energies

Article

Toward Zero Emission Construction: A Comparative Life Cycle Impact Assessment of Diesel, Hybrid, and Electric Excavators

Asmat Ullah Khan and Lizhen Huang *

Department of Manufacturing and Civil Engineering, Faculty of Engineering, Norwegian University of Science and Technology, 2815 Gjøvik, Norway; asmat.ullah@ntnu.no
* Correspondence: lizhen.huang@ntnu.no; Tel.: +47-40380958

Abstract: Due to an extensive usage of heavy machinery, the construction sector is criticized as one of the major CO_2 emitters. To address climate concerns, mitigating these greenhouse gas (GHG) emissions is important. This study aimed to strategize for "zero emission construction" by assessing the life cycle environmental impacts of diesel, electric, and hybrid construction machinery. By applying life cycle assessment (LCA) principles with adherence to ISO 14040/44 methodologies, this study scrutinizes the environmental repercussions of a standard excavator over 9200 effective operational hours, from raw material acquisition to end-of-life disposal. The results demonstrate a significant reduction in global warming potential (GWP), ozone depletion potential (ODP), and acidification potential (AP) in transitioning from diesel to hybrid and fully electric machines. A nominal increase due to this shift also occurred and impacted categories such as human carcinogenic toxicity (HT), freshwater eutrophication (EP), and marine ecotoxicity (ME); however, a more significant upsurge was noted in terrestrial ecotoxicity (TE) due to battery production. Thus, this study highlights the need for a careful management of environmental trade-offs in the shift toward electrified machinery and the importance of centering on the environmental profile of the battery. Future work should focus on enhancing the environmental profile of battery production and disposal, with policy decisions encouraging holistic sustainability based on green energies in construction projects.

Keywords: life cycle assessment; construction equipment; CO_2 emissions; batteries; electrification

Citation: Khan, A.U.; Huang, L. Toward Zero Emission Construction: A Comparative Life Cycle Impact Assessment of Diesel, Hybrid, and Electric Excavators. *Energies* **2023**, *16*, 6025. https://doi.org/10.3390/en16166025

Academic Editor: Anastassios M. Stamatelos

Received: 2 July 2023
Revised: 26 July 2023
Accepted: 28 July 2023
Published: 17 August 2023

1. Introduction

The construction sector, which is responsible for about 23% of global economic carbon emissions [1], is vital for achieving the UN's Sustainable Development Goals (SDGs). Most of the fuel usage and emissions are produced during heavy equipment operations. This off-road machinery accounts for 45% to 48% of all motor vehicle gasoline usage and emitted pollutants [2]. The machinery is mostly deployed at a large scale in mega projects, performing heavy duty operations, which generates a substantial amount of pollutants compared to other sectors. For instance, a middle-sized loader machine produces 500 times more emissions as compared to a private car [2–4]. The large-scale dependency on diesel-fueled machinery, which emits pollutants such as CO_2, SO_2, NO_X, and particulate matter (PM) [5], jeopardizes urban life. For instance, in London, construction contributes to 7.5% of the city's NO_X emissions, 8% of PM10 emissions, and a significant 14.5% of PM2.5 emissions [6]. PM2.5 particles, which are capable of deeply penetrating the body, are associated with increased mortality rates from lung, cardiovascular, and respiratory diseases, particularly among children and the elderly. Similarly, construction sites in Oslo account for 18% of the city's greenhouse gas emissions and 30% of total transportation emissions [6], surpassing emissions of passenger cars and light-duty vehicles and adding an extra 5.1 tons of NO_X.

Given the significant environmental impacts of construction machinery, policies targeting zero-emission construction sites have been introduced. For example, Oslo aims to achieve emission-free construction projects by 2025 and proposed solutions to minimize off-road equipment emissions. Meanwhile, the industry is actively exploring new ways to reduce pollutants and fossil fuel consumption without compromising the productivity of equipment. In this context, decarbonization and CO_2 reduction initiatives are being taken globally. Renewable energy sources such as biodiesel have been explored as an alternative to cut dependencies on diesel fuel, which is environmentally unfriendly and non-sustainable in the long term. Here, green diesel, which is produced via the hydrogenation of vegetable oil, is considered an important biofuel. Thus, to produce high-quality biodiesel, three solutions have been proposed [7]. These include green diesel composure with bio-additives, hydro-treated diesel fuel, and two-component mixtures. Biodiesel reduces water pollution by allowing microorganisms in the soil or water to dissolve 99% of it in 28 days through an extensive decomposition process [7–9]. This fuel is 75% cleaner than an ordinary petroleum diesel [10]. However, developments in this area are in the early phase, and most of the equipment is still equipped with a diesel engine. Thus, the demand for biofuel is increasing [11].

Other innovative technologies, such as selective catalytic reduction and diesel oxidation catalyst, have also been developed to reduce diesel engine NO_X and particle emissions [12,13]. Strategies such as engine and machine component upgrades, process optimization, specialized training for machine operators to decrease fuel usage, and the electrification of construction site equipment can all contribute to an increased efficiency and reduced emissions [14]. In the Nordic region, several companies, including Volvo (Gothenburg, Sweden), Wacker Neuson (Munich, Germany), and PON (Oslo, Norway), have developed environmentally friendly machinery for public projects, citing the forthcoming implementation of stricter and more sustainable public procurement regulations in large cities as motivation [15]. Currently, the construction manufacturers are launching machines with electric technologies due to their greater efficiency and lower environmental impact compared to fossil fuel-based alternatives. Hence, excavators are being upgraded with electrification and advanced features, serving as prototypes of this shift. Notably, Komatsu Ltd. (Tokyo, Japan) [16] designed a battery-powered excavator that can operate between two and six hours on a full charge, depending on the task. Meanwhile, the electric Liebherr (Colmar, France) R 9200 E [17] is purported to have up to 25% lower maintenance costs compared to its diesel counterparts. Wacker Neuson [18] also made strides in this area, launching the battery-powered EZ17e lightweight excavator. These advancements underscore the growing momentum of electrification in the construction industry.

Similarly, technologies with hybrid powertrain architectures offer dynamic, efficient machinery for indoor and outdoor use in full electric and hybrid modes. For instance, reference [19] proposed a solution to determine optimal hybrid configurations, while reference [20] replaced a 14 kW diesel engine with a 10 kW electric motor in excavators, reducing operating times while maintaining performance. Zhang et al. [21] developed an innovative energy recovery system for hybrid hydraulic excavators, whereas Yu et al. [22] emphasized the importance of an effective energy flow balancing for the efficient use of scarce power sources such as battery packs. These studies underscore the potential of hybrid technology in promoting efficiency and reducing the environmental impact of the construction industry.

Despite the growing recognition of heavy duty construction machinery's impact on the environment, research typically places an emphasis only on direct operational emissions, leaving a gap in comprehensive life cycle assessments (LCAs), comparing traditional and alternative powertrains. This creates challenges for decision-makers such as contractors when strategizing a shift toward greener energy sources, especially reflecting debates around the environmental impacts of batteries. To fill this gap, this study aims to answer the following research queries:

- What is the hot spot of environmental impact stemming from construction machinery according to a life cycle perspective?

- How does the level of electrification influence the environmental impact of construction machinery?
- Which measures are key to reducing construction machinery's environmental impact?

The study conducts a life cycle assessment of an excavator, one of the important construction machines mostly used in large-scale projects. Five scenarios are examined, encompassing fully electric, with various levels of hybridization, and diesel-powered equipment. Sensitivity tests are performed to pinpoint key influencers in order to ensure the reliability and robustness of this findings. Given the current state of development and deployment of fully electric machinery in construction projects, these findings are particularly valuable. They can inform decision-making processes for both developers and contractors, aiding in the transition toward more sustainable and efficient practices in the construction industry.

2. Materials and Methods

This LCA study follows the ISO 14040/44 methodology [23,24]. The background data stem from ecoinvent database version 3.9. The ReCiPe Midpoint (H) V1.1 method has been used to calculate the environmental impacts.

2.1. Goal and Scope

The goal of this study is to provide cradle-to-grave attributional LCA for construction machinery to support the green shift of the construction sector. In view of operational efficiency and environment, the engine is considered as one of the important parameters in construction machinery; therefore, the study evaluates five distinct scenarios based on engine powertrain energy distribution. The machines used under these scenarios have comparable weight and operating conditions. Therefore, we focus entirely on the performance of the machine under operation. Thus, the time taken to transport equipment from one job site to another falls outside the scope of this analysis. For charging batteries, we used Norwegian electricity mix (hydro-power), and assumed a grid as a propulsion system. We believed that the charging station has enough potential to provide charging required for batteries in this analysis.

Scenario 1: Utilizes a conventional internal combustion engine (ICE) powered solely on diesel. This scenario is used as a benchmark of comparison for other cases.

Scenarios 2, 3, and 4: These scenarios are based on hybrid engines, with the machine powered by both battery and diesel engine.

Scenario 5: In this case, the machine is completely relied on battery engine. It is important to note that the weight of the machine was estimated as 26 tons in all cases. Therefore, for designing a fully electric machine, we used a 300 kWh battery pack. The weight and capacity of the battery has been adjusted as per Caterpillar [25] and Pon Equipment [18].

The study uses an "effective hour" (eh) metric to compare the performance of equipment running on diesel, electric, and hybrid powertrains. The effective hours measure the time during which a machine is actively performing both direct and indirect productive tasks. We have not counted idle time of equipment; therefore, it is excluded in effective hours. The functional unit in this LCA was used as a machine, weighing 26 tons with an estimated operational life of 9200 (ehs). As the performance of the machine can also be influenced by working environment, for the sake of simplicity and practicality, the study assumed medium operating conditions and a machine with track chain mobility. This study considered the manufacturing, maintenance, operation, and end-of-life stages of a construction equipment, as illustrated in Figure 1.

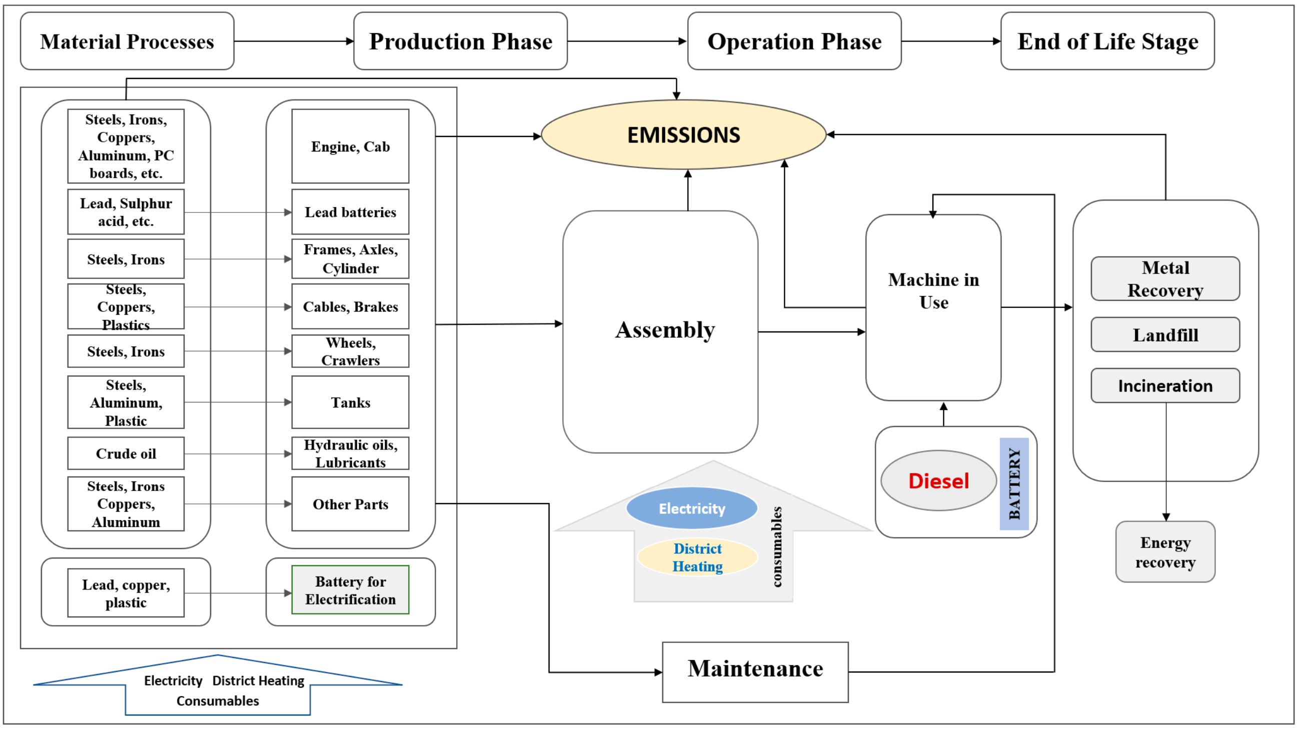

Figure 1. Generic process flow diagram for the life cycle of a conventional excavator.

2.2. Inventory Analysis

2.2.1. Manufacturing, Maintenance, End-of-Life

For each scenario, a machine was designed and the input and output flows were adjusted as per Volvo Construction Equipment (VCE) and Volvo Group Truck (VGT) documentation [26]. Other sources such as manufacturer manuals and the latest literature works were also considered to ensure accuracy and validation. For machines that operated on hybrid (diesel + electric) engine, we incorporated Li-ion batteries, with battery weight calculated based on capacity in each scenario [27]. The capacity of battery for the hybrid and electric scenarios is determined based on the power distribution in the operation mode of equipment. The details of each scenario are illustrated in Table 1.

Table 1. Scenarios for diesel, hybrid, and electric construction equipment.

Scenarios	Diesel (%)	Electric (%)	Details	Battery (kWh)
1	100	0	Fully diesel powered	-
2	75	25	Hybrid	75
3	50	50	Hybrid	150
4	25	75	Hybrid	225
5	0	100	Fully electric	300

To optimize performance and reduce associated maintenance costs, we assumed regular maintenance and repairs throughout the lifespan of the machine. The replacement of the battery was presumed once during the life cycle. As per Bellona [28], only 5% of lithium-ion batteries are recycled in the European Union (EU), the majority are either disposed of in landfills or incinerated. As such, this study considers a 5% recycling rate for battery.

2.2.2. Operation

For evaluating emissions during operation, we used the European Emissions Inventory Guidebook, commonly known as the EMEP/EEA guidebook [29,30], as it provides the baseline emission parameters. Given that we knew the size of the engine for the machinery, we estimated emissions using the Tier 3 method, following the EMEP/EEA guidebook. We also aligned some data of the EMEP/EEA guidebook to one emission standard, i.e., Stage V emission standards [31].

Based on the VOLVO guidebook, we set the power of each machine as 168 kW. Equation (1) was used to calculate emissions for each scenario of equipment, modifying a formula of the EMEP/EEA guidebook according to the statistics of this analysis. The equation includes variables representing calculated pollutant amounts, baseline emission factor, fuel efficiency, energy density of fuel, load factor, adjusted deterioration factor, and electrification coefficient.

$$E_{xi} = \left(\sum_{t=0}^{eh} BEF_{tpi}.\ FC_x.ED_{xy}.\ LF_t.\left(1 + ADF_{tpi}\right)\right).\ (1 - K_x) \tag{1}$$

Here, E represents the amount of calculated pollutants in grams (g), x stands for the specific construction equipment, i represents the type of pollutant, and eh signifies effective hours (in this study, 9200). The baseline emission factor is denoted by BEF. The technology level is represented by t and measured in grams per kilowatt-hours (g/kWh). The power is denoted by p which is determined as 168 kW in this study. FC is used for fuel efficiency, which is calculated in liters per effective hours (l/eh). ED stands for the energy density of the fuel y burned in the specific construction equipment, which is denoted by x, and measured in g/kg fuel. LF is the adjusted load factor, which is set to 100% in the designed scenarios. The load factor is the amount of engine power used during operation. ADF is used for the adjusted deterioration factor, which accounts for emission changes as the machinery ages, and electrification coefficient is denoted by K, which is measured in percentage. In our analysis, we adjusted the value of K as 0%, 25%, 50%, 75%, and 100%, respectively, for scenarios 1–5, as shown in Table 1.

Equation (1) was used to calculate emissions for 9200 effective hours (the economic lifetime) of equipment in each scenario. The baseline emission factors (BEFs) depend on technology levels (t) and power ranges (p) in kilowatts per hour (kWh), as shown in Table 2. CO_2 and SO_2 emissions are primarily considered to be fuel-driven emissions, and depend on the engine type and equipment technology [32]. As the EMEP/EEA guidebook [32,33] does not provide an emission factor for these emissions, we therefore used the CO_2 intensity of fuels, following [34], assuming a value of 3146 g/kg burnt fuel. Diesel fuel was limited to 10 ppm of sulfur [35], presumed to fully convert to SO_2. Additionally, the density of diesel fuel was taken as 0.85 kg/L.

Table 2. Baseline emission factor (BEF) values.

Engine Power (kW)	Technology Level	Pollutant	BEF	Pollutant	BEF
$75 \leq P < 560$	Stage V	BC	0.002	NO_x	0.4
		CH_4	0.003	PM	0.0
		CO	1.5	VOC	15
		NH_3	0.002	CO_2	0.1
		N_2O	0.035	SO_2	3

The performance of engine declines as the machine becomes older. Such degradation often leads to increased tailpipe emissions. To provide a more accurate estimate of emissions for such a degradation, we employed logistic distribution model in our study. This made the calculation of deterioration factors for a set of air pollutants based on their initial emissions standards.

Calculations were performed from the start of the equipment usage (time zero) till the end of its life, providing a comprehensive assessment of the impact of engine degradation on tailpipe emissions. To account for the varying rates of decline, three retardation factors were used, as illustrated in Figure 2. The retardation factor acts as the midpoint between zero and the maximum adjusted deterioration at the end of life. We selected 30%, 50%, and 70% retardation factors to represent a broad scope of scenarios regarding the frequency and rate of pollutant generation. The 30% and 70% retardation factors function as lower and upper boundaries, indicating faster and slower rates of deterioration, respectively. The 50% retardation factor was used here as the baseline, as per [31].

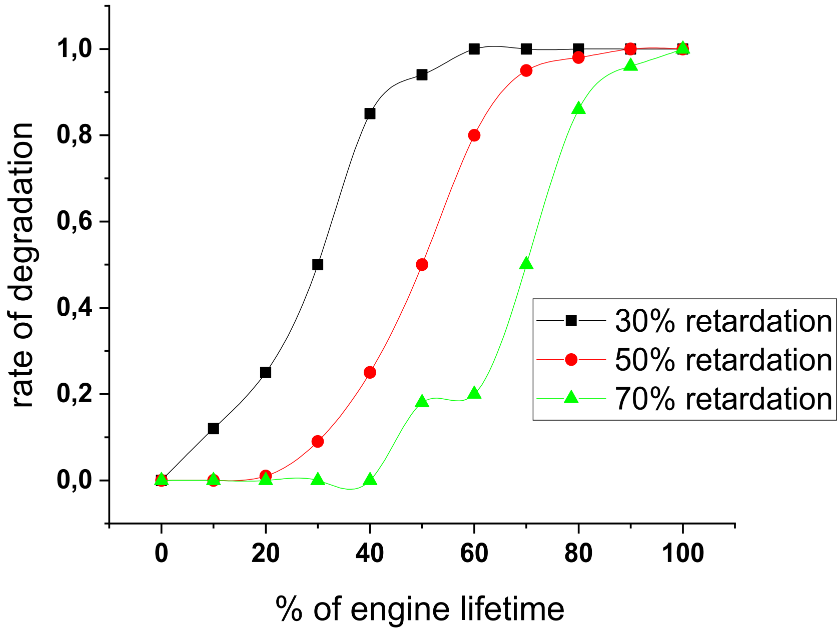

Figure 2. Distribution of engine deterioration.

To adjust the distribution exhibited for various pollutants, we multiplied the rate of degradation with the deterioration factor of each gas. Table 3 shows the modified deterioration factor of each pollutant. Due to the lack of information (deterioration factors) for pollutants like black carbon, dinitrogen oxide, and ammonia, we presumed that engine degradation would not be affected by them. Therefore, emission factors for these pollutants were kept constant during the overall lifespan of equipment.

Table 3. Degradation factors for adjustments.

Pollutant	Deterioration Factor (% Avg. Engine Lifetime)
CH_4	0.15
CO	0.151
CO_2	0.1
NO_X	0.008
PM	0.3
VOC	0.027
SO_2	0.1
FC	0.1

2.2.3. Data Collection

For extraction and processing of materials, the types and quantities of materials were determined from the Volvo group, following VCE and VGT documentations [26]. We also used Bellona Foundation Norway database as an information source for equipment-related data [6,36]. Other information sources, such as emission modeling, reports, the literature, and Environmental Product Declaration (EPD) documents were studied to collect a comprehensive set of data relevant to our study.

Table 4 lists data sources used while creating processes for the production, maintenance, and end-of-life stages of the construction equipment under analysis. This table provides an overview of the key processes and their corresponding ecoinvent entries, offering a clear reference point for each phase of life cycle of the equipment.

Table 4. Boundary of the studied system and data sources.

Life Cycle Stages	Data Sources
Manufacturing	Ecoinvent (v3.9); Volvo EPDs [26]; EMEP/EEA [26,29–33,37,38]
Maintenance	Ecoinvent (v3.9); [18,31–33,37–39]
Operation	Ecoinvent (v3.9); [31–33]
End-of-life	Ecoinvent (v3.9); [31,39]

2.3. Impact Assessment

ReCiPe Midpoint (H) V1.1 method was applied in simapro for calculation. The following seven environmental impact categories were chosen for analysis: global warming potential (GWP, kg CO_2 eq), terrestrial ecotoxicity (TE, kg 1,4-DCB), stratospheric ozone depletion potential (ODP, kg CFC11 eq), human carcinogenic toxicity (HT, kg 1,4-DCB), terrestrial acidification potential (AP, kg SO_2 eq), freshwater eutrophication potential (EP, kg P eq), and marine ecotoxicity (ME, kg 1,4-DCB).

3. Results

The results of this study are shown in Table 5, which presents a comprehensive comparison of the environmental impacts associated with different types of construction machinery. It is observed that multiple impact categories vary in response to differing levels of electrification.

Table 5. Impact of manufacturing, maintenance, operation, and end-of-life stages for diesel, hybrid, and electric machines.

			Contribution (%)				
Impact category	Unit	Total	Manufacturing	Maintenance	Operation	End of life	Scenarios
Global warming (GWP)	ton CO_2 eq	5191.61	1	0.3	98	0.7	1
		3914.09	1.3	0.5	97.7	0.5	2
		2662.83	2	0.8	97	0.2	3
		1405.15	4	1.8	93.8	0.4	4
		145.39	42.3	19.3	34.5	3.9	5
Terrestrial ecotoxicity (TE)	ton 1,4- DCB	574.99	73.9	9.1	15.5	1.5	1
		845.79	58.2	27.3	13.3	1.2	2
		1261.93	54	33.4	11.6	1	3
		1661.18	52	37	10	1	4
		2609.51	40.7	30.8	27.8	0.7	5
Stratospheric ozone depletion (ODP)	ton CFC11 eq	1.43×10^{-3}	1.5	0.46	97.99	0.05	1
		1.11×10^{-3}	1.6	0.7	97.6	0.1	2
		0.80×10^{-3}	2.4	1.3	96.1	0.2	3
		0.69×10^{-3}	3	1.8	95	0.2	4
		0.16×10^{-3}	15	9	75	1	5
Human carcinogenic toxicity (HT)	ton 1,4-DCB	32.86	88.7	6.9	4.2	0.2	1
		29.30	83	10.4	6.3	0.3	2
		31.21	80	11.7	8	0.3	3
		32.85	78	13	8.6	0.4	4
		39.52	66.4	12.4	20.8	0.4	5
Terrestrial acidification (AP)	ton SO_2 eq	1.58	15.3	4.5	80	0.2	1
		1.30	17	8.6	73.9	0.5	2
		1.15	23	13.1	63.1	0.8	3
		0.90	34	21	44	1	4
		0.78	44.3	29.7	24	2	5
Freshwater eutrophication (EP)	ton P eq	0.06	72.9	13.3	13.5	0.3	1
		0.07	60.13	25.37	14	0.5	2
		0.09	56.2	30	13.2	0.6	3
		0.11	54.6	33	11.7	0.7	4
		0.16	46	30.2	23.2	0.6	5
Marine ecotoxicity (ME)	ton 1,4-DCB	16.46	49	6	6	39	1
		21.13	40	16	14	30	2
		28.21	38.6	21	17.4	23	3
		35.09	38.3	24	19.2	18.5	4
		81.55	19.6	13.4	59	8	5

For example, with an increase of 25% electrification, GWP reduces from 5191 to 145 tons of CO_2eq, while switching from fully diesel to fully electric machinery. Similarly, ODP and AP reduce from (1.43×10^{-3} to 0.16×10^{-3}, ton CFC11 eq) and (1.58 to 0.78, ton SO_2 eq), respectively. On the other hand, due to growing electrification, an upward trend was noted in impact categories, notably, TE, HT, EP, and ME. The TE elevated greatly from (574.99 to 2609.51, ton 1,4 DCB) and HT, EP, and ME, respectively, raised from (32.86 to 39.52, ton 1,4-DCB), (0.06 to 0.16, ton P eq), and (16.46 to 81.55, ton 1,4-DCB), as shown in Table 5.

In terms of GWP, ODP, and AP, scenario 1, which uses a machine solely fueled by diesel, records the highest impacts. Conversely, scenarios 2 through 4, which represent equipment with a 25–75% reduction in diesel engine usage due to hybridization, display a notable reduction in environmental impacts in these categories. For these three categories, the operational stage contributes most significantly to the total impact.

However, for TE, HT, EP, and ME, environmental impacts escalate with increasing levels of electrification. In these categories, it is the manufacturing stage that contributes most substantially to the environmental footprint. This is due to that fact that some electrical components use rare earth metals and require a significant amount of energy during production, the emissions produced during their manufacturing phase are higher compared to standard internal combustion engine mechanical powertrain components [40]. We also assessed these seven impact categories for monitoring stage-wise emissions (manufacturing, maintenance, operation, end-of-life phase) in all scenarios, with results presented in Figures 3–6.

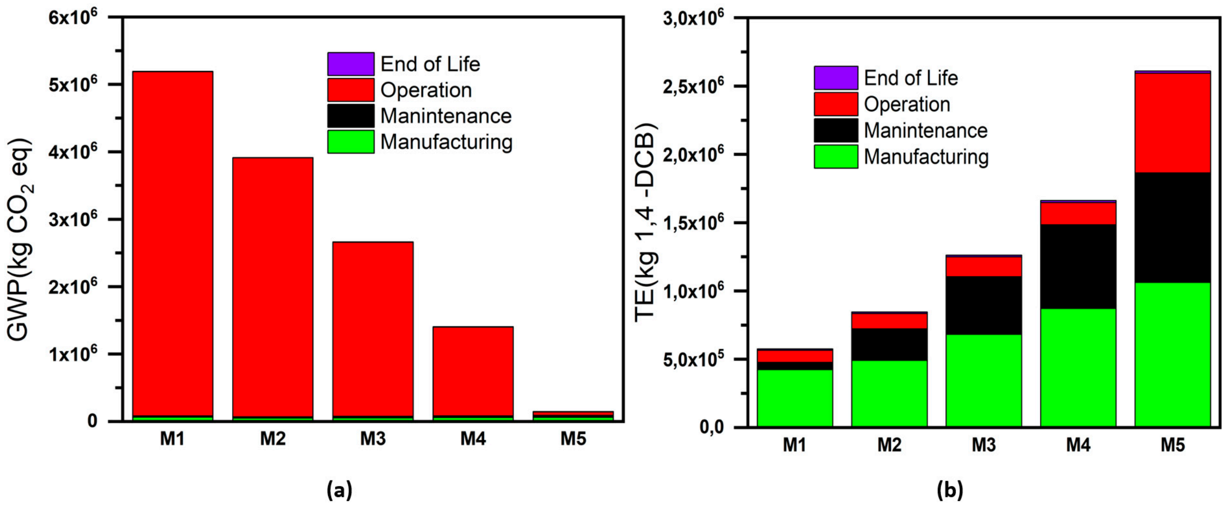

Figure 3. (**a**) Global warming potential (GWP), (**b**) terrestrial ecotoxicity (TE).

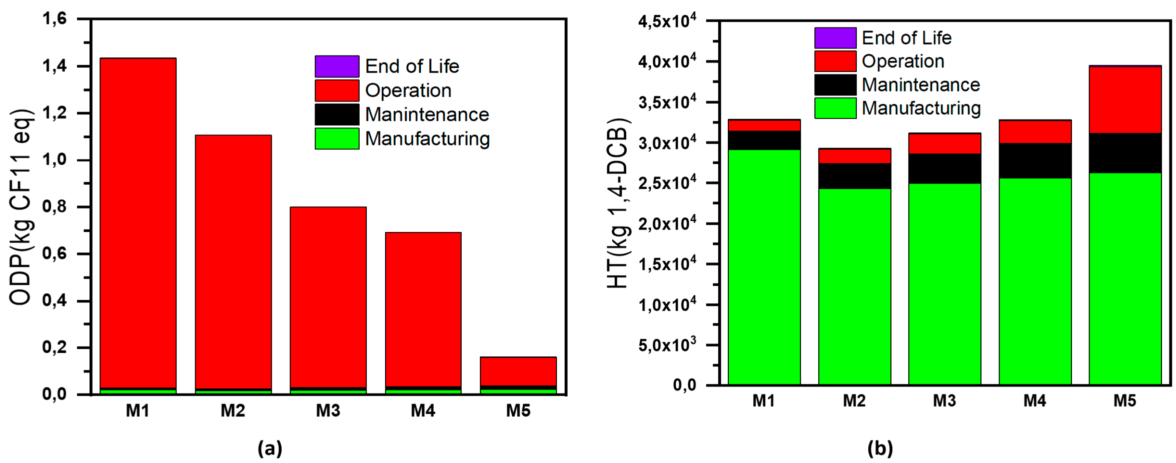

Figure 4. (**a**) Ozone depletion potential (ODP), (**b**) human toxicity (HT).

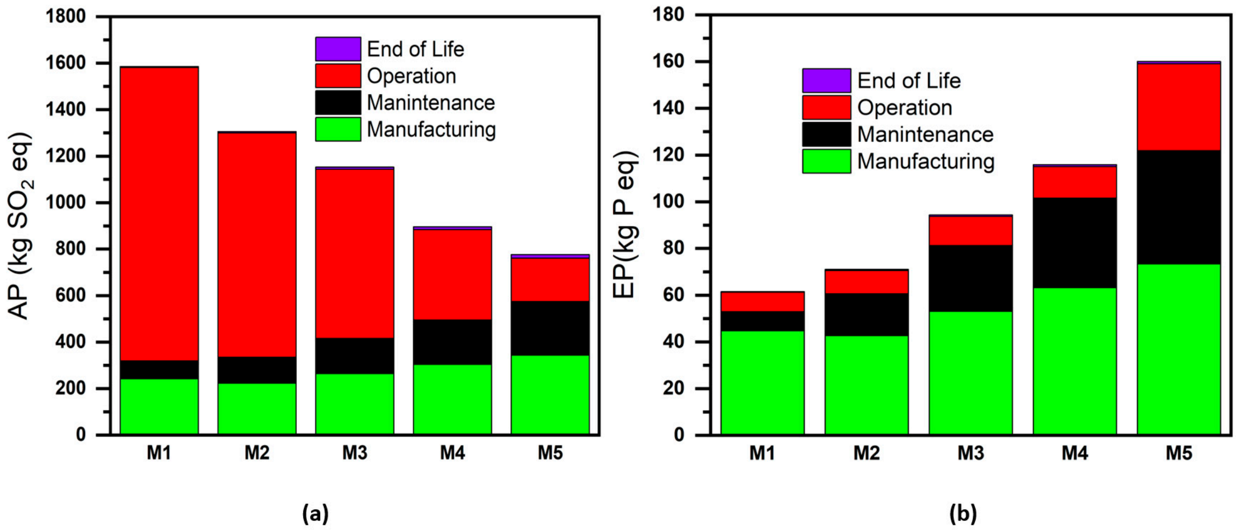

Figure 5. (**a**) Acidification potential (AP), (**b**) eutrophication potential (EP).

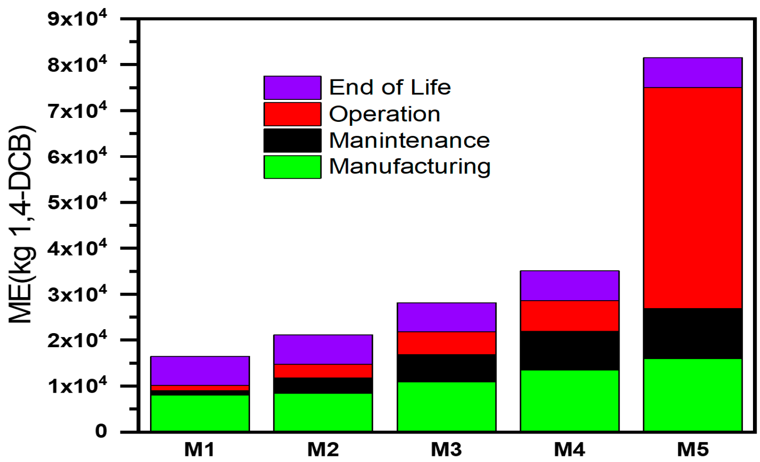

Figure 6. Marine ecotoxicity (ME).

GWP is primarily driven by the combustion of diesel fuel in equipment and upstream diesel production processes. However, a significant decrease in GWP was observed while transitioning from a full diesel to an entirely electric operation. As illustrated in Figure 3a, machines 2, 3, 4, and 5—characterized by 25%, 50%, 75%, and 100% electrification, respectively—presented GWP impacts that were intermediate, falling between machine 1 (highest) and machine 5 (lowest). In Figure 3a, we also observed a decrease in the GWP at the manufacturing stage while moving from scenario 1 to scenario 2. However, the GWP then increases again, primarily due to the environmental impact of battery production. Battery manufacturing significantly contributes to the GWP during the maintenance and end-of-life (EoL) stages, resulting in an increase in GWP as the level of electrification is enhanced. This observation is in line with our expectations.

As per [41], chemicals in batteries can spill into the ground during the manufacturing and disposal processes, leading to the contamination of both groundwater and surface water. This contamination can adversely affect numerous aquatic plant and animal species due to the toxins released by batteries. Therefore, as we increase the level of electrification, we also observe a corresponding rise in TE, as indicated in Figure 3b.

Like GWP, the consumption of diesel fuel in various stages also contributes to ODP. Increasing the level of electrification in machinery operation results in a decrease in ODP as seen in Figure 4a. However, during other stages, ODP is observed to be increasing as the capacity of the battery is enhanced. This can stem from the production of polytetrafluoroethylene, a material used in lithium-ion batteries, which contributes to both ozone layer depletion and global warming emissions [42].

HT in the manufacturing stage shows an interesting pattern. It first decreases while transitioning from diesel engines to electrification, but then increases as the size of the battery becomes larger, as shown in Figure 4b. The production of ferrochromium for low-alloyed steel, and the usage of lithium batteries, which contain potentially hazardous metals and organic substances [43], are linked to this stage of HT. This rise also occurred due to the electricity powering the machine. As a result, HT increases at all stages when the electricity supply is ramped up from 25% to 100%.

As depicted in Figure 5a, AP exhibits a similar pattern to HT in the manufacturing stage but shows a more significant impact due to electrification. In the maintenance and end-of-life stages, AP tends to increase due to battery replacement and treatment. However, during operation, AP diminishes as electrification levels rise. On the other hand, EP and ME, respectively, as shown in Figures 5b and 6, conversely follow different trends in the operation phase. The nitrogen oxides and sulfur dioxide emissions from the diesel engine's operation and diesel fuel manufacturing are mostly accountable for the acidification impact. During the lifespan of diesel machinery, nitrogen oxides are also causing most of the eutrophication [44]. Notably, transoceanic tankers and construction machines using diesel fuel with 10 ppm sulfur, which primarily emit SO_2 and, to a lesser extent, NO_x [45]. EP is also altered by factors such as the disposal of lignite and coal mining waste, on-site petroleum production, and diesel combustion using construction equipment. Major contributors to these results include phosphate and other oxidizable pollutants in water bodies, as well as NOx emissions in the air [46]. Cobalt, nickel, and manganese in lithium-ion batteries can also cause hazards, potentially polluting water and ecosystems if they leach from landfills. The inappropriate disposal of batteries are linked to landfill fires or battery recycling facility fires [47].

Sensitivity Analysis

The study found battery and diesel to be the two most dominant variants with a substantial environmental impact across various categories. To evaluate the sensitivity of the system to changes in these parameters, multiple sensitivity tests were conducted, applying 10% increases and decreases in each input. These tests are detailed in Figure 7 and Table 6. The experiment was carried out using baseline scenario for the impacts, which have been illustrated in the results section. Impact assessments were used to compare scenarios involving diesel, hybrid, and electric equipment. Table 6 illustrates that GWP and TE were significantly influenced by an increased fuel consumption and resultant tailpipe emissions. Machine 1, solely powered by diesel, and machine 5 with 100% electrification, respectively, showed the largest degree of change in GWP and TE.

The deviations curtail in GWP when the machinery is electrified, with a reduction in diesel fuel usage in hybrid scenarios, and the smallest deviation displayed in the fully electric machine. The impact of the battery was observed in all categories as its capacity increased; however, the nominal variations in EP, ME, and the highest in TE were noted with an increasing electrification, as shown in Figure 7. The battery manufacturing process generates various emissions such as sulfur dioxide, nitrogen dioxide, and carbon dioxide [48]. These pollutants are produced mostly due to energy used in the production and assembly phases of various battery cells and raw material processing [40,48].

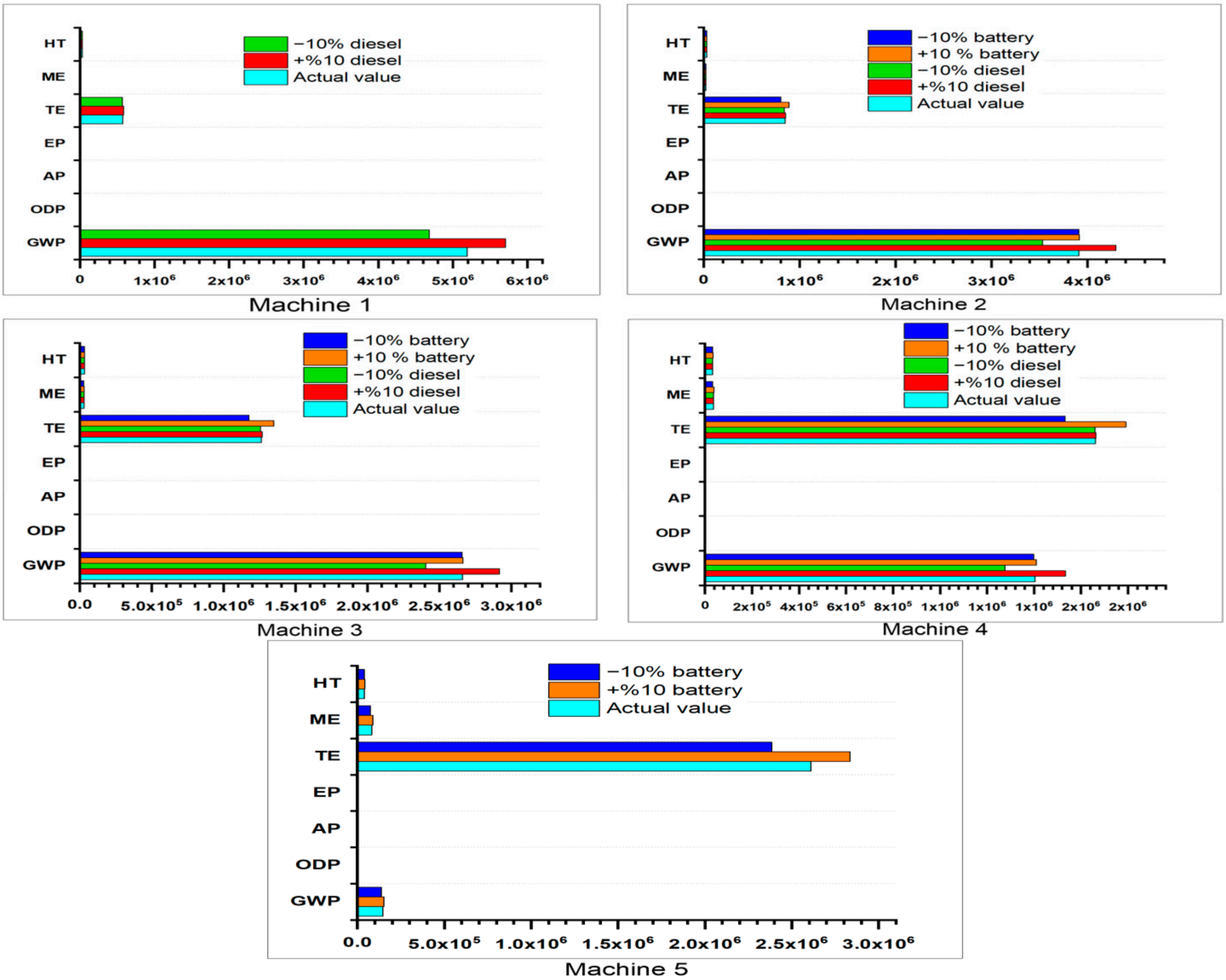

Figure 7. Sensitivity testing of system model to changes (±10%) variations in diesel and battery values.

Table 6. (±) Breakdown in % of impact categories changes to inputs.

Impact Category	Machine Type	Diesel (±10%)	Battery (±10%)
Global warming (GWP)	1	9.83	0
	2	9.78	0.04
	3	9.61	0.14
	4	9.1	0.40
	5	0	5.45
Stratospheric ozone depletion (ODP)	1	9.80	0
	2	9.51	0.30
	3	8.90	0.83
	4	2.74	0.48
	5	0	8.68
Terrestrial acidification (AP)	1	7.97	0
	2	7.19	0.82
	3	4	2.69
	4	3.5	3.59
	5	0	6.64

Table 6. *Cont.*

Impact Category	Machine Type	Diesel (±10%)	Battery (±10%)
Freshwater eutrophication (EP)	1	1.34	0
	2	0.85	3.42
	3	0.51	5.15
	4	0.17	6.29
	5	0	7.44
Terrestrial ecotoxicity (TE)	1	1.55	0
	2	0.77	5
	3	0.41	6.8
	4	0.13	7.75
	5	0	8.65
Marine ecotoxicity (ME)	1	0.6	0
	2	0.3	3.42
	3	0.2	5.12
	4	0.07	6.18
	5	0	8.39
Human carcinogenic toxicity (HT)	1	0.41	0
	2	0.34	0.71
	3	0.25	1.35
	4	0.10	1.92
	5	0	3.37

4. Discussion

Scenario 5 has the lowest impacts in GWP, ODP, and AP, given the decrease in using diesel. In contrast, scenario 5 demonstrates a higher influence than scenarios 2, 3, and 4 in categories such as EP, ME, HT, and TE due to the maximum battery capacity in these scenarios. For hybrid and fully electric scenarios, we assumed that the machine undergoes with a single battery replacement. Therefore, as we move from scenario 1 to scenario 5, the contribution of maintenance phase rises in almost all impact categories (Table 5), mainly because the battery production phase increases its contribution to most of these categories. Moreover, the sensitivity tests show that battery is one of the most sensitive parameters in transition from fossil fuel to electrification, as evident in Table 6 and Figure 7.

A battery unit has four primary parts: the cathode, anode, electrolyte, and separator. The most active elements for the cathode and anode in the lithium nickel cobalt manganese (NCM) battery are therefore lithium nickel manganese cobalt oxide and graphene [49]. Using a Ni:Mn:Co molar ratio of 2:2:1, the NCM cathode and a graphite anode makes up the current making of LIBs [50], which are most readily available in the market for energy storage industries. Nickel and cobalt sulfate, used as cathode compounds, contribute to photochemical ozone generation [51], which can damage humans and the environment. Polytetrafluoroethylene (PTFE) binder and aluminum current collectors in the cathode contribute to GWP, whereas the extraction and manufacture of nickel and cobalt salts drive AP and ODP impacts [49]. Due to a high energy need, the production of aluminum has a significant influence on the global warming potential [52]. The emissions also vary depending on the battery production site. Although our analysis assumes batteries are manufactured globally, the results could change if the batteries are produced in areas with a cleaner energy mix. While this study did not evaluate this aspect, it is certainly worthy of future research consideration.

The excavator must have enough capacity to be used for five to seven hours before it needs to be charged. Cold and hot climate conditions could influence battery efficiency. Power loss and aging could be reduced by providing adequate cooling and heating to the battery system [53]. The charging infrastructure could also induce equipment operation and lifecycle costs. Fast charging is crucial for heavy machinery due to limited battery capacity. However, battery system design and charging mechanism depend on the local operating environment [53]. Although battery technology is continually evolving, reliability, quality, specific energy consumption, and environmental pollution could decline. The current research mostly addresses bus charging stations due to increasing electrification. For the deployment of electric equipment in construction projects, it is important that the local government, energy providers and equipment manufacturers should work in close coordination to design charging infrastructure for electric gears. Future investigation should consider this element.

Diesel components can be refined in many ways for the environment. These include a deep hydro-treatment of straight run diesel, the esterification of fatty acids with alcohols, the catalytic cracking of vegetable oils, hydrotreating vegetable oils over a catalyst, and the usage of vegetable oils [7]. It is more logical to employ a selective analysis for producing better quality products, notably hydrotreating vegetable oils over a catalyst and trans-esterifying vegetable oils with alcohols [7,54]. Because of reducing oil reserves and poor oil refining (85%), the development of alternative fuel technologies is important in the EU. Currently, most of the on-road and off-road vehicles are relying on diesel engine since the technologies are not fully matured, even though the new cars are equipped with batteries. The drawback of conventional diesel engines is the harmful emissions, which are several times higher than the standard ones [7,54]. Therefore, biodiesel could be a better alternative to counter emission problems. The injection of biodiesel in conventional engines can reduce the number of harmful emissions [54]. Moreover, it was found that Ni–Cd batteries can be recycled more easily, even though the manufacturing process could require excessive energy. Two factors primarily determine how much the recycling step reduces the overall environmental damage [55]. The first is the direct emissions of the recycling technology itself throughout the process and the indirect impacts of the use of energy supplies, the second is the type and number of renewable products, which reflect their potential as raw materials to produce disposable batteries. The gap between the two factors determines recycling the environmental impact of technology. When the recycling process has a lower environmental impact than the raw materials used in production, the overall environmental impact decreases and vice versa [56]. As LiBs become more prevalent, the quantities of important chemical components deposited will be equal to the number of LiBs used after their lifespan has expired. Thus, recycling—the most environmentally friendly approach to handle these wastes—must be taken seriously to decrease environmental toxicity, boost revenue, reduce industrial dependency on imported or virgin materials, and preserve natural resources [38,57–60]. Recycling systems must reduce the number of waste or cases and precisely extract valuable components [61]. The methods could be employed on a small-scale, industrial, or commercial basis. Cobalt, lithium, manganese, and nickel, as recovered metals, or their corresponding compounds, are not only precious metals, but also alternative precursors for novel battery compositions. Laboratories and companies recycle all types of batteries using chemical and physical processes. Physical processes often include pyrolysis, manual or mechanical separation, and dissolution, for example, [57,62] extracting the electrolyte solution into organic solvents like ethanol or iso-butyl alcohol/water after manually or mechanically dismantling LiBs. This reduces environmental pollution caused by the hydrolysis of electrolyte salt, LiPF6, and the toxic electrolyte mixture. LiPF6 was creatively converted for the first time by the authors of [62] into a useful chemical like Li2SiF6. Wang and Yu [60] used LCA and discovered that recycling waste batteries can significantly minimize their environmental impact. Silvestri et al. [63] found that manufacturing electrodes had the greatest environmental impact due to the inclusion of rare earths in the negative electrode that require intensive mining. Quan et al. [64] employed LCA to evaluate and contrast the environmental implications of lithium iron phosphate (LFP) and lithium nickel cobalt manganese oxide (NCM) batteries and found that metal and material recovery can lower environmental burdens. Jiang et al. [65] found that material extraction, processing, and use phases dominated environmental performance. Particularly, Dewulf et al. [58] led to the conclusion that the use of recycled materials may reduce energy consumption by nearly 50 percent compared to the usage of virgin materials in production.

Similarly, for sustainable development, Feng et al. [66] discovered that battery recycling can reduce resource and environmental impact by 5–30%. Additionally, it was found that the processing of metals in the materials used to make power battery cathodes significantly contributes to resource and ecological concerns.

Currently, most of the research on the LCA of power batteries are based on the environmental impacts of the battery manufacturing. Only a small number of studies analyzed the environmental implications of the recycling process while others entirely disregard them. This is because power battery recycling technology is still under development, and it is difficult to achieve their statistics. Since the global demand for batteries is increasing along with electrification, which is raising environmental concerns regarding the use of resources and battery-related implications. The future research necessitates an effective disposal of power batteries to substantially reduce their environmental impacts over the course of their full life cycle.

5. Limitations

This research, although rigorous and detailed, is subject to a few limitations that may affect its practical applicability. Therefore, it is recommended that its outcomes be interpreted with due caution.

This study does not encompass certain components such as catalytic convertors, braking systems, or filters in Life Cycle Inventory (LCI) processes due to data scarcity. The specificity of data in LCI databases, rather than their general nature, could improve future research and render comparisons more insightful. Thus, future studies should strive to include these elements. The analysis considered non-biogenic diesel fuel usage and lithium-ion (Li-ion) battery usage. Alternatives such as biodiesel or natural gas can alter the outcomes in this study due to chemical compositions and environmental friendliness. Moreover, we employed default ecoinvent data for battery manufacturing and overlooked battery manufacturing emissions due to the absence of specific information. The energy mix plays a crucial role in various industrial processes, including electricity, heating, and transportation. For instance, in Norway, most energy consumption is fulfilled by renewable sources like hydropower [67]. In case of coal-fired power plants, several studies suggest that electric vehicles are less ecologically viable than fossil fueled ones [68]. Although noise and air pollutants could be significantly reduced locally via electrification, global CO_2 emission reduction will be determined by energy mix at various regions. The study considered pollutants as per the EMEP/EEA guidelines. Future research should incorporate a wider range of contaminants and an improved load factor. Real-world data should be used to a greater extent, and the emission factors presented in the EMEP/EEA handbook, which are based on steady-state engine dynamometer testing, need to be updated. The engine degradation model represented cumulative engine hours for all exhaust gases using a logistic distribution. Therefore, pollutant formation may differ by component. The estimated energy intensity and emission parameters per hourly fuel consumption may have led to an underestimation of cumulative emissions during operation. Thus, pragmatic energy intensity and emission variables, and engine degradation models must be considered. We assumed that all sulfur was converted to SO_2 during fuel combustion. This premise may be valid only in the absence of catalytic converters. However, all modern equipment are equipped with catalytic converters to perform desulfurization (DeSOx) and denitrogenating (DeNOx), reducing oxidized sulfur and nitrate. Fuel consumption depends on equipment usage and job environment. We counted only the productive lifespan of equipment, disregarding worksite specifications with the presumption of a medium operation condition. The machine would be recharged after seven hours of operation. Both charging infrastructure and battery system depends on local operating conditions. The battery capacities for electric and hybrid cases could also vary due to them. Therefore, the result would also alter due to the consideration of these parameters. Thus, future investigation necessitates a robust LCI.

6. Conclusions

Due to the extensive usage of heavy machinery in the construction sectors, the constructive activities produce greater rates of emissions. As climate concerns rise, addressing emission reduction is crucial to meet increasingly stringent emission controls. Although electrification and green energy alternatives are proposed, such approaches are at the early phases of development and are not yet prepared to be applied in construction. This study discloses substantial variation in environmental impact across differing levels of machinery electrification. The environmental consequences extend beyond merely global warming potential (GWP), and include impacts on ozone depletion potential (ODP), acidification potential (AP), terrestrial ecotoxicity (TE), human carcinogenic toxicity (HT), freshwater eutrophication (EP), and marine ecotoxicity (ME).

For GWP, ODP, and AP, diesel-powered machinery (scenario 1) records the most significant impacts, while hybrid and fully electric machinery (scenarios 2–5) demonstrate a considerable reduction in these environmental categories. This indicates that transitioning to electrified machinery can greatly alleviate global warming, ozone depletion, and acidification impacts associated primarily with the operation phase of machinery life.

However, in contrast, increasing electrification escalates environmental impacts in the categories of TE, HT, EP, and ME. This underscores that while electrification can alleviate some environmental loads, it introduces others, notably due to battery manufacturing and disposal processes. Hence, while the transition to electrified machinery is beneficial from a climate change perspective, it does introduce new environmental challenges that must be carefully managed.

Therefore, a transition toward more electrified machinery must consider these trade-offs. Future technological and research efforts should focus on improving the environmental profile of battery production and disposal. Similarly, policy makers should familiarize themselves and decisions should be based on these trade-offs when encouraging the electrification of construction machinery. Ultimately, the road toward sustainable construction practices must encompass a holistic consideration of environmental impacts across the lifecycle of machinery, not merely focusing on operational emissions.

Author Contributions: Conceptualization, A.U.K. and L.H.; methodology, A.U.K. and L.H.; data curation, A.U.K.; investigation, A.U.K.; software, A.U.K.; visualization, A.U.K.; validation, A.U.K. and L.H.; writing—original draft preparation, A.U.K.; supervision, L.H.; writing—reviewing and editing, A.U.K. and L.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Norwegian University of Science and Technology, Project No. 81148050.

Data Availability Statement: The dataset used in this analysis can be provided upon request from the corresponding author. Due to confidentiality agreement the data cannot be made publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sizirici, B.; Fseha, Y.; Cho, C.-S.; Yildiz, I.; Byon, Y.-J. A review of carbon footprint reduction in construction industry, from design to operation. *Materials* **2021**, *14*, 6094. [CrossRef] [PubMed]
2. Barati, K.; Shen, X. Modelling Traffic Conditions on Fuel Use and Emissions of On-Road Construction Equipment. In Proceedings of the ISARC International Symposium on Automation and Robotics in Construction, Banff, AL, Canada, 21–24 May 2019. Available online: https://www.proquest.com/docview/2268537821?pq-origsite=gscholar&fromopenview=true (accessed on 25 March 2023).
3. Barati, K.; Shen, X. Comprehensive methodology for emission modelling of earthmoving equipment. In Proceedings of the 33rd International Symposium on Automation and Robotics in Construction and Mining (ISARC 2016), Auburn, AL, USA, 18–21 July 2016.
4. Kaboli, A.S.; Carmichael, D.G. Emission and cost configurations in earthmoving operations. *Organ. Technol. Manag. Constr. Int. J.* **2012**, *4*, 393–402. [CrossRef]
5. Lewis, P.; Rasdorf, W. Fuel use and pollutant emissions taxonomy for heavy duty diesel construction equipment. *J. Manag. Eng.* **2017**, *33*, 4016038. [CrossRef]

6. Aragones, M.; Serafimova, T. Zero Emission Construction Sites: The Possibilities and Barriers of Electric Construction Machinery. Bellona Europe. 2018. Available online: https://bellona.org/publication/zero-emission-construction-sites-the-possibilities-and-barriers-of-electric-construction-machinery (accessed on 16 April 2023).
7. Eremeeva, A.M.; Kondrasheva, N.K.; Khasanov, A.F.; Oleynik, I.L. Environmentally Friendly Diesel Fuel Obtained from Vegetable Raw Materials and Hydrocarbon Crude. *Energies* **2023**, *16*, 2121. [CrossRef]
8. Hajjari, M.; Tabatabaei, M.; Aghbashlo, M.; Ghanavati, H. A review on the prospects of sustainable biodiesel production: A global scenario with an emphasis on waste-oil biodiesel utilization. *Renew. Sustain. Energy Rev.* **2017**, *72*, 445–464.
9. Petrova, T.A.; Rudzisha, E.; Alekseenko, A.V.; Bech, J.; Pashkevich, M.A. Rehabilitation of disturbed lands with industrial wastewater sludge. *Minerals* **2022**, *12*, 376. [CrossRef]
10. Eremeeva, A.; Ilyashenko, I.; Korshunov, G. The Possibility of Application of Bioadditives to Diesel Fuel at Mining Enterprises. *Personalii. Spmi. Ru.* **2022**. Available online: http://personalii.spmi.ru/ru/details/36105 (accessed on 25 January 2023). [CrossRef]
11. Aghbashlo, M.; Tabatabaei, M.; Khalife, E.; Shojaei, T.R.; Dadak, A. Exergoeconomic analysis of a DI diesel engine fueled with diesel/biodiesel (B5) emulsions containing aqueous nano cerium oxide. *Energy* **2018**, *149*, 967–978. [CrossRef]
12. Du, J.; Sun, W.; Guo, L.; Xiao, S.; Tan, M.; Li, G.; Fan, L. Experimental study on fuel economies and emissions of direct-injection premixed combustion engine fueled with gasoline/diesel blends. *Energy Convers. Manag.* **2015**, *100*, 300–309. [CrossRef]
13. Joshi, S.; Dahodwala, M.; Koehler, E.W.; Franke, M.; Tomazic, D.; Naber, J. *Trade-Off Analysis and Systematic Optimization of a Heavy-Duty Diesel Hybrid Powertrain*; SAE Technical Paper; SAE Intenational: Warrendale, PA, USA, 2020. [CrossRef]
14. Chen, J.; Li, Y.; Meng, Z.; Feng, X.; Wang, J.; Zhou, H.; Li, J.; Shi, J.; Chen, Q.; Shi, H. Study on Emission Characteristics and Emission Reduction Effect for Construction Machinery under Actual Operating Conditions Using a Portable Emission Measurement System (Pems). *Int. J. Environ. Res. Public Health* **2022**, *19*, 9546. [CrossRef]
15. Koch, C.; Kifokeris, D. Heavy-duty construction equipment: Dinosaurs of black energy? *Management* **2021**, *694*, 703.
16. Komatsu Ltd. Developed an Electric Battery Driven Excavator. 2019. Available online: https://home.komatsu/en/press/2019/technology/1202112_1836.html (accessed on 15 January 2023).
17. Leonida, C. Metso Makes Waves at bauma 2019. *Eng. Min. J.* **2019**, *220*, 40–43.
18. Nevrly, J.; Fichta, M.; Jurik, M.; Nemec, Z.; Koutny, D.; Vorel, P.; Prochazka, P. Battery electric drive of excavator designed with support of computer modeling and simulation. *Proceedings* **2020**, *58*, 25. [CrossRef]
19. Casoli, I.P.; Riccò, L.; Campanini, F.; Lettini, A.; Dolcin, C. Hydraulic Hybrid Excavator: Layout Definition, Experimental Activity, Mathematical Model Validation and Fuel Consumption Evaluation. 2016. Available online: https://core.ac.uk/download/pdf/236373206.pdf (accessed on 28 February 2023).
20. Vauhkonen, N.; Liljeström, J.; Maharjan, D.; Mahat, C.; Sainio, P.; Kiviluoma, P.; Kuosmanen, P. Electrification of Excavator. In Proceedings of the 9th International DAAAM Baltic Conference "Industrial Engineering", Tallinn, Estonia, 24–26 April 2014. Available online: https://www.researchgate.net/publication/287088407_Electrification_of_excavator (accessed on 21 January 2023).
21. Zhang, D.; Gong, J.; Zhao, Y.; Liu, C.; Hu, P.; Tang, Z. Research on a new energy-recovery system for hybrid hydraulic excavators. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *300*, 42003. [CrossRef]
22. Yu, Y.; Do, T.C.; Yin, B.; Ahn, K.K. Improvement of energy saving for hybrid hydraulic excavator with novel powertrain. *Int. J. Precis. Eng. Manuf. Green Technol.* **2023**, *10*, 521–534. [CrossRef]
23. Finkbeiner, M.; Inaba, A.; Tan, R.; Christiansen, K.; Klüppel, H.-J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **2006**, *11*, 80–85. [CrossRef]
24. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
25. Naseem, R.J. *Electrification of the Hydraulic Control System of Off-Road Vehicles*; Politecnico di Torino: Torino, Italy, 2022. Available online: https://webthesis.biblio.polito.it/24703/ (accessed on 5 May 2023).
26. Volvo Maskin, A.S. Volvo Construction Equipment's Product Range- Quality and Productivity. 2023. Available online: https://www.volvoce.com/norge/nb-no/volvo-maskin-as/ (accessed on 24 February 2023).
27. Ramkumar, M.S.; Reddy, C.; Ramakrishnan, A.; Raja, K.; Pushpa, S.; Jose, S.; Jayakumar, M. Review on Li-Ion Battery with Battery Management System in Electrical Vehicle. *Adv. Mater. Sci. Eng.* **2022**, *2022*, 3379574. [CrossRef]
28. Bellona. Bellona Welcomes EU Battery Strategy but Concrete Actions Must Follow. Available online: https://bellona.org/news/transport/electric-vehicles/2018-05-bellona-welcomes-eu-battery-strategy-but-concrete-actions-must-follow (accessed on 27 January 2023).
29. European Monitoring and Evaluation Programme (EMEP). *EEA Air Pollutant Emission Inventory Guidebook. Technical Guidance to Prepare National Emission Inventories*; EEA Report; Publications Office of the European Union: Luxembourg, 2019.
30. EMEP Centre on Emission Inventories and Projections (E.C.o.E.I.a). Data Viewer–Reported Emissions Data. 2020. Available online: https://www.ceip.at/data-viewer (accessed on 3 March 2023).
31. Ebrahimi, B.; Wallbaum, H.; Jakobsen, P.D.; Booto, G.K. Regionalized environmental impacts of construction machinery. *Int. J. Life Cycle Assess.* **2020**, *25*, 1472–1485. [CrossRef]
32. European Monitoring and Evaluation Programme (EMEP). EEA Air Pollutant Emission Inventory Guidebook 2016. In *Technical Guidance to Prepare National Emission Inventories*; EEA Report; European Environment Agency: Copenhagen, Denmark, 2016. Available online: https://www.gtkp.com/knowledge/emep-eea-air-pollutant-emission-inventory-guidebook-2016 (accessed on 5 February 2023).

33. Nielsen, O.-K. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2013. Technical Guidance to Prepare National Emission Inventories. 2013. Available online: https://www.osti.gov/etdeweb/biblio/22128042 (accessed on 12 April 2023).
34. Lindgren, M. A Methodology for Estimating Annual Fuel Consumption and Emissions from Non-Road Mobile Machinery. 2007. Available online: https://pub.epsilon.slu.se/3791/ (accessed on 25 May 2023).
35. Bouwen, P. *Lobbying the European Union: Institutions, Actors, and Issues*; The European Commission: Brussels, Belgium, 2009; pp. 1–38. Available online: https://lobbyists.ru/eu1/lobbyingeu.pdf#page=36 (accessed on 19 March 2023).
36. Bellona. Database: Emission-Free Construction Equipment by Manufacturer. 2023. Available online: https://bellona.org/database-emission-free-construction-equipment-by-manufacturer (accessed on 1 February 2023).
37. Relion Battery. Lithium Iron Phosphate Battery. Available online: https://ceb8596f236225acd007-8e95328c173a04ed694af83ee4e24c15.ssl.cf5.rackcdn.com/docs/product/Relion-Data-Sheet-RB200-noRU.pdf (accessed on 24 February 2023).
38. Higashimoto, K.; Homma, H.; Uemura, Y.; Kawai, H.; Saibara, S.; Hironaka, K. Automotive lithium-ion batteries. *Hitachi Rev.* **2011**, *60*, 17–21.
39. Arshad, F.; Lin, J.; Manurkar, N.; Fan, E.; Ahmad, A.; Tariq, M.-u.-N.; Wu, F.; Chen, R.; Li, L. Life Cycle Assessment of Lithium-ion Batteries: A Critical Review. *Resour. Conserv. Recycl.* **2022**, *180*, 106164. [CrossRef]
40. Lajunen, A.; Sainio, P.; Laurila, L.; Pippuri-Mäkeläinen, J.; Tammi, K. Overview of powertrain electrification and future scenarios for non-road mobile machinery. *Energies* **2018**, *11*, 1184. [CrossRef]
41. Nie, Y.; Wang, Y.; Li, L.; Liao, H. Literature Review on Power Battery Echelon Reuse and Recycling from a Circular Economy Perspective. *Int. J. Environ. Res. Public Health* **2023**, *20*, 4346. [CrossRef] [PubMed]
42. Vandepaer, L.; Cloutier, J.; Amor, B. Environmental impacts of Lithium Metal Polymer and Lithium-ion stationary batteries. *Renew. Sustain. Energy Rev.* **2017**, *78*, 46–60. [CrossRef]
43. Kang, D.H.P.; Chen, M.; Ogunseitan, O.A. Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste. *Environ. Sci. Technol.* **2013**, *47*, 5495–5503. [CrossRef] [PubMed]
44. Chen, Z.S.; Lam, J.S.L. Life cycle assessment of diesel and hydrogen power systems in tugboats. *Transp. Res. Part D Transp. Environ.* **2022**, *103*, 103192. [CrossRef]
45. Lavigne Philippot, M.; Costa, D.; Cardellini, G.; De Sutter, L.; Smekens, J.; Van Mierlo, J.; Messagie, M. Life cycle assessment of a lithium-ion battery with a silicon anode for electric vehicles. *J. Energy Storage* **2023**, *60*, 106635. [CrossRef]
46. Maslennikova, A.; Udachin, V.; Deryagin, V.; Artemyev, D.; Filippova, K.; Gulakov, V.; Udachin, N.; Aminov, P. Sediment records of lake eutrophication and oligotrophication under the influence of human activity and climate warming in the Urals metallurgical region (Russia). *Hydrobiologia* **2023**, *850*, 1669–1698. [CrossRef]
47. Dean, S.; Akhtar, M.S.; Ditta, A.; Valipour, M.; Aslam, S. Microcosm Study on the Potential of Aquatic Macrophytes for Phytoremediation of Phosphorus-Induced Eutrophication. *Sustainability* **2022**, *14*, 16415. [CrossRef]
48. Vidhi, R.; Shrivastava, P. A review of electric vehicle lifecycle emissions and policy recommendations to increase EV penetration in India. *Energies* **2018**, *11*, 483. [CrossRef]
49. Tsai, W.-S.; Huang, C.; Huang, C.-C.; Yang, C.-C.; Lee, M. Environmental trade-offs and externalities of electrochemical-based batteries: Quantitative analysis between lithium-ion and vanadium redox flow units. *J. Environ. Manag.* **2023**, *326*, 116807. [CrossRef]
50. Steen, M.; Lebedeva, N.; Di Persio, F.; Boon-Brett, L. *EU Competitiveness in Advanced Li-Ion Batteries for E-Mobility and Stationary Storage Applications–Opportunities and Actions*; Publications Office of the European Union: Luxembourg, 2017; Volume 44. Available online: https://core.ac.uk/download/pdf/132627095.pdf (accessed on 20 January 2023).
51. Peters, J.F.; Weil, M. Providing a common base for life cycle assessments of Li-Ion batteries. *J. Clean. Prod.* **2018**, *171*, 704–713. [CrossRef]
52. Nunez, P.; Jones, S. Cradle to gate: Life cycle impact of primary aluminium production. *Int. J. Life Cycle Assess.* **2016**, *21*, 1594–1604. [CrossRef]
53. Lajunen, A. Lifecycle costs and charging requirements of electric buses with different charging methods. *J. Clean. Prod.* **2018**, *172*, 56–67. [CrossRef]
54. Kondrasheva, N.K.; Eremeeva, A.M. Production of Biodiesel Fuel from Vegetable Raw Materials. *J. Min. Inst.* **2023**, *260*, 248–256. [CrossRef]
55. Tao, Y.; Wang, Z.; Wu, B.; Tang, Y.; Evans, S. Environmental life cycle assessment of recycling technologies for ternary lithium-ion batteries. *J. Clean. Prod.* **2023**, *389*, 136008. [CrossRef]
56. Peters, J.F.; Baumann, M.; Zimmermann, B.; Braun, J.; Weil, M. The environmental impact of Li-Ion batteries and the role of key parameters—A review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 491–506. [CrossRef]
57. Contestabile, M.; Panero, S.; Scrosati, B. A laboratory-scale lithium battery recycling process. *J. Power Sources* **1999**, *83*, 75–78. [CrossRef]
58. Dewulf, J.; Van der Vorst, G.; Denturck, K.; Van Langenhove, H.; Ghyoot, W.; Tytgat, J.; Vandeputte, K. Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings. *Resour. Conserv. Recycl.* **2010**, *54*, 229–234. [CrossRef]
59. Mohammadi, F.; Saif, M. A comprehensive overview of electric vehicle batteries market. *e-Prime Adv. Electr. Eng. Electron. Energy* **2023**, *3*, 100127. [CrossRef]
60. Wang, S.; Yu, J. A comparative life cycle assessment on lithium-ion battery: Case study on electric vehicle battery in China considering battery evolution. *Waste Manag. Res.* **2021**, *39*, 156–164. [CrossRef]

61. Xu, J.; Thomas, H.R.; Francis, R.W.; Lum, K.R.; Wang, J.; Liang, B. A review of processes and technologies for the recycling of lithium-ion secondary batteries. *J. Power Sources* **2008**, *177*, 512–527. [CrossRef]
62. Bankole, O.E.; Gong, C.; Lei, L. Battery recycling technologies: Recycling waste lithium ion batteries with the impact on the environment in-view. *J. Environ. Ecol.* **2013**, *10*, 14–28. [CrossRef]
63. Silvestri, L.; Forcina, A.; Arcese, G.; Bella, G. Recycling technologies of nickel–metal hydride batteries: An LCA based analysis. *J. Clean. Prod.* **2020**, *273*, 123083. [CrossRef]
64. Quan, J.; Zhao, S.; Song, D.; Wang, T.; He, W.; Li, G. Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies. *Sci. Total Environ.* **2022**, *819*, 153105. [CrossRef] [PubMed]
65. Jiang, S.; Hua, H.; Zhang, L.; Liu, X.; Wu, H.; Yuan, Z. Environmental impacts of hydrometallurgical recycling and reusing for manufacturing of lithium-ion traction batteries in China. *Sci. Total Environ.* **2022**, *811*, 152224. [CrossRef]
66. Feng, T.; Guo, W.; Li, Q.; Meng, Z.; Liang, W. Life cycle assessment of lithium nickel cobalt manganese oxide batteries and lithium iron phosphate batteries for electric vehicles in China. *J. Energy Storage* **2022**, *52*, 104767. [CrossRef]
67. Larsen, M.L.; Dupuy, K. Greening industry: Opportunities and challenges in electricity access for Norwegian industry firms. *J. Clean. Prod.* **2023**, *396*, 136534. [CrossRef]
68. Romejko, K.; Nakano, M. Life cycle analysis of emissions from electric and gasoline vehicles in different regions. *Int. J. Autom. Technol.* **2017**, *11*, 572–582. [CrossRef]