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The economic aspects of vehicle operation in the context of electromobility strategies

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The transformation of the automotive industry towards electromobility is a key step in achieving a sustainable transportation system. To analyze the economic feasibility of electric vehicles (EVs) compared to internal combustion engine vehicles (ICEs), this study assessed the operating costs of both types of vehicles, including fueling and charging costs on a selected theoretical route. The analysis of economic aspects also examined the development of fueling and charging infrastructure and the impact of government programs promoting electromobility. The study employs a comparative analysis of ICE and EV based on fuel and electricity prices, insurance costs, and servicing expenses. The results of the analysis indicate that adopting EVs can lead to significant economic benefits, especially when coupled with government incentives and well-developed charging infrastructure. The network of charging stations and fuel infrastructure serves as an indicator of the market conditions for vehicles equipped with either internal combustion engines or electric powertrains, and forecasts help anticipate their future directions. The decreased pace of new petrol stations being established may indicate a weakening market for internal combustion engine vehicles compared to previous periods. This study highlights the economic aspects of electromobility strategies aimed at accelerating the transition towards a sustainable transportation system.

Key words: *life cycle assessment, electric vehicle, internal combustion engine vehicle, transportation economy*

1. Introduction

Internal combustion engines are one of the most widespread technologies in the automotive sector. Spark-ignition and compression-ignition engines have been used in commercial and passenger vehicles for over a hundred years. They have become a major factor in shaping culture and have also transformed and organized social life. Mobility, spatial planning, and consumer habits are largely structured according to the requirements and capabilities offered by cars. Cars are widely prevalent in developed countries. In Poland, the number of vehicles amounts to 687 cars per 1000 inhabitants [14]. Economic growth in developing countries is strongly correlated with increased access to cars [7], leading to a continuous growth in the size of the global automotive fleet.

Over the years, efforts have focused on diversifying and improving engines. Internal combustion engines (ICE) are fundamental to the automotive industry's development, with ongoing work to enhance their efficiency and performance. However, their high efficiency does not align with low pollutant emissions. Countries are implementing legal concepts to minimize the environmental impact of these engines. The Green Deal, EURO standards, and EU regulations have compelled manufacturers to adopt new strategies. The need to reduce emissions has led to the introduction of new technical solutions for internal combustion engines. “Zero-emission vehicles” are crucial for sustainable mobility and have gained importance through improved performance and infrastructure development. The continuous efforts of EU countries to mitigate the negative impacts of CO_2 emissions resulted in a significant reduction of CO_2 equivalents per inhabitant emissions in 2020 by 13.6% compared to 2019, reaching the levels of 1990 [5]. The term "zero-emission cars" is commonly used to describe electric vehicles, emphasizing their environmental benefits. However, it's a simplification as these vehicles are not entirely zero-emission. Emissions can still occur during energy production, battery manufacturing, tire wear, and the use of air conditioning or heating systems. While electric cars are more environmentally friendly than their internal combustion engine counterparts, achieving true zero emissions requires further advancements in energy production and battery sustainability. However, many researchers emphasize the overall carbon footprint that includes resource extraction, production of car components including batteries, electricity generation, and maintenance of electric vehicles in the context of a specific EU country [2].

The examination of the progress of electromobility pertaining to technical infrastructure, software systems, motor design, construction techniques, and related aspects is the focal point of investigation for numerous scientific research teams [4, 9, 11]. At the same time, the cost-effectiveness of electric vehicles, compared to traditional internal combustion engine vehicles, is a sensible step forward in adopting electric transportation, and it serves as a subject of analysis for the environmental, technical, and economic conditions of individual countries. [6, 8, 12]. The level of development of the energy infrastructure, such as photovoltaics, in a given country is also subject to consideration in the economic analysis of the cost-effectiveness of electric vehicles [1].

The availability of an adequate number of charging stations plays a vital role in encouraging private users to embrace electric cars. Despite efforts made, certain regions in Poland still lack adequate infrastructure for charging electric cars, especially considering their limited range. However, the development of new technologies and the construction of additional charging stations and supporting infrastructure provide hope for ensuring sufficient availability of charging stations in all regions of Poland [3].

The designs of internal combustion engines and electric engines are diversified. Combustion engines emit environmentally degrading substances, while zero-emission vehicles produce no pollutants during their operation. This difference in adapted technology also impacts the vehicles usage. One of the factors significant for users is the cost associated with operating a particular propulsion system, which plays a crucial role in choosing a suitable vehicle. Lower operating costs make a potential vehicle more appealing to customers.

Electric vehicles have a relatively shorter range compared to vehicles powered by combustion engines. This is due to the limited energy storage capabilities. In a conventional vehicle, fuel is burned inside the engine chamber. In contrast, electric vehicles store converted energy using batteries.

2. Economic analysis of operating a combustion engine and electric engine from the user's perspective

In this article, we embark on a comprehensive exploration of the factors influencing the choice between Internal Combustion Engine vehicles and Electric Vehicles within the context of Poland. Two representative cars, the Toyota Corolla XII and the Volkswagen ID 3 PRO S, have been selected to illustrate the contrasting aspects of ICE and EV technology. Our investigation covers critical aspects such as purchase price, maintenance costs, insurance expenses, travel expenditures, and the evolving charging infrastructure in Poland. Additionally, we explore the strategies and visions of leading automotive manufacturers as they shift towards electric mobility solutions.

2.1. Car service costs

In order to identify the operating costs of ICE and EV vehicles, two cars were selected and used to calculate the operating costs based on a proposed tourist route in Poland.

The representative of internal combustion engines was the Toyota Corolla XII in the sedan version (Fig. 1). The market value of the model in the comfort version is 124,999 PLN (Q2 2022). The Toyota Corolla vehicle has a displacement of 1.490 cm^3. It is equipped with a gasoline engine, which has a maximum torque of 153 Nm at 4800 rpm (Table 1).

Fig. 1. Compared ICE vehicle – Toyota Corolla XII [15]

The representative of EV vehicles is the 2022 Volkswagen ID 3 PRO S (Fig. 2). In 2017, the Volkswagen brand announced plans to focus on electric vehicles. The strategy of the company includes introducing at least 30 EV models to the market by 2025 and achieving 20–25% of total annual sales (2–3 million) from electric vehicles. The ID model is the first series of electric cars by the VW group, designed from scratch as electric vehicles. According to Volkswagen, ID stands for "Intelligent Design, Identity, and Visionary Technologies". The market value of the model is 187,990 PLN (Q2 2022). The Volkswagen ID 3 PRO S vehicle is equipped with an electric motor, with a maximum torque of 310 Nm (Table 1).

Fig. 2. Compared EV vehicle – Volkswagen ID 3 PRO S [16]

Table 1. Comparison of selected parameters of ICE and EV vehicles [15, 16]

Parameter	ICE	EV
Name	Toyota Corolla XII	Volkswagen ID 3 PRO S
Number of doors	4	4
Number of seats	5	4
Turning diameter	10.4 m	10.2 m
Production year	Since 2019	Since 2020
Engine type	Petrol	Electric
Engine power	132 HP	204 HP
Maximum torque (electric)	153 Nm	310 Nm
Engine displacement	1490 cm³	–
Battery capacity	–	77 kWh
Length	4630 mm	4261 mm
Width	1780 mm	1809 mm
Height	1435 mm	1552 mm
Wheelbase	2700 mm	2770 mm
Front wheel track	1530 mm	1536 mm
Rear wheel track	1545 mm	1513 mm

The selected vehicles are representatives of the C segment, which is the medium-sized car class. Despite similar parameters, the purchase price of both vehicles differs significantly. The cost of purchasing an ICE vehicle is 33.5% cheaper than that of an electric drive. Servicing is an important aspect of operating each vehicle, and due to differences in vehicle designs, the price varies. Example repairs related to the combustion engine and their prices are presented in Table 2.

Table 2. Prices for service of an internal combustion car (Q2 2022)

Service	ASC	Non-ASC (A)	Non-ASC (B)	Non-ASC (C)
Engine oil and filter replacement	622	231	217	604
Spark plug replacement	320	216	–	176
Air filter replacement	147	72	71	64
Cabin filter replacement	131	67	86	26
Fuel filter replacement	121	100	130	102
Coolant replacement	–	–	120	175
Brake fluid replacement	150	52	110	148
A/C refrigerant replacement	150 + refrigerant	175 + refrigerant	318	80 + refrigerant
Air conditioning disinfection	80–100	included in the price of a refrigerant exchange	included in the price of a refrigerant exchange	50
Suspension check (checking clearances and alignment)	250	57 (check) 145 (alignment)	115	included in the inspection price
Inspection of the braking system	80 (cleaning) 180 (cleaning with brake pads dismantling)	228	70	included in the inspection price
Total [PLN]	**2071**	**1343**	**1237**	**1415**

The highest costs for a user of a vehicle equipped with an internal combustion engine are incurred when using an authorized service centre (ASC). The lowest price for servicing a car is approximately 1237 PLN.

Brand new vehicles do not require frequent servicing. In the event of such a situation, the manufacturer's warranty usually applies. However, after the warranty period, annual costs can be high. These costs can be effectively reduced by using non-authorized service centres, but for calculation purposes, only the costs from ASC have been considered.

In the case of an electric vehicle, the amount of maintenance required is significantly lower. The batteries need to be replaced after approximately 8 years. Recommended maintenance procedures along with their prices at ASC are presented in Table 3.

Table 3. Prices for service of an electric car (Q2 2022)

Service	ASC
Air filter replacement	149
Cabin filter replacement	119
Coolant and brake fluid replacement	225
Traction battery test	49
Disinfection and replacement of air conditioning refrigerant	299
Inspection activities	199
Total [PLN]	**1040**

The annual maintenance at an authorized service centre costs 1040 PLN. This amount is 50% lower compared to internal combustion engine vehicles. The difference is noticeable in terms of the number of tasks performed during the service. In EVs, the quantity of fluids and oils is much lower, resulting in lower overall costs. In ICE vehicles, the most expensive tasks are related to the engine operation, spark plug replacement, filters, and engine oil change.

2.2. Insurance expenses

Among the operating costs, we can mention car insurance. Prices vary depending on the vehicle, the user, selected packages, and the insurance company. For the analyzed vehicles, insurance costs (third-party liability + comprehensive motor insurance + personal accident insurance with assistance package) were determined based on the following assumptions:

- the first user was born on May 25, 1987, and has held a driver's license since 2006
- the second driver was born on May 3, 1986, and has held a driver's license since 2004.

It was also assumed that the car owners had not caused any collisions since obtaining their licenses. This factor is crucial as it allows for cost minimization compared to individuals with an accident history. The total insurance cost for both types of cars was verified with a reputable insurer. The cost of insuring an electric vehicle is significantly higher and amounts to 3703 PLN. In the case of a conventional combustion engine vehicle, the price is 2204 PLN. The difference of 1499 PLN is due to the higher purchase cost of an EV and a higher comprehensive insurance premium. This is because total loss claims are more frequently accepted for electric vehicles, requiring the payout of the full insured value. Another cause is that repairs for electric cars are often uneconomical, and specific components are very expensive and hard to obtain.

2.3. Travel expenses

To conduct an economic analysis of ICE and EV vehicles, a travel route was established. The starting point was Wrocław, while the final stage of the journey was determined in close proximity to Bieszczady mountains (Fig. 3).

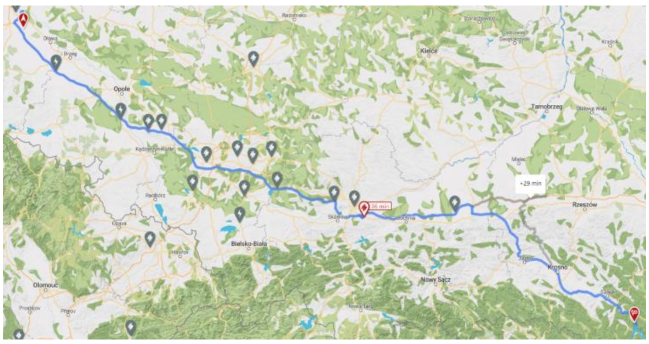

Fig. 3. Travel route – Wrocław–Solina [17]

The optimal distance between Wrocław and Solina is 518 km. The A4 motorway section covers 81% of the route, while the remaining part is traversed in urban and mountainous conditions. The Toyota Corolla XII has the following fuel consumption parameters:

- highway conditions – 6.2 dm^3/100 km
- urban and mountainous conditions 7.3 dm^3/100 km.

The travel time of a vehicle equipped with an internal combustion engine is approximately 5 hours and 49 minutes. The travel costs were determined based on the average fuel price on May 20, 2022, which was 7.21 PLN per litre.

The fuel tank capacity of the ICE vehicle is 55 litres. This value, combined with the fuel consumption parameters of the Toyota Corolla model, allows for covering the designated distance without the need for refuelling breaks. During the journey, 36.29 litres of gasoline will be consumed. The cost of the 518-kilometer trip will amount to 233.25 PLN.

Vehicles using electric power units during the journey must undergo the charging process. The stop will be made in the town of Wieliczka, at a fast-charging station. The proximity of charging points near the highway sections does not affect the maximization of the covered distance. The length of the route is 522 km, which is 4 km more than in the case of an ICE vehicle. Well-developed charging infrastructure along the A4 highway allows for minimizing the mileage. By using special software that takes into account the terrain conditions and the EV-specific specifications, the battery consumption level has been determined. The charging time during the stop is 36 minutes. The battery will be replenished using a CHAdeMO connector with a power of 44.5 kWh.

In the case of an electrically powered vehicle, the total cost of covering the designated distance is 138.8 PLN. The cost of charging using dedicated infrastructure is significantly higher than home charging conditions. Charging the battery using charging points is 2.02 kWh/PLN more expensive. Charging time is one of the crucial factors. The use of superchargers allows for charging at a rate of 44.5 kW within a 36-minute period. In home conditions, using the provided charger, charging the vehicle to its initial state can take up to 28 hours. This time is not included in the total travel time, as the charging process will take place upon reaching the destination.

The total travel time is 6 hours and 17 minutes. The charging process took 36 minutes. The duration of the journey was determined based on a best-case scenario, assuming that the charging station would not be occupied by another user. In the analyzed scenario, the driving time was 5 hours and 41 minutes. In the Wrocław–Wieliczka route, the EV vehicle completes the journey with a battery level of 20% and will then be charged up to 81%. The EV device will reach the final destination with a battery charge level of 10%. A buffer of 10% is maintained in case of unforeseen road circumstances.

The vehicle equipped with an internal combustion engine (ICE) exhibits a shorter travel time on the Wrocław–Solina route. The duration of this distance for electric vehicles was 7% longer (28 minutes). The faster arrival of ICE vehicles is due to the absence of the need for mandatory stops, allowing for continuous driving.

Despite the longer travel time, the cost of the journey for an electric vehicle (EV) is significantly lower. The total price amounts to 138.8 PLN. Reducing the charging costs of EVs is possible by using a charger in home conditions. However, minimizing costs may maximize charging time. The adopted charging structure for the vehicle through home conditions and charging points is the most probable scenario. The cost per kilometre of travel is as follows: 0.27 PLN/km for EV and 0.45 PLN/km for ICE.

Table 5 presents the annual fees that need to be covered for each vehicle type. The annual operating costs of different vehicle types are diversified. Internal combustion engines have higher values, which are caused by current gasoline prices. Low insurance costs, servicing, and covering a distance of 10,000 kilometers generate significant expenses. In the longer term, EVs are more advantageous. The low cost-effectiveness of the covered distances does not minimize the total price presented in Table 4. The annual cost value is due to expensive insurance, which accounts for approximately 50% of all operating expenses. The costs of powering EVs can be eliminated by using home charging connectors. The high price of purchasing an electric vehicle results in a low return rate. Under current conditions, the value of an EV may be recouped after approximately 47 years. However, the average lifespan of an electric vehicle is relatively shorter. In Scandinavian countries, 54% of EVs are deregistered after 2–3 years.

Table 4. Annual maintenance costs – EV and ICE (Q2 2022).

Type of cost	**EV**	**ICE**
Service maintenance	1040	2071
Insurance	3703	2204
Travel (10,000 km)	2700	4500
Total [PLN]	**7443**	**8775**

2.4. Forecasting fuel and charging infrastructure in Poland

An essential element of the comparative analysis of the economic viability of EVs and ICE vehicles is the infrastructure of fuel stations and charging points. The increase in the number of vehicles on the roads contributes to the demand for and development of this network. Its condition reflects the trends and preferences of users. Based on historical data, a forecast regarding the number of points in the future has been developed. The number of vehicle charging stations located within the territory of Poland is presented in Table 4 [13].

Table 5. The number of refuelling and charging stations in Poland [1]

Year	The number of retail fuel outlets	The number of charging stations
2010	6755	–
2011	6771	–
2012	6756	–
2013	6746	–
2014	6486	119
2015	6591	298
2016	6803	324
2017	6643	552
2018	7765	836
2019	7628	884
2020	7739	1792
2021	7852	2811

The fuel infrastructure has been developed for over a decade. The difference between 2010 and 2021 shows an overall increase of 1097 stations. The first charging points were established only in 2014. The growth is characterized by a much more dynamic form compared to the distribution of fossil fuels.

Exponential smoothing is the most widely used class of procedures for smoothing discrete time series in order to forecast the near future. Its idea is to reduce the influence of the original series. It utilizes the moving average of the smoothed series to forecast future values. The forecast is constructed based on exponentially weighted averages of past observations. The highest weight is assigned to the current observation, a lower weight to the preceding observation, and an even lower weight to the earlier observation [10]. Exponential smoothing was used to estimate the forecast of the development of fuel and charging station infrastructure. The selected model has a relative error of 4.8%.

By 2025, the number of fuel stations will experience a slight increase. The diversification of the actual and modelled values is due to difficulties associated with the growth and decline of the discussed infrastructure elements. The forecast focuses on balancing the challenging-to-predict trends. The trend line predicts a decrease in the number of stations to 7,535 in 2022, followed by a gradual increase in the subsequent years:

- 2022 – 7535 objects
- 2023 – 7596 objects
- 2024 – 7658 objects
- 2025 – 7720 objects.

The increasing number of registered vehicles is correlated with the development of fuel station infrastructure. The Polish market is characterized by a high average age of vehicles and a small share of EV devices compared to Western countries. The well-developed fuel infrastructure does not require immediate expansion. The existing facilities meet the demand for such services.

The charging station infrastructure in Poland has been developed since 2014. The relatively new type of facilities creates favorable conditions for growth. It should be noted that the increasing number of electric vehicles creates a strong demand for expanding the charging station network. For the year 2022, the model indicates just under 3,981 points. In the following years, the number of charging stations will increase significantly, reaching 13,666 by 2025. Compared to the developed countries, the number of 13,000 facilities is relatively low. Currently, there are 59,410 active charging stations in Germany. Poland is likely to reach this number only after 2025.

The fuel infrastructure and charging station network reflect the market conditions of ICE or EV vehicles. The forecast allows for predicting their development directions. The decreasing pace of new petrol stations indicates a weakening market for combustion engine vehicles compared to previous years. Currently, the automotive industry focuses on reducing emissions. These efforts lead to minimizing fuel consumption levels, which correlates with the overall number of fuel distribution points. On the other hand, the charging station network is constantly expanding. The rapid growth is driven by the increasing number of electric vehicles on the roads.

Table 6. Electrification strategies of automotive manufacturers.

Manufacturer	Strategy
Jaguar	British luxury car brand Jaguar announced in February 2022 that starting from 2025, it will fully utilize electric power. The brand has committed to achieving zero carbon dioxide emissions by 2039. The first fully electric model of Land Rover is expected to debut in 2024, with the ultimate goal of phasing out internal combustion engines.
Audi	From 2026 onwards, all new models manufactured by the German car producer Audi will be powered by batteries. Vehicles with gasoline, diesel, and hybrid engines produced before 2026 will continue to be manufactured and sold until the beginning of 2030. The company, which belongs to the Volkswagen Group, will cease the development of internal combustion engines by 2033.
Alfa Romeo	Italian car manufacturer Alfa Romeo has announced that from 2027 onwards, it will be selling battery-powered cars in Europe, North America, and China.
Rolls-Royce	Luxury car manufacturer Rolls-Royce announced in September 2021 that it will exclusively produce electric vehicles by 2030. The brand, which is owned by BMW, is set to unveil its first fully electric car named "Spectre" by the end of 2023. By 2030, Rolls-Royce will no longer produce or sell any products powered by internal combustion engines.
Mini	The brand belonging to BMW announced in March 2021 that it will exclusively produce battery-electric vehicles by the end of the decade. The last model with an internal combustion engine will be released in 2025.
Volvo	The car manufacturer Volvo has committed to producing exclusively fully electric vehicles by 2030. By 2025, they aim for approximately 50% of their cars sold worldwide to be battery-powered, with the remaining 50% being hybrids.
Mercedes-Benz	Mercedes-Benz, a subsidiary of Daimler, aims to fully embrace electric power by the end of the decade. The company has taken actions focused on ensuring that battery-electric vehicles and plug-in hybrids account for 50% of its global sales by 2025.
Fiat	The Italian car manufacturer, owned by Stellantis, is taking steps towards a complete departure from the production of vehicles equipped with internal combustion engines by the end of 2029. The CEO of Fiat announced that between 2025 and 2030, cars of this brand will gradually be equipped exclusively with electric propulsion.
Ford	The American car manufacturer Ford has announced that by 2030, all of its passenger cars in Europe will be fully electric. The company expects that by the same year, 40 to 50% of its global sales will be comprised of electric vehicles with battery power. In September, Ford Motor and its Korean partner SK Innovation announced plans to build an electric vehicle assembly plant and three battery factories in the United States, scheduled to open in 2025. This $15.7 billion investment plan represents the largest manufacturing investment in Ford's 118-year history.
Volkswagen	By 2035, the German car manufacturer VW has committed to selling only battery electric vehicles in Europe. It plans to discontinue the sale of combustion engine cars in the United States and China at a slightly later date. VW aims to make its entire fleet carbon-neutral by no later than 2050 in terms of CO_2 emissions.

2.5. Strategies and visions of automotive manufacturers

The visions and strategies adopted by automotive manufacturers reflect the consumer needs of specific target groups. The visions often align with the main goals of the pro-environment policies in European countries, which aim to shift away from traditional sources of energy towards alternative ones. Harnessing solar, wind, and hydro energy is at the core of the modern energy revolution.

Planned changes to the existing paradigms strongly impact the transportation sector as well. In recent times, the automotive industry has been taking steps towards the mass introduction of electrified vehicles into the market. Table 6 presents the electrification strategies of car manufacturers, along with their declarations regarding the future and the development of transportation.

Each car manufacturer intends to increase its sales share in the zero-emission vehicle market in the future. British brands such as Mini, Jaguar, and Rolls-Royce plan to completely phase out internal combustion engines. However, the automotive industry is divided between the European market and the USA along with China. Ford and Volkswagen declare their intention to introduce only electric vehicles on the European continent while continuing to produce combustion engines in other countries. Mercedes-Benz aims to combine the advantages of both types of engines, creating modern hybrids. Audi stands out with an interesting aspect, as it is the only manufacturer that officially declares the development of combustion technologies until 2033.

3. Conclusions

The conducted economic analysis allowed for the identification of the electric propulsion system as more advantageous in terms of efficiency and operating costs. The problematic area lies in the range of vehicles, which is limited by the number of charging stations and low consumer awareness. The costs of purchasing new vehicles are diversified. Devices equipped with internal combustion engines are still less capital-intensive. However, ICE vehicles generate high financial and environmental costs. The price of acquiring an ICE vehicle and insurance costs are determining factors for their selection by consumers.

The conducted analysis of the number of fuel and charging infrastructure for both types of engines indicates intermediate directions for the automotive industry's development. The fuel infrastructure shows a small growth in the future. This may be attributed to the changing market share of internal combustion and electric vehicles. Most designs in the future aim for full or partial electrification. This fact organically reduces the consumption of fossil fuels while simultaneously increasing the demand for electric energy. The rapid development of charging points indicates the maximization of electric vehicle numbers. The evolving pro-environmental policies and the pursuit of carbon neutrality proclaim the emergence of efficient charging networks. Infrastructure investment is crucial for achieving emissions reduction and transportation system efficiency improvements. Governments need to provide regulatory frameworks and support for upgrading charging infrastructure to make EVs convenient for consumers.

Nomenclature

ASC authorized service centre
CEO Chief executive officer
CHAdeMO CHArge de Move (DC charging technology)
EV electric vehicle
EU European Union
ICE combustion engine

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