Institute of Transport Economics
Norwegian Centre for Transport Research

The end of the ICE age?

Life cycle assessment of diesel, fuel cell, and battery electric heavy-duty freight vehicles

Linda Ager-Wick Ellingsen, Rebecca Jayne Thorne, Ingrid Sundvor

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Summary

This study compares the environmental performance of diesel, fuel cell, and battery electric powertrains for regional trucks with trailers and long-haul tractors with semi-trailers. Using the life cycle assessment (LCA) method, the environmental impacts were evaluated across five categories, covering the entire life cycle—from cradle to grave—including both vehicle equipment and energy carriers. The results show that no single powertrain is superior across all impact categories. The electric vehicles had lower impacts in two categories, including climate change, whereas the diesel vehicles performed better than both electric powertrains in three of the five categories. That said, climate change mitigation remains the primary driver for electrification. Although both electric powertrain types exhibited similar environmental profiles, notable differences were found between them. Given the rapid pace of technological advancements, regular updates to the assessment will be necessary to reflect the latest developments and help stakeholders identify effective strategies for enhancing environmental performance as these technologies evolve.

Kort sammendrag

Denne studien sammenligner miljøpåvirkningen til diesel, brenselcelle og batterielektriske drivlinjer for lastebiler med tilhengere for regionaltransport og trekkbiler med semitrailere for langtransport. Ved bruk av metoden livløpsvurdering (LCA) ble miljøpåvirkningene vurdert på tvers av fem kategorier, som dekker hele livsløpet – fra vugge til grav – og inkluderer både kjøretøyutstyr og energibærere. Resultatene viser at ingen av drivlinjene er overlegen på tvers av alle påvirkningskategoriene. De elektriske drivlinjene hadde lavere påvirkning i to kategorier, inkludert klimapåvirkning, mens dieselkjøretøyene hadde lavere miljøpåvirkning enn begge de to elektriske drivlinjene i tre av de fem kategorier. Når det er sagt, forblir klimatiltak den primære drivkraften for elektrifisering. Selv om det var visse likheter i miljøpåvirkningen til de elektriske drivlinjene, identifiserte vi vesentlige forskjeller mellom dem. Gitt den raske teknologiske utviklingen av elektriske drivlinjer vil regelmessige oppdateringer av vurderingen være nødvendige for å reflektere de nyeste utviklingene og hjelpe interessenter med å identifisere effektive strategier for å forbedre miljøprestasjonen ettersom disse teknologiene utvikler seg.

Preface

While Norway has made significant progress in electrifying its passenger vehicle sector, the heavy-duty vehicle segment has experienced a notable increase in emissions since 1990. This sector is expected to face substantial challenges in meeting emission reduction targets by 2035. To tackle this issue, the FME MoZEES (Centre for Environment-friendly Energy Research) has focused on advancing the battery and hydrogen value chains to accelerate the transition to cleaner heavy duty transportation solutions.

As part of this effort, a comprehensive framework was developed to assist decision-makers in evaluating the sustainability of heavy-duty freight vehicles across three key dimensions: economic, societal, and environmental. This report presents the findings from the environmental component of the framework, applied to assess the environmental performance of 50-ton freight vehicles operating in Norway. Specifically, the study focuses on regional trucks with trailers and long-haul tractors with semi-trailers. The environmental impacts were evaluated using life cycle assessment (LCA), a comprehensive method for analyzing the environmental potential of products and services throughout their life cycle.

The report was written by Linda Ager-Wick Ellingsen, Rebecca Thorne, and Ingrid Sundvor. Battery cell data from the MoreIsLess project was provided by Julia Wind at the Institute for Energy Technology (IFE). The report was quality checked by Erik Figenbaum, Frants Gundersen and Bjørne Grimsrud.

Oslo, January 2025
Institute of Transport Economics

Bjørne Grimsrud	Frants Gundersen
Managing Director	Director of Research

Contents

Figures

Tables

ENGLISH **Summary**

The end of the ICE age?

Life cycle assessment of diesel, fuel cell, and battery electric heavy-duty freight vehicles

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This study uses life cycle assessment (LCA) to compare the environmental performance of diesel, fuel cell, and battery electric powertrains for 50-ton freight vehicles across five impact categories. The results indicate that electric vehicles have lower impacts in two categories, including climate change, while the diesel vehicles perform better than both electric powertrains in three of the five categories. While climate change is the primary driver for electrification, decision-makers in industry and policy must consider the environmental trade-offs and potential problem shifting associated with each powertrain alternative to minimize other environmental impacts. Therefore, policymakers should promote effective recycling and circular economy practices, such as battery recycling, repurposing, and reuse, which can help mitigate production-related environmental impacts and reduce supply chain dependency. The transition to electric vehicles must be guided by a robust and comprehensive understanding of their full life cycle impacts to ensure sustainable outcomes. Given the rapid pace of technological advancements, this requires regularly updated LCAs.

Background

In Norway, greenhouse gas (GHG) emissions from the heavy-duty vehicle sector have increased significantly since 1990, and meeting emission reduction targets by 2035 presents major challenges. Transport activity is expected to grow faster than the benefits of technological advancements of diesel engines and trucks and increased biofuel blending, prompting exploration of fuel cell and battery electric powertrains as alternatives to diesel powertrains for heavy-duty freight vehicles. To assess the environmental impacts of these powertrain technologies, this study applies the LCA method to evaluate their environmental impact throughout their life cycle.

While most LCA studies focus on GHG emissions, they often overlook other environmental impacts. Some LCAs only partially consider the life cycle, excluding commonly used vehicle components or necessary infrastructure. Furthermore, technology descriptions are often incomplete, and some studies suffer from outdated or inappropriate inventory data for heavy-duty applications. Additionally, none of the studies consider vehicles with a 50-ton gross weight, which are more prevalent than 40-ton trucks in Norway. This study addresses these gaps by focusing on the life cycle environmental performance of 50-ton freight vehicles in Norway.

Method

The study compares diesel, hydrogen fuel cell, and battery electric powertrains for both regional trucks with trailers and long-haul tractors with semi-trailers. The goal is to provide insights into the environmental performance of these technologies, supporting decision-making for fleet operators and policymakers. The LCA considers the entire life cycle—from cradle to grave—including both the equipment and energy carriers. The equipment life cycle includes the vehicle and cargo transport units (trailers and semi-trailers), covering material extraction, component manufacturing, assembly, operation, maintenance, and end-of-life treatment. The life cycle of the energy carriers, commonly referred to as Well-to-Wheel (WTW), covers both Well-to-Tank (WTT) and Tank-to-Wheel (TTW). For all energy carriers, the life cycles of the necessary infrastructure, including refuelling stations and battery charging stations, were included in the WTT phase.

The functional unit of the study is defined as "the delivery of one ton of freight over one kilometer," with environmental impacts reported per ton-kilometer (tkm). This accounts for differences in load capacity in terms of weight between vehicle configurations and powertrain technologies. For further reference, results expressed on a per-vehicle basis (without accounting for variations in cargo capacity) are provided in Appendix B.

The assessment focuses on five environmental impact categories: climate change, freshwater ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, and photochemical ozone formation related to human exposure. These categories were selected for their relevance to vehicle technologies. Impacts were calculated using the ReCiPe 2016 characterization method in the openLCA software.

Results

The results revealed trade-offs in environmental performance across powertrain technologies. Electric vehicles had lower impacts in climate change and ozone formation, primarily due to reduced impacts during the use phase. Diesel vehicles performed better than both electric powertrains in three of the five impact categories: freshwater toxicity, terrestrial toxicity, and terrestrial acidification. Among electric vehicles, battery electric vehicles exhibited lower impacts in freshwater ecotoxicity, terrestrial acidification, and ozone formation, while hydrogen fuel cell vehicles had lower impacts in terrestrial ecotoxicity. In terms of climate change, both vehicle types had similar impacts, with battery electric vehicles having an advantage in regional applications, while fuel cell vehicles slightly outperformed battery electric vehicles in long-haul scenarios.

When comparing powertrain technologies, it became evident that electrification generally incurs higher production impacts compared to diesel vehicles. Our findings suggest that electric vehicles will struggle to offset their higher production impacts in categories such as freshwater ecotoxicity, terrestrial ecotoxicity, and terrestrial acidification. The use of metals in powertrain production and energy carrier life cycles was a significant contributor to these impacts, as electric vehicles typically rely more heavily on metals than their diesel counterparts. While both electric powertrains may achieve a net life cycle benefit for climate change, stricter constraints apply to fuel cell vehicles compared to battery electric vehicles, which are more likely to succeed due to their more efficient energy life cycle.

Discussion and conclusion

The findings underscore the importance of considering all life cycle stages and several environmental impact categories to gain a comprehensive understanding of the environmental performance of different powertrain alternatives. A narrower focus—such as on just WTW or GHG emissions alone—would have overlooked the significance of components in electric powertrains and failed to highlight key differences between fuel cell and battery electric vehicles. The life cycle perspective is crucial for making informed, environmentally sound decisions that guide both fleet managers and policymakers. That said, climate change mitigation remains the primary driver for electrification. When using the Norwegian electricity mix for hydrogen production via electrolysis and battery charging, both fuel cell and battery electric trucks offer net life cycle climate benefits.

Future studies should address data uncertainties, particularly for electric powertrains, and account for rapid technological advancements, especially in fuel cells and Li-ion batteries. Policymakers should prioritize R&D funding to ensure that LCAs reflect the latest developments in battery technologies, hydrogen production, and recycling processes. This will be crucial for supporting the transition to a more environmentally sustainable transportation system.

NORSK **Sammendrag**

Slutten på forbrenningsmotorens æra?
Livsløpsvurdering av diesel-, brenselcelle- og batterielektriske tunge kjøretøy for godstransport

TØI rapport 2072/2025 • Forfattere: Linda Ager-Wick Ellingsen, Rebecca Jayne Thorne, Ingrid Sundvor • Oslo, 2025 • 46 sider

Denne studien anvender livsløpsvurdering (LCA) for å sammenligne miljøpåvirkningen til diesel, brenselcelle og batterielektriske drivlinjer for 50-tonns vogntog på tvers av fem miljøpåvirkningskategorier. Resultatene indikerer at elektriske drivlinjer har lavere påvirkning i to kategorier, inkludert klimapåvirkning, mens dieselkjøretøyene har lavere miljøpåvirkning enn begge de to elektriske drivlinjene i tre av de fem kategorier. Selv om klimatiltak er den viktigste drivkraften for elektrifisering, bør beslutningstakere vurdere de miljømessige avveiningene og potensielle problemforskyvninger knyttet til hver drivlinje for å minimere andre miljøpåvirkninger. Derfor bør politikere fremme effektiv resirkulering og sirkulær økonomi, som for eksempel batteriresirkulering, ombruk og gjenbruk, som kan bidra til å redusere produksjonsrelaterte miljøpåvirkninger og redusere avhengigheten av forsyningskjeder. Overgangen til elektriske kjøretøy bør styres av en robust og helhetlig forståelse av deres totale miljøpåvirkning over hele livsløpet for å sikre bærekraftige resultater. Gitt den raske teknologiske utviklingen, vil dette kreve jevnlig oppdaterte LCA-studier.

Bakgrunn

I Norge har klimagassutslippene fra tunge kjøretøy økt betydelig siden 1990, og det forventes store utfordringer med å møte målene for utslippsreduksjon innen 2035. Etterspørselen for tungtransport forventes å vokse raskere enn fordelene av teknologiske fremskritt for dieselmotorer og lastebiler og økt innblanding av biodrivstoff, noe som har ført til økt oppmerksomhet rundt brenselcelle- og batterielektriske drivlinjer som alternativer til dieseldrevne drivlinjer for tunge kjøretøyer. For å vurdere de miljømessige konsekvensene av disse teknologiene, anvender denne studien LCA for å evaluere deres miljøpåvirkning gjennom hele livsløpet.

Mens de fleste LCA-studier fokuserer på klimagassutslipp, overser de ofte andre miljøpåvirkninger. Videre vurderer noen LCA-er kun deler av livsløpet, og ekskluderer ofte felles kjøretøykomponenter eller nødvendig infrastruktur. Dessuten er teknologibeskrivelser ofte ufullstendige, og noen studier bruker utdaterte eller upassende data for tungtransportapplikasjoner. Ingen av studiene har heller vurdert 50-tonns kjøretøy, som er vanligere enn 40-tonns kjøretøy i Norge. Denne studien tar tak i disse forskningshullene ved å fokusere på miljømessig bærekraft for 50-tonns vogntog i Norge.

Metode

Studien sammenligner diesel, brenselcelle og batterielektriske drivlinjer for både lastebiler med tilhengere for regionaltransport og trailere for langtransport. Målet er å gi innsikt i de miljømessige effektene av disse teknologiene og støtte til forskjellige beslutningstakere. LCA-studien vurderer hele livsløpet—fra vugge til grav—og inkluderer både utstyr og energibærere. Utstyrsløpet inkluderer kjøretøyet og transportenhetene (tilhengere og semitrailere), og dekker materialutvinning, komponentproduksjon, montering, drift, vedlikehold og slutt-behandling. Livsløpet til energibærerne, ofte referert til som "Well-to-Wheel" (WTW), dekker både "Well-to-Tank" (WTT) og "Tank-to-Wheel" (TTW). For alle energibærere ble livsløpet for nødvendig infrastruktur, inkludert drivstoffstasjoner og ladestasjoner for batterier, inkludert i WTT-fasen.

Den funksjonelle enheten for studien er definert som "levering av ett tonn gods over én kilometer," med miljøpåvirkninger rapportert per tonn-kilometer (tkm). Dette tar hensyn til forskjeller i lastekapasitet i form av vekt mellom kjøretøykonfigurasjoner og drivlinjeteknologier. For ytterligere innsikt er resultater uttrykt per vogntog (uten å ta hensyn til variasjoner i lastekapasitet) tilgjengelige i rapportens vedlegg.

Studien fokuserer på fem miljøpåvirkningskategorier: klimaendringer, ferskvannsøkotoksisitet, terrestrisk økotoksisitet, terrestrisk forsuring og fotokjemisk ozondannelse relatert til menneskelig eksponering. Disse kategoriene ble valgt på grunn av deres relevans for kjøretøyteknologier. Påvirkningene ble beregnet ved bruk av karakteriseringsmetoden ReCiPe 2016 i programvaren openLCA.

Resultater

Resultatene viser at det er en avveining mellom miljøpåvirkning på tvers av drivlinjeteknologiene. De elektriske drivlinjene hadde lavere påvirkninger når det gjaldt klimaendringer og ozondannelse, primært på grunn av reduserte miljøbelastninger i bruksfasen. Derimot hadde kjøretøy med drivlinje basert på forbrenningsmotor lavere miljøpåvirkning enn begge de elektriske drivlinjene i tre av de fem kategoriene: ferskvannsøkotoksisitet, terrestrisk toksisitet og terrestrisk forsuring. Blant de to elektriske drivlinjene hadde batterielektriske lavere ferskvanns-økotoksisitet, terrestrisk forsuring og ozondannelse, mens brenselcelledrevne hadde lavere terrestrisk økotoksisitet. Når det gjelder klimaendringer, hadde de to elektriske drivlinjene tilsvarende livsløpsutslipp, men batteridrevne lastebiler med tilhengere hadde noe lavere klimapåvirkning enn brenselcelledrevne, mens for trailere var det omvendt.

I sammenligningen av drivlinjeteknologiene, ble det tydelig at elektrifisering generelt fører til høyere miljøpåvirkninger i produksjon sammenlignet med dieselkjøretøy. Våre funn tyder på at elektriske kjøretøy vil slite med å kompensere for sine høyere produksjonspåvirkninger i kategorier som ferskvannsøkotoksisitet, terrestrisk økotoksisitet og terrestrisk forsuring. Bruk av metaller i produksjon av drivlinjer og energibærere for elektriske kjøretøy var en betydelig bidragsyter til disse miljøpåvirkningene, ettersom elektriske kjøretøy typisk innebærer mer bruk av metaller enn dieselkjøretøy. Selv om begge de elektriske drivlinjene kan oppnå en netto livsløpsfordel når det gjelder klimagassutslipp, er det likevel vanskeligere å oppnå denne fordelen for brenselcellekjøretøy ettersom livsløpet til deres energibærer (WTW for hydrogen) er mindre effektivt enn batterielektriske kjøretøyers energibærer (WTW for elektrisitet). Dette gjelder spesielt dersom strømproduksjonen har andeler av ikke-fornybar elektrisitet.

Diskusjon og konklusjon

Funnene understreker viktigheten av å vurdere alle livsløpsstadier og flere miljøpåvirknings-kategorier for å få en helhetlig forståelse av miljøpåvirkningene til ulike drivlinjealternativer. Et smalere fokus—som for eksempel bare på WTW eller klimagassutslipp—ville ha oversett den miljømessige viktigheten av ulike komponentene i de elektriske drivlinjene og heller ikke fremhevet nøkkelforskjellene mellom brenselcelle- og batterielektriske kjøretøy. Livsløpsperspektivet er avgjørende for å ta informerte, miljømessig bærekraftige beslutninger som kan veilede ulike beslutningstakere. Når det er sagt, forblir klimatiltak den primære drivkraften for elektrifisering. Ved bruk av norsk strømmiks for hydrogenproduksjon via elektrolyse og batterilading, tilbyr både brenselcelle- og batterielektriske lastebiler netto livssyklus-klimafordeler.

Fremtidige studier bør adressere usikkerheter i data, særlig for elektriske drivlinjer, og ta høyde for raske teknologiske fremskritt, spesielt innen brenselceller og Li-ion-batterier. Beslutningstakere bør prioritere FoU midler for å sikre at LCA-er reflekterer de nyeste utviklingene innen batteriteknologi, hydrogenproduksjon og resirkuleringsprosesser. Dette vil være avgjørende for å støtte overgangen til et mer miljømessig bærekraftig transportsystem.

1 Introduction

1.1 Background

In Norway, the transport sector is responsible for approximately one-third of total greenhouse gas (GHG) emissions, with road transport alone accounting for over half of this share (Samferdselsdepartement, 2024). This high proportion of emissions from road transport underscores the need for significant reductions within the sector. While the passenger vehicle segment has already seen notable emission reductions—largely due to the rapid adoption of fully battery electric vehicles—further reductions are expected as the share of electric vehicles continues to grow, with substantial progress anticipated by 2035 (Samferdselsdepartement, 2024).

In contrast, the heavy-duty vehicle segment has experienced a substantial increase in emissions since 1990 and is expected to face significant challenges in achieving emission reductions by 2035 (Samferdselsdepartement, 2024). This is due to the expectation that growth in transport activity will outpace the benefits of technological advancements of diesel truck technologies and increased biofuel blending. While battery electric powertrains have been widely adopted for passenger vehicles and city buses, both fuel cell and battery electric powertrains are now being explored as viable options for heavy-duty freight vehicles.

FME MoZEES, a Centre for Environment-friendly Energy Research (FME), focuses on advancing battery and hydrogen value chains, systems, and applications where Norway can establish a leader-ship position in the future. Within Research Area 4, 'Policy & Techno-economic Analysis,' TØI has developed a framework to evaluate sustainability across three key dimensions: economic, societal, and environmental, see Figure 1.1. This framework was designed to support decision-makers in making informed, sustainable choices. It enables a consistent assessment of the business costs, societal costs, and environmental impacts of heavy-duty freight vehicles.

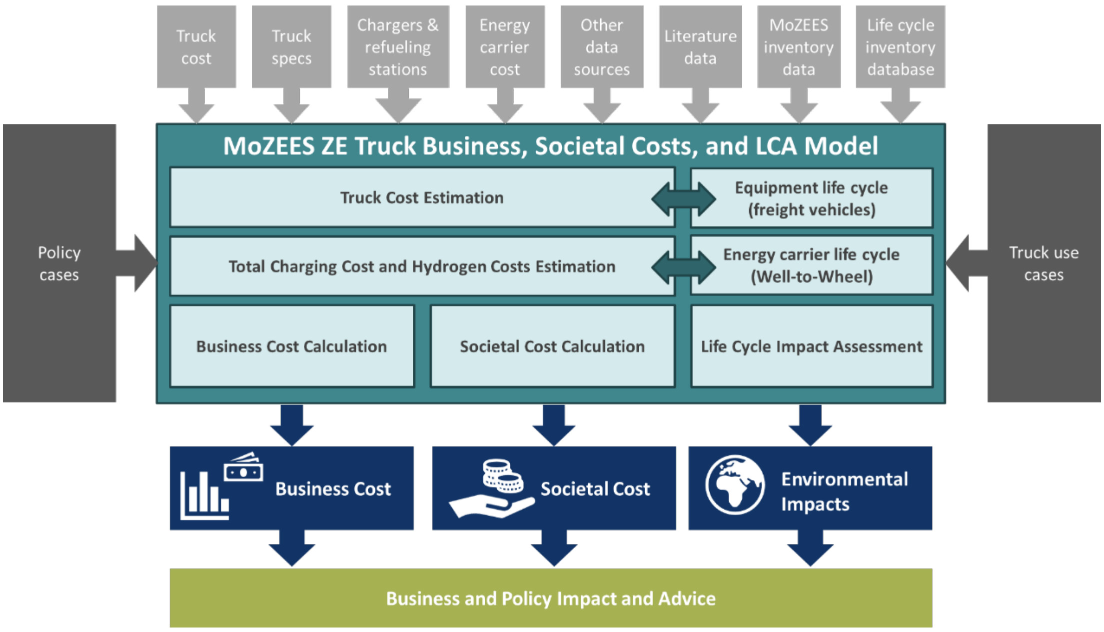


Figure 1.1: Overview of developed framework for estimating business cost, societal cost, and environmental impacts.

This report evaluates the life cycle environmental impact of various powertrain technologies for heavy-duty freight vehicles. The evaluation relies on the life cycle assessment (LCA) method, which is widely regarded as the most effective framework for assessing the environmental impact potential of products and services (European Commission, 2003). Standardized through ISO 14040/14044, LCA provides a systematic approach to estimating environmental impacts. It offers valuable insights into the environmental performance of products and services, while also identifying key sources of emissions and opportunities for improvement within complex supply chains.

1.2 The life cycle assessment method

To assist readers who may not be familiar with the LCA method, a brief description is provided. The LCA procedure consist of four steps: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (see Figure 1.2). A brief description of each step is provided below.

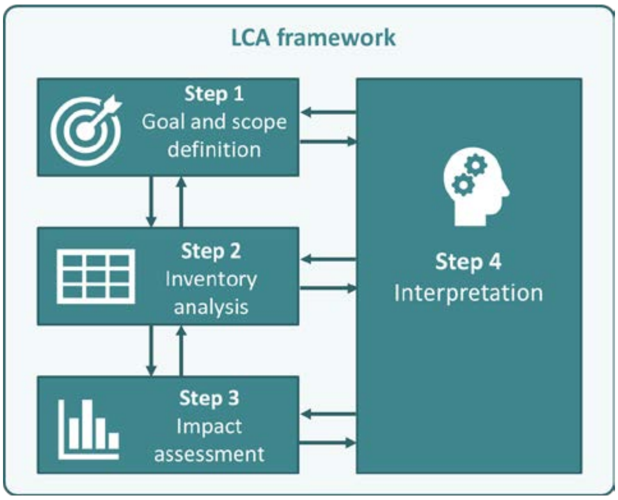


Figure 1.2: The four steps of life cycle assessment.

Goal and scope definition establishes the objectives of the study. In this step, the functional unit and system boundary are defined, along with the types of environmental impacts to be assessed. Additionally, the level of detail in the study, and thus the requirements for the data, are determined in this step (Baumann and Tillmann, 2004).

Inventory analysis involves compiling a life cycle inventory (LCI) data in accordance with the defined goal and scope of the study. This process includes collecting data on the inputs and outputs of all activities, such as raw materials, energy carriers, products, as well as solid waste and emissions to air and water (Baumann and Tillmann, 2004). Data collection is often the most time-consuming phase of an LCA (Rebitzer et al., 2004). Once the data is gathered, the pollutant emissions and resource use associated with the system are calculated relative to the chosen functional unit (Baumann and Tillmann, 2004).

Impact assessment involves grouping resource extractions and emissions from the LCI results into the types of environmental impacts they contribute to (this is referred to classification) and translating these into a limited number of impact scores (this is referred to as characterization). The translation is a quantitative step performed using so-called characterization factors, which represent the environmental impact per unit of stressor (e.g., per kg of resource or emission released) (Huijbregts *et al.*, 2016). Environmental impacts can be derived at both the midpoint and endpoint levels (Hauschild *et al.*, 2013). These two approaches are complementary; midpoint-level impacts are more directly linked to environmental flows and generally exhibit lower uncertainty, while endpoint-level impacts are typically easier to interpret in terms of their final consequences for human health, ecosystems, and resource availability (Huijbregts *et al.*, 2016).

Interpretation is the final step of an LCA and involves two key processes. The first is analyzing and presenting the results, while the second is evaluating those results to assess their reliability and establish confidence in the findings. Throughout the LCA process, the quality and uncertainty of the data are continually assessed.

Although the four steps of an LCA are typically presented in a sequential order, the process is inherently iterative, as the steps are closely interrelated. This iterative approach allows for the refinement, and adjustment of earlier stages based on new insights gained during later phases of the study. Consequently, multiple iterations may be required to ensure the robustness and accuracy of the results.

1.3 LCA literature review

This section reviews the expanding body of LCA research that evaluates and compares the environmental performance of freight vehicles powered by diesel, hydrogen fuel cell electric, and battery electric powertrains. From the holistic systems perspective provided by LCA, the complete vehicle life cycle encompasses both the equipment life cycle and the energy life cycle – commonly referred to as "Well-to-Wheel" – as illustrated in Figure 1.3. The complete vehicle life cycle is often referred to as "cradle-to-grave". Some studies conduct partial LCAs, considering only parts of the complete vehicle life cycle, such as a "cradle-to-gate" perspective, which includes material extraction, component manufacturing, and assembly.

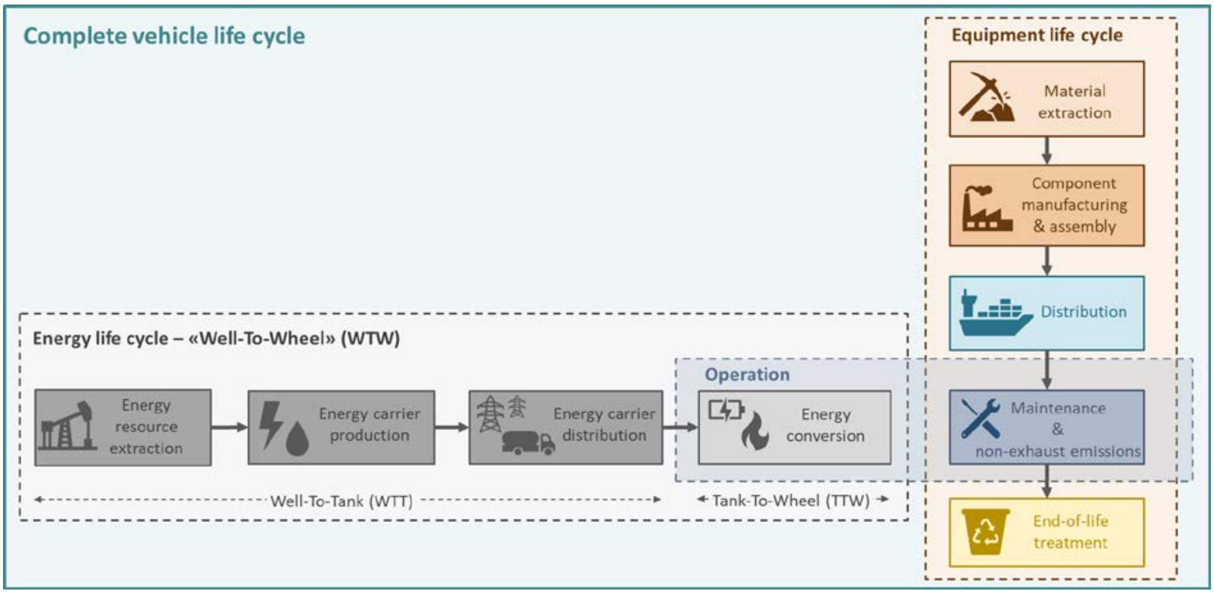


Figure 1.3: Complete vehicle life cycle; figure adapted from Nordelöf *et al.*, (2014).

Rupp, Schulze, and Kuperjans (2018) compare the life cycle GHG emissions of a 40-ton conventional diesel truck and a hybrid electric truck. In their study, they assume a uniform vehicle glider and focus their analysis on the differing powertrain components. Their findings reveal that while the hybrid truck has higher production emissions compared to the diesel truck, it compensates with lower use phase emissions compared to the diesel truck; based on a functional unit of ton-kilometer (tkm), the study finds that emission break-even (i.e., the point beyond which the hybrid truck has lower life cycle GHG emissions than the diesel truck) occurs after approximately 15 800 km.

Wolff *et al.* (2020) build on existing literature on light- and heavy-duty vehicles to create a scalable cradle-to-gate inventory for tractors with various powertrain technologies: conventional diesel, hybrid electric, plug-in hybrid electric, and two battery electric trucks with 675 kWh and 1000 kWh battery packs, respectively. This inventory provides detailed data on materials and assembly energy for a generic vehicle glider, including main components such as the frame, cab, tires, wheels, suspension, and additional elements like powertrain components, rear underride guard, tool kit, and fluids. Their cradle-to-gate analysis shows that per vehicle, both primary energy demand and GHG emissions increase with the level of electrification.

Sacchi, Bauer, and Cox (2021) conduct a comprehensive assessment of how truck size, load factor, range autonomy, and application type affect the life cycle GHG emissions of medium- and heavy-duty trucks for both current (2019) and future (2050) scenarios. Their study evaluates six powertrain technologies (conventional diesel, hybrid electric, plug-in hybrid electric, hydrogen fuel cell electric, battery electric, and compressed gas) across seven size classes (3.5-ton, 7.5-ton, 18-ton, and 26-ton rigid trucks, as well as 32-ton, 40-ton, and 60-ton articulated trucks) and twelve fuel pathways (including diesel, biodiesel, natural gas, biomethane, and hydrogen). They find that GHG emissions per ton-km decrease with increasing truck size and load factor and that currently, large batteries for high range autonomy penalize battery electric trucks. However, as the carbon intensity of the average European electricity mix used for charging decreases and battery energy density improves, battery electric trucks are expected to offer the lowest life cycle emissions in the future. The study also finds that with hydrogen produced through electrolysis using the average European electricity mix, fuel cell trucks are less competitive compared to diesel or hybrid trucks. The authors note that nevertheless, this could change if hydrogen is produced using low-carbon electricity instead of the average grid mix.

Iyer, Kelly, and Elgowainy (2023) evaluate the life cycle GHG emissions of current (2021) and future (2035) medium- and heavy-duty trucks. Their analysis covers both regional and long-haul trucks, including conventional diesel, battery electric, and hydrogen fuel cell electric trucks. They report emissions per mile and per US ton-mile, considering both equal and maximum payloads. The authors find that both battery and fuel cell electric trucks currently offer lower life cycle GHG emissions compared to diesel trucks, with these benefits expected to increase in the future. They also highlight that variation in payload significantly affects the relative life cycle performance of these trucks.

Booto, Aamodt Espegren, and Hancke (2021) evaluate the environmental performance of 40-ton diesel, battery electric, and hydrogen fuel cell electric trucks by examining seven impact categories in a case study focused on use in Norway. For their assessment, the researchers compiled cradle-to-gate inventory data derived from a bill-of-materials for a 12-ton diesel truck and incorporated previously published cradle-to-gate inventories for the battery pack and fuel cell system. The study specifically designed each vehicle to be powered exclusively by its respective energy source, meaning that high-power batteries were not considered for the hydrogen fuel cell electric truck. The authors find that, per kilometer driven, both the fuel cell and battery electric vehicles offer GHG advantages over the diesel truck. While trade-offs exist across multiple impact categories, the battery electric powertrain consistently shows lower impacts than the fuel cell electric powertrain.

While the studies mentioned above are highly relevant to our research, additional literature on the environmental performance of heavy-duty freight vehicles also exists. For example, Syré *et al.* (2024) conduct a consequential LCA comparing GHG emissions from fuel cell and battery electric powertrains across various vehicle types, including 40-ton trucks. Rial and Pérez (2021) assess the environmental impact of diesel, diesel-hybrid, spark-ignited natural gas, and high-pressure direct injection natural gas vehicles. Manufacturers have also published LCA results for commercially available trucks, such as Scania's report comparing diesel and battery electric distribution vehicles (Scania, 2021), and Volvo Trucks' online environmental footprint calculator (Volvo Trucks, no date). A more narrowly focused study by JEC (M. Röck, Rexeis, and Hausberger, 2020), evaluates the TTW energy consumption and CO_2-eq per tkm for heavy-duty vehicles. Additionally, while not framed within an LCA methodology, Raghavan *et al.* (2023) examine the metal requirements for electrifying Swedish cars and heavy-duty trucks, as well as associated infrastructure, providing valuable supplementary environmental insights.

While the existing literature has provided valuable data and insights into the GHG emissions of freight vehicles significant knowledge gaps remain. Current literature primarily focuses on GHG emissions, often neglecting other environmental impacts. Additionally, some LCAs only partially consider the equipment life cycle, excluding commonly used vehicle components in the equipment life cycle as well as hydrogen refueling stations and battery charging stations associated with the energy carrier life cycle. Furthermore, technology descriptions are often incomplete; for instance, few provide details on the specific battery technologies or capacities used in hydrogen fuel cell electric powertrains. Additionally, some studies suffer from outdated or inappropriate inventory data for heavy-duty applications. For example, Booto, Aamodt Espegren, and Hancke (2021) use inventory data for a passenger vehicle battery pack (compiled in 2012) to assess battery electric trucks and rely on data for motorcycle fuel cell stacks and hydrogen tanks for evaluating fuel cell trucks. Beyond these gaps, it is worth noting that the only study focusing on heavy-duty freight trucks in Norway examines 40-ton trucks, which are common across much of Europe. However, in Norway, vehicles with a 50-ton gross weight are more prevalent.

This study addresses identified research gaps in the LCA literature considering heavy-duty freight vehicles with different powertrains, particularly with regard to their use in Norway. The evaluation focuses on two types of 50-ton freight vehicles operating in Norway. The analysis relies on updated inventory data and assesses environmental impact potentials across five impact categories. By doing so, we aim to expand the knowledge of the environmental performance of heavy-duty vehicle operation in Norway, as well as broaden the scope of LCA research within the vehicle freight segment.

1.4 Structure of the report

This report is organized into five sections, beginning with the introduction. Section 2 outlines the method and analysis, while Section 3 presents the results of the assessment. Section 4 discusses the findings, addresses the study’s limitations, and suggests directions for further research. Finally, Section 5 concludes the study.

2 Method and analysis

A cradle-to-grave LCA was conducted to quantify the environmental impacts of the freight vehicles, following the ISO 14040/14044 international standards. Subsection 2.1 outlines the goal and scope definition (Step 1 of LCA), Subsection 2.2 describes the inventory analysis (Step 2 of LCA), and Subsection 2.3 covers the impact assessment (Step 3 of LCA).

2.1 Goal and scope definition

2.1.1 Goal definition

The goal of this study was to evaluate the life cycle environmental performance of 50-ton freight vehicles operating in Norway. The study aimed to provide a comprehensive understanding of both regional trucks with trailers and long-haul tractors with semi-trailers. The assessment focused on comparing different powertrain technologies, including diesel, hydrogen fuel cell electric, and battery electric alternatives, to determine their relative contributions to key environmental impacts.

The results are part of the broader sustainability analysis outlined in Figure 1 and were designed to support decision-making for stakeholders in the transportation sector, particularly fleet operators and policymakers. By providing insights into the environmental trade-offs of various powertrain technologies, these findings aim to guide the adoption of more sustainable transportation solutions and inform strategies for reducing the overall environmental impact of freight transport.

2.1.2 Scope definition

The study was conducted using hypothetical case studies of regional trucks with trailers and long-haul tractors with semi-trailers. The complete life cycle from cradle to grave was considered and the system boundaries encompassed the life cycles of both the equipment and the energy carriers (as shown in Figure 1.3). These system boundaries were streamlined with the other elements of the overall sustainability analysis.

For the equipment life cycle, the study encompasses the life cycle of the vehicle and cargo transport units, including material extraction and processing, component manufacturing, assembly, distribution, maintenance, and end-of-life (EOL) treatment. The study also assessed the life cycle of the energy carriers (i.e., diesel, hydrogen, and electricity) used in these vehicles, commonly referred to as Well-to-Wheel (WTW). Therefore, this analysis covered both the Well-to-Tank (WTT) and Tank-to-Wheel (TTW) phases. For all energy carriers, the life cycles of the necessary infrastructure, including refuelling stations and battery charging stations, were included in the WTT phase.

This study focuses on 50-ton freight vehicles operating within Norway, with the geographical scope defined by the country’s distinct operational conditions. Norway’s unique geography and climate significantly influence the characteristics of freight transport operations. The country's terrain, including its mountainous areas and coastal regions, as well as its colder climate, play critical roles in shaping vehicle performance and energy consumption patterns. Additionally, Norway’s energy mix differs notably from other countries. The country boasts a high proportion of biofuels in its diesel blend and relies extensively on hydroelectric power for its electricity generation. These factors directly impact the environmental performance of freight vehicles. The study includes both regional freight transport, which typically occurs over shorter, localized routes, and long-haul freight transport, involving longer distances across the country. These differences in operational scope affect energy use across all vehicle types and impact the battery capacity required for battery electric trucks to achieve sufficient range for long-haul applications.

For all trucks, a standard engine power rating of 500 kW was assumed as this is a common motor size for these types of trucks in Norway (based on the categorization in Hovi *et al.* (2021)). The diesel powertrain was modeled with an internal combustion engine (ICE) and a 1 000-liter fuel tank. The hydrogen fuel cell electric powertrain was equipped with a proton exchange membrane fuel cell (PEMFC) system rated at 360 kW, along with a high-power lithium-ion (Li-ion) battery with a 50-kWh capacity that provides additional power. The battery electric powertrains featured high-energy Li-ion batteries, with capacities of 750 kWh for the regional freight truck and 1 000 kWh for the long-haul tractor. These values were chosen as examples of realistic battery sizes towards 2030 (740-kWh trucks are currently available) and as a compromise between range, cost, and payload requirements. The different powertrains and combinations of vehicles and cargo transport units result in varying weights, which in turn affect cargo capacity. Similarly, energy use and annual mileage differ between regional and long-haul vehicles.

The data used in this study were derived from a combination of sources. The foreground system includes original inventory data, in-house datasets for batteries, inventory data from the LCA literature, as well as other sources. The *ecoinvent* database version 3.10 was used as the background system for material extraction and production, electricity generation and transmission, and EOL treatment processes. The transport of materials, components, and finished vehicles was modeled using generic background data, with specific distances and transport modes defined for the foreground system. Global averages were used for production data, or European averages when global data were unavailable. For operational data, Norwegian averages were applied where relevant. For EOL treatment, we considered disassembly and material recycling, assuming that vehicles and battery packs are disassembled and recycled within Europe. Consequently, European averages were used for EOL processes.

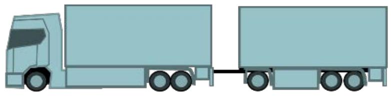
The functional unit of the study was defined as "the delivery of one ton of freight over one kilometer," with environmental impacts reported per ton-kilometer (tkm). This functional unit accounts for differences in load capacity in terms of weight between the vehicle configurations and powertrain technologies. For impact estimation, we consider a vehicle lifetime of 8 years, with annual mileages of 70 000 km for the regional trucks with trailers and 95 000 km for tractors with semi-trailer based on data of daily distances in Hovi *et al.* (2021). Appendix B presents the results for an alternative functional unit, expressed on a per-vehicle basis.

This report focuses on midpoint impacts, as they provide more detailed assessment of environmental characteristics and are generally associated with lower uncertainty. To evaluate the environmental performance of the various freight vehicles assessed in this study, we considered five impact categories: climate change, freshwater ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, and photochemical ozone formation related to human exposure. These categories were selected because they encompass a broad range of environmental aspects relevant to vehicle technologies, covering global effects (climate change), regional effects (acidification and photochemical ozone formation), and local effects (freshwater and terrestrial ecotoxicity). Global and regional impacts are typically linked to energy consumption, while local impacts are usually caused by release of substances or pollutants during raw material extraction and processing.

2.2 Inventory analysis

To assess the life cycle environmental performance of 50-ton freight vehicles, we compiled cradle-to-grave inventory data for the selected powertrains and vehicle configurations. The inventory data were compiled using a process-based approach. Table 2.1 summarizes key data and differences between the vehicles and powertrains, which is further detailed in the sections below.

Table 2.1: Key data and differences between vehicles and powertrains considered in study.

	Regional truck with trailer			Long-haul tractor with semi-trailer		
						
	Diesel	**Fuel cell**	**Battery**	**Diesel**	**Fuel cell**	**Battery**
Total curb weight (kg)	14 299	13 386	16 497	16 064	15 151	19 843
Glider (kg)	*5 558*	*5 558*	*5 558*	*5 558*	*5 558*	*5 558*
Powertrain (kg)	*3 141*	*2 228*	*5 339*	*3 141*	*2 228*	*6 920*
Cargo transport unit (kg)	*5 600*	*5 600*	*5 600*	*7 365*	*7 365*	*7 365*
Cargo capacity (kg)	34 700	36 530	33 500	32 940	34 770	30 160
Li-ion battery capacity (kWh)		50	750		50	1 000
Energy use (per km)	0.380 L	0.098 kg	1.78 kWh	0.392 L	0.10 kg	2.04 kWh
Yearly mileage (km)	70 000	70 000	70 000	95 000	95 000	95 000
Total freight transport (tkm)	19 430 079	20 459 048	18 761 402	25 027 993	26 424 451	22 919 302

2.2.1 Production

For production (cradle-to-gate) of the trucks with trailers and tractors with semi-trailers, we compiled original data as well as inventory data from published studies and *ecoinvent* process data. The cradle-to-gate inventories are sub-divided into three main component groups: glider, powertrain, and cargo transport units (i.e., superstructure, trailer, and semi-trailer).

The gliders were assumed similar across both vehicle types and powertrain technologies. For the glider, we primarily relied on the scalable cradle-to-gate inventory by Wolff *et al.*, (2020). The dataset was complimented with inventory data for auxiliary and house batteries (Sacchi, Bauer and Cox, 2021), chassis electronics (Nordelöf, Romare and Tivander, 2019), wheels (Alcoa, 2012), as well as original datasets for tires and cooling system. The weight of the various glider component groups is provided in Appendix A. We compiled original inventory data for heavy-duty freight tires and motor cooling system, these are also provided in Appendix A.

For the diesel powertrains, we assumed a 500-kW diesel ICE. For the ICE, we relied on the inventory provided by Wolff *et al.* (2020). For the transmission, diesel tanks, retarder, and exhaust system, we used inventory data provided by Sacchi, Bauer and Cox, (2021). The weight of the ICE, transmission, drive shaft, AdBlue tank, exhaust system, fuel tanks were based on the JEC Tank-To-Wheels report for heavy-duty vehicles (M. Röck, Rexeis and Hausberger, 2020), while the weight of the retarder and transmission oil were scaled based on Wolff *et al.* (2020). The weight of the various powertrain components as well as the inventory for AdBlue tanks are provided in Appendix A.

The hydrogen fuel cell trucks were assumed powered by three 120-kW PEMFCs, a 500-kW permanent magnet synchronous electric motors, and a 50-kWh high-power NMC532 LIB used for load levelling and recapturing braking energy. For the fuel cell, we adapted the cradle-to-gate inventory compiled by Usai *et al.* (2021) by adjusting the platinum loading. The higher loading at 0.75 g Pt/kW ensures the longer lifetime required for heavy-duty vehicle applications (Raghavan *et al.*, 2023). We assumed a composition of 30% secondary (recycled) and 70% primary (virgin) platinum, based on market share distributions. For the carbon fiber tanks used to store compressed hydrogen, we relied on data published by Sacchi, Bauer, and Cox (2021). For the electric motors, we relied on a scalable inventory model (Anders Nordelöf *et al.*, 2017; Nordelöf and Tillman, 2017). For the high-power Li-ion battery cells, we obtained material information from the MoreIsLess project considering commercial battery cells. These battery cells use a lithium nickel manganese cobalt oxide cathode with a 5:3:2 ratio (NMC532). The cradle-to-gate LCI for the battery is provided in Appendix A. The electric motor was modeled based on a scalable inventory that can model motors up to 200 kW (Anders Nordelöf *et al.*, 2017; Nordelöf and Tillman, 2017). Thus, the 500-kW motor was modeled as four motors, each rated as 125 kW.

For the battery electric powertrain, we modelled high-energy Li-ion batteries and a 500-kW motor. Also here, we relied on the previously published scalable inventories for batteries (Ellingsen *et al.*, 2022) and electric motors (Anders Nordelöf *et al.*, 2017; Nordelöf and Tillman, 2017). The high-energy Li-ion batteries used in the regional delivery truck and long-haul tractor were modelled with capacities of 750 kWh and 1 000 kWh, respectively. To obtain a higher energy density, these batteries have a lithium nickel manganese cobalt oxide cathode with a 6:2:2 ratio (NMC622). Information and inventory data for the high-energy battery can be found in Appendix A.

Vehicle assembly was modelled after Wolff *et al.*, (2020). While it is likely that there are some differences in assembly among the trucks and tractors as well powertrain technologies, it was assumed to be the same for all vehicles and powertrains in our study.

We gathered original inventory data for cargo transport units. For the regional truck, we modeled it with a trailer, while for the long-haul tractor, we modeled a semi-trailer. Detailed inventories and weights are provided in Appendix A.

2.2.2 Vehicle distribution

Finished trucks and trailers were assumed to be transported 1 000 km from factory gate to dealerships by trucks (>32 metric ton, EURO6). The majority of heavy-duty vehicles sold in Norway are Swedish, with smaller shares from other European countries. Thus, a distribution from producing countries abroad and within Norway of 1 000 km was deemed as an approximate average distance.

2.2.3 Operation

For the use phase, we considered both WTT and TTW that combined make up the total energy life cycle as well as non-exhaust emissions and maintenance.

2.2.3.1 Well-to-Tank

We consider here the delivery of energy from its source to the storage equipment in the vehicle (e.g., tank or battery). Impacts associated with WTT are often referred to as indirect or upstream impacts as they occur in connection with extraction, production, and distribution of the energy carriers.

For the diesel trucks, we considered auto diesel sold on the Norwegian market in 2021. This fuel is a blend of fossil diesel and biodiesel, with biodiesel in Norway comprising both fatty acid methyl ester (FAME) and hydrotreated vegetable oil (HVO). While FAME is blended into auto diesel up to a maximum of 7%, HVO is a “drop-in fuel” that can directly replace fossil diesel due to its almost identical technical properties. As different biodiesel feedstocks have varying environmental impacts, we also considered these feedstocks in our analysis. This estimation was based on data from a previous report (Wangsness *et al.*, 2023) and performed using statistics provided by the Norwegian Environment Agency (Miljødirektoratet, 2021, 2022). The resulting blend was estimated to have a total biodiesel content of about 14% and specific energy of 42.6 MJ/kg. To model the diesel blend, we modified the ecoinvent process "*market for diesel | diesel | Cutoff, U - Europe without Switzerland*", reducing the amount of fossil diesel and incorporating FAME and HVO. For biodiesel, we relied on LCI results from f3 – the Swedish Innovation Cluster for Sustainable Biofuels (*Well-to-wheel LCI data for fossil and renewable fuels on the Swedish market | f3 centre*, 2019).

For hydrogen used in fuel cell trucks, we considered hydrogen produced via electrolysis. We compiled an inventory based on previous LCA publications (Ghandehariun and Kumar, 2016; Wulf and Kaltschmitt, 2018; Bareiß *et al.*, 2019) as well as available PEM electrolyzer operation data (H-TEC systems, no date). Based on these data sources, the electrolysis process was modelled using 53 kWh of electricity and 13.9 litres of water to produce hydrogen at a pressure of 30 bars. Furthermore, compression was modelled to require 2.2 kWh/kg for compression to 500 bars for transport as well as an additional 1.0 kWh/kg for compression to 800 bars during fuelling (Wulf and Kaltschmitt, 2018). We assumed hydrogen production in Norway using the average Norwegian consumption mix at low voltage. We also assumed that 200 km of transport by truck (>32 metric ton, EURO6) was required for the compressed hydrogen as there are no hydrogen pipelines in Norway. The hydrogen refuelling stations were modelled after Sacchi, Bauer, and Cox (2021).

For charging the battery electric trucks, we used the Norwegian consumption mix at low voltage. We assumed that the trucks primarily charge their batteries at the depot, with each truck having its own charger. Each charger was assumed to have a lifetime of 10 years. Since the vehicles were assumed be in use for 8 years, 0.8 chargers were ascribed to each vehicle. The battery charging stations were modelled based on inventory data provided by Zhao *et al.* (2021).

As the Norwegian consumption mix has a high share of renewables and low carbon footprint (25 g CO_2/kWh), the baseline analysis can also be seen as representing a renewable energy scenario. For wider transferability of study results and to evaluate the sensitivity of the energy source, we performed two sensitivity analyses considering the GHG emissions effect of using alternative sources for battery charging and hydrogen production. For hydrogen production, we additionally considered steam methane reforming (SMR) using natural gas as well as electrolysis using the average European electricity mix. The average European electricity mix was also considered for charging the battery trucks. See Appendix A for further information about inventory data.

2.2.3.2 Tank-to-Wheel

Energy consumption for the various vehicles was estimated based on reported diesel usage for heavy-duty vehicles operating in Norway (Hovi *et al.*, 2021). The dataset differentiates between motor power, axle configuration, drive wheels, and daily mileage. Diesel consumption was converted to energy use in kWh/km and compared with that of fuel cell and battery electric heavy-duty vehicles. Hydrogen and electricity consumption were estimated using studies that assess real-world energy consumption and efficiency differences among diesel, fuel cell, and battery electric HDVs. Additionally, energy efficiency variations reported in other studies were considered. For battery electric powertrains, electricity consumption was adjusted to account for differences in battery size and weight compared to those reported in the literature. Total efficiency losses during charging, accounting for both the charger and the battery, were assumed to be 10%.

Inventory data for the combustion of the auto diesel blend, was compiled using data for bio-diesel combustion (*Well-to-wheel LCI data for fossil and renewable fuels on the Swedish market | f3 centre*, 2019) and modifying the ecoinvent process transport, freight, lorry >32 metric ton, EURO6. Modifications entailed separating out combustion emissions and adjusting these according to fuel consumption.

2.2.3.3 Non-exhaust emissions

Inventory data for non-exhaust emissions stemming from brake, tire, and road wear were adapted from the *ecoinvent* database to account for differences in gross vehicle weight and load factor for each of the vehicles.

2.2.3.4 Maintenance

For maintenance, we modeled the replacement of tires, oil changes, and AdBlue use for diesel vehicles.

For tires, we assumed replacement rather than retreading Since winter tires are mandatory for trucks in Norway from November 15th to March 31st, we estimated that winter tires are used for half of the driving distance, as winter conditions often persist outside the mandatory period. With two sets of tires per year, we assumed the tires would last for two years, averaging one set per year.

For oil changes, we assumed that transmission oil (for diesel vehicles only), differential oil, and steering oil (for all vehicles) are replaced annually.

As part of maintenance, EURO 6 diesel vehicles also require AdBlue to reduce NOx emissions. We assumed an AdBlue consumption rate of approximately 6 liters per 100 liters of diesel fuel. An inventory for AdBlue production was compiled for the study and is provided in Appendix A.

Potential replacements for PEMFCs and Li-ion batteries were not considered in the assessment. However, their implications are considered in the Discussion section.

2.2.4 End-of-life treatment

EOL modelling was done in line with the cut-off approach, where no burden (or benefit) is allocated to the recycled materials (i.e., down-stream products) and instead, raw material input upstream of component and vehicle production has a recycled content (Nordelöf et al., 2019).

For all vehicles, EOL entails treatment of the used glider, tires, paint, glass, and oils.

For all Li-ion batteries, we assumed mixed treatment consisting of both hydro- and pyrometallurgical treatment from the ecoinvent process "*market for used Li-ion battery | used Li-ion battery | Cutoff, U – GLO*".

For EOL treatment of PEMFCs a specific EOL treatment was not obtained. Therefore, we assumed hydrometallurgical treatment of batteries as a proxy as hydrometallurgical treatment is a common platinum recovery process (Ellingsen et al., 2016) because this proxy has been used previously (Simons and Bauer, 2015). For this purpose, we made a slight modification to "*treatment of used Li-ion battery, hydrometallurgical treatment | used Li-ion battery | Cutoff, U*" where we added transport (same as used in the market process for the used Li-ion battery).

2.3 Life cycle impact assessment

We employed the ReCiPe 2016 characterization method to assess the midpoint impacts from a hierarchist perspective. The calculations were done using the openLCA software (version 2.1.1). Table 2.2 provides an overview of the assessed environmental impact categories, along with their respective indicators, characterization factors, and units.

Table 2.2: Overview of assessed environmental impact categories, their respective indicators, characterization factors, and units; table adapted from Huijbregts et al., (2016).

Midpoint impact category	Indicator	Characterization factor	Unit
Climate change	Infrared radiative forcing increase	Global warming potential (GWP)	kg CO_2-eq to air
Freshwater ecotoxicity	Hazard-weighted increase in freshwater	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-eq to freshwater
Terrestrial ecotoxicity	Hazard-weighted increase in natural soils	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-eq to industrial soils
Terrestrial acidification	Proton increase in natural soils	Terrestrial acidification potential (TAP)	kg SO_2-eq to air
Photochemical ozone formation, human exposure	Tropospheric ozone population intake increase	Photochemical ozone formation potential: humans (HOFP)	kg NOx-eq to air

Institute of Transport Economics, Gaustadalléen 21, N-0349 Oslo, Norway, E-mail: toi@toi.no www.toi.no

3 Results

In this section, we present the results of our assessment, detailing the contributions of each impact category and highlighting the differences between the various powertrains. Special attention is given to identifying the sources of environmental impacts for fuel cell and battery electric vehicles, which are being considered as potential alternatives to ICE technology in the freight vehicle sector. In subsections 3.1 through 3.5, we explore the key environmental differences between the powertrain technologies. **While the results for both the regional truck with trailer and the long-haul tractor with semi-trailer are presented together, direct comparisons between these two vehicle types are not intended, as they are designed for different applications**. Subsection 3.6, therefore, focuses on summarizing the environmental impact of these vehicle types and explaining the reasons behind the differences between regional trucks and long-haul tractors. Finally, subsection 3.7 presents the results of the sensitivity analysis, considering the impact of energy carrier production pathways on climate change.

3.1 Climate change impact

Figure 3.1 illustrates the climate change impact in terms of g CO_2-eq per tkm. The results are presented for the regional truck on the left and the long-haul tractor on the right. Contributions to the total impact are categorized as follows: production (broken down into glider, powertrain, and trailer/semi-trailer) is shown in orange shades; vehicle distribution is depicted in turquoise; WTW impact (further divided into WTT and TTW) are shown in grey shades; maintenance impacts appear in ice blue; and EOL treatment is presented in yellow. Non-exhaust wear emissions, which do not contribute to climate change impacts, are not displayed in the figure.

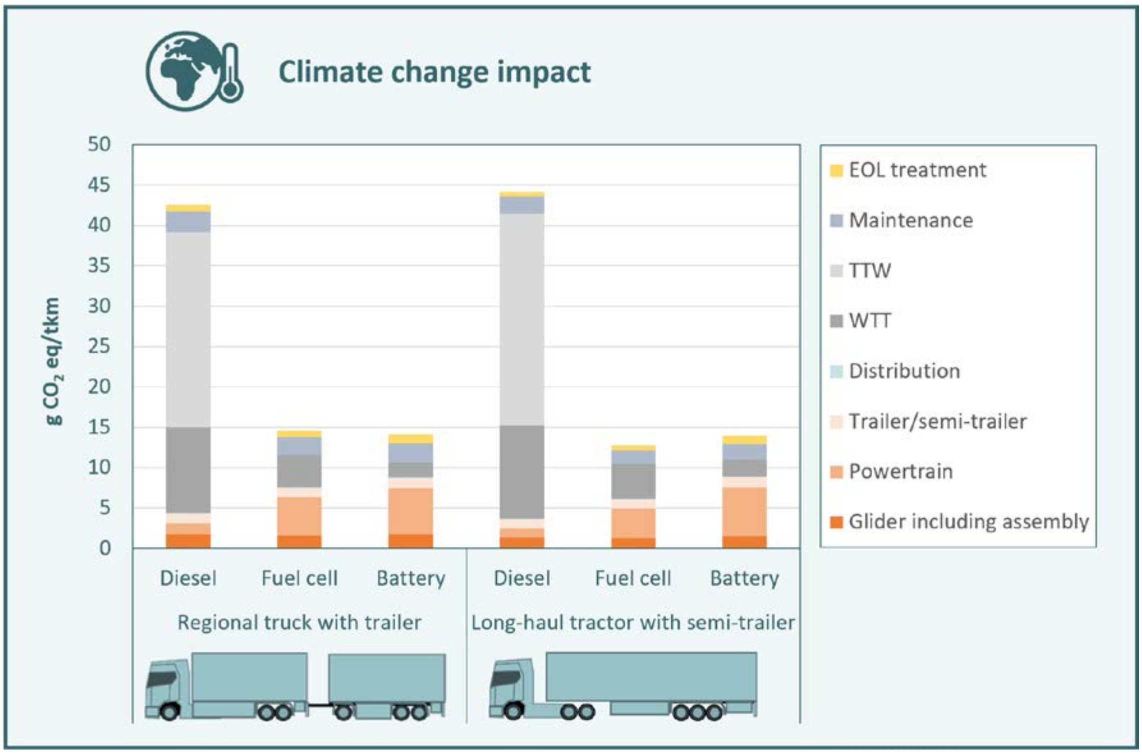


Figure 3.1: Climate change impact per tkm.

Overall, **the electric vehicles demonstrated a lower life cycle climate change impact compared to their diesel-powered counterparts.** Although the production of electric powertrains generated higher emissions, the significant reduction in emissions during the use phase resulted in a net climate benefit over their life cycle of the electric vehicles.

3.1.1 Production phase

The only difference in production impact between the vehicles stemmed from the powertrain, as the glider and trailer or semi-trailer units were identical across vehicles. For the fuel cell vehicles, the higher production emissions were primarily due to the hydrogen tank (accounting for 60% of the powertrain impact) and the PEMFC system (23% of powertrain impact). The hydrogen tanks were primarily made of carbon fibre, an energy-intensive material that contributed to more than one-third of the fuel cell powertrain emissions. The PEMFC system's emissions were largely due to the use of platinum, which contributed to 15% of total powertrain impact.

For battery electric vehicles, the powertrain impacts were predominantly driven by battery packs, which accounted for 92% and 94% of the total powertrain impact for the regional truck and long-haul tractor, respectively. The most significant source of emissions within the battery packs was the production of the NMC622 cathode, which contributed to about 41% of total battery electric powertrain impacts.

3.1.2 Distribution

The distribution of finished vehicles to dealerships has a minor effect on overall climate change impacts, and this contribution is not visible in the figure. However, the scale of distribution emissions was higher for battery electric vehicles, followed by diesel and fuel cell vehicles. These emissions were primarily caused by CO_2 emissions during transport, with heavier vehicles resulting in greater emissions.

3.1.3 Energy carrier life cycle

The life cycle of energy carriers significantly influenced the climate change impacts. For the diesel vehicles, WTW accounted for 82% and 86% of the total life cycle impacts for the regional truck and long-hauls tractor, respectively. Within the WTW phase, 30% of the impact came from WTT emissions, while the remaining 70% was attributed to TTW emissions. The primary source of TTW emissions for diesel vehicles was the release of CO_2 emissions from diesel fuel combustion.

The low carbon footprint of the Norway's electricity mix – which was used for both hydrogen production (for fuel cell vehicles) and battery charging – resulted in relatively low WTT emissions. However, fuel cell vehicles exhibited higher WTT emissions than battery electric vehicles, primarily due to the energy-intensive hydrogen production process via electrolysis and the relatively lower efficiency of the fuel cell powertrain compared to the battery electric powertrain. For fuel cell vehicles, hydrogen refuelling stations contributed minimally to WTT emissions. In contrast, battery electric vehicles saw more significant contributions from battery charging stations. For the regional battery electric truck, 28% of WTT emissions were associated with depot battery charger, with the remaining 72% stemming from electricity production and distribution. For the long-haul battery electric tractor, depot chargers accounted for 20% of WTT emissions, while the electricity production and distribution contributed to 80%.

3.1.4 Maintenance

Maintenance activities, including annual tire replacement, oil changes, and AdBlue consumption for diesel vehicles, were also considered in our analysis. For all vehicle types, tire replacement was the largest contributor to maintenance-related emissions, accounting for 87% and 85% of emissions for regional and long-haul diesel vehicles, respectively, and up to 99% for electric powertrains. Diesel-powered vehicles also had slightly higher maintenance emissions compared to electric powertrains, mainly due to AdBlue consumption (13% and 18% higher for regional and long-haul diesel vehicles, respectively). EOL treatment of the spent tires were accounted for along with other EOL treatment, rather than as part of the maintenance emissions.

3.1.5 EOL phase

EOL emission contributed only a small fraction of the total life cycle climate change impact for all vehicle types. The majority of these emissions resulted from the treatment of used tires. The treatment of large, high-energy Li-ion batteries was also a notable contributor to emissions for battery electric vehicles.

3.2 Freshwater ecotoxicity impact

Figure 3.2 shows the freshwater ecotoxicity impact in terms of kg 1,4-DCB per tkm. The contributions to this impact are represented by the same color scheme used for climate change impact, with non-exhaust wear emissions shown in charcoal.

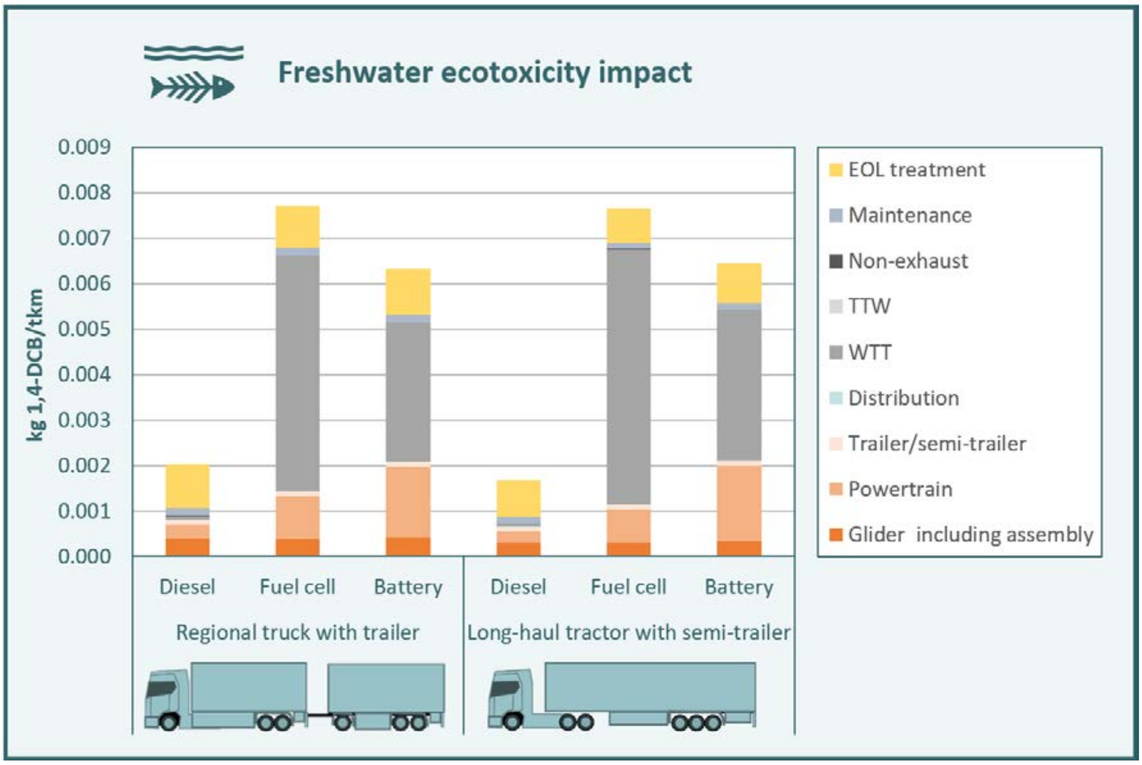


Figure 3.2: Freshwater ecotoxicity impact per tkm.

We found that electric vehicles had a higher overall freshwater ecotoxicity impact compared to their diesel-powered counterparts. These overall trends showed similarities with the climate change impact results but also had some distinct differences. Like climate change, the production of electric powertrains contributed more significantly to freshwater ecotoxicity compared to diesel power-trains. However, the energy carrier life cycles also contributed higher freshwater toxicity impacts for the electric vehicles.

3.2.1 Production phase

During the production phase, fuel cell and battery electric vehicles had significantly higher freshwater ecotoxicity impacts compared to diesel-powered vehicles. For the fuel cell vehicles, the majority of the impact was attributed to the PEMFC system (52% of powertrain impact), the hydrogen tank (15%), and the high-power battery pack (15%). The platinum catalyst in the PEMFC system was a major contributor, accounting for 37% of the total fuel cell powertrain impact.

For battery electric vehicles, the majority of the freshwater ecotoxicity impact came from the production of the battery packs, which accounted for 89% and 91% of the total powertrain impact for the regional truck and long-haul tractor, respectively. Copper used in the anode current collectors was the largest contributor, responsible for 46-47% of the total powertrain impact. The environmental consequences of copper production, including the release of copper ion as well as zinc(II) and silver(I) from waste disposal of sulfidic tailings from copper mine operation in tailings impoundment, were the main drivers for the high upstream impact.

3.2.2 Distribution

As in the climate change category, distribution of finished vehicles to dealerships had a minimal effect on freshwater ecotoxicity impacts and is not clearly visible in the figure. The primary contributors to impacts during distribution were the release of zinc(II) to water compartments and antimony ion emissions to the air.

3.2.3 Energy carrier life cycle

A notable finding in the freshwater ecotoxicity analysis was the significant impact from the energy carriers. While WTW impacts of diesel vehicles were negligible, WTT impacts for both fuel cell and battery electric vehicles were notably high. These impacts were primarily driven by the use of copper in electrical distribution networks and the chargers for the battery electric vehicles. The production of virgin copper, particularly from the treatment of sulfidic tailings and copper smelting, was a key source of freshwater ecotoxicity. Additionally, controlled landfilling of bottom ash from municipal solid waste incineration of scrap copper also contributed to the impact, with copper ion leaching into water as a significant source of contamination.

3.2.4 Non-exhaust emissions

Non-exhaust emissions contributed to freshwater ecotoxicity, but their impact was so low that it is not visible in the figure. The primary sources of impact were the release of zinc(II) to water and antimony ions to the air from brake (78%) and tire (22%) wear.

3.2.5 Maintenance

The primary contributor to maintenance impact was tire replacement. The steel fraction in the tires was the main source of impact, with the release of copper ion as well as chromium(VI) and zinc(II) being the key contributors to freshwater ecotoxicity.

3.2.6 EOL phase

EOL treatment was a sizeable contributor to overall freshwater ecotoxicity impact. The most significant source of impact was the landfilling of bottom ash from municipal solid waste incineration, which was the treatment method for shredder residues and used tires. As EOL treatment of batteries was not a significant source of impact, fuel cell and battery electric vehicles only had marginally higher impact from EOL treatment.

3.3 Terrestrial ecotoxicity impact

Figure 3.3 shows the terrestrial ecotoxicity impact in terms of kg 1,4-DCB per tkm.

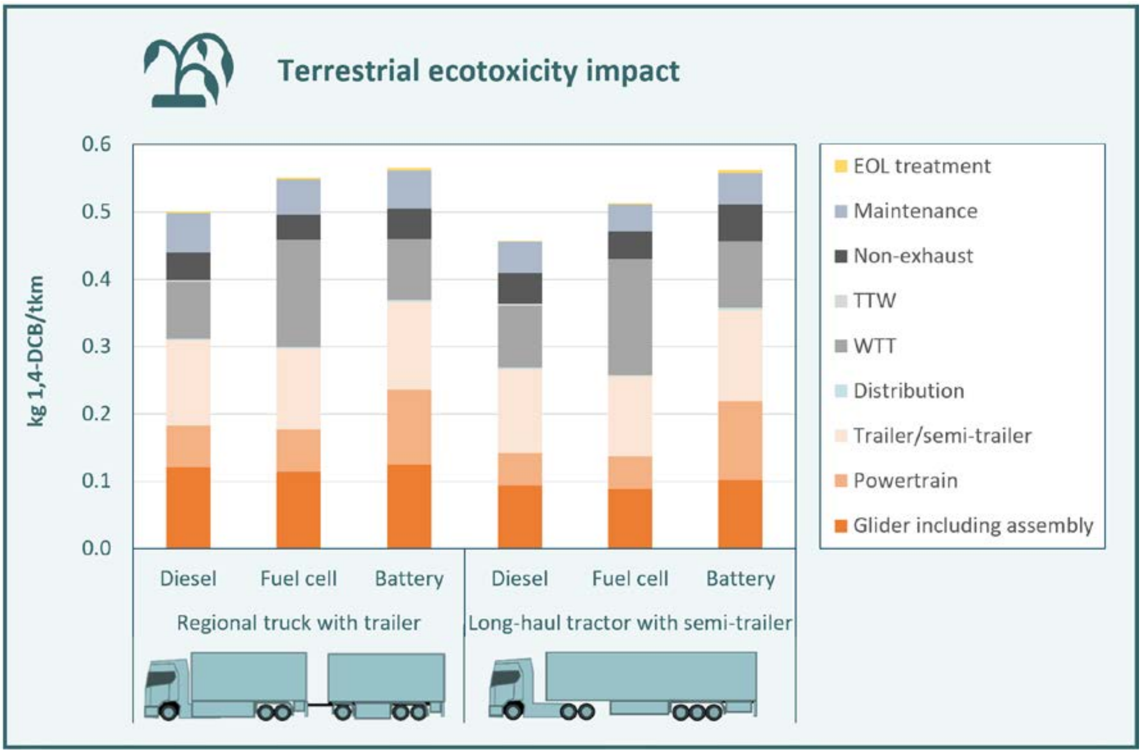


Figure 3.3: Terrestrial ecotoxicity impact per tkm.

For terrestrial ecotoxicity we observed significant variations in the contributions to impact across vehicle types. Battery electric vehicles had the largest impact, followed by fuel cell vehicles, while diesel vehicles had the lowest impact.

3.3.1 Production phase

For all vehicles, we found that much of the production impact was attributed to steel use in the gliders and trailers or semi-trailers. The impacts stemmed primarily from production of coke used in pig iron production. The higher powertrain production impact for the battery electric vehicles stemmed from battery production, with about half of these attributed to the cathode active material (NMC622).

3.3.2 Distribution

Distribution of finished vehicles to dealerships contributed minimally to overall terrestrial ecotoxicity impacts, and these are hardly visible in the figure. The impact was primarily associated with the release of copper ion and cobalt(II) into the air during transportation.

3.3.3 Energy carrier life cycle

The WTW impacts varied across the different powertrain technologies. For the diesel vehicles, 99.9% of impact stemmed from WTT while only 0.1% stemmed from TTW. The WTT impact for the diesel vehicles primarily traced back to use of steel in oil extraction infrastructure.

For the fuel cell electric vehicles, 99.8% of the WTT impact stemmed from electricity used to produce hydrogen in the electrolysers, while only 0.2% was associated with hydrogen refuelling stations. Much of the impact was linked to steel production for hydropower plants and wind turbines, with a smaller share attributed to copper production used in the distribution network.

For the battery electric vehicles, the WTT impacts derived from electricity used for charging (60% of WTT impact) and chargers (40% of total WTT impact). Both of these impacts were heavily influenced by copper use.

3.3.4 Non-exhaust emissions

Terrestrial ecotoxicity was the only impact category where non-exhaust emissions made a substantial contribution. The majority of the impact stem from brakes (97%), while tires had a smaller contribution (3%). Impacts traced back to release of copper ion, antimony ion, and zinc(II) emissions to air.

3.3.5 Maintenance

Maintenance-related impact was primarily associated with tire replacement. The two main sources of impact were steel and rubber fractions in the tires, which together contributed to approximately 64% of the total maintenance impact (44% from steel and 20% from rubber).

3.3.6 EOL phase

EOL treatment contributed minimally to overall terrestrial ecotoxicity impact. The small contribution primarily resulted from the landfilling of bottom ash from municipal solid waste incineration, which is used as treatment of shredder residues and used tires.

3.4 Terrestrial acidification impact

Figure 3.4 shows the freshwater ecotoxicity impact in terms of g SO_2-eq per tkm.

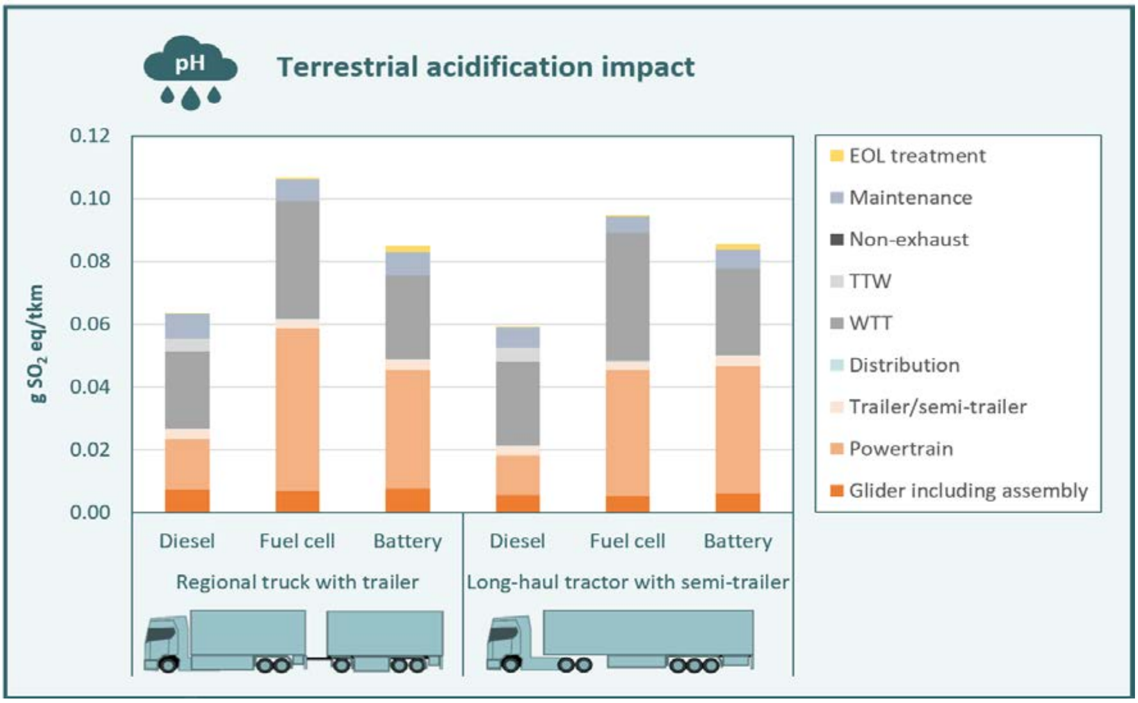


Figure 3.4 Terrestrial acidification impact per tkm.

The overall terrestrial acidification impact trends mirrored those observed for freshwater ecotoxicity, with fuel cell electric vehicles having the highest impact followed by battery electric vehicles, and diesel vehicles having the lowest impact. However, the contributions to the impact differed across vehicle types, with the electric vehicles' higher production impacts being a major factor in their higher overall acidification impacts.

3.4.1 Production phase

For the fuel cell vehicles, the higher powertrain impact was primarily attributed to the PEMFC system, which accounted for 72%, and the hydrogen tank, contributing 17%. The high impact for the fuel cell powertrain was largely due to the use of platinum catalyst. Platinum mining indirectly causes the release of SO_2 emissions, which contributes significantly to terrestrial acidification.

For the battery electric vehicles, the majority of powertrain impact came from battery production, with the battery packs accounting for 92% and 93% of the total powertrain impact for the regional truck and long-haul tractor, respectively. The most significant source of impacts was the battery cells, particularly the use of transition metals in the electrodes. A detailed contribution analysis revealed that the supply chains for copper (used in the anode current collector) as well as cobalt and nickel (both used in the NMC622 cathode) were responsible for release of SO_2 emissions, which was the primary contributing stressor to acidification impact in the battery electric powertrain.

3.4.2 Distribution

Distribution of finished vehicles contributed marginally to overall terrestrial ecotoxicity impacts, and these impacts are not clearly visible in the figure. The primary contributing stressors were NOx and SO_2 emissions, primarily due to the use of fossil fuels for transportation.

3.4.3 Energy carrier life cycle

Among the five impact categories, the WTW acidification impacts were the most similar across the different powertrain alternatives. For the diesel vehicles, 85% of impact occurred upstream (WTT), with the remaining 15% arising from combustion (TTW). The WTT impact was largely driven by the SO_2 emissions released in the fossil diesel supply chain. The TTW impact was primarily caused by NOx emissions from the combustion of fossil diesel.

For the fuel cell electric vehicles, 99.9% of the impact was related to hydrogen production, with only 0.1% stemming from hydrogen refuelling stations. The WTT impact was primarily due to use of copper in the distribution network and was driven by SO_2 emissions copper smelting.

For the battery electric vehicles, 58% of impact was attributable to the electricity use, with the remaining 42% due to the chargers. In both cases, copper was the primary source of impact, particularly due to SO_2 emissions associated with copper concentrate smelting.

3.4.4 Non-exhaust emissions

Non-exhaust emissions contributed modestly to the overall acidification impacts for all vehicle types. Brake wear was responsible for 84% and wear contributed 16% to the total non-exhaust acidification impact. The main emission driving this impact was SO_2, formed during the wear process.

3.4.5 Maintenance

The maintenance-related acidification impact was primarily caused by tire production, which accounted for approximately 99% of the total maintenance impact. The rubber and steel fractions in the tires contributed 27% and 25% of the overall maintenance impact, respectively. SO_2 emissions from the upstream supply chain for tire production were the main driver of this impact.

3.4.6 EOL phase

The EOL phase contributed relatively modestly to the overall terrestrial acidification impact. However, the battery electric vehicles exhibited higher EOL impacts compared to diesel and fuel cell vehicles. This higher impact was primarily due to the treatment of large, high-energy Li-ion batteries, where combined hydro- and pyrometallurgical treatment contributed to approximately 85% of the EOL impact for BEVs. For fuel cell vehicles, the EOL impact from the smaller high-power Li-ion batteries and the hydrometallurgical treatment of fuel cells contributed 18% and 32% of the overall EOL impact, respectively.

3.5 Photochemical ozone formation impact, human exposure

Figure 3.5 shows the photochemical ozone formation impact, human exposure in terms of g NOx-eq per tkm.

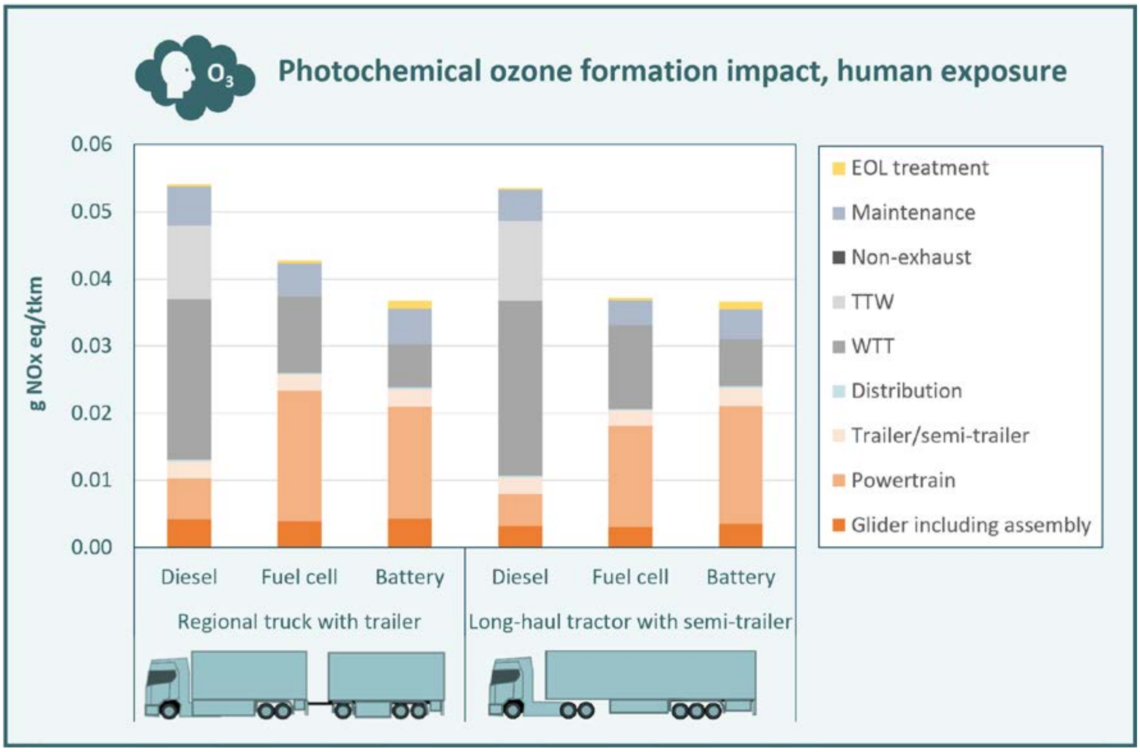


Figure 3.5: Photochemical ozone formation impact, human exposure per tkm.

The ozone formation impact varied significantly between diesel and electric vehicles. Diesel vehicles were characterized by higher contributions from the WTW phase, whereas electric vehicles had larger higher contributions from the production phase.

3.5.1 Production phase

For production impact, fuel cell and battery electric powertrains exhibited higher contributions compared to the diesel-powered vehicles. For the fuel cell vehicles, the higher primary contributors to the higher impact were the PEMFC system (55% of powertrain impact) and the hydrogen tanks (29% of powertrain impact). The platinum catalyst used in the PEMFC was a major contributor, accounting for 50% of the total fuel cell powertrain impact.

For the battery electric vehicles, most of the impact came from the battery packs, which accounted for 87% and 90% of the total powertrain impact for the regional truck and long-haul tractor, respectively. A significant portion of the battery-related powertrain impact (approximately 35%) was due to the production of cathodes.

3.5.2 Distribution

As with the other impact categories, distribution of finished vehicles to dealerships contributed only marginally to overall photochemical ozone formation impacts. This phase primarily resulted in NOx emissions released into the air, but these emissions were relatively small compared to other phases of the life cycle.

3.5.3 Energy carrier life cycle

The energy carrier life cycle had a considerable effect on photochemical ozone formation, especially for the diesel vehicles. For diesel-powered vehicles, 69% of the impact originated from upstream emissions (WTT), with the remaining 31% stemming from diesel combustion (TTW). The majority of the WTT impact was caused by NOx and non-methane volatile organic compound (NMVOC) emissions associated with the fossil diesel supply chain, while TTW impacts were largely driven by NOx emissions from combustion.

For fuel cell vehicles, 99.9% of the photochemical ozone formation impact was linked to hydrogen production, with the remaining 0.1% from hydrogen refueling stations. The main contributors to the impact in hydrogen production were indirect NOx emissions associated with the construction of hydropower plants and the production of copper for the distribution network.

For battery electric vehicles, WTT impact was more evenly distributed between electricity generation and the charger. For the regional trucks, 58% of impact stemmed from the electricity use and 42% from the chargers, while for long-haul battery electric tractors the contribution was 68% and 32%. Use of copper in charging stations and distribution networks as well as construction of hydropower plants were important sources of NOx emissions, which was the main emission source to WTT impacts.

3.5.4 Non-exhaust emissions

Although non-exhaust wear emissions contributed to photochemical ozone formation, their impact was minimal and not visible in the figure. Tire wear contributed to 64% and brake wear the remaining 36%. Impact was caused by release of nitrates into the air, contributing to the formation of ozone.

3.5.5 Maintenance

Maintenance primarily contributed to ozone formation through tire replacement. The rubber and steel fractions in tires accounted for approximately 30% and 23% of total maintenance impact, respectively. NOx emissions from the manufacturing processes were the primary source of the impact.

3.5.6 EOL phase

Impact during the EOL phase was relatively modest, but as in other categories, battery electric vehicles had higher impacts than both diesel and fuel cell electric vehicles. This higher impact was primarily due to the treatment of large, high-energy Li-ion batteries, which contributed about 70% of the overall EOL impact for battery electric vehicles. For fuel cell vehicles, EOL treatment of both fuel cells and smaller high-power Li-ion batteries accounted for approximately 12% and 12% of the overall EOL impact, respectively.

3.6 Differentiating the environmental impacts of regional and long-haul vehicles

In subsections 3.1 through 3.5, we focused on explaining the differences in environmental impacts between the various powertrain technologies. In this subsection, we shift our focus to summarizing the overall environmental impact of the regional trucks and long-haul tractors, while also exploring the reasons behind the differences between these two vehicle types. To facilitate this, we present an overview of their relative environmental impacts, as shown in Figure 3.6. The figure displays the relative results for the regional truck with trailer on the left and those for the long-haul tractor with semi-trailer on the right. Results for the diesel vehicles are shown in brown, fuel cell vehicles in blue, and battery electric vehicles in turquoise.

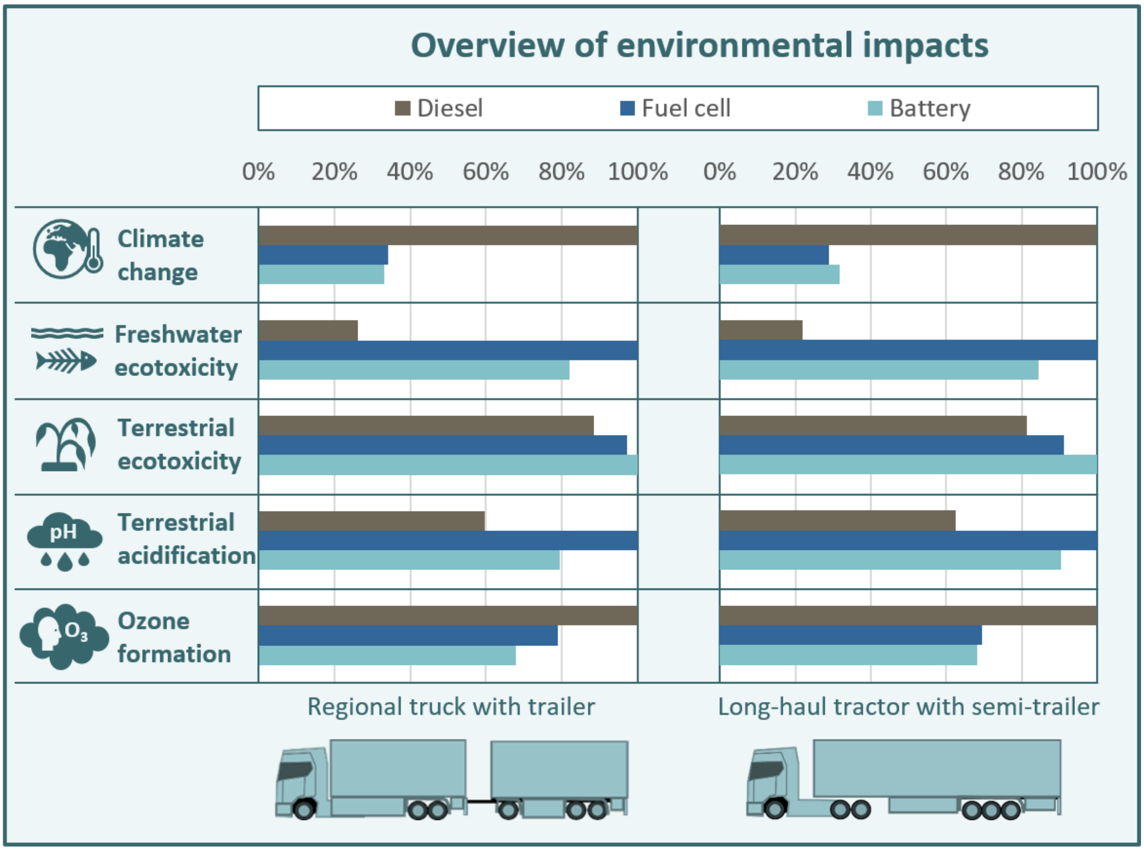


Figure 3.6: Relative environmental impacts, per vehicle type.

We observed notable differences in the relative environmental impacts of the regional truck and long-haul tractor. For example, the battery electric truck had a lower environmental impact than the fuel cell truck in four out of five impact categories, while the battery electric tractor had a lower impact than the fuel cell tractor in only three of the five categories. While the battery electric powertrain provided a climate benefit over the fuel cell powertrain for the regional truck, this was not the case for the long-haul tractor. The primary reason for this was the difference in battery sizes between the battery electric vehicles: the regional truck was equipped with a 750-kWh battery, whereas the long-haul tractor had a 1 000-kWh battery pack. Since the battery pack was a major contributor to the climate change impact for battery electric vehicles, the larger battery for the long-haul tractor resulted in a slightly higher overall impact compared to the fuel cell tractor. A similar trend was observed in other impact categories, though the overall environmental performance of the long-haul battery electric tractor remained favorable compared to the fuel cell alternative. In addition to battery size, it is also worth noting that the fuel cell vehicles were estimated to have the largest cargo capacity of the three powertrains. This factor also influenced the results, as they were reported per tkm. Had the same cargo capacity been assumed for all powertrains in the assessment, the battery electric long-haul tractor would have had lower impact than the fuel cell tractor. In Appendix B, interested readers can find the results expressed in terms of an alternative functional unit, expressing results per-vehicle basis.

3.7 Sensitivity analysis of energy carriers

In this subsection, we present the results of the sensitivity analysis, which examines the impact of alternative production pathways for hydrogen used in fuel cell vehicles and electricity used to charge battery electric vehicles. For hydrogen, we considered two production pathways: electrolysis using the average European electricity mix and steam methane reforming (SMR). For electricity used in battery charging, we considered the average European electricity mix. Two main reasons motivated the inclusion of alternative production pathways: first, to assess their significance and effect on climate change impact, and second, to improve the transferability of results and provide additional insights. The focus is primarily placed on climate change impacts, with other impact categories briefly addressed at the end of this subsection. Figure 3.7 presents the results of the sensitivity analysis, with results for the regional trucks on the left and for the long-haul tractors on the right. Results for the diesel vehicles are shown in brown, fuel cell vehicles in blue, and battery electric vehicles in turquoise. Solid fill is used for the baseline results, while pattern fill denotes the sensitivity analysis results.

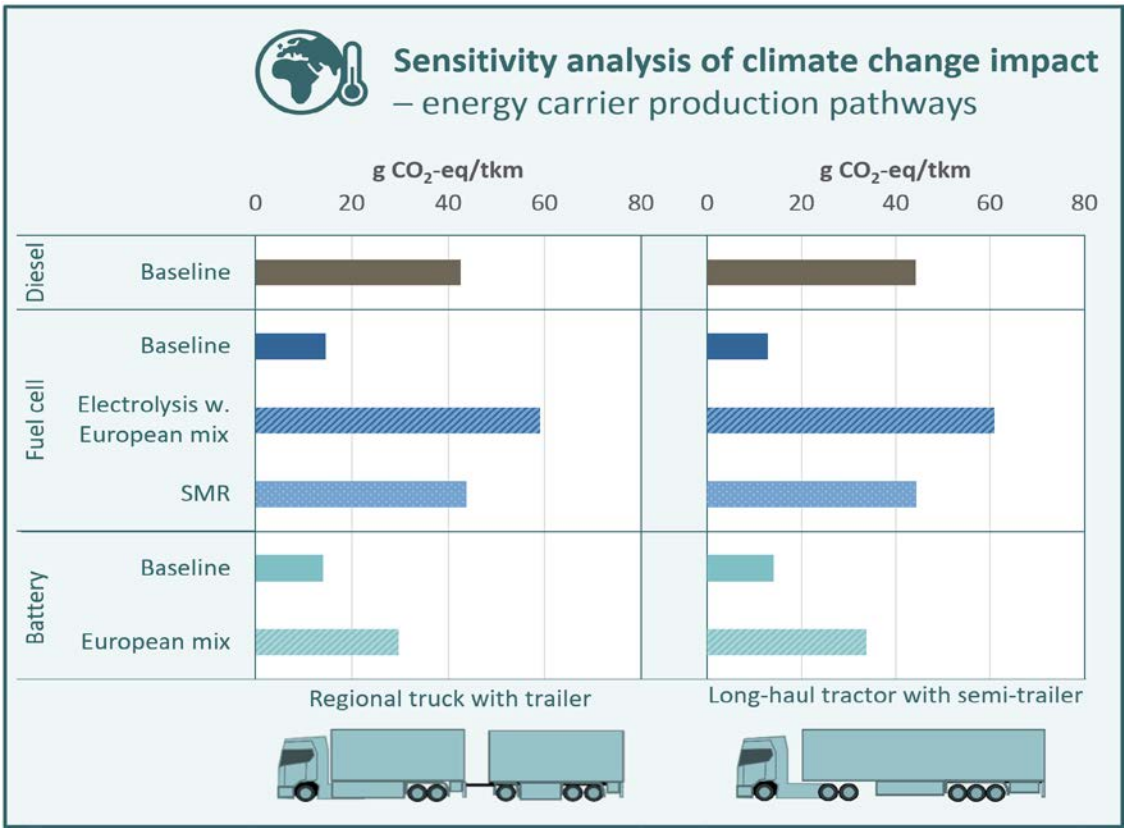


Figure 3.7: Sensitivity analysis of the impact of energy carrier production pathway on climate change.

For fuel cell vehicles, we found that using hydrogen produced via electrolysis with the average European electricity mix resulted in higher climate change impact compared to diesel vehicles. However, when fuel cell vehicles were powered by hydrogen produced through SMR, their impacts were approximately the same as those of diesel vehicles. Thus, neither of the two alternative hydrogen production pathways offered climate change benefits for fuel cell vehicles when compared to diesel vehicles.

For battery electric vehicles, using the average European electricity mix more than doubled their overall life cycle climate impact compared to baseline results. However, when **compared to diesel vehicles, battery electric vehicles still provided significant net life cycle climate benefit, even with the average European electricity mix. This benefit is expected to increase over time as the European electricity mix continues to transition towards less carbon intensive electricity sources**.

The sensitivity analysis also revealed that fuel cell vehicles relying on hydrogen produced via electrolysis were much more sensitive to increases in the carbon intensity of the electricity mix compared to battery electric vehicles. This is because both WTT and TTW energy use are higher for fuel cell vehicles than for battery electric vehicles.

In terms of other impact categories, we generally observed significant increases in environmental impacts, with one notable exception. Hydrogen produced from SMR reduced terrestrial acidification impact by 16% for the fuel cell regional truck and 19% for the long-haul tractor. In contrast, both fuel cell and battery electric vehicles showed relative increases in impacts compared baseline results, with magnitudes of these being considerably higher.

4 Discussion

4.1 Result analysis

The goal of this study was to assess the life cycle environmental performance of 50-ton freight vehicles operating in Norway. To achieve this, we compiled both original and previously published data to create detailed cradle-to-grave LCIs for diesel, fuel cell, and battery electric regional trucks and long-haul tractors. These inventories allowed us to comprehensively evaluate the environmental performance across five impact categories. In this section, we discuss the key findings of our analysis.

Our results revealed that no single powertrain consistently outperformed the others across all impact categories. Instead, we observed trade-offs in environmental performance among the various powertrain technologies. Specifically, the electric trucks and tractors demonstrated lower impacts in terms of climate change and ozone formation, primarily due to lower impacts during the use phase. Conversely, diesel vehicles outperformed both electric options in three of the five impact categories: freshwater toxicity, terrestrial toxicity, and terrestrial acidification. That said, **climate change mitigation remains the primary driver for electrification. When using the Norwegian electricity mix for hydrogen production via electrolysis and battery charging, both fuel cell and battery electric trucks offer net life cycle climate benefits**. In addition, the battery electric trucks also offer net life cycle climate benefits when charged with the average European electricity mix.

Although the electric vehicles shared similar environmental profiles, there were notable differences between the two electric powertrain types. Battery electric vehicles exhibited lower impacts in freshwater ecotoxicity, terrestrial acidification, and ozone formation. In contrast, fuel cell vehicles showed a lower impact in terrestrial ecotoxicity. Regarding climate change, the overall impact was similar for both electric vehicle types, though the battery electric regional truck had a lower impact compared to the fuel cell truck, while the battery electric long-haul tractor had a slightly higher impact for the chosen functional unit.

When comparing powertrain technologies, it became evident that electrification generally incurs higher production impacts compared to diesel vehicles. This shift towards higher production impact presents constraints for the hydrogen production pathways for fuel cell vehicles and the electricity production for battery electric vehicles, as both require a lower use phase impact to achieve an overall life cycle environmental benefit. Our findings suggest that electric vehicles will struggle to offset their higher production impacts in categories such as freshwater ecotoxicity, terrestrial ecotoxicity, and terrestrial acidification. The use of metals in the production and energy carrier life cycles of electric vehicles was a significant contributor to these impacts, as electric vehicles typically rely more heavily on metals than their diesel counterparts. While both electric vehicle types may achieve a net life cycle benefit in terms of climate change, stricter constraints apply to fuel cell vehicles compared to battery electric vehicles, which are more likely to succeed due to their more efficient energy life cycle.

4.2 Uncertainties

This study can be considered a preliminary assessment, as electric powertrains are still in their early stages, and electric heavy-duty freight vehicles primarily exist as pilot projects with limited production volumes and sales. While rigorous efforts were made to model and compare the various powertrain technologies and vehicle types in an objective and realistic manner, data availability and quality vary between diesel and electric vehicles, introducing uncertainties in the results. In this section, we highlight some of the key uncertainties in this regard.

Within our modeling framework, we assumed that powertrain components would last for the full lifetime of the vehicles, with no need for replacements. This assumption carries significant uncertainty, as we identified notable impact contributions from key components (i.e., hydrogen tanks, fuel cell stacks, and Li-ion batteries) in the electric powertrains. Since electric vehicles showed net life cycle benefits primarily in terms of climate change and ozone formation, we consider the impact of replacing powertrain components for these two categories. For climate change, the contribution of key powertrain components was significant, but with the assumed Norwegian electricity mix for hydrogen production via electrolysis and battery charging, both vehicle types provided substantial net climate benefits. In fact, the net climate benefits were so significant that both fuel cell and battery electric vehicles could accommodate up to five full powertrain replacements before matching the lifetime climate change impact of diesel vehicles. Therefore, this assumption has minimal implications for climate change impacts. However, for ozone formation, the contribution of powertrains to the total life cycle impact was higher. As a result, the assumption of no replacements has greater implications in this category. If one replacement of the main powertrain components were required, electric vehicles would lose much, if not all, of their life cycle ozone formation benefits compared to diesel vehicles.

Another uncertainty relates to fuel cell vehicles, where the platinum loading in the fuel cell stack—a key contributor to many environmental impacts—is still under active development. As this parameter is optimized, impacts are expected to decrease. In this study, platinum loading was modeled at 0.75 g/kW, but ongoing research and development projects for PEMFC heavy-duty applications are targeting much lower values. For example, the EU-funded Horizon Europe PEMTASTIC project aims for a platinum loading of 0.3 g/kW (PEMTASTIC, 2023). In our study, reducing the platinum loading to 0.3 g/kW could result in varying impact reductions depending on platinum's contribution. For instance, climate change impacts would decrease by 2.5%–2.9%, while terrestrial acidification would be reduced by as much as 17%–20%.

Uncertainties also exist for the battery electric vehicles. For instance, energy demand and its origin in battery cell manufacturing is still uncertain and may vary significantly depending on factors such as production technology, plant capacity, throughput, and production origin (Chordia, Nordelöf and Ellingsen, 2021; Bauer *et al.*, 2022). Recent studies report energy demands around 30–55 kWh per kWh of cell capacity when considering plant operations, excluding material mining and refining (Degen *et al.*, 2023). In our assessment, we modeled cell manufacturing energy demand based on Degen *et al.*, (2023), who estimate a total of 27 and 29 kWh of production energy per kWh of cell capacity for NMC622 and NMC532, respectively. Another relevant factor is the energy sources used to meet these energy demands. In our inventory modeling, we assumed global averages for heat from natural gas and electricity, as no specific location for cell manufacturing was considered. While significant uncertainties exist regarding energy use in battery production, it is important to note that it was not found to be a major contributor to overall battery impact. More significant factors include assumptions regarding the amount of cathode and anode materials, which contributed substantially to battery impacts. Additionally, we focused our analysis on NMC batteries, but other Li-ion battery chemistries, such as lithium iron phosphate (LFP) and lithium nickel cobalt aluminium oxide (NCA) batteries, are also applicable for heavy-duty vehicle applications. Due to differences in both extrinsic and inherent parameters, different Li-ion batteries have been found to have different life cycle impacts (Ellingsen *et al.*, 2022; Kim, Lee and Wallington, 2023). Consequently, the life cycle impact of battery electric trucks and tractors may vary depending on the battery chemistry.

Both WTT and TTW impacts were identified as significant contributors to the total life cycle impacts. Since these impacts are directly linked to energy consumption during vehicle use, the estimated energy consumption for the various vehicles is a key parameter in our analysis. More data are available on energy use for heavy-duty diesel vehicles compared to electric vehicles, which introduces greater uncertainty regarding hydrogen and electricity consumption in fuel cell and battery electric vehicles, respectively. For electric vehicles, uncertainty associated with energy use has larger implications for impact categories with high WTT contributions, such as freshwater ecotoxicity, and smaller implications for categories with lower WTT contributions, such as climate change (in the Norwegian context).

There is also uncertainty associated with the WTW impacts of diesel vehicles, which extends to the variability in biodiesel blending and feedstock use. In terms of climate change impact, we estimated that emissions from the WTT and TTW phases accounted for approximately 30% and 70%, respectively, of total WTW impact. This distribution differs from findings in other studies, which typically report WTT and TTW contributions of around 20% and 100%, respectively (Hawkins *et al.*, 2012; Nordelöf, Romare, and Tivander, 2019; Prussi *et al.*, 2020). This discrepancy can be attributed to the high proportion of biodiesel in the Norwegian diesel blend, which results in higher WTT emissions compared to fossil diesel, but lower TTW emissions due to the lower carbon intensity of biodiesel. Since data on blending and feedstock use are based on historic reports, our estimates do not predict future WTW impacts, which are likely to differ on a yearly basis depending on the biodiesel blending and feedstock use.

Additional uncertainties in WTT impacts are associated with the infrastructure requirements for electric powertrains, particularly for battery electric vehicles, where battery chargers were found to contribute significantly to the WTT impact. To model the chargers, we relied on literature data for bus chargers to estimate depot charger impacts. Due to the lack of primary data on chargers, the magnitude of impact attributed to each vehicle is highly uncertain. However, our results suggest that these impacts could be significant. Further data and analysis are needed to reduce this uncertainty and provide more reliable estimates.

While impacts related to distribution, maintenance, non-exhaust emissions, and EOL treatment were generally found to be small, uncertainties remain due to use of generic data and simplified assumptions for modelling these life cycle stages. LCA studies often model these stages in a rudimentary manner because of their perceived small contribution to life cycle impact, as well as the data-intensive nature of LCA. However, when considering alternative powertrain technologies, differences between technologies can be significant, making improved modelling of these life cycle stages increasingly important.

4.3 Limitations

While LCA can be used to address potential environmental impacts, it does not predict absolute or precise environmental impacts. This is due to the relative expression of impact potentials to a reference unit, the integration of environmental data over space and time, the inherent uncertainty in modelling environmental impacts, and the fact that some possible environmental impacts are projected for the future (ISO 14040, 2006). For instance, there are uncertainties associated with the results, particularly in terms of toxicity categories. These impacts are highly dependent on local background concentrations and chemical interactions between pollutants – factors that are not fully captured in LCA characterization methods (ACEA, 2021). Therefore, caution should be exercised when interpreting the toxicity results, which should be considered as indicative of potential environmental concerns related to electric powertrains, rather than as providing a definitive environmental ranking of powertrains. In terms of freshwater ecotoxicity, we observed a significantly lower impact for diesel vehicles compared to electric vehicles, while the terrestrial ecotoxicity impact was more similar across the various powertrain technologies.

In our study, we used average data to offer a general comparison of powertrain technologies. However, environmental impacts can vary significantly depending on supply chain differences, including production technologies and regional variations. Additionally, the results are based on two hypothetical case studies – one for 50-ton regional trucks and another for 50-ton long-haul tractors, each used for a specific number of annual kilometers driven. Therefore, transferability of these results beyond this scope is not recommended, as key parameters were specifically tailored to these case studies.

Applying circular economy principles, such as reusing or repurposing key powertrain components, can offer environmental benefits. However, we did not consider potential reuse or repurposing of fuel cells, hydrogen tanks, or Li-ion batteries due to uncertainties surrounding the lifetime of these components. Additionally, including such practices would introduce further uncertainties related to the allocation of their environmental burdens.

We limited the assessment of mineral resource use to the environmental impacts associated with mineral resource extraction, without considering criticality aspects. Several elements, such as lithium, cobalt, and platinum group metals, used in electric powertrain components and necessary infrastructure are considered critical raw materials by the EU due to their high economic importance, combined with a comparatively high risk of supply disruption due to the concentration of sources and lack of good, affordable substitutes (Council of the European Union, 2024). Complementary sustainability studies on electrification and metal use have highlighted that, while electric powertrains reduce tailpipe emissions and fuel dependency, the benefits come at a cost of higher metal requirements compared to ICE powertrains (Bhuwalka *et al.*, 2021; Raghavan *et al.*, 2023; Zhang *et al.*, 2023). For example, a study examining the metal requirements for electrifying Swedish cars and heavy-duty trucks found higher metal use for both fuel cell and battery electric vehicles compared to ICE vehicles. The increased use of metals and critical raw materials is driven not only by the electric powertrain components but also by the supporting infrastructure (Raghavan *et al.*, 2023).

Another limitation is the static nature of the analysis. Potential changes in supply chains or future improvements in energy efficiency were not considered. For example, potential improvements in the energy efficiency of hydrogen production via electrolysis were not factored into the assessment. Such improvements could reduce the WTT impact of fuel cell vehicles. However, it is important to note that, given the low-carbon Norwegian electricity mix was assumed in the baseline, significant impact reductions may not be expected. A prospective LCA could be performed to address this limitation, but due to time and budget restrictions, this was not possible within the scope of this study.

Finally, we considered only diesel, fuel cell, and battery electric powertrains in this study. Due to limitations in data and time available within the project, hybrid powertrains or alternative fuels were not included. For instance, for combustion engine vehicles, this study focused on diesel sold on the Norwegian market, a blend of fossil diesel and biodiesel. Unblended HVO was not considered in isolation due to its limited supply, while alternative fuels, such as e-fuels, synfuels, or biomethane, were not considered, as they fall outside the scope of the FME MoZEES project.

4.4 Recommendations

This LCA study provides valuable insights into the environmental performance of freight vehicles operating in Norway, offering guidance for developing more sustainable transport solutions and informing strategies to reduce the environmental impact of freight transport. Our results indicate that, although fuel cell and battery electric trucks can offer net life cycle climate change benefits, there is no "silver bullet", as no single powertrain consistently outperforms the others across all impact categories. Consequently, decision-makers must carefully weigh the environmental trade-offs and potential problem shifting associated with each powertrain alternative to minimize other environmental impacts. In this section, we provide recommendations for stakeholders within the Norwegian context.

4.4.1 Fleet operators

The optimal powertrain choice for fleet operators depends on the specific requirements of their operation, including vehicle range, refueling/recharging times, and payload capacity. Given the significant contribution of key powertrain components–such as fuel cell stacks, hydrogen tanks, and Li-ion batteries–to the overall environmental impact of electric freight vehicles, fleet operators should carefully evaluate their operational needs and assess the most suitable vehicle specifications. While the LCA performed in this study was based on two hypothetical case studies, more detailed, route-specific assessments can help operators optimize the environmental footprint of their fleets.

Fleet operators should regularly assess the environmental performance of their fleet, including both climate emissions and other impacts. By staying informed on technological advancements and regulatory changes, operators can continuously improve fleet performance and reduce environmental impacts. Although hybrid powertrains were not considered in this study, they may present a viable alternative in a transition phase, as they have been found to offer net life cycle environmental benefits compared to pure diesel powertrains—particularly in terms of climate change impact (Sacchi, Bauer, and Cox, 2021), though their broader environmental performance requires further investigation.

Component and supply chain considerations are also critical. Investing in high-quality, durable components that can last the full lifespan of vehicles is essential, as this can reduce the frequency of replacements and mitigate long-term environmental impacts. Fleet operators should engage with suppliers and manufacturers that prioritize sustainability, particularly in sourcing of metals and materials for electric vehicle powertrains. This includes promoting transparency in material sourcing and supporting recycling initiatives to reduce the environmental impact of supply chains. For fuel cell vehicles, operators should also pay close attention to the hydrogen production pathway, as this is a key factor influencing the environmental performance of the vehicles. Fleet operators may also consider repurposing and reusing EOL batteries if replacements are needed, to maximize the use (and associated environmental impact) of the produced battery.

Finally, operators should consider the broader aspects of sustainability. Therefore, the findings presented in this study should be considered in conjunction with the economic and societal cost analysis provided in the framework. Technologies that strike a balance between practical requirements, cost-efficiency, and environmental impact are more likely to achieve widespread adoption.

4.4.2 Policymakers

Policymakers should base electrification strategies on robust understanding of the environmental performance of heavy-duty vehicles, which requires a life cycle perspective. LCA offers the most effective framework for assessing the environmental impact potential of products and services (European Commission, 2003) and should be employed to ensure that policies achieve their intended environmental goals. LCA is essential for understanding the full environmental impact of vehicles across their entire life cycle. These assessments can provide valuable insights to identify emerging trends, evaluate the effectiveness of current policies, and pinpoint areas where improvements in vehicle design, energy sources, or infrastructure could further reduce environmental impacts.

When using the Norwegian electricity mix for hydrogen production via electrolysis and battery charging, both fuel cell and battery electric trucks offer net life cycle climate benefits. While climate change mitigation is a primary driver for electrification, policymakers should also consider the environmental trade-offs and potential problem-shifting associated with powertrain technology changes. This proactive approach will help prevent unintended environmental consequences and identify areas for further improvement. For the electric freight vehicles, we found that the extraction and processing of metals used in powertrains as well as charging infrastructure significantly contribute to life cycle environmental impacts. Furthermore, electrification has been shown to increase metal dependency and use of critical raw materials. Therefore, policymakers should promote effecttive recycling and circular economy practices, such as battery recycling, repurposing, and reuse, which can help mitigate production-related environmental impacts as well as reducing supply chain dependency. Advancements in recycling technologies for batteries and fuel cell components will be crucial in making electric powertrains more sustainable over time.

Complementary to circular economy principles, it is also beneficial to integrate strategies from the Avoid-Shift-Improve (ASI) framework. This approach fosters a holistic perspective on freight transport, promoting not only the adoption of less carbon-intensive technologies but also the optimization of transport systems through avoidance of unnecessary freight movement (Avoid), shifts to more sustainable modes of transport (Shift), and improvements in efficiency and technologies (Improve). By incorporating these strategies, policymakers can more effectively address and mitigate the environmental impacts and resource use of freight transport, regardless of the chosen powertrain technology.

Another form of trade-offs/problem shifting associated with use of alternative powertrain technologies is carbon leakage. As Norway is an importer of trucks, the transition to electric trucks reduces domestic GHG emissions but increases emissions in the truck producing countries. In a climate political context, these emissions are the responsibility of the producing countries. Our results suggest that this transition is also likely to cause increased local and regional environmental impacts abroad, as observed in the contributions to toxicity and acidification. These impacts were particularly linked to metals, which are not produced domestically, used in the supply chains of electric powertrains and energy carriers (i.e., hydrogen and electricity).

The availability of charging and refueling infrastructure is another critical factor influencing the adoption of electric and fuel cell vehicles. Widespread, efficient refueling and charging stations are essential to support adoption, particularly in regions with insufficient infrastructure. Collaborating with fleet operators, local authorities, and private stakeholders can accelerate the deployment of this infrastructure and facilitate a smoother transition to electrified transportation.

Given the rapid pace of technological advancements in the electric vehicle sector, ongoing R&D funding is essential to ensure that LCAs remain up-to-date and reflective of the latest innovations, such as advancements in battery technologies, hydrogen production, and recycling processes. By prioritizing R&D investments in LCAs, policymakers can ensure electrification strategies are continuously guided by reliable and current environmental data, supporting informed decision-making and facilitating a sustainable transition to electric heavy-duty vehicle fleets.

5 Conclusion

We conducted this study to evaluate and expand knowledge on the life cycle environmental performance of heavy-duty freight vehicles with different powertrains, with a particular focus on their use in Norway. Our evaluation focused on 50-ton regional trucks with trailers and long-haul tractors with semi-trailers powered by diesel, fuel cell, and battery electric powertrains.

We found that no single powertrain consistently outperformed the others across all impact categories. Instead, we observed environmental trade-offs and problem shifting among the various powertrain technologies. Both fuel cell and battery electric vehicles offered net life cycle climate and ozone formation benefits compared to diesel vehicles but exhibited higher freshwater ecotoxicity, terrestrial ecotoxicity, and terrestrial acidification impacts. The use of metals in powertrain production and energy carrier life cycles was a significant contributor to these impacts, as electric vehicles typically rely more heavily on metals than their diesel counterparts. Thus, our results indicate that no single powertrain technology serves as a 'silver bullet' across all environmental impact categories. However, **both fuel cell and battery electric trucks offer significant net life cycle climate benefits when using the Norwegian electricity mix for hydrogen production and battery charging, which is the primary driver of truck electrification.**

The findings underscore the importance of considering all life cycle stages and various impact categories to obtain a holistic understanding of the environmental performance of different powertrain alternatives. A narrower focus—such as on just WTW or GHG emissions alone—would have overlooked the significance of the components in the electric powertrains or failed to highlight key differences between fuel cell and battery electric vehicles. The life cycle perspective is crucial for making environmentally sound decisions, guiding both fleet managers and policymakers.

While this study offers useful insights about diesel, fuel cell, and battery electric powertrains for heavy-duty freight vehicles, further research is necessary. Future studies should seek to address uncertainties pertaining to data availability, particularly for electric powertrains. Rapid advancements in technologies, such as fuel cells, Li-ion batteries, and energy carrier production and delivery, will necessitate frequent updates to ensure that assessments remain reflective of the latest developments. These updates will help guide progress toward more environmentally desirable outcomes and enable stakeholders to identify meaningful strategies for improving environmental performance as these technologies evolve.

The transition to electric vehicles must be guided by a robust and comprehensive understanding of their full life cycle impacts to ensure sustainable outcomes. This can only be achieved through comprehensive and regularly updated LCAs. Policymakers should prioritize R&D funding to ensure that LCAs reflect the latest technological advancements, including those in battery technologies, hydrogen production, and recycling processes.

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Appendix A – Inventory data

Glider

Table A 1 Weight of glider component groups

Component group	Weight (kg)
Frame, blanks, and saddle	924
Cabin	1 500
Rearguard & toolkit	168
Chassis & suspension	1 645
Auxiliary batteries 24 V	90
Chassis electronics	18
Tires	660
Wheels	308
Motor cooling system	151
Coolant	72
Differential oil	15.8
Steering oil	7.5
Total glider	**5 558**

Truck tires

For tires, we compiled an original inventory based on publicly available data about heavy-duty vehicle tires (U.S. Tire Manufacturers Association, no date) and literature data (Andersson and Diener, no date; Dong *et al.*, 2021). For production of the tires, we assumed 10% losses. Tires for long haul trucks used by Volvo Group typically weigh between 54 and 67 kg (Andersson and Diener, no date). We assumed a tire weight of 66 kg each. Both vehicles as well as trailers and semi-trailers were modelled with six tires each, for a total of 12 tires. The inventory for tires is provided in Table A 2.

Table A 2 Inventory data for tires, per tire.

Tires	Amount	Unit
	66.0	kg
Material inputs		
Natural rubber	24.9	kg
Synthetic rubber	8.1	kg
Carbon black	14.7	kg
Silica	2.9	kg
Zinc oxide	1.8	kg
Sulphur	1.0	kg
Organic chemical	3.8	kg
Stearic acid (antiozonants)	0.7	kg
Steel	15.4	kg
Process input		
Water	220.0	kg
Steam	133.1	kg
Energy input		
Electricity (low voltage)	74.7	kWh
Waste		
Waste water	33.2	liter

Motor cooling system

For the motor cooling system, we compiled original inventory data. The motor cooling data were based on publicly provided information (MAHLE, 2021) and previously published inventory data (Ellingsen *et al.*, 2014) and used for all trucks and tractors, regardless of powertrain.

Table A 3 Inventory data for motor cooling system

Motor cooling system	Amount	Unit
	151	kg
Material inputs		
Radiator	100.6	kg
Coolant pump	13.6	kg
Thermostat (glass fibre reinforced plastic, polyamide, injection moulded)	8.32	kg
Expansion tank (polyethylene, high density, granulate; injection moulding)	6.7	kg
Heat exchanger (cast aluminum)	13.3	kg
Hoses (silicone product)	8.31	kg

For the thermostat, we assumed the *ecoinvent* process "*market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U – GLO*". For the expansion tank, we assumed it was made of polyethylene and produced via injection moulding, using the ecoinvent processes "*market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U – GLO*" and "*market for injection moulding | injection moulding | Cutoff, U – GLO"*. The expansion tank was assumed to be made from cast aluminum, with inventory data sourced from Nordelöf, Romare and Tivander, (2019). The hoses were assumed to be made of silicone, for which we used the process *"market for silicone product | silicone product | Cutoff, U – RER".* Sub-inventories for the radiator and coolant pump are provided in Tables Table A 4 and Table A 5, respectively.

Table A 4 Sub-inventory data for radiator, per motor cooling system

Radiator	Amount	Unit
	100.7	kg
Material inputs		
All-aluminum radiator (cast aluminum)	66.6	kg
Oil cooler (cast aluminum)	6.7	kg
Coolant tanks (glass fibre reinforced plastic, polyamide, injection moulded)	26.6	kg
Seals (seal natural rubber based)	0.8	kg

Previously described inventory data were used for cast aluminum and glass fibre reinforced plastics. The ecoinvent process *"market for seal, natural rubber based | seal, natural rubber based | Cutoff, U – GLO"* was used for the seals.

Table A 5 Sub-inventory data for coolant pump, per motor cooling system

Coolant pump	Amount	Unit
	13.7	kg
Material inputs		
Aluminum (cast aluminum)	10.82	kg
Chromium steel (steel, chromium steel 18/8, hot rolled)	2.50	kg
Integrated electronic control (PCB Signal)	0.33	kg
Process input		
Metal working (average for steel product manufacturing)	2.50	kg

For chromium steel we assumed “*market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Cutoff, U – GLO*” and “*market for metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U – GLO*”. For the integrated electronics control we assumed a signal-type printed circuit board, with inventory data sourced from Nordelöf, Romare and Tivander, (2019).

Conventional powertrain

Table A 6 Weight of conventional powertrain component groups

Component group	Weight (kg)
Internal combustion engine	1 749
Gearbox and clutch	620
Retarder	103
Driveshaft	121
Exhaust system	394
AdBlue tank	23
Fuel tanks	120
Transmission oil	12.9
Total powertrain	**3 141**

AdBlue tank

Table A 7 AdBlue tank, per tank

AdBlue tank	Amount	Unit
	22.8	kg
Material inputs		
High density polyethylene	22.8	kg
Process input		
Injection moulding (proxy for tank production)	22.8	kg

Electric powertrains

Table A 8 Weight of electric powertrain component groups

	Weight (kg)		
	Fuel cell	Battery electric	
Component group	truck and tractor	truck	tractor
Electric motor	220	220	220
Main inverter	43.6	43.6	43.6
Gearbox	250	250	250
PEMFC system	525	-	-
Hydrogen tank	765	-	-
DC/DC boost converter	68.3	-	-
Li-ion battery	356	4 769	6 350
Integrated onboard charger/converter	-	56.5	56.5
Total powertrain	**2 228**	**5 339**	**6 920**

Battery packs

The cradle-to-gate battery inventory data were compiled from the modular inventory published in Ellingsen *et al.*, (2022). The high-energy NMC622 batteries, used in both the battery electric regional trucks and long-haul tractors, power the electric motor exclusively. In contrast, the high-power NMC532, used in both fuel cell vehicles, support load levelling and energy recovery through breaking. Table A 9 presents the battery inventory for each battery pack.

Table A 9 Battery pack inventory, per battery pack

Module	NMC532 for truck and tractor Amount	NMC622 for battery electric truck Amount	NMC622 for battery electric tractor Amount	Unit
Weight (kg)	356	4751	6350	kg
Product inputs				
Cells	236.6	3056.5	4087.1	kg
Module packaging	46.5	714.4	955.2	kg
Cooling system	10.2	128.6	171.3	kg
Electrical system	10.2	51.3	66.1	kg
Battery packaging	52.1	800.1	1069.9	kg
Energy use				
Electricity, low voltage	0.0016	0.0256	0.0343	kWh
Infrastructure				
Battery pack assembly facility	9.9E-10	1.5E-08	2.0E-08	item

Inventory data for NMC532 cells, as well as thermal management system, electrical system, and battery packaging for both battery cell types, are provided below. Inventory data for module packaging, which scales linearly for both battery cell types, can be found in in Ellingsen *et al.*, (2022). Similarly, readers interested in more detailed sub-inventory datasets for the NMC622 battery cells can refer to the original publication. Additional inventory data for the NMC532 battery cells, electrodes, and non-scalable components for all battery packs are provided below.

Battery cells

The high-power NMC532 battery cells differ somewhat from the high-energy NMC622 as the ratio of cathode materials differ as well as the ratio of cell materials. For both NMC622 and NMC532 cells, we relied on the *ecoinvent* process data for separators and electrolytes as well as for current collectors (which were also assumed for tabs), while inventories for the pouches were taken from Ellingsen *et al.*, (2014). Cell composition for the NMC532 battery cells were provided from the MoreIsLess project. For energy use in cell manufacture as well as electrode production, we relied on published data (Degen *et al.*, 2023).The inventory data per battery cell is provided in Table A 10.

Table A 10 NMC532 pouch cell inventory, per battery cell

Pouch cell	**Amount**	**Unit**
Number of cells	1	item
Weight	1.16E+03	g
Material inputs		
Cathode	5.53E+02	g
Anode	4.26E+02	g
Electrolyte	1.06E+02	g
Separator	4.64E+01	g
Pouch	1.84E+01	g
Tabs (3.53 g Al and 6.25 g Cu)	9.79E+00	g
Process input		
Water	8.11E+00	kg
Energy use		
Electricity (low voltage)	3.02E+00	kWh
Heat (from natural gas)	1.54E+00	kWh
Wastewater		
Wastewater for treatment	8.11E+00	kg
Transport		
Transport by truck	2.82E-01	tkm
Transport by container ship	8.00E+00	tkm
Infrastructure		
Battery cell manufacturing facility	4.64E-10	item

Inventories for the NMC532 cathode and anode are provided in Table A 11 and Table A 12.

Table A 11 NMC532 cathode inventory, per high-power cathode

Cathode	**Amount**	**Unit**
Weight	553.1	g
Material inputs		
Positive active material	383.7	g
Binder (PVDF)	25.6	g
Conductive carbon	17.1	g
Positive current collector (Al)	126.7	g
Process input		
Solvent (N-methyl-2-Pyrroliodone)	9.4	g
Foil production	126.7	g
Energy use		
Electricity	0.184	kWh
Heat (NG)	1.033	kWh
Emissions		
NMVOC (solvent evaporation)	9.4	g

Table A 12 NMC532 anode inventory, per high-power anode

Anode	Amount	Unit
Weight	426.2	g
Material inputs		
Graphite	168.8	g
Binder (CMC)	5.6	g
Binder (PAA)	5.6	g
Conductive carbon	7.5	g
Negative current collector (Cu)	238.6	g
Process input		
Aqueous solvent	4.13	g
Foil production	238.6	g
Energy use		
Electricity	0.185	kWh
Heat (NG)	1.033	kWh
Emissions to air		
Water (steam)	4.1	g

Thermal management system

The inventory for the thermal management system was compiled using the scalable battery inventory model published in Ellingsen *et al.*, (2022), where further details can be found. Table A 13 provides the inventory for the thermal management system for the various battery packs considered in the current study.

Table A 13 Thermal management system inventory, per battery pack

Thermal management system	Fuel cell truck and tractor NMC532 Amount	Battery electric truck NMC622 Amount	Battery electric tractor NMC622 Amount	Unit
Weight	10.2	128.6	171.3	kg
Product inputs				
Radiator	5.2	79.3	106.0	kg
Manifolds	0.57	8.70	11.63	kg
Clamps and fittings	0.34	5.22	6.98	kg
Pipe fitting	0.014	0.218	0.291	kg
Thermal pad	0.29	4.52	6.05	kg
Glycol coolant	3.87	30.71	40.39	kg
Infrastructure				
Metal working factory	1.55E-09	1.23E-08	1.62E-08	item

Electrical system

The inventory for the electrical system was also compiled using the scalable battery inventory model published in Ellingsen *et al.*, (2022), where further details can be found. Table A 14 provides the inventory for the electrical system for the various battery packs considered in the current study.

Table A 14 Electrical system inventory, per battery pack

Electrical system	Fuel cell truck and tractor NMC532 Amount	Battery electric truck NMC622 Amount	Battery electric tractor NMC622 Amount	Unit
Weight	10.2	51.3	66.1	kg
Product inputs				
Low voltage system	1.76	27.0	36.1	kg
High voltage system	2.8	2.8	2.8	kg
Module control units	1.11	17.0	22.7	kg
Logic board (finished with connectors)	0.591	0.591	0.591	kg
Fixings	0.03	0.028	0.028	kg
Battery management box with standoffs	3.88	3.88	3.88	kg
Infrastructure				
Manufacture facility	2.0E-07	1.0E-06	1.3E-06	item

Battery packaging

The inventory for the battery packaging was also compiled using the scalable battery inventory model published in Ellingsen *et al.*, (2022), where further details can be found. Table A 14 provides the inventory for the battery packaging for the various battery packs considered in the current study.

Table A 15 Battery packaging inventory, per battery pack

Battery packaging	Fuel cell truck and tractor NMC532 Amount	Battery electric truck NMC622 Amount	Battery electric tractor NMC622 Amount	Unit
Weight	52.11	800.11	1069.87	kg
Product inputs				
Module fixings	0.27	4.17	5.57	kg
Battery frame	3.78	58.00	77.56	kg
Aluminium components:	48.07	737.94	986.75	kg
Battery lid	8.59	131.92	176.40	kg
Crash structure	15.30	234.90	314.10	kg
Housing tray	9.85	151.3	202.3	kg
Lower protection cover	14.32	219.87	294.00	kg

Trailer and semi-trailer

Trailer and semi-trailer were considered as cargo transport units for the regional and long-haul vehicles, respectively. Both trailer and semi-trailers were modelled with six wheels each.

Table A 16 Cargo transport unit inventory, per cargo transport unit

Cargo transport unit	Trailer 5600	Semi-trailer 7365	Unit kg
Component group			
Trailer chassis	1779	2467	kg
Tires	396	396	kg
Wheels	185	185	kg
Box with curtain	3240	4317	kg

Box with curtain

We modelled the cargo box to be equipped with curtains. We assumed that the curtains were made of polyester (50% weight) and polyvinylchloride (50% weight).

Table A 17 Box with curtain inventory, per cargo transport unit

Box with curtain	**Trailer 3240**	**Semi-trailer 4317**	**Unit kg**
Components			
Frame (reinforcing steel)	2122	2590	kg
Roof (polyvinylchloride, bulk polymerised)	259	363	kg
Curtain (polyvinylchloride, emulsion polymerised and textile, nonwoven polyester)	50	69	kg
Floor and wall support (sawnwood, board, hardwood, dried (u=10%), planed)	810	1295	kg
Process input			
Metal working, average for steel product manufacturing	2122	2590	kg
Injection moulding (for making roof)	259	363	kg

Maintenance

AdBlue fluid

Table A 18 AdBlue fluid, per kg

AdBlue fluid	**Per kg 1.00**
Material inputs	
urea	0.500
water, deionized	0.500
Transport	
transport, freight train	0.044
transport, freight, inland waterways, barge	0.022
transport, freight, lorry, unspecified	0.171

Hydrogen production

Hydrogen from electrolysis

Table A 19 Hydrogen from electrolysis, per kg

Hydrogen from electrolysis	**Per kg 1.00**	**Unit kg**
Process input		
Deionized water	13.9	kg
Energy input		
Electricity, low voltage (electrolyzer)	53	kWh
Electricity, low voltage (compression for transport)	2.2	kWh
Electricity, low voltage (compression for fueling)	1.0	kWh
Transport		
transport, freight, lorry >32 metric ton, EURO6	0.2	tkm
Infrastructure		
Electrolyser plant	3.42E-07	item

Hydrogen from SMR

Table A 20 Hydrogen from steam methane reforming using natural gas, per kg

Hydrogen from SMR	**Per kg** **1.0**	**Unit** **kg**
Process input		
hydrogen production, steam methane reforming	1.0	kg
Energy input		
Electricity, low voltage (compression for transport)	2.2	kWh
Electricity, low voltage (compression for fueling)	1.0	kWh
Transport		
transport, freight, lorry >32 metric ton, EURO6	3.0	tkm

For hydrogen production, we used the ecoinvent process “hydrogen production, steam methane reforming | hydrogen, gaseous, low pressure | Cutoff, U – RER”.

Appendix B – Results per vehicle

The results presented here are based on an alternative functional unit that expresses the environmental impact on a per-vehicle basis. It is important to note that this approach does not account for variations in cargo capacity across different vehicles and powertrains.

As with the main functional unit, we observe that electric powertrains offer net life cycle benefits in terms of climate change and ozone formation, while diesel-based powertrains have lower life cycle impacts in freshwater ecotoxicity, terrestrial ecotoxicity, and terrestrial acidification. Additionally, when ignoring differences in cargo capacity, we find that the battery powertrain offers net life cycle impact benefits over the fuel cell powertrain across all impact categories for both regional trucks and long-haul tractors.

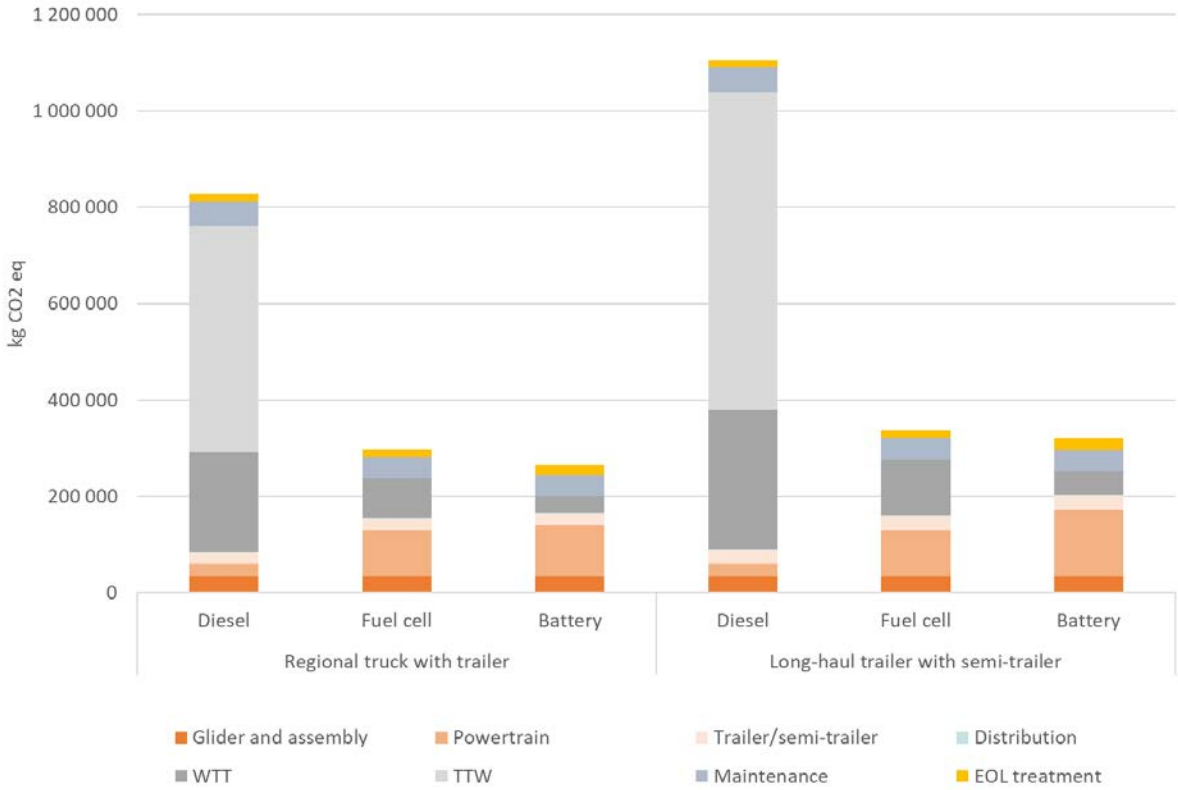

Figure B 1 Climate change impact per vehicle

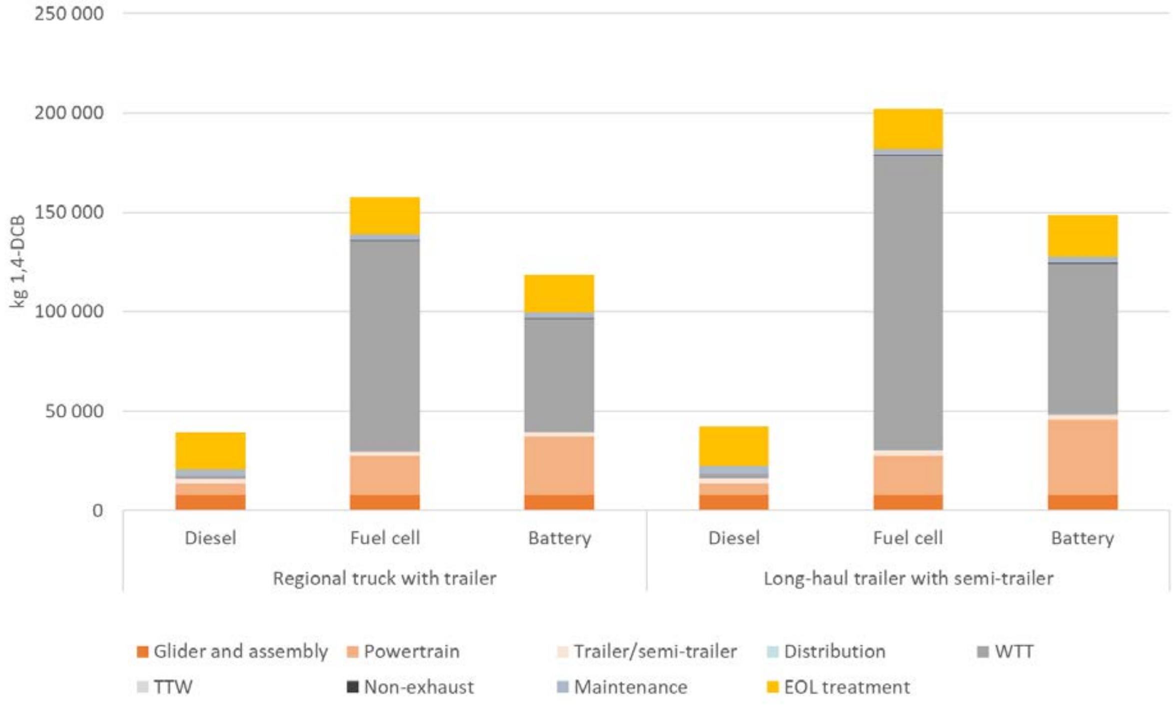

Figure B 2 Freshwater ecotoxicity impact per vehicle

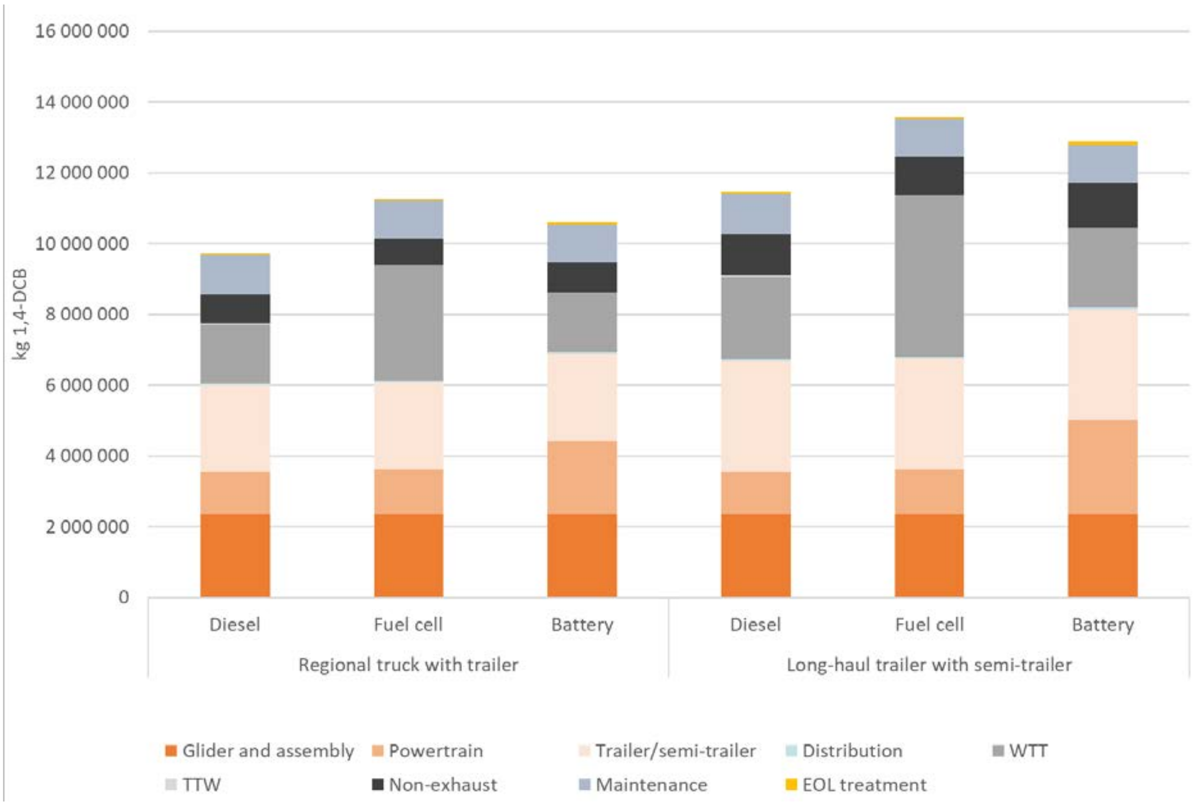

Figure B 3 Terrestrial ecotoxicity impact per vehicle

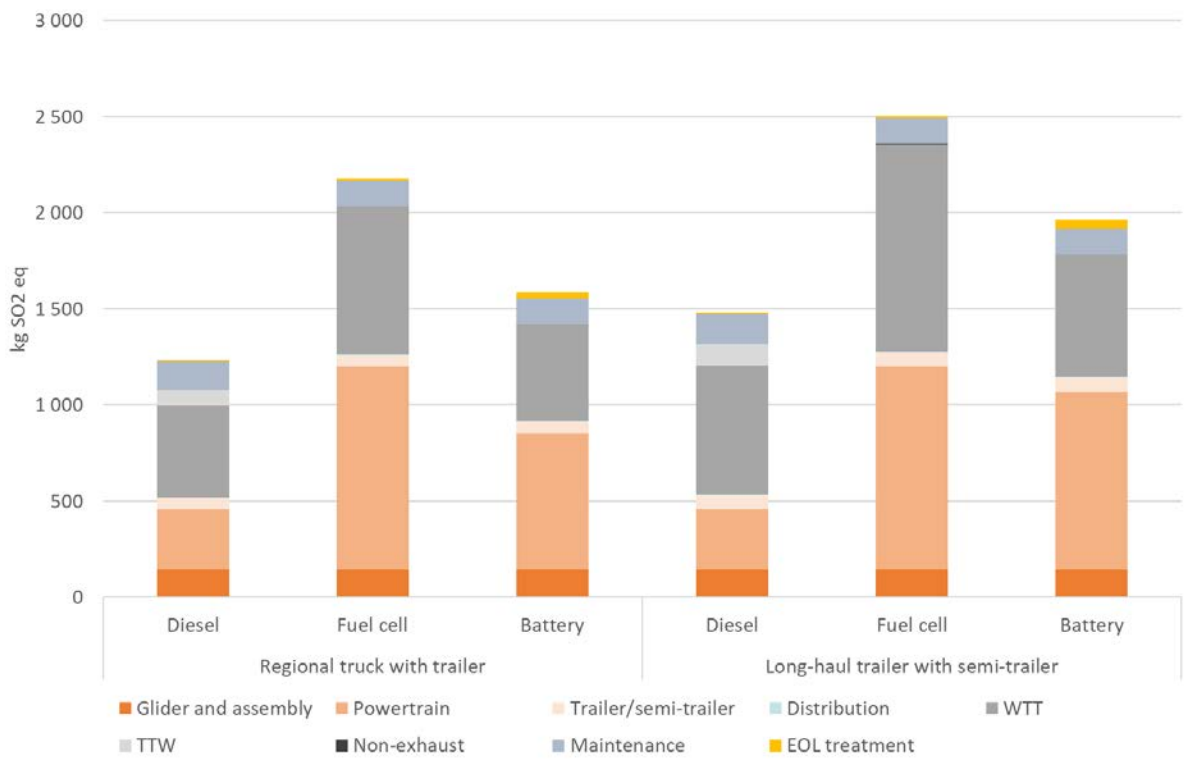

Figure B 4 Terrestrial acidification impact per vehicle

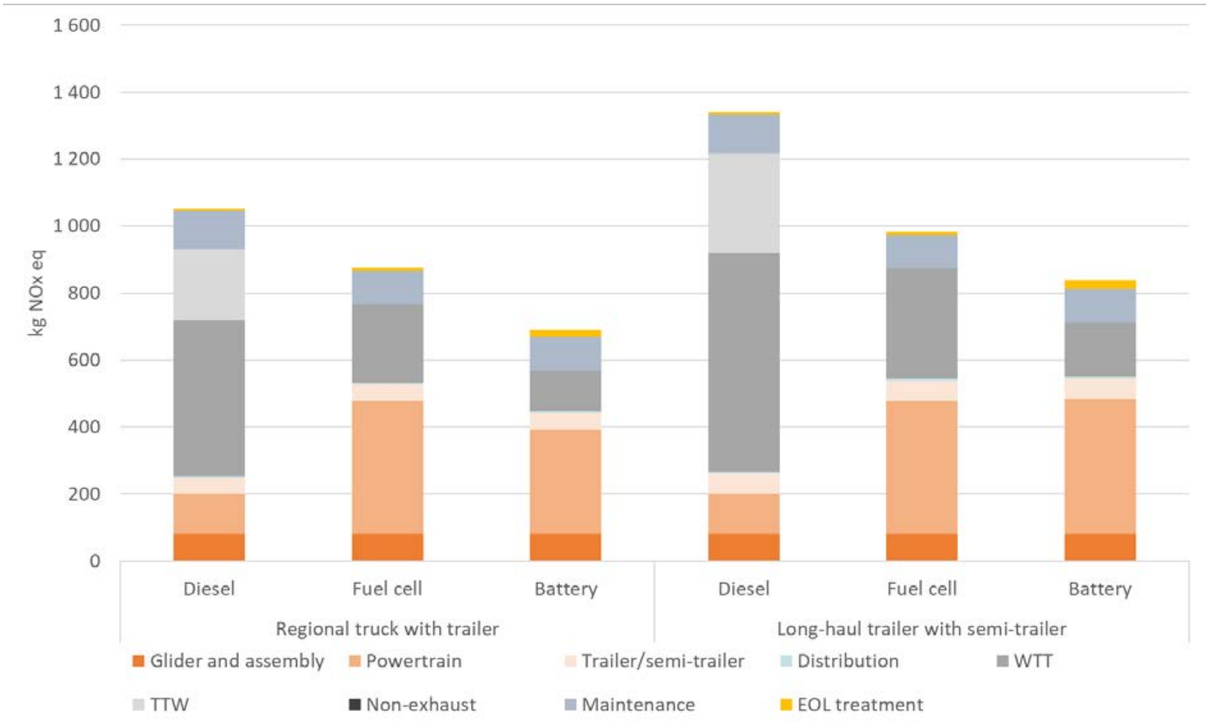

Figure B 5 Photochemical ozone formation impact, human exposure per vehicle

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Postal Address:
Institute of Transport Economics
Postboks 8600 Majorstua
N-0349 Oslo
Norway

Email: toi@toi.no

Business Address:
Forskningsparken
Gaustadalléen 21

Web address: www.toi.no