCHASPOR network test bench schematics. (B) Equivalent dual cylinder eCHASPOR network test bench schematics. (C) Picture of dual cylinder eCHASPOR network test bench implemented at Aalborg University.

In 2025, the project's organizational and partnership risks materialized fully. Despite continuous technical support from Bosch Rexroth throughout 2024, the demonstration partner failed to carry out the necessary corrections. In December 2024, demonstration partner announced that it would withdraw from the project unless the consortium covered their remaining costs for completing the installation—contrary to prior agreements. Since Bosch Rexroth and FLSmidth had already invested significant unbudgeted resources to sustain project progress, they were unable to meet this new demand. Consequently, the Spanish cement manufacturer officially withdrew from the project in early 2025, leaving the fully functional prototype installed but inactive at their site. Efforts to retrieve the prototype and demonstrate it with a new partner were approved through an official project change request in February 2025, extending the project's end date to June 2025. However, the Spanish cement manufacturer did not cooperate on this task, preventing the removal of the equipment before that date. This obstruction ultimately made it impossible to conduct the planned demonstration before project closure, despite repeated attempts and negotiations by the consortium.

4.3 Risks Associated with Conducting the Project

The project encountered both technological and organizational risks during its execution. Technologically, the development of advanced control systems for multi-axis hydraulic operation, efficient cooling mechanisms, and dynamic decoupling introduced inherent uncertainties. These were effectively mitigated through extensive simulation, laboratory validation, and progressive refinement of design methodologies. Organizationally, however, the reliance on a single external demonstration partner proved to be the greatest vulnerability. The inability of the demonstration partner to fulfil their commitments—combined with communication difficulties, delays in technical corrections, and eventual contractual non-compliance—directly hindered the project's final demonstration phase.

In summary, the eCHASPOR project largely succeeded in achieving its technical objectives and producing a validated prototype that met or exceeded performance expectations in laboratory conditions. The project's early and mid-term phases followed the agreed milestones with only minor, manageable delays. However, the final implementation phase did not unfold as foreseen due to the unexpected withdrawal and non-cooperation of the demonstration partner. This unforeseen issue prevented the technology from being showcased in an industrial setting within the project's official timeframe. Nevertheless, the main project partners—Bosch Rexroth, Aalborg University, and FLSmidth—fulfilled all their contractual obligations, maintained strong collaboration, and ensured that the technology is ready for future demonstration once an alternative industrial partner can be secured.

4.4 Approved Change Request & Milestones

In December 2023, a project change request was approved, which, among other things, extended the project period from September 30, 2024, to February 28, 2025. This was based on the fact that the Spanish demonstration host operates with continuous production campaigns lasting 12–14 months, which would also serve as the demonstration period, starting in January 2024. As described above, the commissioning set for January 2024 was not successful due to leakage and pipe bursts in the demonstration plant's pipework and deficiencies in the electrical installation.

A second project change request was approved in 2025, aiming to extend the project deadline once again, in order to have the possibility to deinstall the prototype in order to demonstrate this at another cement manufacturer. At the same time a request to delay the milestones M6, CM4, and CM5 until the demonstration has been carried out at another demonstration host was approved.

From the above descriptions, the status on project milestones appear as outlined below.

Technical milestones:

- M1: Final eCHASPOR architecture design finalized, including safety, cooling, filtering and oil-filling functionalities — reached
- M2: Physical prototype realized — reached
- M3: System control function finalized — reached
- M4: Validation of prototype functionality validated — reached
- M5: Prototype implemented in operational environment — reached
- M6: Demonstration of prototype in operational environment completed — pending

Commercial milestones:

- CM1: Design tool to facilitate commercialization of eCHASPOR Network technology — partly reached
- CM2: Press release on eCHASPOR Network technology — partly reached
- CM3: Presentation of eCHASPOR Network technology and commercial aspects at customer event — reached
- CM4: Press release on eCHASPOR Network technology in operational environment — pending
- CM5: Article in trade magazine on functionality/operation of

eCHASPOR Networks pending

5. Project results

As described in Section 4, project implementation, the main obstacle in the project was that the final demonstration phase did not unfold as foreseen due to the unexpected withdrawal of the demonstration partner. Nevertheless, the project largely succeeded in achieving its technical objectives and producing a validated prototype that met or exceeded performance expectations in laboratory conditions.

5.1 Technological Results

A high degree of power recuperation was achieved as originally intended, partly through short circuiting of the rod side chambers of the hydraulic cylinders, and partly due to the shared electric power supply. This highly integrated network architecture came with the consequence of control complexity, and the necessity to develop a system wide control structure able to handle this.

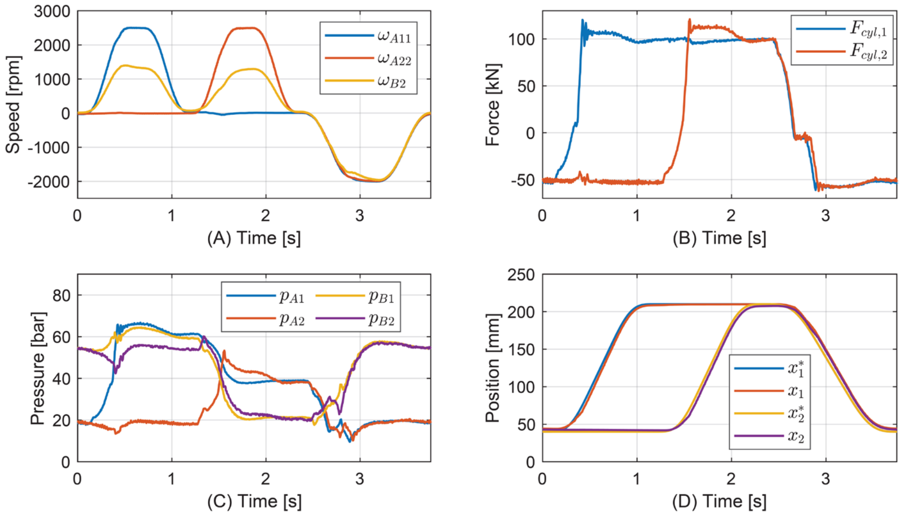

Fig. 5.1. Prototype states for one of the laboratory test cycles, operating at 16 motion cycles per minute (fastest speed requirement). (A) Actual electric motor shaft speeds. (B) Hydraulic pressure forces of main cylinder pistons. (C) Chamber pressures of main cylinders. (D) Main cylinder piston positions and position commands (marked with superscript $*$).

Two functional control structures were developed where especially one of these proved applicable with sensors commonly available in industry, while at the same time providing the desired control of the cylinder pistons and controlling the lower system pressure to some vicinity of a lower pressure setting. Results of a single motion cycle at the highest "cycles per minute" requirement is shown in figure 5.1, obtained during the laboratory tests.

Due to limited ability to load the cylinders in the laboratory at Aalborg University, efficiencies could only be obtained for part loads. However, based on measured states and mathematical models the project team managed to predict efficiencies for nominal load conditions. The efficiencies are shown in figure 5.2, demonstrating that the predicted and measured efficiencies closely resemble each other in the lower output power range. The main discrepancies between the measured and simulated efficiencies are related to the predicted displacement unit efficiencies, which slightly deviate at the lower output power levels. However, the main interest is the predicted efficiency from the electric motor shafts to the cylinder pistons depicted in the right-most part of figure 5.2, suggesting a maximum efficiency for the considered motion cycle of approximately 77% from the electric motor shafts to the cylinder pistons at an average output power of 110 [kW]. The clinker/cement transport system is, for the considered motion cycle, expected to have an average output power of 80 [kW], and, hence, a predicted efficiency from the electric motor shafts to the cylinder pistons of approximately 76%. Assuming a total average electric system efficiency of 90% under this load, the total average system efficiency from mains to the cylinder pistons is predicted to be approximately 68%, which is close to the target of 70% for the project.

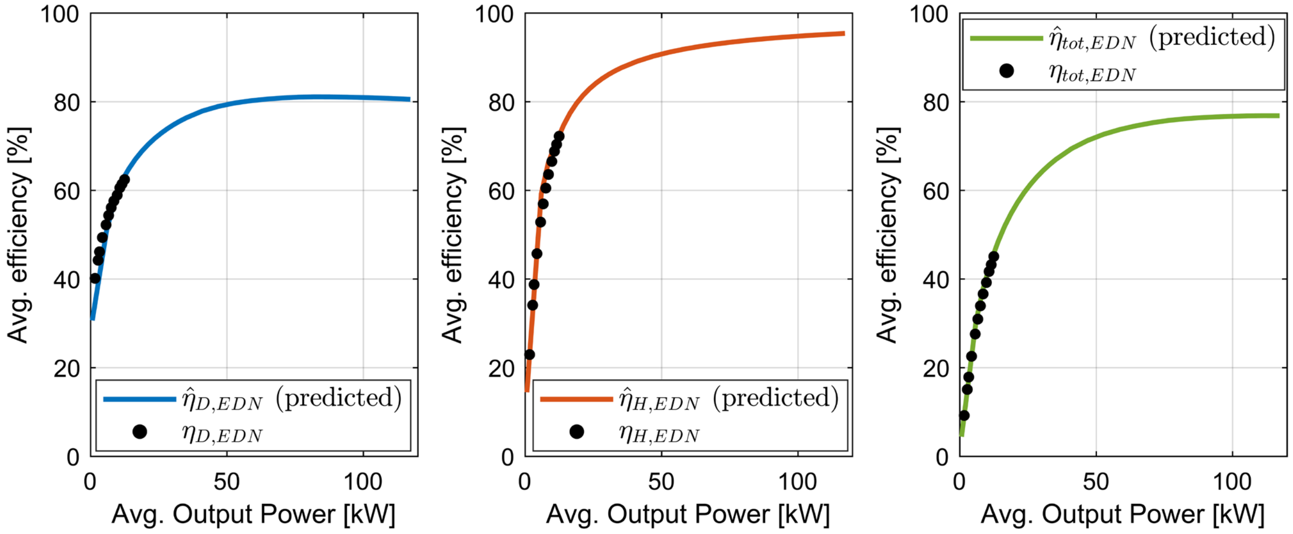

Fig. 5.2. Predicted efficiencies for specified motion cycles and increased loads, and comparison with experimental tests. (A) Total average efficiency of all displacement units for the load cycles considered. (B) Total average efficiency of all pipes/hoses/fluid exchange mechanisms for the load cycles considered. (C) Total efficiency from electric motor shafts to the main cylinder pistons for the load cycles considered.

Considering the current design approach for clinker/cement transport systems, these are commonly based on throttle valves and may appear as depicted in figure 5.3. Evidently, the efficiencies of the VDSs are lower than those of the eCHASPOR network, which is mainly due to the fact that the supply pressure is dictated by the highest chamber pressure plus an additional pressure margin and the resulting throttle losses. The predicted efficiency results appear as depicted in Figure 9. It is found that the total VDS efficiencies never exceed 55% in any case for this system with the specified motion cycle, even when hose losses are neglected as considered here. Furthermore, it is notable that the eCHASPOR network improves the system efficiency by ≈40% and ≈47% compared to the VDSs with matched and symmetric valves, respectively.

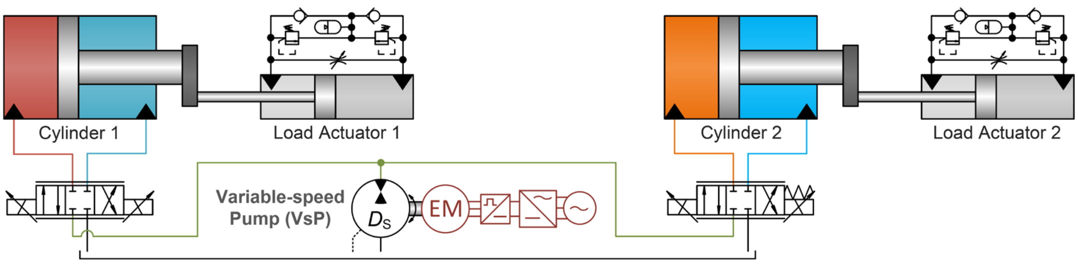

Fig. 5.3. Schematics of proportional valve drive system fed by variable-speed pump (VDS).

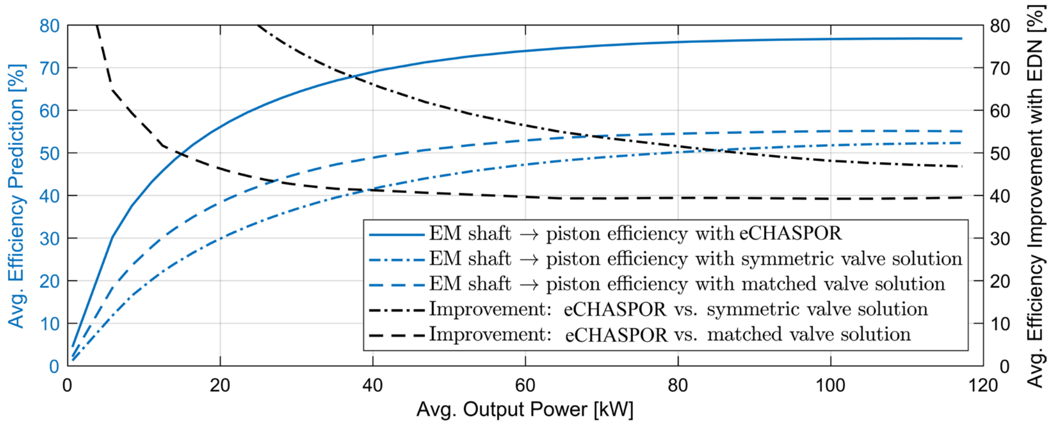

Fig. 5.4. Predicted EM shaft-to-piston efficiencies with eCHASPOR network and VDS solutions with symmetric and matched valves, and improvements with eCHASPOR network compared to VDSs.

In terms of installation space, the clinker/cooler transport drive system at the demonstration host occupies roughly ~ 26 [m^2] floor area and has a volume of ~ 52 [m^3]. The eCHASPOR network prototype supposed to replace this has dimensions (HxWxL) ~ 1.8x1.2x3.3 [mm] for the hydraulic installation and (HxWxL) ~ 2.2x0.6x4.2 [mm] for the electric cabinet. This corresponds to occupying a floor area of ~ 6.5 [m^2] and having a volume of ~ 12.7 [m^3], hence the eCHASPOR network prototype only consumes ~ 25% floor area and a volume of ~ 25% compared to the *original* clinker/cooler transport drive system, i.e. a reduction of 75% in both area and volume.

In addition, the hydraulic fluid tank volume of original clinker/cooler transport drive system at the demonstration host is 6000 [l] whereas the eCHASPOR network prototype only has a hydraulic fluid tank volume of 500 [l]. This corresponds to a reduction in hydraulic fluid tank volume of more than 90%, saving both cost of hydraulic fluid at installation and fluid replacement during maintenance, and hence a much more sustainable solution as hydraulic fluids generally are made from fossil oils.

5.2 Commercial Results

The commercial results are achieved on several levels as outlined below.

- The energy use and associate emissions are significantly reduced compared to traditional technology owed to high energy efficiency primarily related to the absence of throttle control.
- The power installation requirements are significantly reduced, partly due the increased energy efficiency and partly due to the energy regeneration capability offered by the cylinder chamber short circuits and the network configured hydraulic pumps/motors which enables both electric and hydraulic power sharing. The latter property is unprecedented in standalone electro-hydraulic and electro-mechanical actuator systems and allow both reduction in cost and material use in comparison.
- The technology may be built from standard components as was the case for the prototype, dramatically reducing cost and risks in the market introduction as components used are already proven for decades in most cases.
- The technology is scalable from a few kW output power to hundreds of kW using standard components, and hence broadly applicable and its realization mainly related to systems engineering and not component development.
- The requirement for hydraulic fluid is dramatically reduced compared to traditional technology, which is mainly owed to the absence of throttle control and the associated air bubble formation. Consequently, the degasification requirements are dramatically reduced which in turn reduces the necessary fluid requirement. Hence, the required fluid volume and associated cost are significantly reduced both at commissioning and fluid replacement during maintenance.

These features fit key performance indicators in terms of initial/installation cost, cost of ownership, broad applicability and sustainability. A main drawback is that the project failed in demonstrating the technology in an industrial environment. Indeed, introducing radically new technology necessitates demonstration for the market to be confident in pursuing this, and hence this is a key task in advancing the commercial side of the technology.

5.3 Target Group & Added User Value

The target group for the eCHASPOR drive network technology developed in this project is primarily the cement manufacturing segment, and mainly for use in clinker/cement transport applications. Furthermore, the technology may be directly applied in various other application areas such as incinerator plants and steel rolling mills. However, the fundamental idea of organizing hydraulic cylinders with chamber short circuits actuated by hydraulic pumps/motors organized in network configurations turns out to have a significantly larger and much broader potential. It turns out that the combination of hydraulic cylinder chamber short circuits and hydraulic pump/motor networks pose a significant amount of unique system architectures, ranging from 189 unique solutions for a two-cylinder system whereas the number of unique solutions for a triple cylinder system exceeds 36,000. In fact, the number of unique solutions increases exponentially with the number of cylinders in a system. This suggest that one may find solutions especially suited for a specific application. The main challenges are how to find the “optimal” solution for a certain application, and how to control it. The benefits are high energy efficiencies due to the absence of throttle control and low fluid volume requirements. Another benefit is the potentially lower power installation required compared to standalone electro-hydraulic actuators as well as electro-mechanical actuators, owed to the power sharing capability on the hydraulic side as well as the electric side, which may be directly related to lower cost and material use. Hence, the project results serve as an essential baseline for further development of the technology.

5.4 Dissemination of Results

The project results have been disseminated at various levels, both at conferences, in conference proceedings, in journals, at other Bosch Rexroth country units and at a customer event, including two journal articles and four conference papers. The publications are listed below with links available in the Appendix of Section 8:

1. 2022 – MDPI Energies: Electro-Hydraulic Variable-Speed Drive Networks—Idea, Perspectives, and Energy Saving Potentials

2. 2022 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: State Decoupling & Stability Considerations in Electro-Hydraulic Variable-Speed Drive Networks

3. 2022 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: Perspectives on Component Downsizing in Electro-Hydraulic Variable-Speed Drive Networks

4. 2024 – MDPI Energies: Electro-Hydraulic Variable-Speed Drive Network Technology: First Experimental Validation

5. 2024 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: Experimental Investigation of Hydraulic Power Sharing Potential in a Dual Cylinder Electro-Hydraulic Variable-Speed Drive Network

6. 2024 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: Experimental Validation of a State Decoupling Method Applied to a Dual Cylinder Electro-Hydraulic Variable-Speed Drive Network

6. Utilisation of project results

6.1 Future Utilization of Technological Results

In the future, the technological results will be utilized at several levels, with these described below.

- Clinker/cement transport systems – Indeed, the project succeeded in developing a highly energy efficient, scalable and functional technology. As the demonstration phase in an industrial environment was not completed, the next step is naturally to demonstrate this in partnership with another cement manufacturer. As the technology remain relevant, and maybe even more relevant than at project start, the technology is expected to gain momentum in this application area beyond demonstration in an industrial environment.
- Other application areas for the technology concept – as described above, the technology concept turns out to have potential for application in a broad range of industry segments. The more or less direct application the developed technology in incinerator plants and steel rolling mills appear possible. Considering the technology concept in terms of cylinder chamber short-circuiting and pumps/motors in network configurations, the application areas are very broad, such as pitch systems for wind turbines, injection molding machinery and heavy-duty mobile machinery to name a few. At this point two projects, considering medium-sized excavators and loader implements, have been initiated. Here the technology aims to reduce energy consumption, paving the way for commercially feasible electrified mobile machinery.

6.2 Future Utilization of Commercial Results

The commercial results will be utilized for various industry areas, and the technology is already subject to additional development efforts as described above. The results obtained in this project will be commercialized by Bosch Rexroth directly, and by Bosch Rexroth customers indirectly.

The project has not yet led to increased turnover and exports, which primarily is related to the lack of demonstration in an industrial environment. However, as mentioned above the technology concept is already under further development via two projects related to medium-sized excavators and loader implements, mainly funded by Bosch Rexroth. For these project activities, Aalborg University has employed a PhD fellow, and Bosch Rexroth have involved multiple design engineers ensuring both technical and commercially feasible outputs of those projects. Hence the future commercial results will be achieved through:

1. Introducing the developed technology into the cement OEM market once this has been successfully demonstrated.
2. Further developments via the mentioned projects taking offset in both the technical and commercial findings of this project.
3. The project results will be actively used to engage in customer collaborations related to application prototype demonstrations, supporting future sales processes.

6.3 Competitive Situation in the Market

The current situation in the market for cement handling machinery, remain unchanged since the mid 2010 with this mainly focused open circuit system architectures relying on pump supplied proportional valves, and simple conventional closed loop motion control systems. The trend in this market is to reduce energy consumption and associated emissions, and even though the main challenges in this regard are thermal processes, the handling processes also consume significant amounts of energy and must be improved in terms of energy efficiency at a competitive cost level. This is exactly what the technology considered in this project, targets.

However, the trends of reducing energy consumption and associated emissions are not restricted to clinker/cement transport systems, but virtually the entire industry, especially in Europe. For this reason, the technology concept will target several other application areas, including heavy duty machinery such as excavators and wheel loaders which also may support the competitive electrification of such machinery.

6.4 Sales Barriers in the Market

The key performance indicators offered by the technology imply that this suits the market requirements and needs in terms of reduced cost, scalability and sustainability. However, as mentioned above, demonstration in an industrial environment was not achieved in this project, with this serving as a main sales barrier at this point.

Hence, it is essential to demonstrate the technology in the cement industry segment. Furthermore, it is essential to further develop the technology for use in various other application areas, including demonstration in relevant industrial environments. This combined effort will serve the purpose of making the market confident in the technology and combined with the very attractive features the technology offers as described above, it is expected that the market will accept the technology broadly.

6.5 Contribution of Project Results to the Realization of Energy Policy Objectives

The project results contribute substantially to realize energy policy objectives. The high energy efficiency and power regeneration capabilities compared to existing technology and reduction in hydraulic fluid requirements, and the broad applicability of the technology concept tabs into the energy policy areas of efficiency, electrification, sustainability and e-mobility.

The project results may and should provide a basis for realization of the energy policy objectives as substantial energy efficiency increases are achievable with the technology compared to traditional technology.

The wide applicability of the technology developed, as well as the broad perspectives of the technology concept suggests that substantial reductions in energy consumption and associated emissions are achievable. Hence, the technology may play a key role in the competitive decarbonization that is now a key priority in the EU and national policies. Furthermore, the energy reduction potential of the technology may provide the foundations for electrifying heavy duty machinery in a commercially feasible way, as battery capacity requirements may be substantially reduced.

7. Project conclusion and perspective

The project results are defining for the advancement of electro-hydraulic drive network technology. Initially the idea of shorting cylinder chambers, connect displacement machines to different cylinders etc., was by many considered a very "academic" idea, that in theory was good, but practically very hard to make functioning. This project allowed the project group to work with the concept in great detail, uncovering it potential and perspectives, and to realize and validate a prototype.

In conclusion, the results were indeed impressive, convincing the project group and people outside of this, that electro-hydraulic drive network technology in not just an academic creature. It can function and provide excellent performance, significant energy savings, be realized with substantial hydraulic fluid requirements and consuming much less than conventional technology.

Considering the perspectives of the technology, it was found that concept of electro-hydraulic drive networks has great potential across industries, from industrial manufacturing systems such as the one considered in this project, to marine, offshore, agriculture and construction machinery, and so forth. Surely, the technology needs much more research, development and innovation to mature across industry segments, and much more demonstration, with the support key industry players. However, the perspectives of the technology are clear, and the technology may play a key role in the green transition.

8. Appendices

- Links to relevant publications.

7. 2022 – MDPI Energies: **Electro-Hydraulic Variable-Speed Drive Networks—Idea, Perspectives, and Energy Saving Potentials**
   Link: https://www.mdpi.com/1996-1073/15/3/1228
8. 2022 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: **State Decoupling & Stability Considerations in Electro-Hydraulic Variable-Speed Drive Networks**
   Link:https://asmedigitalcollection.asme.org/FPST/proceedings-abstract/FPMC2022/86335/V001T01A028/1150184
9. 2022 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: **Perspectives on Component Downsizing in Electro-Hydraulic Variable-Speed Drive Networks**
   Link:https://asmedigitalcollection.asme.org/FPST/proceedings-abstract/FPMC2022/86335/V001T01A027/1150215
10. 2024 – MDPI Energies: **Electro-Hydraulic Variable-Speed Drive Network Technology: First Experimental Validation**
    Link: https://www.mdpi.com/1996-1073/17/13/3192
11. 2024 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: **Experimental Investigation of Hydraulic Power Sharing Potential in a Dual Cylinder Electro-Hydraulic Variable-Speed Drive Network**
    Link:https://asmedigitalcollection.asme.org/FPST/proceedings-abstract/FPMC2024/88193/V001T01A021/1207668
12. 2024 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: **Experimental Validation of a State Decoupling Method Applied to a Dual Cylinder Electro-Hydraulic Variable-Speed Drive Network**
    Link:https://asmedigitalcollection.asme.org/FPST/proceedings-abstract/FPMC2024/88193/V001T01A016/1207684