

Comparison of CO₂ emissions and costs of combustion and electric light commercial vehicles

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This paper compares CO₂ emissions, energy use, operating costs, and external climate costs of light commercial vehicles (N1-I–N1-III) with spark-ignition, compression-ignition, and battery-electric propulsion, operating under the Polish electricity mix. Fuel and electricity consumption, as well as CO₂ emissions, for ICE vehicles were obtained from the COPERT 5 model, while BEV emissions were calculated using national KOBIZE emission factors. Annual mileage was set at 30,000 km. The results show that BEVs reduce CO₂ emissions by approximately 25–50% and energy costs by 35–55% compared with combustion vehicles, with the most significant benefits in the heaviest N1-III class. External costs of CO₂ are also substantially lower for BEVs. However, the high carbon intensity of the Polish power sector limits achievable reductions, underscoring that fleet electrification must be accompanied by power system decarbonization to fully exploit its climate benefits.

Key words: *light commercial vehicles, battery electric vehicles, CO₂ emissions, operating costs, external costs*

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1. Introduction

Transforming transport systems towards low emissions is a key element in achieving the EU's climate goals. Light commercial vehicles (LCVs) play a significant role in this context, as they are heavily utilised in urban and regional logistics and account for a substantial share of carbon dioxide (CO₂) emissions from road transport. In recent years, battery-electric vehicles (BEVs) have garnered increasing attention as an alternative to internal combustion engine vehicles (ICEVs), in both the passenger car and commercial vehicle segments.

The literature emphasises that a fair comparison of BEVs and ICEVs requires a life-cycle analysis (LCA) that encompasses vehicle production, operation, and disposal. Most studies indicate that BEVs generate lower total greenhouse gas emissions than ICEVs, with the scale of this advantage depending on the energy mix, battery technology, and regional conditions [12, 18, 24, 32, 43, 50]. On the other hand, in regions with a high share of fossil fuels in electricity generation, the climate benefits of transport electrification may be limited or even reversed [13, 54].

This is particularly important for countries with a highly emission-intensive electricity sector, such as Poland. Numerous studies indicate that the dominance of coal in the national energy mix limits the potential climate benefits of electric vehicle adoption, and in specific scenarios, BEVs may have comparable or higher CO₂ emissions than modern combustion-engine vehicles [1, 28, 46, 54, 55]. At the same time, the electrification of city fleets is seen as an important tool for improving air quality and public health [30].

In Europe, the COPERT model is a commonly used tool for estimating road transport emissions, serving as the basis for national emission inventories and transport policy scenarios. Numerous analyses have also demonstrated the sensitivity of COPERT results to assumptions regarding speed, traffic structure, and fleet composition, as well as the need for local calibration [16, 37].

Against this backdrop, this study aims to compare CO₂ emissions and the associated operating and external costs for light commercial vehicles with combustion engines (Diesel, Euro 6) and electric vehicles operated within the Polish energy mix. The analysis is based on fuel and energy consumption data, CO₂ emissions from the COPERT model, and electricity emission indicators published by KOBIZE, with reference to research on the impact of the energy mix on BEV climate efficiency.

2. Literature review

Literature reviews comparing BEV and ICEV life-cycle emissions consistently indicate that electric vehicles can reduce greenhouse gas emissions by about 40–70%, and under favourable conditions up to 97%, relative to combustion vehicles [12, 14, 33, 42, 52]. The most significant advantage of BEVs is evident in operation, thanks to the higher efficiency of the propulsion system and the absence of tailpipe emissions [12, 53].

At the same time, it is emphasised that the production of electric vehicles – especially traction batteries – is associated with higher emissions during manufacturing, which may partially offset the benefits obtained during use, especially in regions with high electricity emission intensity [12]. The literature also highlights other categories of environmental impacts, such as metal depletion and human toxicity, in which BEVs often fare less favorably due to the consumption of raw materials and the production of batteries [12].

The vast majority of studies emphasise that the climate-enhancing effect of BEVs depends strongly on the emission intensity of the energy mix supplying charging energy. In regions with a high share of renewable energy or nuclear power, electric vehicles show a significant advantage over ICEVs in GHG emissions, whereas in countries with a mix of coal or other fossil fuels, the advantage may decrease or even reverse [2, 30].

Many studies analyse scenarios for transitioning from a coal-based to a low-emission mix, showing that the cli-

mate benefits of BEVs increase with the share of renewable energy sources, making transport electrification an increasingly effective tool for reducing emissions [29, 30]. Attention is also paid to the temporal and spatial variability of emissions – the carbon footprint of electric vehicles may vary not only between countries but also with time of day, grid load profile, and local generation structure [2, 29].

Analyses of EV indirect emissions from the power sector lead to similar conclusions: in fossil-fuel-dominated systems, BEV indirect emissions can be similar to or exceed those of efficient combustion vehicles [35, 49], while in low-emission energy countries, EVs achieve significant GHG reductions [5, 49].

On a European scale, well-to-wheel studies indicate that EVs generally reduce GHG emissions compared to ICEVs, but the scale of the reduction depends on the mix of individual countries and the pace of their decarbonisation [6]. In countries with a clean mix (such as France, Norway, Austria, and Switzerland), the benefits are the greatest. In contrast, in countries with a high share of coal (such as Poland and Estonia), a parallel acceleration of energy sector decarbonisation is necessary for transport electrification to achieve full climate benefits [15].

In Poland, where the energy mix remains heavily reliant on coal, the literature highlights the limited effectiveness of BEVs as a short-term tool for reducing CO₂ emissions. It is indicated that, with a dominant share of coal-fired power plants, electric vehicles can generate CO₂ emissions comparable to or higher than those of combustion vehicles, especially in higher vehicle segments and with high mileage [1, 46, 54, 55]. Simulations of scenarios for increasing the share of renewable energy sources (e.g. 25–75% in the mix) show a gradual reduction in BEV emissions relative to ICEV, reaching several dozen per cent, with a clear advantage achieved only with a high share of renewable sources [19, 21, 46, 55].

Electricity emission indicators published by KOBiZE play a crucial role in emission analyses, serving as a standard in national carbon footprint calculations. It has been shown that electricity emission intensity in Poland is among the highest in the EU, with values of ~1.06 kg CO₂-eq/kWh resulting from the dominance of hard coal and lignite in the generation structure [4, 20, 46]. These studies emphasise that improving the BEV emission balance in Poland is closely related to the decarbonisation of the electricity sector [22, 40, 44, 53].

LCVs are a significant source of CO₂ and air pollutant emissions, particularly in urban environments. The literature highlights that, despite tightening Euro emission standards, real-world NO_x and CO₂ emissions from LCVs – especially those with diesel engines – often significantly exceed the approval values [38]. A gap persists between approval emissions and measurements in real-world driving conditions, which are sensitive to driving style, traffic conditions, and ambient temperature [7].

Studies comparing BEVs and diesel LCVs in urban applications indicate that electric vehicles can reduce CO₂ emissions by 15–98% and air pollutant emissions by 7–99%, depending on the age of the vehicles being replaced, the intensity of use, and the energy mix [27, 48]. The most

significant benefits are observed when replacing older diesel vehicles and when powered by clean energy sources, while GHG emission reductions are limited in coal-based systems [27, 34].

More broadly, studies on the electrification of urban fleets (buses, delivery vans, taxis) show that switching to electric drives can reduce GHG emissions by 33–92% over a decade and bring significant health and social benefits, provided that the appropriate energy mix and infrastructure support are in place [31, 39].

COPERT is the standard tool for estimating road transport emissions in Europe and forms the basis for national GHG and air pollutant emission inventories. This methodology is based on emission factors dependent on vehicle class, technology, speed, and traffic conditions, and its use is recommended by the European Commission and the IPCC [11, 16]. For diesel LCVs, COPERT provides CO₂ emission and energy demand factors, widely used in comparative analyses of ICE vs. BEVs.

At the same time, numerous studies indicate a significant sensitivity of COPERT results to the quality of input data (fleet composition, speed structure, trip lengths) and to underestimation or overestimation of emissions under certain conditions, especially in urban traffic and at low speeds [16, 36]. Hence, it is recommended to calibrate the model using local data and use bottom-up approaches where possible [8, 25].

Comparisons of the operating costs of combustion and electric vehicles indicate that, despite the higher purchase price of BEVs, lower energy and maintenance costs may lead to a levelling or superior total cost of ownership (TCO), especially with high annual mileage and a longer operational period [3, 41]. For light commercial vehicles in urban applications, it has been shown that BEVs can achieve TCOs comparable to or lower than those of diesel LCVs, provided sufficient mileage and charging infrastructure are available [3].

In turn, the literature on the external costs of transport shows that transport emissions generate significant health and climate costs, amounting to hundreds of billions of euros per year in Europe [10]. The standard valuation methodology is the “Handbook on External Costs of Transport” and the Impact Path Approach Pathway Approach), developed, among others, in the ExternE projects [23]. Valuation of climate damage related to CO₂ emissions is crucial for comparing drive variants and serves as the basis for applying the “polluter pays” principle [26].

The contribution of this work is to combine the COPERT model emission and energy data with national energy emission indicators (KOBiZE), allowing for a clear comparison of CO₂ emissions, operating costs, and external costs for N1 light-duty vehicles under the Polish energy mix. Unlike previous analyses, actual energy demand and emissions for three LCV classes (N1-I, N1-II, N1-III) were used, rather than catalogue values, enabling a realistic assessment of the cost-effectiveness and environmental impact of BEVs and combustion vehicles.

3. Methodology – analysis of CO₂ emissions and total costs

3.1. Input data and scope of analysis

The analysis compared light commercial vehicles (LCVs) of class N1 in three subclasses: N1-I, N1-II, and N1-III, encompassing three drive types: internal combustion engine SI (Petrol), CI (Diesel), and electric (BEV). Fuel consumption for internal combustion vehicles and electricity consumption for BEVs were obtained from the COPERT 5 model, which determines a vehicle's specific energy demand based on the assumed traffic pattern and annual mileage.

The analysis was limited to carbon dioxide (CO₂) emissions because they are a key climate indicator and their values are stable, comparable, and directly available in both emission models and the literature. CO₂ emissions for BEVs were calculated using the national electricity emission index KOBIZE (kg CO₂/MWh), based on the annual energy consumption determined by COPERT.

Annual vehicle mileage was assumed to be 30,000 km, reflecting typical fleet use of light commercial vehicles in urban and regional transport, in line with values commonly adopted in European studies on LCV operation and total cost analyses. Based on this, annual fuel consumption (ICE) and electricity consumption (BEV) were calculated, followed by annual CO₂ emissions and annual energy costs.

The environmental costs of CO₂ emissions were determined according to the unit external costs recommended by the European Environment Agency (EEA), using a reference value of €25/tonne CO₂ corresponding to the “average” scenario recommended in the EEA Handbook on the External Costs of Transport. Conversion to Polish zloty was based on current exchange rates. The procedure used is consistent with the EEA's recommended methodology, ensuring comparability of results with European analyses.

3.2. Driving pattern structure

The share of journeys in road classes was adopted in accordance with the official data of the national greenhouse gas emission inventory used in the COPERT model calculations:

- 35% urban traffic
- 50% extra-urban traffic
- 15% motorways.

This structure reflects the average vehicle activity distribution used for national emissions reporting. This distribution is significant because specific fuel consumption and emissions are strongly dependent on traffic conditions – in particular, the higher energy intensity of urban driving and the more stable emission profile on rural roads. The adopted proportions are consistent with the literature on the Polish road traffic profile [53] and the operational characteristics of light commercial vehicle fleets.

3.3. CO₂ emissions of combustion engine vehicles (ICE)

CO₂ emissions for combustion engine vehicles were determined based on the results of the COPERT 5 model, which gives:

- specific CO₂ emissions [g/km] for individual road categories

- total emissions after considering the annual mileage and use structure.

The COPERT model calculates CO₂ emissions indirectly, based on fuel consumption and fuel physicochemical properties, using formulas consistent with the EMEP/EEA and IPCC methodologies. This approach ensures complete consistency with national emission inventories, enabling the comparability of results with official national and European reports.

3.4. Electric vehicle (BEV) CO₂ equivalent emissions

Since the COPERT model does not calculate emissions for electric vehicles, the equivalent CO₂ emissions for BEVs were determined using the approach described in [27]. CO₂ emissions were calculated based on specific energy consumption and the electricity emission index according to the following formula:

$$E_{CO_2} = N \cdot EF_{CO_2} \cdot M \quad (1)$$

where: N – specific electricity consumption [Wh/km], EF_{CO_2} – emission factors for electricity [g/Wh], M – annual mileage [km].

The value of the EF_{CO_2} was adopted based on the current “CO₂, SO₂, NO_x, CO, and total dust emission indices for electricity” [52] published by KOBIZE/IOŚ-PIB for the national energy mix. This indicator was converted from kg/MWh to g/Wh, enabling its direct use in the above formula.

The use of the national emission factor reflects the actual CO₂ intensity of the Polish electricity sector. It is a key element in assessing the environmental impact of BEVs in national conditions.

3.5. Energy-related operating costs

Due to the limited availability of reliable data on vehicle maintenance costs, the analysis considered only fuel costs (ICE) or electricity costs (BEV). The annual cost was determined as:

$$C_{exp} = Q \cdot C \quad (2)$$

where: Q – annual fuel or energy consumption (from COPERT), C – average price of fuel or electricity in Poland in 2024, used as annual mean values to maintain consistency with the yearly aggregation of mileage, energy consumption, and emissions.

The operating cost, defined in this way, reflects the main component of commercial vehicle fleets' operating expenses and, at the same time, ensures comparability across different drive types.

3.6. External costs of CO₂ emissions

The external cost of CO₂ emissions was calculated according to the formula:

$$C_{ext} = E_{CO_2, year} \cdot C_{CO_2} \quad (3)$$

where: $E_{CO_2, year}$ – annual CO₂ emissions [t], C_{CO_2} – unit climate cost [PLN/t].

The unit cost of CO₂ emissions was adopted in accordance with the recommendations of the Handbook on the External Costs of Transport (EEA), using the average scenario (€25/t CO₂). Values were converted to Polish zloty

using the exchange rate and conversion method used in the Central Statistical Office (GUS) reports on environmental damage costs, ensuring consistency with national economic analyses [17].

This approach enables the comparability of results with both European studies (EEA, OECD) and national studies using the environmental damage valuation method.

4. Results

4.1. Annual fuel and energy consumption

This chapter presents the results of calculations regarding energy consumption, CO₂ emissions, operating costs, and external costs for N1 light commercial vehicles. The analysis covers three vehicle subclasses (N1-I, N1-II, N1-III) and three drive types (SI, CI, and electric), in accordance with the methodology's assumptions. The results are presented in bar charts, allowing easy comparison of relationships between segments and identification of differences between combustion and electric vehicles. The following subchapters discuss energy consumption, CO₂ emissions, annual costs, and external costs of emissions.

A summary of the annual energy consumption for all N1 classes and drive types is shown in Fig. 1.

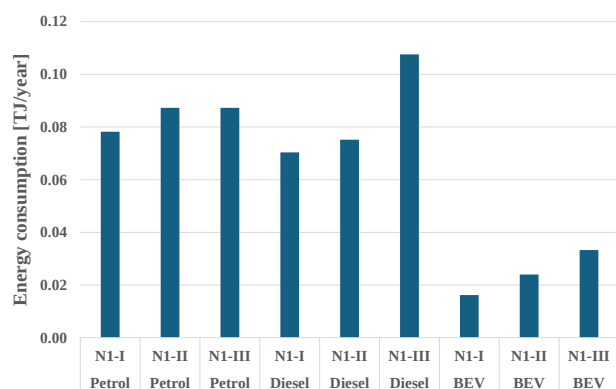


Fig. 1. Annual energy consumption of N1 light commercial vehicles with ICE SI and CI and BEV

Annual energy consumption shows a clear differentiation between drive types and N1 segments (Fig. 1). For gasoline vehicles, annual energy consumption is approximately 0.078 TJ/year (N1-I) and 0.087–0.088 TJ/year (N1-II and N1-III), indicating an increase in demand within the N1 segments.

For diesel vehicles, even more pronounced differences are observed: from approximately 0.071 TJ/year (N1-I) to 0.108 TJ/year (N1-III). The extreme increase between N1-II and N1-III is due to the greater curb weight and operational characteristics of this vehicle class.

For BEVs, annual energy consumption ranges from 0.019 to 0.034 TJ/year, increasing in proportion to the segment. However, the growth rate is significantly slower than for combustion vehicles. This is due to the higher efficiency of the electric drive and the lower dependence of energy consumption on vehicle weight.

4.2. Annual CO₂ emissions

A comparison of the annual CO₂ emissions for all vehicles analysed is shown in Fig. 2.

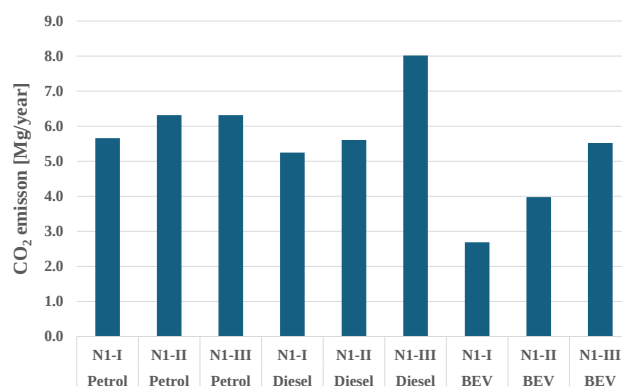


Fig. 2. Annual CO₂ emissions of N1 ICE SI and CI light commercial vehicles and BEV

Annual CO₂ emissions from combustion vehicles show an apparent increase with the transition to higher N1 segments (Fig. 2). For vehicles with a spark-ignition engine, these values are about 5.7 Mg/year (N1-I) and 6.3 Mg/year for classes N1-II and N1-III. For vehicles with a CI engine, CO₂ emissions are slightly lower for segments N1-I and N1-II (approx. 5.2–5.6 Mg/year), while in class N1-III an apparent increase to about 8 Mg/year is observed.

This means that the differences between segments are significantly larger in diesel vehicles than in petrol vehicles, due to higher fuel consumption in heavier, higher-payload vehicles.

Electric vehicle CO₂-equivalent emissions are significantly lower than those for ICE vehicles in all segments. For BEVs, they are approximately 2.7 Mg/year (N1-I), 4.0 Mg/year (N1-II), and 5.5 Mg/year (N1-III). Emissions growth between segments is due to higher electricity consumption; however, the rate of growth is slower than that of combustion vehicles.

4.3. Annual operating costs

The annual fuel and electricity costs corresponding to the analysed energy consumption are illustrated in Fig. 3.

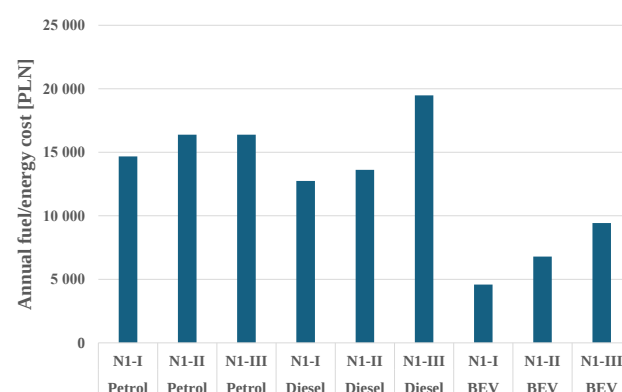


Fig. 3. Annual fuel (ICE) and electricity (BEV) costs for light commercial vehicles

Annual fuel costs for gasoline vehicles range from PLN 14,700 to PLN 16,500 per year (Fig. 3). The cost increase between segments N1-I and N1-II is significant, while the values for classes N1-II and N1-III are very similar, which results from similar fuel consumption determined by COPERT.

For diesel vehicles, operating costs are lower than those of petrol versions in the N1-I and N1-II segments (approximately PLN 12.8–13.7 thousand/year). However, in the N1-III class, they increase significantly to approximately PLN 19,500 per year. This means the segment's impact on fuel costs is much greater in diesel vehicles than in petrol units.

Annual electricity costs for BEVs are significantly lower than fuel costs for ICEs, amounting to approximately PLN 4,500 (N1-I), PLN 6,600 (N1-II), and PLN 9,500 (N1-III). The increase in energy costs across segments is proportional to the increase in energy consumption with greater vehicle weight.

4.4. External costs of CO₂ emissions

Figure 4 shows a comparison of the annual external costs of CO₂ emissions for all vehicle variants.

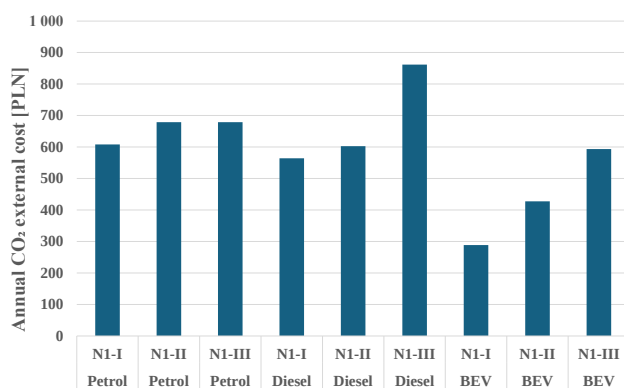


Fig. 4. Annual external costs of CO₂ emissions of light commercial vehicles N1

The external costs of CO₂ emissions for combustion vehicles increase with the N1 segment, with the strongest relationship for diesel vehicles (Fig. 4). In the petrol segment, these values are approximately PLN 600/year (N1-I) and approximately PLN 680/year for classes N1-II and N1-III, reflecting minor differences in their annual CO₂ emissions.

For diesel vehicles, climate costs are lower than for gasoline vehicles in the N1-I and N1-II segments (approximately PLN 560–595/year), but in the N1-III class, they increase significantly, reaching approximately PLN 860/year. This means the segment's impact on CO₂ emissions is particularly strong for the heaviest diesel vehicles.

External costs for BEVs are significantly lower than those for ICE vehicles in all segments, ranging from PLN 285 to PLN 595/year. The cost increase for N1-I to N1-III results from growing electricity consumption but remains significantly lower than that for combustion vehicles.

The analysis revealed apparent differences between internal combustion engines (ICEs) and electric vehicles across the three N1 segments. ICE vehicles are characterised by higher energy consumption, higher CO₂ emissions, and higher operating and external costs, with the scale of these differences increasing with vehicle weight. The increase in fuel consumption, emissions, and costs is particularly noticeable in the N1-III segment, especially for diesel vehicles.

Electric vehicles are characterised by significantly lower energy consumption and CO₂-equivalent emissions, as well as the lowest operating costs among the drive types analysed. The increase in energy and cost burdens, particularly in the N1 segment, is significantly less pronounced for BEVs than for ICE vehicles, confirming the greater energy efficiency of electric drive.

The results indicate that even with Poland's current emissions-intensive energy mix, BEVs remain more advantageous in terms of CO₂ emissions, operating costs, and environmental impact. These differences are most pronounced in the N1-III segment, highlighting the significant potential for electrification, especially in heavier vehicle classes and those with intensive fleet use.

5. Summary and discussion

The results of this analysis are consistent with observations from recent literature comparing internal combustion and electric vehicles during their operational phases. They confirm that BEVs are characterised by significantly lower energy consumption and lower CO₂-equivalent emissions than ICE vehicles, even in highly carbon-intensive energy mix conditions, such as those in Poland. According to numerous studies [46, 47, 55], the advantage of BEVs in the operational phase stems primarily from the high efficiency of the electric drive and the absence of tailpipe emissions.

Although the present analysis focuses on operational energy costs and CO₂ emissions, it should be noted that battery-electric vehicles typically have higher purchase costs than conventional light commercial vehicles. At the same time, BEVs generally require less maintenance due to the absence of components such as internal combustion engines, oil systems, and exhaust aftertreatment, which reduces both operating expenses and the environmental burden associated with vehicle servicing. These aspects are relevant for a full total cost of ownership and life-cycle assessment; however, they were intentionally excluded from the present study to maintain a clear focus on the operational phase and ensure comparability of emission and cost indicators.

However, the scale of CO₂ emission reduction in BEVs in Poland is still limited by the high share of coal in electricity production, as previously noted in KOBiZE analyses and numerous studies on the Polish power system [4, 20, 44]. Our results are consistent with the conclusions of [53, 54], who showed that BEVs in Poland outperform ICEs in terms of CO₂ emissions only to a moderate extent, and a clear advantage becomes apparent only after significant decarbonisation of the mix.

In the analysis of this paper, the BEV emission reduction relative to ICE was approximately 25–50% and was the highest in the N1-III segment, which confirms that the electrification of heavier delivery vehicles has the most significant reduction potential, similarly to what was indicated in studies on city and logistics fleets [27, 51].

The substantial increase in energy consumption and emissions for diesel vehicles in the N1-III segment is entirely consistent with previous observations on real-world LCV emissions [9, 38]. These studies indicate that the higher the vehicle mass, the greater the fuel consumption in

real-world driving conditions, especially in delivery applications with high dynamic loads.

In the case of BEVs, this dependence is milder, resulting from the higher efficiency of the drive system and the lower sensitivity of the electric system to load and driving conditions – phenomena confirmed in many comparative analyses [12].

The results on annual operating costs confirm the literature's findings that BEVs can be cheaper to operate than diesel and gasoline vehicles, especially with higher mileage and intensive use [3]. In this analysis, cost differences were significant across all segments, with BEVs generating 35–55% lower energy costs than ICEs, which is consistent with the observations by [3] that the price of electricity, even in an environment of rising energy prices, remains a relatively stable and predictable component of TCO.

The external costs of CO₂ emissions were also significantly lower for BEVs. This is a direct result of lower CO₂-equivalent emissions and of the linear climate damage pricing formula, based on EEA and OECD recommendations. The results are consistent with the literature on the impact of transport emissions on health and climate costs [35].

The analysis confirmed the usefulness of the COPERT model as a reference tool for analysing LCV emissions. At the same time, as noted by Orynych [37], Smit [45], and Dey [16], it is important to be aware that the model results are sensitive to traffic structure, speeds, and fleet parameters.

Therefore, the use of national data and Polish energy emission indicators (KOBiZE) provides significant added value to this work.

6. Conclusions

1. BEVs have lower CO₂ emissions than combustion vehicles in all N1 segments, despite the high emissions intensity of the Polish energy mix.
2. The reduction ranges from 25 to 50% and increases with the vehicle segment.
3. Energy consumption and CO₂ emissions in combustion vehicles increase strongly with vehicle weight, especially in the case of Diesel in the N1-III segment, which confirms literature observations on real LCV emissions.
4. BEVs are significantly cheaper to run – energy costs are 35–55% lower than ICE fuel costs, even at 2024 energy prices.
5. The external costs of CO₂ emissions are significantly lower in BEVs, confirming their environmental advantage and compliance with the polluter pays principle.
6. The most significant potential for emission and cost reductions is in the N1-III segment, i.e. the heaviest LCVs used in fleets – their electrification brings the most significant benefits.
7. A key factor for further reducing BEV emissions in Poland is the decarbonization of the electricity sector, as emphasised by numerous studies [44, 47, 55, 56].

Nomenclature

BEV	battery electric vehicle	ICE	internal combustion engine
CI	compression ignition	IPCC	Intergovernmental Panel on Climate Change
COPERT	Computer Programme to calculate Emissions from Road Transport	LCA	life cycle assessment
EMEP/EEA	European Monitoring and Evaluation Programme/European Environment Agency	SI	spark ignition
		TCO	total cost of ownership

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