HEAVY-DUTY CONSTRUCTION EQUIPMENT: DINOSAURS OF BLACK ENERGY?

Christian Koch[1] and Dimosthenis Kifokeris[2]

[1] *School of Business, Innovation and Sustainability, Halmstad University, 1 SE-301 18 Halmstad, Sweden*

[2] *Division of Building Design, Architecture and Construction Engineering Chalmers University of Technology Sven Hultinsgatan 6, 42199, Gothenburg, Sweden*

Construction equipment emissions in civil engineering are a major sustainability issue. However, the industry continues investing in diesel (and/or biodiesel) machines - which, even if compliant with EU regulations, are far from “clean”. Cleaner technologies in construction equipment, like electrical engines, are considered more expensive investments; moreover, they are dependent on the available power supply while operating in confined areas. So, transitioning these machines sustainably involves changing technologies, business models, and public regulation. In Scandinavia, heavy-duty engines (over 25 tons) have only recently become (limitedly) available. Therefore, the current paper analyzes enablers and barriers for a sustainable transition of civil engineering construction equipment to on-site electrical machines in Scandinavia. The sustainable transition theory, combined with sustainable business models, serves as the framework of understanding. Empirically, a desk study of governance and regulation is combined with material from four fossil-free test building sites in Norway, Denmark, and Sweden. The results highlight the importance of a public-private business model, where public client-driven transition is subsidy-supported (e.g., making electrical equipment available through concession, and encouraging small innovative machine manufacturers to develop electrical equipment), while waiting for international construction equipment players to become transition-ready. Recommendations for the transition thus include strengthening public-private collaboration.

Keywords: heavy-duty; electrical engines; sustainable transition; Scandinavia

INTRODUCTION

Over 2018-2021, emission-free civil engineering projects have been introduced within the core of various European cities - e. g. Oslo (2018), Copenhagen (autumn 2019), Bergen (summer 2020), Helsinki (autumn 2020), Amsterdam, Brussels, Budapest, Lisbon, Vienna (BBI 2021, SPP 2021). Construction equipment manufacturers are also in the process of providing electrical machines. According to BBI (2020), electrical machines up to 2.5 tons are now available all over Europe. But it is also documented that it is the heavy-duty machines, above 10 tons, that are the heaviest contributors to CO_2, NO_x, PM, CO, and other emissions (DNV GL 2018). Despite this, over 2018-2020 we have witnessed an unprecedented investment rate in

[1] christian.koch@hh.se

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traditional diesel-driven machines. In Sweden, about 10000 new machines bought in 2018-2020 are probably at a high environmental standard (EU step 5) but are still diesel-driven; some 20000 diesel machines from 2011-2018 are at a somewhat lower standard (Maskinleverantörerna 2021). For the same period, the sales of electrical machines up to 2.5. tons can be counted in hundreds, and above 2.5 tons are close to absent. The sustainable transition is thus very slow and only recently have heavy-duty engines (over 25 tons) become available in a Scandinavian context, and only in a limited amount.

The research aim of this paper is therefore to investigate enablers and barriers for a sustainable transition of civil engineering construction equipment in Scandinavia. The sustainable transition theory is adopted as the framework of understanding, combined with contributions on sustainable business models (Schot and Geels 2008, Koehler *et al.,* 2019, Schaltegger *et al.,* 2020).

The empirical material combines a desk study on the material of three national settings (Norway, Denmark, and Sweden), with interviews and material from four test projects of emission-free building sites. The contributions of this paper include the documentation of an absent and emerging sustainable transition. There is a co-existence of a traditional incumbent regime of diesel engines, and a commencing niche of an emission-free constellation of particular public-private stakeholders. Those employ a new resource-economic business model, where public client-driven transition is supported with subsidies (like making electrical equipment available through concession in a particular area and encouraging small innovative machine manufacturers to develop electrical equipment) - while waiting for the large international construction equipment players to become transition-ready. Recommendations for the transition thus include strengthening public-private forms of collaboration.

METHOD

We hereby adopt a sociomaterial interpretive understanding of sustainable transition (Orlikowski and Scott 2008, Schot and Geels 2008), viewing sustainable transition as a negotiated process of interaction between actors and materiality/technology. The sustainable transition perspective requires a broad elaboration on and coverage of stakeholders, from niches of companies over national incumbent regimes (i.e., government and corporations) to an international landscape of stakeholders (Koehler *et al.,* 2019). Here, the coverage is somewhat more modest and predominantly focuses on three national contexts, Sweden, Denmark, and Norway - and even more narrowly, on the cities of Gothenburg, Copenhagen, and Oslo, respectively. In these contexts, city policy (i.e., municipality and public client strategy) turned out to be central.

Moreover, the sustainable transition perspective asks for a longitudinal processual perspective; however, here this is limited to the period of 2018-2021. The empirical material combines a desk study of the three aforementioned national settings, with interviews and material from four test projects of emission-free building sites. This involves governmental announcements, municipality investigations, planning and strategy documents, contractors company websites, rental companies, and machine manufactures. When identifying relevant actors, a snowballing approach was adopted. This became particularly expansive in the Norwegian context, where far more stakeholders were active in the sustainable transition than expected - as emerged from a relevant Oslo City project entailing a cluster of the state, four municipalities, two machine manufacturers, four rental companies, five contractors and more. Particularities of the three city studies are entered below.

Gothenburg

No emission-free building projects have been carried out so far. The empirical material includes dialogues with City Procurement project members (WSP 2020), and site measurement project members (Bernholdsson *et al.,* 2020) and documentation gathered through the collaboration and retrieved from the net.

Copenhagen (Denmark)

No emission-free building projects have been carried out so far. The empirical material includes dialogue with a representative of a large-scale research project about "green building sites" and documentation on governmental climate initiative (Klimapartnerskab 2020).

Also, two specific projects are mentioned:

1. City Center electric cabling substitution (video footage documentation retrieved from the Internet encompassing the municipality, the electricity company, the contractors, and the rental companies).
2. Day Care institution in suburb (one interview with the sustainability manager at the contractor, and documentation retrieved from the Internet).

Oslo (and beyond)

Four emission-free building projects have been carried out so far - all elaborately documented. The empirical material includes:

- A series of government and municipal reports and documents.
- Interview with a municipality representative.
- Dialogues with two machine manufacturer representatives.
- Interview with the measurement research project representative.
- Documentation gathered through the dialogues and retrieved from the Internet.

It should be noted that the paper relies mostly on documentation material and to lesser degree interviews. Moreover, no site measurement was carried out. Most of the documentation was available in the respective national languages only. Most of these references have not been included in the references list here. Also, at present most in-depth studies of emission are ongoing and not prepared for sharing results yet.

Framework of Understanding

The main framework of understanding is the sustainable transition theory, within which the multi-level perspective (MLP) is coined (Schot and Geels 2008, Koehler *et al.,* 2019). Approaches within MLP look upon innovation in a sector as a sociotechnical phenomenon and identify three levels of sociotechnical interaction within which sectorial innovation can be explained in the micro-, meso- and macro-levels and interactive domains (Schot and Geels 2008). We here extend this argument to understand the intertwined linkages between the social and the technological as sociomaterial (Orlikowski and Scott 2008). Moreover, adopting a sociomaterial lens implies cautiousness in accepting levels too readily - as "classic" MPL does. In a sociomaterial multilevel perspective, niches form the micro-level, where radical novelties emerge. The sociomaterial regime forms the meso-level, which accounts for the dominant stabilized sociomaterial pattern of interaction, which is reproduced by institutionalised learning processes. The macro-level is formed by the sociomaterial landscape, an exogenous environment beyond the direct influence of niche and regime actors (e.g. macro-economics, deep cultural patterns, macro-political developments).

According to Scott and Geels (2008), researchers within sociology of technology and evolutionary economics have stressed the importance of niches as drivers of innovations, from where a new sociomaterial regime can be developed. Niches work as incubation environments for new ideas, by being protected from the traditional selection mechanisms of the marketplace. By distinguishing between market and technological niches, Schot and Geels (2008) explain the way innovation can be achieved through institutional learning processes, which link technological niches to niche markets. These changes could potentially lead to a regime shift. According to MLP, the central dynamic of sustainable transition is the regime being challenged by emerging technologies from niches. This occurs in "classic" MPL as: (1) technology maturing in some closed technological niches, (2) these technical solutions addressing a limited market need, and (3) the technologies further maturing through the growth of the markets, thereby winning wider acceptance in the entire regime. This understanding is extended here to think of the constitutive element as sociomaterial, i.e., a constellation of social actors, methods, materials, and technologies, rather than just technology alone.

An important premise for the development and maturation of ideas within niches are learning processes and the building of social networks that support new innovations and investments (Schot and Geels 2008). The development of niches through these activities is achieved through ongoing project-based learning processes, which over time provide a certain direction and rationality. In early versions of MLP, the transition was expected to originate in niches of emergent clean technologies. However, as studies of transitions flourished, cases of incumbent regimes driving sustainable change emerged (Schot and Geels 2008, Koehler *et al.,* 2019). The incumbent regimes also turned out to be capable of driving sectors and/or nations in a sustainable direction. Travelling from niches to an altered incumbent regime is not particularly specific in transition theory. Within the expectation of a niche growth, we therefore distinguish between punctual and clustered niche activity, denoting a continuous occurrence of single projects without agglomeration. This transition can occur through micro-steps over a long time (Sovacool 2016).

State of the Art

The emission of large civil engineering machines has gradually been better understood and also reduced (Krantz *et al.,* 2017, Hajji *et al.,* 2019, Masih-Tehrani *et al.,* 2020), including the important impact of the idle time of the engines (Lewis *et al.,* 2012). But many interests still keep the focus on diesel-driven engines, i.e., the machine manufacturers, the rental companies and the contractors. The investment in such traditional machines has boomed over the last four years. The investment binding in the relatively young machine portfolio is considerable, and a barrier for sustainable transition. Medium-old machines are however at larger challenge (bought 2011-2018) due to their emission of CO_2, NOx, PM, CO a.o. An interesting alternative path is to rebuild diesel engines. Rebuilt machines have been calculated to reach the same lifecycle costs after 10 years (Wiik *et al.,* 2020). But despite these substantial barriers in a series of countries, projects and activities are ongoing were manufacturers, municipalities, contractors and others are collaborating on emission-free building sites (BBI 2020, Bernholdsson *et al.,* 2020, Gill 2020, Hajji *et al.,* 2019, Masih-Tehrani *et al.,* 2020, WSP 2020, Riemer Sørensen 2020, mfl). Moreover, manufacturers of machines are gradually offering electrical machines. According to BBI (2021), electrical machines up to 2,5 tons are available all over Europe.

The Case of Gothenburg: Still Waiting

The sustainable transition of the transportation sector has received a lot of state, public, and private enterprise attention over the years. In 2018, a government-business initiative issued a plan for fossil-free construction and civil sectors. This plan was backed by important industry interests - but focused mainly on cement and steel production (constituting a substantial transition issue) and did not include heavy construction machines. In 2019, the government announced a premium for investors in electrical machines as a symbolic gesture, as well as a new research initiative for sustainable transition of construction machines. It focused on fossil-free engines - but not necessarily electrical, thus leaving the biodiesel option open.

The municipality of Gothenburg was active in this national development, launching a series of initiatives with local stakeholders - introducing electrical buses, electrical machines for road and park maintenance, and other. In 2019, a project was launched to investigate the possibilities of raising a demand in public procurement of civil works. This involved market dialogues with civil contractors and resulted in a demands proposal reported in August 2020. The municipality of Gothenburg has still not announced its first fully emission-free building or civil project, but the local stakeholders are getting ready to take up the challenge when it arrives. In 2018-2020, a large project measured the emissions on 22 civil works sites around Gothenburg, estimated electrical charging scenarios, developed a business case for the economy of electrical machines, and mapped the way electrical machines can be used in the near future (Bernholdsson *et al.,* 2020). All 22 sites encompassed excavation, 13 involved stone paving, and six included asphalting. Each site used one to three machines; in total, seven wheel-loaders, 15 belt excavators (six larger than 20 tons), 25 wheel-excavators (21 11-20 tons, none above 20 tons), were used (Bernholdsson *et al.,* 2020). Another pilot and demonstration project will be launched in late spring 2021, carrying out pilots of electrical machine usage in urban sites.

The Case of Copenhagen: Punctual Transition

Emission-free building sites and civil machines entered the Danish government's tripartite initiative (the "Climate Partnerships") in the spring of 2020, and since then the national institutional context is on the move. However, the municipality of Copenhagen initiated its practical projects before the national agenda emerged. At least four projects have been carried out - two are described below. The first project concerns the municipality framing an electricity cable renovation project in central Copenhagen in late 2019, as emission-free. The direct client was the electricity company. The contractor hired was a well-known collaboration partner to the municipality, however not having worked with electrical machines before. An alliance with a machine rental company enabled the use of electrical Wacker Neuson machines, some only just introduced by the manufacturer; this was an estimated 20% extra cost for the contractor. The project was relatively small and short, placed on four central streets, including the Strøget pedestrian main street. It encompassed 5 to 600 m. of cabling, dismantling existing pavement, excavating, removing existing cables, establishing the new, and reestablishing pavement. The machines used included a dumper, a wheel loader, an excavator, and compactors - all small machines, with the wheel loader having a charging capacity of 0,3 m^3. A charging station nearby was established, and changeable batteries in the compressors were also used. The transportation to and from the site was not included in the project. Apart from using electrical machines, a further innovation was to operate on-site during the night. The noise reduction also marked the daytime operation. The project was monitored in a measurement program with a view to future post-project evaluation: "The Municipal Environmental Department permitted longer hours worked, which decreased the project timeline by 50% overall and resulted in savings that compensated the 20% higher initial investment for emission-free equipment" (BBI 2020). The second project is a daycare institution in a suburb close to the city center, initiated in the autumn of 2020. This project is carried out under the auspices of a strategic partnership between the municipality of Copenhagen and building companies. The contractor employs fossil-free and electrical machines only for the groundworks. The municipality supports economically the on-site CO_2 reduction efforts with around 25000 €. The building period is estimated to be 16 months. As with the previous project, the transportation to and from the site was not included, there was on-site operate during the night, the noise reduction also marked the daytime operation, and the project was monitored in a measurement program for post-project evaluation.

The Case of Oslo: Clustered Transition

Transitioning to electrical vehicles (also including civil construction machines) has long been in the Norwegian state agenda. From around 2016, the Norwegian state has issued a series of support programs and subsidies for promoting fossil-free and electrical machines. In 2016-2018, a number of Norwegian municipalities (e.g. Bergen, Stavanger, Trondheim, Tromsö) carried out pre-investigations and dialogues with the civil construction sector; several of those pre-investigations concluded that electrical machines were not on the market, and biodiesel was the realistic alternative. Nonetheless, the Norwegian state's rigorous support for innovation led two machine suppliers with local offices in Norway to commence rebuilding more heavy civil machines.

In 2018, Pon Equipment, a reseller of CAT machines, had a 25 tons electrical belt excavator ready for testing. Around the same time, NASTA announced their first rebuilt Hitachi machine, and several equipment manufacturers (including Volvo Construction Equipment, Kramer, and Wacker Neuson) launched small machines (less than 2.5 tons) on the market. The electrical CAT machine was sold to both large and small contractors in Norway (including Veidekke, Betonmast and Firing and Thorsen), as well as the municipality of Østfold Fylkeskommune, which commenced renting out the machine. The Hitachi NASTA so-called ZERON machine was sold to Skanska Rental, as well as Marthinsen and Duvholt. The municipality of Oslo became "green" after the local election in 2015. The city council commenced a strategic process of sustainability, focusing on construction and civil engineering emissions in Oslo city center. It was claimed that 30% of the CO_2 emissions in Oslo came from building sites. This was later modified to 8% (DNV 2018), but the focus was maintained. The municipality continued planning their policy of emission-free building sites, and in 2018 they tendered the site of Olav V Gata and Klingenbergsgata in central Oslo as a pilot for the demands of emission-free building sites. The project included the renovation of three strings of a street crossing, each with a length of ca. 250 m. The VA works of cloaks, pipes, and cables, needed to reach a depth of three (occasionally 3.5) m. The project involved some site concrete molding with steel reinforcement, while the substitution of masses went to a depth of 88 cm. The two strings of the crossing were fitted with broader pavement and one string became a pedestrian area. The municipality carried out a market dialogue with contractors and clearly got the impression that the project was doable, including it in the climate budget of 2019. The tender entailed strict procurement demands, placing a weight of 30% on the environment (with about half of it on the construction equipment), 40% on quality, and merely 30% on price. The winner was a previous collaboration partner, a small contractor specialized in parks and gardening. When finalizing the contract, the municipality had not only gotten good and qualified bits, but also many of the wished machines - through a concession agreement with a rental company (Servi). The machines cost roughly 2-3 times more than conventional ones, but with a 40% public state support from ENOVA, this was reduced to a double price. Eventually, the construction works were carried out from October 2019 to summer 2020, and the resulting CO_2 reduction was measured to be over 90% (Wiik *et al.,* 2020). The electrical equipment included a wheel excavator ZERON/NASTA with rotor tilt and three buckets (eight tons), a big track cable excavator ZERON/NASTA (16 tons), and a Hitachi ZX 160 with rotor tilt and three buckets. Later, a PON Equipment/CAT 353 (25 tons), and two wheel-loaders Kramer 5055e with a bucket and pallet fork, were rented. However, the project did not receive a wished wheel excavator (15 tons), a dumper, and a compressor. Nonetheless, the role of subsidies should be noted: the municipality signed a concession agreement with an equipment supplier/rental company (Servi) that provided the electrical machines for the contractor at reasonable costs. The contract between the municipality and the contractor implied that the latter was obliged to use these machines.

The machines were ready by September 2019, while the municipality was ready to provide sufficient electrical power supply by the October of 2019. Some deviances between what was planned, and the actual practical experiences are worth noting. The electrical wheel loader (Kramer) was too weak to lift pallets with pavement stones. The contractor had arranged for repacking the pallets with stones in smaller portions on a buffer site operated by them. Also, the two electrical wheel loaders had too low a capacity, and so an extra biodiesel wheel loader had to be rented. Similarly, the electrical compressor tested did not have enough compressing power, so a biodiesel version was chosen instead. Apart from the above, four more fossil-free projects are found in Greater Oslo (in Fornebu, Gjøvik, Asker, and Tonsen) (Wiik *et al.,* 2020). According to the municipality's strategy, buildings sites in Oslo municipality must be emission-free before 2025 (BBI 2020). However, roughly 80% of sites are state- or private-driven and the municipality currently lacks the regulatory instruments to control those. Further initiatives in Norway include at least two projects in Bergen and four projects in Trondheim. In Bergen, the utility company Kraftselskabet BKK is responsible for two building projects (a nursery home and a wardrobe facility). The rental company CRAMO is part of this set-up, with a mobile charger (battery container) system. One of the projects in Trondheim included demands about emission-free personal transport to and from the site but faced challenges as the electricity supply was not in place.

DISCUSSION

The cases described in the three national contexts inform us about the barriers and enablers of a sustainable transition of heavy-duty construction machines - which is a complex sociomaterial setting with somewhat contradictory dynamics. Gothenburg represented a sociomaterial constellation preparing for the transition, Copenhagen represented the first paradigmatic pilot constituting a new niche, and Oslo represented the clustered sociomaterial constellation where the niche has commenced influencing the incumbent regime - especially municipal policy, but less so the machine manufacturers, even if two major manufacturers have designed and implemented electrical machines sold in the greater Oslo area. In the Copenhagen electric cabling case, the municipality tendered a civil project to a contractor backed by their usual equipment supplier (a rental company that had invested in a series of Wacker Neuson machines). The exception for this punctual innovation was nighttime work, enabling the works to be done in a very short time and with minimum pedestrian nuisance. But where this pilot appears as punctual innovation, the Norwegian cases represent important clustered innovations of financial, technological, and organizational character. The Olav V Gata case stands out as an internationally radical innovation, even if it simply was about bringing existing elements together. This case drew directly on at least three manufacturers (Kraemer, Hitachi and CAT) having developed their machine technology. CAT and Hitachi directly benefited from the state's support. The municipality could make an agreement with a machine rental company, contractually demanding that the contractors operate the electrical machines. The case represents a public-private partnership and a joint business model for doing emission-free building project. In Sweden and Denmark, the incumbent large machine manufacturers, rental companies, contractors, and public clients (e.g. municipalities, the Swedish Transport Authority) are hesitant in taking the more far-reaching steps of electrification. This might stem from a lack of public client demand and the massive investments in diesel engines in both countries. The Danish state can be understood to not challenge the present "glass ceiling" of large machines, claiming these are not market-available (similar to what is reported in Helsinki (BBI 2021)), whereas Sweden invests massively in the sustainable transition of their automotive industry (including heavy-duty construction engines and trucks). A further barrier is the interpretation of investment and operation costs.

In Norway, a full business case is established for the transition (Wiik *et al.,* 2020), whereas in Sweden only certain conditions (e.g. over 7000 hours of operation) would make the investment economically sustainable (Bernholdsson *et al.,* 2020). Both the Swedish and Norwegian cases come with uncertain repair and maintenance costs - but the latter is now backed by several cases operating longer than a year. In one of those, a Hitachi 38 tons excavator used a bare 24% of the energy that a corresponding diesel engine would do (Wiik *et al.,* 2020). In Denmark a business case is lacking and sorely needed, as electricity is more expensive there - but a possible link could be made to the surplus production of electricity by wind power. Connected to these considerations, Wiik *et al.,* (2020) translated the (larger than 90%) CO_2 reduction into economic value, through adapting the CO_2 trading price in Norway. As such, environmental and economic sustainabilities get integrated in a resource-economic business model (Conrad 2020). It can be noted that while EU has been successful in driving down particle emissions of diesel engines, this relative improvement now tends to legitimize the sector's investments in diesel engines, which in turn become a barrier for the transition to electrical engines). A backlog of traditional - albeit low-emission - engines is the resulting present status of 2021. This can be seen as a lack of transition - continued acceptance of (mostly larger) diesel engines, and too little articulated demand for electrical machines.

This analysis thus points to a coexistence of an absent sustainable transition (a continued diesel regime), and an emerging sustainable transition of electrical machines. The commencing niche of an emission-free constellation of public-private stakeholders is at the moment clearly strongest in southern Norway. Therefore, recommendations for the transition include strengthening public-private forms of collaboration. When subsidizing sustainable innovation like the electrical rebuilt of machines, the societal and private investment is a bit longer-term. But it is not an unlikely scenario that the continued adoption of electrical machines will lead to standardization, efficiency improvement, and even mass production - meaning that the cost of rebuilding may fall to an economically feasible level for a private business. The Oslo case also showed the way the municipality systematically planned and realized the needed electrical power infrastructure, which in other attempts of electrification had actually led to unnecessary barriers (e. g. see the case of Helsinki (BBI 2020)). Posing the demand in public procurement also exhibits a curious apparent paradox. When municipalities carry out a market dialogue about electrical machines, they are frequently met with the argument that the machines are not on the market. But as soon as Oslo and Copenhagen actually raised the demand formally in a tender, the contractors and rental companies became ready rather quickly. Finally, when the impact of these projects on the climate is conceptualized independently from the economic cost, there is a risk that the CO_2 reduction becomes a qualitative benefit. A more direct resource-economic appreciation of the impact on the climate (Conrad 2020) might help these initiatives on their way. As such, sustainability development measurements are coming increasingly to the fore.

CONCLUSIONS

The objective of this contribution was to investigate what kind of enablers and barriers there are for a sustainable transition of civil engineering construction equipment in Scandinavia. Among the three investigated cases, the Norwegian case has shown how public subsidies and municipal client demand during the project procurement can drive a commencing sustainable transition, as well as the fact that private players contribute significantly in rebuilding, investing, and operating the machines. The analysis points to a situation where, at a time, there is an absent and emerging sustainable transition. There is a coexistence of a traditional incumbent regime of diesel engines, and a commencing niche of an emission-free constellation of particular public-private stakeholders - a niche clearly strongest in southern Norway. Here a new resource-economic business model is emerging, where public client-driven transition is supported with subsidies (i.e. making electrical equipment available through concession in a particular area, and encouraging machine builders to develop electrical equipment) - while waiting for the large international construction equipment players to become ready for the transition. The resulting CO_2 reduction in these cases has been measured at over 90%. Recommendations for the transition therefore include strengthening public-private forms of collaboration, like subsidizing sustainable innovation, supporting electrical power infrastructure, and posing the demand in public projects. A resource-economic appreciation of the impact on the climate might further help such initiatives.

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