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Calculating use-phase greenhouse gas emissions of hydraulic components

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Abstract.

Climate change, increasing regulation, and heightened customer demand require transparent emissions calculations and sustainable product development. Currently, no standardized procedure to quantify use-phase greenhouse gas emissions of hydraulic components exists. On machine level emissions can be measured at the tailpipe or calculated, but the link to components is missing. This paper addresses this gap by developing and validating a methodology as baseline for further standardization. Using a wheel loader as a reference, two allocation approaches are derived for a hydraulic pump in a travel drive: First an approach based on the component's energy loss and second an extended approach that additionally accounts for primary energy supply efficiency. Meaningful comparisons across energy carriers such as diesel and electricity require qualitative emission results from machine level being reflected on component level. The proposed methodology provides, to the authors knowledge for the first time, such a framework for calculating use-phase greenhouse gas (GHG) emissions of hydraulic components. Further, it establishes the methodological foundation for assessing the impact energy carriers on component emissions and supports sustainability-oriented design decisions in fluid power systems. This work thus contributes to the creation of a standardized emissions assessment method that allows companies to promote sustainable products and differentiate themselves in the market through reduced energy losses and thus lower emissions.

Keywords. greenhouse gas emissions, use phase, hydraulic components, product carbon footprint, non-road mobile machinery, mobile working machines.

1. INTRODUCTION

Hydraulic machinery, including non-road mobile machinery (NRMM), is estimated to contribute nearly four percent to global greenhouse gas (GHG) emissions [1], thereby significantly influencing climate change. In response to increasingly stricter regulatory frameworks – such as the EU Green Deal [2] – industrial stakeholders are under growing pressure to implement credible emission reduction strategies. Compliance with these requirements is not only a legal obligation but also gaining economic importance, as companies seek to avoid penalties and strengthen their market competitiveness. Consequently, many companies are establishing strategic sustainability targets that rely on robust and comparable metrics, particularly for GHG emissions. Customers and investors are also increasingly demanding such transparency, making these metrics a key differentiator.

The concept of a “footprint” as a quantified measure of the ecological impact of human activities has gained significant traction across society. Given the urgent need for climate action, the quantification of GHG emissions has become highly relevant. The Product Carbon Footprint (PCF) refers to the total GHG emissions associated with a product across its entire life cycle, expressed in carbon dioxide equivalents (CO_2e). This measure encompasses all greenhouse gases, not only carbon dioxide. [3]

Several frameworks exist for calculating GHG emissions, including the Greenhouse Gas Protocol (GHG Protocol), DIN EN ISO 14067, and the Product Environmental Footprint (PEF). These frameworks offer standardized guidance for companies to systematically assess, quantify, and reduce GHG emissions [4], [5], [6]. However, while they provide general methodological scaffolding, they leave room for interpretation. To increase comparability and specificity, Product Category Rules (PCRs) have emerged [7]. These are often initiated by industry consortia to define more granular rules for specific product groups. Furthermore, more specific standards like DIN EN ISO 14083 (ISO 14083) can arise. This specific one focusses on emission accounting for supply chains [8]. Currently, no PCRs or specific standards exist for either NRMM or hydraulic components to the authors knowledge. Some companies have disclosed internal procedures for PCF calculation, yet these remain proprietary and are not standardized. The existing more specific standards are mainly used by companies for calculating cradle-to-gate GHG emissions and do not offer companies enough guidance to calculate use-phase emissions.

The present work addresses this gap by developing a methodology as baseline for further standardization in calculating use-phase GHG emissions of hydraulic components in NRMM, while accordance with existing standards is not the focus. The goal is to provide a methodology that enables companies to transparently assess and reduce these emissions of individual hydraulic components including comparison of application in NRMM using different energy carriers. Firstly, section 2 introduces a representative reference machine. Based on this, a method for calculating use-phase GHG emissions at machine level is illustrated. In the end of section 2 the research question is derived describing the challenge of emissions attribution to component level, especially with different energy carriers. In section 3 a methodological approach based on component’s energy losses for assigning use-phase GHG emissions is developed, validated and discussed for an exemplary hydraulic component. In section 4 this approach is extended to include the primary energy supply to achieve consistent results between component and machine level emission calculations with different energy carriers.

2. GHG EMISSIONS OF REFERENCE WHEEL LOADER

2.1. Definition of the Reference Wheel Loader

To understand the relevant interdependencies and to ensure comparable emissions results, it is essential to first define system boundaries. A wheel loader serves as the reference machine in this study. Using a system perspective similar to [9], the wheel loader as a machine can be structured into systems such as the primary energy supply, travel and implement drives, and auxiliary systems, shown in Figure 1.

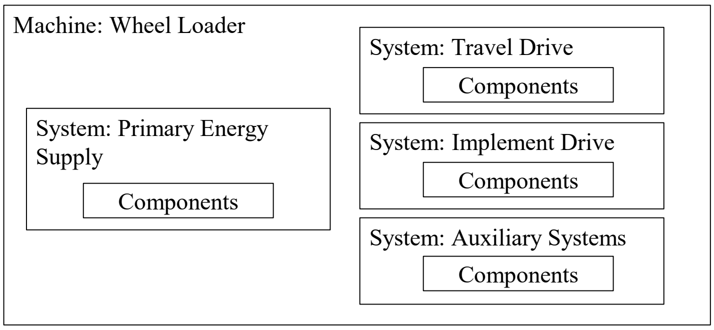

Figure 1: Structuring of wheel loader (based on [9])

The primary energy supply can be realized with various energy carriers, including diesel fuel, electrical energy, or hydrogen [9]. In this study, two configurations are examined:

- A diesel-powered wheel loader.
- A battery-powered wheel loader.

For the diesel variant, the primary energy supply consists of a fuel tank and an internal combustion engine on component level. In contrast, the electric version replaces these components with a battery, an inverter, and an electric motor. Other topologies for electric powertrains are not considered here to maintain conceptual clarity.

This study focuses on component level analysis of an axial piston unit (swashplate type) as pump within the hydrostatic travel drive system (closed circuit). The internal charge pump is excluded from the analysis for simplification. It is further assumed that the operating points of the hydraulic pump remain identical across both energy configurations.

2.2. GHG Emissions Calculation of Wheel Loader

Initially, the reference machine is analysed in both energy configurations. The methodology for calculating use-phase GHG emissions of the reference machine is based on established frameworks and industry practices in automotive and construction equipment sectors like [10].

The cited share of around 4 % of global GHG emissions coming from hydraulic machinery refers to emissions from diesel combustion [1]. These emissions can be measured at the tailpipe, but with the large variety of possible configurations of NRMM, this would lead to high measuring efforts being time- and cost-intensive. As an alternative, the GHG Protocol recommends calculating emissions via Activity Data and Emission Factors, as illustrated in Equation 2.1.

$$\text{GHG Emissions} = \text{Activity Data} \times \text{Emission Factor} \qquad (2.1)$$

Activity Data quantify the extent of a process that emits GHG emissions (e.g. energy consumed). An Emission Factor denotes the GHG emissions per unit of activity, expressed in CO_2e. The chemical energy of combusted diesel fuel over an assumed reference lifetime represents the Activity Data of the diesel machine. Since measurement data of the amount of fuel combusted are available from the diesel-powered wheel loader, it serves as the base case. From this, Activity Data for the electric variant are derived.

A usage profile was needed to obtain this measurement data. Unlike passenger cars, where standardized drive cycles like Worldwide Harmonized Light Vehicle Test Procedure (WLTP) exist, no standardized usage profiles are available for NRMM like wheel loaders [11]. Hence, a representative usage profile was used consisting of working and driving tasks as well as idling. Such a usage profile consists of typical cycles and their time shares within the overall operating period. This work provides no further details concerning the used cycles since they are subject to many parameters and therefore very individual.

During test drives with the wheel loader, the fuel consumption for each cycle was measured. Average values were calculated per cycle and weighted according to their time shares. Concluding, the average fuel consumption for the assumed usage profile of the wheel loader is 7.7 $\mathrm{l/h}$. With a density of 0.743 $\mathrm{kg/l}$ and a lower heating value of 42.5 $\mathrm{MJ/kg}$, according to [16], and an assumed reference lifetime of 10.000 h equates to 675.42 MWh, equaling the Activity Data of the diesel configuration ($\mathrm{E_{In,Diesel}}$).

A diesel engine efficiency of 40 % is assumed similar to [12] and [13]. In the electric configuration, the efficiency of battery, inverter, and electric motor is assumed to be 81 %. To provide the same useful energy, only around 49 % of the diesel input energy is required electrically equating to 330.96 MWh as Activity Data of the electric configuration ($\mathrm{E_{In,Electric}}$).

An **Emission Factor** is now needed to translate Activity Data into GHG emissions. If only tailpipe emissions were considered, the electric loader would appear emission-free. However, GHG emissions are also generated during electricity generation and supply. Hence, system boundaries must be distinguished [14]. For instance, [14] uses well-to-tank and tank-to-wheel which are also used by companies like Volvo Construction Equipment in their emission reporting [10]. ISO 14083 introduces the terms energy provision and operation for these boundaries [8]. ISO 14083 aims to define guidelines for quantifying GHG emissions from passenger and freight transport chains. The term GHG emissions from energy provision refers to the release of greenhouse gases during the production, storage, processing, and distribution of energy carriers for use in transport chains. GHG emissions from operation, on the other hand, refer to the release of greenhouse gases due to the operation of vehicles or locations. This enables ISO 14083 to also make statements about locations in logistics where the term tank-to-wheel would be inappropriate. At the same time, energy supply can serve as a direct substitute for well-to-tank and operation for tank-to-wheel in vehicles, which is why the terms used in ISO 14083 are used for this work. [15]

- Energy provision (well-to-tank) and
- Vehicle operation (tank-to-wheel).

The total use-phase GHG emissions for the diesel configuration ($\mathrm{GHG_{Machine,Diesel}}$) are calculated as:

$$\mathrm{GHG_{Machine,Diesel}} = \mathrm{E_{In,Diesel}} \times \left(\mathrm{EF_{Operation,Diesel}} + \mathrm{EF_{Provision,Diesel}}\right) \quad (2.2)$$

For diesel, Emission Factors from [16] are used within the framework of ISO 14083, which are also used here. According to [16], the Emission Factor for diesel combustion ($\mathrm{EF_{Operation,Diesel}}$) is 0.271 kg $\mathrm{CO_2e/kWh}$. An additional 0.081 kg $\mathrm{CO_2e/kWh}$ is released during diesel supply chain processes ($EF_{Provision,Diesel}$). According to these Emission Factors, total use-phase GHG emissions from the diesel-powered wheel loader are

- 77 % from operation, and
- 23 % from energy provision.

With Equation 2.2 $GHG_{Machine,Diesel}$ calculates to 237.75 t CO_2e with the earlier calculated Activity Data and introduced Emission Factors, being the total of the left bar in Figure 2.

For the electric variant GHG emissions ($GHG_{Machine,Electric}$) are calculated as:

$$GHG_{Machine,Electric} = E_{In,Electric} \times EF_{Provision,Electric} \tag{2.3}$$

Since no emissions occur during operation, only the energy provision is relevant. The Emission Factor for energy provision ($EF_{Provision,Electric}$) in the German electricity mix is both region- and time-dependent. [16] provides a value for energy supply in the German electricity mix for 2022. The values change every year by a significant amount [17]. In this work, the 2024 factor published by the German Environment Agency (UBA) of 0.427 kg CO_2e/kWh is used [17]. This factor includes all processes mentioned earlier for energy provision. Not taking all the provision processes into account is one reason why varying factors may arise. Since the efficiency of the electric drivetrain is assumed with 81 % instead of the 40 % of the diesel drivetrain and with the different Emission Factors, $GHG_{Machine,Electric}$ equates to 141.32 t CO_2e. This results in total use-phase GHG emissions of the electric wheel loader being approximately 59 % of the diesel variant, a 41 % reduction in use-phase emissions, as shown in Figure 2.

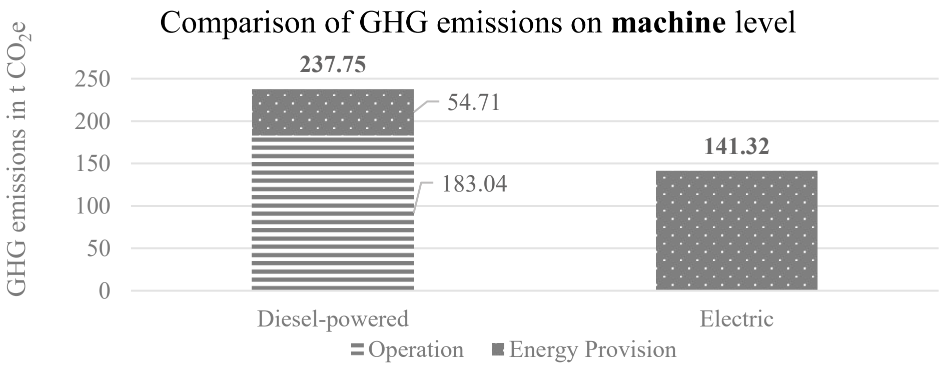

Figure 2: Comparison of wheel loader's use-phase GHG emissions for operation and energy provision with different energy carriers

Emissions from operation are depicted striped in white and grey and energy supply emissions are white dotted on grey background. While the electric loader produces no operational GHG emissions, the energy provision emissions are higher than those of diesel. Nonetheless, the overall emissions are significantly lower in the electric configuration under the given assumptions.

2.3. Research Questions

However, the presented approach offers no resolution at system or component level. While methods for assessing emissions from hydraulic components during production stages exist, a methodology for evaluating their use-phase emissions remains absent to the authors knowledge. Even though the emissions of the use-phase on machine level are dominant, especially for diesel-powered machines [18]. Given that GHG emissions of hydraulic components cannot be measured, it remains uncertain how their use phase emissions can be quantified. However, for regulatory and customer requirements, companies must be able to disclose and ultimately reduce these emissions transparently.

As used for the machine level approach shown previously, this paper investigates how a component level approach can also rely on Activity Data and Emission Factors. As alternative energy carriers like electricity rise in importance, e. g. [12] [19], a key requirement is that qualitative emission trends at the component level must be consistent with those at machine level, when comparing different energy carriers. In order to attribute use-phase GHG emissions to hydraulic components the following research question must be answered:

How can use-phase GHG emissions of hydraulic components be determined, while allowing consistent comparisons across different energy carriers?

In the following, approaches to answer this question are developed, validated and discussed by focusing on the hydraulic pump of the travel drive of the wheel loader in two different energy carrier configurations.

3. FIRST APPROACH

3.1. Methodology

In the first step, the diesel-powered wheel loader is taken as a reference. Firstly, only GHG emitted during machine operation are considered. The activity that causes these emissions is characterized by energy flow, as illustrated in Figure 3.

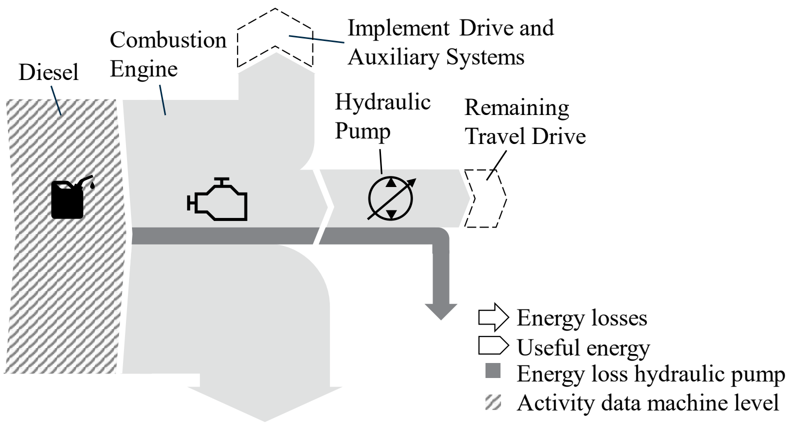

Figure 3: Sankey diagram of diesel-powered wheel loader

In this configuration, diesel serves as input energy. Through combustion in the internal combustion engine, chemical energy is partially converted into mechanical energy, while the remaining portion dissipates, indicated by the light grey arrow pointing downwards. The mechanical energy is distributed among the implement drive and auxiliary systems (indicated by the upward pointing arrow) as well as the travel drive (indicated by the arrow pointing right), which includes the here focussed hydraulic pump. The pump transforms mechanical energy into hydraulic energy, whereby hydromechanical and volumetric losses occur [20], which are summarized as dark grey arrow.

The combustion results in GHG emissions, which are measurable at the tailpipe. As diesel is both an energy carrier and a source of emissions, the chemical energy supplied to the machine is directly proportional to the resulting GHG emissions. Accordingly, the supplied chemical energy (E_{In}) represents the Activity Data on machine level, depicted with a grey hatch, for use-phase emissions, as used in Equation 2.2.

The engine supplies this energy to downstream systems and components, which in turn dissipate part of it and pass the remainder along. The sum of energy loss from each component ($E_{Loss,Component}$) and the useful energy output, for working or driving tasks, (E_{Task}) equals the input energy:

$$E_{In} = \sum E_{Loss,Component} + E_{Task} \tag{3.1}$$

With Equation 2.2 this leads to Equation 3.2 with EF representing Emission Factors for energy provision and operation.

$$GHG_{Machine} = \left(\sum E_{Loss,Component} + E_{Task}\right) \times EF \tag{3.2}$$

Even though emissions are not directly measurable at a component, its energy demand has a causal influence on total emissions. Each component’s energy loss contributes to the overall demand for energy supply, thereby to the amount of diesel burned in the combustion engine finally resulting in GHG emissions. This contribution is shown in Figure with the dark grey arrow being part of the grey hatched input energy. The component’s contribution can be represented by a ratio of the component’s energy loss to the machine’s energy input. The first approach uses the same ratio for the component’s contribution to machine level GHG emissions leading to:

$$\frac{E_{Loss,Component}}{E_{In}} = \frac{GHG_{Component}}{GHG_{Machine}} \tag{3.3}$$

Hence the machine’s energy input is used as Activity Data for machine level emissions calculation, in this first approach the energy loss of a component is taken as its Activity Data for calculating its use-phase GHG emissions ($GHG_{Component}$), as shown in the following expression:

$$GHG_{Component} = E_{Loss,Component} \times EF \tag{3.4}$$

Therefore, the dark grey arrow in Figure depicts the Activity Data of the hydraulic pump.

This aligns conceptually with the delta approach described in the Product Environmental Footprint (PEF): Additional consumption compared to a reference is assigned to a product. Here, the losses represent the deviation from an ideal, loss-free component. An alternative would be to consider the total energy throughput of a component. However, this would include energy that is passed on to downstream components, leading to double-counting in the GHG balance of the machine. The sum of component emissions would then exceed the measurable tailpipe emissions of the machine. Therefore, the use of loss energy is preferable for accurate allocation.

The useful energy ultimately delivered by the machine (E_{Task}) also represents Activity Data and can be used to assign the remaining GHG emissions to the task (GHG_{Task}) like driving or working:

$$GHG_{Task} = E_{Task} \times EF \tag{3.5}$$

This approach pushes the idea to not only optimize components, rather holistically including the machine's task. The total machine emissions ($GHG_{Machine}$) can thus be partitioned into task and component emissions:

$$GHG_{Machine} = GHG_{Task} + \sum GHG_{Component} \tag{3.6}$$

Consequently, this enables a causal allocation of GHG emissions to components (e. g. the hydraulic pump) and functional processes (e. g. driving or working tasks).

In the second step, the same approach is applied to the electric variant of the reference vehicle. Importantly, the hydraulic pump's operating points are assumed to remain unchanged across both drivetrain configurations. Therefore, the energy loss (and thus the Activity Data) of the hydraulic pump is considered identical in both systems (see dark grey arrow in Figure).

However, just as with machine level, the electric system emits no operational GHG emissions, which could be measured like tailpipe emissions, the only relevant emissions stem from the provision of electricity. Accordingly, no emissions from operation could be assigned to a component and therefore only the Emission Factor for energy provision applies, just as on machine level.

Finally, the proposed answer by the first approach to the research question is Equation 3.4:

The GHG emissions of a component can be calculated by multiplying the average loss energy of the component over a usage profile for a reference lifetime as Activity Data with the respective Emission Factor for operation and energy provision for the energy carrier.

3.2. Validation

During test drives with the diesel-powered wheel loader, pressure, swivel angle, and shaft speed of the hydraulic pump were recorded across work cycles from the same usage profile as defined earlier. Using the pump's characteristic maps, volumetric and hydromechanical losses were determined. Losses from the integrated charge pump are disregarded. The power loss is integrated over each cycle and divided by the duration of the cycle to calculate the pump's mean power loss during the respective cycle. For each cycle in the usage profile this is then weighted by its time share to obtain the mean power loss for the specific usage profile. Multiplied by the assumed reference lifetime of 10.000 h, this yields for this specific example a total energy loss of 27.1 MWh ($E_{Loss,Pump}$) which is according to the first approach equivalent to the Activity Data of the pump.

Special consideration is required for overrun (regenerative) operation, e. g. during coasting. In such cases, no diesel is injected [21], hence no GHG emissions occur, although energy is dissipated. Concluding, only load operation is relevant for accounting emissions. To exclude this, fuel flow measurements are used to identify periods with 0 l/h diesel consumption, which indicate coasting. Only the losses during load operation are included in the Activity Data.

The same Activity Data are applied for both the diesel and electric configurations, as operating points of the hydraulic pump are assumed identical. Use-phase GHG emissions of the pump are then calculated for the diesel-powered wheel loader by values from Table 1 in Equation 3.7.

$$\mathrm{GHG_{Pump,Diesel}} = \mathrm{E_{Loss,Pump}} \times \left(\mathrm{EF_{Operation,Diesel}} + \mathrm{EF_{Provision,Diesel}}\right) \quad (3.7)$$

Table 1: Values for parameters in Equation 3.7

$\mathbf{E_{Loss,Pump}}$	$\mathbf{EF_{Operation,Diesel}}$	$\mathbf{EF_{Provision,Diesel}}$
27.1 MWh	0.271 kg CO_2e/kWh [16]	0.081 kg CO_2e/kWh [16]

For calculating use-phase GHG emissions of the hydraulic pump in the electric wheel loader Equation 3.8 is used with values from Table 2.

$$\mathrm{GHG_{Pump,Electric}} = \mathrm{E_{Loss,Pump}} \times \mathrm{EF_{Provision,Electric}} \quad (3.8)$$

Table 2: Values for parameters in Equation 3.8

$\mathbf{E_{Loss,Pump}}$	$\mathbf{EF_{Provision,Electric}}$
27.1 MWh	0.427 kg CO_2e/kWh [17]

Figure depicts the resulting GHG emissions assigned to the hydraulic pump in each configuration.

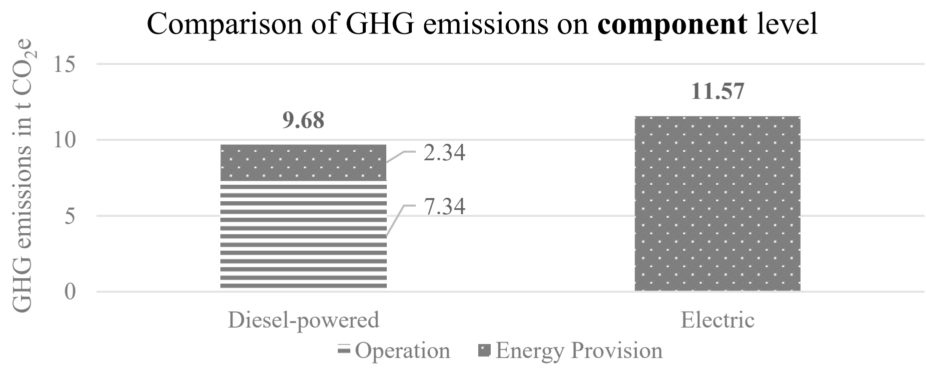

Figure 4: Comparison of hydraulic pump's use-phase GHG emissions for operation and energy provision with different energy carriers

Both bars show the GHG emissions assigned to the hydraulic pump. The left bar shows the hydraulic pump's emissions in the diesel-powered wheel loader, grey-white striped for operation and white dotted on grey background for energy provision. The right bar shows only emissions assigned to the hydraulic pump during energy provision, as no operation emissions occur in the electric wheel loader which could be allocated. However, the total use-phase emissions assigned to the hydraulic pump in the electric wheel loader are higher.

3.3. Discussion and Conclusion

The result contradicts the machine level finding that the electric variant emits fewer use-phase GHGs. To analyse this discrepancy, the ratio of GHG emissions from Equations 3.7 and 3.8 is formed:

$$\frac{\mathrm{GHG_{Electric}}}{\mathrm{GHG_{Diesel}}} = \underbrace{\frac{\text{Activity Data}_{\mathrm{Electric}}}{\text{Activity Data}_{\mathrm{Diesel}}}}_{\text{Ratio of Activity Data}} \times \underbrace{\frac{\mathrm{EF_{Provision.Electric}}}{\mathrm{EF_{Operation,Diesel}} + \mathrm{EF_{Provision,Diesel}}}}_{\text{Ratio of Emission Factors}} \tag{3.9}$$

This concludes that, independently of machine or component level, the ratio of GHG emissions from different energy carriers is equal to the ratio of Activity Data and the ratio of Emission Factors.

At machine level, as found in section 2.2, the electric variant requires 49 % less input energy, equalling a ratio of Activity Data between diesel and electric of 0.49. Though the ratio of Emission Factors, with values previously used, concludes that electricity has a 21 % higher total Emission Factor. Consequently, for the electric drivetrain in comparison to the diesel-powered less energy is required in total, but per unit of energy provided more GHG emissions are emitted. However, the higher efficiency outweighs the worse Emission Factor, leading to a 41 % reduction in total use-phase GHG emissions.

At component level, the Activity Data are assumed identical for both configurations. The ratio of Emission Factors still differs. Therefore, the ratio of Activity Data is not able to outweigh the ratio of Emission Factors like it did on machine level. This leads to higher assigned emissions for the hydraulic pump in the electric wheel loader, despite the machine emitting less overall. This inconsistency arises because the share of the hydraulic pump's energy loss relative to the machines total input energy ($\mathrm{E_{Loss,Component}}/\mathrm{E_{In}}$) increases due to higher primary energy supply efficiency and therefore less input energy needed:

- In diesel-powered wheel loader: 4 % of total input energy
- In electric wheel loader: 8.2 % of total input energy

Not only the share of the hydraulic pump's energy loss relative to the machines total input energy increases but according to Equation 3.3 a larger fraction of the machine's emissions is allocated to the hydraulic pump in the electric case. This leads to higher absolute component's emissions, despite the absolute machine's emissions being lower. The total GHG emissions of the component appear to grow solely because of being accounted for a larger fraction of the machine's emissions.

This reveals a key weakness of the first approach: It does not maintain proportional consistency across energy carriers. While suitable for comparing different components with everything else staying the same, therefore changing only Activity Data due to efficiency differences of the components, it leads to qualitatively misleading results when introducing other changes like comparing across energy carriers.

The first approach offers an answer to the research question and enables to allocate use-phase GHG emissions to a hydraulic component with minimalistic data input. As soon as more than one energy carrier is of relevance, it fails since misleading conclusions concerning impacts of different energy carriers can be made on component level. A second approach is required to resolve this issue and ensure component level emission assessments align with machine level trends, also with different energy carriers.

4. SECOND APPROACH

4.1. Methodology

In the first approach, the ratio of Activity Data between the two energy carriers remained constant, while only the ratio of Emission Factors changed. This simplification neglects a crucial interdependency: a change in energy carriers and Emission Factors inherently implies a change in the primary energy supply, which in turn alters the overall system efficiency and thus the machine's total energy input. By keeping the component's Activity Data constant between energy carriers, these upstream effects were not reflected. Consequently, the resulting component emissions did not scale consistently with the machine level emissions when switching energy carriers. Since components do not emit measurable GHGs themselves, their calculated GHG impact is always linked to the chosen energy carrier via the Emission Factor. When comparing different energy carriers, not only the Emission Factor but also the primary energy supply system changes. The first approach captured only the former, dismissing the latter. This led to only comparing Emission Factors when comparing component's emissions. Therefore, in the second approach, the Activity Data are extended to incorporate the influence of the primary energy supply efficiency.

While it would be most straightforward to base energy carrier comparisons directly on machine level energy inputs, this is often not feasible in practice. Component manufacturers typically lack access to complete machine level energy data and instead only possess information about the operating points and energy losses of their components. Furthermore, a methodology relying solely on machine level data would not support the practical need for component-specific GHG reporting. Therefore, the proposed method focuses on extending component level data in a way that remains applicable even without full system information.

Energy flows in the machine for each energy carrier configuration are shown in Figure .

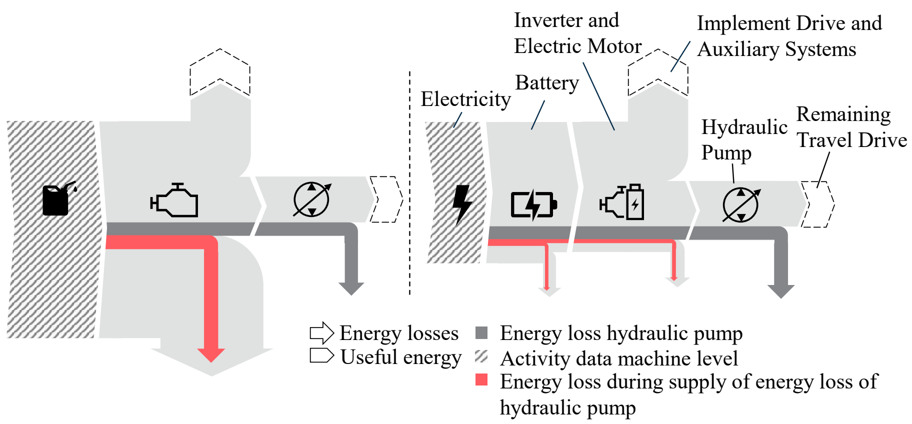

Figure 5: Sankey diagrams for electric and diesel-powered wheel loader

The dark grey arrow represents the hydraulic pump's energy losses, as used in the first approach. The first approach failed to account for the different efficiencies of the primary energy supply, leading to inconsistent results when comparing diesel and electric configurations. In the second approach, the Activity Data are therefore extended to include the energy required to supply the pump's losses, represented by the red arrows. These arrows indicate the additional energy that must be provided – depending on the primary energy supply's efficiency – to compensate for the component's energy losses.

The adjusted Activity Data for the hydraulic pump are calculated by expanding the measured loss energy by the inverse of the primary energy supply efficiency ($\eta_{\text{PrimaryEnergySupply}}$), as expressed in Equation 4.1:

$$\text{Activity Data}_{\text{Component}} = \frac{E_{\text{Loss,Component}}}{\eta_{\text{PrimaryEnergySupply}}} \tag{4.1}$$

By incorporating these upstream losses, the Activity Data now reflect the full energetic impact of the component within its respective drivetrain, now including the 40 % efficiency of the diesel engine versus 81 % for the electric drivetrain.

The second approach extends the Activity Data in comparison to the answer of the first approach to the research question as follows:

Activity Data for components must include not only the energy losses occurring at the component itself, but additionally the energy losses at the primary energy supply when supplying these losses. To translate Activity Data into use-phase GHG emissions Emission Factors for energy provision and operation must be used.

4.2. Validation

In the following the same assumptions for efficiencies of the primary energy supply system are used as before. Component's Activity Data are now expanded according to Equation 4.1. This leads to 67.75 MWh as Activity Data in the diesel configuration and 33.46 MWh in the electric configuration. As a result, the ratio of Activity Data in Equation 3.9 on component level between the two energy carriers is 0.49, matching the ratio used at the machine level. The share of the pump's Activity Data relative to the machine's total energy input (Activity Data on machine level) becomes identical across energy carriers: 10 % for both configurations. The resulting emissions are calculated as in the first approach with the same emission factors but with the adjusted Activity Data and are shown in the center bar chart of Figure 6. Consequently, with Equation 3.3 the emission share attributed to the hydraulic pump aligns proportionally with the overall emissions of the reference machine. This resolves the mismatch observed in the first approach.

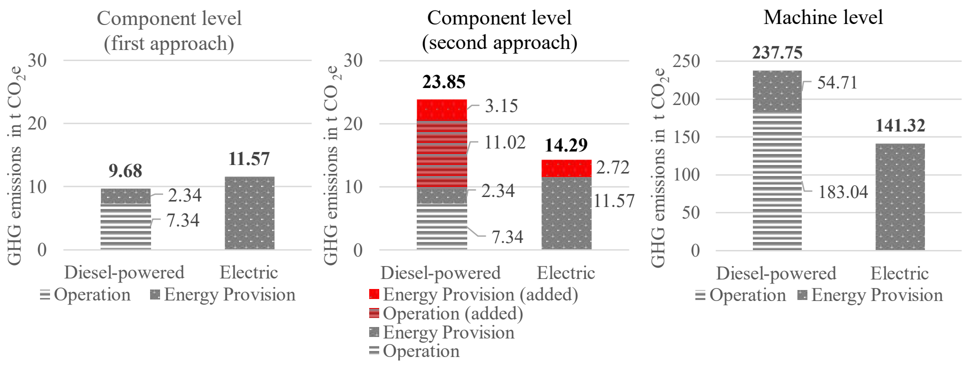

Figure 6: Comparison of use-phase GHG emissions of different approaches on component level and machine level

In Figure 6, the left bar chart shows the result of the first approach on component level for comparison. The center bar chart shows the result of the second approach on component level. The red-hatched section equals emissions linked to the red arrows in Figure 5. The red arrows represent additional energy from losses in the primary energy supply to supply the pump's energy losses, which are now included in the Activity Data of the hydraulic pump. The right bar chart depicts the total emissions of the machine as shown before in Figure 2.

Coming from the left bar chart the red hatched sections in the center bar chart add to GHG emissions of the hydraulic pump exactly so that the ratio of its emissions in diesel and electric drivetrain matches the ratio on machine level comparison. With the second approach, the pump in the electric drivetrain is assigned approximately 41 % fewer GHG emissions, consistent with the machine level analysis.

4.3. Discussion and Conclusion

In the first approach when the drivetrain becomes more efficient, total machine emissions decrease, yet the relative share of individual components in those emissions rises. In other words, a component appears "responsible" for a larger portion of a smaller total. Resulting in higher absolute emissions in comparisons, even though machine level comparisons show reduced emissions.

The second approach demonstrates that the consistency between component level and machine level GHG assessments critically depends on capturing all dependencies, including primary energy supply losses. By extending the Activity Data with the inverse of the primary energy supply efficiency, the second approach establishes a link between the component and the primary energy supply system. A change in energy carrier (for instance, from diesel to electricity) not only modifies the Emission Factor but also alters the efficiency of the primary energy supply system. These two effects are interdependent: the Emission Factor determines the environmental impact per energy unit, while the primary energy supply efficiency dictates how much energy must be provided to sustain component operation. Neglecting this link leads to incomplete or misleading comparisons. Using the second approach, the resulting emissions attributed to components scale proportionally with the overall machine behavior, thereby resolving the inconsistency observed in the first approach, allowing for a holistic and physically consistent comparison of different drivetrain configurations.

The second approach offers a practical compromise for real-world implementation. In industrial practice, complete machine data are often unavailable to component manufacturers. The proposed approach allows them to approximate realistic emissions by expanding known component level Activity Data with a representative efficiency factor of the primary energy supply. This ensures a balance between methodological rigor and practical applicability, enabling consistent use-phase emission allocation for reporting purposes.

5. CONCLUSION AND OUTLOOK

This study developed and validated a methodology for calculating the use-phase greenhouse gas (GHG) emissions of hydraulic components in non-road mobile machinery (NRMM). The work addresses a key gap in current sustainability assessment frameworks: while machine level GHG emissions can be quantified using established standards, no consistent procedure exists to attribute these emissions to individual hydraulic components, whose emissions cannot be measured.

Using a wheel loader as a reference machine, the machine level emission calculation was first established by combining Activity Data, defined as the total supplied energy, with Emission Factors for energy provision and operation. On this basis, two allocation approaches were derived and validated for a hydraulic pump in the travel drive, addressing the central research question:

How can use-phase GHG emissions of hydraulic components be determined, while allowing consistent comparisons across different energy carriers?

The first approach, based solely on the component's loss energy as Activity Data, provides a clear causal link between component efficiency and total machine energy demand. As long as only one energy carrier is relevant, it allows to report GHG emissions of hydraulic components with minimal effort. Alternative energy carriers are rising in importance though, creating the need for comparisons. This is where the first approach leads to inconsistent results, because it neglects the impact of the primary energy supply efficiency only taking the difference in Emissions Factors into account. Although the overall machine emissions decreased for the electric configuration, the pump appeared to contribute higher emissions due to the constant Activity Data definition. Thus, the first approach failed to maintain proportional consistency between component and machine level analysis.

The second approach resolves this inconsistency by extending the Activity Data to include losses in the primary energy supply system required to supply the component's losses. This adjustment ensures that both dependencies, the Emission Factor and the primary energy supply efficiency, are consistently reflected in the component level emission assessment. The approach thereby aligns component and machine results, enabling a physically consistent and holistic comparison between drivetrain configurations such as diesel and electric systems. It bridges the gap between machine level energy-based emission accounting and component level data availability, offering a robust foundation for sustainable design and emission transparency in fluid power systems.

Further concluding from the developed method, efficiency improvements, for example through optimized component operating points, directly translate into lower use-phase emissions within the operational boundary. Similarly, improvements in energy provision, such as the use of renewable electricity, further reduce emissions in the energy provision boundary, leading to two main levers to reduce use-phase emissions:

- Efficiency improvements
- Usage of "green" energy

The model neglects potential optimization of the hydraulic pump's operating points when comparing different primary energy supplies. Building on this, system optimization offers high potential for efficiency improvements. While this work mainly addressed reporting requirements for components, future research should aim to expand the method beyond energy carrier to system comparisons.

To extend the demonstrated method to other components in other machines measurement data, from real-world testing with a suitable machine-level operating profile, is needed to calculate the needed loss data. However, real-world testing introduces non-repeatable conditions, such as varying soil properties, weather, and operator behavior. To ensure reproducibility and comparability and to address high efforts in collecting measurement data for the high variance of NRMM a shift from real-world testing to a simulation-based approach will be required in future work.

In the long term, the methodology presented with the second approach can form the foundation for a standardized, modular, and simulation-supported emission-accounting framework for fluid power systems. By providing a consistent way to attribute use-phase emissions to individual hydraulic components, it contributes to greater transparency, supports the development of sustainable hydraulic designs, and thereby advances the decarbonization of NRMM and fluid power applications.

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Ulrich Lenzgeiger received his Diploma degree in mechanical engineering from the Technical University of Munich, Germany in 2006. He started his industrial career at Bosch Rexroth AG in System Development, focusing on system integration and functional development for mobile machinery. From 2019 onwards, he has been a Senior Manager in System and Software Development, responsible for mechatronics, reliability, and vehicle system testing.