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ASSESSING THE FEASIBILITY OF ELECTRIC ROAD TRANSPORT IN EUROPE USING THE INTEGRAL EMISSIONS INDEX

Summary. This article reviews the development of electric road transport and assesses its feasibility in European countries based on an analysis of CO₂ emissions using an integral index. Electric road transport is evolving in three main directions: battery-powered vehicles, hydrogen fuel cell vehicles, and road electrification. Battery electric vehicles are widely used, but their future may be constrained by issues related to cost, charging infrastructure, and raw material availability. Hydrogen-powered vehicles offer fast refueling but require substantial investments and strict safety standards. Road electrification includes both contact and wireless energy transfer systems. Contact-based systems, in particular, provide high power and low energy losses, making them optimal for vehicles with significant energy demands. The environmental efficiency of electric vehicles largely depends on the electricity source. Countries with a high share of renewable energy, such as Norway and France, demonstrate greater environmental efficiency in electric vehicle adoption. Special attention should be given to road electrification, which reduces the duration of battery-powered autonomous driving and allows for smaller battery sizes, thereby extending their lifespan. This approach not only increases battery longevity but also has a positive environmental impact by reducing emissions associated with battery production and disposal.

1. INTRODUCTION

Globally, electric vehicle sales have been increasing [1-3], driven by significantly lower battery charging costs compared to refueling with conventional fuel, reduced maintenance expenses, and the strong marketing appeal of these modern vehicles. In 2024 alone, nearly 17 million new electric vehicles were registered worldwide, bringing the total global fleet to 58 million [3].

In public perception, electric vehicles are considered environmentally friendly because they do not emit pollutants such as nitrogen oxides, carbon dioxide, or particulate matter while in operation – emissions typically associated with traditional vehicles. Additionally, electric vehicles offer another environmental advantage: they are significantly quieter than internal combustion engine (ICE) vehicles, thereby reducing noise pollution. While the latter point is indisputable, the former claim is more complex.

In reality, all electric transport indirectly contributes to atmospheric emissions by increasing electricity demand, thereby shifting the burden of pollution to energy generation sources. When considering the full energy supply chain, the environmental footprint of electric vehicles is far from

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negligible [4, 5]. A comprehensive comparison of greenhouse gas emissions from the production, operation, and disposal of both traditional and electric vehicles can yield similar results – or even suggest that electric vehicles are more environmentally harmful in some cases.

For instance, if electricity is generated solely from coal-fired power plants, the total CO₂ emissions over an electric vehicle's entire lifecycle – including production, operation over a distance of 150,000 km, and disposal – reach 43,186 kg, exceeding the emissions of a gasoline-powered vehicle under the same conditions (37,322 kg) [6]. However, if electricity is sourced entirely from renewable energy sources, such as solar or wind power, the electric vehicle's CO₂ emissions are significantly reduced, amounting to just 16,106 kg over its lifetime.

The structure of electricity generation has a significant impact on the environmental feasibility of electric vehicle adoption. This impact can be quantitatively assessed using a specific metric – the **Electric Vehicle Emissions Index (EVEI)**. This index, proposed in [7], accounts for emissions from conventional vehicles as well as emissions generated during electricity production and consumption. It considers the entire energy supply chain, including power generation, transmission through electrical grids, and energy conversion within the electric vehicle's internal systems.

The EVEI allows for regional emission differences to be factored into assessments, making it a valuable tool for shaping policies and incentives for promoting renewable energy sources and electric transport.

This article is intended to review the development of electric road transport and evaluate its feasibility in European countries based on an analysis of CO₂ emissions using an integral index.

To achieve this objective, this study aims to accomplish the following research tasks:

1. To review the current state of the electric vehicles market.
2. To analyze vehicle electrification technologies.
3. Investigating the impact of battery electric vehicles on CO₂ emissions.

2. CURRENT STATE OF THE ELECTRIC VEHICLES MARKET

By 2024, the global electric vehicle fleet had grown to 58 million, with sales increasing by more than 25% compared to 2023. Electric vehicles accounted for 20-21% of global new light-duty vehicle sales in 2024, up from approximately 18% in 2023. The primary markets, which collectively accounted for 95% of global sales, were China (50–60%), Europe (15-25%), and the United States (10-11%) [1-3]. The dynamics of electric vehicle growth worldwide and in Europe from 2018 to 2023 are shown in Figures 1 and 2.

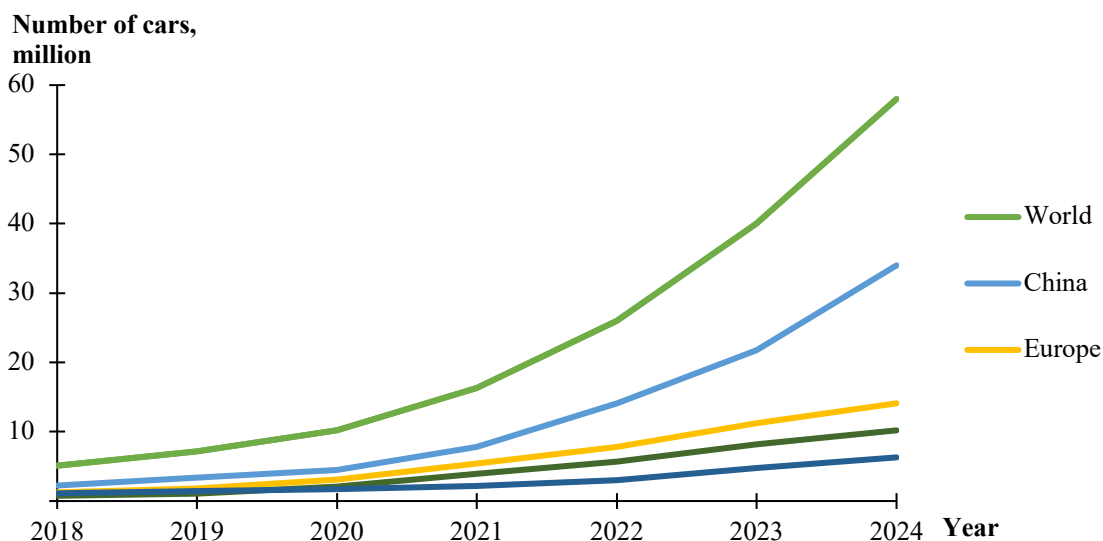


Fig. 1. Number of electric vehicles worldwide and leading countries, 2018–2024

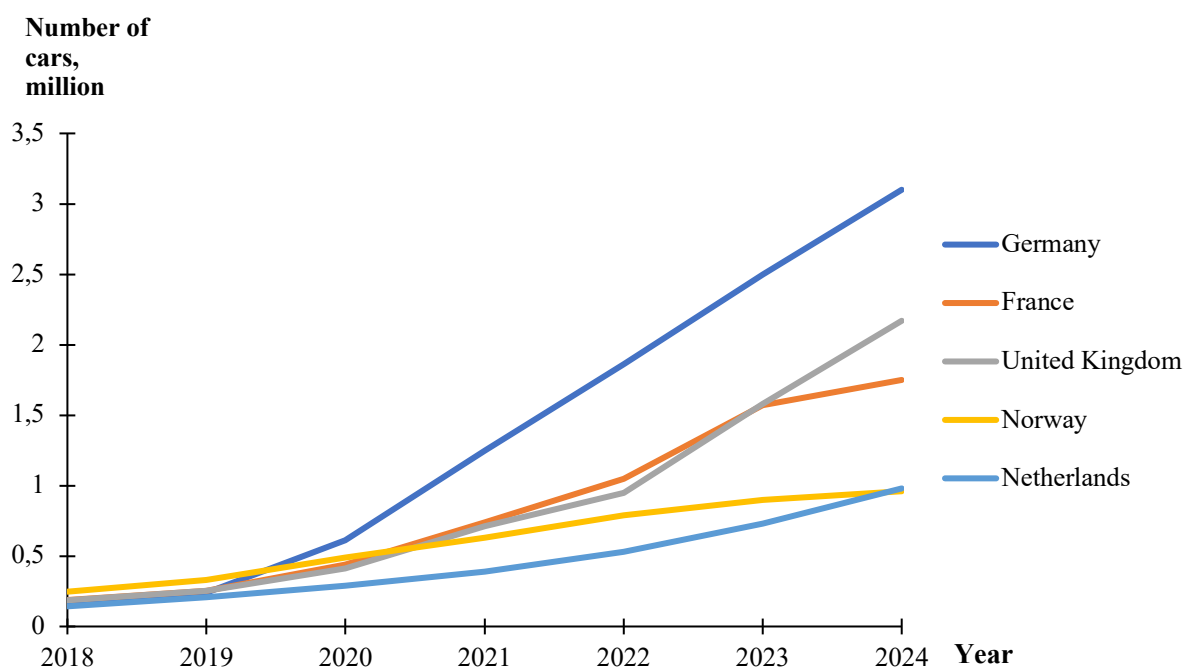


Fig. 2. Leading European countries by number of electric vehicles, 2018–2024

In 2024, electric vehicle sales in Europe accounted for approximately 22% of all new passenger cars sold, totaling around 2.38 million units. In Germany, about 210,000 new battery-electric vehicles (BEVs) were registered, comprising roughly 14% of new car sales. In Sweden, electric vehicles made up 58% of all cars sold, with BEVs representing about 42%. In Norway, this figure reached 91.6%, including 88.9% BEVs. Figures 3 and 4 illustrate electric vehicle sales statistics from 2018 to the most recent year (2024), highlighting how actively these countries are transitioning to new forms of transportation.

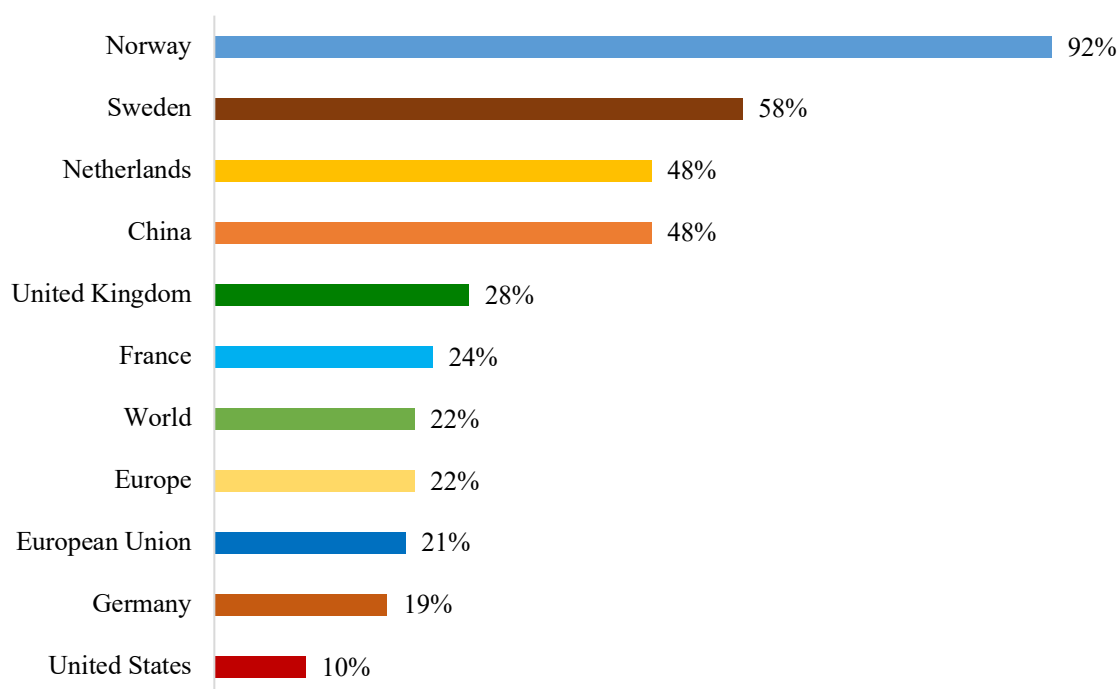


Fig. 3. Share of new electric vehicles among total vehicles sold in 2024

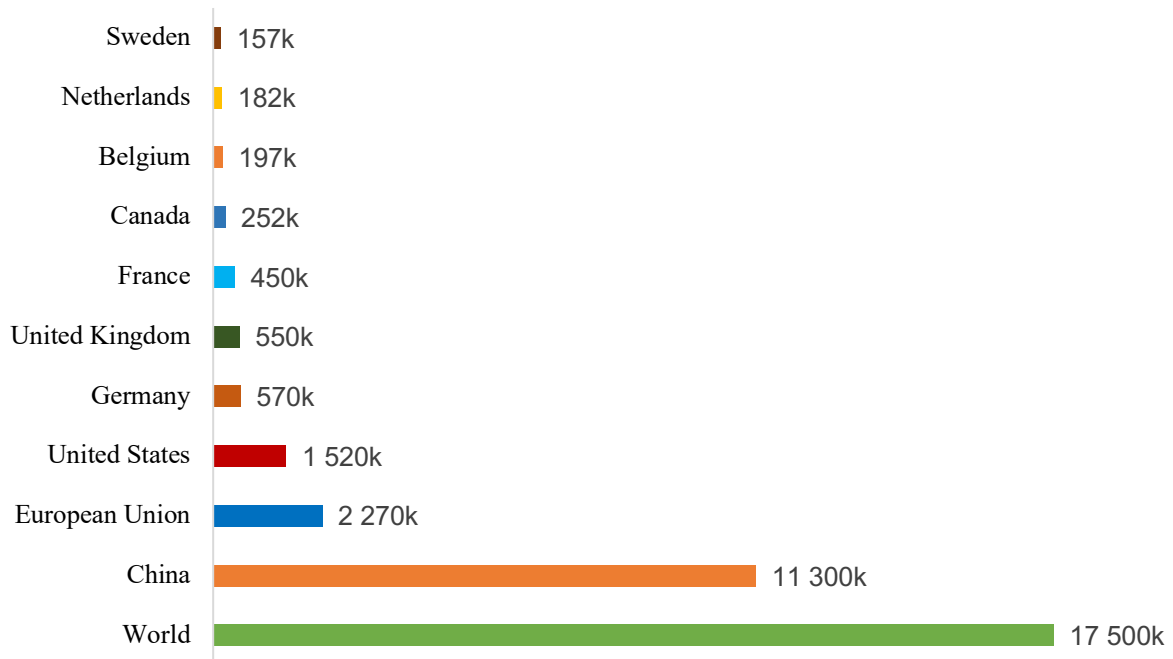


Fig. 4. Number of new electric vehicles sold in 2024

As of 2024, the total number of passenger vehicles in the European Union reached approximately 289 million. Among them, 1,672,998 are electric vehicles, of which 66.4% are BEVs, 33.3% are hybrid vehicles with ICEs, and 0.3% are hydrogen fuel cell vehicles.

Electric transport is expanding rapidly, covering not only passenger cars but also public and freight transport. In 2023, electric bus sales in Belgium, Norway, and Switzerland surpassed those of conventional buses. Overall, in the European Union, battery-electric buses accounted for 43% of all urban buses purchased that year.

Global sales of electric trucks have also grown significantly, increasing by 35% in 2023 compared to 2022. The trend in Europe is equally dynamic: in 2021, 1,700 electric trucks were registered, and this number rose to 3,700 in 2022 and 10,800 in 2023.

Sales of electric trucks are increasing largely due to government support. For example, European Union regulations mandate a 90% reduction in CO₂ emissions by 2040. At the same time, the UK government is investing \$250 million in the Zero Emission HGV and Infrastructure Programme [8], which aims to conduct real-world trials of environmentally friendly trucks. As part of this initiative, 370 trucks will be deployed, and nearly 60 modern charging and refueling stations will be built.

As of 2024, there are approximately 800,000 charging stations for BEVs in Europe, while there are 269 hydrogen fuel cell vehicle refueling stations.

Thus, the further development of the electric road transport market, following the saturation of personal electric vehicles and electric buses, will be determined by the demand from commercial carriers for electric trucks capable of competing with rail transport in commercial freight operations.

3. ANALYSIS OF VEHICLE ELECTRIFICATION TECHNOLOGIES

The idea of using rail-free electric transport is not new, as it was first implemented at the end of the 19th century. At the beginning of the 20th century, electric vehicles powered by lead-acid batteries competed with ICE vehicles. However, with the development of manufacturing processes and the introduction of the mass production of cheap ICE cars, electric transport gradually lost its competitive edge. Furthermore, the invention of electric ignition further slowed the development of battery-powered vehicles until the late 1980s.

The worsening of environmental issues and the intensive development of alternative energy sources prompted companies to reinvest in the development of electric vehicles. In 1996, General Motors released the GM EV1, a series of electric vehicles powered by lead-acid batteries, which was a significant step in reigniting interest in electric transport. The following year, Toyota introduced the first hybrid car, the Toyota Prius, equipped with a gasoline engine and a nickel-metal hydride (NiMH) battery. These steps demonstrated that electric motors could effectively compete with ICEs by overcoming the limitations associated with low energy storage capacity [9].

In addition to battery systems, hydrogen fuel cells are being considered as an alternative energy source for electric vehicles. The first hydrogen fuel cell vehicle was the Chevrolet Electrovan, produced by General Motors in 1966. However, further developments in this field were economically impractical at the time. After a long period of stagnation, in 1996, Toyota unveiled the FCHV-1, the company's first fuel cell vehicle.

Another technology with a long history, dating back to 1882, is the trolleybus system, which began when W. Siemens tested a vehicle powered by electricity from a flexible cable attached to an overhead contact wire – hence the name “trolleybus.” Trolleybuses are a popular form of public electric transport, characterized by their pantograph collector, which allows for maneuverability on roadways. In the 20th century, there were experiments with trolleytrucks – freight vehicles equipped with trolleybus-style current collectors. The main advantage of trolleytrucks is their ability to achieve high speeds on inclines. Modern trolleytrucks, such as the Hitachi mining dump truck [11], are equipped with pantographs because they are unlikely to detach from the contact wire, and there is no need for high maneuverability in mining environments.

Thus, three main directions for the development of road transport should be considered:

1. The use of energy storage systems;
2. The use of hydrogen fuel cells;
3. The electrification of roadways.

3.1. Vehicles with energy storage systems

For a vehicle with onboard energy storage, the energy stored in the battery is transferred to the electric drive of the electric vehicle, which consists of an inverter and an electric motor. The overall efficiency of energy transfer from the battery to the wheels is around 80%. The battery is charged from the electrical grid. Among electric vehicles with energy storage systems, several types are distinguished:

- Hybrid electric vehicle (HEV) – hybrid electric vehicles that combine an ICE and an electric motor, with the battery charged during ICE operation or through energy regeneration.
- Plug-in hybrid electric vehicle (PHEV) – hybrids with a larger battery that allows the vehicle to be charged from external power sources.
- Range-extended electric vehicle (REEV) – electric vehicles with a range extender, where the ICE is used only for charging the battery, and the movement is entirely powered by the electric motor.
- Battery electric vehicle (BEV) – fully electric vehicles that operate solely on a battery, which is charged from external sources, without an ICE, and the range depends on the battery capacity.

An analysis of sources [9-13] indicates that the use of battery-powered vehicles is associated with several challenges. In particular, it is necessary to scale up battery production, expand the charging station infrastructure, and create corresponding logistics centers. Despite progress in reducing costs and improving battery performance, raw material shortages may lead to a supply-demand imbalance, increased battery costs, and production delays.

Modern electric trucks can travel between 300 and 500 km on a single charge, depending on the manufacturer, driving style, operating conditions, and the surrounding environment. At the same time, diesel-powered trucks can cover up to 2000 km on a full tank of fuel. While this distance is typically not covered in one day, it indicates the potential for the multi-shift use of such vehicles. One of the key competitive advantages of diesel vehicles is their fast-refueling time, which is significantly shorter than the battery charging process.

In general, energy storage systems are best suited for short planned transport routes where extended charging times are possible. For long-haul routes, charging station infrastructure with pre-booking capabilities is needed to ensure high availability and economic efficiency.

3.2. Vehicles with hydrogen fuel cells

A hydrogen fuel cell is a device that converts the chemical energy of hydrogen into electrical energy through an electrochemical reaction between hydrogen and oxygen. As a result of this reaction, water and energy are produced, which are stored in the vehicle's battery. Energy recovery directly into the fuel cell is not possible. The fuel cell is connected to the battery via a DC-DC converter. The efficiency of such a system is approximately 45% [9].

The use of hydrogen as an energy source for vehicles, especially for long-distance transportation, is an innovative technology with great potential, provided that hydrogen production is carried out using renewable energy sources. At the same time, scientific publications dedicated to this technology [9, 14-16] emphasize the high costs associated with using hydrogen-powered vehicles. It is thought that Europe will not have enough renewable energy to produce all the necessary hydrogen to power fuel cell vehicles, meaning their implementation will require hydrogen to be imported. This necessitates large-scale hydrogen production abroad and the development of means for its transportation.

Among the key advantages of hydrogen trucks are the fast-refueling process and the high energy density of hydrogen. However, hydrogen takes up more space than other fuel sources, which reduces the available cargo volume. Furthermore, hydrogen is explosive, requiring high safety standards.

The range of trucks with fuel cells that require no additional refueling varies depending on the model and manufacturer. For example, [17] indicates a distance of about 1000 km without refueling, while [18] suggests a range of 500 km.

3.3. Electrification of roads

Another direction of development for road transport is the use of various technologies for transferring electricity to moving vehicles. An analysis of analytical reports and scientific publications [19-26] allows us to highlight the key characteristics of this direction. First, methods of transferring electricity to a vehicle are divided into contact and non-contact systems. Contact systems involve the use of overhead lines (contact network) or rails placed in or above the roadway. For example, as shown in Fig. 5, Siemens's solution with contact wires uses a pantograph to connect to overhead lines along the roadway.

Implementing and using contact networks in railway transport and urban passenger transportation offers numerous advantages. It enables consideration of all potential technical and operational challenges, particularly aspects related to system safety and reliability. Moreover, due to the availability of qualified specialists who have undergone specialized training, the rapid deployment of such systems on highways is possible. This professional resource ensures high-quality installation and further maintenance of aerial contact networks, making them attractive for integration into road infrastructure.

Rail systems, which have a short distance between the vehicle and the point of contact, offer a wide range of applications and can be used to power various types of transport. The electrical connection to the rail is made using a retractable current collector located underneath the vehicle.

Several solutions with different design features are available. For example, Evias has implemented a system in which two rails are placed in grooves on the road surface. These rails are divided into 50-meter segments and are activated only when a vehicle drives over them. The Elonroad solution involves a rail made up of short grounded segments installed along a single line. These segments are sequentially activated only when a vehicle passes over them. Honda has developed a system where the rail is not integrated into the road but is attached to a roadside barrier. In this system, the current collector extends from the side of the vehicle and connects to the positive and negative poles of the rail. The maximum allowable distance between the vehicle and the rail is 1.3 meters. The placement of current-carrying components of the contact system near the road surface requires special attention to safety. This increases the risk of damage, which can have serious consequences. Specifically, the likelihood of

vehicles colliding with the current-carrying elements increases, as does the impact of adverse external factors, such as weather conditions or mechanical damage from road traffic.



Fig. 5. The current collector of a freight vehicle with a contact network

In contactless systems, energy is transferred from the road to the vehicle without wires through inductive coupling. This is achieved by using two sets of coils – one in the road and one in the vehicle. Accordingly, contactless systems have advantages. For example, there is no current collector outside the vehicle body, which positively affects the vehicle's aesthetic appearance and reduces the likelihood of mechanical damage. Additionally, by closing the system's elements from direct access, the risk of electric shock is lowered. However, it complicates maintenance. A disadvantage of contactless systems is energy losses in their elements and the road surface. Another area of research is the electromagnetic compatibility of the system with adjacent devices and vehicles.

Contact-based systems transmit significantly more power than any contactless system. For example, Siemens and Evias provide up to 200 kW, and Honda provides up to 450 kW, while the Electreon contactless system only transmits 20 kW. A challenge faced by contact systems is the wear of the devices at the point of contact, which requires the regular monitoring of the condition of wires or rails. Rail-based technology requires constant monitoring and maintenance of the joints between the rail and the road surface to prevent water from penetrating the road surface. Another issue is the aging and contamination of the rails. This is especially relevant for the Evias system, for which the rails are located below the road surface. Overall, for rail systems, solving the problem of providing protection against electric shock is very complex. Meanwhile, solutions with a contact network only impact the road structure by installing support poles for the overhead line near the road surface, which can affect the stability of the road foundation and cause ground settlement if the supports are located too close to the road.

Additionally, localizing vehicles in one part of the roadway leads to uneven load distribution. As a result, areas of the road where the vehicle wheels contact the surface gradually develop depressions. This problem is relevant for all vehicle charging systems during movement, as these technologies assume that vehicles must move in designated lanes where charging infrastructure elements are embedded. As a result, the constant load on the same areas of the road can significantly accelerate its wear.

4. THE IMPACT OF BATTERY ELECTRIC VEHICLES ON CO₂ EMISSIONS

Currently, most of the electric vehicles widely used in European countries are of the battery type. Therefore, we will analyze the CO₂ emissions caused by this type of electric vehicle during operation, depending on the structure of electricity generation.

The assessment will be carried out for a hypothetical battery electric vehicle without referring to a specific model. The results vary depending on the regional features of electricity generation and the efficiency of its transmission through the energy grids of each individual country.

The Electric Vehicle Emissions Index (EVEI) is the ratio of the total emissions of the electric vehicle to the emissions of an ICE vehicle while covering the same distance:

$$EVEI = \frac{\varepsilon_{EV}}{\varepsilon_{ICEV}}, \quad (1)$$

where ε_{EV} is the emission from the electric vehicle,

$$\varepsilon_{EV} = \frac{d\gamma_E\rho_{EV}}{\eta_N\eta_{WW}}, \quad (2)$$

and ε_{ICEV} is the emission from a conventional vehicle,

$$\varepsilon_{ICEV} = d\gamma_G k \rho_{ICEV}. \quad (3)$$

The expression (1) for calculating the emissions index includes the following components:

γ_E – specific greenhouse gas emissions per unit of electricity;

ρ_{EV} – specific electricity consumption of the electric vehicle while driving;

η_N – efficiency of the electricity grid;

η_{WW} – efficiency of energy conversion in the electric vehicle;

γ_G – specific greenhouse gas emissions from the combustion of a unit of fuel;

ρ_{ICEV} – specific fuel consumption per unit of distance for a conventional vehicle;

k – emission factor in the production chain, accounting for additional emissions arising from the production, transportation, storage, and processing of fuel.

For the calculation, the following values were taken from sources: γ_E from [27], $\rho_{EV} = 0.15...0.25$ kWh/km [28], η_N from [29], $\eta_{WW} = 0.8$ from [9]. The product $\gamma_G \cdot \rho_{ICEV} = 122.7$ g/km for a gasoline ICE [30], with $k = 1.25$ [7]. Thus, the CO₂ emissions from a conventional vehicle, considering the production chain, are 153.4 g/km.

The result of the emissions index calculation is presented in Table 1, and the clustering of countries by the level of EVEI (max) emissions for the upper boundary of ρ_{ICEV} is shown in Figure 6.

Using [6], which specifies CO₂ emissions from electric vehicles and ICE vehicles over their entire life cycle, we find that the CO₂ emissions from an electric vehicle, without considering the transport work, amount to 15,500 kg over 10 years. Assuming that the vehicle will travel 150,000 km over this period and using the CO₂ emission calculation results from Table 1, we can estimate the total greenhouse gas emissions over the same period. After comparing these with the emissions from ICE vehicles over 10 years, it can be determined that at an EVEI value of 0.96 or higher, the total emissions from the electric vehicle exceed those of the conventional vehicle.

Therefore, in countries where electricity is mainly generated from coal and gas power plants, such as Poland, Cyprus, Malta, and the Czech Republic, the use of battery electric vehicles will lead to an increase in greenhouse gas emissions in the atmosphere.

Norway and France demonstrate a high level of environmental responsibility based on the structure of their energy systems. Norway almost entirely relies on hydroelectric power, which provides clean and renewable energy for domestic consumption. In France, the majority of electricity is produced by nuclear power plants, which have low CO₂ emissions. The development of electric transport in these countries will have a significant positive environmental effect.

Countries with moderately low EVEI values, such as Denmark, Portugal, and Luxembourg, have an energy structure with a low share of renewable and nuclear energy. At the same time, they continue to use fossil fuels, which affects the overall level of emissions.

Among countries with medium EVEI values, Ukraine, Italy, and Germany stand out. These countries have a mixed energy structure, still largely dependent on coal and gas, which results in a medium level

of CO₂ emissions. However, the development of electric transport also reduces carbon dioxide emissions.

Table 1
Calculation of CO₂ Emissions Index

Country	γ_E , g/(kWh)	η_N	ε_{EV} (min), g/km	ε_{EV} (max), g/km	EVEI (min), g/km	EVEI (max), g/km
Norway	30	0.94	6.01	10.01	0.04	0.07
Switzerland	35	0.93	7.02	11.71	0.05	0.08
Sweden	41	0.95	8.01	13.36	0.05	0.09
France	56	0.94	11.22	18.7	0.07	0.12
Finland	79	0.96	15.47	25.79	0.1	0.17
Luxembourg	105	0.94	21.06	35.11	0.14	0.23
Austria	111	0.95	21.95	36.58	0.14	0.24
Slovakia	117	0.98	22.45	37.41	0.15	0.24
Latvia	123	0.91	25.4	42.33	0.17	0.28
Belgium	138	0.95	27.38	45.63	0.18	0.3
Denmark	152	0.94	30.29	50.49	0.2	0.33
Lithuania	160	0.78	38.47	64.11	0.25	0.42
Portugal	166	0.9	34.5	57.5	0.22	0.37
Spain	174	0.9	36.1	60.17	0.24	0.39
Hungary	204	0.88	43.68	72.8	0.28	0.47
Croatia	205	0.87	44.24	73.73	0.29	0.48
Slovenia	231	0.95	45.54	75.9	0.3	0.49
United Kingdom	238	0.92	48.61	81.01	0.32	0.53
Romania	241	0.89	50.62	84.36	0.33	0.55
Ukraine	260	0.89	54.64	91.07	0.36	0.59
Netherlands	268	0.95	52.69	87.82	0.34	0.57
Ireland	291	0.92	59.22	98.69	0.39	0.64
Europe	319	0.94	63.78	106.3	0.42	0.69
Italy	331	0.93	66.67	111.12	0.43	0.72
Greece	337	0.92	68.78	114.63	0.45	0.75
Germany	381	0.96	74.31	123.86	0.48	0.81
Estonia	417	0.93	83.79	139.66	0.55	0.91
Czech	450	0.95	88.32	147.19	0.58	0.96
Malta	459	0.95	90.31	150.52	0.59	0.98
Cyprus	534	0.96	104.33	173.89	0.68	1.13
Moldova	643	0.78	154.68	257.80	1.01	1.68
Poland	662	0.94	132.69	221.15	0.87	1.44

5. CONCLUSIONS

The analysis of static information and review of analytical reports indicate continued development and interest in electric vehicles in the long term. In Europe, battery electric vehicles have become widespread, driven by easier access to energy sources compared to hydrogen fuel cell-based technologies.

Despite their potential, hydrogen fuel cell vehicles currently have limited application, mainly because of the high cost of hydrogen production, insufficient refueling infrastructure, and challenges related to hydrogen storage. Evaluating road electrification technology requires significant investments in

infrastructure and limits the use of vehicles to route-based connections. However, this technology offers significant environmental advantages, as it reduces the ecological footprint of electric transport by eliminating batteries and, thus, the emissions from their production and disposal. Combining road electrification with battery vehicle technology allows for the use of smaller batteries and conserving their resources during the journey when the vehicle is connected to the network, which also reduces harmful environmental impacts.



Fig. 6. The Integral Emissions Index for European countries

The structure of electricity production plays a crucial role in the ecological aspect of electric transport. The best prospects in this regard are demonstrated by the Scandinavian Peninsula and France, where the EVEI index does not exceed 0.2. According to calculations, the integral value of EVEI for Europe is 0.69, confirming the viability of using electric road transport. In Ukraine, the implementation of road electrification technologies for freight and passenger transport is also promising. This approach can provide several important advantages:

1. Electrification of transport infrastructure will significantly reduce greenhouse gas emissions, which will positively impact the environment.
2. The implementation of these technologies will contribute to the country's energy independence. The use of electricity generated from renewable sources, such as wind, solar, and hydroelectric power, will reduce dependence on oil and gas imports.
3. Expanding the use of electrified roads could act as a catalyst for the development of transport infrastructure and innovative solutions in the sector. Such projects are capable of attracting investment and creating new jobs. Overall, the integration of electric road transport technologies aligns with global trends in the decarbonization of the transport sector, which also provides opportunities for regional and international cooperation in the field of green energy and transport.

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