Article citation info:
Szumska EM, Jurecki R. Technological developments in vehicles with electric drive. Combustion Engines. 2023;194(3):38-47. https://doi.org/10.19206/CE-168219

Emilia M. SZUMSKA
Rafał JURECKI

Combustion Engines
Polish Scientific Society of Combustion Engines

Technological developments in vehicles with electric drive

ARTICLE INFO

Received: 16 May 2023
Revised: 11 June 2023
Accepted: 12 June 2023
Available online: 15 June 2023

The fleet of electric vehicles is systematically growing. Many passenger car manufacturers are already reporting that after 2030, vehicles equipped with electric propulsion will account for half of the models produced. Vehicles equipped with an electric drive include: battery-powered electric vehicles, hybrid electric vehicles and fuel cell electric vehicles. Over the years, these vehicles have undergone constant change. The aim of this paper was to review trends in the development of pure electric vehicles and plug-in hybrid vehicles.

Key words: *electric drive; electric vehicle; plug-in hybrid vehicle, hybrid electric vehicle*

1. Introduction

The electric powered vehicles are gaining an increasing share of the passenger vehicle market. There are three types of electric vehicles: battery electric vehicles (EV), hybrid electric vehicles (HEV), and vehicles equipped with fuel cells electric vehicles (FCEV). Despite the many challenges facing electric drive technology, there is a great reason to be optimistic about its future. New technologies in the field of electric vehicle drive systems have great potential to stimulate the development of intelligent and sustainable transport [56, 59]. Despite the many challenges facing electric drive technology, there are good reasons to be optimistic about its future [12, 32, 44].

The automotive industry is currently facing a profound transformation toward electric mobility. Diverse electric vehicle models in different price ranges available from automakers are resulting in a noticeable increase in EV sales. In Europe, sales of electric passenger vehicles in 2021 increased by over 65% compared to 2020. In 2021, electric vehicles accounted for 17% of all passenger cars sold in Europe [28]. In the first half of 2022, electric passenger vehicles reached an 11.1% share of European's overall automotive market [26].

Car manufacturers put close attention to the customers' likings. Based on the observation of the increase in interest in electric cars and the increase in sales of electric models, car manufacturers are form their offer. Carmakers aiming to gain a greater share of the electric vehicle market offer a wide range of models with electric drives to appeal to a growing group of consumers. The offer of each passenger car manufacturer includes models with hybrid or electric drives. These trends are observed both in the sector of small and city passenger cars, as well as sports cars and SUVs. According to the report [62], over the last 2 years, all car manufacturers have increased sales of electric vehicles. The development of electric drive technology is also taking place in light commercial vehicles. Electric and hybrid heavy-duty vehicles have already been developed. They are currently the subject of extensive testing and research [37]. Research shows that consumers who are interested in buying an electric vehicle pay attention primarily to its range, charging time, and purchase price [15, 40, 65]. The continuous development of battery technology already allows you to cover an increasingly longer distance on a single charge [60]. In addition, with the use of fast chargers, battery charging times have also been significantly reduced [54, 61, 64]. However, the high cost of purchasing an electric vehicle is a barrier for many potential buyers. In many countries, subsidies and financial incentives are available for EV buyers to attract potential customers. In addition, many cities offer facilities for electric car owners in the form of parking fee exemption, toll road exemption, and bus lane use [14, 34, 38].

Among the charging technologies for electric vehicles, wireless charging methods can be distinguished. It can be a flexible and promising alternative to standard plug-in battery chargers [7, 45]. Wireless charging is easier to use as it does not require a cable to be connected to the vehicle. This is a technology still in development. However, thanks to properly placed charging infrastructure, it will be possible to recharge the battery (e.g. in parking lots or while waiting at red lights), which will further extend the range [24, 33, 68].

Many automobile concerns have set themselves ambitious plans to increase the share of vehicle models with electric drives in the entire assortment of vehicles produced. The Volkswagen Group assumes that in 2030 every second vehicle produced will be equipped with an electric drive. It should also be emphasized that in 2021 Volkswagen was the second largest car manufacturer in the world [35, 48], and the share of battery electric vehicles in its total sales volume was 5.1%. The Stellantis Group, which brings together the following brands: Citroen, DS Automobiles, Jeep, Fiat, Opel, and Peugeot, announced a new strategy in March 2022, which assumes the sale of 5 million purely electric vehicles by 2030 [20, 57].

Asian automobile companies also have extensive vehicle electrification plans. Toyota is a pioneer in the production of hybrid vehicles. The Prius, unveiled in 1997, was the first widely available and mass-produced hybrid vehicle, which continues to be very popular. Toyota has not put a purely electric model into production until 2021. With its recently announced strategy, Toyota aims to introduce 30 new EV models by 2030 [3, 19]. Nissan plans to introduce 23 new electric models, including 15 new electric models by 2030. The company aims to achieve more than 50% share of electric vehicles in total global vehicle sales for the Nissan and Infiniti brands by 2030 [47]. Honda plans to introduce 30 electric models to the global market by 2030, with a production volume of more than 2 million vehicles per year. The company has announced that by 2040 it will completely phase out the production of gasoline-powered cars. In addition, Honda intends to engage in research and development of new battery technologies [58].

Ford Group has ambitious plans to develop electric vehicle technology. The corporation intends to introduce three new electric passenger vehicles and four new electric commercial vehicles in Europe by 2024. Planned sales are more than 600,000 electric vehicles by 2026 in the European market only. In addition, Ford plans to open one of Europe's largest commercial vehicle battery plants in Turkey [25].

Plans to increase the share of electric cars are observed in the luxury and sports car sectors. For example, Mercedes-Benz assumes that in 2025, 50% of the planned revenues will come from the sale of EV and plug-in hybrid vehicles. In 2021, Mercedes-Benz sold 2.4 million vehicles, of which 4% were EV vehicles [42, 43]. The BMW Group predicts that at least half of the vehicles sold in 2030 will be BEV models [9]. In 2021, the share of electric vehicles in the total number of vehicles sold was 4% [21, 42]. The Volvo Group assumes that by 2025, electric cars will account for half of the models produced, and after 2030, all models produced will be equipped with electric drives [67]. In 2021, about 4% of vehicles sold by the concern were models equipped with an electric drive [65, 66]. In its strategy, Audi concern assumes that by 2025 its offer will include more than 20 fully electric models. The concern clearly focuses on electromobility and plans to invest around EUR 18 billion in electrification and hybridization in the years 2022-2026. From 2026, two fully electric models will be available. A key element of Audi's electrification strategy is a new factory in China, where a state-of-the-art production facility for all-electric Audi models will be built by the end of 2024 [5].

Electrification of means of road transport is an opportunity to reduce CO_2 emissions. The Green Deal for Europe (GDE) presented by the European Commission in 2019 assumes the achievement of zero net greenhouse gas emissions by 2050. The intermediate goal of the GDE is to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990. The document also contains legal regulations responding to the challenges in the transport sector related to reducing energy consumption and increasing the use of the so-called clean energy, more efficient use of modern infrastructure, and reduced environmental impact [16]. In "Fit for 55" announced on 14 July 2021 the European Commission announced a package of legislative postulates. One of the calls is the introduction of CO_2 emission limits for passenger vehicles and light-duty vehicles. Starting in 2030, new vehicles are assumed to emit less CO_2 (compared to 2021) by an average of: 37.5% – for passenger cars and 31% – for light-duty vehicles. CO_2 emission limits have also been set for trucks and other heavy-duty vehicles. The new regulations oblige manufacturers to reduce their CO_2 emissions (compared to 2019) by an average of 15% by 2025, and then by 30% by 2030 [22]. The "Fit for 55" project assumes that from 2035 all new passenger vehicles and light-duty vehicles will be completely emission-free. Member States will be obliged to develop infrastructure for electric vehicle charging and increase the number of hydrogen refueling stations.

Technologies used in EVs can increase the flexibility of their use, which can be important in energy management optimization systems. The possibility of using electric vehicles in systems supplying energy to the electric network of the Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) type means that electric vehicles can change their role from a means of transport into an energy storage system. V2G systems can reduce the pressure on the grid during peak EV charging and connect the vehicle to the grid to use electricity more rationally [4, 51, 70]. V2H and V2G systems mainly consist of battery management software, equipment supporting two-way transmission of electricity, and communication modules between the vehicle and the power grid. A properly designed V2G and V2H systems are aimed at optimizing charging costs for owners of electric vehicles while providing auxiliary services to the grid [4, 10].

Electric vehicle drives are undergoing continuous development. New technologies related to energy storage, charging methods, or energy transfer allow electric vehicles to become more accessible to average consumers. The aim of this paper is to present trends in the development of electric-powered vehicles. The paper provides a review of electric drive vehicles and the development of electric drive technology in vehicles over the years.

2. Electric-drive vehicles

Classification of electric vehicle propulsion systems can be done by electrification level. The main parameter for this classification is considered to be the amount of electricity that drives the vehicle. This is determined by the energy capacity of the battery, which determines the amount of energy expended and recuperated [69]. Vehicles equipped with electric drive include:

- battery electric vehicle (EV) – a vehicle with an electrochemical battery as the energy source and an electric motor as the drive unit
- hybrid electric vehicle (HEV) – a vehicle that combines an internal combustion engine and an electric motor – the internal combustion engine is the main energy source
- plug-in hybrid vehicle (PHEV) – a vehicle in which electric and combustion drives work together, but the electric drive is the main drive
- fuel cell electric vehicle (FCEV) – a vehicle in which a fuel cell and an electro-chemical battery cooperate, and the drive unit is an electric motor.

The specifications of vehicles with electric drive systems are summarized in Table 1.

Table 1. Technical features of vehicles with an electric drive train

Type of vehicle	Drive system	Power unit	Energy sources
BEV – Battery Electric Vehicle	Electric motor drives	Electric machine	Battery charged from the electrical grid
HEV – Hybrid Electric Vehicle	Internal combustion engine	HEV – Hybrid Electric Vehicle	Internal combustion engine
PHEV – Plug-in Hybrid Electric Vehicle	Electric motor drives	PHEV – Plug-in Hybrid Electric Vehicle	Electric motor drives
FCEV – Fuel Cell Electric Vehicle	Electric motor drives	Electric machine	Fuel cells

3. Development of electric drive technology in passenger vehicles

In order to determine the development trends in the field of electric drives used in vehicles, the parameters of selected drive components were analyzed. On the basis of the report [52], models of electric and plug-in hybrid passenger cars of various segments were selected. A few of the longest-running models on the market were chosen. In the case of electric vehicles (EV), the following technical parameters were analyzed: total power, top speed, battery nominal capacity, range, and curb weight. For plug-in hybrid vehicle analyses, the parameters selected were: internal combustion total power, electric machine total power, battery nominal capacity, electric range, and fuel consumption.

3.1. Technological developments in electric vehicle propulsion

Electric passenger vehicles from the four categories highlighted in the European Commission's Regulation [30] were investigated:

– B-segment small cars: Peugeot iOn, Renault ZOE
– C-segment medium cars: Nissan Leaf, Volkswagen e-Golf
– D-segment large cars: Tesla Model 3
– E-segment executive cars: Tesla Model S.

According to reports [1, 59, 71] the models under discussion are the longest-produced electric vehicles on the market and are still very popular with customers.

The first parameter under consideration is total power (Fig. 1). The drive unit in electric vehicles is exclusively an electric motor. Its task is to convert the electrical energy from the battery into mechanical energy used to drive the wheels of the vehicle. Total vehicle power is not constant and may depend on many factors such as ambient temperature, battery temperature and state of charge, battery type, battery state of age and battery age.

As can be observed on Fig. 1, the total power of electric vehicles has been increasing over the years. In the B-segment of small passenger cars, the available total power of the Peugeot iOn was increased by only 4% over the production period (2009-2022), while that of the Renault ZOE (over a much shorter period: 2012-2022) was increased by as much as 286%. For electric vehicles in the C-segment of medium-sized passenger cars, the available total power has also increased over the years. In the Nissan Leaf, the available total power has been increased by 158% compared to the first version of this model in 2010. The VW e-Golf in the years 2014-2022 recorded a slight increase in engine power of 18%. Tesla models from the D-large car segment and the E-executive car segment recorded a significant increase in total power, with 96% and 186% respectively.

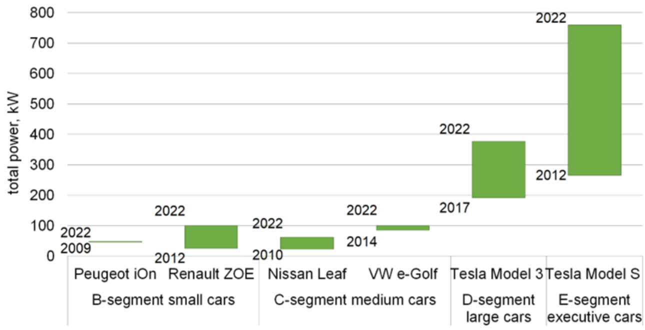

Fig. 1. The total power output of the selected electric vehicle models from the start of their production until 2022

Due to the increase in total power in the electric car models analyzed, there was also an increase in top speed (Fig. 2). However, while the increase in top speed in vehicle segments B and C was small (up to around 8%), increases of 20% and 61% were noted in vehicle segments D and E.

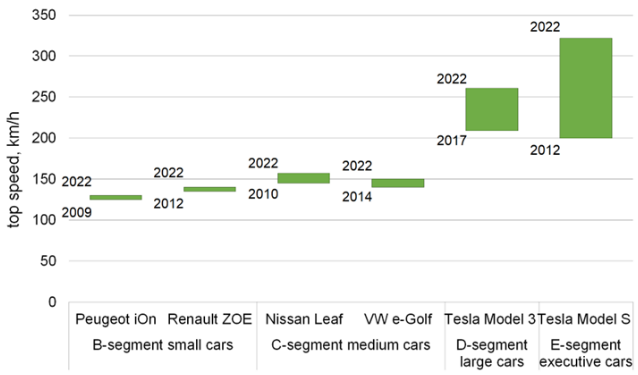

Fig. 2. The top speed of the selected electric vehicle models analyzed from the start of their production until 2022

An important parameter affecting the functionality of an electric vehicle is the battery nominal capacity. Figure 3 shows the battery nominal capacity over the years of production of electric models.

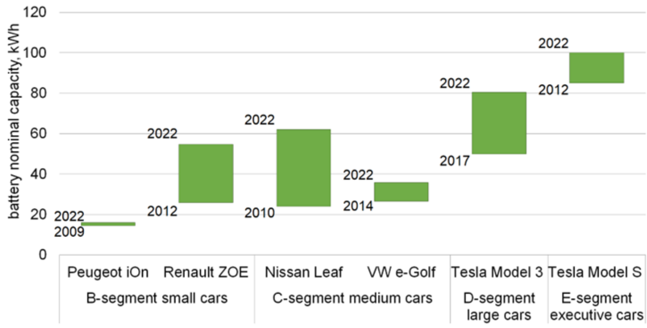

Fig. 3. The battery nominal capacity of the selected electric vehicle models from the start of their production until 2022

The amount of energy stored depends on the energy capacity of the battery. Energy storage technology is still undergoing significant advances, such as in the area of materials used in cathodes and anodes. Current studies are aimed at obtaining the highest possible energy density and high energy density at the same time, while reducing the size and weight of the battery. As shown in Fig. 3, the nominal battery capacity increased in the analyzed models of electric vehicles. The nominal battery capacity has slightly increased in the Peugeot iOn, by 10%. Over the years of production, the nominal battery capacity of the Nissan Leaf (by 158%) and Renault ZOE (by 111%) has been significantly increased. For Tesla vehicles, the nominal battery capacity has been increased by 61% on the Model 3 and 18% on the Model S, respectively.

The popularity of electric vehicles is largely determined by their functional features. One of the important parameters taken into account by future users is the range. The range can be defined as the distance that an electric vehicle can travel from fully charging the battery to its discharge to the limit level. From the point of view of especially new EV users, range is a key issue in the operation of this type of vehicle. The concern about the limited range of electric vehicles causes a phenomenon called "range anxiety" [13, 49, 50]. A properly placed charging network can reduce range anxiety. The problem with EV use is the long battery charging time, which, depending on the battery capacity and charging method, can take up to several hours. Figure 4 shows the range of the analyzed EV models during their production period.

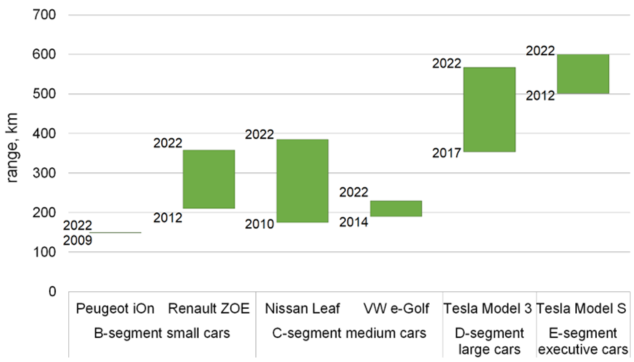

Fig. 4. The battery nominal capacity of the selected electric vehicle models from the start of their production until 2022

As shown in Fig. 4, the range of most of the analyzed vehicles has increased. This is mainly due to the development of energy storage technology. In the initial period of production, the analyzed vehicle models from the B and C segments showed a similar range. Compared to that period, the largest increase in range was recorded for Nissan Leaf (by 120%) and Renault ZOE (by 80%). It is worth mentioning that these vehicles saw the largest increase in nominal battery capacity during their production period. The range of the VW e-Golf has been extended by 20%. Based on the information provided by the manufacturers of the analyzed models from 2022, the range varied. Electric vehicles in the B segment had a range from 150 to about 400 km. In the case of C-segment electric vehicles, the range arrays from 230 km to approximately 400 km. In the case of Tesla's Model 3, the range has been extended by 60% compared to the first generation of this vehicle. In the Tesla Model S over the years of production (2012-2022), the range increased by 20%. In 2022, the range of Tesla vehicles from segments D and E was even 600 km.

The increase in battery capacity not only extends the range but also results in an increment in EV weight. The increase in battery capacity not only extends the range but also results in an increase in the curb weight of electric vehicles. In the analyzed models of vehicles from segments B and C, the increase in curb weight was small, up to 10% over the years of production. The relatively highest increase in curb weight was recorded for the Tesla Model 3 (20%). Figure 5 presents the curb weight of the analyzed vehicle models over the years of production.

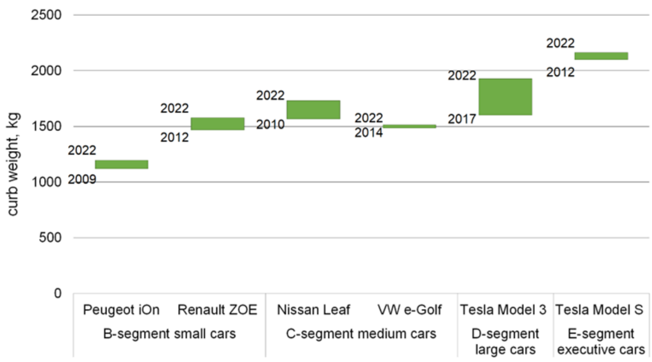

Fig. 5. Curb weight of the selected electric vehicle models from the start of their production until 2022

3.2. Technological developments in plug-in hybrid vehicles

In recent years, plug-in hybrid vehicle technology has undergone significant development. For this reason, selected models of passenger cars with the plug-in hybrid drive from the following segments were analyzed:

– B-segment small cars: Chevrolet Volt, Ford Fusion Energi
– D-segment large cars: Volvo V60 Plug-in Hybrid
– J- sport utility cars: Mitsubishi Outlander PHEV, Audi Q7 e-tron
– S- sport coupés: Porsche Panamera S E-Hybrid, BMW i8.

Selected hybrid vehicles are vehicles relatively the longest available on the market according to reports [2, 18, 63]. The chosen models represent different segments, so they have different parameters of the drive system components.

In plug-in hybrid vehicles, the combustion engine is intended to support the electric drive. Fig. 6 shows a comparison of the power of internal combustion engines in the analyzed PHEVs. As can be seen, the power of the internal combustion engine in-creased in each of the analyzed PHEV models during their production period. On most selected models, ICE power has been increased slightly. The largest increase in ICE power was recorded in J-segment vehicles (Audi Q7 e-tron) and S-segment vehicles (Porsche Panamera S E-Hybrid), by 32%.

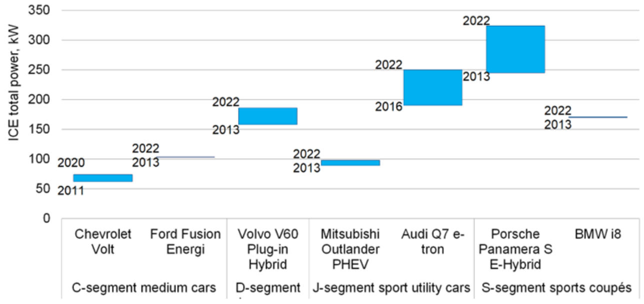

Fig. 6. Internal combustion engine power of the selected PHEV models from the start of their production until 2022

The basic propulsion system of plug-in hybrid vehicles is the electric drive. The electric drive system carries out the movement of the vehicle while the internal combustion engine is turned off. Figure 7 shows the power of the electric motor in PHEV models during their production period.

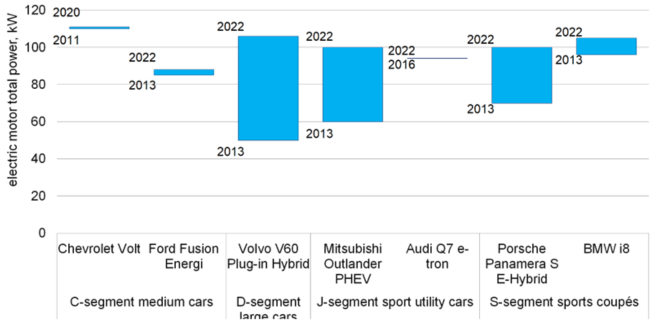

Fig. 7. Electric motor total power of the selected PHEV models from the start of their production until 2022

Over the years of production, the total power of the electric motor has increased in most of the analyzed PHEV models. Among the selected vehicles, the largest in-crease in electric motor power was shown by the S-segment model, the Volvo V60 (up 112%). The total power of the electric motor in the Mitsubishi Outlander and Porsche Panamera S E-Hybrid has also been significantly increased, by 67% and 43% respectively.

Studying the growth of available power from both combustion and electric drives, it can be seen that the total power increased and ranged between 185 and 424 kW. However, the percentage increase in power was not identical for all models. From an almost imperceptible increase in total power for the Ford Fusion to more than 40% for the Volvo v60 and Mitsubishi Outlander.

Figure 8 presents the nominal capacity of the batteries used in selected PHEV models over the years of production. In the two analyzed vehicles, the battery capacity remained unchanged. In other vehicles, the nominal capacity of the batteries was increased.

The nominal battery capacity of the Chevrolet Volt has been slightly increased by 15%. Over the years of production, the battery capacity of the Porsche Panamera S E-Hybrid has significantly increased by 90%. For the Volvo V60, Mitsubishi Outlander and BMW i8, the nominal battery capacity has increased by nearly 70%. The nominal battery capacity of the hybrid drive system determines the electric range. Figure 9 presents the electric range of the analyzed models of plug-in hybrid vehicles over the years of production.

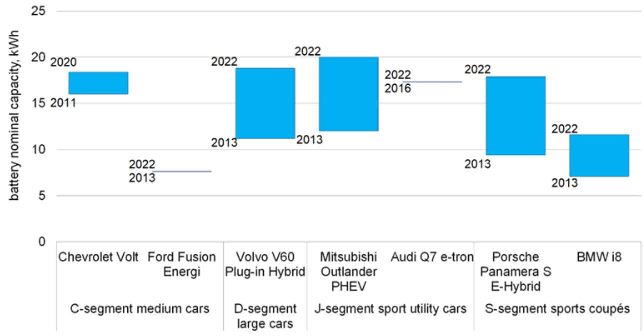

Fig. 8. Battery nominal capacity of the selected PHEV models from the start of their production until 2022

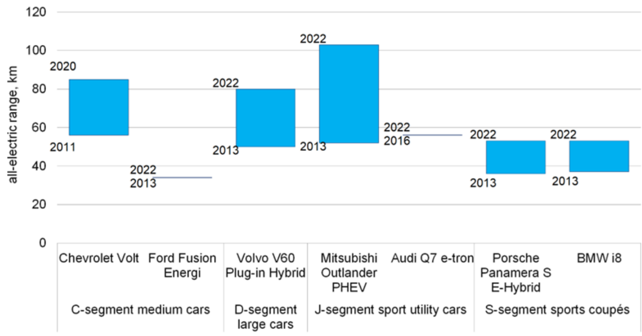

Fig. 9. The electric range of the selected PHEV models from the start of their production until 2022

In the first versions of the analyzed PHEV models, the electric range includes 34 km to 56 km. Extending the range resulted in a growth in the energy capacity of the battery. According to the manufacturers, in the 2022 PHEV versions, the electric range was from 35 km to 104 km. Over the years of production, the electric range of the Mitsubishi Outlander has approximately doubled. The electric range was significantly extended for the Volvo V60 (60%), the Chevrolet Volt (52%), the Porsche Panamera S E-Hybrid (47%), and the BMW i8 (43%).

One of the factors determining the popularity of hybrid vehicles is the possibility of using two power sources. It is possible to recover energy during braking, as well as driving only with an electric motor over relatively short distances, especially at low speeds, e.g. in traffic jams. An important argument for using this type of vehicle is lower fuel consumption compared to the classic internal combustion drive. In PHEV vehicles, after the battery is discharged to the limit point, the vehicle uses the internal combustion engine. In each of the considered PHEV models, fuel consumption has been reduced over the years of production (Fig. 10).

In the initial production period, fuel consumption for C-segment vehicles given by manufacturers was about 6.3 dm^3/100 km. In the 2022 versions of PHEV models, the reported average fuel consumption was about 13% lower. In the analyzed models from the D and J segments, over the years of production, the fuel consumption indicated in terms of fuel consumption ranges from 1.1 dm^3/100 km to 2.0 dm^3/100 km. Over the years of production of PHEV models in the S-segment, average consumption ranged from 2.0 dm^3/100 km to 2.1 dm^3/100km. Among the analyzed PHEV models, the largest reduction in fuel consumption over the years of production was recorded by the Volvo V60 (around 40% less). It is worth mentioning that among the selected PHEV models, it was the Volvo V60 that increased the battery capacity and electric motor power the most, resulting in a longer range in electric mode.

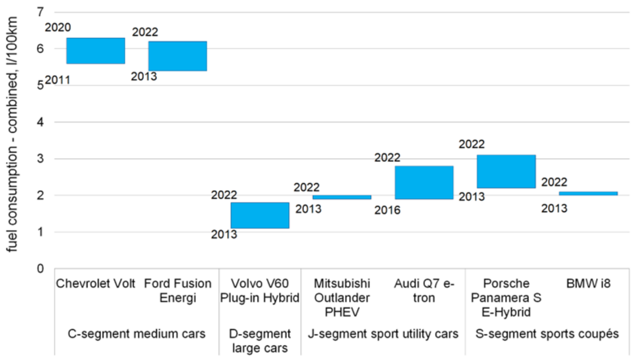

Fig. 10. Fuel consumption of the selected PHEV models from the start of their production until 2022

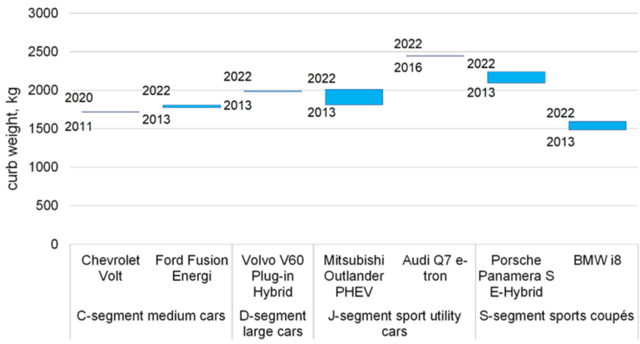

Fig. 11. Curb weight of the selected PHEV models from the start of their production until 2022

Plug-in hybrids are characterized by a much higher weight compared to conventional vehicles, as they are equipped with both a classic internal combustion engine and an electric drive. In addition, the large weight of the vehicle is affected by the weight of the battery. In PHEV, the battery has a much higher energy capacity than in other types of the hybrid drive. Figure 11 shows the curb weight of selected PHEV models over the years of production.

Of the vehicles analyzed, curb weight was slightly reduced in the Chevrolet Volt and Audi Q7 e-tron. For the other models, curb weight has slightly increased over the years of production. The Mitsubishi Outlander curb weight increased the most, by 11%.

4. Discussion

With the continued development of energy storage technology, the rapid expansion of the charging infrastructure, and the growing ecological awareness of society, vehicles equipped with electric drives (EV and PHEV) are expanding their market share [6, 11]. The energy capacity of the battery largely determines the range of an electric vehicle. Taking into account the values of the nominal energy capacity of the battery and the range provided by the manufacturers of the electric vehicle models analyzed earlier, the relationship between these parameters can be determined.

As the energy capacity of the battery increases, the range becomes longer (Fig. 12). Analyzing the parameters, based on the R^2 determination index, it can be seen that there is a correlation between these factors, especially for EVs it is very strong. A similar relationship occurs for plug-in hybrid vehicles.

Analyzing selected electric vehicle models, it can be observed that as the energy capacity of the battery increases, total power also becomes higher (Fig. 13). This was needed to ensure adequate range. In electric vehicles, the electrochemical battery is the source of energy. The battery capacity has a direct impact on EV operation. The currently used lithium-ion batteries provide a range of up to several hundred kilometers on a single charge with a relatively moderate lifespan [27, 39, 72]. The energy capacity decreases over time [17, 23, 29]. The high costs associated with the production of lithium-ion batteries contribute to the increase in vehicle prices, thus becoming a financial barrier for many potential buyers [36, 41, 53]. It is necessary to develop new technologies that enable the storage of large amounts of energy with the lowest possible weight.

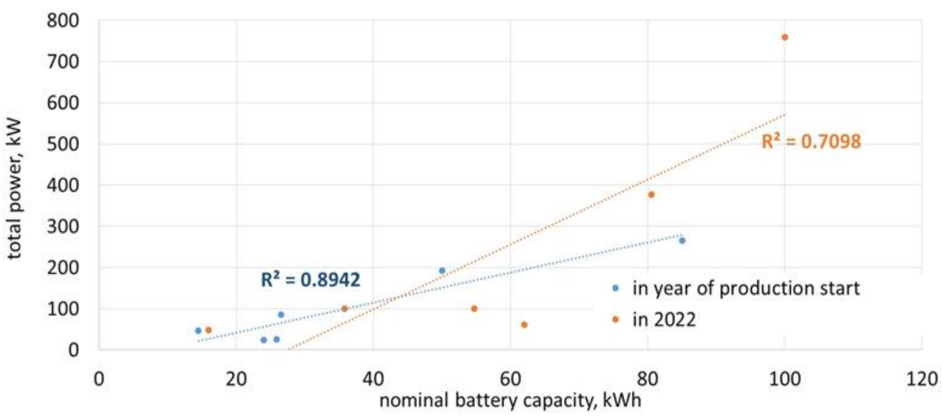

Fig. 12. Distribution of nominal battery capacity and range of EVs and PHEVs

Unfortunately, the increase in the electric capacity of the battery results in an in-crease in the weight of the vehicle (Fig. 14). There is a high correlation between these parameters. The coefficient of determination R^2 ranges from 0.85 to 0.97. Work is still being carried out to increase the battery capacity (energy density) without the need to enlarge them [8, 31, 46]. Research work on new battery technology could reverse this trend.

Taking into account the care for the natural environment, plug-in hybrid vehicles are an important alternative to electric vehicles. Compared to an electric vehicle, a PHEV has a combustion engine that is used when the battery is discharged. Plug-in hybrids provide a relatively long-range (electric and combustion). This means that the user does not have to worry about the range and plan routes taking into ac-count the available charging infrastructure. Driving in pure electric mode and regenerating energy during braking contributes to lower fuel consumption and emissions. In a plug-in hybrid, the electric drive is the main electric drive. The size of the battery should be selected so as to be able to provide the longest possible range in electric mode. Over the years, plug-in hybrid technology has undergone continuous development.

Taking into account the care for the natural environment, plug-in hybrid vehicles are an important alternative to electric vehicles. Compared to an electric vehicle, a PHEV has a combustion engine that is used when the battery is discharged. Plug-in hybrids provide a relatively long-range (electric and combustion). This means that the user does not have to worry about the range and plan routes taking into account the available charging infrastructure. Driving in pure electric mode and regenerating energy during braking contributes to lower fuel consumption and emissions. In a plug-in hybrid, the electric drive is the main electric drive. The size of the battery should be selected so as to be able to provide the longest possible range in electric mode. Over the years, plug-in hybrid technology has undergone continuous development.

As in the case of electric vehicles, PHEVs are significantly affected by the development of energy storage technology. Taking into account the parameters of the drive components provided by the manufacturers of the analyzed PHEV models, it can be seen that the increase in battery capacity translates into a longer electric range, which in turn reduces fuel consumption. The authors of the paper [55] studied the electric range value of a PHEV vehicle during regular driving on routes of various lengths. The results of the study showed that a route of about 20 km is covered between 15–35% in electric mode, a route measuring 40 km is carried out about 50% exclusively in electric mode, and a route of about 60 km is traveled about 75% using the electric drive. In most of the tested PHEV models, over the years of production, the electric range was extended, while fuel consumption was reduced. The increase in the energy capacity of the battery also contributes to the reduction of fuel consumption. In most of the tested PHEV models, the battery capacity has increased over the years of production, resulting in lower fuel consumption.

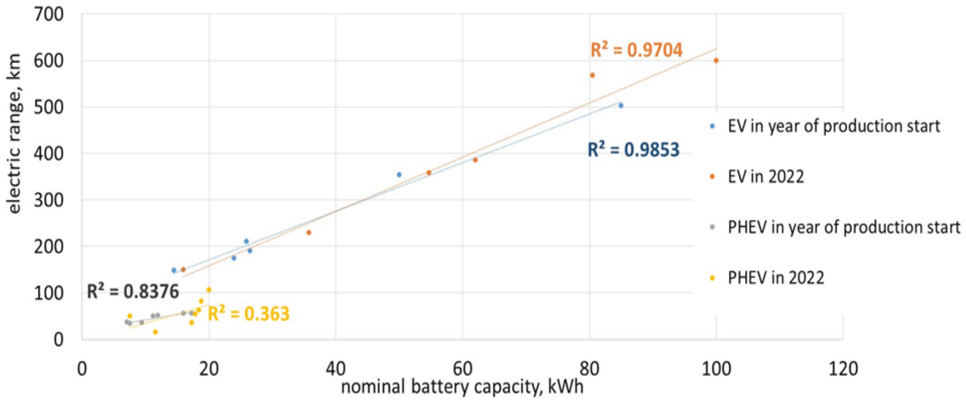

Fig. 13. Distribution of nominal battery capacity and total power of EVs

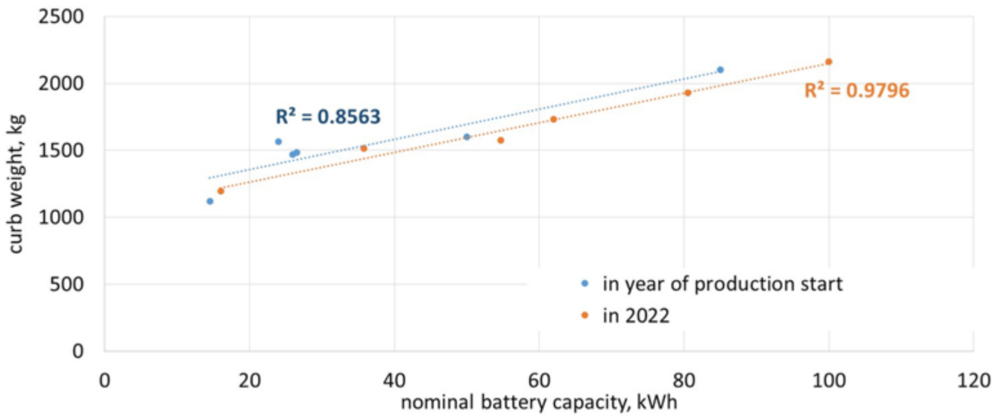

Fig. 14. Distribution of nominal battery capacity and curb weight of EVs

5. Conclusions

EU policy is aimed at reducing vehicles powered by internal combustion engines. Great emphasis is placed on the electrification of transport and the reduction of greenhouse gas emissions. Incentives and subsidies for the purchase of electric cars and the development of charging infrastructure may contribute to increasing the share of EVs in the automotive market.

Over the years, electric vehicles have undergone constant changes. The purpose of this work was to present trends in the development of electric vehicles. Based on the results of the analyses, it can be observed that over the years the energy capacity of the battery has increased with a slight increase in the weight of the vehicle. Thanks to the development of energy storage technology, a longer electric range could be achieved. An alternative to electric vehicles are plug-in hybrid vehicles. Compared to traditional hybrid electric vehicles, PHEVs are equipped with batteries with a higher energy capacity that can be charged from the power grid. In plug-in hybrid vehicles, the internal combustion engine is designed to support the electric drive after the battery is discharged. Over the past years, the energy capacity of the battery in plug-in hybrid vehicles has been increased, with a slight increase in the vehicle's curb weight. There was also an increase in the total power of the electric motor. This results in a longer electric range and lower fuel consumption.

Electric vehicles are currently one of the solutions to reduce greenhouse gas emissions in transport. During operation, EVs do not emit harmful substances into the air, unlike conventional combustion vehicles. There is still scope to further reducing greenhouse gas emissions over the entire life cycle of a vehicle, both in the operational phase by expanding the renewable energy infrastructure and in the production phase. Sustainability should not be limited to the use of hybrid or electric vehicles. It should take into account the modification of their construction by using new, more environmentally friendly, or recycled materials.

Nomenclature

EV battery electric vehicles
FCEL fuel cell vehicles
HEV hybrid electric vehicles
ICE internal combustion engine
ICEV conventional vehicle
PHEV plug-in hybrid electric vehicle
V2G Vehicle-to-Grid
V2H Vehicle-to-Home

Bibliography

[1] 100 best selling BEVs in 10 European countries. https://cleantechnica.com/2023/01/08/100-best-selling-bevs-in-10-european-countries/ (accessed on 18 January 2023).

[2] 2021 (Full Year) Europe: new car sales and market analysis. https://www.best-selling-cars.com/europe/2021-full-year-europe-new-car-sales-and-market-analysis/ (accessed on 20 January 2023).

[3] Akio Toyoda shares Toyota's strategy for achieving carbon neutrality through battery electric vehicles. https://pressroom.toyota.com/akio-toyoda-shares-toyotas-strategy-for-achieving-carbon-neutrality-through-battery-electric-vehicles/ (accessed on 12 January 2023).

[4] Amamra SA, Marco J. Vehicle-to-grid aggregator to support power grid and reduce electric vehicle charging cost. IEEE Access. 2019;7:178528-178538. https://doi.org/10.1109/ACCESS.2019.2958664

[5] Audi continues clear course towards e-mobility. https://www.audi.com/en/innovation/e-mobility/clear-course-towards-e-mobility.html (accessed on 12 January 2023).

[6] Austmann LM, Vigne SA. Does environmental awareness fuel the electric vehicle market? A Twitter keyword analysis. Energy Economics. 2021;101:105337. https://doi.org/10.1016/j.eneco.2021.105337

[7] Aydin E, Aydemir MT, Aksoz A, El Baghdadi M, Hegazy O. Inductive power transfer for electric vehicle charging applications: a comprehensive review. Energies. 2022;15:4962. https://doi.org/10.3390/en15144962

[8] Bastida-Molina P, Hurtado-Pérez E, Pérez-Navarro Á, Alfonso-Solar D. Light electric vehicle charging strategy for low impact on the grid. Environ Sci Pollut R. 2021;28:18790-18806. https://doi.org/10.1007/s11356-020-08901-2

[9] BMW Group report 2021. https://www.bmwgroup.com/en/report/2021/downloads/index.html?pdf-viewer=report (accessed on 12 January 2023).

[10] Borge-Diez D, Icaza D, Acikkapl E, Amaris H. Combined vehicle to building (V2B) and vehicle to home (V2H) strategy to increase electric vehicle market share. Energy. 2021;237:121608. https://doi.org/10.1016/j.energy.2021.121608

[11] Canals Casals L, Etxandi-Santolaya M, Bibiloni-Mulet PA, Corchero C, Trilla L. Electric vehicle battery health expected at end of life in the upcoming years based on UK data. Batteries. 2022;8z:164. https://doi.org/10.3390/batteries8100164

[12] Casella V, Fernandez Valderrama D, Ferro G, Minciardi R, Paolucci M, Parodi L et al. Towards the integration of sustainable transportation and smart grids: a review on electric vehicles' management. Energies. 2022;15:4020. https://doi.org/10.3390/en15114020

[13] Chakraborty P, Parker R, Hoque T, Cruz J, Du L, Wang S et al. Addressing the range anxiety of battery electric vehicles with charging en route. Scientific Reports. 2022;12:5588. https://doi.org/10.1038/s41598-022-08942-2

[14] Chinoracky R, Stalmasekova N, Corejova T. Trends in the field of electromobility – from the perspective of market characteristics and value-added services: literature review. Energies. 2022;15:6144. https://doi.org/10.3390/en15176144

[15] Coffman M, Bernstein P, Wee S. Electric vehicles revisited: a review of factors that affect adoption. Transport Rev. 2017;37:79-93. 10.1080/01441647.2016.1217282

[16] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic And Social Committee and the Committee of the Regions the European Green Deal. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640 (accessed on 12 January 2023).

[17] Costa N, Sanchez L, Ansean D, Dubarry M. Li-ion battery degradation modes diagnosis via Convolutional Neural Networks. J Energ Storage. 2022;55C:105558. https://doi.org/10.1016/j.est.2022.105558

[18] Dutta B, Hwang H-G. Consumers purchase intentions of green electric vehicles: the influence of consumers technological and environmental considerations. Sustainability. 2021;13:12025. https://doi.org/10.3390/su132112025

[19] Electric Vehicle market update. Manufacturer commitments & public policy initiatives supporting electric mobility in the U.S. & worldwide. https://blogs.edf.org/climate411/files/2022/04/electric_vehicle_market_report_v6_april2022.pdf (accessed on 12 January 2023).

[20] Electrification. Accelerating the drive to electrification. https://www.stellantis.com/en/technology/electrification?adobe_mc_ref= (accessed on 12 January 2023).

[21] Electromobility. https://www.bmwgroup.com/en/sustainability/our-focus/electromobility.html (accessed on 12 January 2023).

[22] European Parliament and Council of the European Union. Regulation (EC) No. 443/2009 of the European Parliament and of the Council of 23 April 2009 Setting Emission Performance Standards for New Passenger Cars As Part of the Community's Integrated Approach to Reduce CO_2 Emissions from Light-Duty Vehicles. 2009. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R0443&from=EN (accessed on 12 January 2023).

[23] Fanoro M, Božanić M, Sinha S. A review of the impact of battery degradation on energy management systems with a special emphasis on electric vehicles. Energies. 2022;15:5889. https://doi.org/10.3390/en15165889

[24] Feng H, Tavakoli R, Onar OC, Pantic Z. Advances in high-power wireless charging systems: overview and design considerations. IEEE Transactions on Transportation Electrification. 2020;6(3):886-919. https://doi.org/10.1109/TTE.2020.3012543

[25] Ford takes bold steps toward all-electric future in Europe; 7 new connected EVs support plans to sell 600K+ EVs annually by 2026. https://media.ford.com/content/fordmedia/fna/us/en/news/2022/03/14/Ford-Takes-Bold-Steps-Toward-All-Electric-Future-in-Europe.html (accessed on 12 January 2023).

[26] From boom to brake: is the e-mobility transition stalling?. Transport & Environment, 2022. https://www.transportenvironment.org/wp-content/uploads/2022/10/2022-10_Car-CO2-report-2022-recommandations-corrected.pdf (accessed on 12 January 2023).

[27] Gandoman FH, El-Shahat A, Alaas ZM, Ali ZM, Berecibar M et al. Understanding voltage behavior of lithium-ion batteries in electric vehicles applications. Batteries. 2022;8:130. https://doi.org/10.3390/batteries8100130

[28] Global EV Outlook 2022 securing supplies for an electric future. International Energy Agency, 2022. https://iea.blob.core.windows.net/assets/e0d2081d-487d-4818-8c59-69b638969f9e/GlobalElectricVehicleOutlook2022.pdf (accessed on 12 January 2023).

[29] Gómez Vilchez JJ, Smyth A, Kelleher L, Lu H, Rohr C, Harrison G et al. Electric car purchase price as a factor determining consumers' choice and their views on incentives in Europe. Sustainability. 2019;11:6357. https://doi.org/10.3390/su11226357

[30] Hall D, Wappelhorst S, Mock P, Lutsey N. European electric vehicle factbook 2019/2020. International Council on Clean Transportation (ICCT). https://theicct.org/sites/default/files/publications/EV-EU-Factbook-2020.pdf (accessed on 18 January 2023).

[31] Handbook on Battery Energy Storage System. Asian Development Bank. https://www.adb.org/publications/battery-energy-storage-system-handbook (accessed on 20 January 2023).

[32] Iqubal M, Sathiyan P, Stonier AA, Peter G, Shunmugham Vanaja D et al. An extensive critique on electric vehicle components and charging systems. Electric Vehicle Charging Technologies and Infrastructure. 2022;2022:3612032. https://doi.org/10.1155/2022/3612032

[33] Jang YJ, Jeong S, Lee MS. Initial energy logistics cost analysis for stationary, quasi-dynamic, and dynamic wireless charging public transportation systems. Energies. 2016;9:483. https://doi.org/10.3390/en9070483

[34] Jreige M, Abou-Zeid M, Kaysi I. Consumer preferences for hybrid and electric vehicles and deployment of the charging infrastructure: a case study of Lebanon. Case Studies on Transport Policy. 2021;9(2):466-476. https://doi.org/10.1016/j.cstp.2021.02.002

[35] Kaynar E, Rijk G. Quick charging the share prices. Faster EV adaptation can generate EUR 806 billion more equity value. Profundo, Amsterdam, Netherlands, 2022.

[36] Krishnan VV, Koszhy BI. Evaluating the factors influencing purchase intention of electric vehicles in households owning conventional vehicles. Case Studies on Transport Policy. 2021;9(3):1122-1129. https://doi.org/10.1016/j.cstp.2021.05.013

[37] Liimatainen H, van Vliet O, Aplyn D. The potential of electric trucks – An international commodity-level analysis. Appl Energ. 2019;236:804-814. https://doi.org/10.1016/j.apenergy.2018.12.017

[38] Macioszek E. The role of incentive programs in promoting the purchase of electric cars – review of good practices and promoting methods from the world. Lecture Notes in Networks and Systems. 2021;207:41-58. https://doi.org/10.1007/978-3-030-71708-7_4

[39] Małek A, Taccani R. Long-term test of an electric vehicle charged from a photovoltaic carport. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2019;86(4):55-63. https://doi.org/10.14669/AM.VOL86.ART4

[40] Manutworakit P, Choocharukul K. Factors influencing battery electric vehicle adoption in Thailand – expanding the unified theory of acceptance and use of technology's variables. Sustainability. 2022;14:8482. https://doi.org/10.3390/su14148482

[41] Mau P, Eyzaguirre J, Jaccard M, Collins-Dodd C, Tiedemann K. The 'neighbor effect': simulating dynamics in consumer preferences for new vehicle technologies. Ecol Econ. 2008; 68(1-2):504-516. https://doi.org/10.1016/j.ecolecon.2008.05.007

[42] Mercedes-Benz strategy update 2020. https://group.mercedes-benz.com/investors/events/capital-market-days/2020-mercedes-benz-strategy-update.html (accessed on 12 January 2023).

[43] Mercedes-Benz strategy update: electric drive. https://group.mercedes-benz.com/company/strategy/mercedes-benz-strategy-update-electric-drive.html (accessed on 12 January 2023).

[44] Mo T, Li Y, Lau K-T, Poon CK, Wu Y, Luo Y. Trends and emerging technologies for the development of electric vehicles. Energies. 2022;15:6271. https://doi.org/10.3390/en15176271

[45] Mohamed N, Aymen F, Alqarni M, Turky RA, Alamri B, Ali ZM et al. A new wireless charging system for electric vehicles using two receiver coils. Ain Shams Eng J. 2022;13:101569. https://doi.org/10.1016/j.asej.2021.08.012

[46] National Blueprint for lithium batteries. Federal Consortium for Advanced Batteries. https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf (accessed on 20 January 2023)

[47] Nissan unveils ambition 2030 vision to empower mobility and beyond. https://global.nissannews.com/en/releases/nissan-ambition-2030-vision-to-empower-mobility-beyond (accessed on 12 January 2023).

[48] On the Way to ZERO – The General Strategy. https://www.volkswagen-newsroom.com/en/on-the-way-to-zero-the-general-strategy-7226 (accessed on 12 January 2023).

[49] Pevec D, Babic J, Carvalho A, Ghiassi-Farrokhfal Y, Ketter W, Podobnik V. A survey-based assessment of how existing and potential electric vehicle owners perceive range anxiety. J Clean Prod. 2020;276:122779. https://doi.org/10.1016/j.jclepro.2020.122779

[50] Plug-In hybrids pull up Europe's plug-in market – October EV sales report. https://cleantechnica.com/2019/11/29/plug-in-hybrids-pull-up-europes-plug-in-market-october-ev-sales-report/ (accessed on 20 January 2023).

[51] Rahman MS, Hossain MJ, Lu J, Rafi FHM, Mishra S. A vehicle-to-microgrid framework with optimization-incorporated distributed EV coordination for a commercial neighborhood. IEEE Transactions on Industrial Informatics. 2020;16(3):1788-1798. https://doi.org/10.1109/TII.2019.2924707

[52] Regulation (EEC) No 4064/89 Merger Procedure. https://ec.europa.eu/competition/mergers/cases/decisions/m1406_en.pdf (accessed on 18 January 2023).

[53] Roadmap on advanced materials for batteries. European technology and innovation platform on batteries – Batteries Europe. https://energy.ec.europa.eu/system/files/2021-12/vol-3-008-2.pdf (accessed on 20 January 2023)

[54] Sadeghian O, Oshnoei A, Mohammadiivatloo B, Vahidinasab V, Anvari-Moghaddam A. A comprehensive review on electric vehicles smart charging: solutions, strategies, technologies, and challenges. Journal of Energy Storage. 2022;54:105241. https://doi.org/10.1016/j.est.2022.105241

[55] Šarkan B, Gnap J, Kiktová M. The importance of hybrid vehicles in urban traffic in terms of environmental impact. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2019;85(3):115-122. https://doi.org/10.14669/AM.VOL85.ART8

[56] Skuza A, Jurecki R, Szumska E. Influence of traffic conditions on the energy consumption of an electric vehicle. Communications – Scientific Letters of the University of Zilina. 2023;25(1):B22-B33. https://doi.org/10.26552/com.C.2023.004

[57] Stellantis long-term strategic plan. https://www.stellantis.com/content/dam/stellantis-corporate/investors/events/strategic-plan-2030/2022_03_01_Strategic_Plan.pdf (accessed on 12 January 2023).

[58] Summary of Honda briefing on automobile electrification business. https://hondanews.com/en-US/releases/summary-of-honda-briefing-on-automobile-electrification-business (accessed on 12 January 2023).

[59] Szumska E, Jurecki R, Pawełczyk M. Evaluation of the use of hybrid electric powertrain system in urban traffic conditions. Eksploat Niezawodn. 2020;22(1):154-160. https://doi.org/10.17531/ein.2020.1.18

[60] Szumska EM, Jurecki RS. Parameters influencing on electric vehicle range. Energies. 2021;14(16):4821. https://doi.org/10.3390/en14164821

[61] Szumska EM. Electric vehicle charging infrastructure along highways in the EU. Energies. 2023;16(2):895. https://doi.org/10.3390/en16020895

[62] The electric drive chargers forward. Annual Report. Implementing agreement for co-operation on hybrid and electric vehicle technologies and programmes (HEV TCP), 2022. https://ieahev.org/wp-content/uploads/2022/05/DIGITAL-HEVTCP_2022_Annual_Report_Final-with-Cover.pdf (accessed on 12 January 2023).

[63] Tsakalidis A, Thiel C. Electric vehicles in Europe from 2010 to 2017: is full-scale commercialisation beginning? An overview of the evolution of electric vehicles in Europe. EUR 29401 EN. Publications Office of the European Union, Luxembourg, Luxembourg, 2018; JRC112745. https://doi.org/10.2760/565748

[64] Ullah I, Liu K, Yamamoto T, Zahid M, Jamal A. Prediction of electric vehicle charging duration time using ensemble machine learning algorithm and Shapley additive explanations. International Energy Research. 2022;46:3. https://doi.org/10.1002/er.8219

[65] Verma M, Verma A, Khan M. Factors influencing the adoption of electric vehicles in Bengaluru. Transp Dev Econ. 2020;6:17. https://doi.org/10.1007/s40890-020-0100-x

[66] Volvo Car Group electrification strategy press conference. https://www.media.volvocars.com/global/en-gb/media/videos/210448/volvo-car-group-electrification-strategy-press-conference (accessed on 12 January 2023).

[67] Volvo Cars to be fully electric by 2030. https://www.media.volvocars.com/global/en-gb/media/pressreleases/277409/volvo-cars-to-be-fully-electric-by-2030 (accessed on 12 January 2023).

[68] Yang Y, El Baghdadi M, Lan Y, Benomar Y, Van Mierlo J, Hegazy O. Design methodology, modeling, and comparative study of wireless power transfer systems for electric vehicles. Energies. 2018;11:1716. https://doi.org/10.3390/en11071716

[69] Yong JY, Ramachandaramurthy VK, Tan KM, Mithulananthan N. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. Renew Sustain Energy Rev. 2015;49:365-385. https://doi.org/10.1016/j.rser.2015.04.130

[70] Zagrajek K, Paska J, Sosnowski Ł, Gobosz K, Wróblewski K. Framework for the introduction of Vehicle-to-Grid Technology into the Polish electricity market. Energies. 2021;14:3673. https://doi.org/10.3390/en14123673

[71] Zhang Z, Tian R. Studying battery range and range anxiety for electric vehicles based on real travel demands. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Baltimore, MD, USA, 4-7 October 2021;65(1):332-336. https://doi.org/10.1177/1071181321651243

[72] Zhao G, Wang X, Negnevitsky M. Connecting battery technologies for electric vehicles from battery materials to management. iScience. 2021;25:103744. https://doi.org/10.1016/j.isci.2022.103744

Emilia M. Szumska, DSc., DEng. – Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Poland.

e-mail: *eszumska@tu.kielce.pl*

Prof. Rafał Jurecki, DSc., DEng. – Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Poland.

e-mail: *r.jurecki@tu.kielce.pl*