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Investigating the potential for reduced emissions from non-road mobile machinery in construction activities through disruptive innovation

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ABSTRACT

The construction industry relies heavily on non-road mobile machinery (NRMM) for transportation and earthmoving operations, and it is therefore important, from a sustainable perspective, to reduce emissions from NRMM in construction activities. This paper analyses the European emission inventory to find out if technological development has lowered the environmental impact of NRMM over time, with a focus on local, regional and global air emissions. The findings suggest that current regulations have been successful in reducing local and regional emissions ($PM_{2.5}$ and NO_X) by sequentially imposing more stringent requirements, which has promoted incremental innovations in existing technology. However, global emissions in terms of greenhouse gases have not been reduced due to the present regulations. The results are analysed and interpreted using Christensen's theory of disruptive innovations for technological change to assess whether the development appears to progress incrementally or if the data point towards a required technology shift. Currently, the signal of a broad technology shift towards zero-emission solutions is not evident, but at the niche level activities are progressing with new technology. This paper proposes that a shift will require not only a technical transition, but also a sociotechnical change, involving stakeholders acting in symbiosis.

1. Introduction

The expansion of urban areas, including local housing and transport networks, offers an opportunity for growth in the construction industry and benefits for society. However, the construction industry and the built environment put significant pressure on the environment by being the largest consumers of natural resources and using a substantial amount of the energy produced annually worldwide (Munaro et al., 2020). Although material use and energy consumption represent the largest impact in this respect (Wiik et al., 2018), recent research focus has been directed towards the emissions from the operational activities themselves (Keegan, 2021). The construction industry relies heavily on non-road mobile machinery (NRMM) for transportation and earthmoving operations, and it is therefore important from a sustainable perspective to reduce emissions from NRMM accordingly.

The emissions from NRMM include greenhouse gases (GHGs) and other air pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_X), sulphur dioxides (SO_2), fine particulate matter ($PM_{2.5}$ and PM_{10}) and volatile organic compounds

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(VOCs). Emissions from construction activities which affect local and regional air quality, in this paper exemplified with $PM_{2.5}$ and NO_X emissions due to data availability, have been well documented for a long time (Waluś et al., 2018). It is estimated that the construction sector, through its use of NRMM, annually contributes 15 and 34% of the total particle emission ($PM_{2.5}$ and PM_{10} respectively) and 7% of the total NO_X emissions worldwide—being the third largest, largest and the fifth largest contributor, respectively (Desouza et al., 2020). Values from the European Union (EU) indicate NRMM being responsible for 5% of the total PM and 15% of the total NO_X emissions (Lončarević et al., 2022). The impact on global emissions is uncertain since not all countries, regions and cities include NRMM in their emission inventories. However, Lončarević et al. (2022) estimate that 2% of the GHG emissions in Europe may come from NRMM. Depending on the share of renewables in the energy mix, NRMM is responsible for 10%–50% of the total GHG emissions at the construction site (Fufa et al., 2019; Hong et al., 2015).

Substantial legislative regulations on engine technology have been introduced over the last two decades to generally reduce NRMM emissions with impact on the local and regional environment (Desouza et al., 2020). In recent years, the concept of emission-free construction activities has specifically highlighted the role of NRMM to reduce the overall cycle of GHG emissions from the construction site. This twofold aim then requires improvements in engine technology and a shift from traditional fossil-driven NRMM to equipment driven by power trains using renewable sources only (Fufa et al., 2019). This acknowledgement requires a more fundamental shift in technology compared with the present development to achieve this ambitious technological goal.

Public procurement and market dialogues may in addition play a key role in initiating the demand for zero-emission construction (Hamdan and de Boer, 2019), while the market needs a greater demand for innovation and zero-emission solutions to invest in the required research, development and production. Researchers have investigated the role of green public procurement (GPP) in reducing the environmental impact by driving the market from the demand side (Sparrevik et al., 2018; Sönnichsen and Clement, 2020). Innovation for something as novel as emission-free construction sites is likely to require cooperation to bridge the gap between buyers and suppliers by establishing a functioning buyer–supplier 'ecosystem' type of cooperation, where public buyers need to actively demand innovation from the market instead of waiting for the technology to mature.

In this paper, we focus on the role of innovation in the development of NRMM as a vital part of the transformation towards emission-free construction sites. The main question guiding our research is whether the development appears to progress incrementally improving the resilience of the existing system or if emission data point towards a required disruptive technology shift driven by a necessary sustainability transition (Kuokkanen et al., 2019). Traditionally, disruptive changes have been connected to technical moments completely changing the market as happened when traditional film was overtaken by digital photography (Nunan, 2017). Nowadays, we speak of more complex waves of disruption involving social, technical and regulatory changes exemplified with the current transition from fossil fuel to clean energy (Johnstone et al., 2020). For the mobility sector this may be exemplified by the ongoing transition of diesel buses to more environmentally friendly electrical alternatives (Borén, 2020).

We use Christensen et al.'s disruptive innovation model (Bower and Christensen, 1995; Christensen et al., 2018, 2015) as our main theoretical lens. Briefly, this model describes a process where smaller initiatives successfully challenge the present technology by means of innovative solutions, gradually gaining a foothold by delivering a more suitable technology for the market. Over time, by keeping its advantages when entering the main market, the novel technology eventually causes a disruptive change from the old technology to the new one. While Christensen et al. focus on product performance in economic terms, i.e. price; we focus on environmental performance as regulatory bodies are willing to accept it, thus extending the theory's scope to an environmental performance and regulatory perspective.

The remainder of the paper is organised as follows. The methods section contains the details of the data sets we used as the basis for our research where we analyse an overview of emission data covering particle emission, NO_X emissions and GHG emissions in the EU over the last two decades. In the results and discussion section we analyse these data against Christensen's innovation model and, following the analysis, we envisage possible pathways towards zero-emission NRMM. In the conclusion, we return to our main research question and discusses whether a disruptive shift is likely to happen and what factors that may contribute.

2. Materials and methods

2.1. Methodology

In this paper we have collected and analysed the data on NRMM emission levels in Europe and the European policies aimed at emission reduction and used these data to analyse and reflect on the impact of this present strategy on the innovation and technology development for NRMM. These data are reported annually by European Commission's member states under Directive 2016/2284 of the European Parliament and of the European Council regarding the reduction of national emissions of certain atmospheric pollutants (EEA, 2021). This dataset on the emissions of air pollutants includes ammonia (NH_3), non-methane volatile organic compounds (NMVOCs), NO_X, $PM_{2.5}$ and sulphur dioxide (SO_2). In this paper, we focus on the main local and regional air pollutants from engines in construction machinery, which are $PM_{2.5}$ and NO_X in addition to global GHG emissions from the stochiometric combustion of fossil fuels.

2.2. Data collection

Data from 18 countries have been used, corresponding to the countries having the most continuous emission data set during the period. The reporting of the air emissions from NRMM can be found under several categories in the database. According to investigations (Vafiadis et al., 2019), the data category '1a2gvii' (Mobile combustion in manufacturing industries) is the commonly used indicator for NRMM, and most European Union (EU) countries report their emissions from construction machinery using this category. It includes all mobile emissions in manufacturing and construction but is separated from other NRMM emission sources as agriculture, residential and military use. It is worth noting that the category also includes mobile machinery used in industrial applications other than construction; however, to our knowledge, it is the only logical category to measure the use of the construction machinery at an aggregated scale. Therefore, we follow the measurement method by Geilenkirchen et al. (2021) and Vafiadis et al. (2019) and use the data category as our main indicator for NRMM.

In addition to quantitative emission data, we also used a selection of documents and individual and joint reports on initiatives provided by a growing number of major European cities towards developing zero-emission construction sites including emission free NRMM. In particular, we present several reported experiences and practices of the cities of Copenhagen, Oslo and Stockholm, which have been working with this objective at least since 2016, as reported by the Scandinavian GPP Alliance on NRMM (Rambech et al., 2019). These cities, together with others such as Budapest, Amsterdam and Helsinki, also participate in an initiative managed by Local Governments for Sustainability (ICLEI), funded partly by the European Commission, called Big Buyers Initiative for Climate & Sustainability (Big-Buyers, 2021), which hosts a working group specifically on zero-emission construction sites and has published several documents on past and ongoing activities in participating cities.

3. Results and discussion

3.1. Use of EU emission data to analyse the market development

The emission data on NRMM from EU countries and selected EU member states reveal a clear pattern on how emissions have been developing over time. Fig. 1 presents the data on particle ($PM_{2,5}$), NO_X emissions and GHG emissions from 1991 to 2019. The figure also marks the major dates of the changes in EU NRMM emission regulation initiatives, which have imposed subsequently more stringent requirements for emission control for the NRMM engine technology.

Introducing emission control and the requirements for better engine technology in 1997 helped (after an initial lag phase) to achieve a large reduction of local emissions, both in terms of $PM_{2.5}$ and NO_X, until approximately 2016, when the curves start to flatten out. During this period, old equipment had likely been phased out and better engine systems and exhaust cleaning systems had been developed and introduced to the market. This finding supports those of other studies confirming 70%–95% reduction, which corresponds to the movement from Stage I to IIIB in the European Emission classification system (Crippa et al., 2016), but only a minor reduction corresponding to the further transition to Stage V engine technology, (ICCT, 2016). The size of the construction activity in the respective country will determine the absolute magnitude, but most important, all the countries presented in Fig. 1a–b follow the same decreasing trend.

The global GHG emissions presented in Fig. 1c reveal a different scenario. The EU emission control regime (Crippa et al., 2016; ICCT, 2016) has not been targeted against GHG emissions, and even if the regulations have enhanced more efficient combustion processes in a variety of NRMM engine types (Waluś et al., 2018), the effect on reduced fuel use and subsequently reduced GHGs is less pronounced. In the early stage of the analysed period a decrease can indeed be observed for some countries, presumably due to their heavy modernisation and replacement of equipment. This is similar to the findings of Desouza et al. (2020) clearly showing less CO_2 emissions from modern NRMM compared with older equipment. However, for other countries, and in later stages, the results indicate stable or even increasing values.

This may be caused by increased construction activity and more use of NRMM machinery in total. It is difficult to conclude precisely due to a lack of detailed machine inventory data (Lončarević et al., 2022), but Hagan et al. (2023) find a similar increasing trend for energy use, and point towards an expanding construction sector for the explanation. However, similarly to Hagan et al. (2023), our results support the conclusion of that the GHG emissions have not particularly been influenced by the emission control regime in the EU.

Lajunen et al. (2018) point to the same conclusion as our analysis. The successful reduction in local emissions is likely attributed to the incremental improvement of conventional technology, rather than regulations, acting as an incubator for the development of completely new power train technologies (biofuel, hydrogen, or electric). We suspect that existing technology is preferred since it is conceived as offering robust, reliable and well-known solutions, which are important for heavy-duty machinery such as NRMM. The long lifetime and the high cost of investment do not incentivise the market to take chances in unproven innovative technology either. According to Lajunen et al. (2018), creating power train systems' shifts to electric or hybrid solutions requires collaboration among the industry, actors in technology research and development, legislative bodies and end users. We shall return to this requirement for collaboration among stakeholders in the following sections in which we discuss the potential of the ecosystems surrounding construction sites as a driving force towards zero-emission.

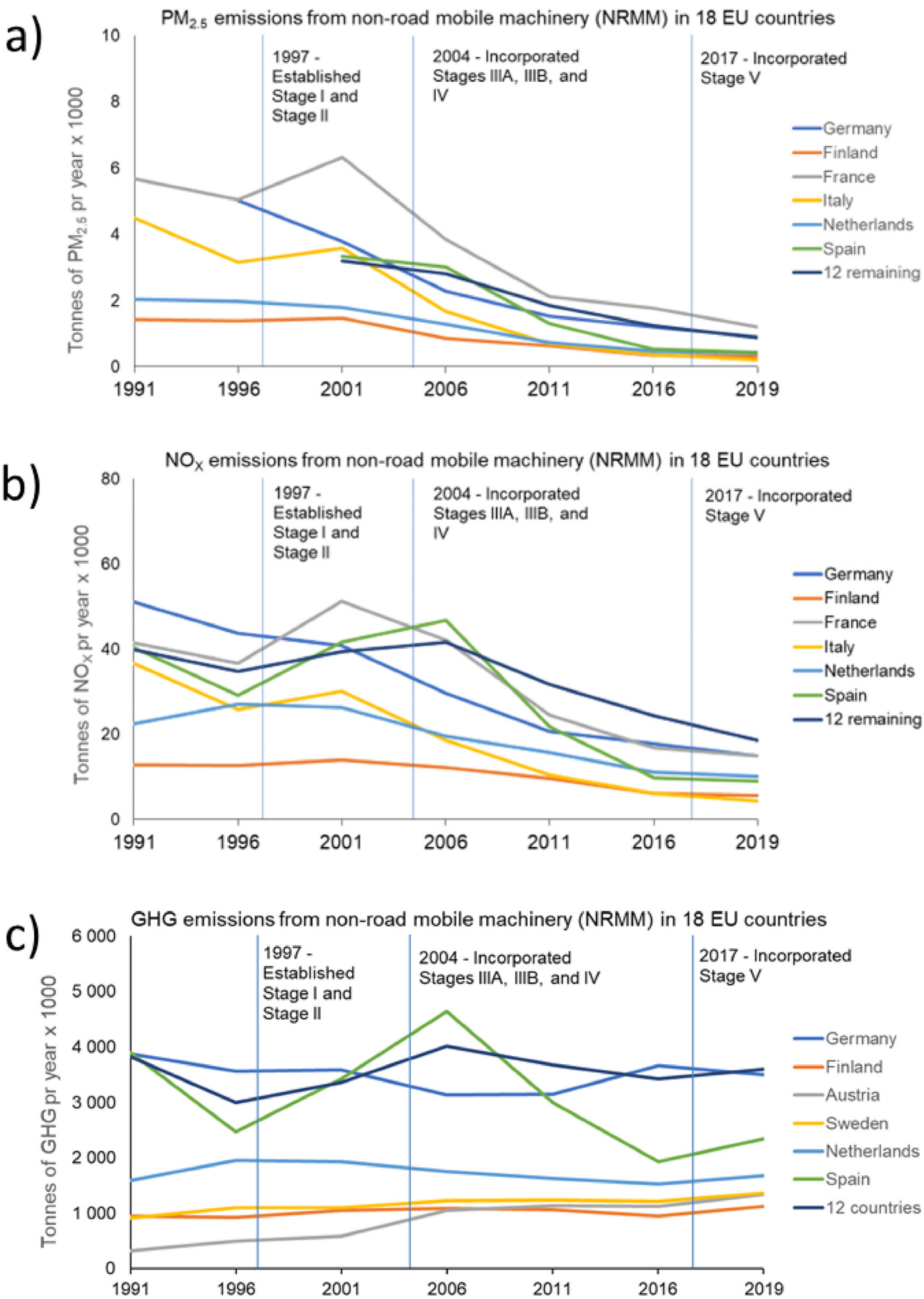

Fig. 1. Emissions from (a) $PM_{2.5}$ (b) NO_X and (c) GHG from NRMM in 18 EU countries during 1991–2019. Six biggest emitters are shown separately, remaining are shown collapsed. Main dates for implementing the different stages in the EU emission regulations for NRMM (ICCT, 2016) are marked in the figure as vertical lines.

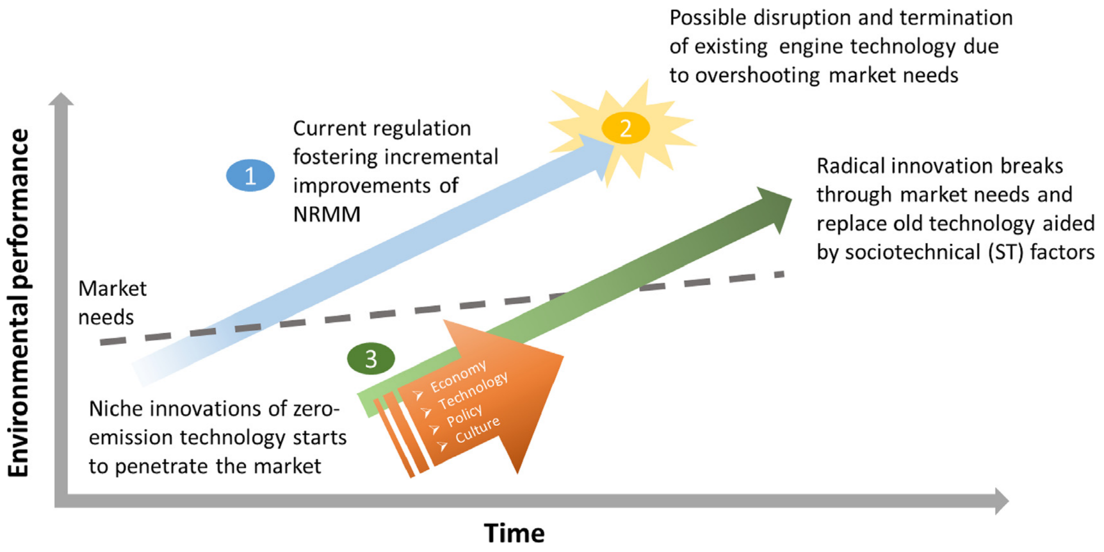

Fig. 2. Use of Christensen's theory on disruptive innovations to evaluate the development of zero-emission non-road mobile machinery (NRMM) in construction activities.
Source: Adapted from Christensen et al. (Bower and Christensen, 1995; Christensen et al., 2018, 2015) and based on presentation in King and Baatartogtokh (2015).

3.2. Analysis against the innovation model

An analysis of the emission data against the innovation model by Christensen et al. (Bower and Christensen, 1995; Christensen et al., 2018, 2015) shows interesting findings. This is depicted in Fig. 2, where a potential pathway towards zero-emission NRMM is outlined.

The increasingly more stringent emission regulations appear to have indeed stimulated the development of existing engine technology to become more efficient in terms of emission control of local emissions. The results suggest that new regulations in the EU have led to incremental innovations that have in turn contributed to the reduction in particle and NO_X emissions in most EU countries from 1991 until 2019. The regulations show less impact after 2017 when the latest regulatory change was imposed. This suggests that the incremental improvements in technology through environmental regulations in more recent years are pushing technology above the market needs for productivity, in this case reduced emissions, in the innovation model (see label 1 in Fig. 2). Further improvements in the technology are possible, especially in comparison to emission levels for road vehicles, but cannot necessary be defended in terms of productivity if substantial redesign of the equipment is necessary to comply with more stringent regulation (Waluś et al., 2018). GHG emissions has not been reduced as a result of the incremental innovations in engine technology. Continuing to follow the existing pathway may eventually even be counterproductive in terms of GHG emissions compared to present situation if the total number of machineries continues to grow due to the increasing demand in the construction sector (Crippa et al., 2016).

Whether this increasing trend of GHG emissions will become unacceptable in terms of environmental productivity and whether this will lead to the disruption of existing technology (see label 2 in Fig. 2) is debatable and depends on how important the reduction in GHG emissions from NRMM will become in the future. Lajunen et al. (2018) argue that the conventional technology solutions (diesel engines and hydraulic systems) will be present for a long time because they offer robust, reliable and well-known options. However, as Fig. 2 indicates, for this type of market, increased GHG emissions may be unacceptable in a society striving to reduce its fossil fuel dependency and fostering rapid reduction in GHG emissions in other areas. Therefore, the disruption of existing technology may be closer to being achieved when viewed from a sociotechnical perspective rather than from a purely technical one.

In terms of the definitions by Geels (2002), zero-emission NRMM is still at the niche level (see label 3 in Fig. 2). The development of niches can be a seedbed for change, but whether innovation will happen depends on if the niche is linked up with the development of a sociotechnical transition (ST), so as the environment outside the regime (Schot and Geels, 2007). The zero-emission NRMM niche may be considered a result of policy developments among certain environmental cautious actors in the construction business, with stringent goals to reduce GHG emissions from construction sites. Although zero-emission NRMM based on retrofitted machinery with batteries and electricity engines instead of diesel power trains exists at the niche level, it is not easy for this technology to progress to the regime level. Geels (2018) proposes that the niche will not break through before it has enough momentum in the internal drivers for the innovation shift and will do so only when an external window of opportunity exists.

Recent research by Huttunen et al. (2021) further illustrates that in order to acquire a more holistic understanding of sustainability transitions, attention should be paid to the links and interactions between different socio-technical systems, blurring the boundaries of micro, and macro-levels. Moreover, people adopting new practices coupled with an enhanced understanding of radical innovation will bring to the forefront viable strategies as a catalyst for sustainability transitions. This will in turn permit a more nuanced awareness of transition dynamics and can significantly advance the holistic understanding of sustainability transition mechanisms.

In the literature, current discussions on the possibilities for a radical innovation shift mainly focus on describing the technological transition but often acknowledge the necessity of technological improvements in symbiosis with the ST perspective (Geels, 2018). Beltrami et al. (2021) remind us that electrical power trains have been used in specialised NRMM (e.g., in mines) for a long time, and they cite successful technical retrofitting examples. Therefore, according to Beltrami et al. (2021), the decrease in fuel consumption, the enhancement of productivity and, more generally, the clear convenience in terms of total cost of ownership, are key points for successfully breaking into the market. Nonetheless, the authorities' political and technical choices with respect to the environment and sustainability will be essential, with economic incentives and taxes as important variables to consider (Kivimaa et al., 2021). They propose and develop a multi-dimensional understanding of disruption, which extends beyond the technical innovation as such and includes four 'non-technical' dimensions: markets, regulations, actors and behaviour, practices and culture. To accelerate sustainability transitions, disruption should take place along multiple dimensions. In this study, we have therefore collapsed the ST perspective further into four distinct dimensions, as indicated in Fig. 2 using the frameworks by Geels (2019) and Kivimaa et al. (2021). We then use; (i) economy (financial instruments to accelerate a shift), (ii) technology (functional value chains for production and use), (iii) policy (markets, practices and regulations) and (iv) culture (actors and behaviour).

3.3. Creating an ecosystem for zero-emission construction sites

In contrast to the present development of NRMM, based on existing technology, a new solution can consist of various competing technologies, where the most environmentally beneficial one may not be an obvious choice (Ratzinger et al., 2021). This is a common aspect of niche development but may slow down the transformation. Further, as shown by Lajunen et al. (2018), in the NRMM market it is also not uncommon for new radical innovations to coexist with old technology, or to appear as modifications or complements to the conventional technology at the start of their breakthrough. The analysis explicitly shows that a radical breakthrough in the environmental performance of NRMM is complicated and not as clearly visible as in other more consumer-driven technical innovations. To penetrate the market, progress is necessary collectively in all described dimensions.

First, *economic value* is perhaps the most important one to achieve, where shorter production series and the need for energy storage systems – which are expensive – and potentially higher investment costs should be balanced with better energy efficiency, controllability, reliability and reduction of maintenance costs (Lajunen et al., 2018). Supportive actions as rental pools for electric machinery supported by suppliers or deduction in electrical fees may be necessary to allow also smaller competitors to bid in innovation competitions including emission free construction sites. A recent survey among cities in Europe points to high cost and a limited market accessibility as two important barriers for innovation propagation (Stokke et al., 2022).

Second, the required change in *technology* will force contractors to use other types of machinery, and the availability and cost level depend on what equipment can be delivered by suppliers further upstream. Additionally, regardless of the availability (e.g., of electrical NRMM), the use may prove difficult if there are no or too few possibilities to charge the equipment, drawing providers of electricity and other critical infrastructure into the chain of actors, thus creating a local or a regional ecosystem. This first part of technological change is essential in the ecosystem since robust and functional technology is necessary to be able to use the equipment on the construction sites. However, as pointed out, fossil-free alternatives to heavy machinery have existed for a long time and the technological challenges can be resolved (Desouza et al., 2020).

Third, the *cultural dimension* of the shift is necessary but may be challenging. The introduction of new technology poses the risk of failure that must be addressed in the procurement process. Several procurement options and contractual procedures may be possible to find a sound way of distributing the risk between suppliers and procurers. Innovative procurement processes with a high degree of end-user involvement (Torvinen and Ulkuniemi, 2016) may be relevant here, in contrast to traditional turnkey contracts, placing all risks on contractors (Sparrevik et al., 2018). Procurement related to construction projects may also involve different departments, functional areas, and management and political levels internally in the city and the municipality, adding to the complexity shift (Stokke et al., 2022).

Finally, the findings show that *policy* plays an important role. The documents available from the Big-Buyers initiative report on activities carried out jointly by cities, among others the efforts of Copenhagen, Stockholm and Oslo in the Rambech et al. (2019) initiative aimed at undertaking a joint, cross-border procurement project as a way of greening the NRMM market. Important recommendations for other cities mentioned in the Rambech et al. (2019) report include dialogue with the supplier market and collaboration with other cities. One could in addition consider high profile policy decisions as zero emission operational zones in larger cities, or similar. This policy dimension is interesting and differs from current regulations, where the EU directives have cascaded into legally binding requirements in the national regulatory frameworks. When using locally based policy initiatives supported by the EU, the requirements may be developed and tailored to local conditions, while organically spreading through more loosely connected policy networks.

We foresee that intense cooperation among the actors progressing along all the four dimension proposed in Fig. 2 is necessary in order to create an ecosystem for zero-emission construction (E-ZEMCON) strong enough to penetrate the larger market for NRMM (Stokke et al., 2022). The ecosystem needs to bridge the gap between buyers and suppliers and ensure involvement of other critical stakeholders. This would allow the coordination of buyers and activities to ensure that buyers represent one large voice and gain volume for setting joint criteria for zero-emission NRMM. This would additionally coordinate demand growth from isolated projects to widespread use in regions and sectors and train buyers to implement zero emission NRMM machinery in existing procurement strategies for construction. Again, from the Big-Buyers initiative, (Big-Buyers, 2021; Rambech et al., 2019), we observe that these cities engage in various activities as setting specific emission requirements for private construction companies when they bid for public construction projects, reducing financial risk through various incentives, organising pilot projects where fossil-free and electrical machinery is used and upgrading the machinery owned by the city to work on fossil-free technology. Working this way, the cities engage the marked in all four ST dimensions will give a potential to successfully progressing the activity from niche activities to more widespread introduction of emission free NRMM.

3.4. A progress towards a disruptive change?

Now, we return to our main research question: 'Will we observe a disruptive change in power train technology for heavy vehicles similar to that of road vehicles?' While there are similar legislative efforts and visible public interest, the differences are also significant (Benzidia et al., 2021; Meckling and Nahm, 2018). Our findings reveal that, unlike the road vehicle situation, the shift in NRMM has not been supported by current legislation, attracting attention instead through voluntary policy processes. First, it has been addressed as one of the pieces to achieve carbon neutrality in the construction sector, not as a singular aim per se. Second, the process of public procurement and network cooperation seems more important in this case compared to the case of road vehicles. The activities are currently progressing in niches with projects based on stringent policy requirements for each city or similar local entity. Whether we will witness a radical innovation shift, as proposed by Christensen's disruptive innovation model, is still unclear. The analysis suggests that the present pathway is fostering technological solutions with environmental performance above the productivity for NRMM, thus suggesting a future disruption. Conversely, machinery's lifetime and requirements differ from those of road vehicles. Different technologies may coexist for a long time. Stokke et al. (2022) shows that progress depends on overcoming the observed barriers relating to high investment costs and technical constraints at the same time using the advantages in better environmental performance, improved work environment and reduced operational expenses. In any case, our analysis suggests that the transition cannot rely on technical changes alone; it also needs to involve sociotechnical issues. This is consistent with findings from Oghazi et al. (2022) which illustrate that actors adopting new ecosystem roles drive the whole ecosystem towards transformation around new value propositions. This further illustrates that disruptive innovation and technological progression enhance ecosystem transformation through new value creation.

4. Conclusions

The development of low carbon solutions in the building and infrastructure sector has highlighted the need to reduce carbon emissions from NRMM activities, in addition to the previous concern of the local and regional emissions from diesel-driven power trains. The improvement of current engine technology supported by continuously more stringent EU emission regulations has been successful in reducing local and regional emissions in the past, in particular NO_X and PM emissions. However, over the last five years, air pollution emission profiles seemed to have levelled out, and in addition, no decrease has been observed for global GHG emissions over the entire period. Thus, further reduction in emissions from NRMM may not be feasible by developing current engine technology and future progress therefore requires a shift in propulsion technology from fossil fuels to other energy sources, such as renewable electricity, biogas or hydrogen. The economic, technical, cultural and policy dimensions must collaborate in an ecosystem to achieve such disruptive shift. Creating ecosystems for implementing emission-free construction (E-ZEMCON), characterised by a heavy emphasis on dialogue-based procurement and progressive piloting, may enhance the transition to emission-free NRMM. Although it has been successful working at the niche level, it remains to be seen in widespread action.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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