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The Supply and Use Framework Can Be Exploited for Comparing Technologies Serving Similar Needs: The Case of the Italian Heavy-Duty Road Sector

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ABSTRACT

In Italy, the transport sector contributes significantly to carbon dioxide (CO_2) emissions, accounting for 30.7% of the total emissions, with road freight transport alone responsible for 25% of this figure. This situation demands urgent emissions reductions to meet the country's national commitment to achieving net-zero by mid-century. The growing affordability of electric vehicles (EVs) due to improved energy densities and reduced lithium storage system costs is extending to heavy transport, promising emissions reductions. Additionally, short-term alternatives like hydrogen and liquefied natural gas (LNG) are being considered. To evaluate the carbon footprint of emerging transportation technologies, including internal combustion engine vehicles (ICEVs), fuel cell electric vehicles (FCEVs), LNG vehicles, and battery electric vehicles (BEVs), a detailed life cycle analysis (LCA) is essential. This research aims to inform decision-making processes, investment initiatives, and regulatory compliance by assessing emissions per kilometer within future scenarios. The study employs an LCA model integrating global supply chain contributions, offering regional context and scenario analysis. Findings indicate higher GHG emissions per kilometer for FCEVs and diesel vehicles, with BEVs emerging as promising alternatives. Moreover, the study highlights significant Scope 3 emissions associated with FCEV supply chains, emphasizing the broader environmental impacts of different vehicle types.

1. INTRODUCTION

Shifting to low-carbon vehicles is a key makeover we need, especially for long-distance transport. On a global scale, the air emissions from the transportation industry make up around one-quarter of global CO_2 emissions from energy. According to the International Energy Agency (IEA), the 91% of the energy used in transportation is still derived from oil products, a decrease of only 3% since the early 1970s [1]. Heavy duty transport, although it represents fewer than 8% of vehicles (excluding two- and three-wheelers), is responsible for more than 29.4% of CO_2 transport emissions [2]. Emissions in the transport sector have rebounded to around pre-Covid-19 pandemic levels in 2023, as reported by the International Energy Agency [3]. This resurgence occurred after a temporary reduction in emissions during the year 2020, when the overall demand for fuel and energy decreased due to restrictions implemented to mitigate the spread of the virus. In order to achieve the EU CO_2 reduction goal of 80% by 2050, road transport must achieve 95% decarbonization. Full decarbonization may not be possible through advancements in the conventional internal combustion engine or alternative fuels alone [3]. Achieving comprehensive decarbonization requires a holistic approach, integrating emerging technologies such as electric and hydrogen propulsion. This should be accompanied by simultaneous adjustments in infrastructure and policies. Opting for these alternatives presents a more promising pathway to effectively reduce carbon emissions within the heavy-duty transport sector [4]. In the year 2022, the worldwide sales of electric medium- and heavy-duty trucks neared 60,000 units, constituting approximately 1.2% of the total truck sales. It's worth noting that China takes the lead in both the production and the sales of electric trucks. However, when excluding China, most countries report cumulative sale in the hundreds, underscoring the early stages of adoption. For instance, the entire European Union recorded just under 2,000 electric truck sales in 2022 [3]. Along with the 2023 Global EV Outlook from the International Energy Agency (IEA), the market has witnessed the introduction of around 220 heavy electric vehicle models since 2022, bringing the overall total to more than 800 models. The increasing momentum within the market to adopt advanced and environmentally sustainable technologies for heavy-duty vehicles is gaining traction, significantly supported by the of governments worldwide. During COP 2023 in Dubai, 27 governments pledged to achieve a 100 percent sales target for zero-emission buses and trucks (ZEVs) by 2040. Furthermore, both the United States and the European Union have submitted proposals endorsing stricter emission standards within the heavy-duty vehicle sector [5].

Moreover, the projected increase in heavy freight transport tons by 2050 reveals the critical need for an in-depth analysis of carbon footprints [6]. Italy reflects a comparable pattern in carbon dioxide (CO_2) emissions stemming from road transport, following the broader global challenge. Over the past decade, the transportation sector, along with electricity and heat generation, has emerged as a primary contributor to CO_2 emissions resulting from fuel combustion [7]. A notable share of these emissions is linked to the activities of heavy-duty vehicles engaged in the transportation of goods and people across the country. These vehicles constitute 36% of the overall energy consumption within the transportation sector [8]. Cutting emissions from the transportation sectors is central into Italy's Integrated National Energy and Climate Plan (INECP). The plan targets a 33% reduction in greenhouse gas (GHG) emissions by 2030 compared to 2005 levels [9].

2. OBJECTIVES

The focus of this investigation pertains to the cumulative emissions of the main greenhouse gases originating from trucks during their operational lifecycle, encompassing emissions linked to their manufacturing, maintenance, and fuel production – collectively constituting the carbon footprint of heavy road transport. Hence, it is evident that addressing the environmental impact reduction of this sector necessitates a comprehensive analytical approach to implement the substantive structural changes required, both in technological and economical terms. Examining the carbon footprint per kilometer traveled, rather than per ton moved, holds particular significance for heavy-duty vehicles, as highlighted by Elhedhli and Merrick [10] in 2012. This approach proves particularly beneficial for heavy vehicles, given their propensity to cover extended distances throughout their lifespan. Consequently, the emissions over their lifecycle are significantly influenced by the fuel efficiency, with the footprint from vehicle and battery production distributed across a larger mileage. This divergence increases the likelihood that the emission reductions achieved by electric trucks, when compared to their diesel, gasoline, and natural gas counterparts, will be even more substantial. However, a notable portion of the supply chain for these technologies is situated outside the borders of Italy, potentially leading to increased dependence on foreign industries and associated costs. Additionally, the adoption of Zero Emission Vehicles (ZEVs), while not reliant on fuel during the operational phase, demands substantial investments in the acquisition of a new vehicle fleet. In the realm of freight transport, a gradual transition must carefully consider both economic and environmental challenges. The pivotal question is: At what point does ZEV technology become more advantageous than Internal Combustion Engine Vehicles (ICEVs) in terms of emissions and cost, assuming an equivalent distance traveled? This question can be reformulated as follows: Will the current production of ZEVs and their components yield a payoff in terms of emissions reduction and the initial investments required, making them more convenient than traditional freight transport? On one hand, comparing the emissions released during the manufacturing process to those avoided during usage can serve as a valuable indicator, known as the Greenhouse Gas (GHG) payback time, revealing how swiftly these technologies contribute to reducing emissions and communicating their practical convenience. On the other hand, sectors and industries interested in this technological shift require economic information to comprehend the substantial economic-environmental trade-off among various technologies.

In this research, the estimation of the carbon footprint utilizes the hybrid life cycle assessment method, based on the input-output methodology. The reason for this choice is explained in the next section. Typically, Life Cycle Assessment (LCA) lacks the capability to comprehensively evaluate the reliance on foreign supply chains within a consistent economic framework, a capability achievable through input-output-based analysis. Expanding the conventional input-output framework is crucial, as it often overlooks the impact associated with capital. Starting with the production of the fuel, its conversion, and its use as fuel in the operational phase of the vehicle, the study aims to evaluate the environmental impacts of a fully electric truck and a hydrogen fuel cell truck. A comparative analysis is then conducted with the performance of the conventional technologies used in trucks, in the context of the Italian scenario.

3. METHODOLOGY MOTIVATION

Numerous Life Cycle Assessment (LCA) studies have been conducted on road transport activities, with a predominant focus on passenger cars, as evidenced by de Souza et al.'s research in 2018, and previously Nordelof et al. [11, 12], in 2014. While a substantial body of literature exists on LCA studies for heavy-duty trucks, they remain relatively fewer in comparison. El Hannach et al. [13] investigated the economic and environmental implications of implementing a hydrogen and diesel dual-fuel solution in a heavy-duty truck. Their methodology employed a Well-to-Wheel (WTW) approach to assess fuel-related environmental impacts and a cradle-to-grave approach to quantify the overall environmental footprint of the truck. Rose et al. [14] compared a diesel truck and a Compressed Natural Gas (CNG) truck assigned to refuse collection in a Canadian city, utilizing a WTW approach for fuel and a cradle-to-grave perspective for the vehicles. Additionally, various studies have examined the potential impacts of different energy carriers in heavy road transport, employing either a WTW or Tank-to-Wheel (TTW) approach, as seen in the works [15-18]. Although they provide partial insights into heavy-duty vehicle footprint assessment, which could be expanded with comprehensive process-based LCA studies, none of these studies attempt to address capital expenditure issues in this sector. In general, these studies focus on the value chain of the vehicle and its fuel. It should be noted that life cycle assessment (LCA) methodologies have traditionally relied on physical information and have only recently begun to incorporate economic information. Typically, such analyses are the domain of input-output-based LCA, where both economic and physical information are considered within the same analytical boundaries. The resulting methodology is usually referred to as Hybrid Life Cycle Assessment [19]. Input-output analysis and process-based life cycle assessment are complementary techniques for measuring emissions and environmental effects connected directly or indirectly to the use or production of goods or services [20]. The advantages and disadvantages of the two approaches differ. IO is mainly used to evaluate the effects of a basket of commodities' consumption (and production), and it is based on national "input-output" inventories that track trading data [21]. IO has historically concentrated on more aggregated goods and economic activities, for national accounting reasons. In other words, it is difficult to directly study particular products (e.g., a specific electric car) with IO alone [22]. On the contrary life cycle assessment (LCA) concentrates on specific goods and services, and for this reason, databases called life cycle inventory (LCI) describe representative production processes [23, 24]. Hence LCA is made to help in comparing particular goods. It would be necessary to inventory all economic and environmental flows through all supply chains pertinent for evaluating the life cycle impacts to do so without leaving out any sources of environmental impacts. Being economy such an integrated and complex field a complete inventory is hard to accomplish. To clarify which processes of the product system are included in the analysis and which are excluded and are thus ignored, the LCA inventory defines clear system boundaries [25]. These system boundaries result in two issues: since LCA is not defined in a univocal way it is possible that same products' analysis is not comparable and, more important, the flows let outside the boundaries could have a not negligible effect on the environment. This omission and underestimation are referred to as truncation in LCA. Because IO analyses depend on complete but aggregated inventories, whereas LCA system descriptions are specific but truncated. The identified gap in the existing literature necessitates the adoption of a hybrid model by comparing the technologies that currently lead the European heavy wheeled transport sector with those that are rapidly gaining market share. As highlighted by Miller and Blair, assessing the latter involves an analysis of the industry's backward linkages [21]. To facilitate this, the Exiobase database [26] was selected as the most fitting input-output dataset. To improve replicability, the entire process is run within the same methodological framework, relying on the open-source software MARIO [27].

The next sections are structured as follows. In Section 3, the chosen methods are discussed in depth from theoretical and practical perspectives. Section 4 presents the case study formulation, which is then discussed in Section 5.

4. METHODOLOGY

4.1 Input-output model

An LCA model with a hybrid input-output calculation structure, based on open source databases available online, was developed and used as the analytical technique. The Input-output analysis is an analytical framework developed by Professor Wassily Leontief in the late 1930s. The input-output framework's main objective is to examine the interconnectedness of the various economic sectors [21]. In fact, it is one of techniques most used in economics analysis [28] and it is an option to process LCA modeling at the industry and commodity/level [29]. Input/output hybrid modeling (I/O-LCA) uses flow databases to model the product system, which comprises of supply chains. Then, various commodity categories are given the emissions and related impacts that, for instance, quantify the needs for transportation, energy generation procedures, manufacturing, etc. In this type of analysis, the degree of detail and the potential for differentiating between similar products (for instance, when comparing two different designs for an electronic appliance) is crucial. Therefore, questions that compare very different options on a regional, national, or international level (such as the effects of introducing fuel cell heavy duty transport compared to the current state) or where the overall environmental impact of a system is the focus are appropriate uses for I/O-LCA [30]. The I/O-LCA model is not mathematically distinct from process-oriented LCA because both are linear models with constant coefficients that can be expressed easily in matrix form.

The model adopted in this study is structured as a Supply-Use Table (SUT). SUT models distinguish among commodities supplied (S matrix) and consumed (U matrix) by industrial activities in each represented country. Reiterating the classical Leontief approach [21], S and U matrices combined represent the so-called *intermediate transactions* matrix Z [31]. Final demand of commodities by households and other economic agents is accounted in matrix Y. By diagonalizing (ˆ operator) the total production vector X (defined as the sum of intermediate transactions and final consumption), it is possible to derive the intermediate technical coefficients matrix z by expressing Z per unit of total production (Eq. (1)) and to formulate the Leontief quantity model (Eq. (2)), where I is an identity matrix of appropriate dimensions and w is known as Leontief inverse matrix.

$$z = Z\hat{X}^{-1} \tag{1}$$

$$X = (I - z)^{-1}Y = wY \tag{2}$$

Input-output models, when applied for LCA analyses, are generally environmentally-extended and allow to evaluate the embedded environmental impact of industrial commodities and activities, on selected impact dimensions. For this study, the analysed dimension is the carbon footprint of steel, limited to the main GHGs (i.e., CO_2, CH_4, N_2O). In particular, E matrix displays information about the environmental transactions that every industry is directly responsible for. Other accounts factors of production related to the value added of each industry (e.g., compensation of employees, taxes…) are allocated into matrix V. Similarly to z, also V and E can be expressed per unit of total production X, therefore matrices v and e can be calculated by Eq. (3) and Eq. (4) respectively.

$$v = V\hat{X}^{-1} \tag{3}$$

$$e = E\hat{X}^{-1} \tag{4}$$

To from direct environmental impact accounting (e) to an embedded (or consumption-based) accounting approach, it is necessary to multiply e by the Leontief inverse matrix (Eq. (5)), where f will be henceforth called specific footprint matrix). In the end, it is also possible to extend the calculation of f by exploding it into a squared matrix f_{ex} as described by Wiedmann [32]. Matrix f_{ex} allocates, for each industrial activity, the responsibility of its footprint to the upstream regions and activities (Eq. (6)), where $\widehat{e_k}$ is the diagonal matrix obtained by the diagonalization of each environmental extension (k) represented in e.

$$f = e\,w \tag{5}$$

$$f_{ex_k} = \widehat{e_k}w, \quad \forall t \tag{6}$$

Recent literature shows that the portioning method in LCA is equivalent to the industry-technology model in input-output model [30]. According to the industry-technology model, every procedure has its own unique technology that cannot be shared across various products. In this instance, the process' inputs and outputs are proportionately split among several products to the allocated key. As a result, this model perfectly matches the LCA division method.

4.2 Heavy-duty transport supply chains models

The SUT model has been extended to take into account the new E chains that resemble the production and use of heavy vehicles through innovative routes. These were added as new industrial activities, such as new rows of S and new columns of U, V and E. Hydrogen is not represented in Exiobase, so it had to be modelled as a new commodity provided by two additional activities responsible for its production through steam reforming and electrolysis. It is assumed that the fraction of hydrogen currently produced by electrolysis is negligible. In addition to the final transport activities, the heavy-duty transport services activity in Exiobase needed further modifications. These included the characterisation of the following: gas production, domestic and foreign LNG biogas, diesel, gasoline and HVO production, and electricity production from all sources. Once the intermediate demand was characterised, the transport demand was defined, namely the mileage and the market share for each product. The resulting model is used as the basis for the case study and represents the situation in 2022. The SUT model was extended to take into account new supply chains E. These were added as new industrial activities as new rows of S and new columns of U, V and E. Subsequently, each pathway was characterised with its specific life cycle.

5. CASE STUDY

5.1 Goal and scope definition

The goal of this LCA analysis is to provide information to policymakers regarding the impact of the heavy-duty road transport technologies by comparing the total emissions (GHG and pollutants) of each ton per km traveled as a specific functional unit. In this case the functional unit refers the weight of cargo (measured in metric tons) transported per kilometer of travel by a vehicle, serving as a key indicator of transportation efficiency in terms of payload-to-distance ratio. This metric facilitates assessments of cost-effectiveness and environmental implications of freight transport, with higher values correlating to more efficient resource utilization. To this purpose the system boundary is defined by the combination of powertrains (ICEV, BEV, FCEV) and fuel pathways (traditional fuel and innovative ones) in the Italian transport sector able to make shock analysis in the period 2023-2050. The system boundaries consider the different life cycle stages of the powertrains including raw material extraction, component manufacturing, vehicle assembly and use. The impacts from collection, recycling, energy recovery and disposal of vehicles and batteries has not been taken into account because the results show a negligible value respect to the entire life cycle, the outcomes of our research are in accordance with the existing body of literature [33]. While the boundaries referring to the fuel pathways include feedstock extraction, fuel production, distribution, and combustion or usage. The associated upstream and downstream processes, including the transportation, and infrastructure for fuel production and distribution, as well as the emissions or waste generated during combustion or usage are also considered. The supply chain under study is even beyond the Italian perimeter, and it is linked to the production of the inputs adopted for the performance of the km travelled.

5.2 LCA inventory and database

The input data used were experimental data, process simulations and were supplemented by scientific and grey literature references to provide results closer to real conditions. Three main categories of data can be identified: vehicle (powertrain) and fuel (fuel pathways) technology data, emission factors and global warming potential, and fuel production data. Fuel economy and production mix data are available with a high level of detail and reliability, while emission factor data are also available in the literature, although some of them require assumptions and elaboration. For example, many sources report the manufacturer's stated emission factor, but this is often different from the emission factor recorded during vehicle operation. Data on transport technologies are based on general assumptions:

- The average archetypal HDV (heavy-duty vehicle) travels 800,000 km in its service life, expected to be almost 15 years, with each powertrain ICEV (Diesel, LNG, CNG) EV (Electricity) and FCEV (Fuel cell electric vehicle).
- In the use phase of the transport system, greenhouse gas emissions depend on the emission factors of the fuel consumed, while pollutant emissions depend on the technology (powertrain) adopted.
- The vehicle production phase has a large numerical uncertainty. This is due to the large number of vehicles and manufacturers which needs to identify average data and already existing LCA literature studies. Furthermore, lack of supply chain data openness, especially for local contaminants, contributes to increased uncertainty, necessitating assumptions or extrapolations.

In the Energy carriers supply chains electricity was supposed to be produced from various fossil and renewables generation plants (including imported electricity). Coal, petroleum, natural gas, biofuels, hydropower, geothermal, solar (photovoltaic), and wind energy are used to power the generation plants under consideration.

5.3 Impact assessment

The emission footprint of the functional unit is classified based on three primary criteria:

1. Type of greenhouse gas:

The model delineates emissions of specific greenhouse gases, notably carbon dioxide (CO_2) and methane (CH_4), for each industrial activity.

2. Emissions scope:

- Scope 1: This category encompasses emissions resulting directly from combustion processes during vehicle operation.
- Scope 2: Includes emissions originating from energy conversion processes associated with fuel production, including the production of electricity utilized in electric vehicle (EV) operations.
- Scope 3: Encompasses all other emissions not categorized under Scope 1 or Scope 2. This covers emissions linked to extraction and refining processes of primary fuels,

transportation of refined fuels, and vehicle manufacturing.

3. Powertrain or fuel pathway:

Emission impacts are specifically attributed to either the fuel production chain (fuel pathway) or the vehicle production chain (powertrain), providing distinct analyses of emissions from these two critical components.

This classification framework facilitates a comprehensive assessment of emission sources, aiding in the identification and quantification of greenhouse gas contributions across various industrial activities and processes.

6. RESULTS

The attributive life cycle assessment (LCA) analysis demonstrates the economic break-even point quantified for a defined functional unit equivalent to the ton-kilometres traveled by specific combinations of powertrains, relative to cost considerations. Total costs are computed by accounting for varying fuel costs expressed in €/ton-km required to transport the payload (ton) throughout the operational lifetime of individual vehicles (kilometres), in addition to the purchasing costs of the units under consideration. The graphic visualization of the results, disaggregated by powertrain is described in the Figure 1 below.

The starting costs of the different powertrains refers to the purchasing cost, as expected BEV and FCEV are the most expensive units. Immediately, among internal combustion engine vehicles (ICEVs), diesel becomes the least competitive option due to the combination of high fuel costs and lower efficiency compared to other powertrain technologies, when considering cost per ton transported per kilometer. Hydrogen vehicles, despite their higher initial cost compared to conventional diesel-powered heavy transport vehicles, offer a more cost-effective solution due to superior efficiency and lower lifetime fuel expenses. Internal combustion engine vehicles (ICEVs), specifically those utilizing liquefied natural gas (LNG) and compressed natural gas (CNG), demonstrate lower lifecycle costs attributed to the affordability of the fuel source. Ultimately, battery electric high-duty vehicles (BEVs) become immediately more cost-effective due to the enhanced efficiency of their electric propulsion systems and the lower expense of electricity relative to conventional fossil fuels and hydrogen. The subsequent analysis centers on the CO_2-equivalent emissions generated by each powertrain and fuel pathway throughout its life cycle, as described in Figure 2. The findings align with key studies documented in the literature [33]. Vehicles fueled by natural gas, when compared to diesel and hydrogen vehicles, demonstrate an average reduction of approximately 20% in overall carbon footprint. Diesel-powered vehicles notably involve significantly higher direct emissions compared to natural gas engines, amounting to approximately 30% more emissions on average. In contrast, hydrogen and electric vehicles exhibit zero direct emissions (Scope 1). During the vehicle production phase, diesel and natural gas vehicles share a comparable impact in absolute terms, contributing to around 15% of total emissions. However, this impact is more pronounced for hydrogen and electric vehicles, accounting for approximately 22% of total emissions, attributed to the intricacies of their manufacturing processes.

Upon comparison of different technologies, it is observed that Fuel Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs) initially exhibit higher emission values attributed to the complexity of vehicle construction. The emission breakeven point for diesel FCEVs is promptly reached, highlighting the substantial impact of direct emissions. In contrast, BEVs, Compressed Natural Gas Internal Combustion Engine Vehicles (ICEV CNG), and Liquefied Natural Gas Internal Combustion Engine Vehicles (ICEV LNG) emerge as the least environmentally impactful alternatives.

It is important to note that Battery Electric Vehicles (BEVs) may not be considered the least impactful alternative when accounting for the Italian national electricity mix, which includes the fuel conversion associated with the portion of electricity generated from non-renewable sources.

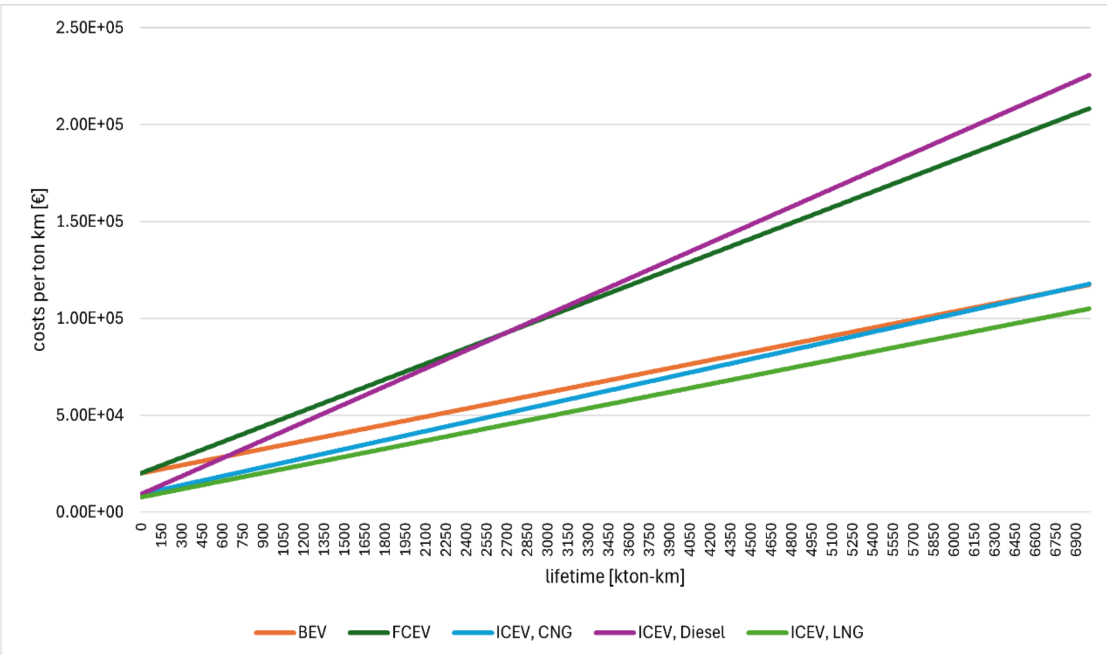

Figure 1. Economic costs

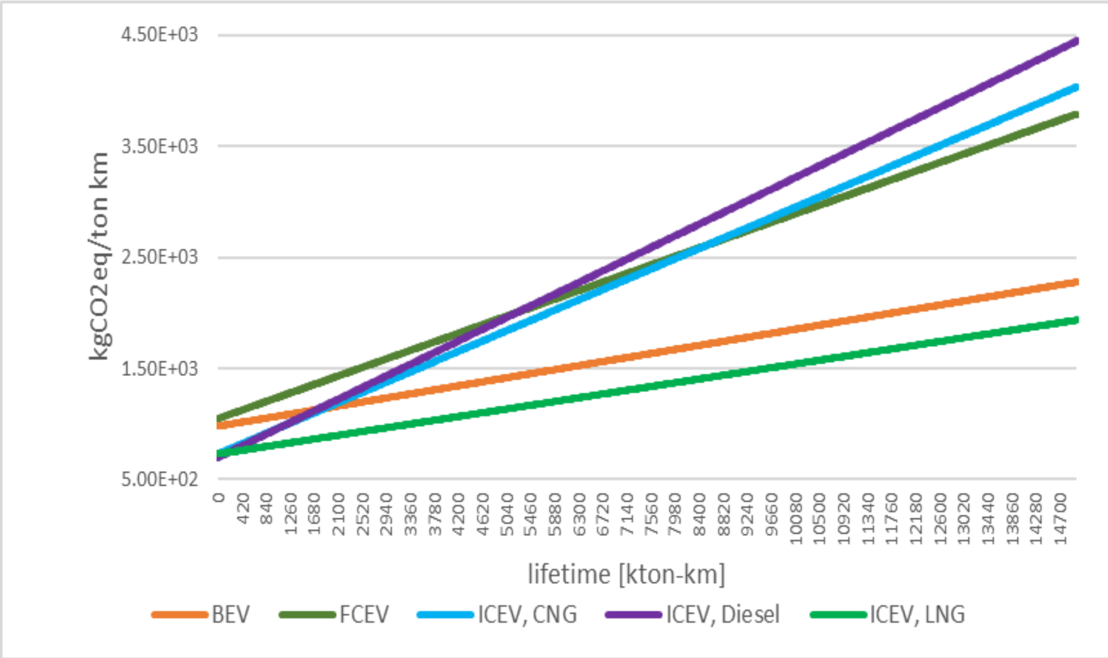

Figure 2. CO_2 equivalent emissions

7. CONCLUSIONS

This paper presents an initial methodological framework for assessing the environmental footprint of heavy-duty vehicles using an LCA model with a process-based input-output computational structure. The next phase of this research will involve developing a consequential LCA analysis to evaluate the overall emissions of the heavy transport sector based on defined scenarios that incorporate changes in the technological mix. This forthcoming analysis will entail modifying the current attributive LCA model and establishing scenarios that outline potential shifts in technology penetration and electricity mix from the years 2022 to 2050. The scenarios will consider the adoption of new fuel pathways, including electrolysis (Green H_2), increased penetration of renewables in the electricity mix, and the utilization of bio components (HVO), each of which could impact the environmental footprint of diesel and electric vehicle (EV) fleets. The formulation of future scenarios will follow this pathway:

• Business as Usual Scenario: This scenario assumes no policy interventions altering current trends, thereby projecting the expected evolution of emissions from the light transport sector in Italy.

• Net Zero Scenario: This scenario envisions transportation fleets equipped with technologies necessary to achieve the objectives outlined in FitFor55 policies, accelerating emissions reduction efforts. It aims to forecast the expected evolution of emissions from the transport sector in Italy to align with FitFor55 objectives.

These scenario-based findings will integrate technical and economic performance data of the examined alternatives, providing policymakers and decision-makers in Italy with a comprehensive knowledge foundation to inform future green mobility objectives. This approach will enable strategic planning and policy formulation aimed at advancing sustainable transportation practices and achieving emissions reduction targets in the transportation sector.

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