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Towards Sustainable Earth-Moving Machinery: A Study on Emission-Free Drivetrain Applications

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Abstract *- Mitigating climate change by reducing carbon emissions represents one of the most significant challenges across all industries. The earth-moving machinery industry has thus far received negligible attention from research endeavours in this particular field. Most earth-moving machinery is currently still powered by fossil diesel, and it remains to be seen which sustainable drivetrain concept will emerge as a viable alternative. The objective of this study is hence to give an overview of emission-free drivetrain concepts for earth-moving machinery in different application scenarios and infrastructural framework conditions. A market analysis of five major earth-moving machine manufacturers focusing on current drivetrain concepts is conducted. The results indicate that currently only one in 20 products offered in Europe is equipped with a sustainable drivetrain, while the overall market share of emission-free vehicles remains at approximately one percent. Results include that for existing vehicles, HVO100 and e-fuels can already be used and represent promising alternatives. For new machinery, in addition to electrification through battery-electric or cable-connected drivetrains, hydrogen combustion engines exhibit high potential, particularly in addressing the lack of electrical infrastructure on construction sites and the high-performance requirements of the machines. In sum, a diversification of drivetrain concepts in the earth-moving machinery sector will most likely occur, presenting challenges for both manufacturers and contractors.*

Keywords: sustainable drivetrains, earth-moving machinery, construction equipment, sustainability, civil engineering

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1. Introduction

As stated by the Intergovernmental Panel on Climate Change, anthropogenic greenhouse gas emissions are the leading cause of climate change [1], [2]. The continued increase in global carbon emissions highlights the need to reduce emissions across all industries, including the construction machinery industry [3]. The production and operation of mobile construction machinery accounts for roughly 1.3% of total greenhouse gas emissions, a figure that is comparable to that of the shipping and aviation industry [4]. In Europe alone, a region with a comparatively high regulatory environment with regard to emission regulations, the use of fossil diesel in construction machinery is responsible for the emission of over 100 million tons of carbon dioxide on an annual basis [5], [6]. Compared to other industries, there is still no clear roadmap within the earth-moving machinery industry as to which (locally) emission-free drivetrain concept is viable for a variety of construction scenarios and tasks. Especially the challenge of operating machinery on uneven ground, in dusty environments, with a high variance of power demand, and limited access to charging infrastructure, currently inhibits the transition.

In consideration of the substantial heterogeneity that characterizes construction machinery in general, the present study concentrates solely on earth-moving machinery [5]. According to the standards set forth in DIN EN ISO 6165:2022, an earth-moving machine is defined as a self-propelled or towed basic machine on wheels, tracks or stabilizers, which may have attachments and/or working equipment, primarily designed for digging, loading, transporting, drilling, spreading, compacting or milling earth, rock and other materials [6]. In contrast with the prevailing view, König [5] excludes compaction equipment from the category of earth-moving machinery in his comprehensive study, 'Machines in Construction Operations'. This study follows König's assertion and excludes compaction equipment from the analysis. The objective of this study is then to examine the most suitable emission-free drivetrain concept for each type of earth-moving machinery, considering also different application scenarios. The evaluation excludes economic criteria, such as on-site fuel costs and manufacturing costs. The overarching objective can be broken down into three related subquestions:

- Which sustainable drivetrains are already being used in earth-moving machinery?
- Which sustainable drivetrains can be used in existing earth-moving machinery?
- Which sustainable drivetrains should be optimally used for newly produced earthmoving machinery, considering different application scenarios?

2. Market Analysis

2. 1. Procedure

A market situation analysis following the methodology proposed by Grimm [7] is conducted to determine the current state of science and technology. The initial step therein is to establish a clear definition of the market under consideration [7]. The focus of this investigation lies on the European market, and the number of major manufacturers is limited to five. It is deemed not feasible to conduct a comprehensive analysis of all potential manufacturers within the scope of this study, as this would likely have yielded minimal to no additional insights. The turnover, defined as the number of units sold multiplied by the price per unit, is selected as the most suitable parameter for determining the relevance of each manufacturer [8]. Using turnover instead of the number of units sold is important, as it also accounts for the size of the machine, which in turn affects engine power and correlates closely with carbon emissions. As European sales figures for earthmoving machinery are not publicly available for every manufacturer, global sales figures for 2022 were used.

The world's leading manufacturers of construction machinery, in descending order of sales volume, are Caterpillar, Komatsu, XCMG, John Deere, Sany, Volvo Construction Equipment, Liebherr, and Hitachi Construction Machinery [9]. However, John Deere only offers two product categories of earth-moving machinery, and thus is not considered further in the following analysis [10]. XCMG and Sany are primarily active in Asian markets and have relatively low sales figures in Europe. However, due to a lack of transparency regarding business figures, it is not possible to provide further substantiation of this assumption. Accordingly, the market analysis concentrates on Caterpillar, Komatsu, Volvo CE, Liebherr, and Hitachi CM. Furthermore, only products that explicitly comply with the current European emissions standard Stage V are analysed. Key figures include the machines' engine power, operating weight, predominant drivetrain system, and application scenario [7].

2. 1. Results

Analysing a total of over 500 product data sheets revealed that only around 5% of the earthmoving machinery currently on offer within the European market can be characterized as emission-free. The most common drivetrain concept is battery-electric (BEV) and cable-connected electric (CCEV) [11]. Also, a multitude of engines have already been approved for use with the alternative fuel HVO100 [12]. The decision to use HVO100 is, however, contingent upon the contractor. HVO100 remains considerably less accessible and more costly than fossil diesel [13]. Across all categories, irrespective of size, 3.5% of wheel loaders and 7% of excavators currently on offer are equipped with locally always emission-free drivetrains. In the case of certain machines, such as articulated dump trucks or backhoe loaders, only diesel-powered products are available. Markedly, products within the machine class of hydraulic cable excavators are offered exclusively as CCEV. This is due to high energy demands and mostly static locomotion patterns in mining applications [14].

3. Classification of Earth-moving Machinery

The multifaceted responsibilities of earth-moving machinery during construction processes lead to the existence of a diverse range of machinery in terms of application and corresponding drivetrain concept [15]. Hence, contrary to the prevalent practice in other industries, a universally applicable approach to sustainably power earth-moving machinery across all subcategories in the same manner is not feasible. As application scenarios and machine classes differ significantly, it is necessary to classify earth-moving machinery into distinct categories based on key characteristics before any further analysis into drivetrain concepts can be conducted. In addition to the characteristics of the equipment itself, the location and duration of operation play an essential role [11]. The existing infrastructure is also of importance, as construction machinery in general is lacking in mobility. A distinction must thus be drawn between sites with and without electrical infrastructure [16].

It is not possible to determine typical operation times to a reasonable degree of accuracy within the context of this analysis, given the paucity of publicly accessible data [11], [17]. To address the research question, there is thus a distinction between two general categories of operation: short operations, which last for a maximum of three hours per 24 hours, and long operations, which last for a maximum of eight hours per 24 hours. In all operational scenarios, it is assumed that the uninterrupted operating time will be at most six hours. This assumption is based on the stipulations of EU labour legislation, which requires employees to take a break after six hours of work [18].

Furthermore, equipment locomotion patterns influence drivetrain feasibility. The following subdivisions are established:

- Short locomotion patterns: During the entirety of one operation cycle, the machine covers only short distances (less than 50 m)
- Medium locomotion patterns: During operation, the machine covers medium distances (between 50 m and 1 km) with a high variance and alternating locomotion patterns.
- Long locomotion patterns: During operation, the machine covers long distances (over 1 km) and/or at high speed (greater than 10 km/h).

Table 1 presents an overview of select equipment and its most relevant characteristics. The characteristics are based on the analysis of 162 product data sheets from Caterpillar, 127 from Komatsu, 81 from Liebherr, 76 from Volvo CM, and 56 from Hitachi CM, resulting in an overall sample size of 502 [19], [20], [21], [22], [23]. The findings were condensed significantly to create a concise categorization of the most essential categories. Table 2 answers the first subquestion by outlining the current offering of emission-free machinery for different equipment classes (Table is not exhaustive).

Table 1. Overview of Select Earthmoving Equipment

Equipment Category	Typical Operating Weight [t]	Typical Engine Power Output [kW]	Locomotion Pattern	Typical Duration of Operation [h]
Hydraulic Excavator - Mobile	9 - 28	50 - 160	medium	6
Hydraulic Excavator - Crawler	9 - 100	55 - 300	short	6
Compact Excavator	1-10	5,5 - 55	short	6
Hydraulic Cable Excavator	800 - 1400	540 - 1350	short	6
Small to Medium Wheel Loader	2,5 - 20	35 – 150	long	6
Medium to Large Wheel Loader	15 -250	150 - 1300	long	6
Dump Truck (articulated steering)	22 - 55	200 - 500	long	6
Dump Truck (rigid frame)	30 - 370	260 - 2600	long	6
Bulldozer	7 - 50	50 - 300	long	6
Backhoe Loader	7 - 10	50 - 82	long	6
Grader	12 - 34	90 - 227	long	6

Table 2. Drivetrain Concepts in Earthmoving Equipment

Equipment Category	Products in Category	ICE Drivetrain	Most Prevalent emission-free drivetrain	Ratio
Hydraulic Excavator - Mobile	46	45	BEV	98% ICE
Hydraulic Excavator - Crawler	116	115	BEV	99% ICE

Equipment Category	Products in Category	ICE Drivetrain	Most Prevalent emission-free drivetrain	Ratio
Compact Excavator	31	27	BEV	87% ICE
Hydraulic Cable Excavator	5	0	CCEV	100% CCEV
Small to Medium Wheel Loader	63	60	BEV	94% ICE
Medium to Large Wheel Loader	49	48	BEV	98% ICE
Dump Truck (articulated steering)	17	17	-	100% ICE
Dump Truck (rigid frame)	22	22	-	100% ICE
Bulldozer	37	37	-	100% ICE
Backhoe Loader	14	14	-	100% ICE
Grader	9	9	-	100% ICE

4. Evaluation and Allocation of Drivetrain Concepts

The following selection criteria were considered in the analysis of potentially viable emission-free drivetrains:

- Emissions during the operation of the equipment and during the production of the power source
- Use of critical raw materials
- Infrastructural requirements
- Charging & refueling time
- Weight of the entire drivetrain
- Overall energy efficiency
- Technology maturity level
- Possibility of retrofitting machinery
- Restrictions in mobility

Fuel cell electric vehicles (FCEVs), battery electric vehicles (BEVs), cable-connected electric vehicles (CCEVs), hydrogen combustion engines (HICE), as well as e-fuels and HVO100, meet the criteria [12], [24], [25], [26]. It is important to note that while BEVs and CCEVs, as well as FCEVs and HICE, are locally emission-free, HICE and HVO100 are only considered emission-free or sustainable because the production of HICE and HVO100 absorbs the same emissions as the usage produces [27], [28], [29]In terms of applicability for construction machinery, each drivetrain concept was analysed thoroughly using the selection criteria. Table 3 presents an illustration of the evaluation employing BEV as an exemplary drivetrain concept.

Table 3. Evaluation of BEV

Criteria	Evaluation	Source
Emissions during operation	Emission free	[30]
Use of critical raw materials	Lithium and cobalt for battery, rare earths for engine	[30], [31], [32]
Infrastructural requirements	Adequate power supply on site, ideally with charging stations	[30]
Charging & refueling time	Between ~ 12min up to 50h	Calculated using [33]
Weight of the entire drivetrain	Around 660 kg per 100 kWh	[34]
Overall energy efficiency	Between 70 and 85 %	Calculated using [33]
Technology maturity level	Already in series production	[30]
Possibility of retrofitting machinery	Not possible without significant alterations	-
Restrictions in mobility	none	-

4. 1. Evaluation of Existing Machines

Given the lengthy product lifecycles of construction machinery, it is neither economically nor environmentally feasible to immediately replace all existing machines. The use of HVO100 and the e-fuels within existing ICEs enables a straightforward transition by also not requiring massive processual changes on the construction site in terms of refuelling and construction logistics [27]. The combustion of HVO100 or e-fuels produces emission values that are comparable to those of fossil diesel, but both require carbon dioxide that is already present in the atmosphere during production, resulting in a closed cycle and only negligible new carbon emissions [27], [28]. HVO100 is currently available for purchase in numerous European countries [29]. However, the current supply is insufficient to meet the needs of all existing vehicles [27], [29]. E-fuels are often regarded as a more sustainable alternative, but data indicate that the quantities are not sufficient in the near future [27].

4. 2. Evaluation of New Machines

In contrast to legacy machinery, newly produced earth-moving machinery offers a broader array of viable alternatives. In terms of overall efficiency and technological readiness level (TRL), BEV and CCEV are most advantageous [35]. The latter option offers the advantage of minimal complexity and investment costs [30], [31], [32]. Given that these are accompanied by a limitation regarding the range of locomotion, they are only realizable for a relatively small quantity of machinery in select application scenarios [30]. Both drivetrain concepts necessitate the presence of adequate infrastructure on-site, particularly grid connection. For the BEV, it is also necessary to ensure that the machine's power demand is proportional to its operating weight [30].

As BEVs allow for greater flexibility in various construction scenarios and require fewer infrastructural prerequisites, they are, at least for smaller, mobile machinery, more favorably received by the market than CCEVs. A mixture of BEV and CCEV is a combination particularly well-suited for wheeled excavators with medium power requirements. In cases where infrastructural prerequisites, process-related locomotion patterns, and power demands are incompatible with electrified machines, fuel cells can be utilized for power generation. Fuel cells are generally susceptible to damage from polluted air and vibrations, which are prevalent on construction sites [23], [24]. Furthermore, high peak energy demands are challenging to meet. Nevertheless, fuel cells can be employed as a stationary energy source, especially for power outputs of up to 350 kW. While some original equipment manufacturers (OEMs) are currently engaged in the prototyping phase for HICEs in mobile machines, FCEVs remain below the TRL five threshold.

In comparison to e-fuels, hydrogen-powered equipment necessitates the implementation of considerably more intricate refuelling methodologies [36], [37]. HICE and FCEV both require a considerable amount of energy to refuel, due to the necessity of compressing the hydrogen [38]. At this time, it is not yet evident which drivetrain systems will ultimately prevail in the context of mobile earth-moving machinery applications. Ultimately, the debate might come down to the question of whether hydrogen or e-fuels can be offered on-site at a lower price point. A decision tree (Fig. 1) was developed to provide practitioners with a clear guideline on when and how to transition to different emission-free drivetrain concepts. Figure 2 additionally illustrates a possible allocation of drivetrain concepts in construction sites with and without grid connection. Furthermore, the analysis is divided into two categories: market-ready solutions (TRL nine) and future solutions (TRL five and below). In the areas delineated by a striped pattern, for equipment with short locomotion patterns, CCEVs are feasible. The graphic does not differentiate between individual equipment categories but rather divides earthmoving machinery as a whole by power and operating weight.

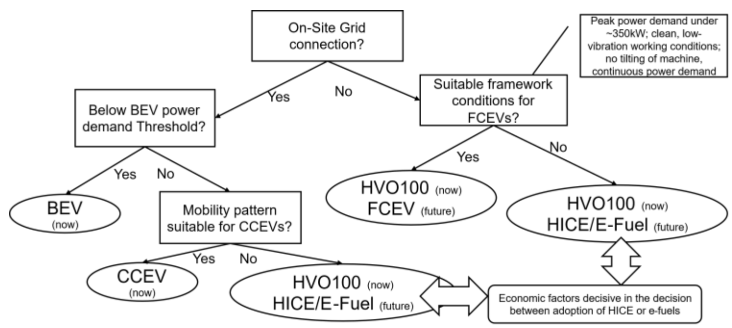

Fig 1. Decision Tree for drivetrain concepts for emission-free construction machinery

4. 3. Evaluation of Construction Site Ecosystems

As a novel approach to the investigation of emission-free drivetrain feasibility for earthmoving machinery, different construction site ecosystems and application scenarios are considered in the following. The main reasoning behind this is that it is uncommon for earth-moving machinery to operate in isolation during a construction process. In the majority of cases, the equipment performs one step in a chain of construction processes, working in conjunction with a variety of other machinery within the context of broader construction site ecosystems. The composition of drivetrain types on a given construction site is, hence, of great consequence from a processual and productivity standpoint and in terms of construction logistics, influencing drivetrain choice as much as technical feasibility alone [39], [40]. Three distinct construction site scenarios are analysed with respect to their influence on the feasibility of different sustainable drivetrain concepts. Firstly, applications of earth-moving equipment in urban gardening and landscaping, which generally entail low power requirements and exhibit short process times, are evaluated [41]. These activities also frequently occur in locations with electrical infrastructure already in place. Considering this, especially BEVs and CCEVs can be regarded as a highly promising alternative to conventional machinery.

Industrial applications of construction machinery, for example, recycling yards or the loading of wood chips onto trains, require more powerful equipment with industry-specific operating times and cycles, often working continuously in multiple shifts [42]. In the case of industrial applications with brief operating periods, the transition to BEV can be initiated easily, for the equipment is mostly operated within the same location. For industry applications where extensive locomotion and continuous operation are required, other drivetrain concepts, especially hydrogen-based solutions, are more feasible. The already industrially available HVO100 solution to mitigate carbon emissions during operation

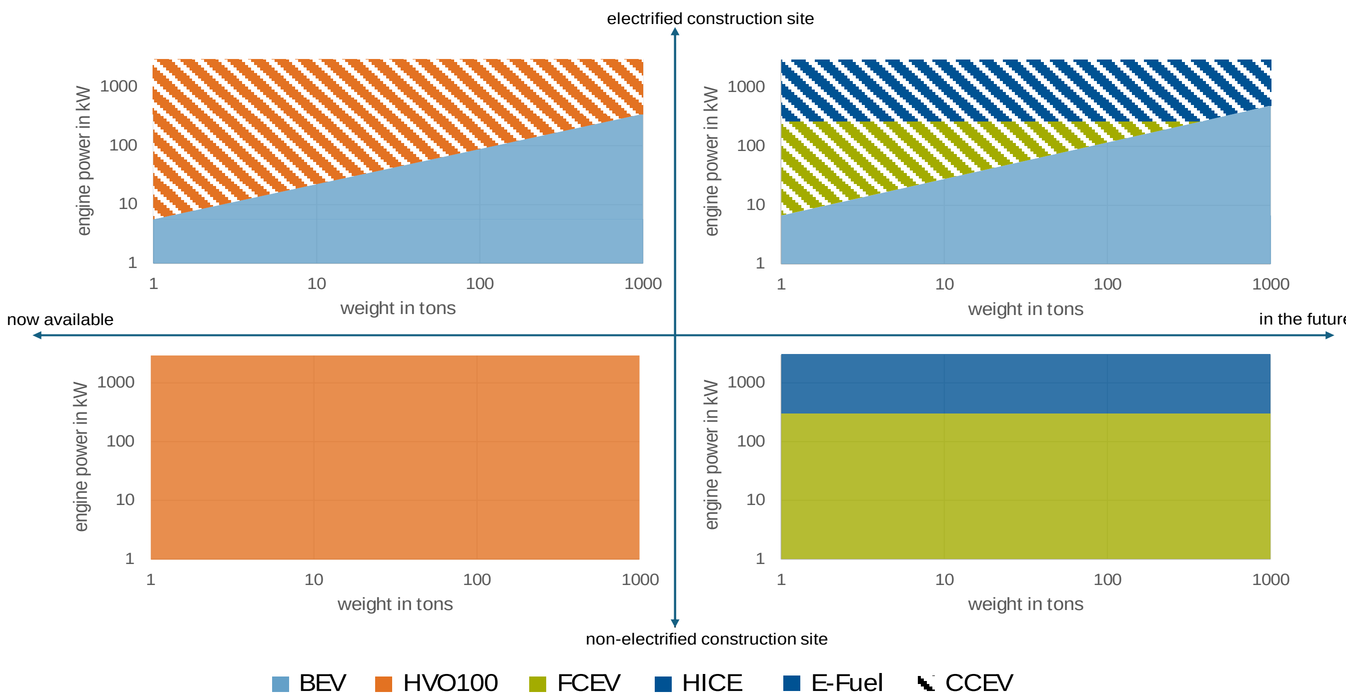

Fig. 2 Allocation of the drivetrain depending on power supply, engine power, and operating weight

Table 4. Earth-moving Equipment and Alternative Drivetrain Concepts in Road Construction

Equipment Category	Typical operating weight [t]	Typical Engine Power output [kW]	Current Drivetrain	Future Drivetrain (no grid connection)	Future Drivetrain (grid connection)
Mobile Excavator	9 - 28	50 - 160	HVO100	HICE or E-Fuels	BEV & CCEV
Crawler Excavator	9 - 25	55 - 120	HVO100	HICE or E-Fuels	BEV
Crawler Excavator	21 - 100	121 - 300	HVO100	HICE or E-Fuels	BEV & CCEV
Small Wheel Loaders	10 - 20	35 – 150	HVO100	HICE or E-Fuels	BEV
Large Wheel Loaders	15 - 53	144 - 300	HVO100	HICE or E-Fuels	HICE or E-Fuels
Dump Trucks (articulated)	22 - 55	200 - 470	HVO100	HICE or E-Fuels	HICE or E-Fuels
Heavy-duty Dump Trucks	30 - 370	260 - 2600	HVO100	HICE or E-Fuels	HICE or E-Fuels
Bulldozer	3 - 50	50 - 300	HVO100	HICE or E-Fuels	HICE or E-Fuels
Grader	3 - 50	50 - 300	HVO100	HICE or E-Fuels	HICE or E-Fuels

will, hence, most likely be replaced by HICE or fuel cell concepts.

In road and highway construction, the utilization of electrified equipment is challenging, as the grid-based power supply is often inadequate [43]. Also, the hydrogen infrastructure remains underdeveloped, rendering the use of HVO100 the sole viable option in the short term. Due to its comparatively low energy density and the necessity for specialized equipment to facilitate its storage and delivery, hydrogen-based solutions, akin to battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), necessitate meticulous construction logistics and well-designed refueling strategies [36], [37].

For the usage of future construction machinery in off-site road construction scenarios, e-fuels and HICE represent the most viable alternative from an economic, ecological, and processual (i.e., construction logistics and handling on-site) standpoint. As infrastructural circumstances evolve, the utilization of electricity may become more prevalent, with e-fuels and hydrogen contributing to the diversification of energy sources. It is highly probable that equipment utilized in road construction will become electrified up to a battery capacity of approximately 100 kWh [44], [45]. Table 4 summarizes the findings for the off-site road construction scenario and showcases potential construction machine drivetrain compositions in current and future road construction scenarios.

5. Discussion

5.1. Discussion of Results

Presently, HVO100 is the sole means of ensuring a more sustainable construction process across a multitude of construction applications, machine types, and the employment of legacy machines [12]. In addition to the advent of electrified construction equipment, HICEs are currently being implemented in machines that are nearing series production as an alternative to HVO100, especially in operation scenarios with limited electrical infrastructure [12], [46]. The probable diversification of drivetrain concepts across a range of machinery and construction scenarios (see Figs. 1 and 2) represents a substantial challenge for manufacturers and contractors. This challenge is further compounded by the potential for divergence across different construction site ecosystems.

For original equipment manufacturers (OEMs), the expansion of a product portfolio necessitates investment in engineering expertise, a broad supplier network, and an agile production system [47]. This investment is essential for the ability to deliver a competitive machine portfolio featuring different drivetrain concepts. For smaller manufacturers with a limited product range, an effective strategy for developing a more sustainable product portfolio would most likely be to conduct a detailed analysis of their individual customers, their construction processes, and the optimal drivetrain concept to achieve the construction task. In cases where similar requirements across machine types are present, focusing on the development of a unified sustainable drive system has the potential to streamline complexity and reduce investments [48].

In the context of construction logistics, the provision of sufficient energy on-site for a multitude of machinery is a significant challenge for contractors [49]. This phenomenon is further accentuated by constant fluctuations in machine park composition and energy demands throughout the construction process. It remains to be seen whether the additional expense and logistical overhead of supplying diverse energy sources and maintaining different drivetrain concepts are offset by the benefit of being able to select the most efficient and optimal drivetrain configuration for each individual machine and application scenario. Contractors with a limited machine portfolio and select applications may find it feasible to focus on a single drivetrain concept. However, they may subsequently encounter constraints in their capacity to accept contracts for certain construction sites that lack the necessary infrastructure [50]. For example, a gardening and landscaping company utilizing only BEVs would be unable to operate its equipment in a construction site devoid of a grid connection. In contrast, non-compliance with local regulations pertaining to investment in sustainable machinery has the potential to preclude contractors from participating in specific projects.

The extent to which drivetrain diversification will materialize in the long term is, according to the current state of research, uncertain [30]. The distribution between HICE, HVO100, and e-fuels is a particularly contentious issue. It is unlikely that HICEs and e-fuels will coexist within construction sites in the long term. It is, as of now, similarly unclear whether the FCEV can be integrated into construction site ecosystems [31]. In the presence of suitable framework conditions (no grid connection, clean air, low vibration, low impacts, and minimal peak power demand), the FCEV represents an efficient alternative.

Nevertheless, it is imperative for companies to operate within the parameters of the market and to achieve profitability. It is thus probable that contractors will continue to rely predominantly on fossil diesel rather than the more expensive HVO100. In the absence of regulatory measures, contractors and manufacturers are currently unable to profit economically from the transition to sustainable drivetrains.

5.2. Limitations

A comprehensive investigation into the full spectrum of all drivetrain concepts and market developments within the earthmoving construction equipment industry would necessitate the examination of internal data from a diverse range of companies and has therefore been neglected.

Another significant limitation of this study is that it exclusively examines the European market for earth-moving machinery. In other markets, particularly in developing countries, contractors frequently utilize previously owned machinery from developed countries in second-life applications, thereby extending the product life cycle even further. Infrastructural conditions, particularly in remote areas, are also often inadequate. Nevertheless, the findings of this study are not contingent on particular European emission standards or other external factors and can be applied to different countries and regions.

6. Summary and Contribution

This paper concludes with a listing of the most significant findings and novel contributions that have emerged from the analysis:

- All types of earth-moving equipment, both existing and new, can already be operated in a more sustainable manner. However, the regulatory and economic incentives are inadequate [12].
- In the short term, there will most likely be an increase in demand for alternative fuels, particularly HVO100, in response to legislative mandates requiring contractors to adopt more sustainable operational practices [51].
- The expansion of infrastructure, particularly the establishment of a grid connection for construction sites, could be identified as a pivotal factor in enhancing the efficiency and sustainability of construction practices [50]. In instances where a grid connection has been established, operations are likely to be conducted using a combination of battery-electric vehicles (BEVs) and cable-connected vehicles (CCEVs), primarily due to their relative cost-effectiveness.
- The prospective diversification of drivetrains presents a significant challenge for both OEMs and contractors [49]. It is not yet evident which type of ICE, and which type of fuel will gain the greatest market share. Ultimately, economic viability on-site will likely supersede technical considerations.
- Despite the advent of alternative energy sources and drivetrain concepts, classic ICEs remain the predominant drivetrain within the earthmoving machinery.

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