Master's thesis

NTNU
Norwegian University of Science and Technology
Department of Energy and Process Engineering

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An environmental assessment of the electrification of construction machinery

Master's thesis in Energi og Miljø
Supervisor: Edgar Hertwich
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1 Sammendrag

En rask overgang til mindre utslippsintensive teknologier er nødvendig for å dempe effektene av klimaendringer. Byggeaktiviteter er en betydelig kilde til utslipp over hele verden, og en stor bidragsyter til dette er den direkte og indirekte miljøpåvirkningen fra anleggsmaskiner. Miljøpåvirkningen av elektrifiseringen av to av de vanligste anleggsmaskinene, hjullastere og gravemaskiner, utforskes som et alternativ for å begrense miljøpåvirkningen.

En sammenlignende livssyklusvurdering gjøres ved hjelp av maskindata fra produsenter, en modell for produktivitet, data for eksos utslipp og modeller for indirekte utslipp ved produksjon, vedlikehold og bruk av maskinene. Miljøpåvirkningen av anleggsmaskinenes levetid finner man ved å bruke disse modellene. Gitt den betydelige forskjellen, brukes både norske og europeiske karbonintensiteter for konsekvensberegning av elektrisitet.

I de fleste tilfeller finner man en betydelig reduksjon i miljøbelastningen ved å ta i bruk elektriske anleggsmaskiner. Norge er spesielt egnet for denne transisjonen på grunn av tilgjengelig lavkarbonelektrisitet. Det viser seg at en elektrisk gravemaskin i Norge i gjennomsnitt har 76% mindre påvirkning på klimaet enn en dieselgraver. I Europa er elektrisitet relativt karbonintensiv, og de potensielle gevinstene for miljøpåvirkningen er betraktelig redusert, så mye at tilpasning av høyere konsentrasjonsblandinger av biodiesel kan helt slette den. Selv om LCA fant at miljøpåvirkningen fra produksjon var høyere for elektriske maskiner, var bidraget fra batterier markant mindre enn forventet. Basert på resultatene konkluderes det med at ytterligere tilpasning av elektriske anleggsmaskiner er fordelaktig på grunn av forbedringen i deres miljøytelse.

2 Abstract

A rapid transition to less emission-intensive technologies is needed to mitigate the effects of climate change. Construction activities are a significant source of emissions worldwide, and a major contributor to this is the direct and indirect environmental impact of construction machines. The environmental impact of the electrification of two of the most common construction machines, wheel loaders and excavators, is explored as an option to limit the environmental impact.

A comparative life cycle assessment is done using machine data from manufacturers, a model for productivity, tailpipe emissions data, and models for imbued emissions in the manufacturing, maintenance, and use of the machines. The environmental impact of the construction machines' life is found by using these models. Given the considerable difference, both Norwegian and European carbon intensities are used for the impact calculation of electricity.

In most cases, a significant reduction in the environmental impact is found for adopting electric construction machines. Norway is especially suitable for this transition because of the low-carbon electricity. It is found that, on average, an electric excavator in Norway has 76% less impact on the climate than a diesel excavator. In Europe, electricity is relatively carbon-intensive, and the potential gains to the environmental impact are considerably lessened, so much that adapting higher concentration blends of biodiesel might completely negate it. Although the LCA found that the environmental impact from manufacturing was higher for electric vehicles, the contribution of batteries was markedly less than expected. Based on the results, it is concluded that further adaptation of electric construction machinery is advantageous due to the improvement in their environmental performance.

3 Background

The thesis aims to conduct a comparative life cycle analysis of Electric construction machinery by quantifying the environmental impact from the manufacturing and operation of an electric excavator and comparing the difference in impact based on the scale of the machinery. The thesis will also consider a scenario for introducing construction machinery to a specific project or company. Finally, the thesis aims to consider the effect of variations in the pattern of use in different situations and conditions.

Table of Contents

List of Figures

List of Tables

4 Introduction

Global warming and environmental pollution are becoming increasingly pressing by the minute. Emissions-reducing actions need to be urgently executed globally to limit the impact on the world. Construction is an essential part of modern human society, providing shelter, mobility, and electricity. However, it is also a significant contributor to the ever climate crisis since construction is highly greenhouse gas emitting approximately 23% of the total global emissions(Huang et al., 2018).

Internationally the big climate conferences have set goals for emissions cuts which requires the commitment of the industry (Paris Agreement, 2015,Masson-Delmotte et al., 2021). In order to reach goals set by internatinally agreed targets if limiting the global rise in temperature, drastic measures are necessary.

In Norway, the procurement act §7-9 specifies minimizing the environmental burden of construction projects. Climate cure 2030 specifies goals of 70% new electric construction machinery by 2030(Miljødirektoratet, 2019). Also, international emissions standards are becoming stricter(EPA, 2010, EMEP/EEA, 2019). This regulation makes it so that the construction industry needs to adjust to satisfy the standards. As the

Excavators and loaders make up a significant part of the construction machinery used by the construction industry, contributing significantly to the overall carbon footprint through their lifecycle due to their low energy efficiency and limited emissions filtering. (Wiik et al., 2020,Wang et al., 2009)

4.1 Research question and objectives

The research question is: IS there a potential for decreasing the current environmental impact of construction machines through electrification?

To figure this out an life cycle assessment is completed to find the environmental impact of moving one loose cubic meter of material with a diesel-driven and electric, excavator or wheel loader. This thesis focuses on the impact of Global warming potential but other impact categories are also considered

4.2 scope

The model in this thesis focuses on estimating the environmental impact of the manufacturing and use of excavators and wheel loaders. This thesis does not consider sources of emissions outside the extraction and refinement of raw resources, manufacturing of the equipment, production of the fuel, and the emissions of combustion of diesel during usage, as well as other use related emissions. Not included are En-of-life, and other administrative impacts in sales and marketing, design and development, and other support roles in the infrastructure surrounding the different sources of emissions. This model does not account for direct impacts other than emissions, so sound, vibrations, and dust generated by the machine operation is not accounted for.

4.3 outline

This article will begin by introducing the method used in calculating the impacts for this study. In the methods part the productivity of a construction machine as well as the method for calculating the emissions from the use phase will be presented, as well as the impacts from manufacturing. Results are then calculated and shown in graphs. The results mainly focus on the productivity, emissions from the production of fuels, the tailpipe emissions, manufacturing and maintenance. Then it is all added together into the total emissions over the construction machines lifetime, and presented in the functional unit of impact per Lm3. The results are the discussed, a construction scenario is considered, as well as a scenario for biodiesel. Lastly the conclusion completes the thesis.

5 Method

A model for the various emissions and environmental impacts over the excavator's lifetime caused by their manufacturing and use is developed to reach the goals of this thesis. This model considers many factors, including machine type, weight, engine power, working conditions, working efficiency, bucket size, engine deterioration, load factor, cycle time, and lifetime.

The components considered here are what is presented in the Volvo CE environmental product declarations for excavators and wheel loaders(Volvo CE, 2019). In addition, less tangible aspects of the manufacturing, such as the energy required. Some parts of the manufacturing might not be taken into account. However, it is considered that the aspects of manufacturing presented here represent the majority of the impact during manufacturing.

After separately calculating the significant emissions sources over the construction machines' lifetime, those being manufacturing, fuel production, tailpipe emissions, and maintenance. These emissions are added together to calculate the total lifetime emissions. The result is divided by the productivity to get the productivity-dependent emissions of excavating 1 Lm^3.

5.1 LCA

The LCA is performed by using characterization and emissions data from SimaPro, while assuming a Hierarchist weighing to take into account the most common principles in terms of time-frame and other issues. The Cut-off method in regards to recycling is chosen as it does not include any process beyond the product lifecycle. This is done due to ont including End-of-life due to lacking data. The LCA considers the extraction and refinement of materials, the manufacturing of the construction machines, and the use phase. This is thus not a full lifecycle perspective since it does not include end-of-life. The functional unit is the environmental impact of moving one Lm3 of material. The final impact is thus expressed as the lifecycle impact of excavating 1 Lm3.

5.2 Use phase model

The use phase consists of tailpipe emissions, maintenance, and fuel production. both electric and diesel electric has no tailpipe emissions both European and Norwegian electricity considered

5.2.1 Productivity

Productivity gives perspective to the emission values. Productivity is here defined in the context of earthmoving and is the amount of material moved from one place to another. There is a distinction between actual, normal, and maximum productivity. Maximum productivity is achieved when there are no delays or waiting time and is a measure of ideal productivity. Normal productivity considers some but not all delays. In comparison, actual productivity includes all waits and delays. Here the actual productivity is calculated.

It should be noted that the productivity calculation only considers the time the construction machine is operating. Inside the frame of an 8-hour working day, including all delays that hinder productivity, the lifetime considers only operating hours.

Here productivity is measured as the hourly rate at which material is moved and is often expressed in units of loose cubic meters of material moved per hour. The productivity dramatically varies from machine to machine. Volumetric measurement is the typical way to quantify earthmoving operations as opposed to using the weight of the material. This norm is caused by how the density of the material would then need to be considered. The density varies with the material excavated and is thus an unnecessary source of error.

The unit loose cubic meters is a unit volumetric unit describing the volume of excavated materials. The volume of the material changes compared to its volume before it was disturbed. Usually, disturbance leads to an increase in volume, called swell. Note that this implies that the volume moved is not the same as the volume removed from the site. Loose cubic meters are used here and measure the volume of the disturbed material, as opposed to bank cubic meters, which measure volume before any disturbance to the material, when it is in its natural ground condition. A swell factor is used to convert from bank cubic meters to loose cubic meters or the opposite. The swell factor measures the percentage increase in the volume of an excavated mass. Some examples of typical values for the swell factor sf are 25% for wet soil, 13% for gravel, 25% for sandy clay, and 65% for rocks (Sağlam and Bettemir, 2018, Caterpillar, 2014, Komatsu, 2009). When considering only the productivity of the construction machine, the productivity is expressed in loose cubic meters. When an actual project is considered, the bank volume must be used. Loose cubic meters are therefore used here. A formula is used to convert the volume from loose cubic meters (Lm^3) to bank cubic meters (Bm^3):

$$Bm^3 = \frac{Lm^3}{1 + \%swell}$$

There are many methods of calculating the productivity of construction machinery (Caterpillar, 2014, Komatsu, 2009, Edwards et al., 2001, Edwards and Holt, 2000, Hajji and Lewis, 2017, Hajji and Lewis, 2013, Alkatiri et al., 2020). Some rely on multi-linear regression, while others, including CAT (2014) and Komatsu (2009), rely on formulas connected to the physical operation of the construction machines. The multi-linear regression approach is avoided here.

For most earthmoving and material handling applications, methods for calculating the production follow the same template by multiplying the average payload per cycle by the number of cycles per hour, usually with only slight variations. The common elements of these methods are the cycle time, which can be given in various units, be it in cycles per hour, cycles per minute, minutes per cycle, or seconds per cycle. This unit is usually converted to cycles per hour. The bucket capacity is usually in heaped volume in either loose or banked volume units. A bucket fill factor and job efficiency factor are usually included. Some choose to calculate the total production or include coefficients for factors such as swing, depth, travel, maneuvering, or ground conditions. For this thesis, a function similar to these is used:

$$P = \frac{3600 \cdot B_A \cdot E}{C}$$

Here the productivity P is measured in Lm^3/h, the average payload B_A is measured in Lm^3, the work efficiency factor E is unit less, and the cycle time C is measured in s. However, it is converted to cycles per hour by dividing 3600 by the cycle time. It should be noted that the productivity of earthmoving is calculated under specific conditions, and it varies a lot based on the activity and conditions (Manyele, 2017). For example, a significant source of variability that is not accounted for here is the distance the construction machine needs to move each cycle. Also, the productivity is calculated based on the excavation of soil types which does not require drilling or the use of special equipment for the excavation.

Ground conditions are often used to indicate how easy or difficult it is to operate in a particular area and its accompanying circumstances. Often ground conditions might consider factors such as the digging depth, swing angle, dumping conditions, loading conditions, soil type, operator skill, weather, environment, and any potential obstructions. Generally, the data will be applicable for average ground conditions, and it will be considered if poor or good conditions affect the parameter.(Caterpillar, 2014, NRAAC, 2010)

Any good estimator should hold up against comparing it with real-world data. However, this is not very easy to do accurately, considering all the factors that might contribute to differences. This challenge is inflated by the unwillingness of manufacturers to release data about their earthmoving machinery and the contractors' reluctance to share information on their operations(Edwards et al., 2001). This challenge will be further explored in the discussion. Further factors affecting the productivity will be presented in the parts which they affect in the parts on cycle time, average payload, and work efficiency.

Cycle time The cycle time is one of the significant factors determining the productivity of a construction machine, to maximize the construction machine performance the cycle time needs to be minimized. It is of great importance to the user as even saving 2 seconds amounts to saving about 20 minutes a day (Fiscor, 2007), increasing productivity, while saving money and the climate through less fuel use and emissions. A shorter cycle time generally raises productivity if all else is kept constant. For a hydraulic excavator, the cycle time can be defined as the time it takes for the excavator to fill the bucket, turn and raise the bucket from the loading position to the unloading position, unload the material in the bucket, and turn and lower the bucket from the unloading position to the loading position (Alkatiri et al., 2020).

For a wheel loader, the same idea is applied, where the cycle time is generally seen as the time the wheel loader uses to fill its bucket, move, unload, and move back. However, there is some difference in its operation as there are two commonly used methods to load using a wheel loader. The V-shape loading method involves reversing back from the pile before swinging and driving to the intended drop-off site before doing the inverse to get back to the pile. While the Cross loading method involves that the Wheel loader reverses from the pile before a truck drives in front of it, is loaded, then drives away, and the loader then drives forwards to the pile again. While the cross-loading method is arguably faster when efficiently performed, it is also more complex, has a higher precision requirement, and needs a truck to load. It is assumed that v-shape loading is primarily utilized in this thesis (Komatsu, 2009).

There are many estimators for cycle time (Komatsu, 2009, Litvin and Litvin, 2020, Edwards et al., 2001,Edwards and Holt, 2000, Sağlam and Bettemir, 2018, Alkatiri et al., 2020,Panagiotou and Michalakopoulos, 2000). To decide which is best suited for this application, they are compared against each other and tested against cycle time data (Caterpillar, 2014, Fiscor, 2007, Manyele, 2017). By comparing the methods, it is found that the data and method used by Komatsu give the best result for both crawler excavators and wheel loaders.Komatsu presents standard cycle times based on their testing and experience. With certain variables to account for differences due to certain operational conditions, such as the machine weight and swing angle, Komatsu employs a conversion factor that is multiplied by the standard cycle times to incorporate digging depth and dumping conditions.

This model relies on typical values for certain thresholds of values instead of formulas. This approach makes the model easier to apply, while it sacrifices some accuracy and granularity. The cycle time calculation can be done with higher accuracy by taking into account more factors (Litvin and Litvin, 2020), but for this thesis, this data is good enough. This method is chosen for its accuracy compared to other methods, such as the often used multi-linear regression. It has greater flexibility regarding the factors and range of machines covered than the CAT data set. While also being significantly less complicated and thus more applicable than the formulas used by Litvin and Litvin (2020), which are bogged down by complexity. An advantage of this approach is that it can incorporate factors without explicitly mentioning them using standard values, given that the gain in precision from these variables is unnecessary and outside the scope of this thesis. Some of the variables included are also unnecessary, so the model is simplified with found typical values.

Standard conditions are assumed for the various variable work conditions. Based on typical values used by the various sources, the standard swing angle is set to its average value of between 60 and 120 degrees, The average value of the digging depth is assumed to be between 40 and 75% of the excavators maximum digging depth, and dumping conditions are assumed to be normal. These values give a conversion factor of 1. This conversion factor makes the standard cycle times equal to the actual cycle times. (Panagiotou and Michalakopoulos, 2000, Sağlam and Bettemir, 2018, Caterpillar, 2014, Edwards et al., 2001,NRAAC, 2010) The cycle time is now only dependent on machine weight. By using a logarithmic regression a good fit for the excavator data is found with the formula:

$$C = 4.158 \cdot ln(W) - 25.058$$

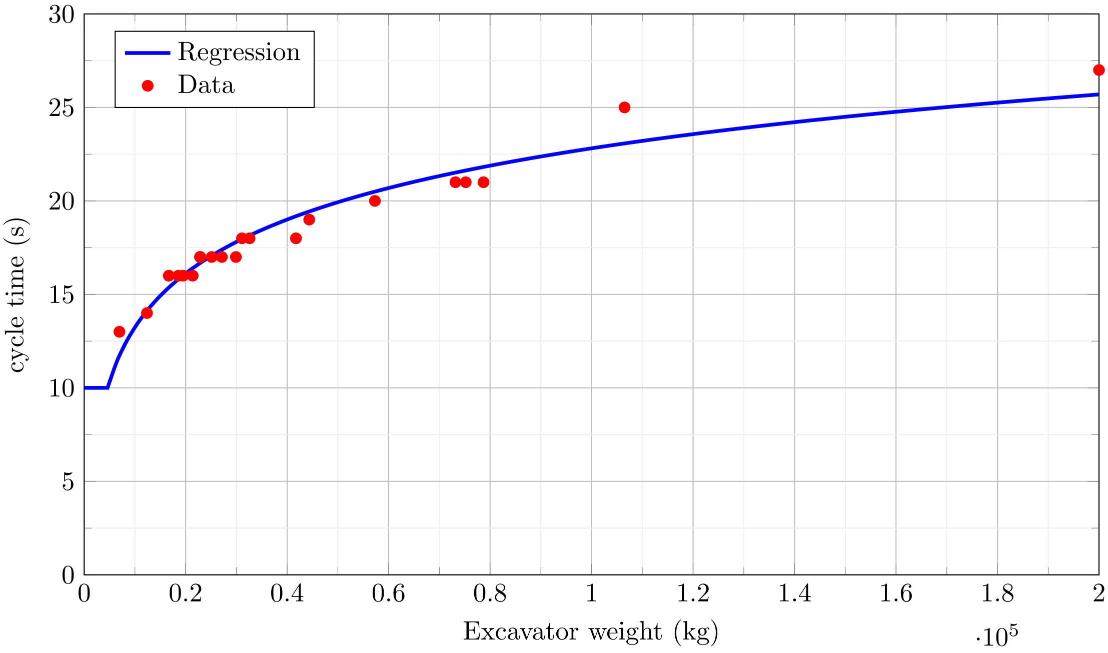
Where C is the cycle time in seconds and W is the machine weight in kg, the plot is shown in fig 1. For machines lighter than 4500 kg the cycle time is kept constant at 10 seconds to avoid too low values. This formula has a good fit of:

$$R^2 = 0,9468$$

For wheel loaders the cycle time is less variable(Caterpillar, 2014, Komatsu, 2009). By assuming average digging conditions the cycle time can be expressed by the wheel loaders bucket size (**B**) as:

$$C = \begin{cases} 33 & \text{if } B < 3m^3 \\ 39 & \text{if } 3 < B < 5.1m^3 \\ 42 & \text{if } B > 5.1m^3 \end{cases}$$

Figure 1: plot of the excavator cycle time data and its fittest regression



The variables taken into account by Komatsu's model are the most significant factors impacting the cycle time of the excavator. For an excavator, the empty swing time is 25%, full swing time is 24%, bucket filling time is 41%, and bucket emptying is 10% of the total cycle time (Fiscor, 2007, Caterpillar, 2014). The proportion of time used on different maneuvers varies on the size of the construction machine. The larger machines are a bit slower than the smaller machines (Manyele, 2017). Shorter cycle times reduce cost and vice versa, while longer cycle times drops productivity. Wheel loaders use more time on moving proportionally and have higher uncertainty than the time used depending on conditions. Due to the proportion of time used, the swing angle is thus a significant factor for excavators. The swing time is proportional to the swing angle. The swing time also depends on the swing speed, which changes with machine size and is incorporated into the model. The depth of excavation greatly influences excavation productivity due to the increased swing time and the difficulty of digging. The weight of the construction machine affects the swing times and loading time, with heavier machines using longer than smaller machines (Caterpillar, 2014). The last factor Komatsu considers as a variable is the dumping conditions, which significantly impact the unloading time due to the precision required, awkward positions, and safety concerns that might occur under challenging conditions (Komatsu, 2009). Soil conditions might also significantly impact cycle time but are not included as a variable. For wheel loaders, only two variables are included in the model, the bucket size and the loading conditions. However, dumping conditions and swing time is usually not as variable as for excavators (Caterpillar, 2014). Should ground conditions be something other than normal, poor or good, an increase or decrease in cycle time of 10% for wheel loader and 20% for excavators is used(Komatsu, 2009).

When the operation of an excavator includes loading into a dump truck, the need for periodically switching the dump truck is not taken into account. Neither is its relative positioning affects the cycle time of the construction machine. The maximum productivity is achieved by positioning the dump truck below the construction machine (Litvin and Litvin, 2020). This positioning is not usually practically achievable outside quarry mining. The Komatsu model assumes that the position of the dumper is on the same level as the excavator by not including it. The same is true for spoil piles, where the cycle time depends both on its relative vertical position to the construction machine and radial distance for excavators and moving distance for wheel loaders. The model assumes a typical distance for earth-moving operations. The cycle time is also affected by variables such as the operator's experience, visibility conditions, soil formation, environment, and weather conditions. These factors lead to some uncertainty when omitted as variables, which can be seen as lacking in this thesis when looking at lifetime estimates. However, these factors matter less as they should average over the construction machine's lifetime if rational differences are not considered. The installation and movement of the excavator are not directly considered but should be seen as part of the work efficiency.

Average bucket load Having established the cycle time model, which characterizes the baseline frequency of loads moved, there is a need to develop a model for the volume in Lm^3 for each load. Heaped capacity is a frequently used method for measuring the rated bucket capacity. The heaped capacity can be defined as the volume enclosed by the bucket and the volume of the heaped material above the bucket rim. The volume over the bucket rim has a pyramidal shape, with an angle of 1:1 being typical for backhoe excavators and an angle of 2:1 for wheel loaders (ISO, 2007, ISO, 1983)

The actual fill of the bucket varies according to the type of soil. A bucket fill factor is defined to get the actual volume of material in the bucket each cycle relative to the rated bucket volume. Besides the type of soil, other factors that influence the bucket fill factor include the operator's experience, the work environment's condition, and the visibility during operation. During real-world operation conditions, achieving rated bucket capacity is generally not feasible over time, and there is some discrepancy, typically 10% (Caterpillar, 2014). Through the lifetime of both wheel loaders and excavators, a bucket fill factor of 80% is typical considering the discrepancy and assuming average digging conditions (Caterpillar, 2014, Sağlam and Bettemir, 2018, Edwards et al., 2001). Under challenging conditions, the bucket fill factor will be less, at 70% and 95%, in easy conditions (Komatsu, 2009).

The bucket size depends on the intended use during operation and might impose requirements for form or toughness. Whether the work is light or heavy duty, it requires precision or mass excavation, ditch digging, ripping, or rock moving will influence that choice. The bucket selection has an impact on the machine's stability. If the bucket is too big, it might result in the danger of the machine tipping over or rolling over. The penetration force of the bucket is essential to consider when digging in soils of varying toughness, and it depends on the bucket's width and tip radius. The structural stresses on the machine and the hydraulic system's lifting capacity also matter (Komatsu, 2009). As such, most construction machines have a range of bucket sizes they can choose from based on these factors. Here the bucket selection is based on mass excavation under average digging conditions. The rated bucket capacities presented by different major manufacturers (Komatsu, 2009, Caterpillar, 2014, Volvo CE, 2022a, Volvo CE, 2022b, Hitachi CM, 2022a,Hitachi CM, 2022b), are considered to find the bucket capacities for the excavators and wheel loaders as a function of the construction machines' size. The best fitting regression is found by using a second degree polynomial for excavators bigger than 10 tons, and a linear function for excavators weighing less than 10 tons, these functions can be used to estimate the bucket capacity should is not be known, the plot is shown in fig 2:

$$B_R = \begin{cases} 3 \cdot 10^{-5} \cdot W + 0.0057 & \text{if } W < 10tons \\ -4 \cdot 10^{-12} \cdot W^2 + 6 \cdot 10^{-5} \cdot W - 0.2502 & \text{if } W > 10tons \end{cases}$$

Where B_R is the rated bucket capacity, and W is the excavator weight. The fitness of this model is:

$$R^2 = 0.9924$$

By using the rated bucket capacity B_R and the bucket fill factor bf The average bucket payload B_A can be calculated as such:

$$B_A = B_R \cdot bf$$

There are fewer Wheel loader models and, as such fewer data points to include, the plot is shown in fig 3. The regression is a second-degree polynomial with the formula and fitness of:

$$B_R = -1 \cdot 10^{-9} \cdot W^2 + 0.0002 \cdot W + 0.1349$$

$$R^2 = 0.8897$$

Figure 2: plot of the excavator bucket capacity data and its fittest regression. Includes data from Volvo CE, Hitachi, Catepillar, and Komatsu

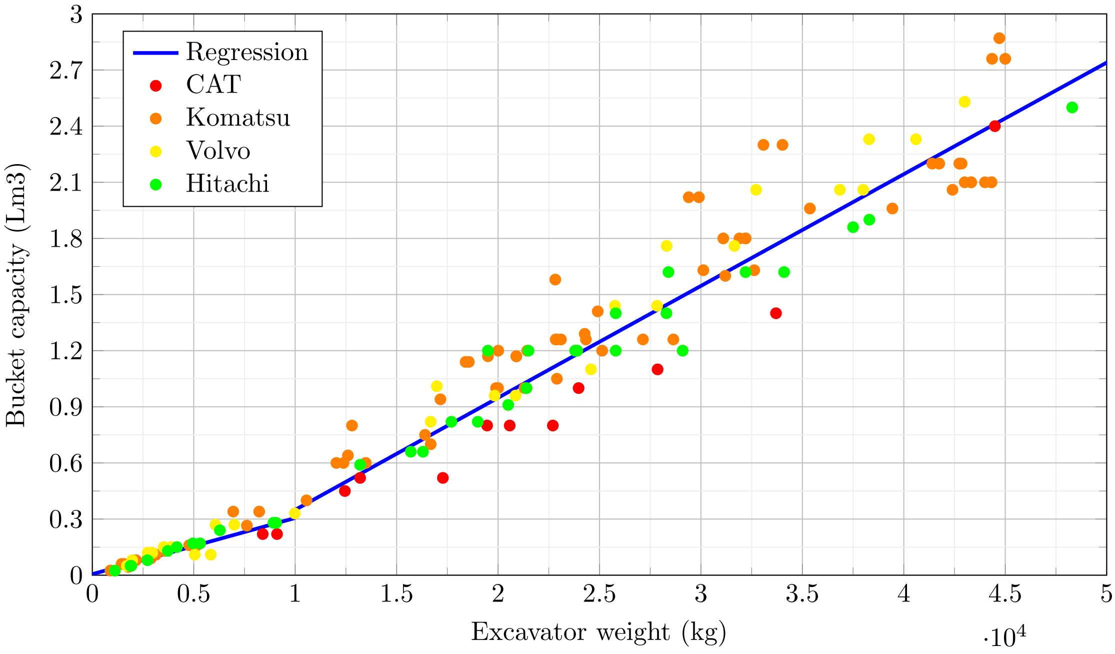
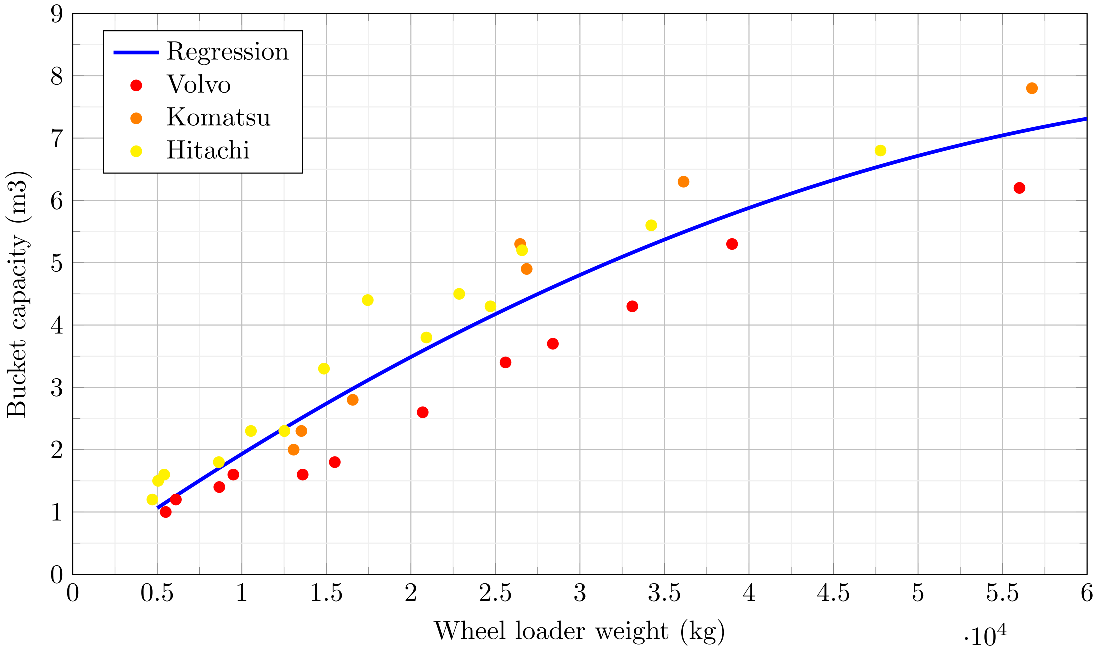


Figure 3: plot of the Wheel loader bucket capacity data and its fittest regression. Includes data from Volvo CE, Hitachi, and Komatsu



Work efficiency Now with the average payload and cycle time, the ideal standard productivity of the construction machine can be found. Work efficiency needs to be considered to get the actual productivity of the construction machine. The work efficiency factor is the percentage of time used on ideal working. It should consider every delay, break, and otherwise unproductive operation time that is not used on digging. The work efficiency factor is multiplied by the standard productivity to get the actual productivity of the construction machine. A work efficiency factor of 100% corresponds to 60 minutes of effective work per hour, and 50% corresponds to 30 minutes of effective work per hour.

Work efficiency losses might be from switching dump trucks and waiting for a new one, moving the constructing machine, or other forms of idling. Idling is when a construction machine is running but not doing anything. A significant part of losses in work efficiency is due to idling. Other losses come from working slower than optimally. These losses might be due to operator skills, terrain, poor selection of machinery, high need for precision, or weather conditions, among other things. Other factors contribute to lower productivity when the machine is turned off, which makes the daily productivity significantly lower in terms of effective hours. These losses are considered in the lifetime section.

Many papers that consider productivity of construction machinery uses a work efficiency factor of 83% corresponding to 50 minutes per hour(Edwards et al., 2001, NRAAC, 2010, Sağlam and Bettemir, 2018, Caterpillar, 2014). This factor can be seen as operating under ideal conditions and is usually only achievable for short periods. A work efficiency factor of 65-75% is more realistic in the long term (Caterpillar, 2014). So a work efficiency E of 75% is chosen for both wheel loaders, and excavators in average ground conditions, 58% for poor ground conditions, and 83% for good ground conditions (Komatsu, 2009).

5.2.2 Lifetime

When considering the lifetime of a construction machine, it is the economic lifetime that is of interest in the Norwegian context. It is the period where the benefit from owning it outweighs the cost of ownership. The lifetime varies between countries. In Norway, the economic lifetime of a construction machine is short due to the strict emissions standards and maintenance regulations, the owner's expectations of performance, and the rough working conditions due to weather and terrain. Considering the lifetime is significant due to its effect on emissions. In absolute terms, a longer lifetime leads to more emissions, but relatively it makes the yearly emissions less if manufacturing is seen as an environmental cost of its operation.(Zarean et al., 2022, Glorstad, 2021)

There is no definitive lifetime of a construction machine as the wear and tear will differ from case to case, based on the type of work done, maintenance, climate, and environment, with estimates ranging from 8000 to 18000 hours (Jeremiassen, 2021, Wiik et al., 2020). For Norwegian conditions, Volvo CE assumes the yearly operation of wheel loaders and excavators to be 1500 hours, and they assume an average economic lifetime of 10000 hours of operation. Volvo CE states that they do not have enough data to make statements on whether the lifetime of electric construction machines differs from diesel-driven ones. In Norway, after an average of 10000 hours, most machines are sold and exported out of the country. Very few excavators and wheel loaders are wrecked in Norway. These data are also supported by separate sources (Wiik et al., 2022, Stripple, 2001, Frischknecht et al., 1996, Komatsu, 2009). (Glorstad, 2021)

One hour of operation is assumed to be the time a machine is running. This assumption avoids the problem of accounting for the work time in a construction project, unlike an effective hour, which supposes that the machine is operated efficiently (Ebrahimi et al., 2020), which would exclude idling and inefficiencies that occur during operation. During a work day, many factors hinder the productive usage of a construction machine. There is an approximate 14% real-world productivity loss just due to a machine not being available, due to scheduled maintenance, daily checks, refueling, pre-start checks, lunch/breaks, and shift changes (Akande et al., 2013). By using the operational time, these factors are circumnavigated.

Unlike Volvo CE, Nasta, who retrofits combustion engine excavators into electric excavators, expects a longer lifetime for battery electric construction machines than combustion engine construction machines. Due to less need for maintenance and fewer vibrations, their estimates vary from 25% to 50% longer lifetimes (Wiik et al., 2020). Some concerns regarding the lifetime of the electric excavators are still held. Often electric construction machines use technology and parts used for diesel-driven machines, which are not designed to the specifications of electric construction machines and might cause unnecessary deterioration. Initially, the lifetime of electric and diesel-driven machines will be considered equal, but a scenario with varying lifetimes will be considered.

5.2.3 Engine load factor

A model for the load factor needs to be used to connect the fuel use, energy use, and emissions to the performance of the construction machines. The engine load factor can be defined as the portion of the engine's rated power being used during the earthmoving process (Klanfar et al., 2016). An engine load factor of 0% indicates that the machine is shut off, so the motor yields 0 kW. At 100%, the engine load factor indicates that the machine's motor yields its rated power. The engine of the machine usually does not perform at its rated power but changes based on the activity and its momentary needs for power.

The fuel consumption has a linear relationship with the engine load (Lewis and Rasdorf, 2017, Caterpillar, 2014). An average engine load can therefore be defined. Using engine load data from Lewis and Rasdorf (2017), an average load of 23% is found for wheel loaders and 38% for excavators. The average engine load factor is specific to the equipment type and the relative work application, but it is assumed that it is not dependent on the equipment size or rated engine power. These values are under normal ground conditions. In poor ground conditions, the engine load factor for wheel loaders might have a value of 15% and for excavators 40%. While in difficult ground conditions, the value for wheel loaders might be 35% and for excavators 60%(Caterpillar, 2014).

Now to use the average engine load factor, the relationship between the weight and the engine's rated power needs to be established. By using regression on the data from construction machine manufacturers a relationship is found (Volvo CE, 2022a,Volvo CE, 2022b, Hitachi CM, 2022a, Caterpillar, 2014, Komatsu, 2009, Hitachi CM, 2022b). The relationship is found independently for wheel loaders, and excavators, respectively plotted in fig 5 and fig 4. It can be observed that the data from the different manufacturers correspond nicely. For the excavators, the regression is split at 25 tons to get the best fit. The relationship between the machine weight W and rated engine power P can be described as:

$$P = \begin{cases} 0.0149 \cdot W^{0.8926} & \text{if } W < 25 tons \\ 211.17 \cdot ln(W) - 2010.4 & \text{if } 25 < W < 100 tons \end{cases}$$

$$R^2 = 0.9534$$

Meanwhile for wheel loaders, given a weight under 100 tons, the relationship can be described as:

$$P = 0.0291 \cdot W^{0.8748}$$

$$R^2 = 0.9824$$

Figure 4: plot of the excavator rated engine power data and its fittest regression. Includes data from Volvo CE, Hitachi, Catepillar, and Komatsu

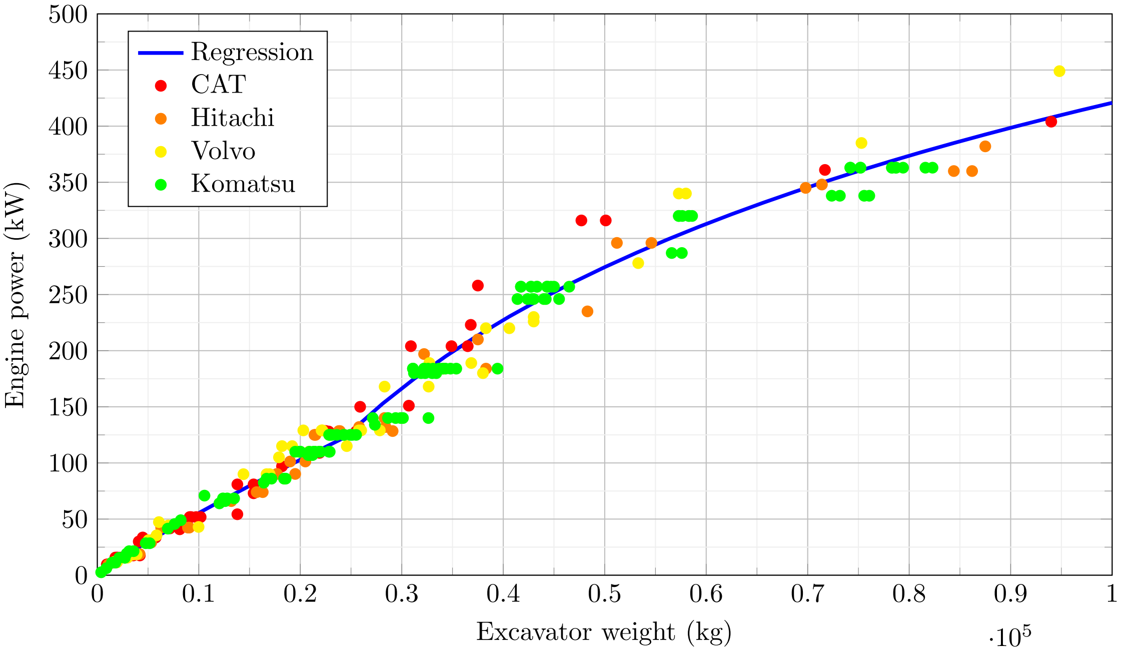
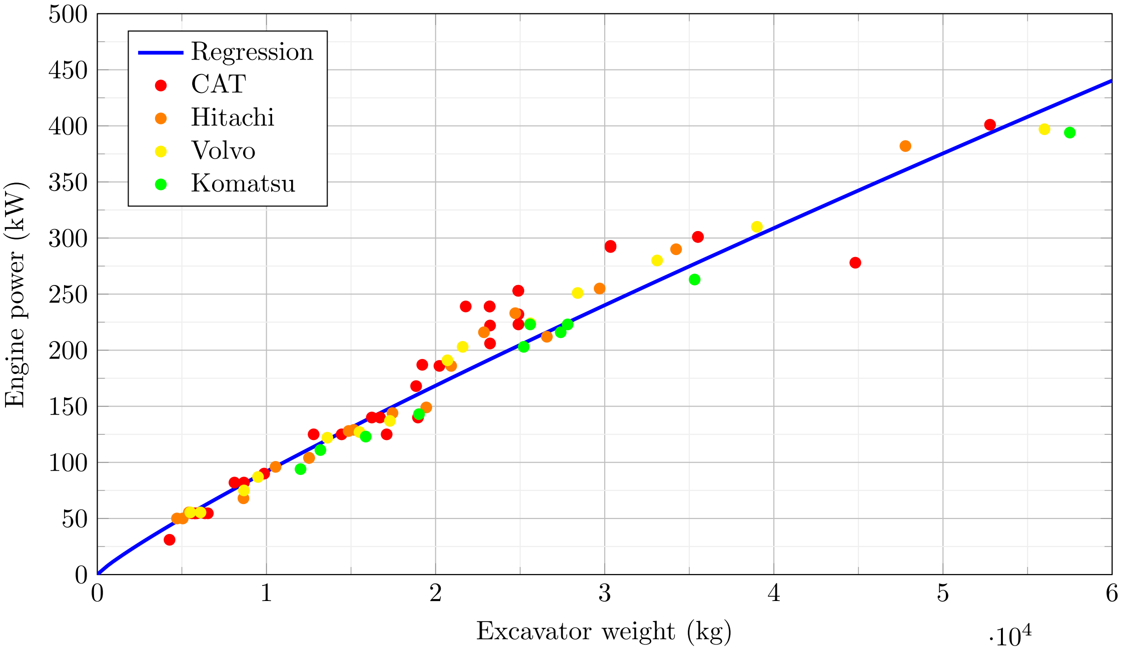


Figure 5: plot of the excavator rated engine power data and its fittest regression. Includes data from Volvo CE, Hitachi, Catepillar, and Komatsu



5.2.4 Fuel consumption

For diesel driven machines, diesel is unsurprisingly the fuel used, for electric machines electricity is the fuel. It is of interest to know the consumption of these fuels as they are imbued with climate impacts from their production, as well as the emissions from usage. To find the fuel consumption for diesel-driven and electric construction machines a fuel consumption model is needed.

Cat (2014) and Komatsu (2009) provide fuel consumption values for various working environments. By adjusting these values from 80% engine load to the rated engine power, a fuel consumption model based on the average engine load factor is developed. Second-degree polynomial regression is used on the data. The regression for the fuel consumption at rated engine power is shown in fig 6 for excavators and fig 7 for wheel loaders. The function found through regression for describing the fuel consumption of an excavator FC_E is:

$$FC_E = -5 \cdot 10^{-5} \cdot P^2 + 0.26 \cdot P - 0.27$$

$$R^2 = 0,9962$$

And the fuel consumption of a wheel loader is described by assuming a constant fuel consumption of 5 litres per hour for wheel loaders with a rated engine power of up to 50 kW. Wheel loaders with more engine power are described by the function:

$$FC_W = -3 \cdot 10^{-5} \cdot P^2 + 0.27 \cdot P - 9.3$$

$$R^2 = 0.9846$$

The fuel consumption of excavators and wheel loaders can now be found using the functions and the engine load factor. The calculation is done by first using the rated power to select a fuel consumption. The fuel consumption at rated engine power can then be scaled to the appropriate level based on the engine load factor. It should be noted that the power can not be scaled before selecting a fuel consumption due to larger engines being more energy efficient than smaller engines (EMEP/EEA, 2019). Scaling before choosing would give incorrect results. For example, it would assume equal fuel consumption of a 50 kW engine running at 100% load and a 100 kW engine running at 50%. This efficiency gain is also why using a single brake-specific fuel consumption value would give less reliable results, as it assumes linear consumption.

Pre-combustive loss of diesel energy contributes to an increase in the overall fuel usage of a construction machine. From fueling the machine until the fuel combustion, there is an approximate 10% loss in energy content. This evaporation leads to emissions, however these evaporative emissions from Non-road mobile machinery are not well known, and is not considered(EMEP/EEA, 2019). These losses might be due to multiple factors, such as leakage, volumetric loss, and evaporation. Since Komatsu (2009) and CAT (2014) use empirical data from their customers and the model is performance-based, these losses are already considered. (Stripple, 2001)

Electricity Due to the lack of available data for energy consumption in electric construction machines, a model based on the diesel consumption in the equivalent machines is developed. There are not enough electrical construction machines, a limited range of sizes, and too little user experience from real-life conditions to make a model. Using a linear model is not ideal. Similarly to diesel engines, the energy efficiency of electric engines depends on their size (De Almeida et al., 2011). So the best option is to use the model for diesel and account for differences in energy efficiency. It is therefore assumed that the difference in energy efficiency is constant.

The relationship between diesel consumption and electricity consumption can be found by assuming that the power output of a diesel-driven construction machine and an equivalent electric

Figure 6: plot of the fuel consumption in litres per hour for an excavator based on engine power and its fittest regression. Includes data from Volvo CE and Komatsu

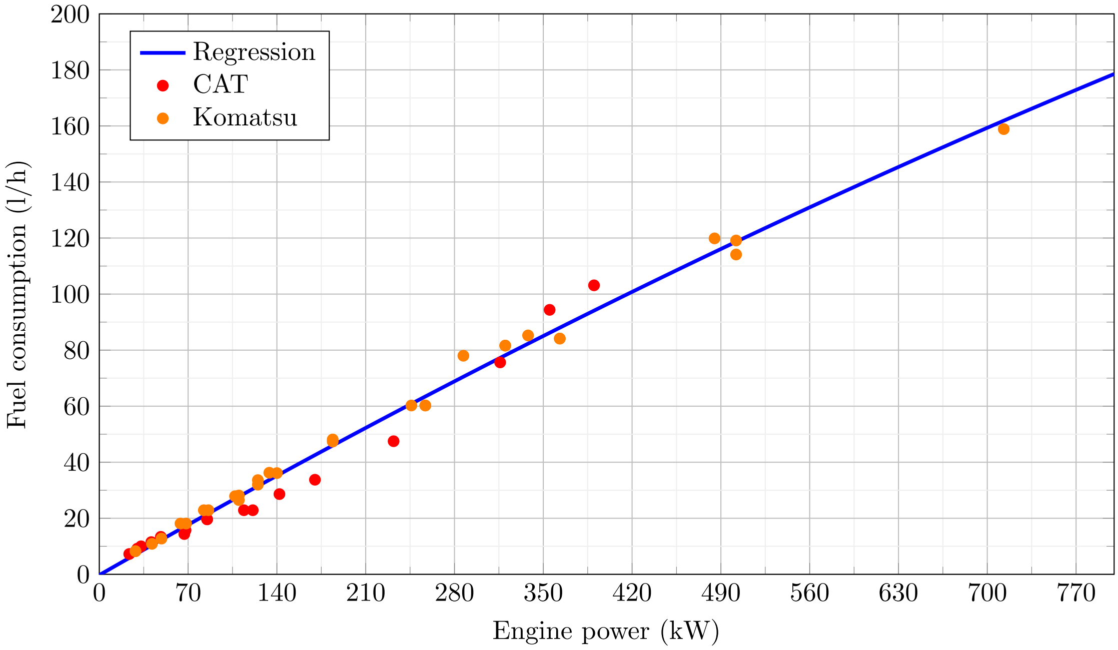
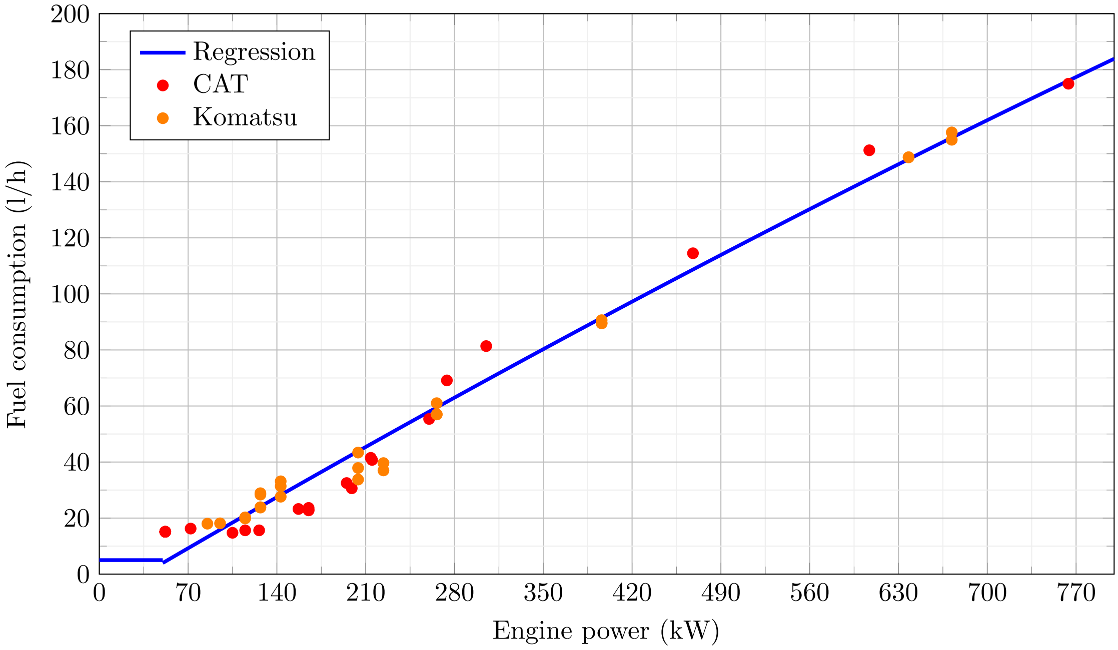


Figure 7: plot of the fuel consumption in litres per hour for an wheel loader based on engine power and its fittest regression. Includes data from Volvo CE and Komatsu

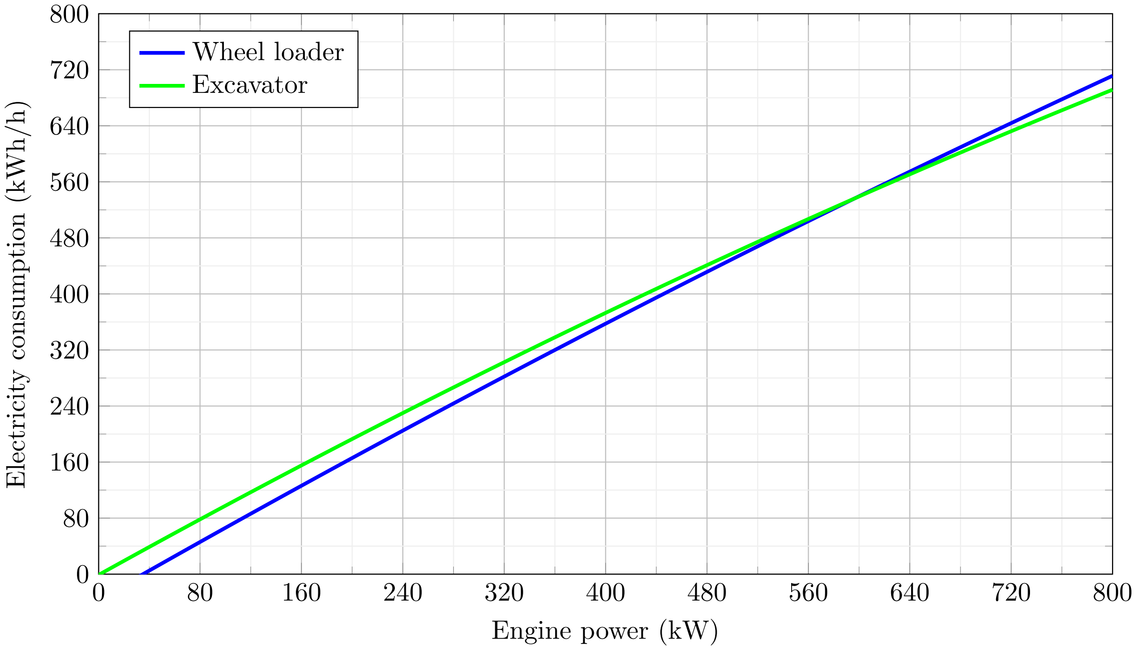


construction machine is the same. The total energy efficiency describes the ratio of energy put into the machine to the energy available for doing work. For an electrical construction machine, the energy efficiency η_{el} is 39%. For a diesel construction machine, the energy efficiency η_{Diesel} is 15% (Lodewyks and Zurbrügg, 2016). The electricity consumption FC_{el} (kWh/h) can then be expressed by the diesel consumption FC_{diesel} (l/h) by using the energy efficiencies, and the energy density of diesel d which is 10.06 (kWh/l)(Wiik et al., 2022).

$$P_{out,el} = P_{out,diesel}(kW)$$
$$P_{in,el} \cdot \eta_{el} = P_{in,diesel} \cdot \eta_{diesel}(kW)$$
$$FC_{el} = FC_{diesel} \cdot d \cdot \frac{\eta_{diesel}}{\eta_{el}}(\frac{kWh}{h})$$

The results are plotted in fig 8 for both electric excavators and wheel loaders. There is little difference between the two functions. There is a big difference in energy efficiency between diesel and electric machines. The main advantage electrical machinery has over diesel machinery is their engines' energy efficiency. Diesel engines only convert 35% of the available energy into power, while electric engines convert about 90% of the energy into power (Lodewyks and Zurbrügg, 2016). This efficiency makes a big difference even though losses in other parts of the machine stay the same. The difference in efficiency would be lower if battery losses were considered.

Figure 8: Plot of the electricity consumption in kWh per hour for wheel loaders and excavators



Biodiesel Biodiesels are an alternative fuel source that can be produced from a variety of sources including from biomass, waste, photosynthesis in microbes, and electrochemical carbon fixation (Liu et al., 2021). The usage of biodiesels in construction machinery might potentially contribute to a decrease in environmental impact. Biodiesel blends are named after the content of biodiesel to diesel in the blend. A pure biodiesel is therefore named B100 (100% biodiesel). A bland that is common for usage is B20 (20% B100 and 80% PD)

Lewis et al. (2009) observed that the most significant benefit of using biodiesel is that emissions of PM, CO, and HC are reduced proportionally to the ratio of biodiesel to petrol diesel in the blend. Using a B20 blend led to a 20% reduction in HC emissions and a 12% reduction in both PM and CO emissions. While using a B100 blend reduced average HC emissions by approximately 67% and 48% for both PM and CO. The effect on NOx emissions was uncertain, with research indicating slight increases or decreases. As biodiesel emissions theoretically replace the emissions from petrodiesel without adding additional carbon to the atmosphere, the GWP of the emissions is assumed to be 0 (Lewis et al., 2009). A scenario will further explore the potential difference different biodiesel blends might have on the impact of construction machines.

5.2.5 Emissions

In the use phase there are primarily four sources of emissions that are considered. The direct emissions to the environment from the combustion of diesel, the emissions from extracting and refining diesel, The emissions from the production of electricity. And the maintenance of the machines through their life is considered.

Prediction of heavy-duty diesel vehicle emissions inventory is substantially less mature than the prediction of gasoline passenger car emissions. The emissions inventory is especially lacking for stage 5 emissions which is the current standard for emissions from non-road mobile machinery in Europe. Currently the emissions inventory assumes emissions based on the regulation limits, and is not based on real world data (Clark et al., 2002,EMEP/EEA, 2019).

Direct emissions Direct emissions encompass emissions for which the owner can be considered directly responsible. The emissions factors are adjusted to consider the deterioration of the construction machine, which is considered later. Electric construction machines have no direct emissions from their operation, other than pollution from maintenance, which are considered separately.

Continuous improvements in technology and stricter regulations on emissions mean that new engines are less emitting than older ones. An engine from 1988 produced 2.5 times more NOx and 12 times more PM than an engine from 1998 (EPA, 2010). As newer machines emit less to abide by the current emissions standard, it is crucial to use current data. It is assumed that all construction machines considered are 2020 models with stage 5 engines.

EMEP/EEA (2019) data is used to represent the emissions from a construction machine. The data is retrieved from the tier 3 methodology for stage 5 engines. For CO_2, SO_2, and heavy metals the emission factors are not dependent on the equipment and is found by directly though fuel consumption. The data adhere to the current emissions standards in Norway and is the most comprehensive dataset for construction machine emissions. EMEP/EEA (2019) uses load-specific fuel emissions factors (EF) in grams per kWh, representing hourly emission of operating at rated engine load. Emissions intensity decrease at higher rated power (P) due to engine efficiency and stricter regulations for larger machines (Volvo CE, 2019). The emissions factors are characterized using Simapro data on the various pollutants. The emissions model is the same for excavators and wheel loaders. The equation to quantify the power dependent emissions E_P over the economic life of the construction machines can be written as:

$$E_P = h \cdot P \cdot LF \cdot (1 + DF) \cdot EF_P$$

The load factor (LF) is applied to emissions factors equivalently to how it was applied to the fuel consumption, and emissions are linearly dependent on the load. Earlier emissions models before stage 5 considered operations as "steady-state" and did not directly account for load-dependent emissions. A transient operation factor was applied to include these emissions. For stage 5 emissions, this is no longer necessary as the transient operation is accounted for in the emissions factors (EMEP/EEA, 2019).

CO_2 and SO_2 are directly proportional to the fuel consumed (EMEP/EEA, 2019). Their emissions are based on the stoichiometric balance of diesel's carbon and sulfur content. The sulfur content of the diesel is assumed to be 10 mg per kg(Council of European Union, 2009). The sulfur content in the diesel is assumed to be completely transformed into 20 mg per kg of SO_2. The CO_2 emissions from diesel are constant, at 3160 g per kg. A fuel density of 0.85 liters per kg is used to make the emissions compatible with the fuel consumption (Klanfar et al., 2016). The equation to quantify the diesel-dependent emissions E_D over the economic life of the construction machines can be written as:

$$E_D = h \cdot FC \cdot EF_D$$

Indirect emissions Here the indirect emissions include all emissions that are a consequence of the usage of the machine for which the owner is not directly responsible. The impact of fuel extraction and refining are represented through the SimaPro process ”Diesel RER”. The emissions impact from electricity production will be calculated based on electricity from the Norwegian market and electricity from the European market to compare the two markets. The SimaPro processes ”Electricity, low voltage NO” and ”Electricity, low voltage Europe without Switzerland” are used.

Maintenance Over a machine’s lifetime, parts break and need repairs, the oil needs to be changed, joints need to be greased, lubrication oil needs to be applied, and tires need to be replaced. All this has an environmental impact that can be quantified using the SimaPro process ”Maintenance, lorry 40 metric ton RoW”. The impacts from the SimaPro process represent the lifetime environmental impacts of maintaining a 40-ton lorry. The impact is converted from describing 40 tons to per kg to make this applicable to all sizes of construction machines. The maintenance impacts of the construction machines are thus assumed equal to that of a lorry per kg. Although maintenance is essential in keeping the construction machine operational both short-term and long-term, it cannot keep the machine from all the deterioration it will inevitably accumulate.

5.2.6 Deterioration

Over the lifetime of a construction machine, as it accumulates usage, the characteristics of the engine change as a result of deterioration. The deterioration generally results in increased tailpipe emissions, which need to be accounted for to estimate the construction machine's lifetime emissions correctly. The deterioration implies that a construction machine would generally have higher tailpipe emissions after ten years of use than when it was new. Although the deterioration is slow from a certification standpoint, it is significant over the lifetime of the construction machine (Clark et al., 2002). The rationale that research suggests is that a lack of maintenance is the primary reason for increases in emissions. Various other potential reasons are also identified as sources of engine deterioration, such as engine tampering and wear on the engine(EPA, 2010).

A deterioration factor(DF) is implemented to account for engine degradation and produce reliable emissions estimates for construction machinery. The DF is used to correct the emissions from the usage of the construction machinery. The emission data is adjusted using this factor based on an engine deterioration model to estimate the increase in emissions throughout the lifetime of the construction machine. Various sources outline the use and derivation of a DF model for Non-road diesel engines. These models are intended to account for how the characteristics of the emissions from the engine change with use. The sources have differing opinions on whether the deterioration of an engine can best be described with a linear, exponential, logarithmic, or logistically distributed model (Borken-Kleefeld and Chen, 2015, Chen and Borken-Kleefeld, 2016, Ebrahimi et al., 2020, EMEP/EEA, 2019, EPA, 2010).

For this thesis, the linear deterioration model used by EMEP/EEA (2019) and EPA (2010) is chosen as the most fitting to be used as a basis for modeling the deterioration, as it matches the purpose of this thesis. The model for diesel engines younger than the average engine lifetime applies the lifetime deterioration (A), which represents the total deterioration after the average lifetime of an engine, and is constant for emissions of certain pollutants and engines at a particular technological stage. The lifetime deterioration is then multiplied by the average lifetime(LT) portion that has occurred at a given time (K). Thus at zero hours of usage, there is no deterioration, but deterioration occurs as time goes by. The deterioration increase is linear until it reaches the average lifetime. For engines older than the average engine lifetime, the DF is constant at the deterioration value for the average lifetime. to use this factor multiplicative, the model needs to be converted from a percentage increase to a growth factor. The conversion is done by adding one to the percentage factor. The model is essentially equivalent to the models employed by EMEP/EEA (2019) and EPA (2010) but differs slightly in the last step of the calculation, where this model adds one to the DF, and they add the plus one later.

$$DF_{p,t} = \begin{cases} 1 + \frac{K}{LT} \cdot A_{p,t} & \text{if } K < LT \\ 1 + A_{p,t} & \text{if } K > LT \end{cases}$$

The DF for a particular technology stage (t) and pollutant (p) where the K is the age of the engine in hours, and LT is the average lifetime of the engine, which is assumed to be equal to the average lifetime of the construction machine. The data for the lifetime deterioration is from EMEP/EEA (2019) and EPA (2010), who both get their data from Lambrecht et al. (2004). The data is presented in Table.1.

The deterioration of the engine affects various pollutants individually. It affects the combustion of the fuel resulting in changes in the exhaust gas composition. NO_x Emissions are not significantly affected and might, in some cases, drop slightly over the engine's lifetime. In comparison, PM emissions may increase a lot as the engine ages, as shown in Table.1. However, CO_2 and SO_2 emissions are assumed to be unaffected by the deterioration since their emissions are based on stochastic conversion. It is assumed that their emissions stay constant over the construction life of the construction machine. The same applies to other pollutants not included in the model.

As an example of the interpretation of DF based on the data from Table.1, the emissions of PM per kWh from an engine increase by 47.3% when it reaches its median lifetime regardless of the engine's technological stage. Another example would be how NO_x emissions for stage 3 and above engines are a third of stage 1 engine's emissions per kWh.

In this thesis, the current proposed model for deterioration is not particularly useful, given that there is never a need to calculate the emissions for a particular known period of a construction machine's life. An average value for the expected lifetime portion is calculated to simplify the model. The age of the engine is assumed to be half of its average lifetime to calculate the average expected value. Given that the model is linear, this gives the average value it will have after its lifetime. Thus generally, the calculations for the DF can be done with the new equation:

$$DF_{p,t} = 1 + 0.5 \cdot A_{p,t}$$

This model applies to diesel engines and assumes that the deterioration is uniform for all non-road construction machinery and only depends on the engine's age. Unlike gasoline engines, the deterioration of diesel engines is not dependent on the engine's size (EPA, 2010). An average load factor is assumed to be applied during the engine's lifetime for the deterioration.

Pollutant	Lifetime deterioration (A)			
	Before Stage 1	Stage 1	Stage 2	Stage 3,4,5
HC	0.047	0.036	0.034	0.027
CO	0.185	0.101	0.101	0.151
NOx	0.024	0.024	0.009	0.008
PM	0.473	0.473	0.473	0.473

Table 1: Contains the percentage increase in emissions of certain pollutants for particular technological stages, as a result of deterioration through the lifetime of a construction machine

A secondary effect of the engine's deterioration is a potential loss in performance and thus increased fuel use, which also applies to electric motors. In a diesel engine, this might be caused by changes to the compression ratio, which directly affects the engine's performance. As the performance deteriorates, more fuel will need to be used to generate an equivalent amount of work. The result is that the operation will take longer, or the engine will need to work harder to achieve the same results. It is assumed that the deterioration factor considers this as it is given in percentage increase of emissions per output.

There is currently much uncertainty regarding the deterioration of electrical construction machinery, which is presented in the estimation of the construction machine's lifetime. Any differences in deterioration between electric motors and diesel engines are represented as differences in their lifetime. Electrical motors have fewer moving parts and thus probably experience less deterioration. They also vibrate considerably less and produce less heat, contributing to less deterioration (Wiik et al., 2020). The differences in deterioration are not adequately taken into account by the current model and are a point of improvement.

Deterioration also affects filtering, hydraulic systems, cooling systems, and lubrication oils, potentially hampering performance and furthering exhaust gas emissions. Filters and cooling liquid can be easily changed, so these systems are assumed to be well maintained, thus not contributing to deterioration emissions. Changing these liquids and filters is also an economic consideration and contributes to the construction machine's emissions due to their production and disposal impacts.

Other components of the construction machine that contribute to the machine's operation also deteriorate, leading to performance losses. Modeling this would be too complex for the level of assessment in this thesis. It is therefore assumed that the other factors consider this in the calculation by representing the average values of the engine's lifetime.

5.3 Manufacturing phase model

The manufacturing phase consists of all upstream activities that occur before the excavator is transported to the customer. The goal of this section is to justify and explain the the process this thesis takes to generalize the impacts of an arbitrary wheel loader or excavator on the basis of its weight. The data used in the LCA is developed from a variety of public data sets from CAT, Komtatsu, and volvo CE, and tried assembled into a coherent whole. A goal of the manufacturing phase is to have all factors be dependent on the weight of the machine, so as to make further calculations easier.

5.3.1 Steel

Steel is one of the significant components in construction machines and is used for most of the framework in a construction machine. Due to the energy-intensive refinement and impacts of raw material extraction, it has a high impact on the environment. It is an easily recyclable material, making it a prime candidate for lowering the extraction of raw materials. If low-carbon electricity is used in the electric arc smelters, it can mitigate much of the environmental impact. That is mostly not the case for now.

The source of the data on the steel content in construction machines is the environmental product declarations(EPD) on compact and E-series excavators from Volvo CE (Volvo CE, 2019). Specifically, the data comes from the "steel and iron" section of the EPD. It is assumed that this is pure steel, in line with SimaPro's calculation.

The impact data for the steel is retrieved from the SimaPro database. Following how other construction machinery models in SimaPro are calculated, it is assumed that the impact from the steel content of the construction machine can be represented using the SimaPro processes "Reinforcing steel {GLO}" and "Steel, low-alloyed, hot rolled {GLO}". The reinforced steel is assumed to make up 70% of the weight of steel, while the low-alloyed steel is assumed to make up the remaining 30% of the steel weight. This assumption is in line with other SimaPro Construction machinery models.

If the data from Volvo CE' Environmental declaration is plotted the correlation between machine weight and steel content can be found(Fig.9). It is clear that there is a strong correlation between steel content and machine weight. By using linear regression the best fit for excavators is found to be a linear equation:

$$W_S = 0.9603 \cdot W_M - 708.74$$

$$R^2 = 0.9986$$

Where W_M is the machine weight in kg and W_S is the steel/iron weight in kg. For

$$W_S = 0.7514 \cdot W_M + 307.48$$

$$R^2 = 0.9835$$

This regression is a good fit for most of the data. However, looking at the lower-end data for excavators, it seems that the fit is not ideal (Fig.10). Note that for machines weighing less than 740 kg, the iron/steel content would be negative. The regression is split into two ranges to amend this; one for excavators weighing less than 4 tons and one for excavators weighing more than 4 tons. This split is not mathematically justified but is based on observation of the data. This adjustment gives the new formulas:

$$W_S = \begin{cases} 0.8105 \cdot W_M + 12.226, & \text{if } W_M < 4000kg \\ 0.9697 \cdot W_M - 1004.7, & \text{if } W_M > 4000kg \end{cases}$$

Which respectively have the fitness of: $R^2 = 0.9984$ and $R^2 = 0.9982$ Although the individual fitnesses are lower than the previous fitness, this is only true if considered separately. If the R^2 is calculated for the whole range, this predictably results in an even better fit than initially:

$$R^2 = 0.9994$$

This fit is better, which is appropriate given the expected relative importance of the steel in the total impact of the manufacturing phase.

Figure 9: Relationship between the weight of the steel in the construction machine and its total weight

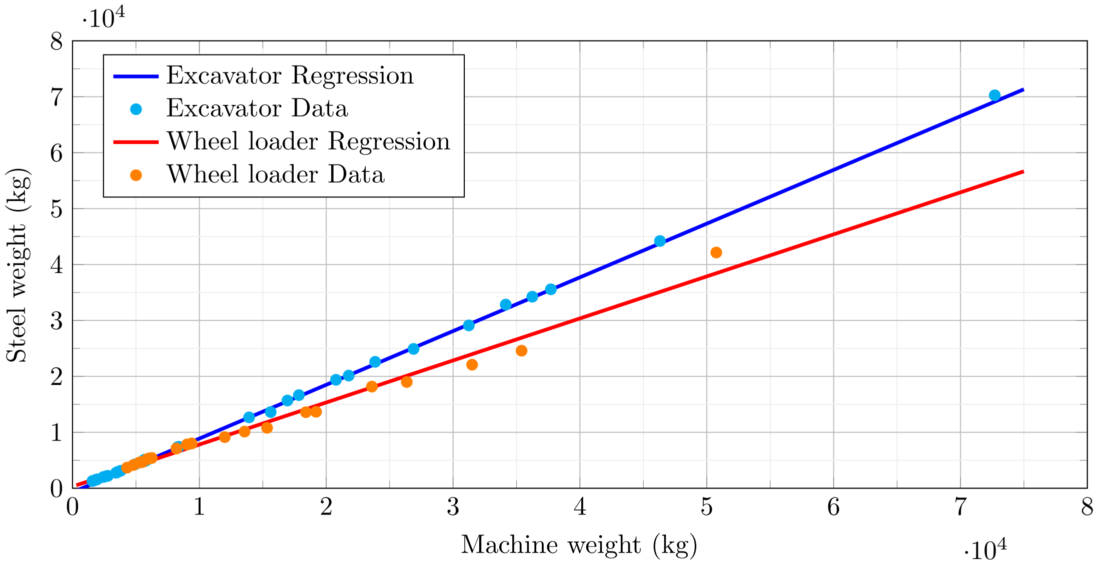
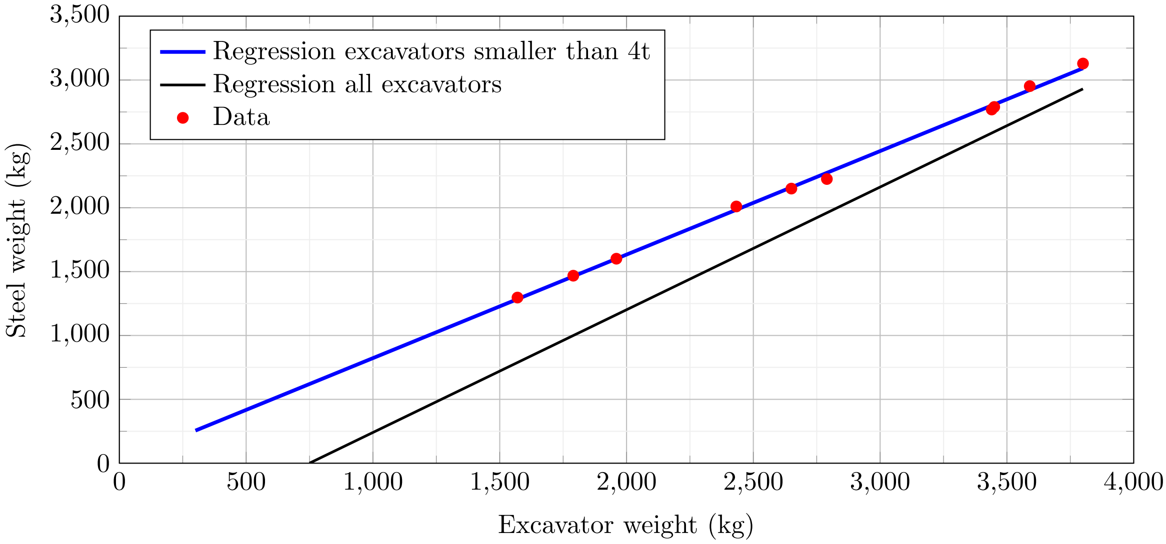


Figure 10: Comparison of the correlation between the regressions based on the data for small excavators and all the excavators, and the data of the weight of the steel in the excavator and the excavators total weight, for small excavators



5.3.2 Li-ion battery

Li-ion batteries have an unmatched energy density making them the backbone of the development of commercially viable battery electric construction machines (Nitta et al., 2015). This development is made possible by the recent advancements in the field, which have seen massive price reductions and energy density increases (Li et al., 2018). The advantages Li-ion batteries have are not likely to be overtaken soon (Nitta et al., 2015).

A wide-scale adaptation of Li-ion batteries will drastically decrease anthropogenic emissions (Pacala and Socolow, 2004). That is not to say that Li-ion batteries do not have high impacts. Li-ion batteries currently have some problems pushing up their environmental impacts, thus weakening their potential for impact reduction compared with diesel machines. These impacts include the leakage of heavy metals during production, usage, and disposal, which are hazardous to the environment and contribute to human toxicity, as well as resource depletion due to resource extraction. (Yu et al., 2012).

Battery size data is needed to develop a relationship between the battery size and machine weight. Given the lack of electric wheel loaders, the battery model is assumed to be equal to the excavator model. This assumption seems reasonable based on the battery capacity of Volvo CE's L25 and L20 and Kramers 5055e. The specifications of existing electrical excavator models are considered to get the necessary data.

The impacts are found using the SimaPro process "Battery, Li-ion, rechargeable, prismatic GLO", which is the most fitting process given the chemistry of the battery (Volvo CE, 2019). The battery market is global, no {RER} alternative exists for the battery market, but transportation to Europe is considered.

The battery data is usually given in kWh, and as the processes in SimaPro are in kg, a battery density is needed. The density is decided with the ECR25 Electric, for which the battery density can be calculated based on the weight and capacity of its battery, giving an energy density of $7.8kg/kWh$. This density is probably more accurate than using other battery densities, given that the battery performance specifications of an electric excavator differ from other applications, indicating a different battery chemistry and energy density. It is furthermore assumed that this energy density is similar for all sizes of excavators.

There are limited machines to get data from, and most of them are not production models. Additionally, most of the excavators are smaller in size and limited range. There are some relatively significant differences in the relationship between battery size and machine weight. Some machines partly cause this difference by being fully battery electric, while some are hybrids between cable and battery electric excavators. As such, they do not have the same need for battery capacity. Another reason for the lack of similarity in specifications is that the battery-electric-excavators are still in the early phase of development, so a standard has not yet manifested. The inability to get a high accuracy for the regression is admittedly a weakness in this report, given the high importance of the battery to the excavator's overall environmental impact as well as it being the sole difference between diesel and electric machines considered here.

By using a linear regression an equation is found which based on the available data can be considered adequate:

$$W_B = 0.0981 \cdot W_M - 4.8174$$

with a fitness of:

$$R^2 = 0.965$$

Where W_B is the battery weight in kg.

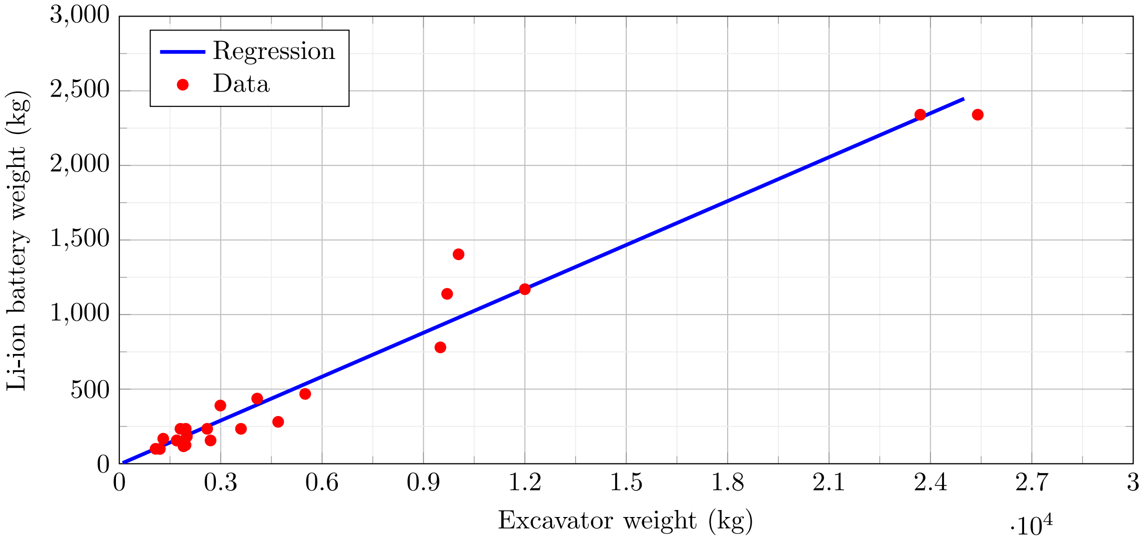


Figure 11: Relationship between the weight of the Li-ion battery and the weight of the electric excavator

5.3.3 Energy

The impact from energy is calculated in a way corresponding with the SimaPro process *"Hydraulic digger {RER}"*. It is assumed that the energy used during manufacturing per kg is about the same as for a car. The processes used by SimaPro to represent the energy use are "Electricity, medium voltage {RER}" and "Heat, district or industrial, natural gas {RER}". It is calculated per kg to fit into the model for the manufacturing phase.

The process is for a 15-ton excavator, so for it to be generally applicable, this data needs to be converted to consumption per kg. This conversion is done by dividing the electricity and heat by the total weight in kg. The process includes 13900 kWh of electricity from the European grid and 135000 MJ of heat from natural gas in Europe during its production. The new values are found to be 0.9 kWh of electricity per kg of machine weight and 9 MJ of heat per kg of machine weight.

This approach assumes that the excavators are manufactured in Europe. Based on the earlier established locations of manufacturing facilities of major companies in the Norwegian excavator market, this seems fair. Whether the assumption that cars and excavators use about the same amount of energy during production is reasonable is debatable. It should be noted that it is pointed out that in the process, it is somewhat inaccurate and should not be used for studies with high relative significance to the result.

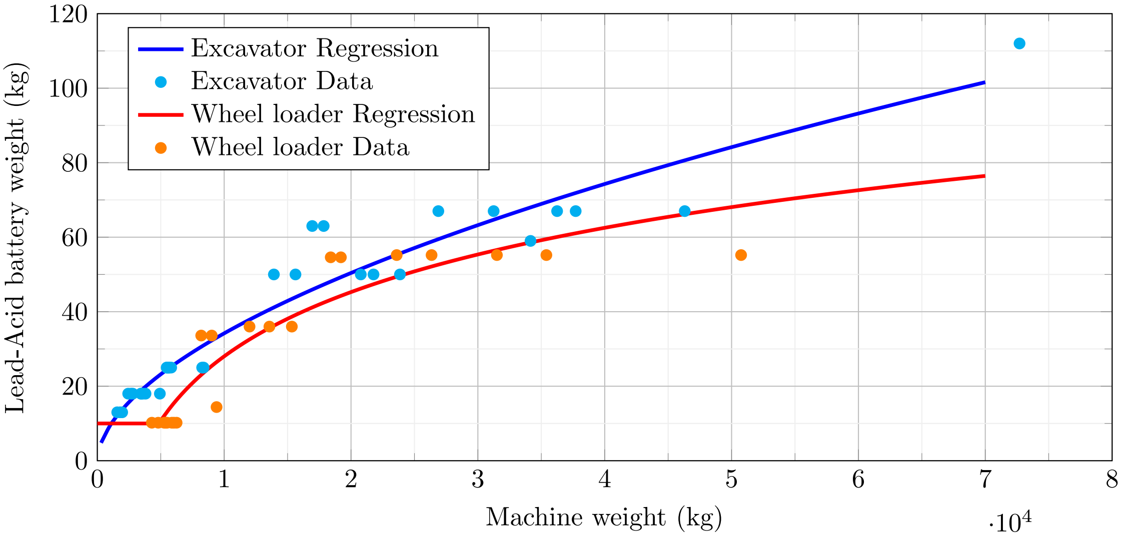


Figure 12: Relationship between the weight of the lead-acid battery and the weight of construction machines

5.3.4 Lead batteries

To find a model for the Lead-acid batteries data from the environmental declarations on compact excavators and E-series excavators from Volvo CE are used (Volvo CE, 2019). While impact data is gathered from the SimaPro process ”Lead {GLO}”.

There is no Lead battery process and no European lead process, which is why the process ”lead {GLO}” is used. {GLO} signifies that it is a globally applicable process. It is assumed that the lead-acid battery only consists of lead to simplify the calculation. This assumption is justified due to the lead’s disproportionally high impact compared with the other components, mostly plastic, water, and some acid(Linden and Reddy, 2002). Note that the composition of the battery is not 100% lead. It is about 60% (Linden and Reddy, 2002), so the weight is adjusted to reflect this.

The inventory data from Volvo CE EPD contains the lead-acid battery weights of specific machines. Regression is used to generalize this to apply to all machines. To find the relationship between machine weight and lead weight. It is found that regression with a power equation gives the best results for excavators, with the equation:

$$W_L = 0.1973 \cdot W_M^{0.5597}$$

$$R^2 = 0.9332$$

where W_L is the weight of the lead in kg based on the approximation of the lead-acid battery. The plot of the regressions can be seen in fig 12. For Wheel loaders a logarithmic equation is found:

$$W_L = \begin{cases} 10, & \text{if } W_M < 5000kg \\ 24.889 \cdot \ln W_M - 201.22, & \text{if } W_M > 5000kg \end{cases}$$

$$R^2 = 0.8814$$

5.3.5 Polymers and rubber

Plastics and rubbers are used in various applications in construction machines. To name some of their functionalities in an excavator, they are used for coverings, sealants, O-rings, and interior and exterior finishing (Volvo CE, 2019).

Values for the content of Polymers and rubber in excavators and wheel loaders are found in the environmental declarations (Volvo CE, 2019). SimaPro processes are used to calculate the impact of the plastic and rubber content of the construction machine. It is assumed that a decent SimaPro process to represent the polymer is "Polycarbonate {GLO}", and for the rubber, the SimaPro process "Natural rubber seal{GLO}" is chosen.

The plastic process is the best alternative of the SimaPro processes, with it being a hard plastic used in many applications. The rubber process is a compromise between the impacts of other rubber candidates. The data is aggregated, so the specifics of the types of materials cannot be obtained. This challenge necessitates that a partition is decided to disaggregate the plastic and rubber. 50 % of each is decided based on no apparent reason to say otherwise. This assumption is not warranted, but due to the low expected impact of plastic and rubber, it is not of much importance.

For the wheel loader, the data is primarily invariable around 170 kg, so it is kept constant. For excavators, a trend is tried implemented for the amount of plastic and rubber content compared with machine weight. There is, however, little correlation between the variables, with much variability of plastic and rubber content between excavator models(Fig.13). The initial model has the following equation:

$$W_{PR} = 164.16 \cdot ln(W_M) - 1213.3$$

Where W_{PR} is the weight of plastic and rubber content in kg. the model has a fitness of:

$$R^2 = 0.7172$$

A new model is developed for the excavator to prevent negative values by observing the linear tendency of polymer and rubber content in the smaller excavator models. The new model splits the range, and new equations are developed. For machines weighing less than 5 tons, a fixed value of 50 kg is set, and for excavators weighing more than 5 tons, a new regression is performed, resulting in an equation. The new model is as such:

$$W_G = \begin{cases} 50, & \text{if } W_M < 5000kg \\ 123.56 \cdot ln(W_M) - 802, & \text{if } W_M > 5000kg \end{cases}$$

The new total fitness of the model is:

$$R^2 = 0,7690$$

The new model's R^2, although a slight improvement compared with the first one, is still not very good. This problem is especially true if the R^2 machines heavier than 5 tons are considered separately from the rest. The value is 0.3984, which is quite a terrible fit, especially considering that it applies for 94% of the weight range that spans from 5 tons to 80 tons. This data shows that the fitness is disproportionately skewed towards the lower-end data, which covers a small range but is quite dense. Regardless, it is assumed that it is not essential to have high accuracy in this aspect due to the low impact and amount of the materials contained in the excavator.

Figure 13: Initial model for the relationship between the weight of rubber and the weight of the construction machine

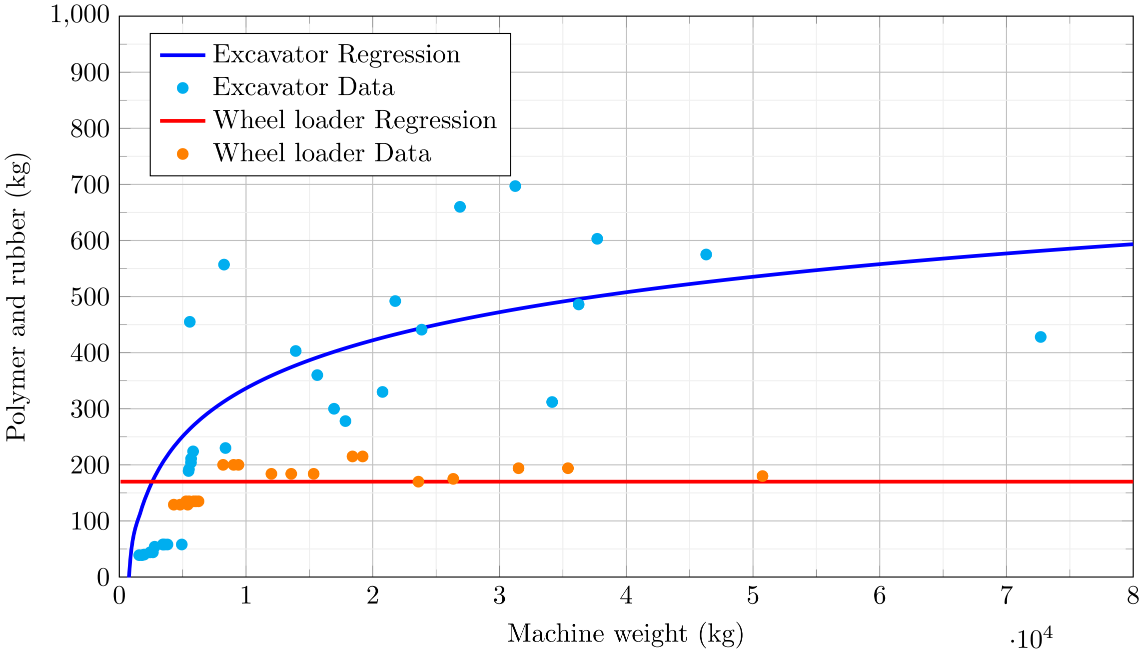
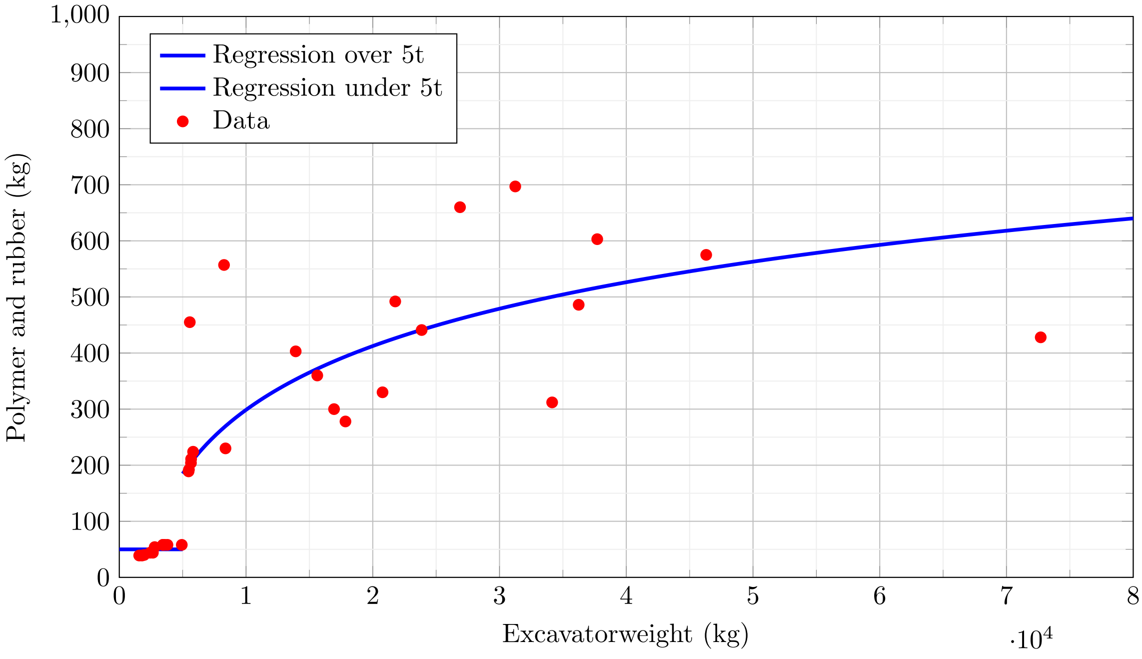


Figure 14: New model for relationship between the weight of rubber and the weight of the excavator



5.3.6 Oil and fluids

The data on the oil and fluids used during manufacturing is from the EPDs of Volvo CE (Volvo CE, 2019). Since there is no specification what these fluids are it is necessary to assume that the oils and fluids used during manufacturing are predominantly lubrication oil. This assumption allows for the impacts to be calculated using the corresponding SimaPro process "Lubricating oil {RER}".

For excavators there is a rather good polynomial fit for the relationship between oil and fluid, and machine weight, but the equation trends downwards after 70 tons. It is not expected that the oil and fluid use of heavier excavators will lessen, so the equation is limited to its peak at 70 tons and is kept constant at a level of 765 kg after that as shown in Fig.15. For wheel loaders a good fitting logarithmic function is found.

For excavators the regression gives the quadratic equation:

$$W_{OF} = \begin{cases} -2 \cdot 10^{-7} \cdot W_M^2 + 0.0223 \cdot W_M + 24.049, & \text{if } W_M < 70000kg \\ 765, & \text{if } W_M > 70000kg \end{cases}$$

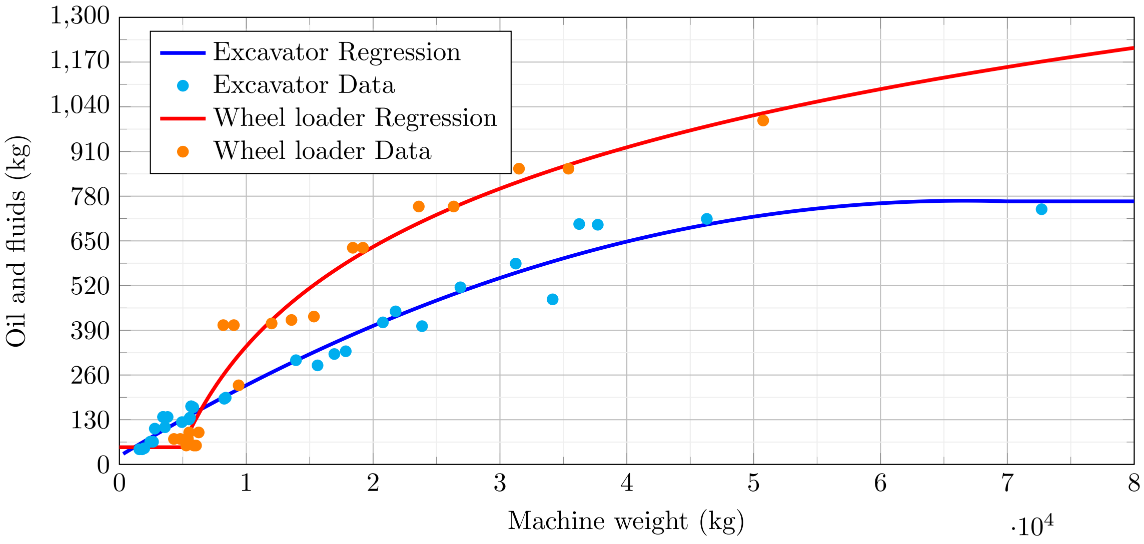
$$R^2 = 0.9725$$

where W_{OF} is the weight of the oil and fluids used during production. For the wheel loaders:

$$W_{OF} = \begin{cases} 50, & \text{if } W_M < 5000kg \\ 417.44 \cdot ln(W_M) - 3501.4, & \text{if } W_M > 5000kg \end{cases}$$

$$R^2 = 0.9613$$

Figure 15: Relationship between the weight of oil and fluids used during manufacturing and the weight of the construction machines



5.3.7 Glass

Glass is used for the windows in the cabin of the construction machine. The SimaPro process "Flat glass, uncoated RER" is used to calculate the impact of the glass. This process is used instead of the coated version because no sources have been found stating that excavator windows are coated.

Volvo CE provides the data of the glass content in their construction machines in their environmental product declarations. For some compact machines, there is no covered cab containing glass, but in general, the glass content seems to be essentially constant for two size ranges for both wheel loaders and excavators. Even though there are some deviations, such as the excavator weighing 35 tons and containing 30 kg of glass, which is significantly lower than the rest. A model is developed by recognizing this, which splits the glass content in the excavator into two ranges. The model sets a constant glass content of approximately 50 kg for machines weighing less than 10 tons and approximately 70 kg for machines weighing more than 10 tons, as shown in Fig.16. Mathematically the model can be described as such:

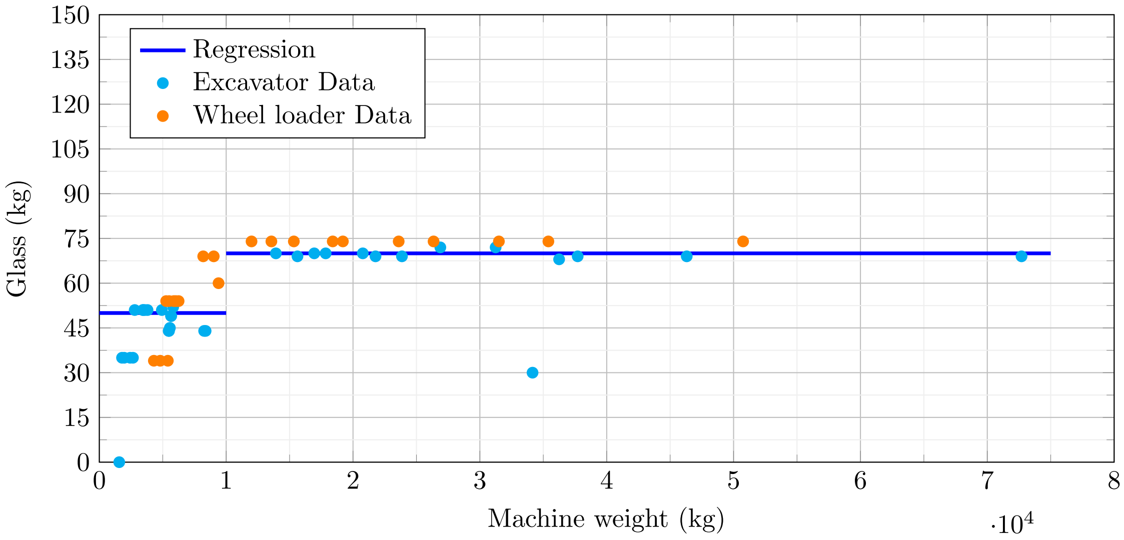
$$W_G = \begin{cases} 50, & \text{if } W_M < 10000kg \\ 70, & \text{if } W_M > 10000kg \end{cases}$$

Where W_G is the glass content of the excavator in kg. The total fitness of the model is:

$$R^2 = 0.8772$$

the R^2 value is relatively low compared with values from other elements of the manufacturing phase. The glass is however of relatively low importance to the result due to its low content, so it is not bad.

Figure 16: Relationship between the weight of glass and the weight of the construction machine



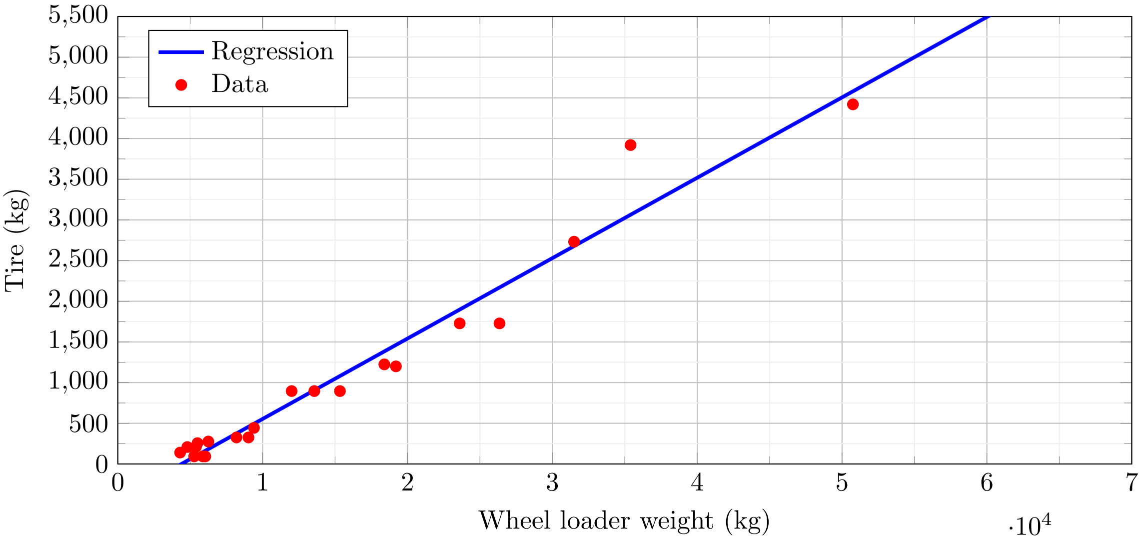
5.3.8 Tires

wheels consist of Polybutadine(Caterpillar, 2014) the SimaPro process "Polybutadiene GLO" is used. Wheeled excavators are not considered The regression is split to prevent negative numbers. A linear regression is found to give the best fit:

$$W_T = \begin{cases} 50, & \text{if } W_M < 5000kg \\ 0.0988 \cdot W_T - 434.13, & \text{if } W_M > 5000kg \end{cases}$$

$$R^2 = 0.9595$$

Figure 17: Relationship between the weight of tire and the weight of the wheel loader



5.3.9 Non-iron metals

The non-iron metals are assumed to consist of copper, bonze, and aluminum (Volvo CE, 2019). Copper makes up about 45 kg Bronze about 30 kg, and Aluminium the rest.

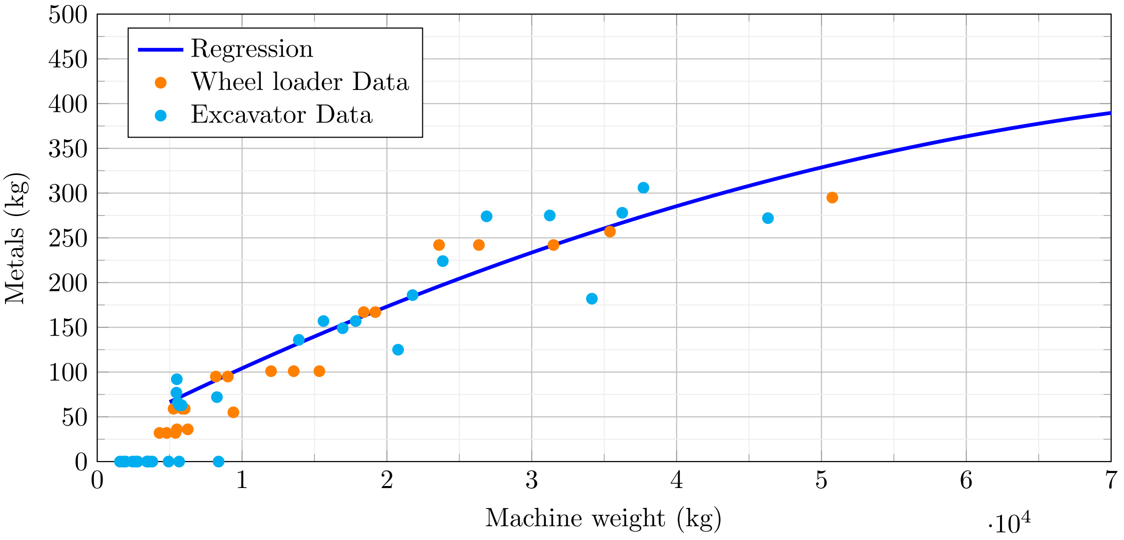
for machines weighing less than 5 tons there is assumed to be no non-iron metals

since the data is very similar a single model is made. metal weight W_m

$$W_m = -4 \cdot 10^{-8} \cdot W_M^2 + 0.0082 \cdot W_M + 26.725$$

$$R^2 = 0.9015$$

Figure 18: Relationship between the weight of non-iron metals and the weight of construction machine



5.4 End-of-life

The end-of-life is not considered here as an environmental impact. This assumption is due to much uncertainty regarding what the end-of-life entails, given how little data is available. Construction machines are usually sold out of the country without a way to track their final destination at the end of their economic life in Norway. Whether they are recycled, scrapped, or rusting on a garbage dump is unknown. Construction machines are primarily made of metals, especially steel, which is very recyclable, so it is very suitable for recycling. The usage of recycled material is neither considered in other sections of this thesis due to the uncertainty. Even if the environmental impact is considered, it is expected to have a minor contribution to the overall environmental impact(Jeremiassen, 2021). (Glorstad, 2021)

6 Results

The results from the calculations are presented. The focus of this thesis is the GWP, but other impacts of not is also pointed out. Abbreviations are used for the different impacts to (Table 2). For many results presenting the complete data set would be impractical so a 15 ton machine is used as a general reference point should it be needed due to it being a medium sized machine.

Impact category	Abbreviation	Unit
Global warming	GWP	kg CO2 eq
Stratospheric ozone depletion	SOD	kg CFC11 eq
Ionizing radiation	IR	kBq Co-60 eq
Ozone formation, Human health	OF_H	kg NOx eq
Fine particulate matter formation	PM	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	OF_T	kg NOx eq
Terrestrial acidification	A	kg SO2 eq
Freshwater eutrophication	E_F	kg P eq
Marine eutrophication	E_M	kg N eq
Terrestrial ecotoxicity	ET_T	kg 1,4-DCB
Freshwater ecotoxicity	ET_F	kg 1,4-DCB
Marine ecotoxicity	ET_M	kg 1,4-DCB
Human carcinogenic toxicity	HT_C	kg 1,4-DCB
Human non-carcinogenic toxicity	HT_NC	kg 1,4-DCB
Land use	LU	m2a crop eq
Mineral resource scarcity	RS_M	kg Cu eq
Fossil resource scarcity	RS_F	kg oil eq
Water consumption	WC	m3

Table 2: Abbreviations of impact categories

6.1 Productivity

The productivity of excavators and wheel loaders are calculated and plotted in figures 19 and 20 respectively. The plots show the relationship between productivity and machine weight. The plots have three different production estimates for the different ground conditions.

Figure 19: Relationship between the weight of an excavator and its productivity

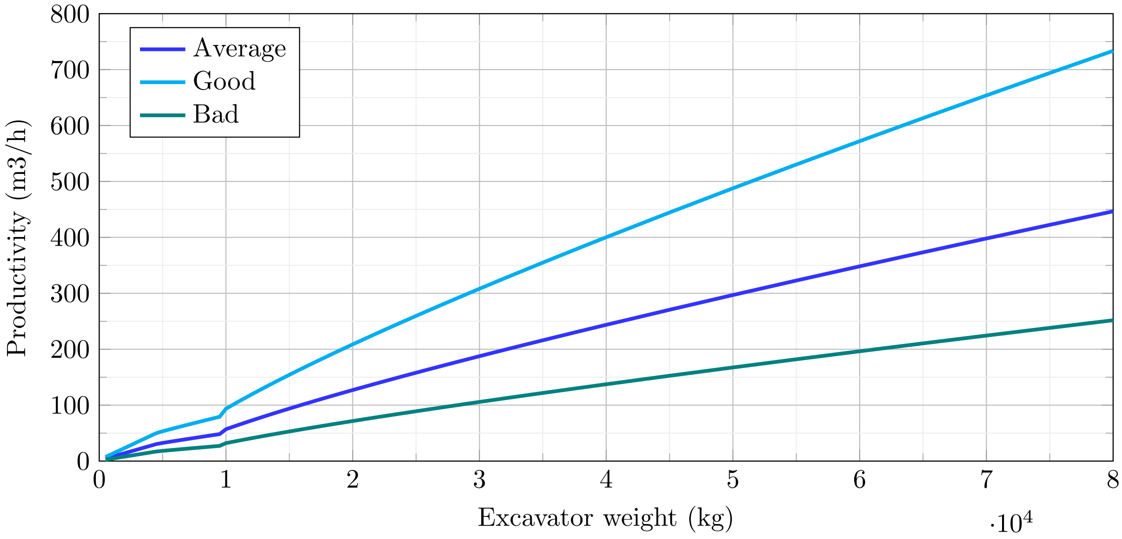
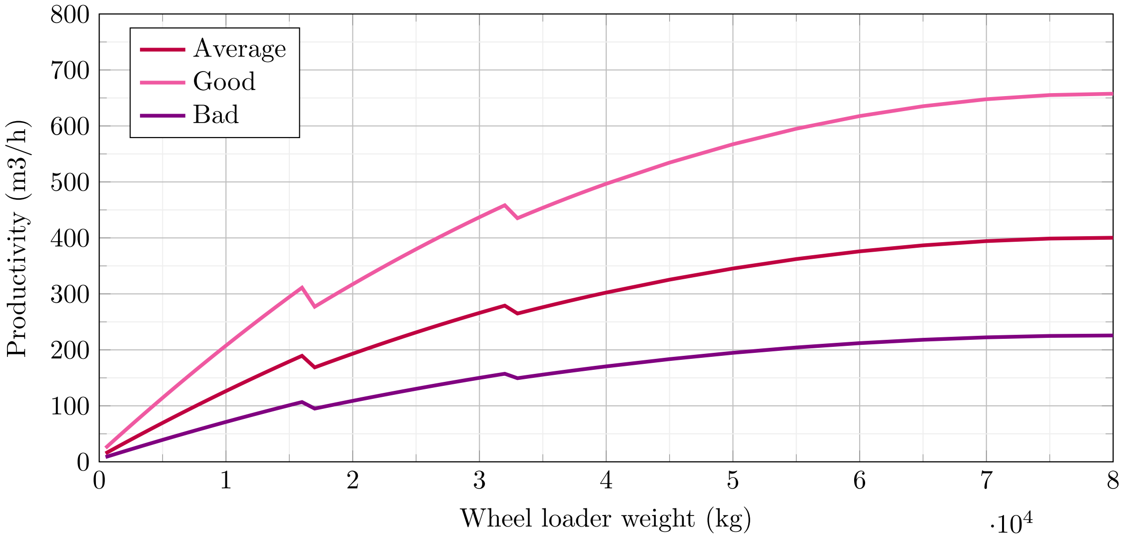


Figure 20: Relationship between the weight of a wheel loader and its productivity



6.2 Fuel production

The fuel production impacts are calculated as established earlier. The impacts from diesel and electricity production are presented for 15-ton wheel loaders and excavators in table 3. The table contains the impacts of diesel and electric machines for the impact categories used by SimaPro. The GWP impact is also further presented for excavators and wheel loaders separately in fig 21 and 22 respectively. The plots show the relationship between the weight of the machine, which dictates the total fuel consumption, and the total lifetime GWP impact from fuel production for the different fuels, diesel, Norwegian, and European electricity.

	Excavator			**Wheel loader**		
	Diesel	**Electric(NO)**	**Electric(EU)**	**Diesel**	**Electric(NO)**	Electric(EU)
GWP	31371,69	7144,524	127684,5	23742,84	5407,145	96634,62
SOD	0,059382	0,022913	0,072068	0,044942	0,017341	0,054543
IR	2297,771	2660,988	63552,5	1739,007	2013,899	48098,03
OF_H	134,0203	15,2565	237,7762	101,4297	11,54648	179,9547
PM	90,83071	15,33488	203,3068	68,74283	11,6058	153,8674
OF_T	142,2335	15,58102	240,1249	107,6457	11,79208	181,7322
A_T	268,3828	38,15379	513,0904	203,1185	28,87569	388,3189
E_F	2,885287	6,117972	127,1803	2,183654	4,630226	96,25303
E_M	0,230172	0,278035	8,883671	0,1742	0,210423	6,723372
ET_T	111257,1	205820	331771,5	84202	155769,5	251092,5
ET_F	496,7096	10165,64	14323,07	375,9215	7693,593	10840,04
ET_M	803,093	12388,69	18074,5	607,7998	9376,055	13679,21
HT_C	691,4684	1582,659	8391,048	523,3196	1197,794	6350,543
HT_NC	13182,26	48707,81	202796	9976,649	36863,22	153480,8
LU	391,1237	608,3759	4796,331	296,0117	460,4332	3629,976
RS_M	74,00061	141,6248	262,681	56,00541	107,185	198,8032
RS_F	75451,79	1096,413	33730,97	57103,7	829,7916	25528,39
WC	30,75835	9201,27	2182,124	23,27864	6963,738	1651,483

Table 3: The lifetime impact from fuel production for a 15 ton construction machine

Figure 21: The lifetime GWP impact from fuel production for excavators

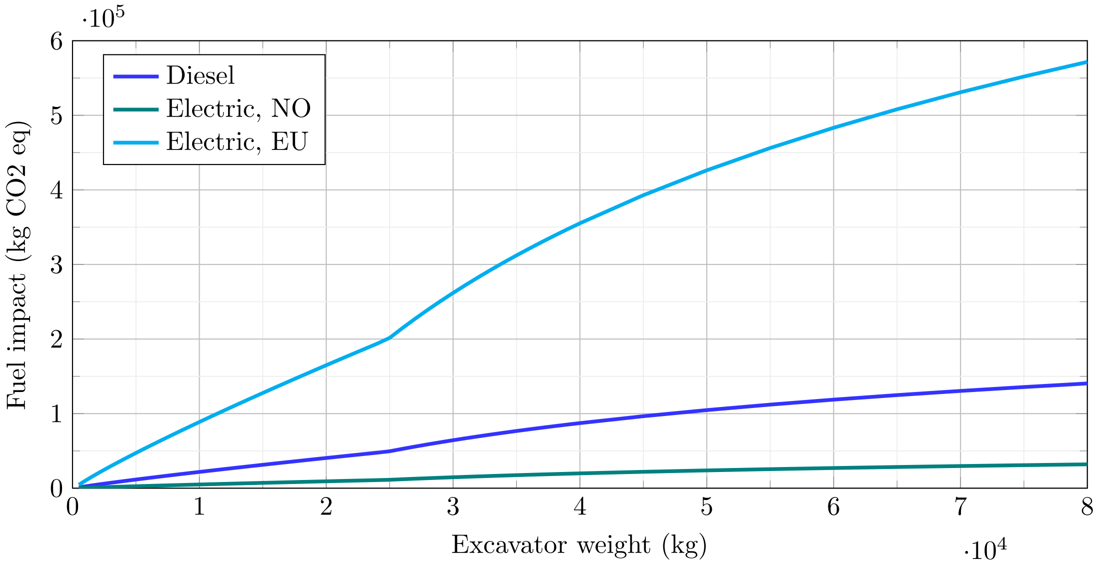
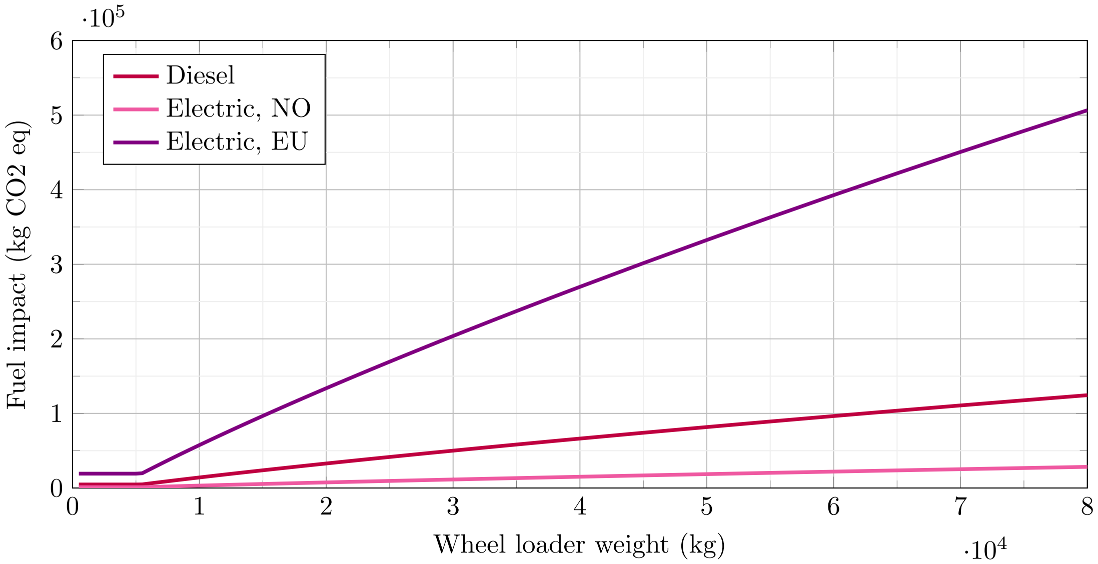


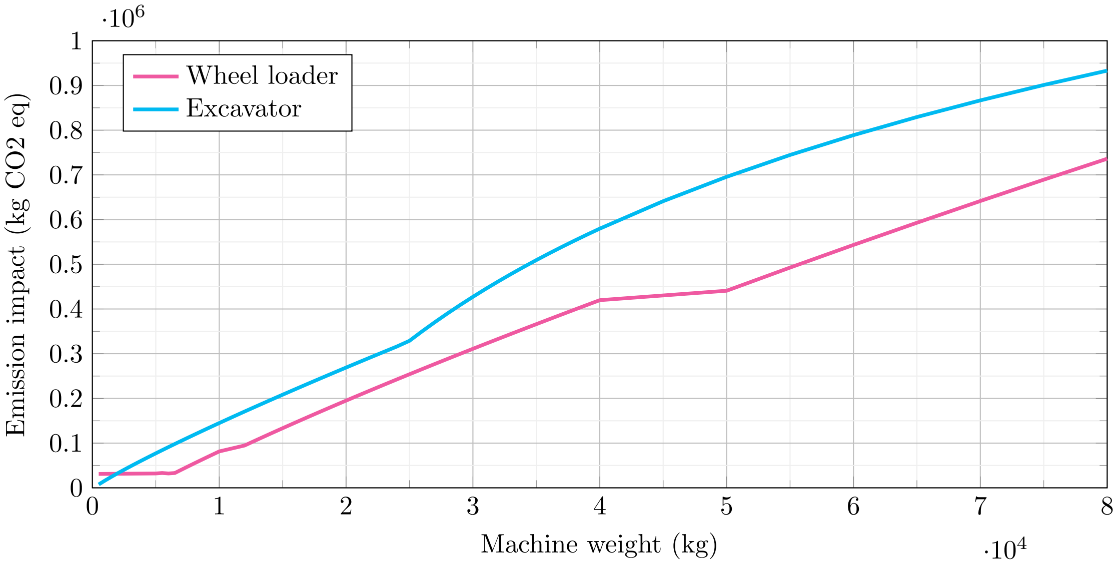
Figure 22: The lifetime GWP impact from fuel production for wheel loaders



6.3 Tailpipe emissions

The tailpipe emissions occurring as a consequence of the combustion of diesel are calculated according to the established method. Fig 23 plots the relationship between weight and GWP impact. It compares the lifetime GWP impact from tailpipe emissions for wheel loaders and excavators. Tables 4 and 5 show the environmental impacts from the lifetime tailpipe emissions of an assortment of weights of excavators and wheel loaders, respectively.

Figure 23: The lifetime GWP impact from tailpipe emissions for construction machines



	5000 kg	15000 kg	25000 kg	35000 kg	50000 kg	75000 kg
GWP	77128,69	208306,1	328859,8	509360,6	695635,4	901061,8
SOD	0,043665	0,116415	0,184398	0,288348	0,39854	0,523805
IR	0	0	0	0	0	0
OF_H	442,4138	128,5103	203,5557	318,3061	439,9463	578,226
PM	50,01968	19,48778	30,86595	48,25702	66,68301	87,6179
OF_T	447,6535	132,8343	210,4048	329,0161	454,7492	597,6816
A_T	157,1072	46,20002	73,17229	114,3907	158,052	207,6457
E_F	0	0	0	0	0	0
E_M	0	0	0	0	0	0
ET_T	53103,52	143502,9	226541,1	350829,9	479038,7	620357,4
ET_F	0,374844	1,012951	1,599096	2,476419	3,381413	4,378946
ET_M	23,85418	64,46172	101,7626	157,5933	215,1849	278,6655
HT_C	0,682904	1,845428	2,913289	4,511626	6,160374	7,977714
HT_NC	208,1553	562,5029	887,9964	1375,184	1877,737	2431,678
LU	0	0	0	0	0	0
RS_M	0	0	0	0	0	0
RS_F	0	0	0	0	0	0
WC	0	0	0	0	0	0

Table 4: The environmental impact from the lifetime tailpipe emissions of an Excavator

	5000 kg	15000 kg	25000 kg	35000 kg	50000 kg	75000 kg
GWP	32119,64	133364,8	254062,4	366105,9	440813,9	689221,4
SOD	0,044355	0,10232	0,168547	0,231141	0,273504	0,418233
IR	0	0	0	0	0	0
OF_H	446,5018	112,9503	186,0584	255,156	301,92	461,6856
PM	50,72529	17,03695	28,12736	38,60565	45,69511	69,90319
OF_T	450,0502	116,7507	192,3187	263,7412	312,0787	477,22
A_T	159,2974	40,29146	66,58803	91,42918	108,2341	165,6038
E_F	0	0	0	0	0	0
E_M	0	0	0	0	0	0
ET_T	21610,12	91343,41	174515,9	251703,5	303158,5	474174,3
ET_F	0,15254	0,64477	1,231864	1,776711	2,139919	3,347076
ET_M	9,707298	41,0316	78,39282	113,0656	136,1793	212,9998
HT_C	0,277903	1,174664	2,244252	3,236874	3,898578	6,097819
HT_NC	84,70738	358,0481	684,0679	986,628	1188,321	1858,669
LU	0	0	0	0	0	0
RS_M	0	0	0	0	0	0
RS_F	0	0	0	0	0	0
WC	0	0	0	0	0	0

Table 5: The environmental impact from the lifetime tailpipe emissions of a wheel loader

6.4 Manufacturing

The stacked bar chart shows the contribution of the materials used in manufacturing to the impact of a 15-ton electric excavator. For a diesel-driven excavator, the only difference is that there would be no Li-ion battery part (fig 24). Lead and oil are so slight that they do not show up. Fig 26 does not include the wheel loader data as it is entirely indistinguishable from the excavator data since there is little difference between the two machine types. Fig 26 shows the relationship between the excavator weight and the GWP impact and how electric machines generally have a higher manufacturing impact than diesel-driven machines. The pie charts in fig 25 show the percentage contribution of different materials to the total environmental impact of manufacturing for 15-ton machines.

Impact	**Unit**	**El excavator**	**Diesel Excavator**	**El Wheel loader**	**Diesel Wheel loader**
GWP	kg CO2 eq	55353,68	43686,62	55323,38	43656,32
SOD	kg CFC11 eq	0,023731	0,01494	0,022655	0,013864
IR	kBq Co-60 eq	4802,808	3943,102	4692,616	3832,91
OF_H	kg NOx eq	154,2849	109,1051	151,4815	106,3017
PM	kg PM2.5 eq	148,6208	85,20859	145,248	81,83576
OF_T	kg NOx eq	165,8201	119,4427	162,1232	115,7459
A	kg SO2 eq	318,9168	157,0633	322,8564	161,003
E_F	kg P eq	52,023	26,9455	49,83164	24,75414
E_M	kg N eq	3,095546	1,888045	2,914189	1,706688
ET_T	kg 1,4-DCB	1320304	400193,3	1298646	378534,7
ET_F	kg 1,4-DCB	25944,41	7918,622	25471,46	7445,672
ET_M	kg 1,4-DCB	32966,56	10134,39	32357,38	9525,203
HT_C	kg 1,4-DCB	16336,09	14320,05	14466,67	12450,63
HT_NC	kg 1,4-DCB	337964,3	111787,8	331132,4	104955,9
LU	m2a crop eq	1195,949	789,6067	1129,913	723,5707
RS_M	kg Cu eq	1985,198	1401,805	1804,63	1221,238
RS_F	kg oil eq	15389,18	12224,73	16655,07	13490,62
WC	m3	532,7907	383,4135	503,2225	353,8454

Table 6: Manufacturing impacts for different a types of 15 ton machine

5 xlabel=Machine weight (kg),

Figure 24: The percentage contribution of materials to the impact of an 15 ton electric excavator manufacturing

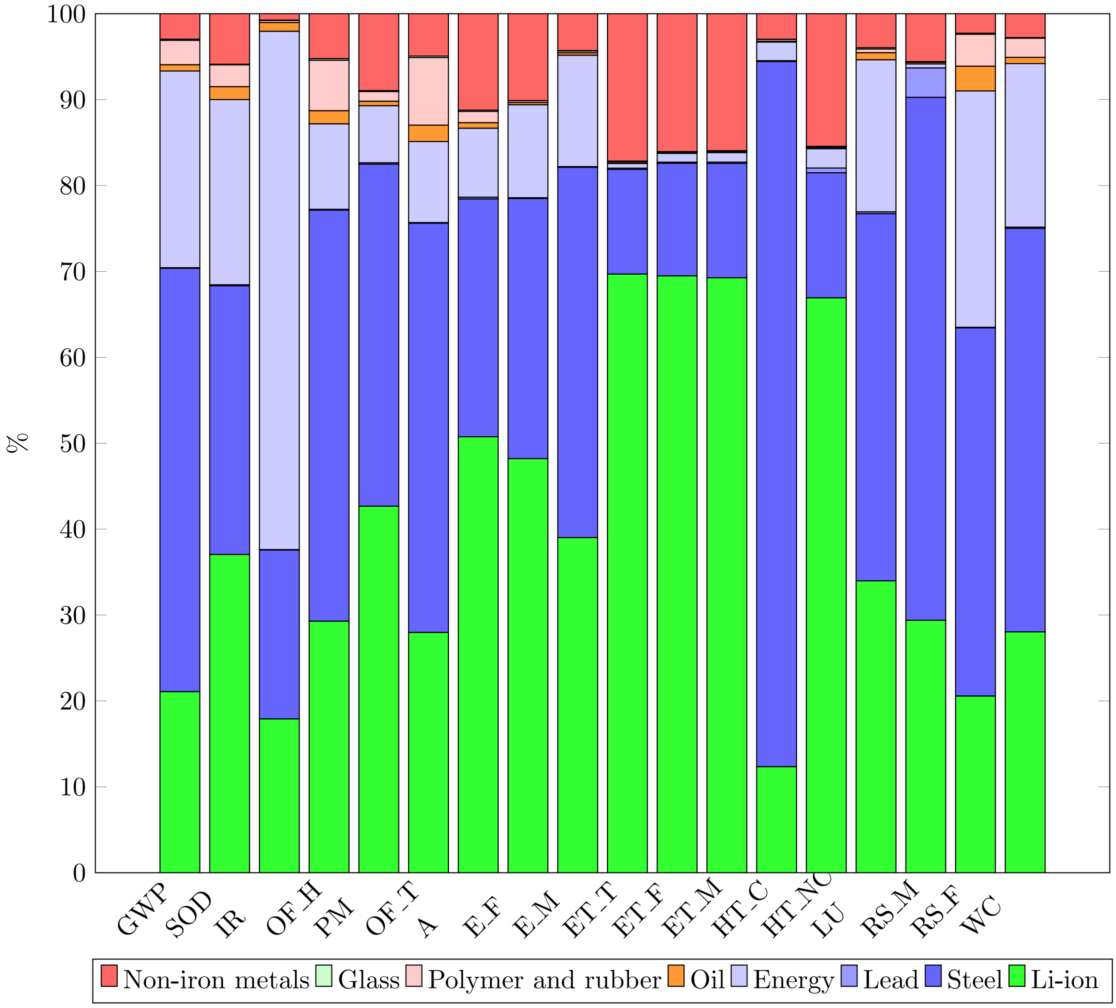


Figure 25: Pie charts of the the contribution of materials to the GWP of the different 15 tons machines. The upper left shows the Diesel wheel loader, the upper right the Electric wheel loader, the lower left shows the electric excavator and the lower right the diesel excavator

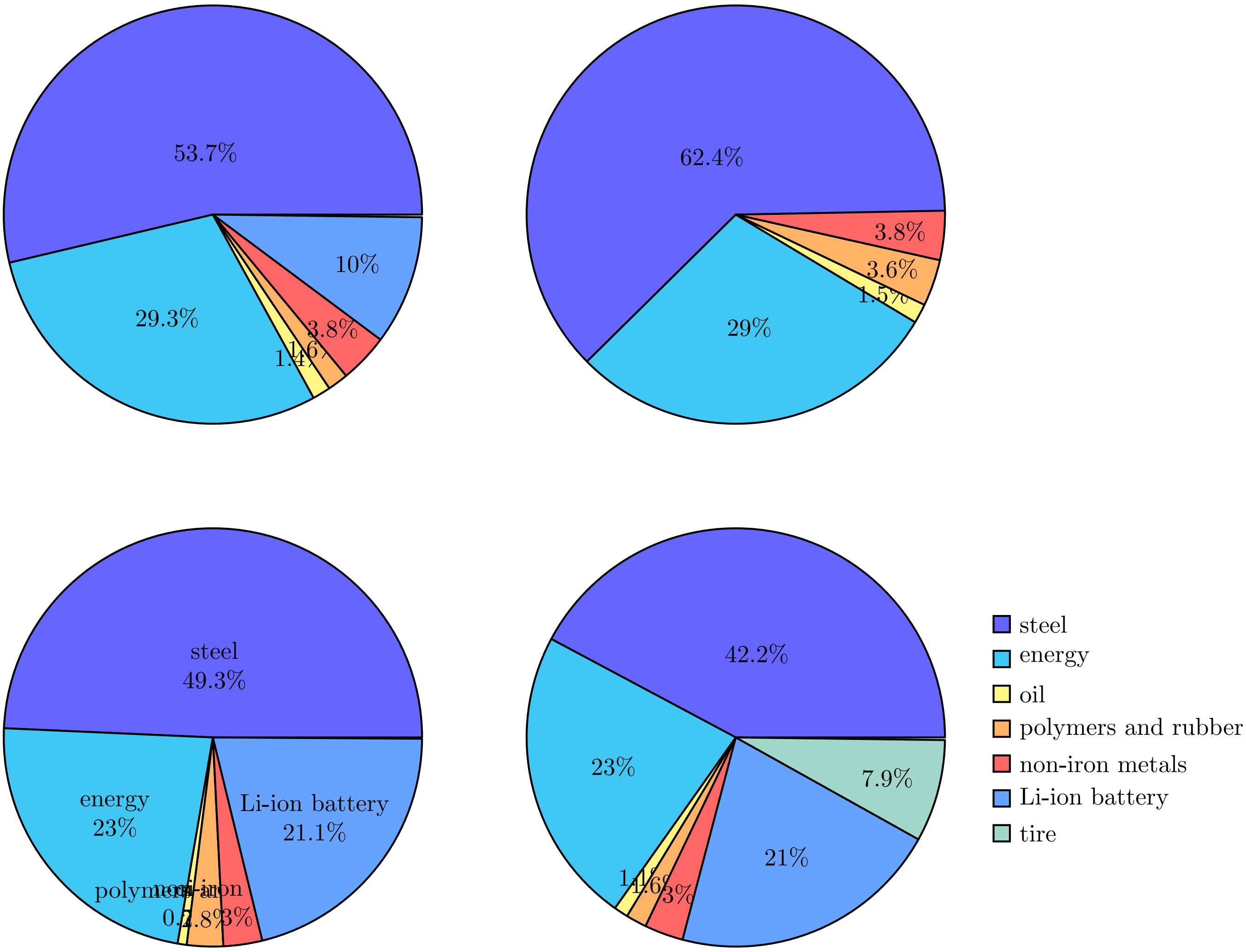
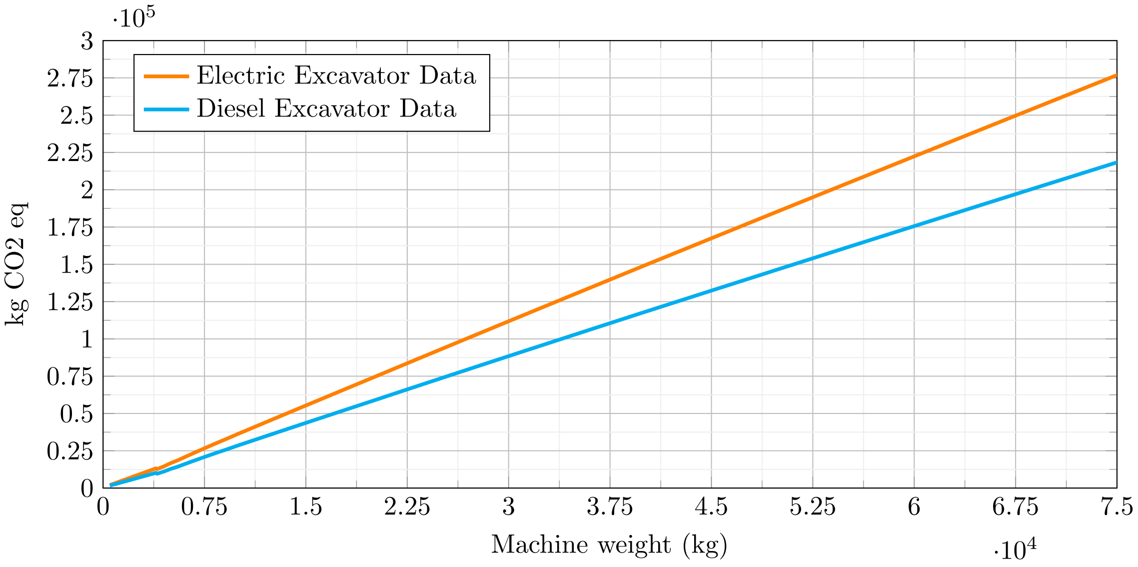


Figure 26: The GWP values for electric and diesel driven excavators



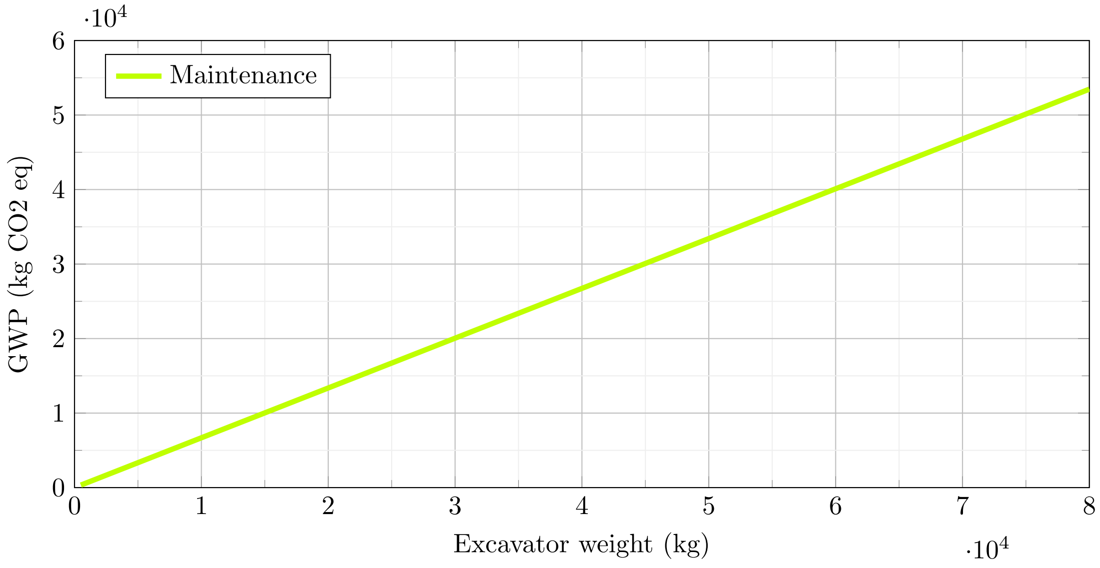
6.5 Maintenance

The last source of emissions considered in this thesis is maintenance. Maintenance is entirely linearly dependent on weight as the emissions factor for maintenance is multiplied by the weight (fig 27). No distinction is made between electric and diesel-driven or excavators and wheel loaders.

Impact categorie	Unit	Maintenance
Global warming	kg CO2 eq	10026
Stratospheric ozone depletion	kg CFC11 eq	0,004699
Ionizing radiation	kBq Co-60 eq	588,9491
Ozone formation. Human health	kg NOx eq	26,86992
Fine particulate matter formation	kg PM2.5 eq	20,08311
Ozone formation. Terrestrial ecosystems	kg NOx eq	29,24958
Terrestrial acidification	kg SO2 eq	44,35237
Freshwater eutrophication	kg P eq	3,583734
Marine eutrophication	kg N eq	0,254982
Terrestrial ecotoxicity	kg 1,4-DCB	34287,83
Freshwater ecotoxicity	kg 1,4-DCB	631,0248
Marine ecotoxicity	kg 1,4-DCB	835,6449
Human carcinogenic toxicity	kg 1,4-DCB	727,083
Human non-carcinogenic toxicity	kg 1,4-DCB	16974,76
Land use	m2a crop eq	309,1416
Mineral resource scarcity	kg Cu eq	391,0077
Fossil resource scarcity	kg oil eq	4478,014
Water consumption	m3	102,7172

Table 7: Impact from the maintenance of a 15 ton machine

Figure 27: Relationship between the weight of an excavator and its GWP impact from maintenance over its lifetime



6.6 Total

Finally the results for the total environmental impact are found. The total lifetime GWP impact is plotted against the machine weight in fig 28. All the variations of machines considered are included. The excavator and wheel loader running on Norwegian electricity are indistinguishable. Fig 30 shows the contribution of different emissions sources to the GWP impact for a 15-ton excavator.

The environmental impact per Lm3 is presented in fig 29. By averaging the GWP ratio of impacts for Diesel excavators and Electric excavators(NO) the average percentage of impact is found to be 24%. Said another way diesel excavators contribute 4 times more on average to global warming than electric excavators in Norway. similarly electrical wheel loaders in Norway are found to have on average 32% of the impact a diesel wheel loader would have, or 3 times less. For electric construction machines in the rest of Europe the data is not quite as promising. with electric excavators and wheel loaders, having an 65% and 74% of an diesel machine's impact respectively.

	Excavator			Wheel loader		
Impact category	Diesel	Electric(NO)	Electric(EU)	Diesel	Electric(NO)	Electric(EU)
GWP	293390,5	72524,21	193064,2	210789,9	161984	70756,53
SOD	0,195437	0,051343	0,100499	0,165825	0,081897	0,044695
IR	6829,822	8052,746	68944,26	6160,866	53379,6	7295,464
OF_H	398,5056	196,4113	418,931	347,5517	358,3061	189,8979
PM	215,6102	184,0388	372,0107	187,6986	319,1985	176,9369
OF_T	423,7601	210,6506	435,1945	369,3919	373,105	203,1649
A_T	515,9986	401,423	876,3596	448,7652	755,5277	396,0845
E_F	33,41452	61,72471	182,787	30,52153	149,6684	58,0456
E_M	2,373199	3,628562	12,2342	2,13587	9,892543	3,379594
ET_T	689241,1	1560412	1686363	588367,9	1584026	1488703
ET_F	9047,369	36741,07	40898,51	8453,263	36942,52	33796,08
ET_M	11837,59	46190,9	51876,7	11009,68	46872,23	42569,08
HT_C	15740,45	18645,83	25454,22	13702,21	21544,29	16391,54
HT_NC	142507,3	403646,9	557735,1	132265,3	501588	384970,4
LU	1489,872	2113,467	6301,421	1328,724	5069,031	1899,488
RS_M	1866,813	2517,83	2638,887	1668,251	2394,441	2302,823
RS_F	92154,53	20963,6	53598,16	75072,33	46661,47	21962,87
WC	516,889	9836,778	2817,632	479,8412	2257,422	7569,678

Table 8: The total impact from the lifetime of a 15 ton construction machine

Figure 28: The total GWP impact from the total lifetime of the construction machine

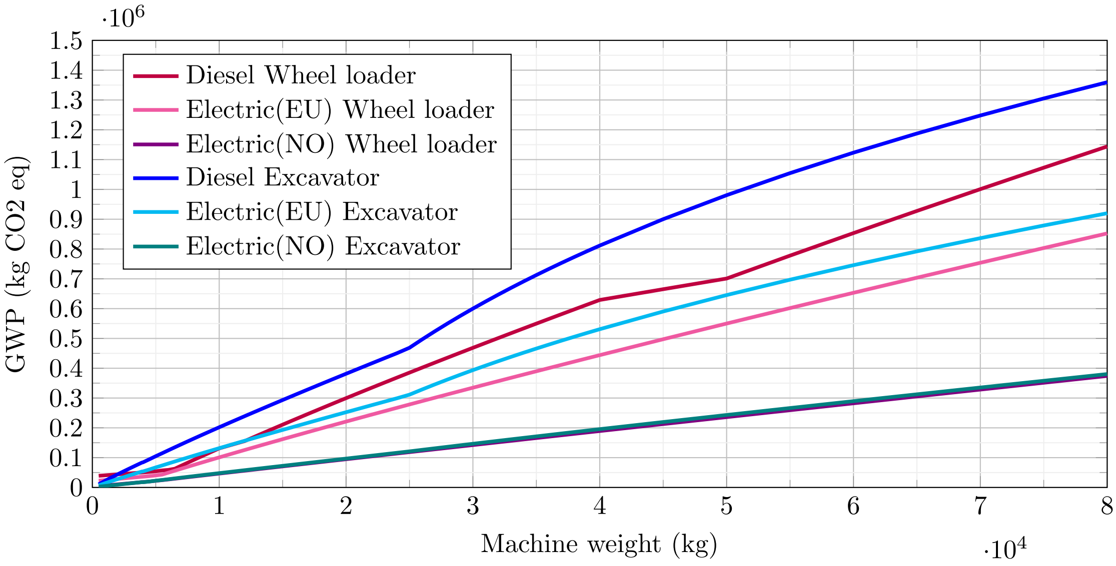
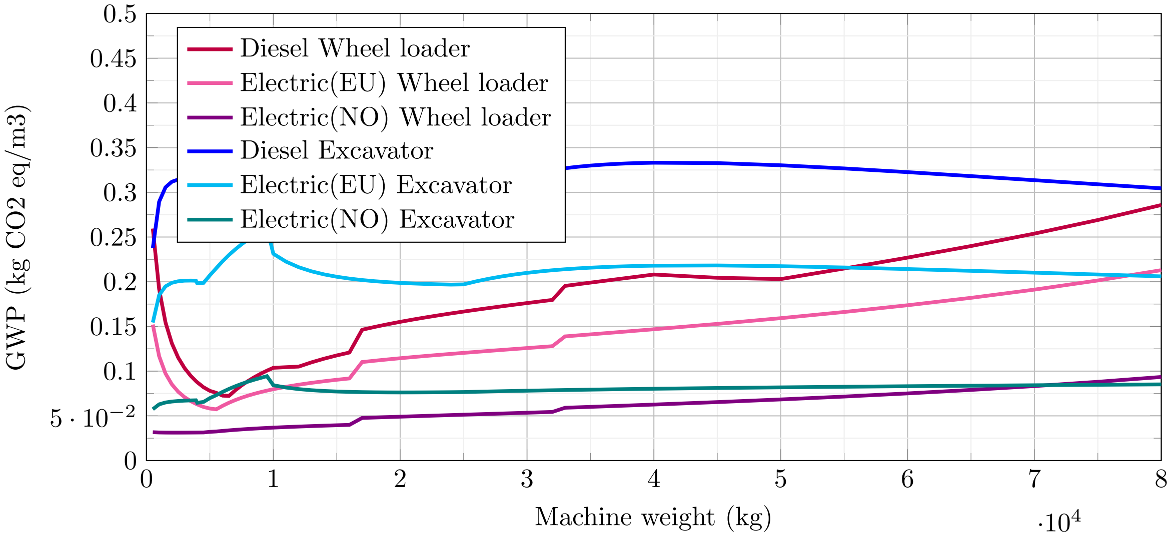


Figure 29: The total GWP impact from the total lifetime of the construction machine per m3 of average productivity



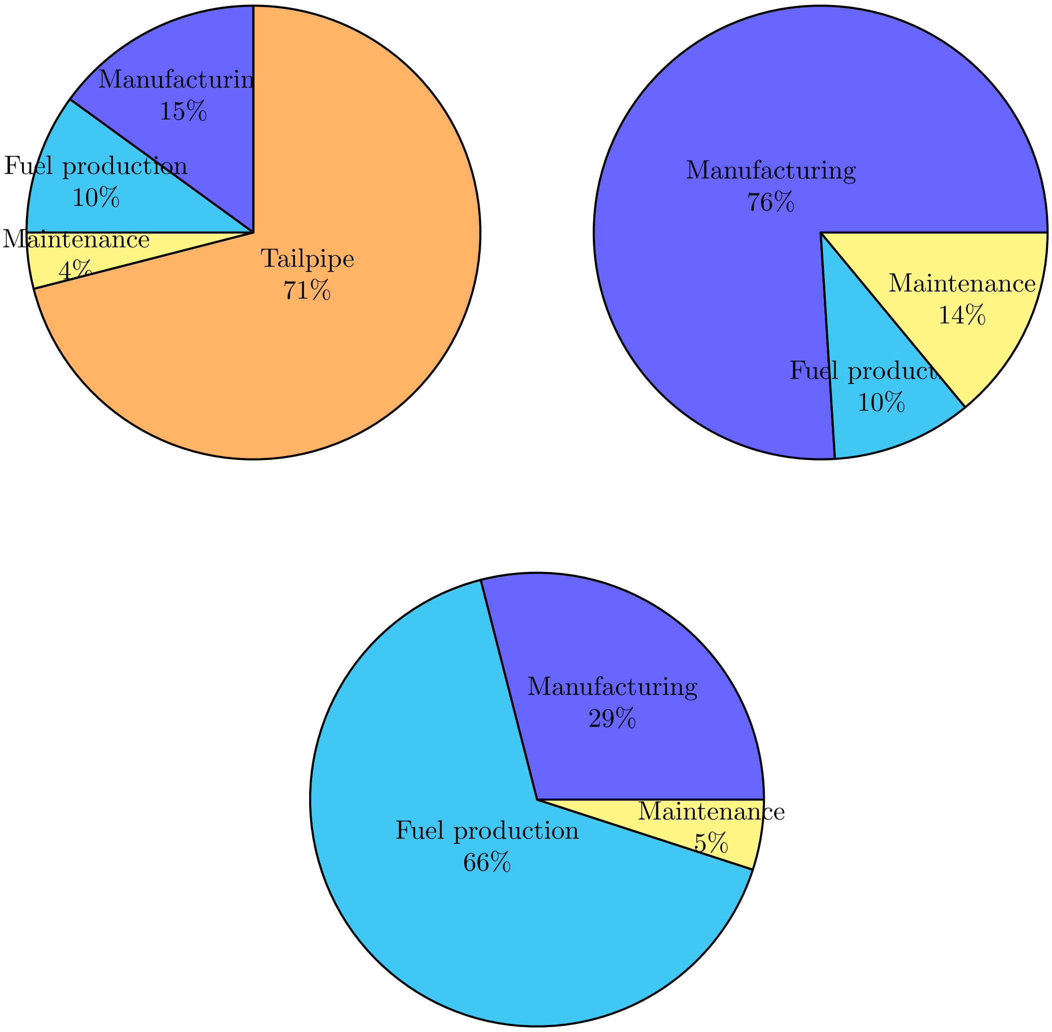
7 Discussion

For productivity, the wheel loader's plot is choppy due to the cycle time being limited to three ranges (fig 20). This choppiness is a weakness of the data used, and a more extensive cycle time model should be applied. The choppy segment has an 11% drop in productivity between the peak and bottom due to the cycle time model. This discrepancy is not enough of a difference to consider the results nonapplicable. The ground conditions have a much more significant impact. For both wheel loaders and excavators, good conditions increase productivity by 64%, while bad conditions decrease productivity by 44% (fig 19). By comparing these results with other productivity estimates, it can be seen that up to 60 tons excavator model fits perfectly. Afterward, it keeps growing while the others dab off but is still a decent fit until 75 tons. The wheel loader model, which slopes more, is an excellent fit (Caterpillar, 2014, Komatsu, 2009, Edwards et al., 2001).

The plots of the fuel production GWP impact, fig 21 and 22 clearly show a big difference in carbon intensity between the fuel types. A surprising result is how much more polluting electricity from the European grid is than diesel production. European electricity consistently has a GWP impact that is four times higher than diesel production. Also surprising is how much more polluting European electricity is compared with Norwegian electricity. SimaPro uses a CO2 intensity of 378 g per KWh for European electricity and 24 g per kWh for Norwegian electricity, which adds up to an almost 18 times higher GWP per kWh produced. Although surprising, these results are not necessarily incorrect. The table of the lifetime impacts from fuel production for a 15-ton construction machine shows that European electricity generally has quite high impacts compared with Norwegian electricity and diesel production. The impact of Ionizing radiation from European electricity has a 20 times higher impact than for Norwegian electricity and diesel production. This difference is probably caused by the presence of nuclear energy, which has a high impact on Ionizing Radiation. Another difference is Freshwater Ecotoxicity which for diesel production is rather low compared with the electricities. This impact is surprising for Norwegian electricity. Its origin is uncertain. Perhaps unsurprisingly, diesel production has quite a high impact on Fossil resource scarcity.

The tailpipe emissions over a diesel-driven construction machine's life are In fig 23, excavators are shown to have continuously higher carbon intensity than wheel loaders. Excavator seems to have 40% higher emissions throughout their life than wheel loaders. Although the excavator and wheel loader uses the same emission intensities and quite similar fuel consumption models, the load factor differs. However, more importantly, the power-weight relationship makes it so that a wheel loader that is as heavy as an excavator has a less powerful engine and thus has comparatively

Figure 30: Pie charts of the the contribution of different emissions sources to the GWP of a 15 tons excavator. The upper left shows the Diesel excavator, the upper right the Electric(NO) Excavator, and the lower shows the electric(EU) excavator



lesser tailpipe emissions. The tables 4 and 5 notably . The impact categories OF_H, PM, OF_T, and A_T, have lower higher impacts for construction machines weighing 5 tons than 15 tons. This conundrum is due to how EEA/EMEP(2019) handles engine size in their emissions factors. Smaller engines have significantly higher emissions of certain pollutants, importantly: NOx, BC, PM, CO, and CH4. Otherwise, there is a predictably increasing impact corresponding with weight.

Amongst the components contributing to the manufacturing impact, battery and steel are the most significant, repeatedly contributing to 70% of the total manufacturing impact between themselves (fig 24). The battery only contributes 20% to GWP, which is surprising when considering how for electric vehicles, the battery can increase the total manufacturing impact by more than double (Temporelli et al., 2020). Construction machines are, however, much heavier than vehicles and thus contain more steel, which also is a significant impact. The battery's biggest percentage contribution is the 70% of ecotoxicity and land use impacts due to the metals it contains and the land-intensive lithium harvesting. For wheel loaders tires are a significant 8-10% of the total GWP impact(fig 25). Fig 26 Shows the relationship between the manufacturing GWP impact and the excavator weight. The difference in GWP impact between the electric excavator and diesel excavator is pretty constant at 27% higher emissions for electric excavators.

The plot of the maintenance shows a linear correlation with the machine weight, which is unsurprising given that the calculation is only dependent on the machine weight(fig 27).

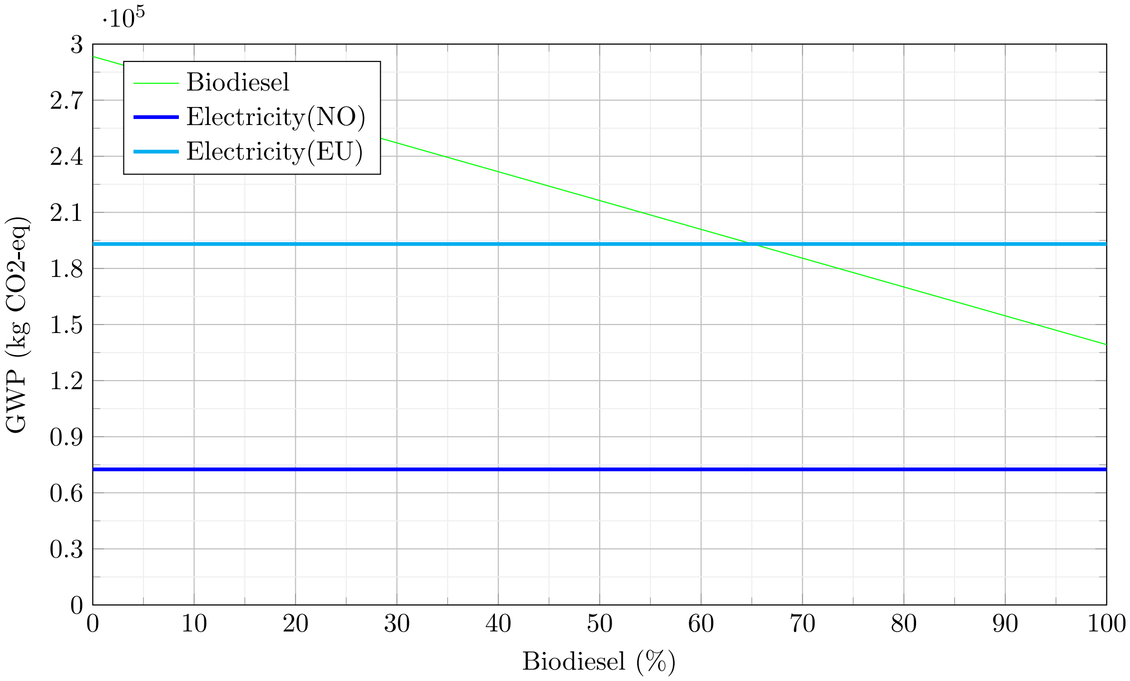
It seems that the GWP impact per Lm3 is almost constant for a given fuel source and construction machine regardless of weight (fig 29). Diesel excavators have a GWP per Lm^3 of about 0.32 (kg CO2-eq/Lm3), while the European electric excavator has a value of about 0.21 (kg CO2-eq/Lm3), and lastly Norwegian electric excavators have a value of about 0.08 (kg CO2-eq/Lm3). This means that Norwegian electric excavators are about four times less emission intensive than a diesel excavator. For wheel loaders the value is more variable. But the still the Norwegian electric wheel loader is about three times less emissions intensive than a diesel wheel loader. The effect of ground conditions are considered, and the Norwegian electric excavator has poor conditions, while the diesel excavator has good conditions. The diesel excavator would then have a average GWP impact per excavated Lm3 of 0.2(kg CO2-eq/Lm3), while the excavator would have a impact of 0.11(kg CO2-eq/Lm3), so the diesel excavator is still about twice as emission intensive than the Norwegian electric excavator.

The percentage contribution of different emissions sources to the GWP impact as shown in fig 30 is interesting. For the diesel excavator the tailpipe emissions represent the majority of emissions almost three quarters. Meanwhile for the European electric excavator the fuel production stands for the majority of emissions at 66%. Lastly for Norwegian electric excavators, the manufacturing is clearly the biggest contributor to the emissions, with over three quarters of the total GWP impact. so different emission sources have the majority of emissions in each of the fuel sources. For the European electric excavator this shows the importance of lowering fuel production emissions by using clean energy.

The effects of biodiesel on diesel-driven construction machines are considered. Biodiesel is assumed to have a direct effect on tailpipe emissions. Here any potential problems with using high percentage biodiesel blends are ignored(Lewis et al., 2009). Fig 31 shows the effect biodiesel has on the GWP impact. A significant decline can be observed with the GWP impact at 100% biodiesel being more than halved. Compared with the modest impact of electric construction machines running on Norwegian electricity, the impact is still relatively high, with it being almost twice as big. However, compared with electric construction machines running on European electricity at 65% biodiesel, these are equal in the GWP impact. At higher percentages, the diesel-driven machine has a lower GWP impact. This conclusion shows that there is potentially a significant gain to using higher concentrations of biodiesel. This scenario is, however, simplified and should be taken as such. Nevertheless, it does show that in countries with high carbon intensity electricity, steps need to be taken to ensure the lowering of the carbon footprint of electricity. It has an enormous effect on the overall impact and might, in this case, contribute to diesel-driven construction machines being a better choice from an environmental perspective.

Steel is a major contributor to the total GWP impact, especially for electric construction machines running on Norwegian electricity, where manufacturing is 76% of the total impact (fig 30). In

Figure 31: comparison between a 15 tons diesel excavator with various levels of biodiesel in its fuel and electric excavators both on Norwegian and European electricity



itself for manufacturing of electric construction machines steel contributes 50-60% (fig 25). Steel is also impactful worldwide, reportedly 8% of the industrial emissions stemming from steel. Any potential impact reduction from steel would therefore be important for lowering the total GWP impact, as well for the other impact categories where steel also is a big factor(fig 24). In 2022 Volvo CE became the first manufacturer to sell a construction machine with fossil-free steel (O'Leary, 2022). Such developments in the construction sector are essential for lowering the environmental impact of construction machines.

Infrastructure is a factor that has not been considered in this thesis but could prove to be a significant factor in the environmental impacts of an electric construction machine. Due to the electrical grid capacity being limited in urban areas or nonexistent in rural areas, or electricity being otherwise unavailable, extra infrastructure is often required for electric construction machines. This extra infrastructure can take the form of a container holding a battery pack, a transformer, and various electrical components. The battery pack used to supply a 25-ton electric excavator has a capacity of 390 kWh, enough to charge it once and some more (Mediaas and Abelgaard, 2022). Such a battery pack has an approximate GWP impact of 24198 kg CO2-eq, which is found using the same SimaPro process as for electric construction machines. The machine itself has an impact of 121062 kg CO2-eq (28). This additional impact represents a significant 20% increase in the excavator's impact if it is assumed to last the whole lifetime of the excavator. .

A case is considered to explore the effect of electric excavators further while adding the impact from the battery pack. In Lademoen Trondheim, a construction project took place in 2021/2022 on the initiative of Trondheim Kommune. A 25-ton electric excavator with an additional battery pack with 390 kWh capacity was used for digging. In one month, the excavator used 8037 kWh. When comparing this performance to a diesel-driven excavator, the gain in GWP is found. In total, by using an electric excavator compared with a diesel-driven excavator, there was a reduction in emissions of 2135 kg CO2-eq for the month. This number was found by using the total GWP and finding how big part of the lifetime this is.

The battery of an electric construction machine will lose some of its capacity over its lifetime. In total, a loss of 30% is expected in the battery's capacity over its lifetime of use (Yang et al., 2019). This loss indicates that there is still much life left in the battery after its useful life in the construction machine is over, which might be used for other purposes, such as grid balancing applications. The loss characteristics also support the claim that electric machines might have longer lifetimes than diesel-driven ones.

There are points of improvement. A better deterioration model that takes into account differences in the deterioration of electrical machines. A uncertainty model should be considered to get a better idea if the results are trustworthy. A sensitivity analysis should have been performed. Regionalization in terms of how operation conditions might impact the machine could have been implemented. Given that regional factors such as weather and ground conditions might significantly impact the results. It can be imagined that in Norway the weathers and climate is generally harsher on construction machinery than the reference data suggests, with more rain and colder climate. ground conditions might also be different with higher content of rocks. This can lead changes in cycle time, bucket fill, load dependent emissions, and ultimately the environmental performance of the construction machine. There is also uncertainty regarding how these potential differences might impact electrical and diesel driven construction machinery differently, such as whether a higher degradation of battery capacity should be expected over time. These regional operational conditions are not considered here. The transportation from manufacturer to Norway and consumer is not considered due to the variability in distance and uncertainty in transportation means. Multiple Scenarios should have been explored with also considering the economic aspects of the machines.

8 Conclusion

The environmental impact of excavating 1 Lm3 was found using a production-based model. It was concluded that there is a significant potential for decreasing environmental impacts by further adopting electric construction machines. With a focus on global warming, there is an apparent environmental gain to the further adaptation of electric construction machinery. However, there is still much potential for reductions in the environmental impacts of diesel-driven and electric construction machines. In the European electrical market, Steps should be taken to ensure the lowering of the carbon footprint of electricity. The carbon footprint has a massive effect on the overall impact and might, in some cases, contribute to diesel-driven construction machines being a better choice from an environmental perspective.

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