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Research Paper

Sustainability in Urban Waste Management: The Efficiency of Electric Waste Transport Vehicles

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Abstract. This study evaluates the long-term economic feasibility of electric waste collection vehicles (EVs) as a sustainable alternative to diesel-powered counterparts in urban municipal services. Using real operational data from a Hungarian waste management company, we developed a total cost of ownership (TCO) model spanning 10 years, which incorporates investment costs, energy consumption, maintenance, depreciation, and battery replacement. Our analysis reveals that although EVs require a significantly higher upfront investment (€350,000 vs. €183,200), their lower operational and maintenance costs result in a break-even point around year 8. When accounting for a €50,000 battery replacement in year 6, the total 10-year cost of the EV remains lower (€431,769 vs. €450,914) than the diesel vehicle, resulting in a net saving of €19,145. The study emphasizes the significance of local energy prices and service structures in assessing fleet electrification. While the findings are based on Hungarian data, the proposed methodology can be adapted internationally to support data-driven decision-making in sustainable waste logistics.

Keywords: Green Logistics, EV Cost Analysis, Urban Waste Management, Sustainable Logistics

Introduction

The level of air pollution has been a growing global problem in our society, particularly in metropolitan environments with high population densities. This is caused by an exceptionally high proportion of harmful gases and greenhouse gases from the use of motor vehicles. Air pollution is, therefore, one of the leading causes of death worldwide, claiming many people's lives.

The solution to this could be the continuous tightening of emission limit values, thereby encouraging the automotive industry to make "forced" developments of green innovations. However, exceeding a certain level, the specific production and operating costs of vehicles will increase drastically in proportion to the further emission reduction that is still available [1]. Another solution could be the use of vehicles in the municipal sector, while electrically powered ones replace the older types of waste collection vehicles. In the communal sector, due to the nature of the service, waste collection vehicles are used continuously and are primarily used in residential areas [2].

In our study, we examined the use of electric-powered waste collection vehicles in a complex manner, as they could become an alternative solution to environmental pollution in the future, compared to

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waste collection vehicles with internal combustion engine (ICE) vehicles. Further alternative solutions, including fuel costs, repair and maintenance costs, investment-related costs, operational safety, and logistical goals, have been examined in our investigation and economic analysis from the operator's point of view [3]. Although it was not examined from an environmental protection perspective, its electric drive is already significantly more environmentally friendly than that of diesel-powered waste collection vehicles. Furthermore, energy policy is a key component of the priority strategy for smart and livable cities [4].

The novelty of this paper lies in the integration of real-life operational data into a total cost of ownership (TCO) framework. Unlike prior studies, this research compares full economic life-cycle costs using field data from a Hungarian municipal waste management company. Although the results are geographically limited to Hungary, the method can be generalized for comparative analysis across countries.

1. Literature review

1.1. Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles

The European Union has targeted developing and promoting the market for energy-efficient and clean vehicles. Primarily, the directive obliges market players using multiple or larger vehicles (e.g. public transport companies) and authorities to take into account the following when purchasing and then operating the vehicle:

- energy consumption,
- carbon dioxide (CO_2) emissions,
- emission of other pollutants [5].

These factors should be considered over the entire lifetime of the vehicle. The energetic and environmental effects established for the full lifespan of the vehicle must be examined already at the time of the vehicle purchase contract, both on the part of the contracting authorities and also on the part of the market participants fulfilling public service obligations under the public service contract. The following are considered energetic and environmental effects:

- carbon dioxide emissions,
- emissions of nitrogen oxides (NO_X), solid particles, and non-methane hydrocarbons (NMHC),
- energy consumption.

In order to fulfill the obligations regarding energy and environmental impacts, contracting authorities and market participants performing public service obligations can establish technical specifications for energy efficiency and performance, or they can incorporate energy and environmental impacts into the purchasing decision [1, 6].

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1.2. Recycling logistics

The environment in which manufacturing and service companies operate has undergone significant changes in recent years. Competitors have grown, markets have become more saturated, and competition has intensified. The result has been a focus on recycling as a technology-related activity, along with the associated logistics [7, 8].

Its main elements are collection, sorting, dismantling, distribution, recycling, and waste treatment [9]. The concept of collection also applies to end-of-life products and waste. Transport is also an integral part of the collection process, as well as sorting, storage, removal of hazardous substances, loading, and the formation of unit loads or picking. Recycling technologies are very closely linked to recycling logistics, and therefore, a good understanding of recycling technologies is essential when designing recycling logistics systems [10].

An essential characteristic of these systems is the need to collect used products for recycling from a large number of suppliers. The population is practically covered by the collection of all household waste. In this case, the population can be considered as the supplier. In such cases, a multi-stage collection system needs to be introduced [11]. Before such a system is introduced, the feasibility of single- and multi-stage systems and the investment and operating costs are examined at the design stage. The design of a multi-stage distribution system may be complicated by the number of actors involved on the other side of the recycling system, such as the number of recycling and processing sites, as well as the number of landfill sites [12].

Sorting is considered to be a rather important technological process as it requires significant logistical tasks such as storage, transport to the recycling site and unit load training. Further steps are loading, warehousing, inter-operational transport, further warehousing and loading, and then storage and packaging of the recycled products. An important part of waste logistics is transport, sorting, landfilling or destruction and recycling [13].

The waste management and recycling process is fully linked to the processes of procurement, production and distribution. When planning, it is essential to carry out the following activities:

determination of generation parameters, such as the location, quantity and type of waste generated:

- identification of the infrastructure and storage sites required for storage,
- planning and scheduling of collection and transport,
- determining the necessary transport and loading equipment,
- planning the specific administrative tasks involved,
- scheduling deliveries [14].

These planning tasks are related to all aspects of waste collection, transport, sorting, storage and, in addition, delivery activities.

2. Methodology

This study employs a Total Cost of Ownership (TCO) approach to evaluate and compare the economic viability of electric and diesel-powered waste collection vehicles over a projected 10-year operational

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period. The methodology integrates real-world operational data, technical specifications, and cost parameters collected from Hungary's municipal waste management sector.

2.1. Research framework

The comparative analysis considers both capital expenditures (CAPEX) and operational expenditures (OPEX), including:

- Initial investment costs (vehicle chassis, body, powertrain)
- Fuel/energy consumption and costs
- Annual maintenance and repair costs
- Amortization and residual value
- Battery replacement (for EV only)

This framework aims to reflect the realistic cost profile that a municipal operator would encounter over the lifecycle of a single vehicle.

2.2. Data collection

The data for the research comes from Debrecen, Hungary's waste management company, A.K.S.D. Ltd., which provides municipal and regional waste collection services. For the comparative analysis, data on consumption, operation, and costs of diesel and electric waste collection vehicles operated by the company were used during a 12-day test period. In addition, the research relies on technical specifications and cost data provided by Electromega Ltd. for electric waste collection vehicles.

The research compared the performance and cost-effectiveness of two types of waste collection vehicles: a conventional diesel and an electric version. The diesel vehicle was a Renault 26t waste collector with a gross vehicle weight of 26 tonnes, while the electric version was an Electromega URBAN 18ST, specifically designed for urban waste management. The diesel vehicle had an average consumption of 43.6 litres/100 km, while the electric version used 1.97 kWh/km of energy, resulting in significant fuel savings. The main advantage of the electric vehicle is its environmentally friendly operation, as it is fully electrically powered and, therefore, does not emit any pollutants. In contrast, the diesel vehicle has significant emissions of carbon dioxide and other air pollutants. The electric model has a battery capacity of 192.3 kWh, which can cover 66 km on a single charge, while the diesel version has a virtually unlimited range, depending on the refuelling options.

2.3. Cost calculation

The economic comparison is based on formulas used to calculate:

a. *Fuel cost per day and total fuel cost*

Based on energy consumption rates and national energy prices.

b. *Annual and total maintenance costs*

Sourced from operator experience and standard service packages.

c. *Amortization schedule*

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Applied using the Sum-of-the-Years-Digits (SYD) method for both vehicle types over 10 years (see Table 5). This depreciation method reflects the accelerated loss of value in the early years, which is realistic for municipal fleet usage.

d. Battery replacement cost

Battery replacement was considered as part of the long-term TCO scenario (see Results section for cost assumptions).

e. Cumulative TCO comparison

All the above costs are summed annually to determine the total ownership cost for each vehicle over time. Sensitivity to energy price trends is considered, with a 2.95% annual increase in diesel prices and a 2% annual reduction in electricity prices, based on historical trends and Eurostat data. The following formulas were applied as part of the TCO model:

$$Daily\ consumption\ (liter) = Total\ distance * \frac{Vehicle\ consumption\ (\frac{l}{100km})}{100} \tag{1}$$

$$Daily\ consumption\ (kWh) = Total\ distance * Vehicle\ consumption\ (kWh) \tag{2}$$

$$Daily\ fuel\ costs = Daily\ consumption\ (kWh\ or\ liter) * Fuel\ unit\ price\ (EUR) \tag{3}$$

$$Unit\ fuel\ cost\ (EUR/tons) = \frac{Daily\ fuel\ cost\ (EUR)}{Weight\ transported} \tag{4}$$

$$Amortization\ of\ X.year = \frac{Percentage\ of\ X.year\ (\%) * Investment\ cost\ (EUR)}{100} \tag{5}$$

This methodological framework is designed to be transferable across countries by substituting local cost parameters such as fuel prices, maintenance rates, or battery cost assumptions.

3. Results

3.1. Comparison of relevant operator aspects

Type of vehicle:	Renault 26t
Test site:	Debrecen
Testing period:	02/27/2023 - 03/10/2023
Type of waste:	Municipal solid waste
Net unit price of electricity:	0.08 EUR/kWh
Vehicle consumption:	1.97 kWh/km
Wholesale gas oil price including excise duty:	1.65 EUR/litre
Vehicle consumption:	43.6 lit/100km
Test run duration:	12 days
Collected waste:	174,680 tonnes
Daily average:	14.557 tonnes
Distance covered:	554 km
Daily average:	46.17 km

Table 1. Summary data for a comparative analysis of fuel costs for waste collection

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From an operational perspective, it is crucial to consider the speed of operation, the payload capacity of the vehicles, investment costs and depreciation, availability, safety, fuel costs, and repair and maintenance expenses [13].

Our comparison is based on waste collection vehicles with a total weight of 26 tonnes, 3-axle, compaction body. The results will include data for this type of vehicle.

The Renault 26t test run took place between 27/02/2024 and 10/03/2024 in and around Debrecen. The results are summarized in Table 1. Data in Table 1. are available information provided by A.K.S.D. Ltd.

Date	Start	Finish	Running (hours)	Daily running (hours)	Withdrawal distance (km)	Collection distance (km)	Entry distance (km)	Total distance (km)	Settlement	Collected weight(t)
02/27/2024	5:40	9:15	3:35	6:30	12	10	14	77	DEBRECEN	11.00
	9:15	12:10	2:55		14	4	23		DEBRECEN	2.56
02/28/2024	5:40	8:25	2:45	6:00	5	4	9	44	DEBRECEN	8.52
	8:25	11:40	3:15		5	16	5		DEBRECEN	10,.30
03/01/2024	5:30	8:35	3:05	6:30	5	7	8	52	DEBRECEN	8.16
	8:35	12:00	3:25		10	10	12		DEBRECEN	6.82
03/02/2024	6:00	8:00	2:00	6:30	2	3	5	45	DEBRECEN	8.54
	8:00	10:35	2:35		6	5	5		DEBRECEN	8,90
	10:35	12:30	1:55		3	6	10		DEBRECEN	5.40
03/03/2024	5:40	8:35	2:55	6:50	1	11	5	40	DEBRECEN	9.36
	8:35	12:30	3:55		3	12	8		DEBRECEN	7.50
03/04/2024	5:45	9:55	4:10	6:00	2	32	14	60	DEBRECEN	7.36
	9:55	11:45	1:50		3	7	2		DEBRECEN	4.26
03/05/2024	6:05	9:35	3:30	5:15	2	16	9	47	DEBRECEN	7.96
	9:35	11:20	1:45		7	5	8		DEBRECEN	4.00
03/06/2024	5:45	8:35	2:50	6:15	1	10	7	39	DEBRECEN	8.12
	8:35	12:00	3:25		6	5	10		DEBRECEN	5.50
03/07/2024	5:30	7:15	1:45	5:30	2	4	4	42	DEBRECEN	8.42
	7:15	9:00	1:45		5	5	5		DEBRECEN	7.72
	9:00	11:00	2:00		5	3	9		DEBRECEN	5.14
03/08/2024	5:45	8:35	2:50	6:15	1	10	5	39	DEBRECEN	9.46
	8:35	12:00	3:25		3	13	7		DEBRECEN	6.82
03/09/2024	5:30	10:00	4:30	6:30	4	30	14	66	DEBRECEN	6.70
	10:00	12:00	2:00		4	6	8		DEBRECEN	3.28
03/10/2024	5:30	6:45	1:15	1:15	2	1	1	4	DEBRECEN	2.00

Table 2. Test plant data summary table

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Based on the data in Table 1 and Table 2, it is possible to calculate the cost of a diesel waste collector at the given diesel consumption. Using the same data, the cost of an electric refuse collection vehicle can be calculated in parallel with the diesel vehicle. Using the TCO model described in the Methodology section, the following operational cost values were calculated for each day of the test.

Date	Diesel vehicle			Electric vehicle		
	Consumption (kWh)*	Fuel cost (EUR)	Unit fuel cost (EUR)	Consumption (kWh)	Fuel cost (EUR)	Unit fuel cost (EUR)
02/27/2024	325.62	55.4	4.09	151.69	12.14	0.89
02/28/2024	186.04	31.65	1.68	86.68	6.93	0.37
03/01/2024	219.59	37.4	2.50	102.44	8.20	0.55
03/02/2024	190.31	32.4	1.42	88.65	7.09	0.31
03/03/2024	169.16	28.78	1.71	78.8	6.30	0.37
03/04/2024	253.75	43.16	3.71	118.2	9.46	0.81
03/05/2024	198.75	33.81	2.83	92.59	7.41	0,62
03/06/2024	164.90	28.05	2.06	76.83	6.15	0.45
03/07/2024	177.60	30.21	1.42	82.74	6.62	0.31
03/08/2024	164.90	28.05	1.72	76.83	6.15	0.38
03/09/2024	279.06	47.48	4.76	130.02	10.40	1.04
03/10/2024	12.61	2.15	1.08	5.91	0.47	024
Total	2342.93	398.54	28.97	1091.38	87.31	6.35

Table 3. Fuel costs for diesel and electric vehicles

**Note: Diesel consumption was converted to energy equivalent using 1 litre diesel = 9.7 kWh for comparison purposes*

Table 3 shows the fuel consumption and fuel costs for both diesel and electric vehicles over a 12-day test period. The data includes the date, the amount of fuel consumed in litres or kilowatt-hours, the fuel cost in euros, and the unit fuel cost in euros per kilowatt-hour. Energy prices are specific to Hungary. Sensitivity analysis is recommended for other countries due to high variability in diesel and electricity costs.

Overall, the diesel vehicle consumed a total of 241.54 litres of fuel over the 12 days, costing a total of € 398.54 at an average unit fuel cost of € 1.65 per litre. On the other hand, the electric vehicle consumed a total of 1,091.38 kilowatt-hours of electricity, costing a total of € 87.31 at an average unit fuel cost of € 0.08 per kilowatt-hour.

The data show that the electric vehicle had significantly lower fuel costs and unit fuel costs compared to the diesel vehicle.

Time is also in favour of electric vehicles, as the average price of petroleum-based fuels is expected to continue on an upward trend in the future, as recent years have shown. The price of this type of fuel will increase more than that of electricity (Figure 1). This difference means that the cost of fuel for

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electrically powered vehicles will, therefore, be more and more favourable. Another positive aspect of electricity is that its price variation is more predictable and less volatile than that of diesel.

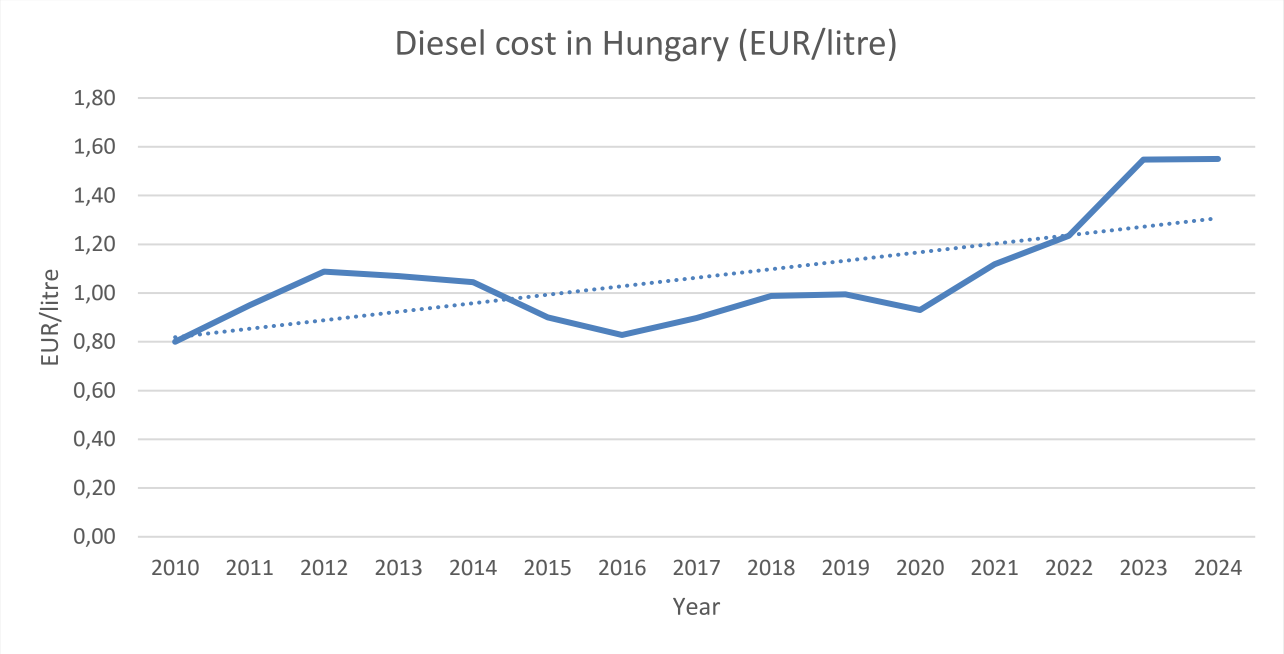

Figure 1. Average cost of diesel in Hungary

3.2. Investment expenditure and amortisation

When investing in a new waste collection vehicle, the following costs are incurred immediately:

- purchase of the chassis,
- the purchase of a body,
- the purchase of the propulsion system *[15]*.

The difference between diesel and electric vehicles will be the difference in propulsion at the time of investment [16]. For conventional refuse collection vehicles, the chassis and the drive train can be purchased as a given, assembled unit. For an electric refuse collection vehicle, a so-called E-drive will replace the conventional drive. This will ensure the operation of electricity. The chassis, which is designed to meet the requirements, will also require a superstructure to be purchased independently of the drive. These three things represent the most significant cost of the investment [17]. Table 4 shows the investment costs.

Diesel waste collection vehicle cost (EUR)		Electric waste collection vehicle (EUR)	
Chassis and drive	97500	Chassis	97500
Body	85700	Body	167000
-	-	E-drive	85500
Total	183200	Total	350000

Table 4. Costs for conventional (diesel-based) and electric waste collection vehicles

There is a big difference in investment costs due to the electric drive technology. This is due to a simple reason, such as low demand, since the high price often prevents sales from increasing sharply. Consequently, the seller offers their product at a higher price to achieve economic efficiency [18]. He is

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forced to maintain a higher price in the face of lower sales figures because he has had to invest in the development of technology in addition to unit production costs. Therefore, it aims to make a quick return on investment or profit. As demand increases, he can start to offer his product at increasingly affordable prices. As electric vehicles become more widespread, it is only a matter of time before prices also come down to lower and more affordable levels [2, 19].

Amortization and residual values were calculated for 10 years of planned use, which could be more depending on the condition of the vehicles. The sum-of-the-year's method was used in the calculations, which show the depreciation for the year in question, and then further calculated to obtain the residual values. To do this, the planned useful life and the cost of vehicles are first required.

Year	Percentage rate of amortisation
1	18.18%
2	16.6%
3	14.55%
4	12.73%
5	10.91%
6	9.09%
7	7.27%
8	5.45%
9	3.64%
10	1.82%

Table 5. Percentage rate of amortisation, calculated over 10 years

The amortisation schedule is based on the sum-of-the-years-digits method, following corporate tax guidelines [20]. Using the percentage rate of amortisation (Table 5), the following formula can be used to calculate the amortisation of vehicles from year to year:

The calculated values for conventional (diesel-based) waste collection vehicles are illustrated in Table 6.

Year	Amortisation (EUR)	Year	Amortisation (EUR)
1	33.335	6	16.500
2	30.000	7	13.500
3	26.500	8	10.000
4	23.500	9	6.500
5	20.000	10	3.500

Table 6. Amortization in the current year of conventional (diesel-based) waste collection vehicles

The amortization rate of electric waste collection vehicles was also calculated using equation 5. The resulting data are shown in Table 7.

Year	Amortisation (EUR)	Year	Amortisation (EUR)
1	63.500	6	32.000
2	57.500	7	25.500
3	51.000	8	19.000
4	44.500	9	12.500
5	38.000	10	6.500

Table 7. Amortization in the current year of electric waste collection vehicles

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It can be said that the amortization of an electric waste collection vehicle is much higher than that of a conventional vehicle every year. However, also considering that it is almost double the cost of the electric waste collection vehicle, these values were expected.

However, due to the cost value, the residual value of an electric waste collection vehicle is always higher than that of a conventional waste collection vehicle. It holds its value better and can be sold at a higher price later if necessary.

3.3. Cost structure, economic analysis

The average rate of change in diesel cost over the period 2010 to 2022 is about 3%. The fuel cost data in Table 14 is further calculated using this value from year to year. This gives the expected fuel costs for diesel collection vehicles in the next few years. For the electricity cost change, we used the value of -2% [21].

Disel waste collection vehicles		Electric waste collection vehicles	
Average cost of diesel	1.5 EUR / litre	Average cost of electricity	*0.08 EUR / kWh*
Consumption	43.6 l/100 km	Consumption	1.63 kWh/km
Daily consumption	46,216 litre	Daily consumption	173 kWh
Annual cost change of diesel	2.95%	Annual cost change of electricity	-2.00 %
Workdays / week	250	-	-
Average daily distance	106 km	-	-

Table 8. Data on which economic calculations are based

Table 8 shows the relevant data for the MAN chassis version used by A.K.S.D Ltd., which is also a 26-ton 3-axle, electrically powered waste collection vehicle.

It was assumed that the number of working days would be the same if a conventional waste collection vehicle were to be replaced entirely by an electrically powered one. The analysis assumes 250 working days, based on the Hungarian municipal waste collection practice, which operates 5 working days a week. However, if 300-320 working days were considered, the utilization rate and operational costs would further favor electric vehicles due to lower variable energy costs.

3.3.1. Diesel waste collection vehicle costs

The cost of vehicle fuel is on an upward trend, increasing by 2.95% per year. The vehicle, which initially had a fuel cost of 16,350 EUR, can be refueled for the same distance and time in the 10th year of use for more than 21,000 EUR. Furthermore, according to A.K.S.D. Ltd., the average annual service cost per diesel waste collection vehicle is around 8,000 EUR. Based on these figures, the total lifetime cost of a diesel refuse collection vehicle is 450,914 EUR, i.e., the cost to the owner over 10 years of expected use. These data are shown in Table 9.

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Year	Investment cost (EUR)	Fuel cost (EUR)	Service cost / year (EUR)	Total time-of-use costs (EUR)
1	183.200	16.350	8000	207.850
2	-	16.840	8000	24.840
3	-	17.345	8000	25.345
4	-	17.865	8000	25.865
5	-	18.400	8000	26.400
6	-	18.952	8000	26.952
7	-	19.520	8000	27.520
8	-	20.105	8000	28.105
9	-	20.708	8000	28.708
10	-	21.329	8000	29.329
Total	183.500	187.414	80.000	450.914

Table 9. Costs of a diesel refuse collection vehicle

3.3.2. Electric waste collection vehicle costs

The fuel costs are reduced by an average of 2% per year due to the decrease in electricity costs. The initial cost of 3,460 EUR in Table 10 for years 1 and 2,627 for year 10 results in a reduction of 833 EUR. This represents a total expenditure of 30,269 EUR for the company. Nevertheless, the repair costs, thanks to the BASIC service package purchased in the first year, will remain at only 150 EUR at the end of year 10, under regular use. Calculated over the whole period of use, the initial cost of the electric waste collection vehicle of 350,000 EUR will amount to 386,769 EUR at the end of the 10th year.

Year	Investment cost (EUR)	Fuel cost (EUR)	Service cost/year (EUR)	Total time-of-use costs (EUR)
1	350.000	3.460	150	358.610
2	-	3.356	150	3.506
3	-	3.255	150	3.405
4	-	3.157	150	3.307
5	-	3.062	150	3.212
6	-	2.970	150	3.120
7	-	2.880	150	3.030
8	-	2.793	150	2.943
9	-	2.709	150	2.859
10	-	2.627	150	2.777
Total	350.000	30.269	1,500	386.769

Table 10. Costs of an electric waste collection vehicle

Based on the costs described in paragraphs 3.3.1 and 3.3.2, the total cost of the vehicles can be provided broken down by year. This is shown in Table 11.

The table shows which vehicle is favoured by the evolution of costs over the years. Based on Table 11, the diesel collection vehicle is the most cost-effective in the first 7 years. However, from year 8 onwards, the data show a bias in favour of the electric collection vehicle. These results suggest that electric refuse collection vehicles are more cost-effective than their diesel counterparts from year 8 onwards. Furthermore, considering that the cars are not only usable for 10 years with proper treatment and maintenance, the electric collection vehicles are significantly more economical in the long run.

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Year	Diesel waste collection vehicle costs (EUR)	Electric waste collection vehicle costs (EUR)	Deviation (EUR)
1	207.850	358.610	-150.76
2	232.690	362.116	-129.426
3	250.035	365.521	-107.486
4	283.900	368.828	-84.928
5	310.300	372.040	-61.74
6	337.252	375.160	-37.908
7	364.772	378.190	-13.418
8	392.877	381.133	11.744
9	421.585	383.992	37.593
10	450.914	386.769	64.145

Table 11. Changes in the cost of diesel and electric refuse collection vehicles over 10 years

Figure 2. Changes in the cost of diesel and electric waste collection vehicles over 10 years

Figure 2 illustrates the annual cost levels of the two vehicles during the examined ten years. At the point of intersection, the cost of the two vehicles will be the same. It can be seen that while the costs of the electric waste collection vehicle show a low level of increase, those of the diesel vehicle increase steeply, eventually exceeding those of its cleaner counterpart.

In setting up the cost structure, however, it is also necessary to establish what proportion of the total cost is made up of its elements, i.e., what weight each factor has in the whole (Fig. 3).

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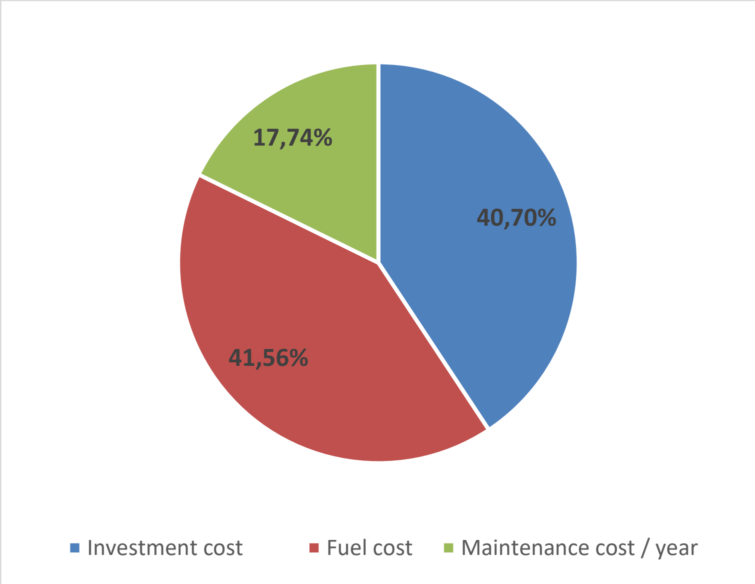

Figure 3. Distribution of the cost of a diesel waste collection vehicle

Most of the cost of conventional waste collection vehicles, 40.7%, is fuel costs. Investment costs follow, and then maintenance costs, which account for the remaining 17.74%. Over 10 years, this means that more is spent on fuel for a diesel-type vehicle than the investment cost.

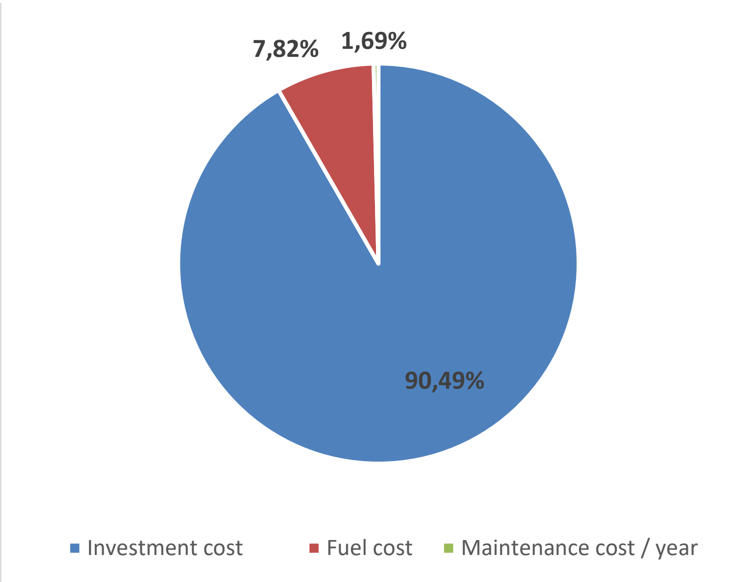

Figure 4. Distribution of the cost of an electric waste collection vehicle

Figure 4 immediately shows that the investment cost is a significant part of the total cost structure, accounting for 90.49%. The other immediately striking aspect is that the maintenance cost is such a negligible part of the total cost structure that it is effectively zero, rounded to 0.38%.

The significant difference in the cost structures of the two vehicles is visible. They are structured in completely different proportions. However, the electric waste collection vehicle not only has lower maintenance costs but also lower fuel costs, which represent 40% less of the total cost compared to the conventional vehicle.

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The low annual maintenance cost of electric vehicles is based on manufacturer service packages and the reduced complexity of electric drivetrains. Since EVs have significantly fewer moving parts and no oil-based systems, their routine maintenance requirements are minimal compared to internal combustion engine vehicles.

3.3.3. Battery replacement costs

While general inflation is not modeled separately, the analysis integrates fuel-specific price changes to reflect real market tendencies. Based on Eurostat trends and operator experience, an annual +2.95% increase in diesel prices and −2.00% decrease in electricity prices were applied over the 10 years. These trends significantly impact the total cost of ownership (TCO) trajectory, increasingly favoring electric vehicles over time.

An important aspect that was not initially considered in the cost model is the cost of battery replacement. Based on current industry data and the experience of operators, the lifetime of electric vehicle batteries is typically around 6 to 8 years. Given the 10-year usage period considered in this study, one battery replacement is anticipated to be necessary to maintain vehicle operation and range reliability. According to data from manufacturers and market estimates, the cost of battery replacement for a 26-ton electric waste collection vehicle ranges from €40,000 to €60,000, depending on capacity, supplier contracts, and installation [22].

In our model, we have used a conservative estimate of €50,000 for the replacement, which we added to year 6 of the cost breakdown. A one-time cost of €50,000 is assumed in year 6 for the electric vehicle, based on market estimates for 192 kWh industrial-grade EV battery systems. The revised cost Table 12 is shown below:

Year	Investment cost (EUR)	Fuel cost (EUR)	Service cost/year (EUR)	Battery replacement (EUR)	Total time-of-use costs (EUR)
1	350.000	3.460	150	-	358.610
2	-	3.356	150	-	3.506
3	-	3.255	150	-	3.405
4	-	3.157	150	-	3.307
5	-	3.062	150	-	3.212
6	-	2.970	150	50.000	53.120
7	-	2.880	150	-	3.030
8	-	2.793	150	-	2.943
9	-	2.709	150	-	2.859
10	-	2.627	150	-	2.777
Total	350.000	30.269	1.500	50.000	431.769

Table 12. Annual costs of an electric vehicle with battery replacement

As seen above, the total cost of the electric vehicle over 10 years rises from €386,769 to €431,769, reducing its cost advantage over diesel vehicles. When compared to the total cost of a conventional diesel waste collection vehicle (€450,914), the economic break-even point shifts from year 8 to year 10, depending on electricity price trends and maintenance incidents.

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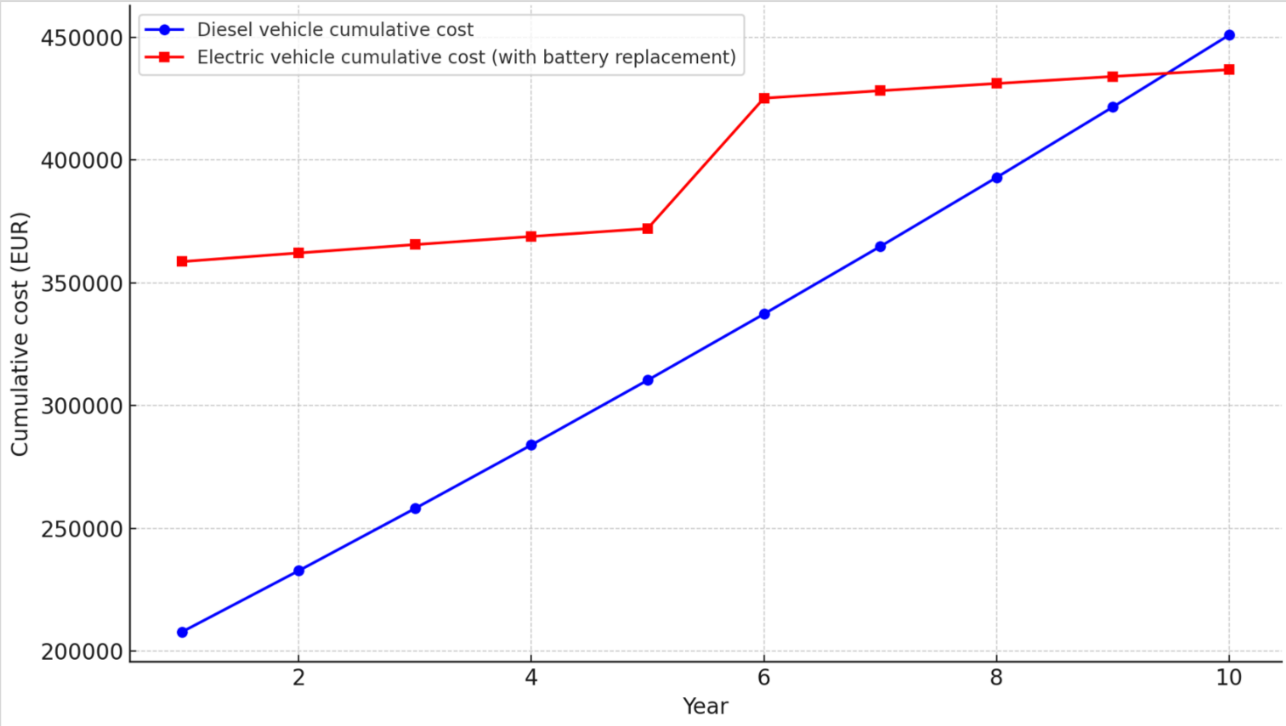

Figure 5. Cumulative Cost Comparison: Diesel vs Electric Waste Collection Vehicles

Figure 5 illustrates the cumulative cost comparison between diesel and electric waste collection vehicles over 10 years. Despite higher initial investment and a significant battery replacement cost in year 6, the electric vehicle's total cost grows at a slower rate than the diesel vehicle's. By the end of the examined period, the electric vehicle has become economically competitive, indicating its long-term financial viability.

Conclusions

This research investigated the cost-efficiency and sustainability potential of electric waste collection vehicles in urban environments through a Total Cost of Ownership (TCO) analysis, supported by real operational data from a Hungarian municipal waste company. By comparing an electric and a diesel-powered vehicle over 10 years, the study provides quantitative insights into the financial and environmental trade-offs of transitioning municipal fleets to electric powertrains. The key finding of the research is that electric vehicles become more cost-efficient than their diesel counterparts in the long term, despite their significantly higher initial investment and battery replacement costs. When battery replacement is included in year 6, the cumulative cost of the electric vehicle reaches €431,769, while the diesel vehicle totals €450,914. This results in a total cost saving of €19,145 over the vehicle's expected lifespan, and a break-even point around year 9. This supports the viability of electric propulsion as a financially sustainable option for municipal fleet managers.

The study also reveals a radically different cost structure between the two vehicle types. While diesel vehicles incur high operating costs primarily due to fuel consumption (over 40% of total cost), electric vehicles front-load their costs through capital expenditure (over 90%), with minimal annual operating and maintenance expenses. The inclusion of battery replacement slightly shifts this balance but does not

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negate the long-term cost advantage. From a sustainability perspective, electric vehicles also bring clear environmental benefits, especially in densely populated urban areas, by reducing local emissions and noise. While this study primarily focused on economic performance, the ecological advantages, although not quantified here, further strengthen the case for adopting electric alternatives.

Lessons learned from this study underscore the importance of incorporating real-world consumption, pricing, and maintenance data into Total Cost of Ownership (TCO) models, rather than relying solely on theoretical assumptions. Furthermore, the analysis highlights the importance of considering battery lifecycle costs when evaluating electric vehicle investments.

However, it should be noted that the results are based on data from Hungary, and as such, fuel and electricity prices, taxation, and service structures may differ significantly across countries. This limits the direct generalization of the findings, though the methodology can be applied elsewhere with local data.

Future research should aim to:

- Expand the model to multi-country comparisons,
- Integrate environmental lifecycle assessment (e.g., CO_2 footprint, resource use),
- Examine operational reliability and risk under various usage profiles,
- Explore fleet-level optimization using mixed vehicle types.

In conclusion, while the initial costs of electric waste collection vehicles remain high, their long-term cost-efficiency and environmental benefits provide strong justification for further adoption, particularly as battery technology advances and market prices continue to decline.

Conflicts of Interests

Judit T. Kiss is member of the Editorial Board of the journal, therefore she did not take part in the review process in any capacity and the submission was handled by a different member of the editorial board. The submission was subject to the same process as any other manuscript and editorial board membership had no influence on editorial consideration and the final decision.

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