

**COMPARATIVE HYBRID LIFE CYCLE
ASSESSMENT OF BUCKET TRUCKS WITH
ALTERNATIVE FUEL TYPES: DIESEL, DIESEL
ELECTRIC-POWER TAKEOFF, AND ELECTRIC
CONFIGURATIONS**

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ABSTRACT

COMPARATIVE HYBRID LIFE CYCLE ASSESSMENT OF BUCKET TRUCKS WITH ALTERNATIVE FUEL TYPES: DIESEL, DIESEL ELECTRIC-POWER TAKEOFF, AND ELECTRIC CONFIGURATIONS

The transportation sector, particularly maintenance vehicles such as bucket trucks, contributes substantially to environmental and economic burdens due to prolonged idling. This thesis compares three bucket truck configurations—conventional diesel, diesel with electric power take-off (E-PTO), and fully electric—using a hybrid Life Cycle Assessment (LCA). A process-based approach was applied to the operational phase to capture direct emissions and costs, while a multi-regional input–output (MRIO) model built with Python and the EXIOBASE database via the Pymrio package assessed indirect impacts across 163 sectors of the U.S. economy. Monte Carlo simulations and sensitivity analysis are performed to address uncertainty and provide a probabilistic picture of daily idling hours, fuel–electricity use, and annual mileage. Results show the electric truck is the most expensive, while the diesel truck remains the most polluting option over 12-year lifetime, mainly due to idling fuel use and engine rebuilds. Adding an E-PTO lowers idling fuel and emissions but increases costs from the unit and battery, making it a temporary improvement rather than a long-term solution. The electric truck requires a higher initial investment and later battery replacement, yet lower fuel and maintenance stabilize lifetime costs. Electric trucks cut CO₂ and NO_x nearly to zero, though SO_x and dust remain higher due to the fossil-fuel-based grid. In conclusion, electric bucket trucks provide the greatest benefits when paired with a cleaner grid, while diesel+E-PTO yields limited short-term gains. Fleet managers and policymakers must consider both direct outcomes and broader impacts when selecting maintenance vehicles.

ÖZET

ALTERNATİF YAKIT TÜRLERİNE SAHİP SEPETLİ KAMYONLARIN KARŞILAŞTIRMALI HİBRİT YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ: DİZEL, DİZEL ELEKTRİKLİ-GÜÇ AKTARMA VE ELEKTRİKLİ KONFİGÜRASYONLARI

Ulaşım sektörü, özellikle sepetli kamyonlar gibi bakım araçları, uzun süreli rölanti çalışmaları nedeniyle çevresel ve ekonomik yüklerin önemli bir kısmına katkıda bulunmaktadır. Bu tez, Hibrit Yaşam Döngüsü Değerlendirmesi (LCA) yöntemiyle üç farklı sepetli kamyonu konfigürasyonunu—geleneksel dizel, elektrikli güç aktarma ünitesi (E-PTO) bulunan dizel ve tamamen elektrikli—karşılaştırmaktadır. İşletme aşamasında doğrudan emisyonları ve maliyetleri belirlemek için süreç tabanlı bir yaklaşım uygulanmış, ayrıca Python ortamında oluşturulan çok bölgeli girdi-çıktı (MRIO) modeli, Pymrio paketi aracılığıyla EXIOBASE veritabanı kullanılarak ABD ekonomisindeki 163 sektörün dolaylı etkilerini değerlendirmiştir. Belirsizlikleri ele almak için Monte Carlo benzetimleri ve duyarlılık analizleri yapılmış, günlük rölanti süreleri, yakıt-elektrik kullanımı ve yıllık kilometre değerleri için olasılıksal bir tablo oluşturulmuştur. Sonuçlar, elektrikli kamyonun en yüksek maliyete sahip olduğunu, dizel kamyonun ise 12 yıllık yaşam döngüsü boyunca rölanti yakıt kullanımı ve motor yenilemeleri nedeniyle en fazla kirlilik yarattığını göstermektedir. E-PTO eklenmesi rölanti yakıt tüketimini ve emisyonları azaltmakta, ancak ünite ve bataryadan kaynaklanan ek maliyetler uzun vadeli bir çözüm yerine geçici bir iyileştirme sunmaktadır. Elektrikli kamyon daha yüksek bir ilk yatırım ve ilerleyen dönemde batarya değişimi gerektirmekte, fakat daha düşük yakıt ve bakım ihtiyacı yaşam boyu maliyetleri dengelemektedir. Elektrikli kamyonlar CO₂ ve NO_x emisyonlarını neredeyse sıfıra indirirken, fosil yakıt temelli şebeke nedeniyle SO_x ve toz emisyonları yüksek kalmaktadır. Sonuç olarak, elektrikli sepet kamyonları temiz enerjiyle kullanıldığında en büyük faydayı sağlar; dizel+E-PTO seçeneği ise sınırlı kısa vadeli kazanımlar sunar. Filo yöneticileri ve politika yapıcılar, bakım araçlarını seçerken hem doğrudan sonuçları hem de geniş etkileri dikkate almalıdır.

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CHAPTER 1

INTRODUCTION

The transportation industry is vital to modern economies and societies, as it connects people, industries, and resources (Ali et al. 2018). However, its importance goes much beyond promoting economic expansion and mobility. One of the main reasons for the environmental problems the world is currently experiencing is transportation. This sector is becoming increasingly important, especially in developing countries. The energy demand of the transportation sector is increasing by approximately 3% to 5% per year, as emphasised by Kiribou et al. (2025), and this rate has a significant impact on energy consumption and greenhouse gas emissions (GHG) worldwide. Factors such as increasing urbanisation, rising road transportation, e-commerce, and the intensity of infrastructure investments are driving the growth of the sector. This rapid growth in the sector has a detrimental impact on the environment (Profillidis, Botzoris, and Galanis 2014). The current trajectory of emissions from this sector seems unsustainable in the absence of significant mitigation measures (Banister et al. 2011). Recent estimates indicate that transportation accounts for nearly 25% of global carbon emissions, with heavy-duty vehicles bearing a significant portion of this burden ("Transportation Sector Emissions," US EPA 2025). The industry's reliance on fossil fuels is a major contributing factor to this concerning situation. Indirect emissions from electricity are negligible in comparison to the direct emissions from gasoline and diesel ("Sources of Greenhouse Gas Emissions," US EPA 2025).

The transportation sector in the European Union accounts for approximately 25% of CO₂ emissions and consumes around one-third of all final energy (Van Mierlo, Messagie, and Rangaraju 2017). As a result, cutting transportation-related carbon emissions has gained international attention (Fan et al. 2023). The use of alternative fuels in road fleets, including maintenance and heavy-duty vehicles, is now required due to these pressures. The primary reason for this is The growing use of gasoline and diesel, along with the rise in car production and automation, has greatly increased the carbon

footprint. This has become one of the main causes of environmental pollution (Sandaka and Kumar 2023). Therefore, electric and diesel-hybrid technologies stand out in reducing direct emissions from the use of traditional fossil fuels (Squalli 2024). Hoekstra (2019) noted that under current conditions, battery electric vehicles (BEVs) can reduce their emissions from 244 g/km to 98 g/km, and this value can be further reduced to 10 g/km in cases where fully renewable energy sources are utilised.

In a similar context, Huang et al. (2022) conducted road tests under various driving conditions to compare fuel consumption and emissions between a hybrid electric vehicle (HEV) and an internal combustion engine vehicle (ICEV). Test results show that HEVs use 41% less fuel than standard vehicles in urban driving and reduce CO₂ and NO_x emissions by 33% and 61%, respectively (Huang et al. 2022). According to another study, plug-in hybrid electric vehicles (PHEVs) can reduce well-to-wheel (WTW) CO₂ emissions by 59% to 68% compared to conventional vehicles, while hybrid electric vehicles (HEVs) can reduce them by 23% to 54% (Soares, Sodre, and Boloy 2025). Although many studies have shown that electric vehicles have a significant potential for emission reduction compared to conventional vehicles, it is now necessary to evaluate environmental impacts using a holistic approach, one that is not limited to the usage phase alone (Ankathi, Bouchard, and He 2024). Therefore, low exhaust emissions during the use phase alone are not sufficient to assess the environmental impacts of alternatives. The environmental impacts of vehicles throughout their entire life cycle, including production, use, and disposal processes, need to be extensively assessed (Accardo et al. 2023).

In this regard, the LCA method is a generally recognised literary technique that allows for a thorough examination of environmental effects by including all phases. The environmental impacts of a product or service can be quantitatively assessed through LCA, which encompasses the entire life cycle, including production, extraction of raw materials, use, reuse, recycling, and disposal (Harding 2011). LCA, especially in vehicle technologies, enables a comprehensive assessment of not only the direct emissions that occur during use, but also the indirect emissions and resource consumption that occur throughout the life cycles of fuel, infrastructure, and vehicles (Zhang et al. 2024). It is well known that the environmental friendliness of electric vehicles largely depends on how their batteries are manufactured and the cleanliness of the electricity they use (Hall and Lutsey 2018). On the other hand, for diesel and hybrid vehicles, factors such as engine

lifespan, frequency of repairs, and fuel consumption are equally important when evaluating their environmental impact. Although the manufacturing and assembly of components also contribute substantially to emissions, Szumska's comparative study of hybrid and diesel vehicles highlights that a large share of lifetime emissions is still generated during the use phase (Szumska 2021).

Studies on maintenance vehicles that ensure the continuity of urban and rural infrastructure services are relatively scarce, despite the wealth of LCA literature currently available for passenger and commercial vehicles. Road, energy, transportation, and other urban services are supported by a variety of vehicle types that fall under the crucial category of maintenance vehicles. This group of heavy-duty vehicles includes snowplows, which are used to load, remove, and clear snow to keep roads accessible during the winter months (Liu and Yi 2021). Truck Mounted Attenuators (TMAs), which are attached to the back of these vehicles, act as moving safety barriers by absorbing crash energy and protecting road workers from vehicles that accidentally enter work zones (White, Mollenhauer, and Talledo Vilela 2021). The purpose of street sweepers, which are specially made vehicles, is to clear asphalt road surfaces of debris, dust, dirt, vegetation, and similar materials (Amato et al. 2010). Bucket trucks, also known as utility vehicles, feature hydraulic lifts that enable workers to reach high places. They are widely used for jobs such as fixing power lines, working on phone networks, cutting trees, and performing repair work on buildings and roads (Parker Hannifin Corporation, 2023). Even though these vehicles vary in their operation and intended use, their long working hours and harsh conditions lead to high fuel consumption and emissions over time. This is especially true for heavy-duty maintenance trucks, which often consume more energy and produce more emissions due to long periods of idling and working under heavy loads (Gao, Lin, and Franzese 2017).

In this context, bucket trucks stand out among the vehicles that require special evaluation not only in terms of the sustainability of infrastructure services but also in terms of environmental impacts. The fact that they cause high fuel consumption and consequently emit serious GHG during both active use and long-term idling mode, due to their duty, makes these vehicles environmentally problematic (Gao, Lin, and Franzese 2017). These differences make it more essential to carefully examine every stage in the life cycle of bucket trucks.

At the same time, changes in government policies have been a major factor driving interest in alternative fuels. As part of global efforts to combat climate change, many countries are shifting away from diesel and placing a greater emphasis on promoting electric vehicles. Electric vehicles have become a key part of sustainable mobility plans. They produce fewer emissions and use less fossil fuel. Estimates show that the number of EVs around the world could grow from 26 million in 2023 to 145 million by 2030 (Udenhran et al. 2025). At the same time, new regulations such as low-emission zones, carbon taxes, and stricter fuel standards have made alternative fuel vehicles a more common choice for both fleet operators and public agencies (Peters, Burguillo, and Arranz 2021). For bucket truck fleets, switching to these technologies no longer seems optional. In the near future, using alternative fuels will likely become a necessity rather than a preference.

1.1. Aim of the Study

Most current life cycle studies rely on national or international data, which often ignore local differences in infrastructure, technology, and energy sources. These local factors can have a significant effect on environmental outcomes. To address this, the study employs a Hybrid LCA approach, which enables more accurate and locally relevant results. However, environmental results can be significantly affected by factors such as changes in electricity sources or the way diesel vehicles are used. In this thesis, a sensitivity analysis was conducted to determine in which situations different fuel types are more suitable choices. This analysis helps create more effective sustainability strategies by highlighting uncertainties in environmental impacts and identifying potential weaknesses. Since there is a lack of research comparing diesel, hybrid, and electric bucket trucks from the past to the present, this thesis aims to help fill a significant gap. It employs straightforward methods, including Hybrid Life Cycle Assessment and sensitivity analysis. These tools can guide fleet managers and policy makers in choosing the most suitable trucks and ways to operate them.

1.2. Thesis Organization

This thesis is divided into five main chapters. After the Introduction, Chapter 2 gives a detailed review of LCA. It introduces the basic ideas of LCA and explains three main types: process-based, input–output, and hybrid. It also reviews studies about alternative fuels in transport, with a focus on maintenance vehicles, and includes a short part on Monte Carlo simulation.

Chapter 3 describes the method of the study step by step. It explains the study scope, vehicle features, data used, and the assumptions made. It then shows how the hybrid LCA model was set up and how Monte Carlo and sensitivity analysis were applied.

Chapter 4 presents the results and the discussion. It first reports the lifetime direct economic impacts, then the wider indirect effects on other sectors, and finally the environmental impacts of diesel, diesel with ePTO, and electric trucks. Each part is discussed in detail with figures and tables.

Chapter 5 concludes the thesis with overall results. It presents the main findings, highlights practical implications, and suggests directions for future studies. The references and appendix follow this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1. Life Cycle Assessment

A scientific tool called LCA measures the environmental impacts of a product or system throughout its entire life cycle. Looks at all effects from raw material extraction, manufacture and use to recycling, reuse and final disposal. Often referred to as a "cradle to grave" study, this comprehensive method examines every phase of a product's life cycle to assess its entire environmental impact (Jensen et al. 1998). LCA's main objective is to contrast environmental loads inside a specified functional unit (Udo de Haes et al. 2004). Comparisons inside LCA should honestly represent all inputs and outputs, including energy, materials, and emissions (Harding 2011).

Historically, starting as an energy-focused tool, LCA has expanded over time to include broader environmental and sustainability aspects. Its practical applications began with the assessment of Coca-Cola packaging in 1969. By the 1980s, its use had greatly expanded in importance due to the increasing emphasis on environmental management and sustainability. Between 1990 and 2000, LCA standards were formalised in the context of intense scientific discussions, resulting in the development of ISO standards that clarified their methodological framework. After 2000, known as the "Age of Elaboration and Expansion", dynamic, regional, and risk-based LCA approaches emerged that integrated economic and social dimensions (Guinée et al. 2010).

In the early stages of LCA research, static approaches, such as Attributional LCA (ALCA) and Consequential LCA (CLCA), formed the foundation of methodological development. ALCA evaluates environmental impacts based on average data from existing systems, while CLCA considers possible changes and alternative scenarios. Although socioeconomic factors have been gradually introduced into both approaches, they still primarily rely on environmental indicators. There is a growing need for more

comprehensive and multi-dimensional assessment methods in today's LCA studies (Liu, Zhu, and Tian 2024).

Despite this progress, significant methodological uncertainties remain. Challenges such as defining the functional unit, subjectively drawing system boundaries, dealing with allocation in multifunctional processes, and the lack of clear cutoff criteria were all discussed in detail (Reap et al. 2008). These problems still make it challenging to obtain consistent and comparable results from LCA studies (Reap et al., 2008). To address these challenges, using dynamic modelling methods instead of the static and linear models commonly employed in traditional LCA studies was suggested (Udo de Haes et al. 2004).

Dynamic Life Cycle Assessment (DLCA) differs from traditional static methods in that it also considers time and location. This enables a better understanding of how products or systems evolve and how they are influenced by various geographical conditions (Liu, Zhu, and Tian 2024). Adding DLCA to current models is one of three main ways to improve what LCA can do. Another approach is to combine different modelling methods to address the gaps that older LCA approaches can't handle. This has led to the creation of the Life Cycle Sustainability Assessment (LCSA) framework, which considers environmental, economic, and social impacts collectively (Liu, Zhu, and Tian 2024). The third method is a hybrid approach that utilises process-based LCA for the main components of the system and input-output LCA for the background components (Udo de Haes et al. 2004). These methods and strategies will be explained in more detail in the next section, under the heading "LCA Methods".

2.2. Life Cycle Assessment Methods

There are three methods most used in LCA studies today: process-based, economic input-output, and hybrid LCA, which will be discussed in detail within the scope of the literature review.

2.2.1. Process Based LCA

Process-based LCA is an approach that directly addresses all processes in the life cycle of a product or service (raw material supply, production, distribution, use, disposal, etc.) and reveals their environmental impacts. Thanks to this method, energy use, emissions, and other environmental loads of each stage can be examined in detail (Abdalqadir et al. 2023).

Each process is evaluated individually during the production process. This facilitates the comparison of different options, especially in complex and multi-stage production systems. Thus, it becomes an effective tool that facilitates decision-making during the product development process. Because the data flow at each stage can be clearly monitored, and the results of changes in the design can be seen immediately (Escobar and Laibach 2021).

While classical LCA methods are typically limited to retrospective analyses performed after the product has been developed, this method can be applied at earlier stages of the product development process, offering a predictive evaluation opportunity (Poudelet et al. 2012).

Process-based LCA is a common choice in the industry for determining critical points in the process, from raw material supply to the final product. For example, Zhang and his team examined the sub-processes involved in the production of polyester-linen textiles in detail, including cotton farming, yarn production, weaving, printing, dyeing, and waste management (Zhang et al. 2018). Similarly, Sala and Castellani used this method in the "Consumer Footprint" indicator they developed to assess the environmental impacts of household consumption (Sala and Castellani 2019). Fang and his colleagues also applied a process-based life cycle inventory (P-LCI) approach to assess the carbon footprint of dual-phase steel production used in the automotive industry. The authors examined each stage, such as milling, melting, and rolling, in detail and presented various optimisation suggestions, especially for the Blast Furnace Plant (BFP), which is one of the high-impact processes (Fang et al. 2024). Dale and his team examined the natural gas production in the Marcellus Shale region, focusing on well development, drilling, fracking, and processing steps, and found that environmental burdens were more concentrated in the middle and final stages (Dale et al., 2013). Abdalqadir et al. (2023)

conducted a process-based LCA to assess the use of waste clay in agriculture, revealing the CO₂ removal potential of mineral carbonation and enhanced weathering methods.

Although this method provides a clearer view of environmental impacts by considering the processes in detail, it also has some limitations. The failure to account for inputs outside the system boundaries is referred to as “truncation error” (Pomponi and Lenzen 2018). Additionally, this method requires a significant amount of time and effort. The analysis of inputs that cannot be directly measured, such as services received from outside, is challenging (Junnila 2006). Some system parts may be excluded from the analysis due to time and resource limitations, which may result in incomplete estimates (Mattila, Pakarinen, and Sokka 2010).

However, the fact that Process-based LCA does not have a data structure covering the entire economy is also a limitation in comprehensive economic analyses (Yang, Heijungs, and Brandão 2017). Therefore, economic-based methods such as Input–Output LCA (IO-LCA) stand out as alternatives to fill these gaps. The studies covered in this part are summarized in Table 1, which provides an overview of previous research that applied these methods to assess environmental and economic interactions across different sectors.

Table 1. Summary of Process-LCA Literature

Author(s)	Year	Study Focus and Method
Zhang et al.	2018	Analyzed polyester-linen textile production sub-processes such as farming, weaving, dyeing, and waste management
Sala & Castellani	2019	Developed the “Consumer Footprint” indicator to assess household consumption impacts
Fang et al.	2024	Assessed the carbon footprint of dual-phase steel production in detail
Dale et al.	2013	Evaluated shale gas production stages (drilling, fracking, processing) in Marcellus region
Abdalqadir et al.	2023	Investigated CO ₂ removal potential of using waste clay in agriculture

2.2.2. Economic Input Output LCA

Economic Input-Output Life Cycle Assessment (EIO-LCA) analyses the social, economic, and environmental impacts of a good or service throughout its life cycle, using inputs and outputs within the supply chain. This approach was developed by Leontief, who used the input-output analysis model. The methodology examines both direct and indirect consequences using matrices that summarise economic relationships between various sectors (Chen et al. 2020).

Unlike traditional life cycle assessments, EIO-LCA considers the interdependencies of the economic system and the direct and indirect environmental impacts at specific production stages. This method considers the economic interactions between sectors to calculate the environmental impacts of economic activities at the national or regional level. Environmental impacts, such as indirect emissions and energy consumption, arising during the production process can be clearly demonstrated, especially in models based on economic relationships between countries or regions (Lenzen, Pade, and Munksgaard 2004).

The basic application phase of this method is to combine economic input-output tables with environmental data sets. These data include energy consumption and emission factors corresponding to the economic output of each sector. Therefore, it is possible to find the total environmental impact by multiplying the economic interaction matrices with the sectoral environmental coefficients (Norman, Charpentier, and MacLean 2007).

With this approach, which was developed to examine the environmental impacts across various sectors, Cicas and colleagues analysed the environmental emissions from electricity generation and petroleum refineries in eight U.S. states, using the Far West region as a case study. The analysis revealed that the model's predicted toxic emissions were less than 8% lower than the official reports, demonstrating the model's capability to accurately assess the environmental impacts of the entire region (Chen et al. 2020).

In consumption-based analyses, the EIO-LCA approach is used to account not only for production-related environmental impacts within a country's or region's borders but also for the impacts caused in other countries through imports (Wiedmann et al. 2011). In this context, Lenzen (1998) conducted a study in which he calculated energy consumption and GHG emissions for a set of final consumption categories within

Australia, considering both domestic production and imports across 45 different sectors. In the same study, Lenzen (1998) noted that including imports in EIO-LCA analyses enables a more accurate assessment of environmental impacts.

The EIO-LCA model can calculate the economic impacts of even one dollar of spending in each sector on other sectors, as well as the associated emissions. In the study conducted by Ochoa, Hendrickson, and Matthews (2002), this model was used to assess the environmental impacts of residential buildings in the United States throughout the construction, operation, and demolition phases for the year 1997. As a result of this assessment, outputs such as electricity and energy use, GHG emissions, hazardous waste, and toxic air emissions were obtained. Furthermore, although the residential sector accounted for only 5.3% of the total U.S. economy, it was responsible for 24% of GHG emissions and 38% of electricity consumption. This suggests that the residential sector bears a disproportionately large share of environmental impacts compared to its economic size.

In EIO-LCA analyses, the number of sectors and sector-level details have a significant impact on environmental analysis results and CO₂ multipliers. In the study conducted by Steen-Olsen et al. (2014), it was shown that when sector details are reduced and some sectors are combined, significant deviations occur in CO₂ multipliers, which leads to substantial information losses. These findings demonstrate that considering sectors separately and in detail in EIO-LCA analyses is crucial for the accuracy of the analysis results.

Several representative EIO-LCA studies used in many sectors, Vendries and his colleagues divided the electricity generation sector, which is a single sector in the USA, into many sub-sectors and created supply chains and emission factors specific to different sources such as coal, natural gas, nuclear and renewable energy used in electricity generation. In this way, they were able to obtain more accurate results from both economic and environmental outputs, while also examining sector-specific results in detail. According to the results obtained, it was determined that the separated model gave more accurate outputs (Algarin et al. 2014). Shi and colleagues employ the EIO-LCA approach to examine the material production, construction, use, and end-of-life phases, comparing the environmental and sustainability impacts of conventional concrete pavement with those of concrete pavement produced using recycled concrete aggregate.

The study finds that concrete pavement made with recycled concrete aggregate is more advantageous in both social and environmental terms (Shi et al. 2019).

According to Hendrickson et al., EIO-LCA analyses the environmental impacts spread across the entire economy, including indirect impacts, at the sector level. At the same time, it lacks detailed analysis at the product level (Hendrickson et al. 1997). Another shortcoming of this method is that EIO-LCA generalises sector classes too much and does not adequately reflect country-specific characteristics (Junnila 2006). Although EIO-LCA can incorporate elements such as taxes, services, and finance, which are typically excluded in process-based LCA (Junnila 2006), it may also introduce greater uncertainty due to sector aggregation and economic allocation practices (Mattila, Pakarinen, and Sokka 2010). As discussed in the previous and current sections, both the process-based model and the input-output model have their strengths and weaknesses. At this point, the hybrid model comes into play, aiming to overcome the limitations of the process-based LCA with the input-output model and vice versa. A summary of the studies covered in this part is given in Table 2.

Table 2. Summary of EIO-LCA

Author(s)	Year	Study Focus and Method
Chen et al.	2020	Applied EIO-LCA to analyze economic, social, and environmental impacts of goods/services
Lenzen, Pade & Munksgaard	2004	Showed indirect emissions and energy use through economic interdependencies
Norman, Charpentier & MacLean	2007	Combined input-output tables with environmental data to calculate total impacts
Cicas et al.	2020	Analyzed electricity generation and refinery emissions in eight U.S. states
Wiedmann et al.	2011	Accounted for domestic and import-related impacts in consumption-based studies
Lenzen	1998	Calculated energy use and GHG emissions for consumption categories in Australia including imports
Ochoa, Hendrickson & Matthews	2002	Assessed U.S. residential buildings' life cycle impacts (construction, operation, demolition)
Steen-Olsen et al.	2014	Showed that sector aggregation leads to deviations in CO ₂ multipliers

(cont. on the next page)

Table 2 (cont.).

Algarin et al. (Vendries team)	2014	Split electricity generation into multiple subsectors for more accurate results
Shi et al.	2019	Compared conventional and recycled aggregate concrete pavements
Hendrickson et al.	1997	Highlighted that EIO-LCA captures economy-wide indirect impacts but lacks product detail
Junnila	2006	Pointed out that EIO-LCA generalizes sectors and poorly reflects country-specific features
Mattila, Pakarinen & Sokka	2010	Found that sector aggregation and allocation introduce uncertainty in EIO-LCA

2.2.3. Hybrid LCA

Hybrid LCA is a method that combines Process-Based LCA and Input-Output LCA analyses. This method aims to obtain more reliable and accurate results in analyses by combining the details of Process-Based LCA in the production phase of products with the broader economic system advantages of EIO-LCA (Bilec et al., 2006). Hybrid LCA solves the data deficiency and truncation error problems in Process LCA analyses, and the general assumption problems and deficiencies in the production phase of EIO-LCA, by using process data for inputs directly related to products and EIO data for higher-level indirect inputs; thus, system boundaries are determined more completely (Crawford 2008).

There are three basic methods in Hybrid LCA analyses. These are tiered hybrid analysis, IO-based hybrid analysis, and integrated hybrid analysis. Tiered Hybrid Analysis evaluates the environmental impact of products by combining Process-Based LCA data with input-output tables. It is easy, except for problems such as double counting. IO-Based Hybrid Analysis uses sectoral input-output tables instead of processing data and keeps the classification of these tables constant while keeping the country-wide system boundary constant. It expands the sector in detail to consider the different emission loads for each sector. Integrated Hybrid Analysis directly integrates the

interaction between process data and economic system data, utilising cut-off matrices to prevent double counting (Nakamura and Nansai, 2016).

The application area of Hybrid LCA is very wide. Treolar et al. proposed the use of Hybrid LCA in the construction sector to evaluate the environmental impacts of complex products and used this method for detailed analyses of materials such as cement and steel (Treolar et al. 2000). Alloza et al. used process-based LCA to evaluate the energy consumption and emissions of warm mix asphalt (WMA) with and without crumb rubber modified (CRM) binder during the production phase; they also combined these results with multi-region economic input-output data from Australia and applied the hybrid LCA approach (Rodríguez-Alloza et al. 2015). Similarly, Bellic et al. employed Hybrid LCA in the construction industry to gain a deeper understanding of the environmental impacts associated with the construction phase of a precast concrete parking lot in Pittsburgh (Bilec et al., 2006). Martinez et al. employed Hybrid LCA to assess all environmental impacts of the demolition process of a dam in Spain, encompassing earthworks, restoration, waste management, and occupational health (Martinez et al., 2018).

Hybrid LCA is also frequently used in the energy and industry sectors. In a study conducted by Dong et al. (2013), the carbon emissions of an industrial zone in China were examined in detail with the Tiered Hybrid LCA approach to calculate the carbon footprint of this industrial zone. In a study conducted by Wiedmann et al. (2011), the IO-based hybrid approach and the Integrated Hybrid Approach were combined to determine the GHG emissions of wind energy production with a 2 MW offshore wind turbine. While the environmental impacts were calculated in the sector with the IO-based method, a comprehensive analysis was performed by combining physical process data with economic system data with the integrated method. Lenzen (2002) employed the Hybrid LCA method to assess the environmental impacts of system frameworks, including water use, land degradation, and energy consumption, across all industry sectors in Australia. Hybrid LCA, which is used in many other studies, is one of the most frequently employed methods in the Transportation Sector. It has been utilised in numerous alternative fuel studies in this sector. These studies will be examined under the title of LCA-Alternative Fuels. A summary of the studies covered in this part is given in Table 3.

Table 3. Summary of Hybrid LCA

Author(s)	Year	Study Focus and Method
Bilec et al.	2006	Introduced Hybrid LCA and applied it to a precast concrete parking garage
Crawford	2008	Explained how Hybrid LCA better defines system boundaries
Nakamura & Nansai	2016	Defined three types of Hybrid LCA: Tiered, IO-based, and Integrated
Treloar et al.	2000	Applied Hybrid LCA to evaluate construction materials like cement and steel
Rodríguez-Alloza et al.	2015	Combined process data with MRIO data for warm mix asphalt production
Martinez et al.	2018	Assessed the demolition process of a dam in Spain
Dong et al.	2013	Measured carbon footprint of an industrial zone in China with Tiered Hybrid LCA
Wiedmann et al.	2011	Combined IO-based and Integrated Hybrid approaches to study wind energy emissions
Lenzen	2002	Evaluated water use, land degradation, and energy consumption across industries in Australia

2.3. LCA on Alternative Fuels in Transportation Sector

Life Cycle Assessment has been a widely used method, from the past to the present, for comparing the environmental impacts of different fuel types used in various types of vehicles. This method encompasses the environmental impacts of all processes, from fuel production to consumption, and from vehicle production to its end of life. In this context, numerous studies in the literature employ three different methods of LCA: process-based LCA, Input-Output LCA, and Hybrid LCA. Thanks to these methods, in addition to comparing the environmental performances of traditional vehicles with internal combustion engines (diesel) and alternative fuel vehicles such as electric and hybrid, vehicles, the life cycle impacts of alternative energy sources, including biofuels, natural gas, and hydrogen, are also analysed in detail.

After evaluating the general scope and areas of use of the Life Cycle Assessment method in the literature, studies comparing electric vehicles with traditional and alternative fuels were focused on. In a study conducted by Zhao et al. (2016), the environmental impacts of urban delivery trucks were assessed throughout their entire life cycle, comparing diesel, diesel-hybrid, compressed natural gas (CNG), and battery electric types using the multi-region input–output hybrid life cycle assessment method. Additionally, the environmental impacts of battery electric trucks were examined in relation to the regional electricity generation sources. As a result of the study, it was determined that electric trucks produce zero emissions during the usage phase; however, their total emissions can be high due to the dependence of electricity generation on fossil fuels. When the entire life cycle is considered, it was revealed that hybrid fuel trucks are the most suitable option with the lowest GHG emissions.

Zhao and Tatari (2017) evaluated the environmental impacts of garbage collection trucks were evaluated throughout their entire life cycle. The study compared diesel, compressed natural gas (CNG), hydraulic hybrid, and fully electric truck types using a hybrid life cycle analysis. In addition, the impact of different electrical grid mixes on the environmental performance of fully electric garbage trucks was examined in the USA. As a result of the study, it was determined that hydraulic hybrid trucks produce the lowest GHG emissions. In contrast, electric garbage collection trucks have the highest emission values due to the use of fossil fuel-based electricity generation; however, they can be more advantageous from an environmental perspective in scenarios where renewable energy sources are utilised.

According to Van Mierlo, Messagie, and Rangaraju (2017), compressed natural gas vehicles (CNG), battery electric vehicles (BEV), liquefied petroleum gas vehicles (LPG), biogas vehicles (BG), plug-in hybrid vehicles (PHEV), hybrid vehicles (HEV), diesel and gasoline vehicles were compared using the process-based LCA method in order to evaluate the overall impact of battery electric vehicles on transportation emissions in Brussels. As a result of the study, it was determined that battery electric vehicles (BEVs) have the lowest GHG emissions throughout their life cycle; however, it was noted that human toxicity and environmental impacts associated with the battery production process are significant. However, it was emphasised that strategies such as battery recycling and night charging can significantly reduce these negative impacts.

Souza et al. (2018) examined the environmental impacts of current vehicle fuels such as gasoline and ethanol were compared with the effects of electricity, an alternative energy source, based on environmental issues such as high oil and fossil fuel consumption, air pollution, and GHG emissions in Brazil. An attributional approach was adopted in the study, and the process-based LCA method was used. According to the findings, battery electric vehicles (BEVs) have the lowest environmental impact throughout their life cycle, while ethanol and gasoline vehicles create higher environmental burdens in specific impact categories; BEVs are particularly notable for human toxicity.

In the study of Şen, Ercan, and Tatari (2017), alternative fuel technologies of Class 8 heavy-duty trucks, namely B20 biodiesel, compressed natural gas (CNG), hybrid, and battery electric trucks (BE), were comparatively analysed with conventional diesel trucks within the scope of Hybrid LCA in terms of cost, emissions, and externalities. The study revealed that the performance of battery electric trucks varies depending on the carbon intensity of grid electricity. However, they generally have the lowest GHG emissions and external costs throughout their life cycle. It was concluded that trucks using compressed natural gas (CNG) produce the highest emission values and do not offer a significant cost advantage.

Ercan and Tatari (2015) focused on a hybrid life cycle assessment method was employed to compare the environmental impacts of public transport buses using six different fuel options: diesel, biodiesel B20, CNG, LNG, hybrid diesel-electric, and battery electric. As a result of the study, it was determined that the battery electric bus (BE) has the lowest environmental impact throughout its life cycle. However, it was stated that the total environmental impact of these vehicles may be higher in regions where electricity production is based on fossil fuels. When evaluated in terms of water withdrawal, it was concluded that hybrid and diesel buses are in a more advantageous position due to the high water use during electricity and natural gas production.

Following extensive studies comparing various types of electric vehicles in the literature, specific studies on the use of alternative fuels in heavy-duty vehicles have also been included. A study conducted by Rupp, Schulze, and Kuperjans (2018) compared the life cycle of energy consumption and emissions caused by conventional diesel and parallel hybrid heavy-duty trucks used in Germany. The process-based LCA method was employed to analyse at what point the higher emissions of hybrid trucks arising during

the production phase would be compensated during the service life. As a result of the study, it was determined that hybrid trucks compensate for the additional emissions caused by production in a short time and provide lower CO₂ emissions throughout their service life; moreover, they become environmentally advantageous within the first year in almost all scenarios.

In a study conducted in China, Zhang et al. (2024) compared the environmental impacts of heavy-duty trucks powered by alternative fuels such as liquefied natural gas (LNG), biodiesel, hydrogen, and methanol with those of conventional diesel trucks using WTW emissions. Only the process from fuel production to vehicle use was evaluated in the study; therefore, although it is not a complete LCA, it can be considered a process-based LCA with a limited scope, focusing on fuel production processes and emission factors. As a result of the study, it was determined that LNG trucks were the most economically viable option, while B20 biodiesel trucks were found to be the most environmentally sustainable alternative.

El Hannach et al. (2019) assessed the environmental impacts of diesel fuel and partial hydrogen replacement scenarios were comparatively evaluated on Class 8 heavy-duty truck fleets. According to the results of the study conducted using the process-based LCA method, it was determined that total GHG emissions were reduced by 47% and air pollutant emissions by 12% when diesel was replaced by hydrogen at a 50% rate. Additionally, it was revealed that significant economic savings and environmental benefits could be achieved if hydrogen were supplied at an affordable price.

In addition to evaluations carried out on heavy-duty vehicles, studies have also been conducted on the environmental performance of light commercial vehicles used in smaller-scale transportation activities. In the study conducted by Marmioli et al. (2020), electric, CNG, and diesel light commercial vehicles used in urban freight transport were compared within the scope of the attributional process-based LCA method. As a result of the study, it was determined that electric light commercial vehicles demonstrated the best environmental performance, offering advantages such as low energy consumption and zero emissions during the logistics use phase. However, it was stated that these advantages could be further increased if the electricity grid used in the production phase was provided by clean energy sources.

In the study conducted by Yang, Hao, and Chai (2018), light and medium-class diesel, plug-in electric, and battery-swap electric trucks were compared in terms of GHG

emissions and total cost of ownership (TCO) within the scope of delivery trucks. In the study conducted with the process-based LCA method, it was concluded that light-class plug-in electric trucks are the most competitive and advantageous vehicles in terms of both emission reduction and cost savings.

In addition to studies examining the use of alternative fuels in light commercial vehicles, there are also region-specific studies in the literature that reveal the changes in the environmental impacts of electric vehicles according to regional energy production conditions. A study conducted by Mustapa et al. (2024) in Malaysia compared the Well-to-Wheel CO₂ emissions of diesel, gasoline, and electric trucks. In the study, the “top-down” Tier 1 approach was adopted, and a calculation was made through emission factors based on fuel consumption data; in this context, the process-based LCA method was applied. The findings revealed that electric trucks are a more environmentally sustainable option compared to other fuel types.

Findings by Lommahadthai (2022), electric trucks used in freight transport were compared with conventional diesel and compressed natural gas (CNG) trucks in terms of environmental and economic aspects. In the study, which was based on the Cradle to Grave scope and used the process-based LCA method, it was determined that electric trucks were at a disadvantage in some impact categories, such as human toxicity, especially in processes such as battery production; however, when evaluated in terms of emissions, they were environmentally more advantageous compared to diesel and CNG trucks. In this study conducted specifically for Thailand, it was emphasised that policy support and legislative improvements were necessary to increase the adoption of electric trucks.

Following studies examining the environmental impacts of electric vehicles under regional conditions, comparative environmental assessments of alternative systems in municipal services have also been carried out. In a study conducted by Chàfer et al. (2019), the environmental performance of pneumatic municipal waste collection systems was compared with that of traditional truck systems, with a particular focus on how different energy sources affect their life cycle. A study conducted using the process-based LCA method revealed that the energy source is a major determinant of the environmental impact of waste collection systems. It was determined that pneumatic systems exhibited the best environmental performance when renewable energy sources were utilised; on the

other hand, the traditional system had lower environmental impacts when fossil fuel-based energy was employed.

In addition to alternative system evaluations at the municipal scale, studies on environmental comparisons in industrial applications and private use areas have also found their place in the literature. In the study conducted by Balboa-Espinoza et al. (2023), the environmental impacts of diesel and battery-electric trucks used in underground mining were compared using the process-based LCA method with openLCA and MATLAB software. The study revealed that battery electric trucks offer more sustainable and environmentally friendly solutions when powered by renewable energy sources; however, they may have disadvantages in terms of particulate matter formation and water consumption depending on the type of resources used in electricity production.

Ally and Pryor (2007) focused on the process-based LCA method was used to evaluate hydrogen fuel cell buses in comparison with diesel and natural gas systems. As a result of the study, it was determined that hydrogen fuel cell buses performed similarly to diesel in terms of global warming potential but offered better results than CNG systems. However, it was revealed that they had higher environmental impacts in impact categories such as acidification and ozone formation.

As a result, future research needs to extend beyond operational impacts, including comprehensive cradle-to-grave analyses, and address policy implications, technological advancements, and sustainable resource management strategies to fully realise the potential environmental benefits of alternative fuels in the transportation sector. A summary of the studies covered in this part is given in Table 4.

Table 4. Summary of LCA in alternative fuels in transportation sector

Author(s)	Year	Study Focus and Method
Zhao et al.	2016	Compared diesel, diesel-hybrid, CNG, and battery-electric delivery trucks using multi-region input–output hybrid LCA (Hybrid LCA).
Zhao & Tatari	2017	Evaluated garbage truck fuel options (diesel, CNG, hydraulic hybrid, electric) and grid scenarios in the U.S (Hybrid LCA).

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Table 4 (cont.).

Van Mierlo, Messagie & Rangaraju	2017	Compared CNG, BEV, LPG, biogas, PHEV, HEV, diesel, and gasoline in Brussels (Process LCA).
Souza et al.	2018	Compared gasoline, ethanol, and electric vehicles in Brazil (Process LCA).
Şen, Ercan & Tatari	2017	Analyzed Class 8 truck fuel technologies (diesel, biodiesel, CNG, hybrid, BE) (Hybrid LCA).
Ercan & Tatari	2015	Compared six bus fuel types (diesel, biodiesel, CNG, LNG, hybrid, BE) (Hybrid LCA).
Rupp, Schulze & Kuperjans	2018	Compared diesel and hybrid heavy-duty trucks in Germany (Process LCA).
Zhang et al.	2024	Compared LNG, biodiesel, hydrogen, and methanol trucks with diesel in China (Process LCA).
El Hannach et al.	2019	Evaluated Class 8 trucks with 50% hydrogen-diesel replacement (Process LCA).
Marmiroli et al.	2020	Compared electric, CNG, and diesel light commercial vehicles for urban freight (Process LCA).
Yang, Hao & Chai	2018	Compared diesel, plug-in electric, and battery-swap delivery trucks (Process LCA).
Mustapa et al.	2024	Evaluated diesel, gasoline, and electric trucks in Malaysia (Process LCA).
Lommahadthai	2022	Compared electric, diesel, and CNG trucks in Thailand (Process LCA).
Châfer et al.	2019	Compared pneumatic waste collection systems with truck-based waste systems (Process LCA).
Balboa-Espinoza et al.	2023	Compared diesel and electric trucks in underground mining (Process LCA).
Ally & Pryor	2007	Compared hydrogen fuel cell buses with diesel and CNG buses (Process LCA).

2.3.1. Maintenance Vehicles LCA

As a result of the literature review, it was determined that there is a limited number of LCA applications specifically tailored to maintenance vehicles, and a significant lack

of information exists in this area. In particular, the environmental impacts of special-purpose maintenance vehicles such as electric, hybrid, and diesel bucket trucks have not been evaluated in sufficient detail to date. Therefore, to fill this gap, an LCA study specific to bucket trucks is conducted in this thesis.

When the LCA studies conducted specifically for maintenance vehicles in the literature are reviewed, as stated in the introduction of the thesis, Liu and Yi (2021), examined the cost-benefit analyses, depreciation, and performance of snowplows used in winter maintenance activities, together with the factors affecting this performance, at both macro and micro levels and investigated the optimal replacement periods of the vehicles. In other words, an economic LCA study was conducted rather than an environmental impact analysis. In another study conducted by Liu and Yi (2021), a Life Cycle Analysis (LCA) was conducted specifically for maintenance vehicles, considering sweepers used to clean garbage, dust, and dirt on the streets; loaders used to transport bulk materials, and graders used for surface levelling in road construction. The study aims to determine the most appropriate life cycle for each vehicle type. Within the scope of this analysis, factors such as vehicle purchase costs, maintenance expenses, mileage, and replacement intervals were evaluated. In other words, this study adopted an LCA approach from an economic perspective rather than focusing on environmental impacts (Liu and Yi 2021).

In examining bucket truck studies, Jasna Tomic (2010) evaluated the performance of first-generation hybrid bucket trucks in terms of fuel economy, emissions, reliability, and user satisfaction under both laboratory and field conditions. In this study, the Eaton mild-parallel hybrid system was implemented in the vehicles. This system enables both the propulsion and engine power to be supported electrically. The hydraulic functions were powered by an electric motor (ePTO) instead of a conventional diesel engine. As a result of this configuration, fuel consumption was reduced by 38% to 60%, and significant decreases in emissions were recorded.

In a study conducted by Miyasato and Kosowski (2015), a plug-in hybrid system was integrated into medium-class public service vehicles, and the system was tested under field conditions. Data such as performance, fuel economy, and emissions of these vehicles were collected and analysed. Thanks to this system, which works synchronously with the diesel engine, the operator was able to use hydraulic equipment without starting the diesel engine, especially in idling bucket trucks. Thus, the noise level in the work area was

reduced, fuel consumption was reduced by 60%, CO₂ emissions were reduced by 50%, and NO_x emissions by 80%.

The study conducted by Gao, Lin, and Franzese (2017) examines hybrid bucket trucks and electric and hybrid delivery trucks. This study compares the energy consumption and costs of battery electric vehicles (BEVs) with GenSet-type plug-in hybrid vehicles. The study frequently emphasises the long duration of bucket trucks' urban operations. It states that the battery capacity requirement is higher due to the high idle times and increased energy demand during work. The energy consumption of GenSet plug-in hybrid bucket trucks, at 4.3 kWh/mi, offers a potential savings of 54.4% compared to the 11.1 kWh/mi value of diesel bucket trucks.

As a result, upon examining the literature, it becomes apparent that the number of LCA studies specifically conducted for maintenance vehicles is limited, and existing studies primarily focus on economic evaluations. There is no comprehensive study that addresses the environmental impacts of special-purpose vehicles, particularly bucket trucks. In this case, it is believed that an environmentally focused LCA study, conducted within the scope of this thesis, will fill an important gap in the literature and guide policymakers and fleet managers in terms of sustainability.

2.4. Monte Carlo Simulation

Monte Carlo simulation is used to consider the variability and uncertainties in the model (Vinodh and Rathod, 2014), and it is a method that allows analysing complex systems without relying on complicated calculations and advanced statistics (Raynolds, Checkel, and Fraser, 1999). According to Sun and Ertz, Monte Carlo simulation is a method that tries to produce solutions to problems using random numbers. This approach is based on generating random variables according to a specific probability distribution and estimating the numerical properties of the model using statistical methods (Sun and Ertz, 2020).

Monte Carlo simulation is widely used in LCA studies, where uncertainty analysis is crucial. According to Hung and Ma, this method helps determine the stage that contributes the most to uncertainty among the various stages in LCA, allowing these

uncertainties to be analysed in detail and revealing which stages need improvement (Hung and Ma, 2009). According to Morales et al., Monte Carlo Simulation not only evaluates uncertainties in LCA studies but also increases the reliability of the results by providing results within a range of values, without adhering to a single deterministic value. In this way, the misleading effect of slight differences between alternatives is reduced, allowing the decision-making process to be carried out more soundly (Morales et al., 2021).

Monte Carlo simulation is frequently preferred in LCA studies, especially in the evaluation of environmental impacts of alternative fuel types. In the study of Ercan and Tatari (2015), the environmental impacts of public transport buses with six different fuel types throughout their life cycles were compared using the hybrid LCA method. To address the uncertainties in fuel economy that vary depending on different driving cycles, a Monte Carlo simulation was used to randomly assign fuel economy data for each driving cycle and fuel type, assuming a normal distribution with a 10% standard deviation. In this way, uncertainties in fuel consumption were reflected in the model, and possible ranges of life cycle emissions were presented, allowing for a more reliable comparison of minor environmental differences between different fuel types. In the study of Şen, Ercan, and Tatari (2017), the environmental impacts of Class 8 heavy-duty trucks (HDT) in the USA according to alternative fuel technologies were compared using the hybrid LCA method. In this study, where data limitations exist due to the limited adoption of alternative fuel HDTs, a Monte Carlo simulation was employed to perform uncertainty analyses. The effects of variables such as vehicle life, fuel consumption, and battery replacement were evaluated with a probabilistic approach; thus, the analysis aimed to produce more realistic and reliable results. In the study conducted by McCleese and LaPuma (2002), the LCAs of internal combustion vehicles and electric vehicles were evaluated comparatively. The probability distributions defined for the variables in the Life Cycle Inventory created in the study were analysed using a Monte Carlo simulation with more than 10,000 iterations, thereby comprehensively evaluating the effect of uncertainties on the results. Likewise, Krotov et al. (2024) used process-based life cycle assessment (LCA) to assess the environmental effects of biofuels. The study employed a Monte Carlo simulation to model uncertainties and random sampling to analyse the variables defined in the Life Cycle Inventory stage over 10,000 iterations. Sun and Ertz (2020) conducted a LCA to evaluate the environmental impacts of vehicles powered by

liquefied natural gas (LNG). This analysis employs a Monte Carlo simulation with 50,000 iterations to account for the effects of uncertain parameters, including the energy efficiency of LNG engines and the usage rate of LNG filling stations.

As a result, research shows that Monte Carlo simulation systematically assesses differences and uncertainties in LCA analyses, providing more realistic, reliable, and comparable results in studies on alternative fuels and vehicle types, thereby enhancing decision support effectiveness.



CHAPTER 3

METHODOLOGY

LCA, historically defined in the literature as “Resource and Environmental Profile Analysis (REPA),” initially emerged to compare the environmental performance of products in terms of their “greenness” (Curran 2013), and has evolved into a systematic analysis of the quality and quantity of environmental impacts associated with a product, service, or process throughout its entire life cycle—from raw material extraction to production, use, and final disposal (Hunt and Franklin 1996). Initially focused on analysing the process from raw material extraction to end-of-life disposal, this approach has gradually expanded to incorporate strategies such as reuse and recovery (Rigamonti and Mancini 2021). Scholars have attempted to expand the capabilities of the LCA tool by proposing several LCA methodologies. Approaches including process-LCA, attributional LCA (Russell, Ekvall, and Baumann 2005), consequential LCA, and economic input-output (EIO) LCA (Hendrickson et al. 1997; Lenzen 2000) have been applied to many production and consumption systems since their inception. EIO LCA and process LCA, also known as process-based LCA (Udo de Haes et al. 2004), have recently become more widely used in both academia and industry. As mentioned in the literature review and introduction sections, process-based LCA focuses on material and energy flows in the downstream supply chain, while the Economic Input-Output model focuses on sectoral economic data in the upstream supply chain and at the national level (Jiang et al. 2014). The main shortcoming of Process-based LCA is that it suffers from truncation errors, that is, it has incomplete information due to broken system boundaries. The main shortcoming of Input Output LCA is that it suffers from aggregation errors, that is, all products belonging to a sector are considered to have the same emissions (Zhao and You 2019). The model that complements the processes not included in the upstream process-based LCA with EIO data is the Hybrid LCA (Zhao and You 2019). Process-based LCA and EIO analysis approaches make up the hybrid LCA approach used in this study. It may be possible to more accurately quantify the life cycle sustainability impacts through

hybridization. However, LCA has limitations because it primarily examines the energy and environmental effects of an economic activity, making it unable to account for social and economic effects (Sala, Farioli, and Zamagni 2013). As a result, life cycle cost (LCC) analysis is added to LCA by using EIO analysis.

The input-output analysis method introduced by Leontief (1970) and used in this study provides the general operationalization of the manufacturing phase of the Hybrid LCA framework. Similar EIO usage is available in alternative fuel literature (Sen, Ercan, and Tatari 2017; Zhao et al. 2016). For the purposes of this study, the Exiobase database was used to construct a single-region, sector-by-sector Input-Output model for the US economy and to assess the life cycle impacts of the studied bucket trucks. Large-scale MRIO tables are now being compiled by a variety of initiatives, including the World Input-Output Database (WIOD), Global Resource Accounting Model (GRAM), Global Trade Analysis Project (GTAP), Externality Data and Input-Output Tools for Policy Analysis (EXIOPOL), and EoRA (Zhao et al. 2016). EXIOBASE is a global and detailed Multi-Region Environmentally Extended Supply-Use Table (MR-SUT) and Input-Output Table (MR-IOT). It was developed by harmonizing and detailing the supply-use tables for multiple countries, estimating emissions and resource extractions by industry (EXIOBASE Consortium n.d.). EXIOBASE Version 1 was initially utilized in the early 2000s, followed by the release of Version 2 in 2007. The most recent version adopted in this study, EXIOBASE 3 (Version 3.8.2), was published on Zenodo in 2021 (EXIOBASE Consortium 2021). This version provides detailed data across 163 economic sectors and 200 products, covering 44 individual countries and over five world regions. It employs an industry-by-industry supply-use framework for the reference year 2022. To produce background data for the hybrid LCA methodology employed in this investigation, Exiobase was selected. To provide more thorough and precise results, hybrid LCA blends economic input-output (background) data with process-based (foreground) data. The best MRIO database to make this combination possible was found to be Exiobase (Chen et al. 2020). In this study, Pymrio was used to process the exiobase database and automate basic environmental impact calculations. For the analysis of multi-region input-output (EE-MRIO) tables with environmental extensions, Pymrio is an open-source Python module. Working with databases like EXIOBASE, WIOD, and EORA26, it automates data uploading, missing data checks, and computations like environmental footprint and trade-embedded implications (Stadler 2021). In the study by Zhabura (2024), pymrio was used

to assess the environmental impact of electronic products using the EXIOBASE database. Agez et al. (2020) employed Pymrio within the pyLCAIO software to import the EXIOBASE 3 database into the Python environment.

In the analysis part with Pymrio, Z matrix represents the flow of commodities (or monetary values) from one industry to another across 163 sectors in the U.S. economy. This corresponds to the inter-industry flow table, where each element z_{ij} denotes the value of the commodity delivered by industry i to industry j as intermediate input. Y matrix represents the final demand matrix, as per EXIOBASE structure, includes the following final demand components: Household consumption, Government expenditure, NPISH consumption, Gross fixed capital formation, Changes in inventories, Changes in valuables.

This aggregated final demand vector is denoted by f , and each element f_j represents the final demand for the output of industry j . An industry-by-industry IO model can be formulated as the following (Miller and Blair 2009):

$$x = [(I - DB)^{-1}]f \quad (3.1)$$

Where x is the total output vector of industries, D is the market share matrix (commodity composition of industry outputs), B is the technical coefficients matrix (commodity requirements per industry output), DB is the direct requirement matrix in an industry-by-industry system.

Technical coefficient matrix B , derived from (Miller and Blair 2009):

$$b_{ij} = \frac{u_{ij}}{x_j} \quad (3.2)$$

Where u_{ij} is the value of commodity i used by industry j , x_j is the total output of industry j . This matrix shows the direct input requirement per dollar of output. In commodity-by-industry systems, the market share matrix D defines how the output of each commodity is distributed across industries. It is calculated as (Miller and Blair 2009):

$$d_{ij} = \frac{v_{ij}}{q_i} \quad (3.3)$$

Where v_{ij} value of commodity i produced by industry j , q_i is the total output of commodity i . In this study, an industry-by-industry system is employed, it is assumed that each industry produces only its own defined product. In this case, the D matrix is implicitly an identity matrix. That is, each product is produced by only one industry, and production is not shared among other industries. Therefore, the following equality is accepted as valid:

$$A = D * B = B \quad (3.4)$$

Input-output-based environmental analysis (LCA) makes use of the Leontief model. The goal is to compute the environmental effects of product or service creation across economic systems in a comprehensive way, including energy usage and carbon emissions (Lenzen and Crawford 2009). The Leontief equation system can be used to determine the production level of each sector if the technical coefficients (A) and final demand (f) are known. Under the presumption of linearity, this straightforward system of linear equations needs to be resolved. This approach is actually utilized to determine how much output should be generated in different economic sectors to meet a specific end demand (Eurostat 2008). Then the Leontief inverse is calculated as follows:

$$L = (I - A)^{-1} \quad (3.5)$$

It allows to compute the total (direct + indirect) effects of a change in final demand:

$$\Delta x = L * \Delta f \quad (3.6)$$

The shock vector Δf simulates an increase in final demand for selected sectors.

Multipliers are assessed by summing the columns of the Leontief inverse (Miller and Blair 2009):

$$m_j = \sum l_{ij} \quad (3.7)$$

Each m_j represents the total output multiplier for industry j . and the relative effect per sector is also computed which provides insight into the percentage change in output due to the shock — a useful diagnostic for identifying vulnerable or responsive sectors:

$$\frac{\Delta x_j}{x_j} \quad (3.8)$$

The formula and data structure used in environmental impact analysis are based on the consumption-based environmental calculation approach (Miller and Blair 2009). This calculation format is defined as environmentally extended input–output analysis with the Leontief multiplier:

$$r = E_{dim} [(I - DB)^{-1}] f \quad (3.9)$$

$$r = E_{dim} * \Delta x \quad (3.10)$$

Where E_{dim} denotes the matrix of environmental extension coefficients (e.g., in units of kg per million euros), representing the environmental intensity of each sector, Δx is the change in gross output per sector (in million euros), computed as a result of the exogenous final demand shock Δf . r represents the total environmental impact associated with each environmental category. The EXIOBASE-based EIO model developed for the study was used to derive indirect environmental impacts associated with the manufacturing phase. In this model, economic input–output tables derived from transactions completed in 2022 were utilized for the representation of the U.S. economy. The EIO model and process-based models like the GHG, Regulated Emissions, and Energy Use in Transportation (GREET), Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET), and Motor Vehicle Emission Simulator (MOVES) are used to analyse the downstream environmental impacts that result from the use phase. Since the MOVES model was created to account for the air pollutants generated by vehicle operating procedures, the AFLEET tool additionally tracks air pollutant emissions

using the Motor Vehicle Emissions Simulator (MOVES) database maintained by the U.S. EPA (Sen 2019).

The purchase prices of each bucket truck and any other components taken into consideration are the input values used to account for the upstream environmental consequences of the lifecycle stages. In the section on data collecting, each of these input values will be covered in detail. To calculate the environmental impacts during the use phase, WTW and C2G (Cradle-to-Grave) emission values for medium-heavy-duty vocational vehicles (MHVs) from the GREET database were used for the five different emission types considered in this study. These emission values were multiplied by the age-based deterioration factors in the AFLEET database to calculate the bucket truck's lifetime emissions in driving mode. Since the bucket truck spends a large portion of its daily operation in idling mode, its emissions during this period were determined by multiplying the deterioration factors with the emission factors also taken from AFLEET. Thus, the total emissions during the use phase were obtained as the sum of the emissions in driving and idling modes.

This study applies a Hybrid LCA framework to estimate the lifecycle cost and environmental impacts of a bucket truck. Direct costs are derived from purchase prices, while indirect economic and environmental impacts are traced across 163 U.S. economy sectors (EXIOBASE) and combined with use-phase emissions for final interpretation.

3.1. Data Collection

3.1.1. Study Scope and Overview

This study assesses and compares the indirect economic and environmental impacts of three alternative fuel-powered bucket truck types: conventional diesel, diesel with E-PTO, and battery electric. Bucket trucks, or utility vehicles, have hydraulic lifts that allow workers to reach high places. They are widely used for jobs like fixing power lines, working on phone networks, cutting down trees, and doing repair work on buildings and roads (Parker Hannifin Corporation 2023). Even though these vehicles vary in how

they operate and what they are used for, their long working hours and tough conditions lead to high fuel consumption and associated emissions over time. This is especially true for heavy-duty maintenance trucks, which often consume more energy and produce more emissions due to long periods of idling and working under heavy loads (Gao, Lin, and Franzese 2017). The system scope is shown in Figure 1, along with the flow chart of the various life cycle phases used for the LCA study. Accordingly, the following phases are included in the system boundary: manufacturing of the vehicle, battery, and the e-PTO, maintenance/repair, fuel production (diesel and electricity), and vehicle use in the U.S. The end-of-life (EOL) phases of the vehicle and battery are not covered in this study due to the lack of plausible data on the recycling percentage of bucket trucks or a unified technique for recycling or reusing the battery or vehicle body components.

The LCA conducted in the present study includes both economic and environmental impact evaluations for three different bucket truck types. According to economic analysis, expenditures made during the phases of fuel production, maintenance and repair, and vehicle and battery manufacturing all directly contribute to economic activity in their respective industries. These industry-level expenditures also induce indirect economic impacts through intersectoral linkages by affecting upstream and downstream sectors. Leontief's input-output analysis framework serves as the foundation for the linear modelling methodology used by the EIO-LCA tool (Leontief 1970). Economic relationships between the 163 sectors of the US economy are represented by a matrix used in this model. The study uses the EXIOBASE 3 database (EXIOBASE Consortium n.d.) and the Pymrio package (Stadler n.d.) in Python to apply a hybrid LCA model based on a regional environmentally extended multi-regional input-output model (EE-MRIO). To ensure consistency with the Exiobase structure and methodology, all monetary values associated with the 12-year lifetime operation of the bucket truck were converted to 2022 euros (€), using the 2025 U.S. dollar to euro exchange rate and applying appropriate inflation adjustments based on current consumer price indices (US Inflation Calculator Staff 2025).

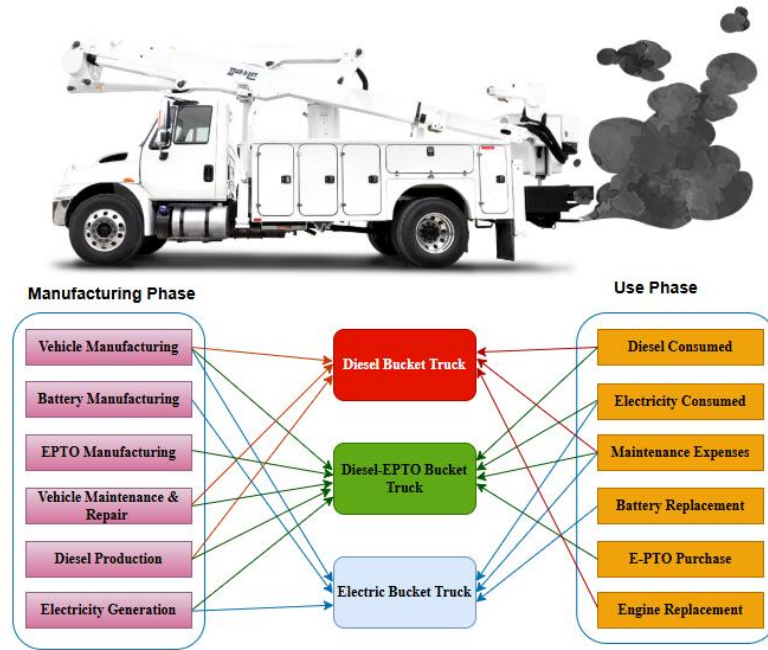


Figure 1. System Boundary for Hybrid LCA
(Source: Pnegg n.d.)

Using the 2022 regional EE-MRIO-based hybrid LCA model once more, the manufacturing phase's GHG emissions and energy consumption are assessed. Using a process-based LCA method, the energy consumption and tailpipe GHG emissions are examined independently during the usage phase. The use-phase energy consumption values related to fuel economy and environmental emissions are derived from the AFLEET and GREET models. As the functional unit of analysis, the total Vehicle Miles Traveled (VMT) of 109,200 miles (or 9,100 miles annually throughout a 12-year lifetime) is used to assess the direct and indirect environmental impacts of each life cycle phase.

3.1.2. Vehicle Characteristics

According to the U.S. Department of Energy's Alternative Fuels Data Center (AFDC), a Class 7 vehicle is defined as a truck with a Gross Vehicle Weight Rating (GVWR) between 26,001 and 33,000 lbs and is classified under Heavy Duty by both the

Federal Highway Administration (FHWA) and the Environmental Protection Agency (EPA) (U.S. Department of Energy, Alternative Fuels Data Center 2024).



Figure 2. Class 7 Bucket truck
(Source: Pngegg n.d.)

3.1.3. Life Cycle Inventory, Parameters, and Assumptions

To evaluate the effects in the following step, inputs to and outputs from a product system are quantified in the inventory analysis phase of a LCA. EIO-LCA requires the monetary values of goods as inputs, whereas Process-LCA requires process-specific data inputs (Sen, Ercan, and Tatari 2017). This study looks at three types of big work trucks called Class 7 bucket trucks. They use different fuels: diesel, diesel with an electric power take-off (E-PTO), and full electric. The goal is to see how these trucks work through their whole life and how much cost and pollution they make. These trucks are mostly used in the United States. They help with power line repair, tree cutting, building work, and street light maintenance. Because they work for long hours and often stay on while not moving, they burn a lot of fuel and make more emissions. This extra idling during work makes pollution even worse.

The analysis is based on a hybrid LCA that combines process-based and input–output models. The model follows the structure of EXIOBASE 3, which covers 163 economic sectors in the U.S. economy, and uses the pymrio package to track indirect effects across industries. The study includes both the environmental and economic sides of the LCA, making it possible to observe how each phase contributes to the overall performance of the vehicles.

The functional unit for this analysis is defined as a total vehicle mileage of 109,200 miles, which represents 9,100 miles per year over a 12-year lifetime. This number shows how a bucket truck is usually used in its life and helps to compare the trucks in a fair way. All results are expressed in relation to this unit so that impacts can be compared on an equal basis.

The system boundary includes the following stages: the manufacturing of the vehicle, battery, and E-PTO components; maintenance and repair; fuel and electricity production; and vehicle use within the United States. The end-of-life (EOL) phase is not included because reliable information on the recycling of bucket trucks and their batteries is limited. Energy use and emissions in the use phase were found separately for driving and idling. The data came from the AFLEET and GREET models. These values were then combined with age-based factors to show how the truck performs over its whole life.

This scope allows the study to evaluate both the direct environmental load and the wider indirect effects that occur through economic activities linked to manufacturing, maintenance, and energy production. By combining real-world fuel and electricity data with sectoral linkages from EXIOBASE, the model provides a complete picture of how alternative fuel choices can influence total emissions, energy use, and economic outcomes over the life of a bucket truck.

3.1.3.1. Manufacturing Inputs

In the manufacturing phase, the bucket truck considered in the study consists of the necessary components for a truck, including truck chassis, boom, battery, and e-PTO. Following the method in Sen, Ercan, and Tatari (2017), the component prices in the

truck's purchase cost were first adjusted for inflation to reflect their value in 2022 U.S. dollars using the U.S. Inflation Calculator Staff (2025), and subsequently converted to 2022 euros based on European Central Bank (2025) exchange rates, in order to serve as input for the EIO model to estimate the environmental impacts of the corresponding 163 economic sectors. All calculated prices were first converted to 2025 U.S. dollars to assess the direct economic impact, while the indirect economic impacts across 163 sectors were evaluated in 2022 euros and incorporated into the analysis accordingly.

For the diesel bucket truck, the total vehicle cost was estimated by subtracting the chassis price of the 2024 Freightliner Business Class M2 106 (Custom Truck One Source 2025a) from the full vehicle price of the same truck equipped with a Versalift VN-555-MHI boom (Custom Truck One Source 2025b). The resulting price difference was interpreted as the standalone boom system cost. This boom cost was assumed to be identical across all drivetrain configurations (diesel, diesel E-PTO, and battery-electric) to ensure consistent system boundary and comparability. Using Exiobase 3 model's available sectors, expenses related to truck chassis manufacturing belong to the 'manufacture of motor vehicles, trailers and semi-trailers' sector, while expenses related to bucket truck booms are associated with the "manufacture of machinery and equipment n.e.c." sectors.

For the diesel E-PTO variant, the same chassis and boom cost structure was retained, with the addition of an electric power take-off system priced according to the reported values (Edison Electric Institute 2014). Trucks in the electric utility industry idle at the job site for a large amount of time, wasting fuel in the process. The truck's hydraulic boom, all emergency lights, auxiliary equipment, and even cabin heating and conditioning are powered silently and effectively by the e-PTO system's batteries, which are charged by the grid or while traveling between job sites (Edison Electric Institute 2014). As seen in Table 5, the E-PTO system operates with a 2-kWh battery capacity and is activated only in idling conditions, providing the necessary energy from the battery without the need for the engine to run. As stated in the report (Edison Electric Institute 2014), since the economic life of the E-PTO system is 12 years for Class 7 bucket trucks, there is no need to remanufacture or replace the system for a bucket truck with a 12-year lifetime. For sectoral classification in the EIO model, the E-PTO was assigned to the "manufacture of electrical machinery and apparatus n.e.c." sector.

The standard battery-electric configuration, the 2024 Kenworth K370 cab and chassis, which includes an integrated 259 kWh lithium-ion battery system, was used (Kenworth Truck Company 2025), and the same boom and E-PTO costs were incorporated to reflect the standard auxiliary hydraulic systems commonly present in electric utility trucks. The sum of the chassis, boom, and E-PTO costs constituted the total electric bucket truck cost. Since the battery cost was already embedded in the truck chassis price, its 2022 value was deducted from the input assigned to the "manufacture of motor vehicles, trailers, and semi-trailers" sector and reallocated to the "manufacture of electrical machinery and apparatus n.e.c." sector. The battery price per kWh was 115 U.S. dollars in 2025, whereas it was 166 U.S. dollars in 2022 (Bloomberg New Energy Finance 2024). Accordingly, the calculation was performed in 2022 U.S. dollars, which were then converted into 2022 euros and incorporated into the analysis. The manufacturer provides an eight-year warranty for the battery (Huotari et al. 2021). Accordingly, it is assumed that the battery of the electric bucket truck would need to be replaced in the eighth year of operation. Since the analysis required all values to be expressed in 2022 euros, the cost of the battery expected to be replaced in the eighth year was calculated using its 2022 price level and added to the "manufacture of electrical machinery and apparatus n.e.c." sector. These values are reported in Table 6. Following the estimation of direct and indirect economic impacts based on expenditure data, the sector-specific consumption-based coefficients from EXIOBASE 3 database were applied to calculate the corresponding indirect environmental impacts. These impacts were assessed across five emission categories: GHG, NO_x, SO_x, PM₁₀, and PM_{2.5}. Because of their extensive usage in literature and their noteworthy values in relation to other contaminants, these pollutants were selected for the study's findings (Ercan and Tatari 2015).

3.1.3.2. Fuel Consumption, and Electricity Generation Inputs

Since fuel consumption/electricity generation accounts for the majority of the use phase of the total lifetime effects, fuel economy is particularly important when analysing the economic and environmental effects of each bucket truck. The total fuel consumption over the vehicle's lifetime is estimated based on the cumulative mileage, fuel efficiency

during driving, total engine idling time, and the corresponding fuel consumption rate while idling.

As shown in Table 5, a previous study indicates that a conventional Class 7 diesel vehicle consumes 3.52 gallons of fuel over 26 miles, which corresponds to a fuel efficiency of 7.39 miles per gallon (Kosowski 2020). This value was adopted for both the diesel and diesel E-PTO configurations. During idling, conventional diesel bucket trucks consume fuel at a rate of 1.2 gallons per hour (Edison Electric Institute 2014). In contrast, the diesel E-PTO configuration utilizes electricity instead of diesel fuel during idling periods. As shown in Table 5, the annual mileage of these vehicles is assumed to be 9,100 miles, based on available data (Argonne National Laboratory 2016). Each vehicle is expected to operate 260 days per year over a 12-year service life, with an average idling duration of 4 hours per working day (Edison Electric Institute 2014). The cost of purchasing fuel is another element that changes based on the type of fuel (Ercan and Tatari 2015), because fuel prices are expected to increase for a given bucket truck usage. The lifetime fuel costs for both driving and idling operations of a diesel bucket truck, as well as the driving-related fuel costs of the diesel E-PTO configuration, were calculated using the diesel price projections published through 2040 (U.S. Energy Information Administration 2025). As shown in Table 6, all fuel-related expenditures on both driving and idling modes were allocated under the "petroleum refinery" sector. To account for the upstream environmental impacts of fuel production through the EIO-LCA tool, the previously calculated fuel consumption values were combined with 2022 fuel price data. Indirect environmental impacts were calculated by multiplying the economic impact results with consumption-based accounts per sector coefficients. To calculate direct environmental impact, emission parameters were modified to use only on-site activity emissions (U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy 2025). Emissions often rise in direct proportion to the age of the vehicle (Argonne National Laboratory 2016). Therefore, when estimating the direct environmental impacts over the vehicle's lifetime, the age-related deterioration factors were considered.

Although EVs are frequently advertised as having zero emissions, upstream operations, like those related to the power generation industry, still produce some emissions (Ercan and Tatari 2015). This may be due to the use of more coal in electricity generation. In 2024, global electricity generation totaled 30.85 petawatt-hours, with the largest share coming from coal (34.4%), followed by natural gas (22.1%), hydro (14.4%),

nuclear (8.99%), wind (8.12%), solar (6.92%), and other sources (5.10%) (Wikipedia contributors 2025). But in this study, these values were taken from EIA according to daily data for May (U.S. Energy Information Administration 2025), as seen in the Figure 3. As shown in Table 5, diesel E-PTO bucket trucks consume approximately 2 kWh per hour during idling (Edison Electric Institute 2014), while electric vehicles consume 1.966 kWh per hour while driving (Argonne National Laboratory 2016). Due to the lack of specific data on idling energy consumption for Class 7 electric bucket trucks in the literature, this study adopts the value of 6.36 kWh per hour reported for Class 6–7 electric trucks (Kushwah and Caldeira 2025).

Electric bucket trucks are assumed to produce zero on-site emissions. Therefore, after calculating the economic impacts associated with electricity use both for vehicle driving and idling in the case of the E-PTO configuration, indirect environmental impacts were assessed. These calculations were based on the assumption that the bucket truck operates 260 days per year over a 12-year service life, with an average of 4 hours of idling per working day. Lifetime electricity costs were estimated using the EIA's projected average transportation electricity prices through 2040 (U.S. Energy Information Administration 2025). The resulting values were converted into 2022 euros and proportionally disaggregated into generation (61.6%), distribution (26.3%), and transmission (12.1%) (Figure 4) components, following the breakdown provided by the EIA (U.S. Energy Information Administration 2025). These components were assigned to their respective sectors: 'Transmission of electricity' and 'Distribution and trade of electricity.' The generation share was further distributed according to the U.S. electricity grid mix into six sectors: 'Production of electricity by wind,' 'by solar photovoltaic,' 'by hydro,' 'by nuclear,' 'by coal,' and 'by gas.' Each of these was analysed separately. However, due to the relatively small and fragmented values resulting from this disaggregation, the final environmental impacts were aggregated and reported under a single category labelled as the 'Electricity sector.' For example, one of the entries in Table 6 can be calculated as follows: The lifetime value is assumed to be 12 years, and the annual vehicle mileage is known as 9,100 miles/year. The driving fuel economy for the electric bucket truck is 1,966 kWh/mile from AFLEET. In addition, the average transportation electricity prices for each year until 2040 are also known (U.S. Energy Information Administration 2025). The cost of charging stations was not added to the

study. The same rule was used for diesel trucks, so no extra cost for fuel stations was included either.

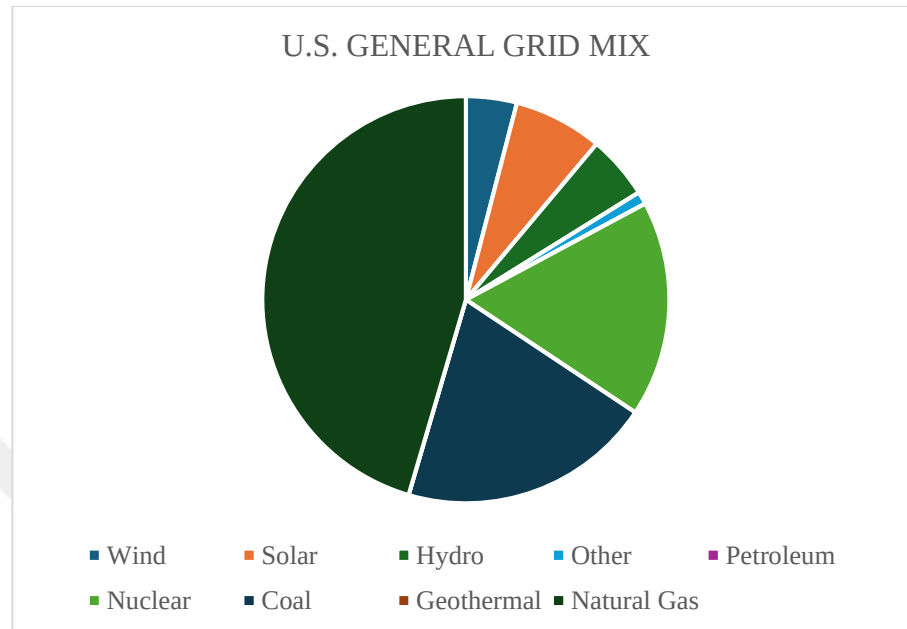


Figure 3. U.S. General grid mixes from a day in May 2025
(Source: U.S. Energy Information Administration 2025)

To calculate the annual electricity cost, first, 9,100 miles is multiplied by 1,966 kWh/mile to find the amount of electricity (kWh) the vehicle consumes annually. This process is done separately for each year of the vehicle's lifetime. The annual costs are then converted to 2025 dollars. However, the EXIOBASE 2022 database used is Pymrio-based and uses euros as its currency. Therefore, the calculated 2025-dollar values are converted to 2022 euros before entering the analysis. The driving fuel economy values are first separated into generation, distribution, and transmission stages like Figure 4. The generation section is then subdivided into subcategories based on energy sources, as

illustrated in Figure 3. Finally, all these disaggregated values are distributed across relevant sectors and included in the analysis via Pymrio.

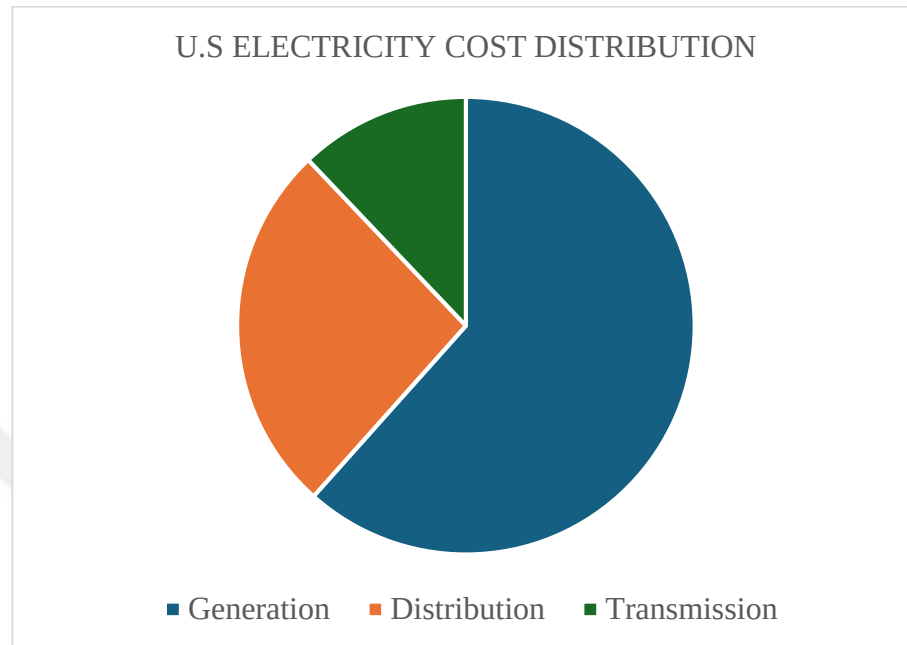


Figure 4. U.S Electricity cost distribution
(Source: U.S. Energy Information Administration 2025)

3.1.3.3. Maintenance and Repair Inputs

As shown in Table 5, the maintenance and repair cost per mile (\$/mile) are provided for all three vehicle types. For the diesel and diesel E-PTO configurations, the cost estimates were originally reported in 2012 for Class 6/7 trucks (Stella, Singh, and Immordino ca. 2012) and have been adjusted to reflect 2025 values using inflation rates. In contrast, the maintenance and repair cost estimate for the electric bucket truck is based on the per-mile value reported in a 2021 study for Class 7/8 trucks (National Renewable Energy Laboratory 2022), adjusted to 2025 U.S. dollars using inflation calculations. As highlighted in (Sen, Ercan, and Tatari 2017), electric vehicles are expected to have significantly lower maintenance costs due to their simpler mechanical design, which involves fewer moving parts and reduced fluid maintenance

requirements. All expenditures related to maintenance and repair were allocated to the sector "Sale, maintenance, and repair of motor vehicles, motor vehicle parts, motorcycles, motorcycle parts and accessories." An important consideration, as noted in (Edison Electric Institute 2014), is that diesel bucket trucks typically require an engine rebuilt after 350,000 miles. Although a bucket truck with an annual mileage of 9,100 miles and a 12-year service life may appear to remain below this threshold, the same study indicates that one hour of idling is equivalent to 33 miles of engine wear for rebuild determination. Given that these trucks idle for approximately four hours per day, the cumulative engine wear results in a rebuild requirement by the eighth year of operation. Therefore, as shown in Table 6, diesel vehicles were assigned a higher input share in this sector. All related cost inputs were converted into 2022 euros, and both the direct economic impacts and indirect environmental effects were calculated accordingly. This approach allows for a more comprehensive understanding of the long-term operational costs and supports a realistic comparison between diesel and electric bucket truck technologies. It is known that the maintenance cost in 2012 was \$0.15/mile (Stella, Singh, and Immordino ca. 2012). This value was adjusted using inflation rates (US Inflation Calculator Staff 2025) to obtain the corresponding 2025 maintenance cost (\$/mile).

In this study, the annual mileage for the bucket truck was assumed to be 9,100 miles. Multiplying this mileage by the 2025 maintenance cost (\$/mile) yielded the annual maintenance cost for 2025. To estimate the lifetime maintenance cost, the 2025 annual maintenance cost was projected forward for each year of the 12-year vehicle lifespan, applying the assumed 2.2% annual inflation rate. This projection provided a comprehensive distribution of maintenance expenses over the vehicle's operational life, reflecting gradual cost escalation due to inflation. These annual values were then expressed in 2025 dollars to maintain consistency in monetary terms. Since the EXIOBASE 2022 database, which is Pymrio-based, operates in euros, the calculated 2025-dollar values were converted into 2022 euros before being incorporated into the analysis to ensure currency and temporal alignment.

Table 5. Vehicle Characteristics and Assumptions
(Source: References Listed Above in the paragraph)

Characteristics	Diesel	Diesel+e-PTO	Electric
Lifetime (year)	12	12	12
Average Annual Mileage	9100	9100	9100
Maintenance/ Repair (2025\$/mi)	0.2215	0.2215	0.1218
Idling Hours (hr/day)	4	4	4
Days of Idling (days/year)	260	260	260
Driving Fuel Economy (mpg or kWh/mi)	7.39	7.39	1.966
Idling Fuel Consumption (gal/hr or kWh/hr)	1.20	2.00	6.36
Battery Capacity(kWh)	-	8.8	259
Battery Replacement (Year)	-	-	8
Engine Replacement (Year)	8	-	-
Battery Cost (2025\$/kWh)	-	-	115
Engine Rebuild Cost (2025\$)	20,685	-	-

Table 6. Inputs for hybrid life-cycle assessment and distribution by sectors
(Source: References Listed Above in the paragraph)

Vehicle Technology	LCA Component	Sector	Cost (2022€)
Diesel-Common	Truck Chassis Manufacturing	Motor vehicles & trailers	€107,307
	Boom Manufacturing	Manufacture of machinery and equipment	€91,410
	Maintenance&Repair	Motor vehicles & parts sales/maintenance/repair	€38,645
Diesel-Driving	Diesel fuel production	Petroleum Refinery	€45,681
Diesel-Idling	Diesel fuel production	Petroleum Refinery	€46,297
Diesel+ePTO- Common	Truck Chassis Manufacturing	Motor vehicles & trailers	€107,307
	Boom Manufacturing	Manufacture of machinery and equipment	€91,410
	Maintenance & Repair	Motor vehicles & parts sales/maintenance/repair	€20,838
	EPTO Manufacturing	Electric machinery & apparatus	€83,830
Diesel+ePTO-Driving	Diesel fuel production	Petroleum Refinery	€45,681
Diesel+ePTO-Idling	Electricity generation	U.S Grid Mix	€2,797
Electric-Common	Truck Chassis Manufacturing	Motor vehicles & trailers	€113,728

(cont. on the next page)

Table 6 (cont.).

Electric-Common	Boom Manufacturing	Manufacture of machinery and equipment	€91,410
	Maintenance&Repair	Motor vehicles & parts sales/maintenance/repair	€11,457
	Battery Manf., Battery Repacement, EPTO Manf.	Electric machinery & apparatus	€165,390
Electric-Driving	Electricity generation	U.S Grid Mix	€25,340
Electric-Idling	Electricity generation	U.S Grid Mix	€9,354

3.2. Monte Carlo and Sensitivity Analysis

Bucket trucks are used in many types of operations such as maintenance of power lines, outdoor electrical installations, cutting tree branches, repairing light poles, and even in construction-related activities. Because these vehicles have many different use cases, the daily mileage and idling time can change a lot from one day to another or from one region to another. When idling hours increase, fuel or electricity consumption also changes. Likewise, when a truck drives in a city area or at a work zone, the driving electricity use for electric trucks and the diesel consumption for conventional ones vary because of different driving speeds and loads. These differences make it hard to fix one single value for the inputs and increase the uncertainty in the analysis. Because these trucks work in many different jobs and places, it is not realistic to use one fixed number for how far they drive or how long they idle. Even among similar fleets, trucks in urban zones often spend more time idling, while rural fleets drive longer distances. This variation increases the uncertainty level of the analysis.

The literature review highlights that Monte Carlo analysis is needed in LCA studies since several inputs, including fuel consumption, energy use, emission factors, grid mix, and battery life, can change rather than remain fixed. Literature or field data often provide different ranges for these parameters. For example, Şen et al. (2019) defined a $\pm 10\%$ variation for parameters such as annual mileage, vehicle lifetime, battery capacity, and fuel economy for diesel and battery-electric heavy-duty trucks (HDT) and

performed a Monte Carlo analysis. For bucket trucks, however, there is no LCA study in the literature that deals with alternative fuel types. Since there are many different duty cycles and operation areas, it is not realistic to fix a single value for driving distance or idling time. Even among similar fleets, trucks in urban zones often spend more time idling, while rural fleets drive longer distances. This variation increases the uncertainty level of the analysis. Because of these uncertainties, Monte Carlo simulation helps represent how real-world operation may differ from the fixed values used in models. It gives a statistical view of how sensitive the results are to different conditions, instead of relying on one static scenario. This improves the credibility and transparency of the study. In addition to operational variation, sectoral data in databases like EXIOBASE or AFLEET are often limited or aggregated. They cannot fully capture the detailed behavior of specialized vehicles like bucket trucks. As a result, assumptions have to be made for several parameters, which makes uncertainty analysis even more important. In this study, the variables considered were annual truck mileage, daily idling hours, and driving fuel economy. For diesel and diesel E-PTO, the driving fuel economy was taken as 7.39 mpg. According to Geotab (2025), the average fuel economy for Class 7 and Class 8 trucks is in the range of 4.51–6.47 mpg, with a mean of 5.49 mpg. The value used in this study (7.39 mpg) is about 1.34 times higher than the mean, which results in an upper bound of 9.29 mpg. Therefore, the driving fuel economy was evaluated in the range of 5.49–9.29 mpg. For the electric bucket truck, the driving fuel economy was taken as 1.966 kWh/mile. Gao, Lin, and Franzese (2017) reported an energy consumption value of 1.89 kWh/mile for Class 7 BEV delivery trucks. The value used here is 1.04 times higher than the literature value. Based on this ratio, the range for electric bucket trucks was defined as 1.89–2.042 kWh/mile. Another uncertain parameter was annual truck mileage. The study used the AFLEET value of 9100 miles. According to the Transportation Electrification report (Edison Electric Institute 2014), the annual mileage of Class 7 bucket trucks varies between 6000 and 12000 miles. This range was therefore used in the Monte Carlo analysis. The last variable was daily idling hours. The study assumed 4 hours per day. According to Gao, Lin, and Franzese (2017), bucket trucks travel about 28.5 miles daily with an average of 3.2 operating hours per day. The value used here is about 1.25 times higher. By applying the same factor to the upper bound, the daily idling hours range was defined as 3.2–4.8 hours. With these ranges, Monte Carlo analysis was carried out with 10,000 iterations, using normally distributed values around the mean. The results

are discussed in detail in the Results and Discussion section. The purpose of the sensitivity analysis was to check whether the ranking of the top 10 sectors would change when the lowest and highest values from the Monte Carlo simulations were used in a new analysis. However, because the pymrio system works in a linear way, all sectors showed lower economic impacts when the lowest values were used and higher economic impacts when the highest values were used. Still, the ranking of the top 10 sectors did not change. If such a change had occurred, the sensitivity analysis would have carried more meaning.



CHAPTER 4

RESULT AND DISCUSSION

4.1. Lifetime Direct Economic Impacts

It can be seen that in Figure 5, the comparison of lifetime direct costs shows clear differences among the three vehicle types. Each bar in the figure presents the distribution of cost items, such as the chassis, boom, ePTO device, second battery, maintenance and repair, fuel or electricity for both driving and idling, as well as the engine rebuild or battery replacement. The error bars reflect the variation obtained from the Monte Carlo analysis, providing insight into the uncertainty range associated with each cost component. Overall, this comparison highlights how electrified configurations can significantly alter the cost structure and long-term economic performance of utility vehicles.

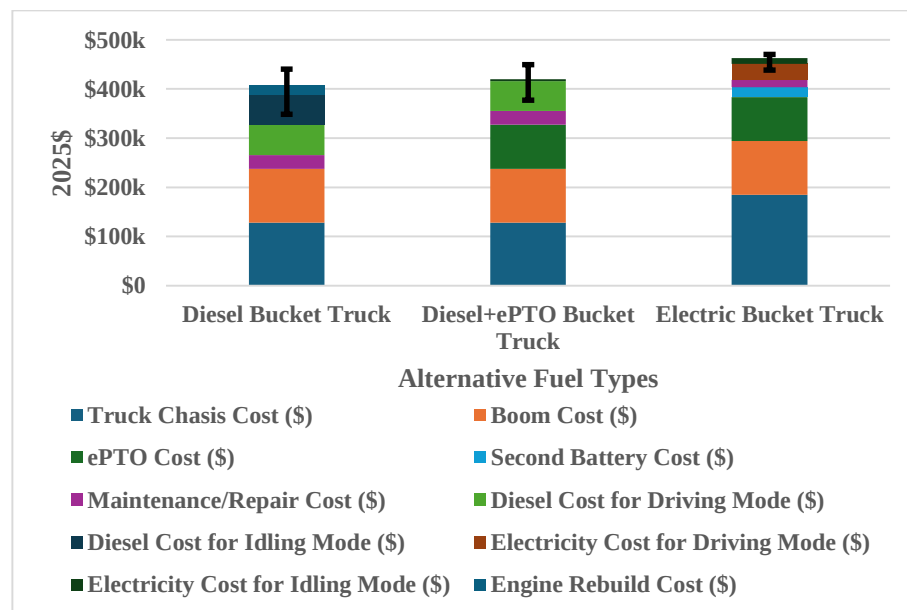


Figure 5. Lifetime Direct Impacts

For the diesel truck, the main cost drivers are the initial chassis and boom investment. Over time, maintenance and repair expenses grow steadily and add a significant burden. Idling is another critical factor. Since these vehicles often remain at job sites with the engine running to supply hydraulic power, fuel consumption during idling becomes a large additional expense. On top of this, the engine rebuild required around the eighth year further increases lifetime costs. The range shown by the error bars is mainly shaped by the uncertainty related to this rebuild.

In the diesel+ePTO case, there is an extra investment because of the ePTO device and the supporting battery. This increases the upfront cost, but it reduces the use of diesel fuel during idling. The equipment can be powered electrically, which cuts idling fuel costs sharply. Electricity costs go up, but they are still smaller than the fuel savings. In total, the costs remain close to those of the conventional diesel option. In some conditions, they can even be lower. However, the additional components bring more variability, and this explains why the error bars are wider compared with the electric option.

The electric truck shows the highest lifetime cost among the three configurations. The purchase price is higher because of the electric chassis and large battery pack, and a second battery replacement is needed during the operation period. Even so, the savings from lower maintenance needs and the absence of an engine rebuild balance part of these expenses. The narrower error bars indicate that lifetime costs of the electric option are more stable, with less influence from external price fluctuations.

When the three types are compared, the electric truck shows the highest lifetime cost, mostly due to its high chassis price, big battery, and the electricity needed for both driving and idling. The diesel+ePTO truck achieves a balanced position by reducing fuel use during idling, though the extra ePTO investment limits the savings. The diesel truck remains the least expensive overall but has higher fuel costs and maintenance needs. This outcome shows that electrification is still costly at present, while the ePTO system serves as a practical step between traditional diesel and full electric solutions.

In summary, each configuration presents a distinct trade-off between upfront investment and long-term operating expenses. Future reductions in battery and component costs, together with improvements in charging infrastructure, could further enhance the economic viability of electric and hybridized utility vehicles.

4.2. Indirect Economic Impacts

In this study, the EXIOBASE database was used with data representing the United States, which includes 163 economic sectors. While analysing the indirect economic impacts, it was not possible to display all 163 sectors in the same figure, because showing that many sectors at once would make the graphs too complicated and hard to read. Therefore, instead of presenting every sector, we focused on the ten sectors most affected by the expenditure in each scenario. These top ten sectors represent those that receive the largest portion of the indirect economic impact from the main spending sector.

However, it is important to note that this visual simplification does not imply that the remaining sectors are unaffected. Any expenditure in one sector of the economy influences all 163 sectors through inter-industry linkages defined by the Leontief input–output structure. To examine whether this simplification could significantly alter the overall outcome, an additional analysis was conducted in which the total indirect economic impact calculated using all 163 sectors was compared to the total obtained when only the ten most affected sectors were considered. The results showed that the difference between the two calculations was relatively small: the total indirect economic impact of all 163 sectors was approximately 10 %–15 % higher than that of the top-ten-sector representation.

Given this small difference, the simplification was accepted as reasonable, and the deviation was considered negligible. In other words, while the full economic model acknowledges that spending in one sector propagates throughout the entire economy, representing only the ten most responsive sectors allows the results to be illustrated clearly without materially changing the total impact. This approach provides both analytical transparency and visual clarity while maintaining consistency with the hybrid LCA–EIO framework adopted in this study.

4.2.1. Diesel Bucket Truck

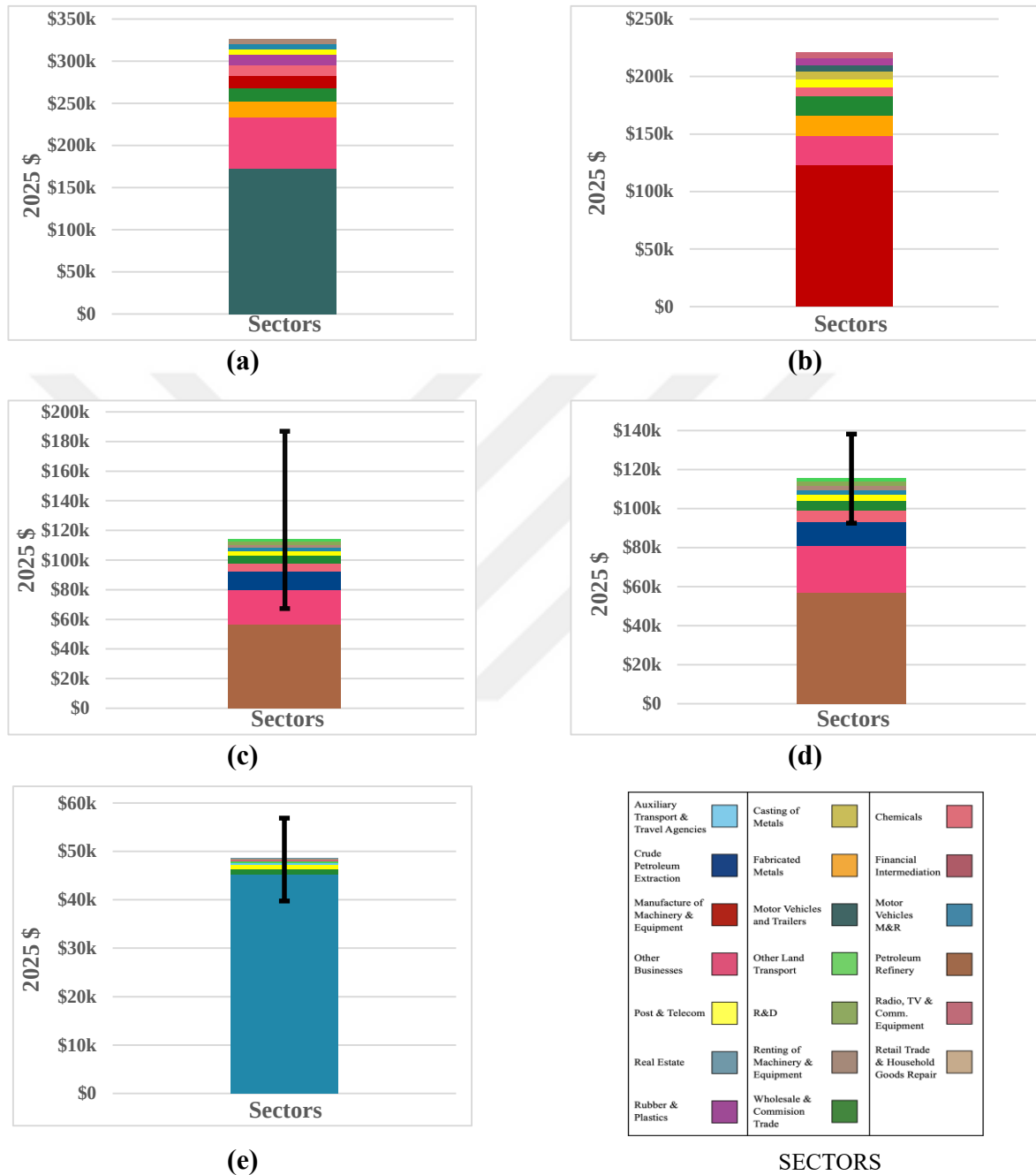


Figure 6. Indirect Economic Impacts on Other Sectors by: (a) Motor vehicles & trailers, (b) Manufacture of machinery & equipment, (c) Petroleum Refinery (driving), (d) Petroleum Refinery (Idling), (e) Motor vehicles M&R

The analysis of the diesel truck shows that the economic effects are not limited to the costs that the owner pays directly. When the supply chains of production, operation, and maintenance are considered, diesel trucks create wide indirect impacts in many industries. The impacts are large, cover different sectors, and are mainly shaped by the high fuel use of these vehicles.

In Figure 6a, the motor vehicle and trailer manufacturing sector has the largest share of indirect impacts. The value is more than 300,000 USD, showing how strong this link is. The total amount is more than 300,000 USD, showing how strong this connection is. The effect is not limited to the factories that build trucks but extends to many other areas that support the automotive industry. This impact is not limited to the factories that build trucks. It also reaches equipment rental companies, wholesale trade, vehicle and parts sales, repair and maintenance services, postal services, and telecom. In practice, when a diesel truck is produced, it creates extra demand for many other industries that support the automotive sector. This shows that the vehicle supply chain is wide and linked with many parts of the economy, not just the assembly plants. It spreads into equipment rental companies, vehicle dealerships, wholesale and trade services, repair shops, postal and communication services, and many others. The result makes it clear that each truck placed on the road activates a network of industries. In other words, the production and sale of a diesel truck bring extra demand not only to the automotive firms but also to many connected services that would not exist without vehicle operations. Figure 6b illustrates that the machinery and equipment sector is another major contributor, adding about 220,000 USD to the total. The breakdown shows that this category is tied to wholesale trade, rubber and plastics, and metal processing. It also links back to vehicle sales and repair. The presence of such diverse connections means that diesel trucks cannot operate without drawing on a very wide industrial base. Every machine, component, and tool used in the operation of these trucks requires materials and labor from different industries, and these requirements create measurable economic outcomes. The sector does not act in isolation but interacts with a chain of suppliers that benefit whenever diesel trucks are produced and used.

The petroleum refinery sector is perhaps the most critical driver of indirect effects according to Figure 6c. Diesel trucks consume fuel while driving and also during long periods of idling at work sites. Because of this, refining activities become a central node in the economic structure. The results indicate that driving-related fuel use alone is

responsible for more than 100,000 USD in indirect activity. These impacts also reach crude oil production, the chemical industry, freight transport, and business services. The error bars are wide, showing that changes in fuel price or refinery activity can affect the results strongly. Idling is also important. Figure 6d shows that when trucks idle for many hours, the extra indirect cost is about 115,000 USD. Fuel use in driving and in idling is the main reason for the indirect costs of diesel trucks. As indicated in Figure 6e, the vehicle sales, maintenance, and repair sector have a smaller total, about 50,000 USD, but it is still important. When a diesel truck goes for service, the money spent does not stay only in the workshop. The payments continue to other areas. Rent goes to landlords of the repair shops, banks handle transactions, and insurance companies are involved in covering some costs. Shops that sell spare parts and materials also take a share. Even a small job, like changing one part, creates a line of payments that touches many actors. In this way, normal maintenance connects the truck to a wide set of industries and brings income to people and companies outside the repair shop.

When all sectors are considered together, diesel trucks create large and different kinds of indirect impacts. The biggest values come from vehicle manufacturing, machinery production, petroleum refining, and maintenance. Other sectors like chemicals, trade, real estate, finance, and transport also benefit from diesel truck use. The size and variety of these impacts illustrate how deeply diesel technology is tied into the wider economy, not only through direct costs but also through extended chains of suppliers and services.

This connection is important for the future. If fleets reduce their reliance on diesel, the impact will not stop with truck owners. The industries that supply diesel-related products and services will also feel the change. Petroleum refining, maintenance, and parts supply will be the first areas to lose demand. Other sectors like chemicals, trade, and finance can also feel the change, but some may adapt by turning to new technologies. Moving away from diesel brings both challenges and opportunities. Some companies will lose business, while others will gain new roles in electric vehicles or other systems. For policy makers and industry managers, this is important because it shows that the shift in transport is not only about fuel or purchase costs, but also about wider economic changes. It is a wider economic change that needs careful planning to reduce risks and to use new opportunities.

4.2.2. Diesel E-PTO Bucket Truck

The analysis of the diesel+ePTO truck shows that the economic effects are again not limited to the direct costs of buying and using the vehicle. When the supply chains of production, operation, and maintenance are considered, the addition of an electric Power Take-Off (ePTO) unit changes some of the flows but still creates wide indirect impacts in many industries. The results look much like the diesel case. There are strong impacts in the automotive sector, in machinery, and in fuel-related areas. At the same time, new effects appear in electric machinery and in industries that support electrical systems.

Figure 7a shows that the motor vehicle and trailer sector has the largest indirect impact, over 300,000 USD. This means that building and selling heavy trucks is the main source of indirect activity. The impact is not limited to the factories that assemble trucks. It spreads outward to equipment rental companies, wholesale trade, vehicle dealerships, repair shops, postal services, and telecom. In practice, every diesel+ePTO truck placed on the road activates a long list of suppliers and service providers. This chain demonstrates how closely the vehicle industry is tied to other sectors, making the truck production process a central node of the economy.

According to Figure 7b, the machinery and equipment manufacturing sector also shows a very strong contribution, close to 220,000 USD. This category is linked to wholesale trade, rubber and plastics, and fabricated metals. It also connects back to the vehicle repair and sales chain. The ePTO technology creates more demand in this sector because extra equipment and parts are needed. This shows that diesel+ePTO trucks rely on a wider industrial base than normal diesel trucks. Every tool, device, and electrical unit used in these vehicles must be produced, moved, and serviced, and this creates clear economic flows across many industries.

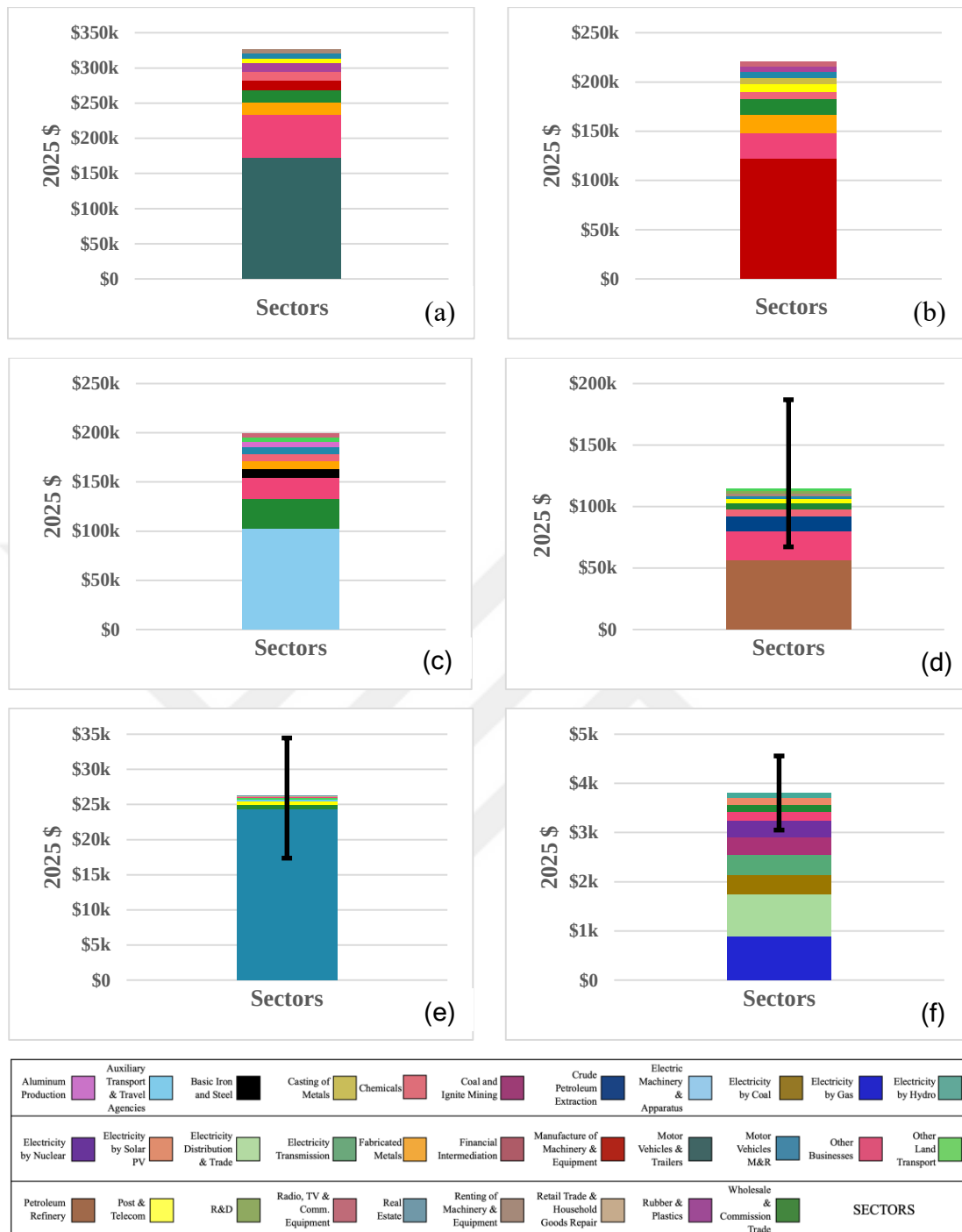


Figure 7. Indirect Economic Impacts on Other Sectors by: (a) Motor vehicles & trailers, (b) Manufacture of machinery equipment, (c) Electric machinery & apparatus, (d) Petroleum Refinery, (e) Motor vehicles M&R, (f) Electric (idling)

Figure 7c shows an important new part in the ePTO case, which is the role of electric machinery and apparatus. This sector adds about 200,000 USD in indirect

impacts. It is linked to aluminium production, iron and steel, metal products, and chemicals. Batteries and electrical devices need input from these heavy industries, and this means that using electric functions brings new demand in another part of the economy. The supply chain is not limited to the machinery itself. It also includes mining, metal work, and component production, all of which gain activity from the use of ePTO. These results underline that electrification does not remove indirect effects but instead shifts them toward new industries, especially those related to advanced materials and electric devices.

The petroleum refinery sector remains an important contributor, though the ePTO reduces its share compared to the pure diesel case according to Figure 7d. Trucks with ePTO consume less fuel when idling, since work equipment can be powered electrically rather than by burning diesel. Still, refineries create more than 100,000 USD in indirect impacts from fuel used while driving. The effects spread to crude oil extraction, chemicals, freight transport, and business services. The error bars for this sector remain wide, showing that changes in fuel price or refining output can strongly affect the results. Although idling-related demand is lower, fuel remains the single biggest factor shaping indirect costs, confirming that energy use is central to the diesel+ePTO scenario as well.

In Figures 7e-7f, the motor vehicle sales, maintenance, and repair sector adds a smaller total, about 25,000 USD, but its effects spread to many areas. When trucks are serviced, the impact is not limited to the repair shop. Money goes to landlords for rent, to banks for services, to insurers for risks, and to shops for parts and materials. Even a small repair task creates transactions that touch different economic factors. In this way, routine servicing of diesel+ePTO trucks still generates income in many connected areas, though the overall value is slightly lower than in the diesel case.

Finally, the electricity sector enters the picture as a separate area of impact. The ePTO system takes electricity from the grid, and this links it to power generation and distribution sectors. The total indirect effect of this sector is smaller, around 4,000–5,000 USD, but it is spread across many different sources such as hydro, solar, nuclear, coal, gas, and distribution systems. This shows that even a small use of electricity creates new links to the larger energy system. As fleets move to more electrification, these effects will grow and become more important.

When all sectors are combined, the diesel+ePTO truck still has large indirect impacts in many areas. The strongest values remain in motor vehicle manufacturing,

machinery production, and petroleum refining, but new contributions from electric machinery and electricity supply make the structure more complex. Other industries such as chemicals, trade, finance, and transport also continue to benefit. The scale and diversity of these results show that adding ePTO technology changes the balance of indirect impacts but does not reduce their importance.

In the future, ePTO works like a bridge. It lowers fuel use by reducing idling, but it makes stronger links with electric machinery and energy. Oil-related firms may lose some market, while electric and material sectors may gain. For policy makers and fleet managers, the point is that trucks affect many parts of the economy. Even small changes in technology can move impacts from one sector to another. This shift needs good planning to reduce risks and to use new opportunities.

4.2.3. Electric Bucket Truck

Figure 8a shows that electric trucks also make big effects on the economy. The picture is close to diesel and ePTO, but some parts are different. The motor vehicle and trailer manufacturing sector is still the largest. The value is more than 300,000 USD. This means that making and selling heavy trucks is still the main source of indirect activity. When one truck is built, it gives work not only to the factory but also to many other sectors. Vehicle dealers, spare part sellers, repair shops, post and telecom, machine renting, and many others get income. Every new truck on the road starts a chain of payments that supports many actors in the economy.

Figure 8b displays that the manufacture of machinery and equipment is also very important. This sector adds about 200,000 USD. It connects with rubber, plastics, metals, wholesale trade, and vehicle services. Electric trucks cannot work without this large base of industries. Every tool, machine, and material used in these trucks comes from other sectors. This creates real economic flows that spread far.

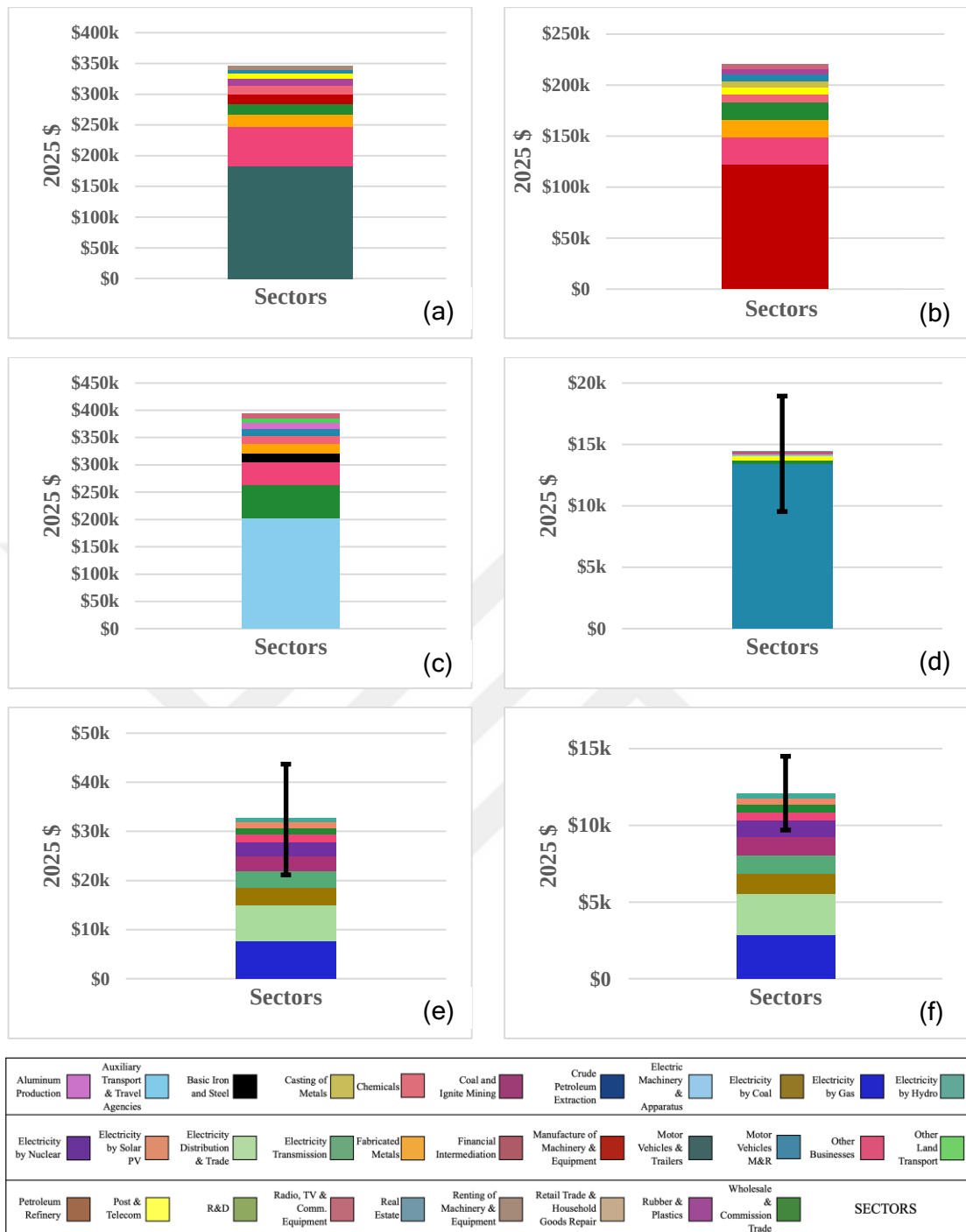


Figure 8. Indirect Economic Impacts on Other Sectors by: (a) Motor vehicles & trailers, (b) Manufacture of machinery & equipment, (c) Electric machinery & apparatus, (d) Motor vehicles M&R, (e) Electric (driving), (f) Electric (idling)

A new and strong part of the electric truck case is the electric machinery and apparatus sector as Figure 8c shows. This sector adds around 400,000 USD in impacts. It

links with aluminium, iron and steel, fabricated metals, and chemicals. Batteries and electric devices need many materials from heavy industry. This means mining, metal works, and chemical plants all play a role. So, the shift to electric trucks moves demand to another side of the economy.

In Figures 8d-8e, petroleum refining is much smaller now, but it does not disappear. Some fuel is still used. At the same time, the electricity sector becomes more important. Power from the grid connects electric trucks to energy industries. Hydro, solar, coal, gas, and nuclear plants all become part of the supply chain. The total value here is smaller (10,000–30,000 USD), but it will grow as more fleets use electric power.

As depicted in Figure 8f, maintenance and repair show smaller totals, about 15,000–20,000 USD. But the influence spreads to many other places. Rent is paid to shop owners, banks provide finance, insurers cover risks, and sellers provide spare parts. Even one small service job touches many people and companies.

When all sectors are put together, the electric truck also creates large and wide effects. Vehicle building, machinery, electric apparatus, and energy supply stand out most. Chemicals, trade, finance, transport, and real estate also gain.

Looking to the future, electric trucks change the shape of the economy. Oil refineries and fuel sectors lose importance. At the same time, electricity, batteries, and heavy materials get more demand. For some companies this is a loss, for others it is a chance. For policy makers and managers, the message is clear: trucks have a very wide footprint. Even a small technology change can move economic effects from one sector to another. This big change needs good planning. Risks must be reduced in losing sectors, and new chances must be used in growing ones.

4.2.3. Total Indirect Economic Impacts

The chart in Figure 9 shows the full picture of indirect economic impacts when all sectors and Monte Carlo results are put together for the three truck types: diesel, diesel with ePTO, and electric.

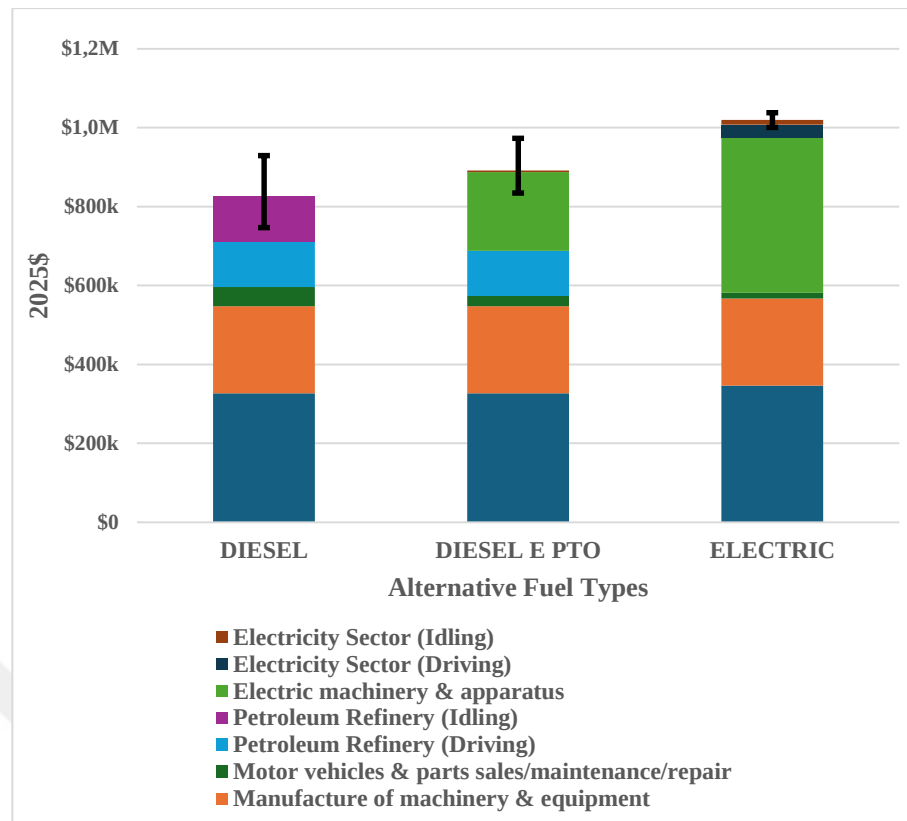


Figure 9. Indirect Economic Impacts

For diesel trucks, the total impact is slightly below 900,000 USD. Most of this comes from the motor vehicle and machinery sectors, while a very large share also comes from fuel use and petroleum refining. Diesel trucks depend heavily on oil, so refineries, crude oil extraction, chemicals, and freight transport all get pulled into the chain. The wide error bar shows that the results can change a lot when fuel prices rise or fall, or when refinery work shifts. This means that the economy around diesel trucks is not only big, but also unstable because it depends on oil markets.

For diesel trucks with ePTO, the total is close to 900,000 USD as well, but the shape of the impact's changes. Fuel costs from idling are lower, because the ePTO system replaces engine idling with electric power. This cuts one of the biggest weaknesses of diesel trucks. At the same time, the new technology creates demand for electric machinery, equipment, and supporting parts. That means money flows not only to traditional sectors like vehicle manufacturing and refineries but also to companies making electrical units, batteries, and other devices. The result shows that even a small change in technology can move the indirect impacts from one set of industries to another.

Diesel+ePTO trucks still connect to oil, but they also create new links with the electrical and machinery industries.

For electric trucks, the picture is different again. The total impact rises above 1 million USD, which is the highest among all three cases. The largest share comes from vehicle manufacturing and electric machinery, but the key change is the very strong role of the electricity sector. Instead of fuel refineries, the grid now becomes the centre of the chain. Driving and idling link back to electricity generation, transmission, and distribution. This includes hydro, solar, coal, gas, and nuclear power, as well as the networks that carry electricity. The error bar is smaller, which means the results are more stable. Electricity prices can change, but not as fast as oil. So, the impacts of electric trucks are easier to guess.

When all three cases are compared, one thing is clear: the total indirect impacts remain large in every case, but the sectors that carry the weight are different. Diesel trucks pull the economy toward oil and refineries. Diesel+ePTO cuts fuel waste and shifts part of the flow toward electric machinery. Fully electric trucks push even harder in that direction, making the electricity system the main source of indirect impacts.

In short, every truck placed on the road activates a wide set of industries, but the type of engine and fuel decides which industries gain and which ones lose. This means that the shift from diesel to electric is not only a question of fuel savings, but also a wider change in how money flows across the economy.

4.3. Total Environmental Impacts

In this study, the GHG emissions were divided into two groups: direct and indirect. Direct emissions come from the truck itself. When the vehicle is moving, the engine burns fuel and produces CO₂ and other gases. This is called the driving mode. When the truck is not moving but the engine keeps running, fuel is still burned, and gases are still released. This is called idling mode. These two parts together create a direct impact, because the emissions happen at the vehicle during operation. Indirect emissions are different. They come from the background industries that support the vehicle. For diesel trucks, this includes the petroleum refinery, because the fuel must be produced

before it can be used. For electric trucks, indirect emissions come from electricity generation, since the power in the grid is not fully clean and part of it comes from fossil fuels. The results show that the size of both direct and indirect emissions depends on technology. Diesel trucks have high direct emissions from driving and idling, and indirect emissions from refining. Diesel+ePTO trucks lower the direct idling impact because the engine does not need to run at the work site, but they still keep high driving emissions. Electric trucks have almost no direct emissions, but their indirect impact depends on how electricity is produced. If the grid uses coal or gas, the emissions are higher. If the grid is clean, the emissions are much lower. This shows that both direct and indirect effects are shaped not only by the vehicle itself, but also by the energy systems that support it.

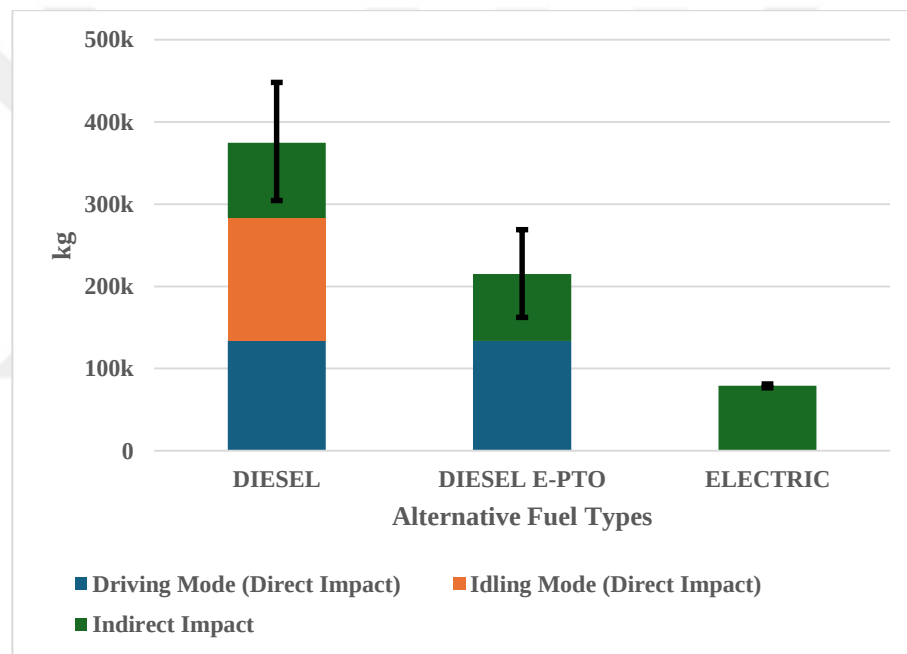


Figure 10. Total GHG Emissions

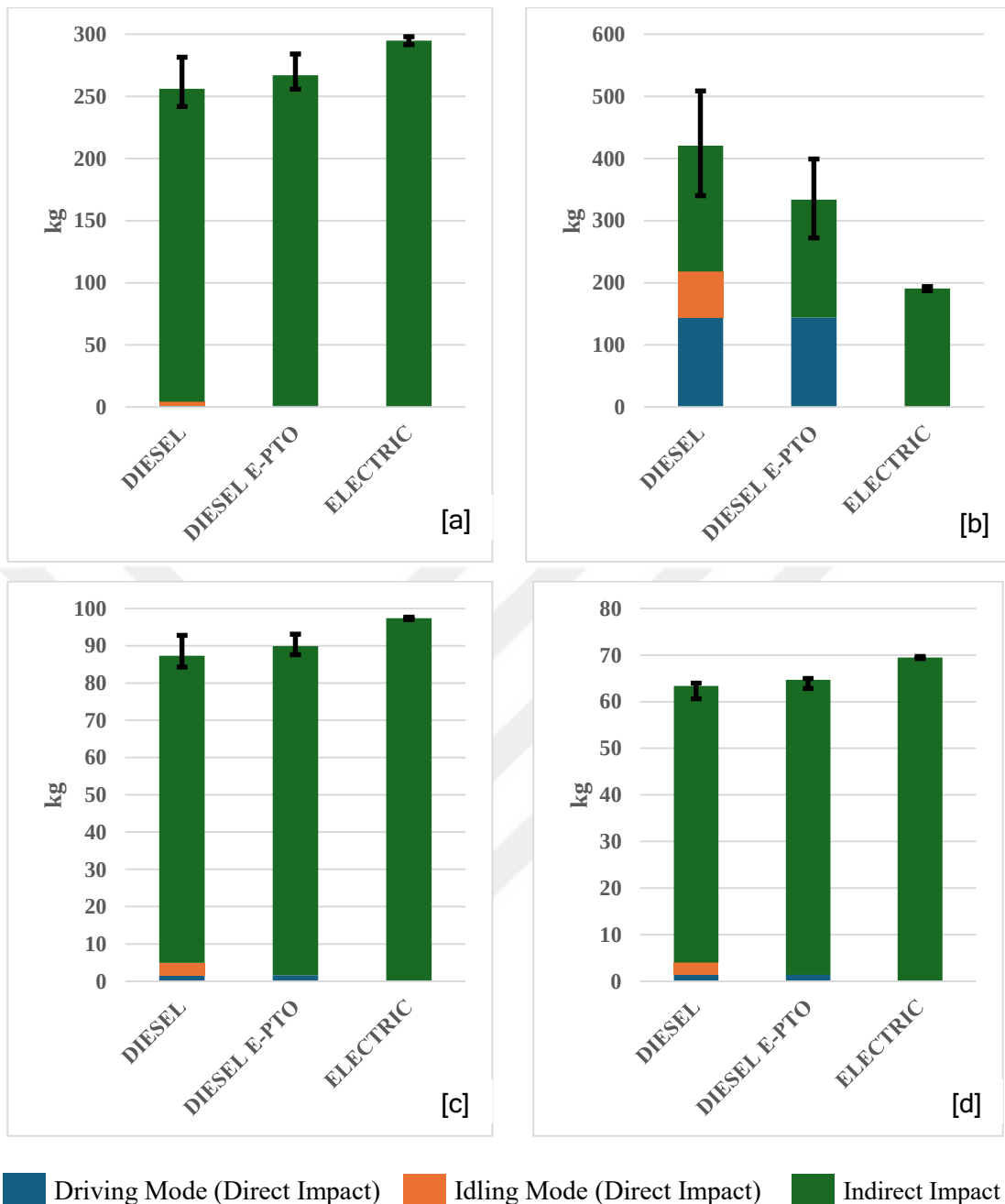


Figure 11. Total environmental impacts other than GHG: [a] Total SOx emissions [b] Total NOx emissions [c] Total PM10 emissions [d] Total PM 2.5 emissions (Where x-axis is the alternative Fuel types and y-axis is the mass of emissions in kilograms)

The results show a very big difference between the three truck types. Diesel trucks release the highest amount of GHG. Both driving and idling add a lot, and the total goes above 350,000 kg. This is because the engine burns fuel all the time, even when the truck

is not moving. Diesel+ePTO trucks reduce this problem. Since idling is replaced by electric power, the total emissions fall to around 200,000 kg. This shows that one small change in technology can make a clear difference. Electric trucks are very different from both diesel options. They do not release direct GHG while driving or idling. The only emissions come from electricity production. These indirect emissions are about 80,000 kg, which is far below the diesel cases. The results make it clear that electric trucks are the best option if the goal is to reduce GHG.

As seen in Figure 11a, for sulphur oxides, the situation changes. Diesel trucks and diesel+ePTO trucks have values around 250 to 270 kg. These emissions come mostly from the burning of diesel fuel. Electric trucks, however, show the highest number, close to 300 kg. The reason is that electricity is not fully clean. A part of the electricity still comes from coal or other fuels that release sulfur oxides. So, while electric trucks are much better for GHG, they can make sulfur emissions worse if the grid depends on fossil fuels. This result highlights the importance of cleaning up the electricity mix, not just changing vehicle technology.

Figure 11b shows that nitrogen oxides are another important pollutant. Diesel trucks produce more than 400 kg, and idling makes this problem even bigger. Diesel+ePTO trucks reduce the total to around 330–350 kg, because they use less fuel during idling. Electric trucks again look much better. They only have about 180–200 kg of emissions, all of which come from electricity production. This is less than half of the diesel level. So, for NO_x, electric trucks show a very strong benefit compared to diesel.

However, as displayed in Figure 11c, particulate matter (PM₁₀) has a different pattern. Most of the emissions are indirect. Diesel trucks release about 90 kg, diesel+ePTO trucks have about the same, and electric trucks are slightly higher at around 98 kg. The higher number of electric trucks happens because part of the electricity still comes from coal and other fuels that make particles in the air. For PM₁₀, electric trucks are not better than diesel, but the gap between them is small.

In Figure 11d, it is seen that for PM_{2.5}, the pattern is the same. Diesel trucks show around 63–64 kg, diesel+ePTO trucks are close to 65 kg, and electric trucks are a little higher at about 70 kg. Again, this is because of the electricity generation process. These particles are more dangerous for human health since they are very small and can enter the lungs. The results show that electric trucks lower gases like CO₂ and NO_x, but particle pollution can rise if the energy system is not clean.

When the results are compared, positive and negative outcomes are observed for each truck type. The highest GHG and NO_x emissions are produced by diesel trucks, making them the most harmful for the environment and health. A reduction in idling emissions is achieved by diesel+ePTO trucks because the engine is not running all the time. Total emissions are still high, and this option is less clean than electric trucks. A big drop in GHG and NO_x is seen for electric trucks, giving clear benefits for air quality and climate.

At the same time, higher SO_x, PM₁₀, and PM_{2.5} emissions are linked with electric trucks. These are mainly caused by electricity generation, as coal, gas, and oil are still used in many power plants. As a result, electric trucks cannot be considered fully green unless the electricity grid becomes cleaner. If more power comes from wind, solar, and hydro, electric trucks will have more benefits. In short, diesel is the most polluting, diesel+ePTO is a small improvement, and electric gives the biggest drop in harmful gases, but it needs cleaner electricity for full benefit.

Although the results of the environmental assessment show that the electric bucket truck performs best in terms of reducing greenhouse gases and nitrogen oxides, this option should not be evaluated only from an environmental perspective. It is also necessary to look at the situation from a broader and more realistic angle. In practical field operations, bucket trucks are not used by individual drivers but by fleet operators, most of which belong to electricity distribution and transmission companies. These vehicles have a critical role, especially during emergency and disaster response operations, where they are among the first to intervene in restoring power lines and repairing damaged infrastructure.

In such emergency conditions, the resilience of the fleet becomes a vital concern. Diesel-powered vehicles can continue to operate if fuel can be transported and stored, since diesel distribution networks are well established even in post-disaster conditions. Fuel can be delivered to the affected region with relative ease, and vehicles can be refueled on-site. However, electric bucket trucks do not have the same level of flexibility. When power lines are damaged and electricity cannot reach the area, it becomes hard to see how these vehicles could be recharged. If there is no stable power supply, electric fleets may face serious problems in operation at the very moment when they are needed the most.

This issue shows an important problem with the strength and reliability of fleets that are fully electric. Electric vehicles are useful for the future because they reduce emissions and make the environment cleaner over time. But they can also bring problems in short emergency or recovery periods. Because of this, the change toward electric fleets in maintenance and utility work should be done carefully. Using only one type of fuel does not work well in practice. It is better to have a mixed fleet that includes diesel, hybrid, and electric bucket trucks together. Such a mix can lower emissions during normal operations while keeping the fleet active and reliable in emergency situations

Future studies should also explore how to keep a fair balance between environmental benefits and reliable performance during difficult times. A fully electric fleet may seem ideal in theory, but in real situations, the ability to respond quickly during disasters and power outages is equally important. The aim should not be to eliminate diesel or hybrid vehicles entirely, but to build a system that can operate under all conditions while remaining both sustainable and reliable.

CHAPTER 5

CONCLUSION

In this thesis, the lifetime economic and environmental impacts of three types of bucket trucks – diesel, diesel + ePTO, and fully electric – were examined using a Hybrid LCA. The method included both process-based data and input–output modelling, allowing for the capture of both direct and indirect impacts. The analysis covered vehicle purchase, operation, fuel and electricity supply, maintenance, and replacement of major components. Monte Carlo simulation and sensitivity analysis were also employed to demonstrate the role of uncertainty and enhance the reliability of the results.

The results of the direct economic impacts showed that electric trucks had the highest lifetime costs. This outcome was mainly caused by the expensive chassis, the large battery pack, and electricity use for both driving and idling. Diesel+ePTO trucks followed, with added costs from the ePTO unit and the supporting battery. Diesel trucks had the lowest total, but fuel consumption during idling and the need for engine rebuilds kept their long-term costs significant.

The study showed that all three truck types had a significant impact on many industries. Diesel trucks were strongly linked to petroleum refining, crude oil extraction, and chemicals. Diesel+ePTO trucks added these same links but also created new demand in electric machinery and energy supply, because the equipment required grid electricity and additional components. Electric trucks shifted the focus even more, reducing oil-related activity and increasing the role of battery production, electricity generation, and heavy industries such as metals. The results showed that trucks are not only vehicles but also part of many industries.

The most significant differences were observed in environmental impacts. Diesel trucks produced the highest GHG and NO_x emissions, making them the most harmful option for both the climate and health. Emissions from idling were lowered by diesel+ePTO, but it was still a polluting option. For electric trucks, direct emissions were almost eliminated, with only indirect emissions remaining from electricity production.

Significant drops in CO₂ and NO_x were seen, but SO_x and particles (PM₁₀, PM_{2.5}) were higher than those from diesel because some electricity came from coal. This means the full benefit of electric trucks depends on cleaner electricity. By using Hybrid LCA with uncertainty analysis, it was demonstrated that results can vary depending on fuel prices, energy sources, and usage patterns. This method enabled the study of both direct and indirect effects simultaneously and the inclusion of local energy systems.

In conclusion, diesel trucks were identified as the most polluting and among the costliest options when the whole lifetime was considered. Their high fuel consumption, especially during long hours of idling at worksites, and the need for major engine rebuilds were shown to create a heavy burden. This situation made diesel trucks not only expensive to operate for their owners but also detrimental to the broader economy and the environment. A strong link with oil refining and fuel supply was also observed, meaning that the continued use of diesel trucks keeps many industries dependent on fossil fuels.

The diesel+ePTO option was shown to create a mixed picture. On the one hand, a reduction in idling fuel use was achieved, as the electric power take-off system allowed worksite equipment to be operated without the diesel engine running continuously. This reduced the environmental burden of idling and showed that improvements are possible when new technologies are added. On the other hand, the installation of the ePTO unit and the supporting battery created new costs that raised the lifetime total above the diesel case. The variability of long-term results was also higher because the durability of the extra components, the price of electricity, and the maintenance of the new system added new uncertainties. For these reasons, diesel+ePTO was recognised as a transitional technology: it is not a complete solution, but it represents an important step away from complete diesel dependence. It reduces the problem of idling, but at the same time, it shifts part of the burden into the electricity system and into industries that produce electric machinery and batteries.

Electric trucks, in contrast, were shown to have the most tremendous potential for long-term improvement. Their initial purchase cost and the cost of battery replacement were very high, but the absence of fuel expenses and the lower need for repairs created a much more stable cost profile over time. From an environmental perspective, direct emissions were almost eliminated, and CO₂ and NO_x levels were significantly lower than those of diesel and diesel + ePTO. The only limitation observed was the dependence on

the electricity mix. Because electricity is still produced partly from coal and other fossil fuels, emissions of particulates and SO_x continue to be visible. This means that the full benefits of electric trucks depend on progress in the energy system. If more renewable energy sources, such as wind, solar, and hydro, are used, the benefits of electric trucks will be greater.

Altogether, the findings indicated that the shift away from diesel trucks should be understood as more than a change in technology at the vehicle level. It should be seen as part of a larger economic and energy transition. The choice of vehicle type affects not only truck owners but also fuel producers, equipment suppliers, energy providers, and numerous other industries linked through supply chains. Careful planning is needed. Sectors that use diesel fuel and those involved in repair may experience a decline in demand. Sectors that manufacture batteries, electric components, and renewable energy may experience increased demand. If this change is managed well, the adverse effects on some industries can be reduced and the benefits in others can be maximised.

The Hybrid LCA with uncertainty analysis revealed that numerous factors influence lifetime costs and emissions. Fuel prices, electricity generation, vehicle design, and usage patterns were all found to influence the results. For this reason, simple comparisons are not enough. A broad and integrated approach is necessary, where economic and environmental effects are evaluated together. By adopting this perspective, more sustainable choices can be supported for both fleets and policymakers, ultimately leading to cleaner and more cost-effective transportation systems in the future.

5.1. Limitations and Future Studies

This research has several points that can be improved in future work. One limitation is that social impacts were not studied. In the next stage, indicators such as worker safety, local job creation, and community effects can be added to give a wider picture of sustainability. Another point is related to price data. In this study, all economic calculations were based on consumer prices. This method shows real market conditions but does not represent producer costs. In the article that will follow this thesis, the same model will be run again using producer prices. When this change is made, the total results

are expected to be smaller in value, because producer prices do not include taxes and retail margins. However, the order of sectors is not expected to change, so the main ranking will stay the same.

The study did not cover what happens at the end of a vehicle's life. Future work can add how trucks and batteries are recycled or disposed of, so the full life cycle can be seen. Only one electricity mix was used in this study. Looking at different regions or years would show how changes in the grid affect the results. The life of batteries and E-PTO units is another part with uncertainty. Collecting more data from real use over time would make the results stronger and more reliable. More field data from real operations can help reduce this uncertainty.

Lastly, this work focused only on bucket trucks. Future studies can apply the same hybrid LCA method to other maintenance vehicles, such as snowplows, street sweepers, or service trucks. These vehicles work in a similar way. They can help compare results for planning fleets and making sustainability choices.

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APPENDIX

Table 7. Sector Names given in the results

Renting of machinery & equipment	Renting of machinery and equipment without operator and of personal and household goods (71)
Motor vehicles M&R	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts and accessories
Post & telecom	Post and telecommunications (64)
Rubber & plastics	Manufacture of rubber and plastic products (25)
Chemicals	Chemicals nec
Manufacture of machinery & equipment	Manufacture of machinery and equipment n.e.c. (29)
Wholesale & commission trade	Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)
Fabricated metals	Manufacture of fabricated metal products, except machinery and equipment (28)
Other business	Other business activities (74)
Motor vehicles & trailers	Manufacture of motor vehicles, trailers, and semi-trailers (34)
Rubber & plastics	Manufacture of rubber and plastic products (25)
Radio, TV & comm. equipment	Manufacture of radio, television and communication equipment and apparatus (32)
Petroleum refinery	Petroleum refinery
Crude petroleum extraction	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
R&D	Research and development (73)
Electricity by coal	Production of electricity by coal
Public administration & defence	Public administration and defence; compulsory social security (75)
Real estate	Real estate activities (70)
Electricity by gas	Production of electricity by gas
Auxiliary transport & travel agencies	Supporting and auxiliary transport activities; activities of travel agencies (63)
Retail trade & household goods repair	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)

(cont. on the next page)

Table 7 (cont.).

Retail trade & household goods repair	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)
Retail trade & household goods repair	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)
Financial intermediation	Financial intermediation, except insurance and pension funding (65)
Electric machinery & apparatus	Manufacture of electrical machinery and apparatus n.e.c. (31)
Basic iron & steel	Manufacture of basic iron and steel and of ferro-alloys and first products thereof
Electricity distribution & trade	Distribution and trade of electricity
Electricity transmission	Transmission of electricity
Coal & lignite mining	Mining of coal and lignite; extraction of peat (10)
Electricity by nuclear	Production of electricity by nuclear
Electricity by solar PV	Production of electricity by solar photovoltaic
Electricity by hydro	Production of electricity by hydro