Review paper

CHALLENGES OF ELECTRIC VEHICLES URBAN TRANSPORT APPLICATION

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Abstract: *As environmental protection becomes a common social narrative, instead of an engineering approach to technical issues and practice evaluation, unverified claims may appear in various periodicals, mostly popular periodicals. One such claim is that electric vehicles do not pollute the environment and have no impact on climate change. This paper aims to demonstrate that electric vehicle technology also has an environmental impact and outlines several challenges that need to be successfully addressed for electric vehicles to be accepted and genuinely represent alternative to liquid fuel powered vehicles.*

Keywords: *electromobility, electric vehicle, battery, fuel efficiency, ecological sustainability, renewable energy sources, cost-effectiveness, electric vehicle maintenance*

1. EFFICIENCY AND CO_2 EMISSIONS

It is often claimed in popular magazine articles that electric motors have an efficiency of 90%, compared to internal combustion engines (ICEs) which have an efficiency of 25 to 30%. It is important to examine what the authors are comparing now. It is true that electric motors have an efficiency of 90%, but this refers only to the conversion of electrical energy into useful work within the motor itself. However, the electrical energy used to power the electric motor has already undergone various forms of transformation with specific efficiency rates from another form of energy into electrical energy. It is also correct that ICEs have an efficiency of 25 to 30%, but it must be made clear that this is the efficiency of the direct conversion of the chemical energy of fuel into useful work. To compare both types of motors, it is necessary to standardize the terminology of efficiency first.

The efficiency of ICEs is referred to the fuel utilization rate, which is about 28%. It is necessary to calculate the fuel utilization rate of electric motors by considering all forms of energy transformation up to the electric energy and electric drive.

The efficiency or fuel utilization rate of a power plant is directly linked to carbon dioxide (CO_2) emissions. CO_2 emissions into the air are considered as undesirable gases, even though they are fundamentally necessary for plant growth and the maintenance of life on Earth. CO_2 is an inevitable product of fuel combustion, specifically the combustion of its carbon element – C. Since CO_2 emissions are an inevitable product of combustion, reducing CO_2 emissions is only relatively possible by increasing the efficiency of the plant, i.e. obtaining more useful work (energy) for the same amount of fuel chemical energy and therefore inevitably emitted carbon dioxide into the air.

For hydrocarbons fuel, there are only three combustible chemical elements: carbon, hydrogen, and sulfur. Sulfur as a source of heat has a minor importance. During combustion, carbon and hydrogen combine with oxygen to form CO_2 and H_2O, according to the following reactions ("BREF LCP", 2006:29):

$$C + O_2 \rightarrow CO_2$$
$$2H_2 + O_2 \rightarrow 2H_2O$$

The type and composition of gases produced during combustion depend on the composition of the fuel used and the type of combustion.

Electricity production methods can be from conventional energy sources (combustion of fossil fuels, nuclear power plants, and large hydroelectric power plants) and unconventional energy sources (mainly renewable energy sources – RES) (Šljivac and Šimić, 2009).
In Figure 1, the energy mix or structure of energy sources in total sold electricity for the year 2021 is shown (adapted from "Report on the structure of electricity in 2021," 2022:20).

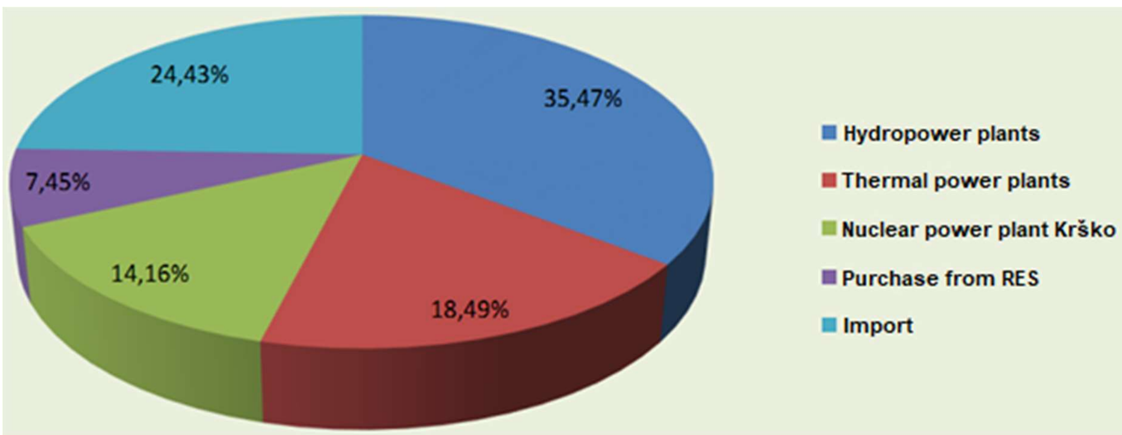

Figure 1: Shares of Different Energy Sources in Total Sold Electricity for 2021

Out of the total electricity produced from thermal power plants in Croatia in 2021, 25,5% came from coal combustion and 53,5% from natural gas combustion, which are the two main fossil fuels in the energy mix (Energy in Croatia 2021, 2022:149). It can be noted that 78,8% of the total 18,49% electricity from thermal power plants was generated by traditional (non-renewable) fossil fuel combustion. The remaining 21,2% of electricity from thermal power plants can be considered renewable energy sources (biogas, biomass, and geothermal energy). For simplification in the analysis, it is considered that all electricity was produced from natural gas combustion in gas-fired thermal power plants in combined cycle mode. Although there are also gas-fired combined heat and power plants installed in the power system (producing both electricity and heat). However, it should be noted that the efficiency figures of the combined heat and power (CHP) cycle are not entirely accurate (the efficiency of plants operating in CHP mode approximates 85%) because they aggregate the efficiencies of converting the internal chemical energy of fuel into two different types of energy – electrical and thermal. This is exceptionally allowed because thermal energy is considered very useful (e.g., for district heating and central heating systems, etc.). For simplicity, it is assumed that all electrical energy from gas-fired thermal power plants is produced in a combined cycle.

For combined cycle gas turbine (CCGT) plants, the fuel utilization efficiency at the generator terminals is considered to be between 54% and 58% for newer plants and between 50% and 54% for older plants ("BREF LCP," 2006:479), ("BREF LCP," 2017:79).
For this analysis, the efficiency of gas-fired thermal power plants in combined cycle mode is assumed to be 54% fuel utilization.
In comparison, coal-fired power plants (without cogeneration) have a lower efficiency, estimated between 36% and 40% fuel utilization („BREF LCP“, 2006:269).
For this analysis, the efficiency of coal-fired thermal power plants is assumed to be 38% fuel utilization. As well, the assumed efficiency of RES and the Krško nuclear power plant in terms of fuel utilization is considered 100%, as electricity is not generated by fuel combustion.
The overall fuel utilization efficiency of the Croatian power system for 2021, with a high share of renewable energy sources and the Krško nuclear power plant, is around 90,1%. This high fuel utilization in electricity production significantly enhances the efficiency of electric vehicles compared to internal combustion engine vehicles.
Therefore, the efficiency of an electric vehicle (neglecting losses in energy distribution and battery storage) is around 81%, compared to about 28% for internal combustion engine vehicles, which undoubtedly represents significant energy savings (in terms of fuel saved for electricity generation alternatively through combustion) and consequently reduces CO_2 greenhouse gas emissions.
For example, based on an average CO_2 emission of 129 g/km for vehicles in Croatia in 2021 (”Now it's official “, 2023.), electric vehicles emit only about 34 g/km CO_2, which is almost four times lower than internal combustion engine vehicles. In other countries, CO_2 emissions from electric vehicles vary depending on the energy mix of that country.

The CO_2 emissions of electric cars in France in 2021 amount to 11,5 g/km, in Germany they amount to 91,2 g/km, and in Poland they amount to 168 g/km (Vučetić, 2023). CO_2 emissions increase with a higher share of fossil fuels in the country's energy mix.
Carbon dioxide is not the only product of combustion; there are also various pollutants such as nitrogen oxides, sulfur oxides, and carbon monoxide as a product of incomplete combustion. As demonstrated, an electric vehicle emits carbon dioxide in its carbon footprint depending on the energy mix in the electricity market, similarly emitting other pollutants from fossil fuel combustion. The only way to reduce air pollutants would be a complete transition to renewable energy sources. On the other hand, if electricity generated from fossil fuels were completely replaced by renewable energy sources (RES), it would inevitably lead to an increase in the cost of electricity.

2. COST OF ELECTRICITY AS AN EXPENSE OF ENVIRONMENTAL SUSTAINABILITY

In this analysis, it is assumed that the cost of electricity is calculated with the premise that electricity obtained from the combustion of fossil fuels is completely replaced by production from renewable energy sources (RES) – alternatively from wind and solar energy as RES, assuming the hydro potential is fully utilized. An overview of the advantages and disadvantages of using solar or wind energy is presented below (adapted from "Electricity Production," 2004 and Kalea, 2009:18):

Wind Power Plants

Advantages:

- environmentally friendly source without emissions of harmful substances during operation,
- wind is a completely renewable energy source,
- technologically simple construction of wind generator units,
- the costs of specific investments are decreasing due to the commercialization of production and state subsidies and compensations,
- possibility of combined operation with other types of power plants.

Disadvantages:

- low overall utilization of wind potential (about 30%),
- low utilization of maximum wind power plant capacity due to wind parameters (speed, intensity, duration),
- relatively large land area required due to the low energy density of wind (for 1000 MW, 50-150 km^2 is needed),
- operates a maximum of 2000 hours annually (figuratively, operates every fifth day, while resting the other four),
- adverse impact on the characteristics of the power system due to production instability,
- limited environmental impacts (noise, pollution during construction and installation, impact on birds, shadow flicker),
- need for subsidies and compensations due to still non-competitive production costs per kWh,
- does not reduce the need for the construction of other types (conventional) power plants.

Solar Power Plants (Photovoltaic Systems – PV)

Advantages:

- inexhaustible source of energy,
- does not pollute the environment chemically, radioactively, or thermally,
- no potential dangers during application,
- suitable for both developed and underdeveloped countries.

Disadvantages:

- geographically uneven distribution,
- fluctuations during the day, month, and year,
- availability of solar collectors is 30% of the day or approximately 7 hours/day,
- operates an average of 1000 hours annually (figuratively, operates one day and rests almost eight days),
- low energy density (average insolation power on the Earth's surface is up to a maximum of 300 W/m^2; in Croatia, the average insolation power is up to 200 W/m^2),
- poor economic feasibility as they occupy large areas (the annual solar radiation on the surface of Croatia ranges from 1200 to 1800 kWh/m^2, average annual solar radiation is assumed 1300 kWh/m^2),
- does not reduce the need for the construction of other types (conventional) power plants.

The number of working hours per year at the rated power of wind power plants and solar power plants is directly related to the production of electricity. A solar power plant can only operate up to a maximum of 12 hours of sunlight per day (no production at night), which is a daily utilization of working hours of up to 50%, but realistically, due to cloudy weather, only 30% (7 hours/day) to just 22% of the day (around 5 hours/day). Moreover, the insolation during the 12 hours of operation of the solar system is not constant. There are fluctuations in production throughout the day, month, and year ("Feasibility Comparison," 2015).

It can be concluded that the number of working hours at the rated power of photovoltaic systems is on average around 1000 hours per year (11,5%). This means that if these systems were to continuously operate at full rated power, they would have to achieve their entire annual production within 1000 hours. A year has 8760 hours. Figuratively speaking, if the systems operated at full power for one day, they would rest for almost eight days, and so on throughout the year ("Feasibility Comparison," 2015).

Electricity production from wind power plants occurs in the rhythm of the wind. The annual number of working hours at the rated power of a wind power plant is slightly above 1840 hours, or figuratively speaking, wind power plants operate at full power for 21% of the year. Additionally, electricity production from wind power plants does not have to be aligned with demand. German experience shows that for every 1 MW of wind power installed, an additional 0,85 MW of power must be installed in conventional power plants to ensure equal supply security for customers. For easier understanding, an average availability of wind power plants of 2000 hours/year is accepted in this paper. This figuratively means that they operate every fifth day and rest for four days ("Feasibility Comparison," 2015).

Comparison of different types of power plants (Kalea, 2012:26):

- 1 MW of installed PV system power produces approximately 1000 MWh of electricty annually;
- 1 MW of installed wind power produces 2000 MWh of electricity annually;
- 1 MW of installed hydro potential produces 3000 - 4000 MWh of electricity annually,
- 1 MW of installed thermal power produces approximately 7000 MWh of electricity annually.
- 1 MW of installed nuclear power produces approximately 8000 MWh of electricity annually.

In Croatia, the average insolation power is up to 200 W/m², which results in a required area of 5000 m² for a 1 MW plant, forming a square with a side length of 70 m. Assuming an average efficiency of 15%, the required area increases to 0,03 km² (3 ha) of open land, or figuratively speaking, a square with a side length of 180 m (for an insolation of 170 W/m², the required area is 200 m²).

The land area required for a 1 MW wind turbine is about 0,1 km² (1 MW turbine has a rotor diameter of about 60 m; the distance downwind is 6 rotor diameters and perpendicular to the wind 4 rotor diameters), or figuratively speaking, a square with a side length of 300 m. The land occupancy ratio of wind power plants to solar power plants of the same power is approximately 3:1.

Regarding construction costs, the investment for building a wind power plant ranges from 1200 to 1500 €/kW. It can be assumed that the average investment is around 1350 €/kW. The investment for building a photovoltaic (PV) system has dropped from 2500 €/kW in 2013 to a competitive amount with wind power plants of the same power today ("Reduce Electricity Bills with a Solar Power Plant", 2024).

It can be assumed that the decision is to build wind power plants as RES to replace 18,49% of electricity from fossil fuel thermal power plants, because with comparative investment costs, they have greater availability in electricity production than photovoltaic power plants.

Since wind power plants produce 3,5 times less electricity than thermal power plants of the same power, it follows that the produced energy will be 3,5 times more expensive, further increased for power reserve or customer supply security by a factor of 1,85 making electricity from wind power plants almost 6,5 times more expensive than from thermal power plants of the same power (assuming the same investment per MW for both energy plants).

If according to this scenario 18,49% of the produced electricity in the power system costs 6,5 times more than before. Simple math shows that the new electricity price on the market will be twice as high as the current price.

3. ECONOMICS OF ELECTRIC VEHICLE CHARGING SERVICES AT DIFFERENT TYPES OF CHARGING STATIONS

Until January 2022, charging electric cars was free. Table 1 shows the price list for electric vehicle charging services on the highway, while Table 2 shows the price list off the highway. The prices differ according to AC and DC connections ("Price List for Electric Vehicle Charging Services," 2023).

Table 1: Price List for Electric Vehicle Charging Services on the Highway

Charging Type	AC - Charging at connectors with a rated power up to 22,1 kW	DC - Charging at connectors with a rated power from 22,2 kW to 50 kW	DC - Charging at connectors with a rated power above 50 kW
Price per kWh during peak tariff period (incl. VAT)	0,36 €/kWh	0,46 €/kWh	0,66 €/kWh
Price per kWh during off-peak tariff period (incl. VAT)	0,31 €/kWh	0,38 €/kWh	0,59 €/kWh
Allowed charging duration	180 min	60 min	45 min
Exceeding allowed charging duration (incl. VAT)	0,14 €/min	0,14 €/min	0,14 €/min

Table 2: Price List for Electric Vehicle Charging Services off the Highway

Charging Type	AC - Charging at connectors with a rated power up to 22,1 kW	DC - Charging at connectors with a rated power from 22,2 kW to 50 kW
Price per kWh during peak tariff period (incl. VAT)	0,29 €/kWh	0,40 €/kWh
Price per kWh during off-peak tariff period (incl. VAT)	0,24 €/kWh	0,34 €/kWh
Allowed charging duration	180 min	60 min
Exceeding allowed charging duration (incl. VAT)	0,06 €/min	0,06 €/min

In Table 3, approximate fuel prices for vehicles with ICE are shown ("Fuel Prices", 2023).

Table 3: Fuel Prices for Vehicles with ICE

Fuel Type	Price (€/l)
Eurosuper 95	1,43
Premium Eurosuper 95	1,80
Eurosuper 100	1,90
Eurodizel	1,44
Premium Eurodizel	1,80
Autogas (LPG)	0,77

Comparing the prices of electric vehicle charging at charging stations and refueling service for ICE vehicles, economic efficiency assessment of the of these two vehicle types can be made.

Assuming an ICE vehicle consumes 7 liters per 100 km on open roads, driving a distance of 100 kilometers on liquid fuel costs approximately €10.
According to the ADAC's electric vehicle consumption test, consumption ranges from 15,5 to 30,9 kWh/100 km depending on the vehicle type ("Energy Consumption Test," 2023). Electric cars on average consume about 20 kWh per 100 kilometers ("Is Croatia Ready?", 2022). As an example, the BMW i7 xDrive 60 has a consumption of 22 kWh/100 km. In this case, to cover a distance of 100 km, 22 kWh of stored energy is required.

If the battery is charged at home at a nighttime tariff rate of approximately €0,08/kWh, the cost of energy will be around €2, but charging will take longer due to the low power of the connection.
Charging at a public charger off the highway with a rate of €0,40/kWh will cost around €9 while on the highway with a rate of €0,66/kWh, it will cost around €14,5, which is more expensive than ICE liquid fuel prices.
Considering the price of electricity at public chargers off the highway, which is very close to the price of liquid fuel, electric vehicles are economically viable only if higher mileage is done. In conclusion, this calculation shows that with current electricity prices, electric vehicles are more economical or comparable to ICE vehicles only in urban transport, but more expensive on highways. For this reason, Mikulić (2020) states that electric vehicles are known for their characteristics as urban vehicles.

It should be noted that in the event of an increase in electricity prices due to the transition to renewable energy sources, the economic viability of electric vehicles, even in urban transport, would significantly decrease.

Assuming that electric cars consume about 20 kWh per 100 kilometers average, multiplying this with average annual mileage driven by cars in Croatia by 11016 kilometers, it results in an annual consumption of about 2200 kWh, or 2,2 MWh per car, which is slightly less than the average annual household electricity consumption in 2021, which is 2,9 MWh. This means that with an electric car charging at a home charger in the garage, household electricity consumption would double ("Is Croatia Ready?", 2022).

Home chargers, or Level 1 chargers, with a power of 2,3 kW, provide a range of approximately 8 km per hour of charging ("Home Charging Stations," 2021). Assuming an overnight charging period of 8 hours, this achieves a range of about 90 km, which is adequate for daily urban transport. Fully charging a small 40 kWh battery will require up to 18 hours of home charging, while a larger 95 kWh battery will require 41 hours of home charging, which is realistically not feasible.

Level 2 charging stations have a power range from 3,7 to 22 kW. For average electric vehicles, a Level 2 charging station with an output of 22 kW will provide approximately 120 km of range per hour of vehicle charging. Level 2 charging stations can be connected to the household electrical network via single-phase or three-phase power connections ("Home Charging Stations," 2021).

Level 3 charging stations have a power range from 20 to 50 kW and are used for public and commercial purposes ("Home Charging Stations," 2021).

3. ECOLOGICAL SUSTAINABILITY ELECTRIC VEHICLES BATTERY PRODUCTION

The production of batteries for electric cars requires extensive mining activities to acquire and refine large quantities of rare earth metals such as lithium, cobalt, and others.

A lithium leaching field is highly neurotoxic. A bird that lands on it could die within minutes ("Driving an Electric Car", 2024).

A Li-ion battery weighing around 160 kg contains 10 kg of manganese, 20 kg of copper, 6 kg of lithium, 8 kg of cobalt, 29 kg of nickel, 35 kg of aluminum, and 52 kg of graphite (Zrna, 2024:51).

The raw materials needed to produce the battery for the Tesla Model Y include 12 tons of rock for lithium; 5 tons of cobalt ore (most cobalt is produced as a byproduct of copper and nickel ore processing, making it very difficult to obtain and very expensive); 3 tons of nickel ore; and 12 tons of copper ore.

For example, to extract: 12 kg of lithium; 13,6 kg of nickel; 22 kg of manganese; and 6,8 kg of cobalt, 250 tons of soil must be moved ("Driving an Electric Car", 2024).

The European Union has mandated by its regulations a recycling rate of 80% for lithium and 90% for cobalt and nickel from electric vehicle batteries by 2031. Currently, only 5% of Li-ion batteries from electric cars are recycled (Zrna, 2024:51).

The recycling processes for such batteries are extremely complex and hazardous, taking place in only a few facilities worldwide.

Figure 2: Battery for Tesla Model Y
(adapted from "Driving an Electric Car", 2024.)

Figure 3: Lithium leaching field
(adapted from "Driving an Electric Car", 2024.)

3. AVAILABILITY AND SAFETY OF USING ELECTRIC VEHICLES

The infrastructure for electric vehicle charging stations is not yet at the desired level, and electric vehicle owners do not have the same conveniences as owners with conventional fuel stations (lack of standardization with a single outlet, shorter driving range). The need to expand the network of charging stations is crucial for the further development and expansion of e-mobility.
Therefore, congestion at charging stations remains an expected occurrence. The EU aims to have at least one charging station every 60 km on highways by 2025 (Vedranić, 2024:41). This of course entails the construction of appropriate power connections.
Battery capacity is directly linked to the driving range of the electric vehicle as well.

Regarding the capacity of electric vehicle batteries, it gradually decreases under different usage conditions, such as extreme operating temperatures, hundreds of partial cycles, and varying discharge rates. This affects the vehicle's acceleration, range, and battery regeneration capacity. After a certain period (approximately 10 years), the battery is considered unsuitable for use in an electric vehicle.

The lifespan of the battery, i.e. the decline in capacity over the years, represents a limiting factor for the availability of electric vehicle usage. For Li-ion batteries, the lifespan is around 10 years, and by then, they retain no more than 70 to 75% of their original capacity (Zrna, 2024:51).
It is considered as the end of the battery's usage in the vehicle; however, they are only halfway through their total lifespan. One idea for utilizing the full lifespan of automotive batteries is to connect multiple batteries into stationary blocks to store excess electricity produced from renewable energy sources (Zrna, 2024:51).

Fires in electric vehicles pose a safety challenge and a significant hazard due to the electric drive batteries. Each battery has a high energy density, storing a lot of energy in a small space. They are composed of many individual cells incorporated into a module. The modules are assembled together to form the electric battery. For example, the Tesla Roadster consists of 7000 cells. If the battery is mechanically damaged, a short circuit and spark can occur, easily igniting the highly reactive lithium. Other situations that can lead to battery ignition include charging and discharging with excessive currents, causing sudden heating of the battery and possible ignition (Šipuš, 2018:54). A burning electric battery becomes very difficult to extinguish with the risk of reignition.

There are no accepted standard operating procedures for responding to such interventions in the event of an electric vehicle battery fire. One practical method for extinguishing an electric vehicle fire is to submerge the entire vehicle in water.

In addition to extinguishing the flames, it is necessary to use personal protective clothing and equipment and respiratory protection devices within a 15-meter radius of the burning vehicle, as toxic gases are released during combustion.

4. ELECTRIC VEHICLES MAINTENANCE CHALLENGES

For the safe operation and maintenance of electric vehicles, it is necessary to be familiar with measures for safely handling high-voltage electric vehicle components. It is important to know the protective measures against direct or indirect contact with high-voltage components. One of the main features of high voltage is the orange colour, and it is the duty of electric vehicle manufacturers to unambiguously mark all live parts, components, and high-voltage cables with orange colour and high-voltage warnings.

The greatest danger in working with electric vehicles is the potential damage to the insulation of conductors that are under voltage.

Before starting the maintenance of an electric vehicle, it is essential to define work zones separated by physical barriers and clearly marked lines on the floor. These are ("Working on Electric Vehicles", 2021):

I. Zone - free movement zone: all areas where an employee cannot inadvertently cause the connection or disconnection of high-voltage battery system electrical power, nor come into close proximity to high-voltage components with their body or tools.

II. Zone - approach zone: access is allowed only for trained personnel and involves the use of proper protective equipment and adherence to work procedures.

III. Zone - danger zone: work area on the battery system itself or near parts that are under voltage, requires the highest level of training for working on high-voltage systems, caution, and full use of protective equipment.

The competences of the maintenance personnel in electric vehicle services should be defined as follows (Jaki, 2020):

Level I – person familiar with electrical engineering: vehicle repairs not related to the high-voltage system and work on certified high-voltage systems without voltage;

Level II – high voltage technician: certified non-voltage connection of high-voltage systems, installation of high-voltage battery, classification of high-voltage battery;

Level III – high voltage expert: disconnection of high-voltage systems, repair of high-voltage battery.

CONCLUSION

The implementation of e-mobility presents a contemporary challenge. Regardless of various claims, fully electric vehicles also indirectly pollute the environment and have an impact on climate change. The battery is considered the most important and expensive part of an electric car because its characteristics (capacity and voltage) determine the other components of the electric vehicle. For ecological sustainability, the method of production and disposal of the battery at the end of its lifespan is crucial.

Electric drive offers temporarily cheaper driving compared to internal combustion engine (ICE) vehicles, but in the long term, due to the energy mix and transition to renewable energy sources, energy will consequently be more expensive. It can be concluded that, at this moment, electric vehicles are suitable only for urban traffic and are recognized as urban vehicles due to their characteristics. The complete transition from ICE vehicles to electric vehicles depends on several factors, some of which are addressed in this article. Only when these factors are satisfactorily met, electric vehicles could outnumber ICE vehicles on the roads.

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