

Article

Energy and Environmental Benefits of In-Motion Charging Trolleybuses: A Case Study of Vilnius

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Abstract: Reducing greenhouse gas (GHG) emissions depends mostly on urban transport electrification. However, the role of trolleybus systems in this process is still under discussion. The objective of this study was to analyze the viability of trolleybus buses in relation to diesel buses regarding environmental and economic aspects. The research was conducted in Vilnius, Lithuania using an extended CO₂ emission methodology incorporating physico-chemical fuel properties and real-world operational data that allowed us to estimate CO₂ emissions and economic impacts. The findings indicate that the Vilnius trolleybus system prevents 84,996.32 kg of CO₂ emissions monthly compared to diesel buses (gross avoided emissions). After accounting for emissions from electricity generation (based on Lithuania's 2023 grid mix), the net avoided emissions are approximately 61,569 kg of CO₂ per month, equivalent to EUR 4284 in carbon credits. The system also significantly reduces local air pollutants. Moreover, the new In-Motion Charging (IMC) technology improves system flexibility by decreasing dependence on overhead wires and maintaining low emission levels. IMC trolleybuses represent a cost-efficient option compared to battery-electric buses (BEBs) and hydrogen fuel cell buses (FCEBs). Our findings support the European Union's decarbonization goals and provide essential insights for policymakers considering public transportation electrification efforts.

Keywords: trolleybus; In-Motion Charging; urban transport; CO₂ emissions; Vilnius



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1. Introduction

The European Union (EU) is pursuing ambitious climate policy goals, based on reducing greenhouse gas (GHG) emissions and moving towards low-carbon technologies in all sectors, including transport [1–4]. Thus, the transformation of urban mobility towards electrified public transport (including trolleybuses) is becoming increasingly important in order to reduce the number of vehicles using fossil fuels [5–7]. In addition, the structure of energy production for these electric vehicles is closely linked to the overall level of cleanliness of the electricity grid [8–10].

In this scenario of transport decarbonization by electricity use, the focus of stakeholders are battery electric buses (BEB) or hydrogen fuel cell buses (FCEB). However, various scientific studies and reports [11–13] have analyzed the importance of trolleybuses as a consistent and reliable system for the decarbonization of the city environment.

Trolleybus technology has historically gone through several stages of development, from rise to decline, but the current EU emphasis on a clean, electric urban transport system promises a new breakthrough. Today, innovative solutions such as In-Motion Charging (IMC)—energy supplied while driving to charge the batteries—allow trolleybuses to operate more flexibly, eliminating long sections of overhead lines.

Trolleybus transport is considered one of the sustainable urban mobility means that can reduce air pollution and noise. According to Wolek et al. [13], the importance of these vehicles increased after the fuel crisis of the 1970s, when European cities realized the need to diversify transport systems and reduce dependence on oil products. Trolleybuses, like other electric vehicles, do not directly emit pollutants on the streets, and the overall level of emissions depends on the sources of electricity production.

As the EU has set a target of achieving climate neutrality by 2050 [14], cities are intensively looking for ways to reduce environmental pollution caused by transport. And, although from the 1980s to the present day, the assessment of the transport sector has evolved into a comprehensive life-cycle cost (LCC) approach, covering both operational and external (ecological) costs, the modern approach to trolleybus transport is not limited to costs related to infrastructure maintenance or energy costs. EU climate policy requires that carbon pricing and other negative environmental consequences also be taken into account. In this sense, trolleybuses have a longer service life, easier maintenance, and lower energy consumption compared to diesel buses [15].

For many years, the EU has been encouraging expenditure on environmentally friendly transport. EU structural grants are available, such as the Cohesion Fund and the European Regional Development Fund (ERDF) to promote innovation, including the launch of less polluting automobiles. According to Kozera et al. [16], in Poland in the period 2014–2020 the EU contributed to 778 projects aimed at developing “green” transport; the value of which reached 7.4 billion euros. A significant part of these funds was allocated to the electrification of public transport—the purchase of both new trolleybuses and electric buses, the development of networks, and the installation of engineering infrastructure.

Another important financial instrument is the green public procurement (GPP) mechanism, which encourages local authorities to choose solutions that meet environmental criteria. According to Yang and Morotomi [17], GPP can promote eco-innovation only if the share of “green” contracts reaches a certain threshold. In other words, if public procurement related to transport essentially requires low-emission or zero-emission vehicles, businesses and municipalities will be forced to look for innovative solutions. This process is especially significant if the state has sufficient human capital capable of effectively implementing new technologies and makes good use of EU funding opportunities.

The combination of national and city-level instruments is also an important research topic. Si et al. and Corazza et al. [18,19] show that most municipalities rely on EU and national subsidies when planning green initiatives. At the same time, it is emphasized that the effective use of funds is often hampered by limited autonomy of municipalities, lack of project management experience, or excessively bureaucratic regulation of processes.

With these ideas in mind, this paper seeks to answer the role of trolleybus systems in the electrification process of public transport in cities. To do so, the objective of the paper was to investigate the environmental and economic impact of trolleybus adoption to attend the EU objective of decarbonization of transport in their cities. We analyzed the trolleybus system of Vilnius, Lithuania and calculated the emissions level using an

extended methodology based on literature. We also use secondary data to perform the extended model of CO₂ emissions and to evaluate the matrix energy of Baltic countries in comparison to Lithuania to identify whether the electrification of transport systems would be really clean in terms of the environment.

2. Literature Review

2.1. In-Motion Charging (IMC)

As mentioned previously, a new technology, IMC, allows a trolleybus to connect to an overhead line while driving and at the same time charge its batteries. Such a solution provides greater freedom of operation where there is no contact line, because the vehicle can drive on battery power. Bartłomiejczyk and Caliandro [20] shows that dynamic charging on the road reduces the overall financial burden, because the battery capacity can be smaller—the trolleybus is replenished with part of the required energy during the route. This reduces the cost and weight of the battery, and the charging itself becomes fast and reliable.

An important advantage of IMC technology is flexibility because IMC trolleybuses are not tied to fixed charging stations, which not only take up space but can also be expensive to install and maintain. Additionally, IMC allows cities, where an overhead trolleybus network already exists, to use the existing infrastructure [21]. However, in some cases, improvements to the electrical supply (e.g., stronger transformer substations or new cables) are required to ensure sufficient power supply.

Bartłomiejczyk and Caliandro [20] highlights that the battery life of such an IMC model can be up to 15 years, especially if an LTO (LiTitanium) battery. This is longer than for most battery-only buses, whose batteries typically last around 7–10 years. The longer lifespan means that in the long term, such transport can be more economically viable for the city. However, the implementation of an IMC system may require capital investment in the modernization of the catenary network—while new lines may be needed less, old lines and electrical infrastructure are sometimes outdated. If a city is starting from scratch, it must be considered whether it is more profitable to invest in an overhead line system or, alternatively, to immediately choose electric buses with high-capacity batteries.

IMC technology allows trolleybuses to cover sections using battery power where there is no catenary. This can significantly reduce the amount of unsightly overhead lines in dense city centers or historic parts of the city. Many cities mention this aspect as a significant reason—the installation of contact lines in old towns can conflict with heritage protection requirements and also cause visual noise. Therefore, partial or selective abandonment of contact lines [22] helps to create a more attractive urban environment and gives the operator the flexibility to change or extend routes without major infrastructure investments.

When assessing the cost-effectiveness of IMC trolleybuses, more than just the initial cost of the vehicles should be considered. Currently, battery prices are a large component of the price of electric buses [20]. IMC allows the use of batteries with a smaller capacity, which can result in lower production and replacement costs. If a city already has some trolleybus infrastructure, the additional costs may be limited to upgrading the network, but not to building a completely new infrastructure. In addition, according to Wolek et al. [13], the life-cycle cost approach often shows a favorable balance for IMC technology, since the costs incurred during operation (fuel/electricity, repairs) are lower compared to diesel buses.

In the long term, an important factor is the trend in energy prices. The more renewable sources are integrated into the electricity grid, the more the price of electricity stabilizes or even decreases (depending on the region), and at the same time the operating costs decrease. This is also supported by carbon dioxide emissions taxation (ETS2 system for

road transport [23])—with the further increase in the price of diesel fuel and the increase in the price of CO₂ pollution, electrification remains increasingly attractive. In this way, IMC trolleybus projects can become more economically viable than initially expected.

2.2. Battery Electric Buses (BEB)

Battery electric buses (BEB) are increasingly used in European cities. Their advantage is that they do not require any contact infrastructure, which is important for cities that do not have a tradition of a trolleybus network or that want a quick start without major construction [24]. However, BEB has a limited range, which is determined by the battery capacity and the charging method. If the routes in the city are long, there is a need for intermediate charging (e.g., at stops or depots), which requires stationary fast-charging stations.

In addition, BEB maintenance and battery replacement represent a significant part of the long-term operating costs. As Gil Ribeiro and Silveira [25] states, there is still a fairly high dependence on financial subsidies to make BEB competitive.

2.3. Hydrogen Fuel Cell Buses (FCEB)

Another alternative technology is hydrogen fuel cell buses (FCEB). These vehicles do not pollute the environment with exhaust gases, as the exhaust product is water vapor. However, the production and supply of hydrogen always pose challenges. Hoch et al. [26] show that hydrogen buses are still significantly more expensive, requiring complex infrastructure (hydrogen filling stations) and safety measures. There are currently only about 1200 FCEBs in European cities (mostly in Western Europe), and although the market growth has intensified, is not yet large enough to be economically comparable to trolleybuses or BEBs.

For FCEB technology to be viable, “green” hydrogen is needed, which is produced using renewable energy. In other words, if hydrogen is obtained from natural gas steam reforming with high CO₂ emissions, the overall climate benefits of the technology are reduced. Therefore, cities that have chosen hydrogen buses (e.g., the case of Germany) must also invest in the development of renewable sources to make hydrogen carbon-neutral [26].

2.4. City Choice and Baltic Countries Applications

Some cities use a mix: some routes are served by trolleybuses with IMC, others by battery buses, and on certain short lines requiring a long distance, hydrogen technologies can also be experimented with. An important point is the appropriate adaptation of different technologies to the specific needs and capabilities of the city.

A connection with urban planning is also necessary. Óvári et al. [11] emphasizes that cities that have a more homogeneous structure (shorter distances, less complex route network) are easier and faster to introduce green vehicles, but often face planning inertia and lack of budgets.

For electric public transport solutions to actually lead to a significant reduction in emissions, the overall energy mix of the country (or region) is very important. The Baltic countries—Lithuania, Latvia, and Estonia—are undergoing a transformation in their energy sectors from fossil fuels to renewables, but the process is not uniform across the three countries.

Lithuania imports a large share of its electricity, Latvia has significant hydropower potential, and Estonia still relies on shale gas for electricity generation. Therefore, if a region generates most of its electricity from renewable sources, electric public transport becomes a highly effective tool in the fight against climate change [16,27,28]. However, if electricity is generated from polluting sources (e.g., shale or coal), indirect emissions from trolleybuses and other electric vehicles will remain significant.

In the future, the development of offshore wind energy, especially in Lithuania and Latvia, and solar energy projects will be of great importance for the Baltic States. Li et al. [29] shows that by successfully increasing the share of renewable sources, it will be possible to significantly reduce indirect emissions from transport, even if the transport sector is rapidly electrified. Thus, trolleybuses are already a promising green solution, which will become even more environmentally friendly as cleaner electricity production grows in the Baltic region.

2.5. IMC Trolleybus Implementation in European Cities

While the European Union supports the decarbonization of cities, several research studies have shown that municipalities lack innovation [11,30,31], and regional or national requirements can be too strict or not flexible enough [31]. At the local level, there may be a lack of competences to effectively integrate IMC trolleybuses or other electric vehicles into the overall urban mobility strategy [32].

There are also questions about the qualifications of transport workers: the transition to electric vehicles requires new skills [8,28,33–35]. When planning the modernization of trolleybuses, municipalities must balance the need to introduce a new vehicle and infrastructure with the available budget and the possibility of obtaining EU support. Sometimes this support is not enough for cities to fully modernize the trolleybus network, so plans may be implemented in parts.

Borowik and Cywiński [12] shows that innovative solutions, such as hybrid traction systems (where the battery is used as a backup source for short sections without a line), have been successfully implemented in the trolleybus network of Tychy (Poland), showing good energy saving and environmental performance.

Despite the importance of public investment, the private sector also plays a significant role [36,37]. In some cases, private capital can help finance the renewal of the electric vehicle fleet, especially if the country has a well-developed electricity market and transparent legal mechanisms [38]. However, in order for private investment to become attractive, it is necessary to ensure long-term economic stability, political support, and infrastructure development.

Various studies in different European cities [23,39,40] have shown that technological progress, especially in the battery sector, is of decisive importance for the development of trolleybus transport. If IMC Trolleybus systems become even more efficient, both the infrastructure needs and battery capacity requirements will decrease. Innovations related to energy recovery during braking, advanced control systems, as well as lighter weight designs can further increase the competitiveness of electrified public transport.

In addition, there is a wide field of cooperation between scientists and cities, including real-time system testing. For example, the idea [24] is to create separate “reference” routes in mountainous areas or countries with a winter climate, so that manufacturers and city planners can test the efficiency of new generations of trolleybuses in difficult conditions.

Trolleybuses, especially IMC technology, are becoming an increasingly promising public transport solution in the context of European climate policy. EU funding mechanisms (Cohesion Funds, ERDF, green public procurement) are a key incentive for cities to upgrade public transport systems and implement more environmentally friendly technologies [41–44].

Compared to battery electric buses (BEB), IMC trolleybuses require that the city has at least partially existing or planned trolleybus infrastructure. Hydrogen fuel cell buses (FCEB) are another zero-emission alternative, but they still face relatively high costs and a lack of fuel supply infrastructure. Thus, the decision of a particular city depends on how

much it is willing to invest in existing or new contact infrastructure, what its possibilities are to receive EU support, and how developed local renewable energy sources are.

In the context of the Baltic States (and also on the EU scale), an important question remains of how clean the electricity is supplied to public transport. With the intensive expansion of wind, solar, and other renewable resources, IMC trolleybuses and other electric vehicles can significantly contribute to improving urban air quality and reducing global GHG emissions. However, if the majority of the electricity is generated using fossil fuels (e.g., from oil shale or coal), the overall climate impact may be less impressive.

Many studies [18,19,45,46] confirm that the electrification of transport creates clear benefits for the health of residents and urban ecosystems, even if the benefits in the overall greenhouse gas balance become apparent only when the energy mix becomes cleaner.

The future perspective sees a systematic improvement of public transport, focused on long-term operation, modular design, more efficient energy use, and wider application of renewable-electricity sources together with the increasing willingness of cities to invest in electric transport and the EU's ambition by 2050. Achieving a climate-neutral continent will open up new opportunities for IMC trolleybuses. Developers of this technology will have to solve additional tasks: reducing the cost of equipment, ensuring operational reliability, improving battery charging strategies, and integrating carrier activities with advanced urban transport management systems [22,47–50].

3. Materials and Methods

3.1. Vilnius Trolleybus System

Vilnius, the capital of Lithuania, has used trolleybus systems for many years as an alternative to diesel buses. Vilnius has a population of 569,700 inhabitants in an area of approximately 400 square kilometers. Around 200,000 passengers are transported every day. The Vilnius trolleybus system was inaugurated in November 1956 with approximately 8 km and 25 trolleybuses on the “Antakalnis-Stotis” line. In 1981, the system was expanded, with the inauguration of a new garage for 150 trolleybuses on 28 December 1985. In 1993, the system began to be operated by the public company UAB (Vilniaus Autobusai) and in 2011, after a reorganization that merged the public companies that operated buses and trolleybuses, the system began to be operated by VVT (Vilniaus Viešasis Transportas).

VVT is 100% from city government and operates municipal and suburban bus and trolleybus lines in the city [51]. In addition to VVT, the system has two concession companies, UAB Transrevis and UAB Kautra. The fleet currently consists of around 150 two-axle Skoda 14 Tr/14 TrM model trolleybuses and two Skoda 15Tr articulated trolleybuses manufactured in the 1980s and 1990s, 45 Solaris Trollino 15 trolleybuses, 41 Solaris Trollino 12 trolleybuses with IMC system, and two AZ 203T Amber vehicles [52,53].

In 2024, the city began receiving new trolleybuses for fleet renewal, the transport authority acquired another 91 Skoda 32 Tr 12-Meter trolleybuses equipped with the IMC system that allows trolleybuses to operate up to 20 km disconnected from the electricity grid [52].

3.2. Emissions of CO₂ by the Bus Service of Vilnius (Trolleybus × Diesel Buses)

In this study, we adopted the Carvalho's methodology [54] to estimate the CO₂ emissions that would have been produced if the Vilnius trolleybus lines were operated by diesel buses. Carvalho's methodology [54] is based on a comprehensive study about vehicle emissions in great urban centers using cities in Brazil as the case of study. The methodology calculates relative emissions according to a modal matrix. Emissions of CO₂ can be established according to Equation (1):

$$E_{km} (bus) = E_{es} / E_f, \quad (1)$$

where $E_{km}(\text{bus})$ —Emissions of CO_2 (kg)/km for bus service, E_{es} —Emissions for energy source in CO_2 (kg)/L, E_f —Energy efficiency in km/L.

Considering the values of E_{es} 3.2 CO_2 [kg/L] and E_f 2.5 [kg/L] obtained for Carvalho [54], is it possible to establish $E_{km}(\text{bus})$, Equation (2):

$$E_{km}(\text{bus}) = \frac{3.2}{2.5} = 1.28 \text{ CO}_2 \frac{\text{kg}}{\text{km}}. \quad (2)$$

For the distance traveled by the Vilnius trolleybus fleet monthly, we verified the timetable of the lines made available by the Vilnius city hall obtained at JUDU's Website [55], and the distances were obtained through the collaborative platform Wikiroutes [37,56] (Table 1).

Table 1. Vilnius trolleybus lines in km.

	Route	Distance	Number of Services			Total km (Month)
			Weekdays	Sat	Sun	
1	Pasakų parkas → Stotis (A)	9.05	42	27	26	859.75
	Stotis (A) → Pasakų parkas	8.60	41	27	16	722.40
2	Senoji plytinė → Stotis (A)	9.81	106	99	96	2952.81
	Stotis (A) → Senoji plytinė	9.63	108	99	96	2917.89
3	Pasakų parkas → Povilo Lukšio st.	12.40	26	25	24	930.00
	Povilo Lukšio st. → Pasakų parkas	12.08	27	24	24	906.00
4	Antakalnio žiedas → Valkininkų st.	13.60	102	0	0	1387.20
	Valkininkų st. → Antakalnio žiedas	13.52	101	0	0	1365.52
	Antakalnio žiedas → Gerosios Vilties st.	9.36	0	84	83	1563.12
	Gerosios Vilties st. → Antakalnio žiedas	9.22	0	84	82	1530.52
6	Šaltinėlio st. → Valkininkų st.	13.29	110	87	86	3761.07
	Valkininkų st. → Žirmūnų žiedas	12.94	111	88	86	3687.90
7	Skalvių st. → Stotis (A)	11.12	149	112	110	4125.52
	Stotis (A) → Skalvių st.	10.90	153	112	111	4098.40
9	Pasakų parkas → Žirmūnų žiedas	11.42	67	45	44	1781.52
	Šaltinėlio st. → Pasakų parkas	10.99	67	45	44	1714.44
10	Senoji plytinė → Naujininkai	12.26	71	45	43	1949.34
	Naujininkai → Senoji plytinė	11.80	73	43	42	1864.40
12	Šaltinėlio st. → Valkininkų st.	13.78	60	29	28	1612.26
	Valkininkų st. → Žirmūnų žiedas	13.77	60	29	28	1611.09
15	Stotis (F) → Titnago st.	9.17	18	0	0	165.06
	Titnago st. → Stotis (F)	8.84	18	0	0	159.12
16	Pašilaičių žiedas → Stotis (F)	11.95	88	74	73	2808.25
	Stotis (F) → Pašilaičių žiedas	12.30	91	74	73	2927.40
17	Šaltinėlio st. → Naujininkai	10.28	120	82	81	2909.24
	Naujininkai → Žirmūnų žiedas	10.21	119	83	82	2899.64
18	Skalvių st. → Titnago st.	14.49	95	40	39	2521.26
	Titnago st. → Skalvių st.	14.89	97	40	40	2635.53
19	Pašilaičių žiedas → Senoji plytinė	14.15	84	59	57	2830.00
	Senoji plytinė → Pašilaičių žiedas	14.21	83	59	58	2842.00
20	Šaltinėlio st. → Stotis (A)	8.96	48	36	36	1075.20
	Stotis (A) → Žirmūnų žiedas	8.70	48	36	36	1044.00
21	Antakalnio žiedas → Žirmūnų žiedas	5.25	24	0	0	126.00
	Šaltinėlio st. → Antakalnio žiedas	4.98	24	0	0	119.52
Total						66,403.37

There are currently 16 trolleybus lines in operation in the city and partial services. However, these partial services were disregarded in this study because they are irregular. Table 1 provided an operational summary of the trolleybus lines monthly (considering 22 working days, 4 Saturdays, and 4 Sundays).

The CO₂ emissions that were not emitted were quantified using the formula adopted in Equation (3):

$$Emta = Fm \times Ekm (bus), \quad (3)$$

where *Emta*—Emissions of CO₂ avoided by trolleybus in kg, *Fm*—Fleet mileage in km, *Ekm(bus)*—Emissions of CO₂ (kg)/km for bus service.

Emissions of CO₂ that were not emitted were converted into carbon credits to establish a monetary value that allowed us to quantify the gains of the system. To this end, we adopted Equation (4):

$$CC = VCC \times \left(\frac{Emta}{1000} \right), \quad (4)$$

where *CC*—Carbon Credits in EUR, *VCC*—Value of Carbon Credits in EUR per ton, *Emat*—Emissions of CO₂ avoided by trolleybus in kg.

Regarding negative impacts to the communities, we obtained the estimated values of local gases and GHG emissions according to Tables 2 and 3 and Equations (5) and (6) [57]. The negative impact is a disadvantage caused by transport systems and refers to the need for infrastructure and the environmental impacts caused by transport systems [58,59].

$$LGC = MAPm \times Dist \times Pas, \quad (5)$$

where *LGC*—Local Gases Cost, *Dist*—Distance of the displacement in kilometers per month, *Pas*—Factor Number of Passengers (passenger transported per month/kilometers per month).

$$GHGC = MCCm \times Dist \times Pas, \quad (6)$$

where *GHGC*—Greenhouse Gases Cost, *Dist*—Distance of the displacement in kilometers per month, *Pas*—Factor Number of Passengers (passenger transported per month/kilometers per month).

Table 2. Marginal air pollution costs for metropolitan area (urban roads) in EUR per passenger × kilometer (MAPm).

Mode of Transportation	Fuel Type	Size (Engine Cubic Capacity or Vehicle Dimension)	Emission Class	Value (EUR/Pass × km)
Bus (Ordinary Bus)	Diesel	15 to 18 tonnes	Euro 6	0.0012
Bus (Coach)	Diesel	>18 tonnes	Euro 6	0.0014

Table 3. Marginal climate change costs for urban roads in EUR per passenger × kilometer (MCCm).

Mode of Transportation	Fuel Type	Size (Engine Cubic Capacity or Vehicle Dimension)	Emission Class	Value (EUR/Pass × km)
Bus (Ordinary Bus)	Diesel	15 to 18 tonnes	Euro 6	0.0061
Bus (Coach)	Diesel	>18 tonnes	Euro 6	0.0062

We considered the values of “ordinary bus” vehicles, which are urban buses with EURO 6 technology in an urban area, that is the vehicle closely similar to the Vilnius Trolleybus size. There are different models of trolleybus in operation. They can operate by merging into some lines, or even eventually replacing diesel vehicles; so it was agreed to use the 12.5 m trolleybus model for this study with a capacity for 100 passengers,.

After establishing the environmental impact costs, we compared the operation of Vilnius trolleybus systems with conventional diesel engine vehicles and battery electric buses.

3.3. Emissions of CO₂ to Atmosphere by Diesel Engines

Additionally, we analyzed the actual values of CO₂ emitted into the atmosphere by diesel engines. The calculations included data from commercial fuel and laboratory-tested fuel from another station. The data are presented in Table 4.

Table 4. Physicochemical properties of diesel fuel.

Indicator Name	Value Fuel 1 (Class B0)	Value the Fuel Test Meets the Requirements of the Standard PN-EN 590:2022-08 [60]
Cetane number not less than (test method PN-EN ISO 5165)	52.6	51
Fractional composition up to 65% distilled at a temperature of °C, not higher (test method PN-EN ISO 3405)	250	250
minimum 5% to a temperature of °C		
95% distilled to a temperature of °C	350 Max. 360	350 Max. 360
Kinematic viscosity at 40° (mm ² /s) (test method PN-EN ISO 3104)	2.0–4.5	2.15
Sulfur content [mg/kg] (test method according to PN-EN ISO 20846, PN-EN ISO 20884 standards)	Max. 10	8.8
Ash content [%], not more than (test method PN-EN ISO 6245)	0.01	0.01
Coking residue in 10% distillation residue (test method PN-EN ISO 10370)	0.30	0.27
Density at 15 °C, kg/m ³ (test method according to PN EN ISO 12185, PN EN ISO 3675 standards)	820–845	833.6
Flash point [°C] (test method PN-EN ISO 2719)	Minimm 56	61
Water content mg/kg/% (test method PN-EN ISO 12937)	Max. 200/0.02	22

A higher cetane number promotes more efficient combustion, which can lead to lower CO₂ emissions. For this reason, the effect of the cetane number on the correction was investigated.

Cetane number coefficient K_{LC}

At the beginning of our study, the effect of the cetane number on carbon dioxide emission was calculated. The cetane number Coefficient K_{LC} was determined for each fuel, assuming a reference fuel with LC = 51, Equations (7)–(9). The coefficient $\alpha = 0.01$ reflects the inverse relationship between the cetane number and CO₂ emissions. Higher CN typically results in more complete combustion, reducing the formation of intermediate hydrocarbons and associated CO₂ output. The literature supports that a 10-unit increase in CN can reduce CO₂ emissions by approximately 1–2% [61,62]:

$$K_{LC} = 1 - \alpha \left(\frac{LC - 51}{51} \right) = 1. \quad (7)$$

Assuming $\alpha = 0.01$ (literature data)

Fuel 1, Table 4: LC = 52.6

$$K_{LC} = 1 - 0.01 \left(\frac{52.6 - 51}{51} \right) = 0.997. \quad (8)$$

Fuel 1, Table 4: LC = 51

$$K_{LC} = 1 - 0.01 \left(\frac{51 - 51}{51} \right) = 1. \quad (9)$$

Density of the fuel

Then the density of the fuel was considered. For this purpose, the density coefficient K_ρ was calculated, Equation (10):

$$K_\rho = \frac{\rho}{\rho_{ref}}. \quad (10)$$

Take $\rho_{ref} = 833.6 \text{ kg/m}^3$ (from the fuel tested in the laboratory in accordance with the normative guidelines). Panel 1, Table 4: $\rho_1 = 845 \text{ kg/m}^3 = 845$, Equation (11).

$$K_{\rho 1} = \frac{845}{833.6} \approx 1.014. \quad (11)$$

Fuel 2, Panel 2, Table 4: $\rho_2 = 833.6 \text{ kg/m}^3$, Equation (12).

$$K_{\rho 2} = \frac{833.6}{833.6} = 1. \quad (12)$$

CO₂ emission

Then, the CO₂ emission formula takes the form, Equation (13):

$$E_{km} (bus) = \frac{E_{es} \cdot K_\rho \cdot K_{LC}}{E_f}. \quad (13)$$

Assuming $E_{es} = 3.2 \text{ kg CO}_2/\text{L}$ and $E_f = 2.5 \text{ km/L}$, Equations (14) and (15).

Fuel 1, Panel 1 Table 4:

$$E_{km1} (bus) = \frac{3.2 \cdot 1.014 \cdot 0.997}{2.5} \approx 1.29 \frac{\text{kg CO}_2}{\text{km}}. \quad (14)$$

Fuel 2, Panel 2 Table 4:

$$E_{km2} (bus) = \frac{3.2 \cdot 1 \cdot 1}{2.5} \approx 1.28 \frac{\text{kg CO}_2}{\text{km}}. \quad (15)$$

Viscosity and sulfur content

In the next stage, in order to compare the emission of the described fuels with the properties presented in Table 4, the viscosity and sulfur content were considered. For this reason, the following coefficients were calculated: viscosity K_v and sulfur content K_s .

It should be emphasized that viscosity affects the process of fuel atomization in the combustion chamber, which in turn affects the combustion efficiency and emission of harmful combustion products into the atmosphere. In the case of kinematic viscosity, we can assume a linear relationship, Equation (16):

$$K_v = \frac{\nu}{\nu_{ref}}. \quad (16)$$

where ν —kinematic viscosity of the tested fuel (mm^2/s), ν_{ref} —reference viscosity (e.g., $2.15 \text{ mm}^2/\text{s}$ for fuel compliant with PN-EN 590).

The calculations adopt the lower and upper limits of the viscosity range given in Table 4: $\nu_{\text{L}} = 2.0 \text{ mm}^2/\text{s}$ (lower limit of the range) and $\nu_{\text{U}} = 4.5 \text{ mm}^2/\text{s}$ (upper limit); hence the middle value $\nu_{\text{M}} = 3.25 \text{ mm}^2/\text{s}$ was adopted for the calculations. From the

experimental data of the tested second fuel, the exact viscosity value was obtained equal to $\nu_2 = 2.15 \text{ mm}^2/\text{s}$. Taking into account the above values, the viscosity coefficients of the first and second fuels are as follows, Equation (17):

$$K_{\nu 1} = \frac{3.25}{2.15} \approx 1.51, \quad K_{\nu 2} = 1. \quad (17)$$

Then, the sulfur content coefficient K_S was determined for both analyzed fuels. Higher sulfur content can lead to incomplete combustion and increased emissions. We can assume an inverse relationship to the sulfur value, Equation (18):

$$K_S = 1 + \beta \left(\frac{S - S_{ref}}{S_{ref}} \right). \quad (18)$$

where S —fuel sulfur content (mg/kg), S_{ref} —reference sulfur content (adopted 8.8 mg/kg), β —impact factor (0.005).

The coefficient $\beta = 0.005$ captures the impact of increased sulfur on CO_2 emissions, as sulfur compounds may inhibit clean combustion and promote particulate formation, indirectly leading to inefficient oxidation of carbon. Empirical data suggest that reducing sulfur from 500 ppm to 50 ppm leads to a reduction in CO_2 emissions of about 0.5–1% [63,64].

The following values were used to calculate the sulfur content coefficients for individual fuels: $S_1 = 10 \text{ mg/kg}$, $S_2 = 8.8 \text{ mg/kg}$, Equation (19):

$$K_{S1} = 1 + 0.005 \left(\frac{10 - 8.88}{8.88} \right) \approx 1.0007, \quad K_{S2} = 1 \quad (19)$$

CO_2 emissions extended Formula

The above analyses allowed us to further extend the formula for CO_2 emissions, Equation (20):

$$E_{km} (bus) = \frac{E_{es} \cdot K_{\rho} \cdot K_{LC} \cdot K_{\nu} \cdot K_S}{E_f}. \quad (20)$$

Assuming the following as in the previous calculations: $E_{es} = 3.2 \text{ kg CO}_2/\text{L}$, $E_f = 2.5 \text{ km/L}$.

Flash point

The next stage of the analysis was to take into account the flash point. Therefore, the flash point coefficient K_T of both analyzed fuels was determined.

It should be emphasized that the flash point affects the safety and stability of combustion—fuel with a higher flash point is less susceptible to premature ignition, which can improve combustion efficiency and reduce emissions. A linear relationship was assumed, Equation (21):

$$K_T = 1 + \gamma \left(\frac{T - T_{ref}}{T_{ref}} \right). \quad (21)$$

where T —ignition temperature of the tested fuel [$^{\circ}\text{C}$], T_{ref} —flash point of the reference fuel (assumed 56°C), γ —ignition temperature influence factor (assumed 0.005).

The coefficient $\gamma = 0.005$ accounts for the role of flash point temperature in combustion stability. Fuels with higher flash points are less prone to premature ignition, leading to more stable and complete combustion, which slightly improves CO_2 performance. While this effect is secondary, it is supported in the following studies [65,66].

The following values from Table 4 were assumed for calculations: $T_1 = 56$ [°C], $T_2 = 61$ [°C]. Substituting into the formula, we obtained, Equation (22):

$$K_{T1} = 1 + 0.005 \left(\frac{56 - 56}{56} \right) = 1K_{T2} = 1 + 0.005 \left(\frac{61 - 56}{56} \right) = 0.9955. \quad (22)$$

Fractional composition

The next very important element of the research was the analysis of the fractional composition, which affects the way the fuel evaporates, which is important for the combustion process. We can assume the average distillation temperature (T_5 , T_{65} , T_{95}) as a representative parameter.

The fractional composition coefficient has the form, Equation (23):

$$K_F = \frac{T_{95}}{T_{ref}}. \quad (23)$$

where T_{95} —temperature at which 95% of the fuel evaporates, T_{ref} —reference temperature (e.g., 360 °C).

For both analyzed fuels, the temperature T_{95} is 360 °C, hence this coefficient will be, Equation (24):

$$K_{F1} = K_{F2} = \frac{360}{360} = 1. \quad (24)$$

Taking into account the subsequent coefficients in the CO₂ emission Formula (20), it takes the form, Equation (25):

$$Ekm (bus) = \frac{Ees \cdot K_\rho \cdot K_{LC} \cdot K_v \cdot K_S \cdot K_T \cdot K_F}{Ef}. \quad (25)$$

3.4. Emissions of CO₂ by Electricity Source

The next stage of the research was to estimate CO₂ emissions based on data collected from the analyzed countries. It should be emphasized that CO₂ emissions from electric vehicles are so-called shifted emissions, which means that the CO₂ emissions occurred during electricity generation. Based on the data included in Table 5 regarding average CO₂ emissions for various sources of electricity and taking into account the percentage share of each source in electricity generation in Lithuania, Latvia, and Estonia, in this way, a model of the energy mix of individual countries was created, which allows for more accurate determination of the shifted emissions.

For electric vehicles, CO₂ emissions depend on the energy mix of the country/region. For this reason, the CO₂ emission factor for electricity (E_{grid}) was introduced, which expresses emissions in kg CO₂/kWh. Only the energy mix of Lithuania was taken into account, due to the fact that the analyzed data come from Vilnius, the capital of Lithuania, and concern trolleybus lines.

General formula of the sources of electricity, Equation (26):

$$Ekm (electric) = \frac{E_{grid} \cdot E_{cons}}{\eta_c}, \quad (26)$$

where $Ekm(electric)$ —CO₂ emissions of an electric vehicle (kg CO₂/km), E_{grid} —average CO₂ emissions for electricity production (kg CO₂/kWh), E_{cons} —energy consumption of an electric vehicle (kWh/km), η_c —battery transfer and charging efficiency (0–1).

Table 5. Summary of average CO₂ emissions for different electricity sources, expressed in grams of CO₂ per kilowatt-hour [67].

Technology	CO ₂ Emissions (gCO ₂ /kWh)
Coal	820
Oil shale	820
Biomass co-fired with coal	740
Natural gas	490
Biomass	230
Photovoltaics (ground-mounted)	48
Photovoltaics (roof-mounted)	41
Geothermal energy	38
Concentrated solar energy	27
Hydropower	24
Wind energy (offshore)	12
Nuclear energy	12
Wind energy (onshore)	11

If energy comes from different sources, the average electricity emission can be calculated as, Equation (27):

$$E_{grid} = \sum (S_i \cdot E_i), \quad (27)$$

where S_i —share of a given energy source in the energy mix, E_i —CO₂ emissions for a given source (kg CO₂/kWh).

The latest available data on the energy mix of Lithuania, Latvia, and Estonia are from 2023. Below are the details for each of these countries, Table 6:

Table 6. Energy percentual by Baltic country.

Lithuania (2023)	Latvia (2023)	Estonia (2021)
Natural gas: ~50%	Hydropower: ~40%	Oil shale: ~60%
Renewable energy sources (RES): ~30% (mainly biomass and wind)	Natural gas: ~35%	Renewable energy sources: ~25% (mainly wind)
Energy import: ~20%	Renewable energy sources: ~15% (mainly biomass) Energy import: ~10%	Energy import: ~15%

4. Results and Discussion

4.1. Comparison Emission CO₂ Trolleybus × Diesel Buses

Emissions avoided in CO₂ by the trolleybuses in Vilnius and the respective calculation of the carbon credits can be seen in Tables 7 and 8.

Table 7. CO₂ not emitted by trolleybus system in Vilnius.

Variable	Fleet Mileage per Month in km (Fm)	Emissions of CO ₂ (kg)/km for Bus Service (Ekm(bus))	Total (kg of CO ₂)
Emissions of CO ₂ avoided by trolleybus in kg (Emat)	66,403.37	1.28	84,996.32

Table 8. Carbon credits equivalent CO₂ not emitted by trolleybus system in Vilnius.

Variable	Value of Carbon Credits in EUR per Ton (VCC) ¹	Emissions of CO ₂ Are Avoided by Trolleybus in Ton. (Emta/1000)	Total EUR
Carbon Credits (CC)	69.56	84,996.32	5912.34

¹ Carbon credits were EUR 69.56 per ton on 25 February 2024 [68].

Vilnius trolleybus system prevents the release of 84,996.32 kg of CO₂ into the atmosphere every month. Our results confirm and contribute to the discussions of the findings of Chamakhi et al. [67] that indicate a significant causality effects between CO₂ emissions and passenger movements, where there is the need to consider multiple economic and situational factors in predicting transportation trends, here indicated by electrification of the bus fleet.

First, the value of 84,996.32 kg CO₂/month presented in Tables 7 and 8, and in the abstract, represents “gross avoided emissions”—that is, the amount of CO₂ that would have been emitted if the trolleybus system had been operated entirely by Euro 6 diesel buses. This value was derived using the methodology proposed by Carvalho (see Section 2.2), based on a fleet mileage of 66,403.37 km/month and an emission rate of 1.28 kg CO₂/km for diesel buses. This figure serves as a comparative baseline.

These figures indicate a monthly carbon credit of EUR 5912.34 for the city. This result is aligned to Yu et al. [69] work that established to mitigate carbon emissions and exploit underutilized lanes (e.g., bus lanes), depending on a credit-based reservation scheme (CRS) proposed to optimize road resources, allowing travelers to switch from the high-emission mode to the low-emission mode and consequently gain obtain carbon credits.

Regarding negative impacts on communities, Table 9 presents the values calculated for Local Gases and GHGs.

Table 9. Negative impacts on communities.

Variable	EUR Pass./km	Passengers (Month)	Distance (Month)	Factor Passenger per km	Total (EUR per Month)
Local Gases Cost (LGC)	0.0116	6,000,000	66,403.37	90.36	69,602.42
Greenhouse Gases (GHG)	0.006	6,000,000	66,403.37	90.36	36,001.25
Total (EUR per Month)					105,603.67

The values for Local Gases and GHGs not emitted by trolleybuses correspond to EUR 105,603.67 per month or EUR 1,267,244.04 per year. Local Gases and GHG are a harsh scenario for transport. According to Henke et al. [70] road transport contributes over 90% of total transport GHG emissions.

The benefits of the reduction of emissions can be seen in Table 10.

Table 10. Benefits of no emissions by Vilnius trolleybus systems.

Variable	Carbon Credits (CC)	Negative Impact on Communities	Total (EUR per Month)
Benefits of no Emissions	5012.34	105,603.67	110,616.01

As stated in Table 10, the favorable impact of trolleybus use in Lithuania is evident, offering rewards to society that go beyond the numbers and involve satisfaction for environmental preservation of the local area. This result confirms the need for continuous

investment in trolley bus technology, mainly using IMC. In this sense, Iliopoulou et al. [21] affirm that cities with extensive catenary networks can establish efficient IMC transit systems with minimal investment, and even a 20% coverage suffices to maintain investment costs low.

4.2. Emission of CO₂ by Diesel Buses

When comparing the cetane number and density of the fuels used, the difference in CO₂ emissions between these fuels is small—the fuel with a higher cetane number and density emits about 0.78% more CO₂ per km, which is mainly due to the greater amount of fuel burned per unit volume.

Assuming the following as in the previous calculations: $E_{es} = 3.2 \text{ kg CO}_2/\text{L}$, $E_f = 2.5 \text{ km/L}$ in the methodology section, the CO₂/km for diesel fuels are as follows.

For the first analyzed fuel the following results were obtained, Equation (28):

$$E_{km1}(bus) = \frac{3.2 \cdot 1.014 \cdot 0.997 \cdot 1.51 \cdot 1.0007}{2.5} \approx 1.95 \text{ kg CO}_2/\text{km} \quad (28)$$

The calculations for the second set of data (Panel 2 Table 4) are presented, Equation (29):

$$E_{km2}(bus) = \frac{3.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1}{2.5} = 1.28 \text{ kg CO}_2/\text{km} \quad (29)$$

Analyzing the obtained results, it can be seen that Fuel 1, despite its favorable cetane number, has higher CO₂ emissions (approx. 1.95 kg/km), which is mainly due to its higher viscosity, which increases fuel flow resistance, with slightly higher density. On the other hand, Fuel 2, which meets the PN-EN 590 standard, is more optimized in terms of emissions, with a value of 1.28 kg/km.

Assuming as before: $E_{es} = 3.2 \text{ kg CO}_2/\text{L}$, $E_f = 2.5 \text{ km/L}$ and substituting the values of the remaining coefficients calculated in the extend CO₂ equation, we obtain the following:

$$E_{km1}(bus) = \frac{3.2 \cdot 1.014 \cdot 0.997 \cdot 1.51 \cdot 1.0007 \cdot 1.1}{2.5} \approx 1.95 E_{km2}(bus) = \frac{3.2 \cdot 1 \cdot 1 \cdot 1 \cdot 0.9955 \cdot 1}{2.5} \approx 1.27 \quad (30)$$

where $E_{km}(bus)$ —Emissions of CO₂ (kg)/km for bus service, E_{es} —Emissions for energy source in CO₂ (kg)/L, E_f —Energy efficiency in km/L.

This part of the paper extends the Carvalho methodology [54] to estimate CO₂ emissions that would result if the Vilnius trolleybus lines were operated by diesel buses burning fuels with the physicochemical properties described in Table 4.

The final formula takes into account the influence of such physicochemical quantities important in the combustion process, such as density, cetane number, kinematic viscosity, sulfur content, flash point, and the temperature at which 95% of the fuel evaporates [71]. The $E_{km}(bus)$ formula has become more universal and allows for the analysis of other commercially available fuels (crude oil) in order to evaluate or optimize the created fuel in terms of emission optimization.

Analyzing the results obtained from the final formula, it shows that Fuel 1 with the value of $E_{km}(bus) = 1.95 \text{ kg CO}_2/\text{km}$, is characterized by higher viscosity and higher density resulting in higher emissions in relation to Fuel 2. On the other hand, Fuel 2 $E_{km}(bus) = 1.27 \text{ kg CO}_2/\text{km}$ has lower viscosity and a slightly higher flash point improving combustion efficiency.

4.3. Emission of CO₂ by Electricity Sources

In order to compare the CO₂ emissions of Lithuania's electric vehicle with other Baltic countries (Latvia and Estonia), the energy mix of all these countries was analyzed. To estimate the CO₂ emissions related to electricity production in the Baltic countries, a

formula can be used that takes into account the energy mix of each of these countries [72]. This formula allows the calculation of the average CO₂ emissions per unit of electricity produced, taking into account the share of individual energy sources in the total production and their individual emission indicators [31,73–75].

The results can be seen in Equations (29)–(31).

1. Lithuania:

$$E_{grid} = \sum (S_i \cdot E_i) = 0.4 \cdot 0.49 + 0.3 \cdot 0.09 + 0.2 \cdot 0 = 0.245 + 0.027 = 0.272 \text{ kg CO}_2/\text{kWh}, \quad (31)$$

2. Latvia:

$$E_{grid} = \sum (S_i \cdot E_i) = 0.5 \cdot 0.024 + 0.35 \cdot 0.49 + 0.1 \cdot 0 = 0.012 + 0.1715 = 0.1835 \text{ kg CO}_2/\text{kWh}, \quad (32)$$

3. Estonia:

$$E_{grid} = \sum (S_i \cdot E_i) = 0.6 \cdot 0.82 + 0.25 \cdot 0.011 + 0.15 \cdot 0 = 0.429 + 0.00275 = 0.49475 \text{ kg CO}_2/\text{kWh}, \quad (33)$$

The above calculations show that the average CO₂ emissions in Lithuania are 0.272 kg CO₂/kWh, which indicates a moderate level of emissions, mainly due to the significant share of natural gas and RES. The lowest average CO₂ emissions of 0.1835 kg CO₂/kWh are in Latvia, due to the high share of hydropower and other RES. Estonia, on the other hand, has the highest average CO₂ emissions of 0.49475 kg CO₂/kWh, which is due to the dominant share of oil shale in energy production. Substituting the obtained values of Lithuania's E_{grid} into the formula gives us the estimated value of the electric vehicle's CO₂ emissions (kg CO₂/km), Equations (32) and (33):

$$E_{km} (electric) = \frac{0.272 \cdot 1.4}{0.85} = 0.448 \text{ kg CO}_2/\text{km}, \quad (34)$$

Comparing the obtained value of z to the obtained emissions of combustion buses

$$E_{km2} (bus) \approx 1.27 \frac{\text{kg CO}_2}{\text{km}}. \quad (35)$$

This means that an electric bus reduces CO₂ emissions by about 64.72%.

4.4. Additional Analysis

Figure 1 illustrates the differences in CO₂ emissions between diesel (a) and electric (b) vehicles, depending on the distance travelled (km). Both graphs show a clear trend—as the use of electric vehicles (EVs) increases and their CO₂ efficiency increases, diesel bus emissions significantly exceed those of electric vehicles.

Figure 1 presents a three-dimensional regression surface obtained using the distance weighted least squares (DWLS) method, illustrating the dependency of CO₂ emissions from diesel-powered vehicles (expressed in kg/km) on two variables: the CO₂ emissions of electric vehicles (also in kg/km) and the driving distance (in kilometers). The purpose of this visualization is to examine the operational and energetic ranges in which electric vehicles offer greater environmental benefits compared to their diesel counterparts.

The analysis indicates that in the range of low electric CO₂ emissions (CO₂ < 0 kg/km), which may correspond to energy sources based on renewables (e.g., photovoltaic or wind power), electric vehicles demonstrate a clear environmental advantage. In this range, the CO₂ emissions of diesel vehicles exceed 300 kg/km, classifying them as high-emission transport options. As the emissions from electric sources increase (e.g., due to a fossil fuel-based energy mix), the relative advantage diminishes, and in certain domains, diesel vehicles may exhibit lower emissions.

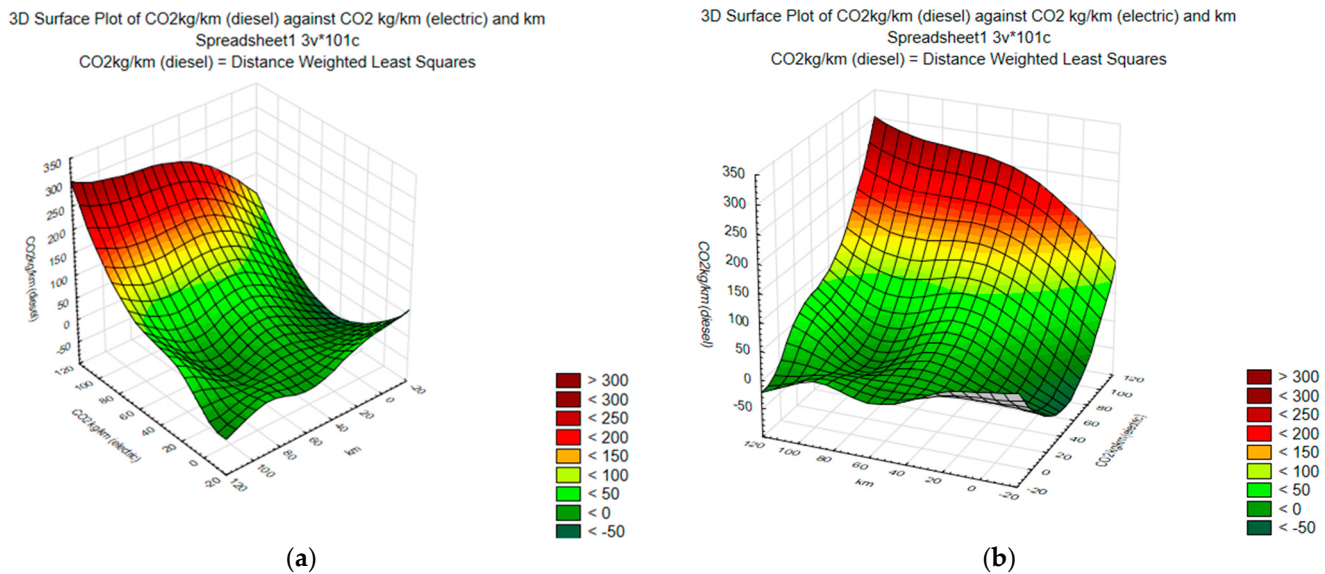


Figure 1. (a,b) 3D Regression surface of diesel CO₂ emissions vs. electric CO₂ and distance.

Moreover, the dependency on driving distance shows a distinct decrease in diesel vehicle CO₂ emissions per kilometer with increasing trip length. Notably high emissions are observed in the short-distance range (0–20 km), which can be attributed to engine inefficiency during cold starts and suboptimal fuel utilization. For longer distances (above 80 km), emissions stabilize or even exhibit local minima, which may indicate optimal engine performance under steady-state driving conditions.

The shape of the regression surface confirms the nonlinear nature of the analyzed relationship and emphasizes the need for locally weighted methods such as DWLS, which are capable of capturing subtle variations and contextual dependencies within the data. Overall, the results underscore the significant influence of the energy source and vehicle usage profile in the assessment of actual transport-related CO₂ emissions.

Red spots depict the highest CO₂ emissions typical of diesel buses, while green areas indicate reduced CO₂ emissions connected with electric transportation. The color gradient of the surface obviously distinguishes the emission levels. Diesel bus emissions are noted as remaining significant even at smaller distances driven, suggesting their great fuel consumption intensity and emission generating power even on short routes.

The study of causal interactions reveals several really significant results. First, diesel buses produce more direct emissions as well as secondary pollutants connected to fuel extraction and processing, which contaminate the surroundings. Second, the growing share of renewable energy sources in the whole energy mix helps to explain the declining emissions from electric vehicles with increasing distance; so, electric transportation becomes an increasingly sustainable choice. Third, there is a strong correlation between the increasing prevalence of electric transport and the decreasing CO₂ emissions from all transport, which confirms the environmental impact of electrification strategies.

In summary, the presented diagrams illustrate the fundamental difference between diesel and electric bus emissions. It is clearly seen that electrification offers the opportunity to significantly reduce the climate-change impact of the transport sector.

5. Conclusions

This paper analyzed the trolleybus contribution to decarbonization of urban public transport system in cities based on the adoption of electric energy using as the study the city of Vilnius, Lithuania. In addition, the article compared and calculated CO₂ emissions

of diesel engines using secondary data and two types of fuel. Eventually, it considered the effects of energy matrix to decarbonization of transport through adoption of electric buses.

The results confirm that the Vilnius trolleybus system significantly reduces CO₂ emissions compared to diesel buses. In addition, the incorporation of fuel physicochemical properties demonstrates a monthly CO₂ reduction of 84,996.32 kg, which directly contributes to air quality improvement and aligns with European Union decarbonization goals. After accounting for the emissions from electricity production, the net reduction is approximately 61,569 kg CO₂/month, equivalent to ~EUR 4284 in carbon credits.

Ultimately, this analysis reinforces our main conclusion: even when accounting for shifted emissions, trolleybuses provide a significantly lower environmental footprint than diesel buses. As Lithuania transitions further towards renewable energy, the environmental benefits of the trolleybus system will become increasingly substantial.

As Lithuania gradually transitions to renewable energy sources, the trolleybus system's environmental benefits will continue to grow. The research highlights that avoided CO₂ emissions translate into approximately EUR 5912.34 per month in carbon credits, reinforcing the economic benefits of trolleybus operations. These findings suggest that trolleybus systems provide both direct financial gains and long-term societal advantages.

Adopting In-Motion Charging (IMC) technology enhances the efficiency and flexibility of trolleybus networks worldwide by allowing partial off-grid operation. The Vilnius case confirms this trend because IMC reduces reliance on extensive overhead wiring, lowers infrastructure maintenance costs, and enables service continuity in areas where aerial networks are impractical. The study suggests that expanding IMC trolleybus use could further optimize public transport efficiency while maintaining low emissions.

This paper has certain limitations as it did not have access to all operational costs of the service. However, this does not interfere in identifying the environmental benefits of trolleybus operation in Vilnius city.

As future research, we suggest understanding how Vilnius actually accesses policy instruments (e.g., GPP, Cohesion Funds), with more case-specific policy implementation, and, in addition, to compare those costs with diesel and battery buses operation.

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