

Innovative Geotechnical Machinery Solutions for Sustainable Construction Sites

Diego Bellato

Digitalization and Methodologies, Comacchio S.p.A., Italy, d.bellato@comacchio.com

ABSTRACT: Geotechnical applications are expected to play a key role in the future, driven by the urgent need to maintain and rehabilitate aging or deteriorating infrastructure. To this purpose, dedicated geotechnical machinery is to be widely employed for soil investigations and the construction of foundation systems. However, the environmental impact of rigs used on building sites remains a significant concern, with fossil fuel consumption, resource-intensive production, and waste generation being the main factors negatively affecting the sector's already high CO₂ footprint. This has progressively emphasized the responsibility of equipment manufacturers to continuously update and align their design with evolving technical standards. Electrification represents a crucial innovation for lowering CO₂ emissions associated with drilling rigs. By shifting from traditional diesel engines to assisted or fully electric powertrains, important reductions in greenhouse gas emissions can be achieved, alongside improved efficiency. Advances in hydraulic systems further complement electrification by increasing performance while limiting energy requirements, addressing both environmental and operational aspects. Design optimization and the enhancement of components' durability additionally promote sustainability by minimizing power losses during execution and extending the lifecycle of equipment, leading to a better control of resources and waste. This paper presents an overview of several innovative approaches in the field of drilling machinery, which, supported by case studies and theoretical calculations, demonstrate the benefits of such technologies and the industry's commitment to sustainable development.

KEYWORDS: sustainability, drilling equipment, electrification, hydraulic optimization, life cycle extension strategies

1 INTRODUCTION

The construction industry has been undergoing significant transformations in the last decade due to increasing pressure from political and standardization institutions, an accrued public attention to topics such as sustainability and climate change along with contextual technological developments. Despite a major part of the environmental impact of this sector being mainly related to the great quantity of natural resources and energy consumed to produce building materials, researchers have recently started focusing also on the operational activities and on the reduction of emissions from off-road machinery. According to Lončarević et al. (2022), off-road construction equipment (CE) is still responsible for 5% of the total particulate matter (PM_{2.5} and PM₁₀), 15% of the total nitrogen oxides (NO_x) and 2% of the greenhouse gases (GHG) emissions in Europe. The introduction of stricter requirements for the admissible amount of gaseous and particulate pollutant emissions of internal combustion engines (ICE) for non-road mobile machinery could effectively contribute to a decrease between 70% and 95% in PM and NO_x by moving from Stage I to IIIB (Crippa et al., 2016) but resulted in only a limited improvement in the further transition to Stage V (ICCT, 2016). At the same time, the trends for GHG have remained substantially unaffected throughout this evolution, probably caused by the combined effect of the increase in construction activities with the consequent number of involved CE and the steady modernization and replacement of old equipment (Lončarević et al., 2022). Based on these considerations and the expected growing demand in the construction sector, Sparrevik et al. (2023) suggested that new approaches and disruptive innovations different than the mere incremental progress in ICE technology need to be investigated and enabled. Other research topics in this field include the overall optimization of CE thanks to the use of telematics, the gradual adoption of advanced algorithms to reduce downtime and maintenance costs, robotics and automation, energy storage strategies (ESS) and the study of more sustainable pure electric and hybrid engines (Naskoudakis and Petroutsatou, 2016). Additionally, attention has also been paid to life cycle extension strategies (LCES) such as remanufacturing of existing construction machinery as

a more effective form than simple material recycling (Jun et al., 2019).

In this context of increasingly restrictive environmental regulations and encouraging new approaches to addressing sustainability, the role of original equipment manufacturers (OEMs) is critical to driving innovation and competition in the global marketplace. Most efforts have been directed so far primarily at general-purpose CE, such as excavators, loaders and forklifts, because of their high sales volume and diffusion worldwide (Huang et al., 2024). Thus, there is a lack of technical literature introducing current trends and solutions in CE specifically dedicated to geotechnical engineering. This paper presents a range of industrial advancements undertaken by Comacchio S.p.A. aimed at enhancing the environmental and operational performance of drilling rigs. Electrification of compact boring machines, improvements in hydraulic energy efficiency, and LCES through regeneration procedures are among the most promising strategies currently implemented and deemed to be further developed in the future.

2 ELECTRIFICATION OF SMALL BORING RIGS AND SITE APPLICATION

2.1 *Challenges and benefits of electrification of CE*

The idea of electrifying large-tonnage equipment by using grid-powered supply has been applied for a long time in the mining industry (Topno et al., 2021) and for at least a decade battery-powered ESS have started to be mounted on CE. Nevertheless, only from 2020 there has been a drastic surge in academic research on pure electric battery-driven or hybrid powertrains (Huang et al., 2024). This delay can be partly attributed to the challenges affecting the full application of battery-powered ESS on typical construction sites, namely the harsh environment (e.g. dust, humidity, temperature), the large variability in energy requirements associated to the operations to be carried out and their duration throughout a working shift. The technical difficulties and the solutions proposed for their mitigation still negatively impact the acquisition costs of these types of driving systems, which are usually higher than their diesel ICE counterparts. However, ICE-based vehicles are expected to gradually become more expensive, thereby

favoring the commercial distribution of electric and hybrid alternatives (Caban et al., 2018). Another important factor explaining their current weak market penetration is the apprehension related to battery longevity, which is on average 4-6 h. This relatively short time span, along with the subsequent recharging period, normally fails to meet the actual energetic requirements at the jobsite.

To improve the adaptability to drastic load fluctuations and extend battery life per operational cycle, several approaches have been investigated in the literature. They included research about the most appropriate types of battery to be used in pure electric and hybrid CE (commonly Li-ion batteries due to their energy density), the possibility of coupling different energy storage components (e.g. supercapacitors, hydraulic accumulators) and energy recovery systems, the advantages and disadvantages of several electric engines (being permanent magnet synchronous motors and brushless motors the more promising ones), and the implementation of various actuator systems and their control strategies according to real working conditions (Huang et al., 2024).

Considering all aspects above, pure electrification seems nowadays more suitable for compact CE, since they are usually employed in urban environments with stringent air quality thresholds or directly within buildings. They are characterized by quick replacement of batteries and, in some cases, by household power source adapters. However, the space available to host the batteries is normally limited, therefore requiring high system integration.

2.2 Comacchio eGEO 405

Following the global thrust towards sustainability and electrification, Comacchio S.p.A. decided to design and build in 2022 its first full-electric compact drilling rig, the eGEO 405. It is a multi-purpose drilling rig with a weight lower than 10 t, a crawler width of 1500 mm, a max torque of 850 daNm, and a max retract force of 6500 daN. The rig is powered by two removable and rechargeable Li-ion battery packs and a standalone battery charger of 33 kW to ensure continuous operations even under intense load activities. The battery ESS delivers a total energy capacity of 78 kWh and reaches a nominal voltage of 350 VDC. The standalone charger allows the spare pack to be charged in less than two hours from 15% at the mains supply or via battery ESS. An onboard charger is also present to enable plug-in work mode. The rig uses inverters to transfer the power from the batteries to brushless motors, which operate the rotary drive, the winches and the hydraulic pumps responsible for the movement of the crawlers.

Preliminary studies comparing the eGEO 405 with its own ICE counterpart have shown that an energy of 10 kWh generated by the rotary head could be derived either from 15 kWh provided by the batteries in the full-electric system or 3.1 l diesel in the ICE version. Assuming the average European prices per kWh and per litre diesel in the second semester of 2024 (Eurostat), a difference of about 0.05 €/kWh in favour of the full-electric rig is expected for this kind of operation (Table 1).

Table 1. Comparison in terms of costs and grams of CO_{2,eq} between the full-electric eGEO 405 and its diesel counterpart based on 10 kWh provided at the rotary head.

Rig version	Energy at the source	€	gCO ₂
eGEO 405 (electric)	15 kWh	4.31	7509 ¹ /2825 ¹¹
GEO 405 (diesel)	3.1 l diesel	4.84	7970*

¹: Department for Energy Security and Net Zero, 2025

¹¹: Association of Issuing Bodies, 2025

*: Istituto Superiore per la Protezione e la Ricerca Ambientale, 2025

Table 2. Comparison in terms of costs and grams of CO_{2,eq} between the full electric eGEO 405 and its diesel counterpart based on 10 kWh provided at the crawlers.

Rig version	Energy at the source	€	gCO ₂
eGEO 405 (electric)	22.7 kWh	6.52	11363 ¹ /4275 ¹¹
GEO 405 (diesel)	3.1 l diesel	4.84	7970*

¹: Department for Energy Security and Net Zero, 2025

¹¹: Association of Issuing Bodies, 2025

*: Istituto Superiore per la Protezione e la Ricerca Ambientale, 2025

The greenhouse gas conversion factors individuated by DESNZ (2025) were used to obtain the equivalent grams of CO₂ from diesel, while ISPRA (2025) and AIB (2025) were taken as references to calculate the equivalent grams of CO₂ from kWh, adopting location-based and market-based factors, respectively. The difference between location-based and market-based is that ISPRA takes into account the total energy utilized in Italy to estimate the emission factors, while the European AIB report neglects all contributions due to renewable energy sources, which is therefore a very conservative condition. Table 1 presents the results of this analysis and shows that full-electric transmission leads to a more economical and sustainable solution when directly applied to rotary heads, even when assuming the cautious AIB conversion factors. This conclusion is further supported by a parallel theoretical study on power transmission efficiency, which confirmed a higher efficiency of the electric energy transmission (66%) compared to the thermal-hydraulic transmission (32%). Yet, the overall efficiency may decrease significantly when coupling battery-powered ESS to existing hydraulic circuits, like that responsible for the movement of the crawlers. For example, to express 10 kWh of energy at the crawlers, 22.7 kWh must be drawn from the batteries, whereas the same amount of 3.1 l diesel would still be necessary in the ICE version. The diesel-powered system seems to become, in this case, more economical and more sustainable than the battery-powered system (Table 2). It is worth noticing that regional differences in energy resources and, consequently, in energy prices among European countries exist and could make the electric version even in the last example a viable alternative (e.g. in Eastern Europe).

2.3 Testing of eGEO 405 at coring sites

In May 2024 the eGEO 405 was transported at a site in the UK to assess its working and energetic performance. The test consisted of drilling boreholes to a depth of 40 m through consolidated clay, sandstone and siltstone. A typical soil profile of the testing field is reported in Table 3. The groundwater was located at a depth of 38.4 m from the ground level. The borehole was supported with a casing of outer diameter 200 mm for the first 3 m and then carried out open hole with a diameter of 145 mm by using air and mist as drilling flushing medium.

Table 3. Soil profile at the eGEO 405 testing site.

Layer description	Coring type	From [m]	To [m]
Stiff clay onto weathered mudstone	Rotary coring	0.0	1.5
Weathered sandstone	Rotary coring	1.5	3.0
Stiff fractured sandstone	Rotary coring	3.0	16.5
Stiff sandstone with siltstone bands	Non coring	16.5	25.4
Extraordinarily stiff grey siltstone	Non coring	25.4	30.0
Stiff grey mudstone	Non coring	30.0	40.0

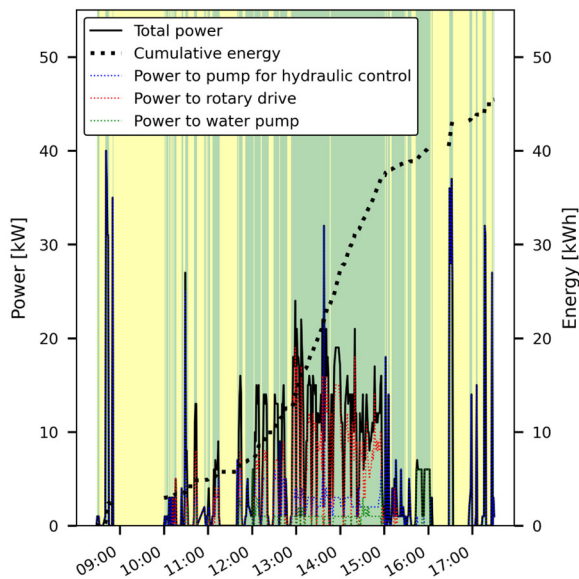


Figure 1. Power readings from eGEO 405 recorded in a complete working shift and related energy consumption.

The study on performance and consumption was based on the analysis of the machine data collected by an advanced on-board telemetry system. Figure 1 shows the power readings measured at the inverters supplying energy to the pump responsible for the main hydraulic controls (crawlers, crowd system, clamps), to the rotary drive, and to the water pump, respectively. It is possible to distinguish in the graph some of the phases which were carried out at the site, i.e. the initial positioning and final repositioning of the rig, the drilling of one complete 40-m deep borehole including cores recovery, and the following cleaning tasks. The total duration of the data set was about 9 h, while the drilling took approximately 6.5 h. By the end of the shift, the battery was 60% depleted and allowed overnight recharging without causing interruptions to the work planned for the next day.

The figure also presents the power envelope together with the corresponding cumulative energy consumption, which reached a total of 45.5 kWh. It is interesting to note that this energy was utilized in different proportions by the three circuits mentioned above, namely 19.7 kWh (43%) by the main hydraulic control system, 21.4 kWh (47%) by the rotary drive, and 4.4 kWh (10%) by the water pump. This result is not surprising, given the demanding drilling operations conducted in the stiff soil layers during coring.

Figure 1 presents also a classification of the site activities subdivided into active (working – dark background) and passive (not working – light background) time slots. The former occupied about 46% (4.22 h) of the total shift (9.13 h), the remaining time being characterized by negligible power absorption, commonly named “parasite energy consumption”. Previous investigations on electric and ICE equivalent powertrains highlighted a significant reduction of parasite energy consumption in pure electric machinery (lower than 10% in a single working shift) compared to the ICE counterpart (typically above 30%). This can be explained by the quicker operational readiness and start-up response of electric motors, which can reach the desired functional regime almost instantaneously from their inactive state. Since construction sites are typically characterized by many disruptions related to unpredictable circumstances or planned pauses, the possibility to switch off completely the power source without the need to delay production is of strategic importance in limiting unnecessary energy losses and negative environmental impacts.

These aspects, together with the higher efficiency of the on-board power distribution system, led to an average weekly saving of about 900 £ and a reduction of 310 kg of $\text{CO}_{2,\text{eq}}$ (DESNZ, 2025) in a single day compared to an equivalent ICE rig.

3 ENHANCED HYDRAULIC DISTRIBUTION SYSTEM

3.1 Recent international research and trends

Hydraulic systems mounted on CE are often affected by significant energy losses and poor controllability. Efficiencies of valve-controlled circuits generally below 30% and the nonlinearity and uncertainty of hydraulic actuators’ behaviour are examples of why international research has been recently focusing on fostering technological advancements in this field (Tong et al., 2020; Huang et al., 2024).

One of the main topics being examined is the improvement in accuracy, efficiency and response speed of valve-pump control systems. Approaches evolved with time from negative flow control to positive flow control and electro-hydraulic load sensing (LS) control systems. The LS technology is nowadays commonly implemented in CE. Its main disadvantage is that it always requires a constant pressure differential (typically 20–25 bar) above the highest expected load between the pump and the distribution block to regulate the flow, which inherently results in a systematic energy loss. To address this issue, electro-hydraulic flow matching (EFM) control systems have been proposed with the aim of achieving pump-valve coordinated control according to the real-time calculated flow and without any imposed pressure differential. They have demonstrated to provide higher energy efficiency and fast response to external loads (Tong et al., 2020).

Another important aspect to consider when designing a hydraulic scheme is the analysis of the possible combinations and simultaneous activation of different functions (i.e. actuators) on the rig. In this circumstance, the system needs to establish sufficient pressure to withstand the highest load among the functions but, at the same time, balance all other actuators by means of pressure compensators. Relevant energy losses are indirectly generated in this balancing process especially when the maximum load anticipated for the actuators differs substantially. The individual metering control system (IMS) has been identified by Beltrami et al. (2021) as a viable solution for this phenomenon. The IMS has excellent energy-saving capabilities and allows configuration flexibility because it decouples the inlet and outlet of actuators through independent valves. Another way currently under investigation consists in replacing the main pump shared by the functions with the so-called “direct-driven hydraulics”, in which every actuator is operated by a standalone pump and, if feasible, motor.

A drastic approach to increasing the efficiency of CE kinematics would involve replacing hydraulic actuators with electromechanical actuators (EMA), as proposed by Beltrami et al. (2021) and Huang et al. (2024). While appealing from an efficiency standpoint, some intrinsic drawbacks affect this choice. On one hand, it would significantly increase the complexity of control algorithms; on the other, it may lead to reduced on-site production due to demanding safety protocols specific to EMA systems.

Finally, several energy saving mechanisms have been discussed in the literature. The most common are based either on kinetic or potential energy regeneration (He et al., 2020). The first form is usually implemented in CE which perform frequent movements and takes advantage of the inertia of the equipment during braking or deceleration, for example when driving or swinging the upper carriage. The second form

benefits from the gravitational potential energy of falling objects. Many developments exist in this context and include the presence of additional electro-hydraulic parts such as extra hydraulic cylinder or innovative three-chamber cylinders and ESS components like auxiliary hydraulic motors supplying dedicated actuators, hydraulic accumulator, or battery-supercapacitors.

3.2 Examples of hydraulic system optimization

To improve efficiency and reduce systematic energy losses, Comacchio S.p.A. decided to introduce on its large diameter drilling rigs a recent version of EFM control system. When the rig operator activates a function by moving the joysticks or the pedals, the pre-assigned pump is automatically instructed to deliver the required flow and the spool in the distribution block is moved accordingly to direct the oil to the corresponding actuator without the need of a 20-25 bar pressure differential. Only a small pressure drop of about 10 bar is expected in this circumstance, significantly cutting hydraulic and mechanical power waste and, consequently, lowering fuel consumption during operation. Analyses were carried out to compare the performance of a CH 850 equipped with a LS control system and its EFM equivalent with increased hose diameters. Computations assuming the maximum flow rate of 680 l/min supplied by the main pump for an 8 h shift showed that an energy saving of approximately 10% could be achieved.

Pursuing the same goal, an innovative potential energy recovery system has been lately developed and applied to large rigs. A detailed description of the apparatus, including its specifications and variations, has been submitted to the relevant regional authorities and is currently under patent review. Figure 2 shows a hydraulic circuit for lifting/lowering loads by means of a motorized winch, in which a version of this new energy recovery system is incorporated. It is possible to distinguish the feed pump, the main distribution block, the supply and return lines, the winch, the selector valve connected to its brake, the overcenter control valve placed on the supply line, and the innovative control manifold. Typically, overcenter valves are set to a pressure 30% higher than that associated with the maximum allowed load. In the event of a malfunction, e.g. an unexpected pressure drop in the descent line, this valve closes, blocking return oil flow and thus preventing the load from falling. At the same time, the sudden pressure reduction closes the brake, to ensure safety. Under normal descent operations, the new control manifold provides oil flow to the lowering system at a pressure determined by the load to be moved. This enables the activation of one or more auxiliary functions, such as an electric generator or a support to the winch itself. In the first case, depicted in Figure 2a, the electric energy stored in an accumulator during the descent of the load is used to power an electric motor, which can, for instance, effectively contribute to the following lifting phase. In the second case (Figure 2b), the winch is fed with the oil from the manifold directly during descent. This leads to an almost complete cut-off of the oil supply from the main distributor, which is then only used for drainage compensation. Preliminary tests in this latter configuration have shown a reduction in energy consumption during descent operations of about 32%.

When dealing instead with small-diameter drilling rigs, one of the major concerns is the available space where the integrated electro-mechanical-hydraulic modules need to be placed. To address this issue, innovative compact filter solutions have been introduced. These devices provide continuous active degassing and drying of the oil while also enabling a downsizing of the oil tank of approximately 40%. This results in an appreciable gain in space dedicated to other components, a lower total weight of the equipment – positively

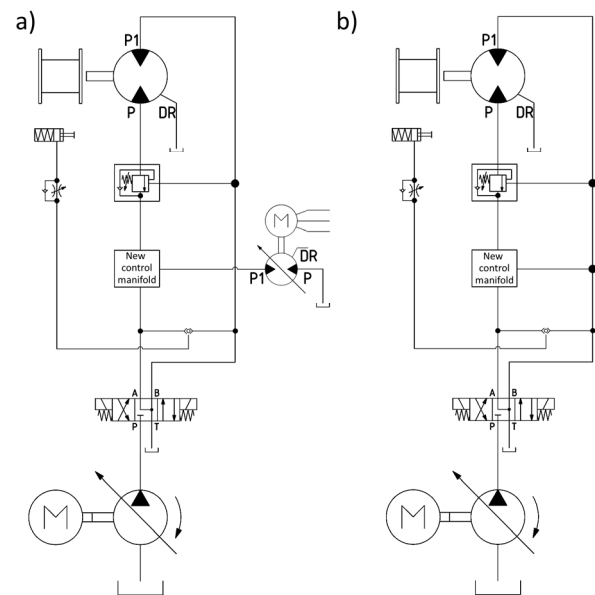


Figure 2. Schematic representation of a lifting/lowering hydraulic circuit incorporating the new energy recovery system developed by Comacchio S.p.A. (patent pending): a) oil flow during descent powering an electric generator/motor; b) oil flow contributing to the winch during descent of the load.

affecting energy utilization – and a reduced volume of oil required to maneuver the rig, which translates into lower environmental impact and operating costs.

Further measures adopted to limit consumption and boost efficiency are related to the choice of suitable hydraulic oils. Special hydraulic oils can significantly improve the working conditions of CE, since they are designed to minimize energy losses and improve responsiveness. Besides preserving their viscosity across a wide range of temperatures, they usually resist deposit formation, promoting system cleanliness and mitigating wear and tear of the parts. Tests have shown that these oils can increase hydraulic pump efficiency by up to 6%, leading to an equivalent saving in power absorption and enhanced system performance (Rydberg, 2013). Similar experimental findings have been observed examining the behavior of rigs under real field conditions.

4 LIFE CYCLE EXTENSION STRATEGIES FOR CONSTRUCTION EQUIPMENT

4.1 Introduction

Life Cycle Extension Strategies (LCES) have the objective of extending the life cycle of a product by “slowing” and/or “closing” its loop (Fontana et al., 2021). An effective approach to slow down the life cycle of a piece of equipment is through maintenance, which can be generally classified according to three different philosophies, namely the fixed time-based maintenance, the operate-to-failure maintenance, and the condition-based maintenance (Naskoudakis and Petroutsatou, 2016). Especially the latter and its natural evolution, i.e. predictive maintenance, are currently subject to intensive research by OEMs due to the recent developments in telematics and the common implementation of sensorics and machine learning algorithms to analyze the great amount of IoT data collected at construction sites. Despite the clear advantages offered by middle-of-life procedures like regular maintenance activities, LCES also imply necessarily the adoption of end-of-life operations, e.g. resell/reuse, remanufacture, recondition, and refurbish (Rossi et al., 2022), here collectively named as “regeneration”. Among them, remanufacturing is defined as a

process for securing the performance of a used product, at least, to the performance specifications of the original equipment manufacturer. On the other hand, refurbishment goes beyond that and points at a complete upgrade (also technological) of the equipment to specified quality standards or satisfactory working and/or cosmetic conditions. This involves extensive quality tests to ensure that refurbished products are safe, functional, and durable, offering an experience comparable to that of new state-of-the-art products. Studies in the literature have suggested that refurbishment is, under some constraints, advantageous compared to linear approaches, which are built instead on extracting raw materials from nature and producing items that are either consumed or discarded (Rossi et al., 2022). LCES have a very important role in fostering sustainability in the CE industry but still suffer from a high level of uncertainty while conducting Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analyses of complex products, where many environmental and social factors need to be considered.

4.2 Regeneration of equipment – a two-year review

Due to the challenges in conducting comprehensive and detailed LCA and LCC analyses in the field of CE, OEMs often refer to ISO 14001, which simply provides the framework to establish, implement, maintain, and continually improve an environmental management system, leaving the specific goals and performance metrics up to each organization, based on their own context, risks, and priorities. One of the goals that Comacchio S.p.A. has set for its future is to promote practices of remanufacturing and refurbishment for old pieces of equipment and components. Tables 4, 5, and 6 present a review for the years 2023 and 2024 of the number of regenerated rigs originally owned by clients, of those which were bought used for the purpose of regeneration, and of repaired components, respectively.

The tables distinguish between small and large diameter drilling rigs and report the quantity of hours worked for each type of activity and year. Comparing 2024 with 2023, there has been an increase of 20% in the time spent on regeneration tasks, which highlights the current interest of the stakeholders on this topic. This is further supported by a 36% rise in regenerated rigs over the two years, particularly evident in the trend for small-diameter drilling rigs.

Table 4. Regenerated rigs originally owned by clients in the years 2023 and 2024.

Dimension	2023	2024
Number of small diameter drilling rigs	39	58
Number of large diameter drilling rigs	2	2
Hours worked on regenerated rigs	3405	5245

Table 5. Used rigs bought by clients to be regenerated in the years 2023 and 2024.

Dimension	2023	2024
Number of small diameter drilling rigs	12	13
Number of large diameter drilling rigs	2	2
Hours worked on regenerated rigs	3135	2375

Table 6. Regenerated components originally owned by clients in the years 2023 and 2024.

Dimension	2023	2024
Number of small diameter drilling rigs	450	344
Number of large diameter drilling rigs	7	4
Hours worked on regenerated rigs	735	1070

Moving towards a LCA/LCC approach requires, however, determining the scope of the regeneration, i.e. remanufacturing or refurbishment, and some characteristic parameters (LCC/LCA indicators) related to the different phases involved in these processes, the hours worked being only one of the contributors. Comacchio S.p.A. has therefore recently started specific procedures to assess in a more objective way such indicators during the initial evaluation of each component to be repaired/substituted. This is expected to pave a path rapidly leading to reasonable LCA/LCC of drilling equipment. In the meantime, LCES are further complemented by the development of more refined on-board telemetry systems and advanced tools for data analytics, which aim at a more punctual maintenance of the fleet and, indirectly, to an extension of its working life cycle.

5 CONCLUSIONS

As global demand for new and rehabilitated infrastructure grows amid rapidly worsening climate conditions, greater efforts are needed to minimize the environmental and social impacts of construction activities as quickly and effectively as possible. All stakeholders in the industry are expected to contribute with innovative solutions to tackle this challenge. In this context, OEMs have an opportunity to promote developments of more efficient and sustainable CE, not only in relation to powertrain technologies, but also beyond the constraints of existing international regulations. This paper is, to the author's knowledge, the first time that an OEM active in the field of drilling equipment manufacturing presents an overview of its recent advancements in areas such as energetic efficiency, hydraulic optimization and life cycle extension strategies.

Electrification of small rigs represents today one of the most promising research topics. Based on the results obtained from a testing site in UK, the eGEO 405 has been found appropriate for coring works in stiff soil and soft rock, demonstrating higher performance and efficiency than the ICE equivalent along with reduced economic and environmental impacts on the project. Experiences from other jobsites have proved that the rig could be used uninterruptedly for a duration between 2 and 5 days before recharging the battery depending on the specific soil profile and the number of positioning operations. Further studies are ongoing to improve the current solution by implementing hybrid forms of ESS (e.g. supercapacitors) or alternative powertrain systems, such as fuel cells or hybrid energy supply. The latter is for example considered the most suitable approach for medium and large CE, due to the frequent and extreme power changes and the high energy consumption.

In addition, several implementations and developments related to the optimization of the hydraulic circuits on small and large diameter drilling rigs have been presented with their corresponding outcomes in terms of energy savings and increased efficiency. It has been shown that the adoption of EFM hydraulic control systems has the potential to reduce total fuel consumption by up to 10% over the course of a working day compared to a typical LS apparatus. The introduction of specific components like a newly developed hydraulic control manifold could also provide an energy saving of more than 30% during load-descent procedures. Moreover, the use of high-performance hydraulic oils has confirmed the advantages reported in the literature associated with the extension of the life span of the parts involved and the enhancement of their efficiency (ca. 6%). Finally, advanced filters installed on small CE could bring a significant reduction of the volume of oil circulating and, therefore, of the oil tank, with positive

consequences with regard to available space, decrease in overall weight and material waste. Due to the limitations of centralized actuator systems (one single power source and multiple actuators) and the challenge to improve their efficiency considerably, distributed or direct-driven hydraulic systems represent a promising solution to be further investigated.

The last topic discussed in the paper refers to LCESs and how they could be used to stretch or close the life cycle of CE. Among the methods suggested by the scientific community, condition-based maintenance stemming from continuous and precise monitoring of equipment data and regeneration procedures such as remanufacture and refurbishment have been identified as the most applicable tools to the field of drilling rigs. Some considerations about how OEMs could reach the target of conducting comprehensive LCA/LCC analyses on their products have also been given.

Sustainability is a complex and inherently interdisciplinary subject that spans natural sciences, engineering, technology, economics, management and ethics. Addressing it effectively requires an integrated approach capable of coping with its various dimensions. Therefore, all potential strategies directed towards a reduction in environmental, social, and economic impacts need to be thoroughly explored and evaluated. Due to its high carbon footprint, the construction industry is one of the sectors which might benefit the most from the application of these policies. Among its stakeholders, OEMs have been increasingly establishing their role by actively contributing with innovative solutions to the development of machinery that aligns with the vision of future zero-impact construction sites. Although achieving this goal will still require additional efforts, the research presented in this paper represents an initial step toward involving the academic and scientific community in engaging with challenges common to all geotechnical projects.

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