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A Method of Analyzing the Residual Values of Low-Emission Vehicles Based on a Selected Expert Method Taking into Account Stochastic Operational Parameters

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Abstract: Increasing the market share of low-emission vehicles in relation to individual mobility is one of the main postulates of modern transport policy. In the discussion on low-emission and the new structure of the car fleet, the role of new vehicles is emphasized above all, ignoring the importance of the secondary market. In recent years, both in Poland and in other European Union countries, there has been a noticeable dynamic development of electromobility implementation processes in urban areas, the initial effect of which is increasing market accessibility to commercial vehicles with electric EV/BEV, hybrid HEV/PHEV and fuel cell powered FCEV. As in the case of vehicles powered by conventional ICEV fuels, also in relation to those defined as low-emission, their residual value is lost along with the operational process. Information on this variable is important both for the owner of a newly purchased vehicle, which after the period of its operation will decide to sell it as well as to the future buyer. The scientific aim of the study is to analyze the residual values of selected vehicle models from the primary and secondary market, with particular emphasis on stochastic operational phenomena. The subject of the research is to obtain extensive knowledge on the achieved changes in the residual values of low-emission vehicles in relation to ICEVs. For this purpose, a comparative analysis of the commercial program, data approximated from auction portals and own numerical modeling tool based on a neural network was performed. The research sample included, among others, selected models of passenger cars, the purchase offer of which included the choice of a drive unit powered by conventional and low-emission fuels. The use of this method allowed to answer the question whether low-emission vehicles are characterized by a greater or lesser loss of value in relation to conventionally powered vehicles ICEV.

Keywords: low-emission; electromobility; residual value; exploitation factors; numerical modeling; development policy

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1. Introduction

1.1. Analysis of the Development of Domestic and International Markets for Electric and Hybrid Vehicles

In the last two decades, changes in the area of creating individual mobility have been one of the fundamental problems of the European transport policy [1–3]. One of the concepts inherent in the considerations on the future of individual transport is the concept of low-emission [4,5]. The development of this idea is based, among others, on the use of vehicles often described as clean instead of those powered by fossil fuels. The key priority of activities in this field has been to reduce environmental pollution by reducing emissions of harmful CO2 and NOx compounds [6–8]. Even though numerous promotional activities were undertaken to reduce the negative effects of individual mobility, min. by promoting low-emission means of public transport, in particular in urban areas [9,10]. In the opinion of many researchers, these activities did not bring the expected result, because still individual transport defined in the form of a passenger car plays the most important role in the negative impact on the natural environment [11–14]. In order to meet market expectations, manufacturers from the automotive industry have introduced to their sales offer, apart from conventional ICEV vehicles, also hybrid vehicles (HEV, PHEV), or only electrically powered vehicles (BEV, FCEV). Observations of the automotive market indicate that the trend has become a global phenomenon and applies to almost every segment of the passenger car market [15,16]. This phenomenon is reflected in the data showing that sales of electric cars (BEV) and plug-in hybrids (PHEV) on the global market have increased 5.5 times in the last five years-from 548,600. units in 2015 to almost 3,000,000 at the end of 2020. Of this number, 68% were exclusively electric long-range BEV cars and 32% were short-range PHEV cars. About the market potential European Union is evidenced by data which indicate that in 2020 cumulative sales in the Old Continent (European Union countries, EFTA and the United Kingdom) amounted to 1,360,000 copies. In total, around 10,000,000 BEV and PHEV vehicles were registered in 2020, 32,000,000 of which in Europe. The scale of this global process is best illustrated by the forecast indicating that in 2040 there will be as many as 500,000,000 electric cars on the roads in 2040 for a total of 2,000,000,000 vehicles [17]. As a consequence, in the coming years, in the era of the ubiquitous phenomenon of market competition in the automotive industry, a significant increase in the market share of low-emission vehicles, in particular those of the BEV and FCEV type, can be expected not only in relation to the cumulative total sales, but also the market share in the total structure of the current market. automotive. The market records from recent months, especially in December, were responsible for the increase in the value of the results. In last in the month of 2020, about 407,000 people have been registered in the world. electric cars and about 164,500. plug-in hybrid. At that time, both vehicle groups also achieved an unprecedented share of the global new car market: 5%. for electric cars EV, including BEV and 2%. for PHEV. According to the estimates of the industry portal EV-Volumes, plug-in electric vehicles accounted for 4.2%. global car sales, while in 2019 this share was 2.5%.

In 2019, only eight countries reported an electric vehicle share of 5% or more. Last year, already 13 countries had a 10% share of sales of new electric cars. As in previous years, Norway was the undisputed leader in this respect, with 75% of plug-in electric vehicles. Iceland, Sweden and Finland were also in the top five, which proves the rapid spread of electric cars in the Scandinavian countries. China, by far the largest electric car market by unit sales, has dropped out of the top 10. Electric vehicles account for 6.2%. sales of passenger cars in this country. Even though Norway is the country with the highest share of electric cars in total passenger car sales, no country comes even close to China in terms of absolute market size. According to the Chinese Association Car Manufacturers (CAAM), sales of battery electric vehicles (BEV) and plug-in hybrids (PHEV) amounted to PLN 100,000 and PLN 250,000, respectively. In 2020, this places China far ahead of Germany (395,000 EVs sold) on this list, which overtook the United States in terms of sales of electric vehicles. While Europe's largest markets saw three-digit growth in electric vehicle sales last year, growth in the US was just 4%, according to industry website EV-Volumes. Despite this, out of 328,000, US electric vehicles sold are still the third largest market, ahead of France, Great Britain and Norway. Vehicle sales in Poland are shown in Figure 1.

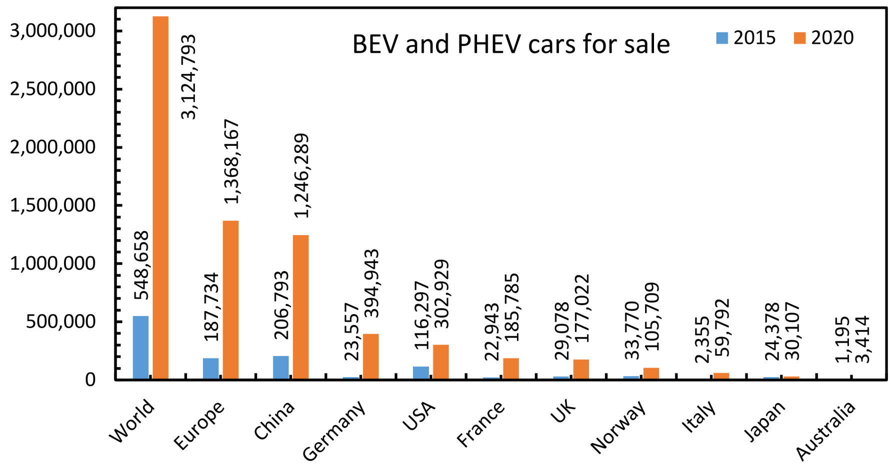

Figure 1. Sales of BEV and PHEV cars in 2015–2020 (Source: ACEA, PSPA, PZPM, IEA, CEPIK).

Regarding the policy of developing low-emission transport, it should be mentioned that the Act on electromobility and alternative fuels was not ignored by the Polish authorities either. The guidelines of the European Union in the form of the directive of 22 October 2014, 2014/94/EU, which imposed on European countries an obligation to transform in the field of fuels, were imperatively treated, at the same time setting a specific direction of changes [18]. An example of further actions in this matter was the adoption by the Polish authorities in 2017 of the Act on Plan for the Development of Electromobility in Poland [19]. The available data indicate that at the end of 2020, there were 20,504 electric passenger cars on Polish roads, 51% of which were fully electric vehicles (BEV)–10 471, and the rest of the plug-in hybrid (PHEV)-10,033 pcs. At the end of April 2021, there were over 23,800 electric cars on the Polish roads. During the first four months of this year, their number increased by 5098, i.e., by 137% compared to the same period of 2020. According to statistical data at the end of April this year. 23,834 electric passenger cars were driving on Polish roads, of which 49.68%. Fully Electric Vehicles (BEVs), with the remainder being 50.32% were plug-in hybrids (PHEV). The fleet of electric vans and trucks consisted of 899 units. The number of electric mopeds and motorbikes continues to grow, reaching 9652 at the end of April. By mid-2021, the electric bus park in Poland has increased to 484 models. From January to April 2021, the electric bus fleet increased by 52 zero-emission vehicles. Compared to the corresponding period of 2020, when 23 such buses were registered, this means an increase by 126%. The report shows that as the number of electric vehicles increases, the charging infrastructure is also developing. This is the basis for acquiring greater profitability by using unconventional drive solutions. Despite the previously observed difficulties related to their charging processes and the frequency of various aperiodic and periodic failures [20,21]. In the first half of 2021, there were 1456 publicly accessible charging stations for electric vehicles in Poland (2838 points). In this case, 33% of them were fast charging stations with direct current (DC), and 67% slow AC chargers with a power less than or equal to 22 kW. The electromobility counter, updated by the Polish Automotive Industry Association and the Polish Alternative Fuels Association, is available on the organization's website. It shows how many electric vehicles are currently driving on Polish roads and how many charging stations are in operation. The data was prepared by PZPM and PSPA on the basis of complex data analyzes from, among others, from the Central Vehicle Register, as well as own research and kept records. This work indirectly focuses on the potential benefits of electrification and the speed with which electric vehicles will become more affordable in different households with varying degrees of affluence. The residual value and the economic dimension of introducing particular types of propulsion systems, depending on purchasing preferences, is the basic parameter that determines the strategy of introducing electrification levels in a given area. To a large extent, attention should be paid to the operational dimensions of electric and hybrid vehicles, the current state of expansion of the charging network infrastructure and the infrastructure of maintenance and repair workshops. The key question is when BEVs and PHEVs will achieve cost parity with equivalent ICEV gasoline vehicles for different socioeconomic groups. A particularly important aspect is the state that electric or hybrid vehicles will become fully profitable economical in non-urban areas. The study used vehicle purchase data to estimate how much each household spends on its current vehicles, broken down by drive systems. An analysis was performed with data on the resale value of electric vehicles on the market in 2020, as well as the bottom-up costs of electric vehicles, forecasts in line with the trends in battery costs (their operation and purchase). From this analysis, it is possible to quantify how much the potential cost savings of electric vehicles vary depending on socio-economic factors.

1.2. Analysis of the Literature on the Methods of Predicting the Residual Value of Vehicles

As indicated in the literature on the subject, numerous studies with regard to the development of the low-emission vehicle market have attempted to identify the determinants influencing the low market share of this vehicle category in the total car fleet of individual countries [22–25]. The available literature successfully identifies barriers of a technical or organizational nature that have a direct impact on the development of the low-emission vehicle market [26,27]. A large role in the profitability of using ICEVs is played by durability tests concerning external factors that do not apply to most EVs [28–30]. Consumers are increasingly distinguishing the advantages and disadvantages of different types of alternative fuel vehicles PHEV, BEV and others, and are increasingly considering switching from ICEV to PHEV hybrids rather than to EV electric cars. Segmentation analysis is used to study different groups of consumers and their probabilities acceptance of cars using alternative fuels. At the same time, the most important areas necessary to increase the market share of this vehicle category were successfully identified [31–33]. There is an increasing number of works on modeling based on machine learning, creating mathematical models of transport systems and energy units [34,35]. Starting from identifying the need for technological progress in the field of batteries consisting in increasing their energy efficiency, which will result in extending the range of vehicles [36–38]. By emphasizing the role of the increase in the availability of charging infrastructure and its efficiency, as well as cooperation with the existing power grid in the form of standardization and tariffication of charges [39–41]. Much work focuses on modeling the energy consumption of electric vehicles and the factors influencing battery life, which is the primary factor in determining the resale value of an electric vehicle after a few years use [42]. It is largely influenced by the failure rate of the energy source and the purchase price of new batteries.

Concern for knowledge and the environment has a weaker influence on preferences than the socio-economic impact and innovation of given electric and hybrid drive technologies. Some authors present business and industrial models for the production, development and servicing of low-emission vehicles and the possibility of achieving a decent synergy effect in the form of the use of intelligent installations based on renewable energy sources [43,44]. The analysis of the literature on the subject shows that many researchers have also successfully undertaken to define legal barriers, comprehensively indicating and describing areas requiring legislative changes [45–47]. However, in the case of attempts to identify economic barriers, the presented research and analyzes on this topic indicate a certain gap and are not fully exhaustive [48]. In most cases, the researchers focused their research on the areas of identification, vehicle operating costs, including purchase, repair costs [49,50] or else purchase preferences analysis [51,52], or determining the total cost of vehicle ownership [53–55]. Disregarding one of the important parameters influencing the purchasing decisions of the demand side and defined in the literature as the residual value [56].

A novelty affecting the demand for electric cars may be the new regulations of the Audible Vehicle Alert System, a sound system that, from 1 July 2021, will be mandatory for all electric and hybrid cars sold in the European Union. Its purpose is to warn pedestrians and cyclists that an electric vehicle is approaching. This is to increase road safety. It may also incur additional costs due to system failure rates and some additional cost factors. Road transport has been present in sustainable development strategies for a long time. Strategic tasks for the development of transport in Poland are related to such activities as: significant reduction of environmental pollution, increasing transport safety, slowing down the growth rate of energy consumption, ensuring an increase in energy and raw material efficiency, and generally-contributing to the environmental policy of the state. Lots of researchers clearly indicates that the residual value is min. one of the key components of the Total Cost of Ownership-i.e., the total cost of using the vehicle [57–59]. In particular, these studies concern the creation of more and more complex mathematical models taking into account an additional stochastic factor affecting the residual value of the car after a given period of use. In particular, at the time of the demand stagnation caused by the economic crisis, in the automotive sector, the parameter defined as the residual value may become more and more important not only for managers of car, car-sharing and leasing fleets, but more and more often also for individual customers. Considering that the key information for each owner is the answer to the question of what cash equivalent will be regained after a few years of vehicle operation [60].

Therefore, the simulation of the residual value of a car, which is the forecast and at the same time the most probable amount that will have to be paid for a vehicle after a given period of operation, in the long term, may play a key role in the development of the low-emission vehicle market, in particular in a country such as Poland. Where, in the case of financial leasing within the meaning of the currently applicable tax regulations, the ownership of the subject of the lease may automatically pass to the financing party right after the end of the contract. In addition, in long-term rental, financial and operating lease contracts, the residual value affects the amount of monthly installments, which has its direct economic dimension. Therefore, in the context of the electro-mobility development plan adopted by the Polish government and the preferential conditions for the import of low-emission cars from European Union countries and the reduction of customs duties on imports from outside the European Union, the issue of value residual problem is a significant research problem, in particular that the available literature lacks such analyzes and studies on such 3–5-year periods of operation of low-emission vehicles as compared to conventionally driven vehicles in relation to a specific market, which is the Polish automotive park.

Correct estimation of the residual value is a process that requires an interdisciplinary and experimental approach. Since this parameter depends on many variables that may not be fully identifiable at the initial stage of the analyzes. However, as in the case of the conventional fuel ICEV market, the knowledge of the parameter defined as the residual value, i.e., the decrease in the commercial value of the vehicle together with the ongoing process of operation, is of fundamental economic importance due to the growing share of these vehicles in the total car park and development plans electromobility. According to the methodology and scenario of analyzing changes in extensive, systemically related communities, it is assumed that among economic sectors, one of the fastest increases in harmful emissions to the atmosphere will be road transport, which will include ICEV vehicles.

1.3. Factors Determining the Residual Value of Hybrid and Electric Vehicles

Currently, road transport plays an important role in the socio-economic development of each country, in particular, targeting low-emission vehicles, regardless of the type of energy source. As one researcher points out, the residual value of a car is its forecast, future market value, that is the price at which the user of the vehicle or another entity will be able to sell it after an appropriate period of use [61]. This parameter is given as an amount or percentage, as a relation of a used vehicle to the price of a new one. Today, the residual value is the basic indicator used by leasing and fleet management companies. As mentioned above, this parameter is a fundamental component of the so-called TCO, i.e., the total cost of using a car. Its value is particularly important, for example, at the stage of determining the rental installments or estimating the buy-back value of the vehicle [62]. Thus, an analysis of the residual value of a specific vehicle can yield measurable economic benefits. The authors agree that the analyzes concerning this variable should be taken into account during the individual purchasing process, thus allowing the demand side to make an informed and informed choice. Hence the importance of the exploration of residual values for the development of the low-emission vehicle market.

In order for the TCO model to be reliable and cover all phenomena, even those of a stochastic nature resulting from external conditions, it is important to identify and calculate the necessary cost categories for a specific type of vehicle and drive system design, in particular for PHEV and BEV vehicles-the most common in terms of electromobility. The cost of purchasing and owning an ICEV or PHEV and BEV comes with many different cost categories, along with a subcategory of vehicle operating costs. The following TCO equation and its detailed description were presented in the authors' work [25]:

$$\begin{aligned} TCO \approx\ & \left(P_{p-x} - \left(R_{p-x}(w_t \times w_z \times w_d)\right)\right) \\ & + E_c\left(w_{d-tm}(D_{v-ee} + D_{v-ce}) + w_{d-tpm}(D_{v-ee} + D_{v-ce}) \right. \\ & \left. - w_{d-rek}\right) + C_{IC} + P_F W_{Pf-x} + A_F W_{Af-x} \end{aligned} \tag{1}$$

In this TCO approach it is assumed that the total cost of ownership during the period of ownership, $P_{p\text{-}x}$ is the purchase price of a new vehicle with the selected driveline, e.g., ICEV, BEV, PHEV (this parameter can include additional variables corresponding to the vehicle price, i.e., comfort, safety equipment and other additional systems increasing the market value of the vehicle), $R_{p\text{-}x}$ is the resale price of the vehicle at the end of the ownership period (taking into account its technical condition and future costs). In this comparison, the age of the vehicle in w_t and the mileage in $\mathrm{w_d}$ are important for determining the mandatory inspection intervals. Therefore, determining the operating distance, without incurring high periodic costs, e.g., replacement of batteries or components of the drive system of ICEV vehicles, and the current state of wear of the vehicle, taking into account the design of the w_z. The nature of the timetable is of great importance when assessing energy consumption, therefore the coefficients have been introduced to define the nature of the timetable driving and driving load and energy systems, including kinetic energy recovery systems for BEV and PHEV. In this case, the urban mode distribution factor w ($d_{\text{-}tm}$), the urban mode distribution factor w ($d_{\text{-}tmp}$) and the amount of energy recovered from the auxiliary systems in ($d_{\text{-}rek}$) are assumed. As the wear of the vehicle progresses, the final price decreases adequately to its technical condition and purchase trends of a given vehicle brand, in a non-linear manner, individually for the vehicle, and the difference between $P_{p\text{-}x}$ and $R_{p\text{-}x}$ is the vehicle depreciation value. E_c is the cost of energy adequate to the current fuel prices or the cost of electricity per kilometer. $D_{v\text{-}ee}$ is the total number of kilometers traveled during the lifetime of an electric vehicle, $D_{v\text{-}ce}$ is the total number of kilometers traveled during the lifetime of a combustion engine vehicle for the ICEV. The operating costs related to vehicle purchase transactions are distinguished by: m—to monthly interest rate, P_c—amount borrowed, n—number of monthly interest payments. In addition, the following should be added: the cost of compulsory third party liability insurance to C_{IC} and the presumed costs related to maintenance and operation, including periodic replacement of components in accordance with the recommendations of the vehicle manufacturer P_f, and costs related to non-periodic faults A_f. The costs of subsidies and taxes can be ignored, as they are not relevant considering the current legal framework in Poland. When considering the costs of P_f and A_f. the analyzed vehicle mileage range should be taken into account, e.g., from 0 km to 100,000 km. Changing this parameter is very important from the point of view of the residual value. The make, model and technological sophistication of the driveline as well as the structure of the vehicle body also play an important role in this system. Therefore, some factor values should be introduced based on actual failure frequency analyzes periodic $W_{Pf\text{-}x}$ and aperiodic $W_{Af\text{-}x}$ within a given group of vehicles according to user opinions and detailed expert analyzes. This condition is also related to the timetable and operating conditions, including environmental factors, especially in a changing climate.

The available literature indicates that in the past attempts were made to identify this parameter in relation to strictly geographically selected markets. For example, several researchers, on the basis of statistical methods, analyzed the resale value of HEV and BEV vehicles for the German market-with an expected service life of up to 4 years [63]. Taking into account the adopted method, the minimum forecast was that BEVs would lose more value than HEVs. However, as the authors themselves emphasize, the results of the analysis of residual values could not be fully satisfactory at that time, given the limited empirical database on the resale value of HEV and BEV for the analyzed market. As for another researcher who predicted a 44% drop in the resale value of this category of vehicles [64]. Some authors predicted that after 5 years of operation, the residual value of HEV and BEV may achieve only 10% of the purchase value of a new low-emission vehicle [65]. All the authors made a reservation, however, that their forecasts were based on unclear expectations regarding issues such as, for example, the life cycle of the drive-battery, the anticipated technical progress and other factors that, in their opinion, have an impact on the achieved values. Moreover, the applied methods based only on static inference and residual data do not fully support the acceptance of the achieved results as final and are not applicable in the case of attempts to determine the residual value of a specific model from a selected market segment.

In the remaining studies, however, referring geographically to another market-the American one, based on the analysis of archival sales data, it was indicated that low residual values were achieved, for some models of BEV Tesla 3, 5 vehicles after the first 3 and 5 years of ownership [66]. In turn, another researcher in relation to this market suggested that the residual values of BEVs may depend on the vehicle brand [67]. On the other hand, other researchers emphasized that the residual values of PHEV and BEV vehicles, compared to vehicles with ICE combustion engines, when settling the tax relief (related to their purchase), may be much higher than in the case of vehicles that were not paid for [67]. Another researcher suggested that in the longer term in the years 2020–2025, in the event of market development, PHEV vehicles will maintain the residual values, similar to their ICE counterparts [68]. However, all researchers emphasized the majority of cases, the attempts at analyzes referred to a geographically limited market, e.g., California USA, or individual brands and models, e.g., Tesla 3 and 5. It is important that none of these studies, based on the adopted methodologies, undertook a comparison of the same vehicle models, or coming from particular market segments but equipped with different drive units BEV, HEV, PHEV, and ICE. Only researchers attempted to develop such a model on the basis of the available data on the market value of BEVs compared to the ICE for the US market [69]. Indicating in the conclusions, inter alia, that high-performance BEV brands such as Tesla 5 type Long Range achieve higher sales values than other PHEV and HEV vehicles. Moreover, BEVs other than Tesla show a faster decrease in market value over a 3-year period than other types of ICEV [70]. However, also in this case, the researchers cautioned that the research was data-driven source and estimated values of selected vehicle models should be supplemented with other vehicle models and compared with the methods obtained using expert methods in order to fully verify them. Therefore, the presented study cannot fully constitute a basis for drawing conclusions in relation to, for example, geographically different markets, e.g., the European market, where the share of individual models in the total car park, e.g., Tesla, is different than on the American market [71] and provide answers on how they are shaped residual values for the same models in individual market segments. In this context, the procurement of vans and the expansion of vehicle fleets in this category are highly dependent on their profitability and reliable performance, with the total cost of ownership being the decisive factor in correlation with the residual value. Other markets, mainly in Asia, were investigated in the works due to the residual value of the vehicle [72–75].

Nobody should have any doubts that low-emission emissions is one of the greatest challenges facing the modern automotive industry [76]. However, changes in individual transport, the pillar of which are vehicles powered by conventional fuels, are inevitable [77]. The introduction of restrictive EURO 6D ISC-FCM emission standards from January 2021 forces transformations not only on the supply side-by replacing ICE-type units with low-emission ones, but also-changes in purchasing preferences defined as an increase in ecological awareness of the demand side [78]. Moreover, in the coming years, a tightening of the EURO standards from 6D ISC-FCE to the EURO 7 standard should be expected [79] In particular with regard to newly sold ICE conventionally powered passenger cars. The authors share the opinion of other researchers that electromobility is the answer to the low-emission needs. Plans for the development of electromobility, for example in Poland they assume that by 2025 [80,81] there will be 1,000,000 electric cars on the roads. Thus, a significant part of the structure of the new car fleet will be low-emission vehicles, both newly manufactured and used [82]. As other researchers show, economic aspects are still one of the key determinants influencing purchasing decisions in the automotive market [83]. The most common identified barriers relate to the high purchase price of a new low-emission vehicle compared to a conventionally powered vehicle [84–87]. However, these considerations ignore one of the key elements of TCO defined as the residual value [88,89]. In a narrower sense, the residual value is defined as the value of the car at the time of resale [90,91]. On the other hand, it is broadly defined by the notion that it is the price that the owner of the car can count on by selling it after the assumed useful life [92].

Environmental certification acts as a sustainable practice for companies to improve their competitive advantage, and its motivation has been widely discussed in the work [93]. An important aspect influencing the residual value is also the recycling value of vehicles in given countries. This topic is described in detail in [94]. Important social, environmental and economic aspects of electric vehicles were also discussed in the works [95–98]. The statistical data used in the work are based on portals [99–103].

The scientific aim of the work is to analyze the residual values of selected vehicle models from the primary and secondary market, with particular emphasis on stochastic operational phenomena. The subject of the research was to obtain extensive knowledge on the achieved changes in the residual values of low-emission vehicles in relation to ICEV vehicles. This study extends the research conducted so far in the field of considerations concerning the low-emission vehicle market by showing the important role of the economic factor defined as the residual value. To the best of our knowledge, this article is the first to link residual value considerations to the development of the low-emission vehicle market (including a comparative analysis of passenger car vehicles equipped with both conventional and low-emission powertrains) and was the first to discuss the case study-domestic market. A key contribution of this study is the pioneering analysis of actual and projected values residual low-emission vehicles based on the expert method used, among others automotive experts, to which only a small number of researchers have access. This method has been enriched with additional factors ignored by many experts, this applies to periodic and aperiodic phenomena that may affect the final value of the vehicle and increase the costs of its operation and use.

In short, this article brings a new look to the existing literature in the following areas: (I) low-emission-electromobility (II) modeling the demand for low-emission vehicles, passenger car segment, (II) technology (HEV, PHEV, BEV, FCEV) and residual value and vehicle impairment (IV) development plans and domestic market.

The article is organized as follows. Section 1 provides an overview of the literature on the factors influencing the residual value of hybrid and electric vehicles compared to combustion engine vehicles. Section 2 provides a detailed description of the research approach. Section 3 describes the results of experimental research along with their interpretation. Section 4 presents the final conclusions of the research, indicating their limitations, practical application and future directions of research in this field.

Therefore, the presented research is the first attempt to fill the gap in the literature on the subject by presenting forecasts of the residual values of low-emission BEVs, PHEVs compared to ICEVs based on the expert method for an incomparable period of 5 years in relation to the unanalyzed automotive market of the European Union country, which is Poland. In addition, expert analyzes were performed with the use of simulation tools over a period of 24 years, using data obtained from vehicle users and the applicable market prices approximated for a given year.

2. Research Method and Methodological Assumptions

The complexity of the subject matter under study, as well as the diversification and progress of the technology used in individual models of low-emission vehicles offered on the Polish market, required the authors of an alternative approach. Therefore, in order to show significant dependencies, preconceived behavior patterns were used. In order to maintain the logical correctness and methodological value of the research, it was assumed that the scope of the analyzes included passenger cars of selected manufacturers from several market segments.

Models with specific features and purpose, which were popular on the analyzed market, were selected for the analysis. In order to illustrate the aforementioned relationships, analyzes were presented including data on residual historical values obtained from the Info-Eskpert system, comparing the ICEV and PHEV driven vehicle as well as the forecasts of values relating to the future residual values of PHEV, BEV, ICEV vehicles in the period of 5 years using the methods.

The author's method illustrates additional factors that may affect the residual price of the vehicle, these are mainly operational, service and repair factors in the case of a diverse external environment and a stochastic nature of extortions. In this case, data from car repair shops, opinions of vehicle users and trends in relation to brands and their assessment by users were used. This is a very difficult task, especially in the case of precise determination of the final residual value of the vehicle depending on their structure and failure frequency of the drive system and drive train. To a large extent, the value of this parameter is also influenced by the comfort equipment and the vehicle class. For convenience, similar values of these parameters were adopted, so as not to introduce an additional disturbing factor.

The "Info-Forecast" program enables an easy and convenient way to forecast the residual values of passenger cars, SUVs and delivery vans [93]. The application enables the analysis of the residual value (sale and purchase) of new and used cars in the range from 6 to 60 months. It also allows you to obtain archival data. Monthly update of the vehicle database, new prices and equipment makes the program an invaluable tool supporting fleet management. Forecast for a group of vehicles with the assumed mileage. The program allows you to forecast for a selected vehicle with different mileage assumed and to compare any vehicles from the database. It also enables the indication of the main vehicle and presentation of differences from this vehicle, determination of the influence of additional equipment on the residual values (analysis of identical vehicles with different completion of optional equipment). With it, analyzes of residual values or loss of value can be presented.

A comparative analysis of the effectiveness of both tools was performed. The "Info-Forecast" program allows you to determine the changes in the residual value based on the variables, such as comfort equipment, engine, vehicle condition and many more. Mainly the analyzes of this program are based on statistical data with a large generalization. It has quite a lot of disadvantages significant for determining the residual value of new, mainly hybrid and electric vehicles. Additional parameters and machine learning analyzes were added to the proprietary expert method, which uses a creature's model. These parameters include factors, i.e., repair and maintenance costs resulting from the frequency of occurrence of periodic and non-periodic defects for a given model. Such data was obtained from car services, from users on the basis of automotive forums. These values were introduced as coefficients decreasing or increasing the residual value in comparison with the data of the "Info-Prognosis" program. As the most a reliable point of reference, approximation data of the current market prices from auction portals was introduced. These data were the average value of the price in a given year. The expert method, which is based on increasing the number of variables in relation to the "Info-Prognosis" program, turns out to be more effective in standard software. In order to obtain such values, the model introduced a methodology for extracting aperiodic phenomena constituting the basis for the energy balance of vehicles for the analysis of electromobility system indicators. The model included in [21] is used to analyze the additional costs resulting from the repair and maintenance of vehicles. Based on the frequency of repairs performed, it is possible to judge the decrease in the residual value after entering this parameter. Such data can be derived from the cost of parts and the frequency of specific faults based on the Automotive Forum or service data from repair shops. This is a highly important parameter. As a result, some vehicle brands are perceived as less attractive and their market value decreases quickly even in the case of high standard of equipment and good parameters of the driveline.

When approximating the residual values from auction portals, 50 vehicles from a given year with similar technical equipment, comfort and technical condition were taken into account. In this study, the replacement cost component was selected as an additional basis introduced into the main model. The basic formula of the replacement cost method of the resale purchase price in a given vehicle year R_{p-x+y1} is:

$$R_{p-x+y1} = P_{p-x-y1} \times R_p \times K_p \quad (2)$$

In the formula, P_{p-x-y1} is the price of the car after periodic and unforeseen replacements, for example, the main source of accumulative energy; R_p is the basic residual directional index of the residual rate; K_p is the residual rate correction factor.

(a) The cost of carrying out the necessary replacements in a given period

The cost of PHEV replacement is enriched mainly by the purchase of new batteries and additional kinetic energy recuperation components. It mainly relates to the cost of re-purchasing the same or a similar vehicle, including: the price of a new vehicle, purchase surcharge and purchase tax.

$$P_{p-x-y1} = P_{dot} - D_{dot} + R_{vat} \quad (3)$$

In the formula, P_{p-x-y1} is the replacement cost; P_{dot} is the indicative price given by the producer before deducting the subsidy; D_{dot} means subsidies for the purchase of vehicles, including state subsidies and local subsidies; R_{vat} stands for Tax on Vehicle Purchase.

(b) The basic residual rate indicator for the remainder

Since the cost of the battery in PHEV and BEV vehicles accounts for a large proportion of the total cost of the vehicle, batteries are important for the residual rate of vehicles of this type. Therefore, in this study, an additional residual rate will be introduced into the model in the form of a complete vehicle from the perspective of the battery power system and other component. For ICEVs, this value is ignored.

$$R_p = \kappa_1 \times R_{p\text{-}bat} + \kappa_2 \times R_{p\text{-}axip} \quad (4)$$

In the formula, R_p is the basic residual rate for PHEV and BEV; $R_{p\text{-}bat}$ is a residual battery power indicator; $R_{p\text{-}axip}$ is the residual stake of another part, except for the battery; κ_1 is the weight of the residual power battery rate; κ_2 is the weight of the residual rate of the other part.

(c) Residual rate adjustment factor

Factors that influence the correction factor for the residual rate of PHEV vehicles include physical depreciation, functional depreciation and economic depreciation.

A_f physical depreciation is expressed as the vehicle condition factor. The total vehicle condition factor relates to the physical loss of vehicle components. Based on the conventional evaluation specifications, the condition of the vehicle during roadworthiness tests. Indirectly, the use of targets is also an important factor influencing the physical depreciation of PHEV and ICEV vehicles. Different use purposes reflect different use habit, intensity and operating environment of the vehicles. Maintenance records as part of the cyclical and necessary maintenance of a PHEV and ICEV vehicle are used to assess the maintenance costs during the historical use of vehicles. This translates into the final cost of ownership for older vehicle models. These costs increase with the age of the vehicle, regardless of its type. Thus, this index can be used for all types of motor vehicles. The fault register of vehicles, especially periodic and aperiodic vehicles, is a key value that has a huge impact on the final result is the value of the residual rate correction factor.

Functional depreciation mainly relates to depreciation caused by vehicle upgrades and depreciation of functions determined by technological progress and a decline in labor productivity. With the progress of science and technology development, the use of new technology will inevitably lead to the depreciation of the old technology, which is particularly reflected in better results of the residual value of PHEV and other vehicles with unconventional drivetrain.

A_o operating depreciation relates mainly to the high operating costs in each coming year due to the high level of energy consumption of battery powered vehicles. The corresponding result can be calculated by comparing the level of energy consumption of the vehicle under review (older generation or older than the year) with the main type of vehicle (new) at the same level-this is the assessment of the loss of efficiency of obtaining and returning energy.

The economic creep of A_e depreciation is mainly due to the reputation of a given vehicle brand, e.g., hence the best brands achieve favorable residual value results. The price of used vehicles is still very high over the years. In this study, brands were included in the residual score by the rate and reputation score correction coefficient-in automotive sites, they are most often used as a quantitative measure to assess a brand's reputation.

$$Kp = \left(\beta_1 A_f + \beta_2 A_o + \beta_3 A_e\right) \tag{5}$$

The values of the coefficients expressing an individual vehicle or group of vehicles are denoted by β_n.

3. Results and Results of Conducted Simulation and Statistical Tests

3.1. Analysis of the Residual Value of PHEV and ICEV Vehicles on the Example of Toyota Prius and Corolla in 1997–2021

One of the first hybrid vehicles offered on the Polish market was Toyota Prius. The analysis of the residual values covered the 5 generations of this vehicle compared to the conventional ICEV Toyota Corolla vehicle from the same market segment in individual periods including the production of this model. It was assumed that the residual value for the initial years includes the older models, and the residual values for the current years include the newer models. The same criteria for validating the results were adopted as the standard of equipment. Moreover, a constant initial value of the purchase was assumed for a given period of its implementation. A number of variables have been introduced that may affect the final residual value.

Figure 2 shows the percentage changes in the residual values based on the prevailing trends at a given point in the life of the vehicle. Detailed data was obtained on the basis of commercial software without using additional factors carried out in the author's method. In Figure 3, for comparative purposes, a detailed analysis with the use of model tools was performed and the results were summarized as a comparative basis. Additional variables were introduced to define mainly changes in the residual values of PHEV and ICEV vehicles. This allows you to significantly increase the accuracy of the residual value results for a given vehicle year with the prevailing market trends. The values of these parameters can be compared based on the approximate prices of the residual values of PHEV and ICEV vehicles on auction protals (Figures 4 and 5). Figures 2–5 show the percentage changes in the vehicle resale value compared to the previous year. Therefore, the resale value for a given year represents a decrease in the value of the vehicle compared to the previous year.

3.2. Comparative Analysis of the Residual Value of PHEV and ICEV Vehicles over a Period of 5 Years for Various Classes of Additional Equipment

Segmentation is perceived as the process of dividing the market into relatively homogeneous market segments which, due to their similarity, have the same consumption needs. This need is a natural consequence of the increasing number of consumers, the growth of their incomes, the development of individual preferences and the possibility of making a choice. Therefore, the fundamental goal of segmentation is to analyze the market structure, i.e., the needs of customers that create the market. The second goal of segmentation is product positioning, i.e., giving it, in the perception of customers, certain specific advantages that distinguish the product from competitors and other segments. With regard to the automotive market, initially the main criterion for belonging to a vehicle class (segment) was its total length, i.e., the size related to the bodywork. The engine displacement was used as an auxiliary criterion. Due to the fact that, alternatively, several engines are often installed in one bodywork different sizes, this division assumed the smallest engine version. Other categories grouped vehicles with specific functional characteristics, for example sports or off-road. Later, the application of the engine criterion was abandoned as the practice of assembling the same engines in different bodies used by larger manufacturers disrupted the transparency of this division. The current version of the market division divides the European passenger car population into 10 categories, the first six resulting directly from the overall length criterion, and the remaining ones from the utility values related to the body type. Individual categories are marked with successive letters of the alphabet. This division is periodically modernized so that it is adjusted to the current situation on the car market as precisely as possible. The limit values of the overall length between the individual categories are only indicative. There is a gradual change in the limit values, co is due to changes in customer preferences and progress in vehicle construction. In particular, the vehicle equipment class plays a key role in the residual value of electric and hybrid vehicles. There is a variation in the residual value for different brands and body types, but it is largely the equipment and the number of additional components that determine the depreciation of a used vehicle. In the case of PHEV vehicles, it can be noticed that the value of the comfort equipment and additional utilities is important only in the initial period of use of the vehicle. Already after 4 years of use from the purchase of the vehicle, the impact of this parameter on the resale price of the vehicle is negligible. Figures 6 and 7 introduce four class designations: A1-low standard, A2-medium, A3-good, A4-very good (the class determines the amount of additional equipment and additional costs related to its operation). In Figures 6 and 7 it can be seen that the standard of equipment of the ICEV and PHEV vehicles is of great importance in the case of vehicles from 1 to 3 years of use. After this period, the impact of the equipment on the resale price is less significant. This is evidenced by the aligning bars of the percentage of the vehicle's resale price to the new car's price for 2016 and 2017. The differences in these values become very similar for each of the 4 equipment classes of the vehicle ICEV and PHEV. It can also be seen from these drawings that the impact of vehicle equipment is more significant on the resale price than for PHEV vehicles. This is due to certain customer trends for these vehicle propulsion sources. ICEVs are viewed in terms of comfort equipment, body preferences and engine performance. In the case of PHEV vehicles, the key parameters determining customer purchasing trends are vehicle maintenance costs and economic benefits of using PHEV vehicles. In this case, the accessories are of less importance. The most important thing is the profit in the form of the cheapest possible ride a certain number of kilometers of the route.

For ICEVs, the residual value strongly depends on the equipment class of the vehicle. The comparison of 3 software methods with the use of standard software ($A_{n\text{-}p}$), analytical software with the use of own simulation tool ($A_{n\text{-}sym}$) and approximated data from auction portals ($A_{n\text{-}apr}$) is presented in Figures 8–15. Based on the obtained data, it can be concluded that the adopted numerical method gives a greater approximation to the values approximated on the basis of market data from auction portals than the proposed tool used commercially in Poland by experts. In Figures 8–15 below, it can be seen that the trendline values for the model program and the approximated data from auction portals are very similar. The values obtained from the program are burdened with a greater error in relation to the reference in the form of approximated data. Therefore, it can be said that the created program and the concept of introducing a more extensive base The introduced variables provide the basis for reliable forecasting data for the following years. You can expect slight deviations in relation to future resale prices obtained on the basis of data from auction websites. To a large extent, this computational accuracy was made possible by taking into account the utility variables, the costs of future faults and operation, and taking into account the influence of trends aimed at the vehicle comfort equipment.

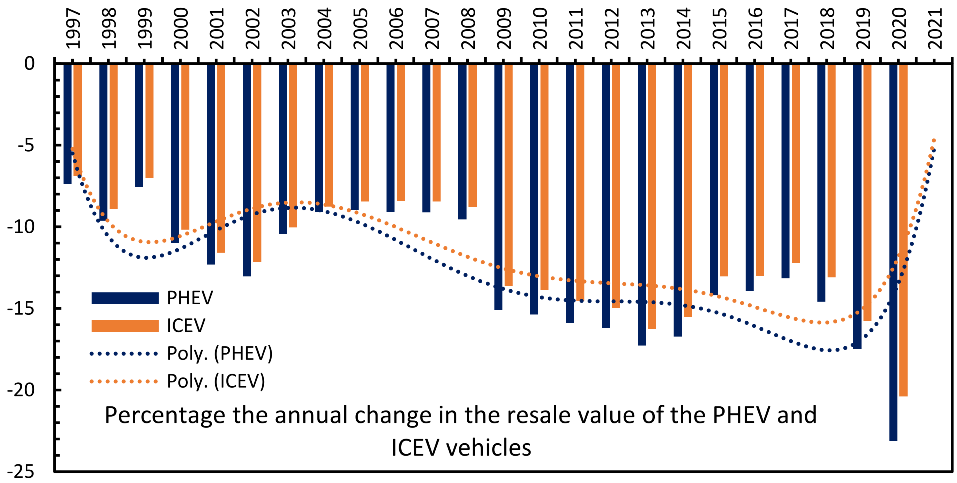

Figure 2. Analysis of the residual value of a PHEV vehicle with ICEV from the same market segment over a period of 24 years on the example of Toyota Prius (all generations) and Toyota Corolla-market values forecast based on simplified data from Info-Forecast program.

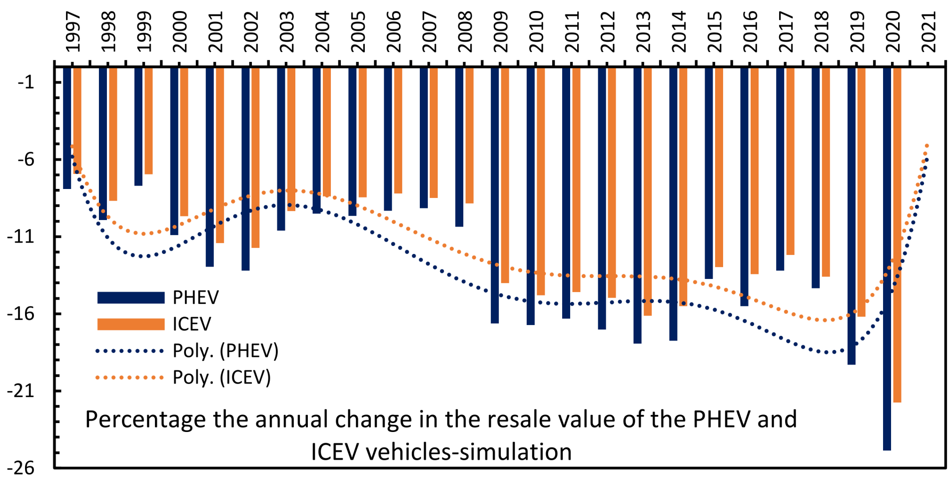

Figure 3. Analysis of the residual value of a PHEV vehicle with ICEV from the same market segment over a period of 24 years on the example of Toyota Prius (all generations) and Toyota Corolla, taking into account the variables simulated in the numerical analysis.

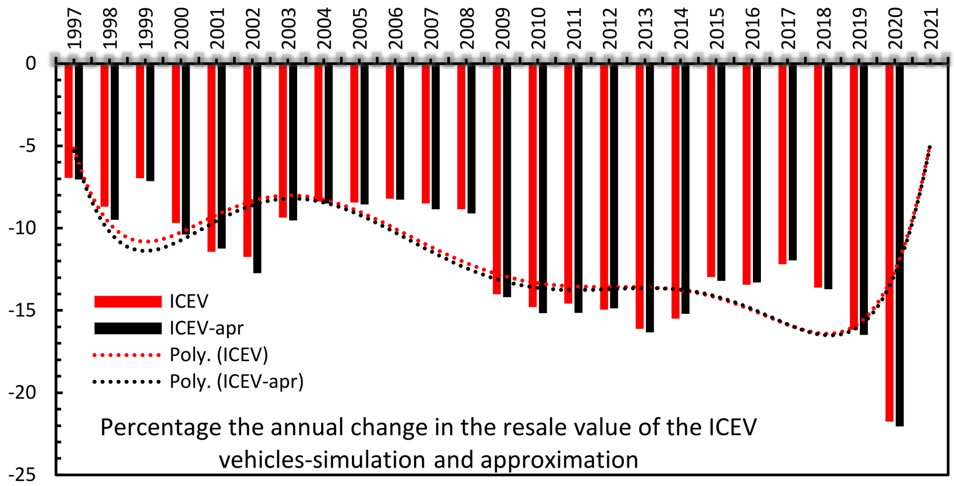

Figure 4. Analysis of the residual value of an ICEV vehicle from the same market segment over a period of 24 years on the example of Toyota Corolla, taking into account the variables simulated in the numerical analysis in comparison with the values approximated from auction portals.

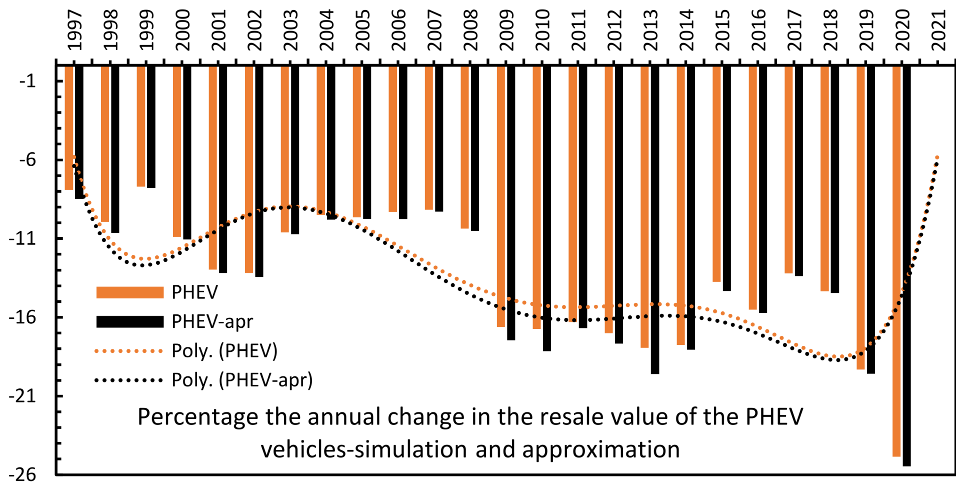

Figure 5. Analysis of the residual value of a PHEV vehicle from the same market segment over a period of 24 years on the example of Toyota Prius (all generations), taking into account the variables simulated in the numerical analysis in comparison with the values approximated from auction portals.

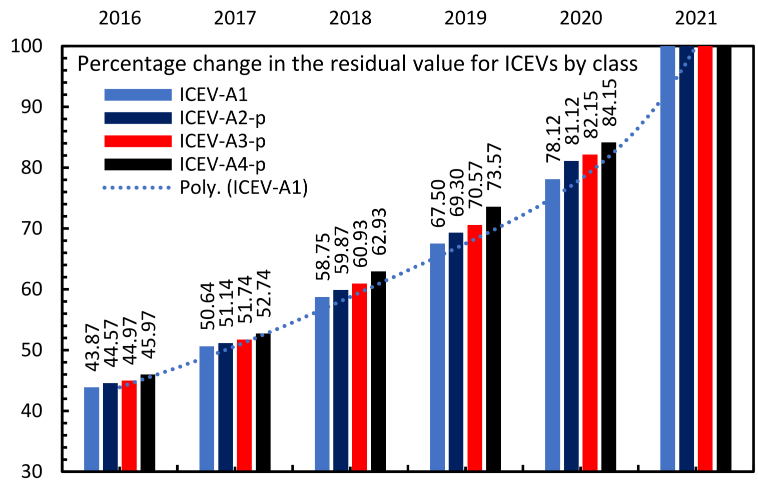

Figure 6. Analysis of the ICEV residual values over a period of 5 years on the example of Toyota Corolla 2021-data values based on a commercial program.

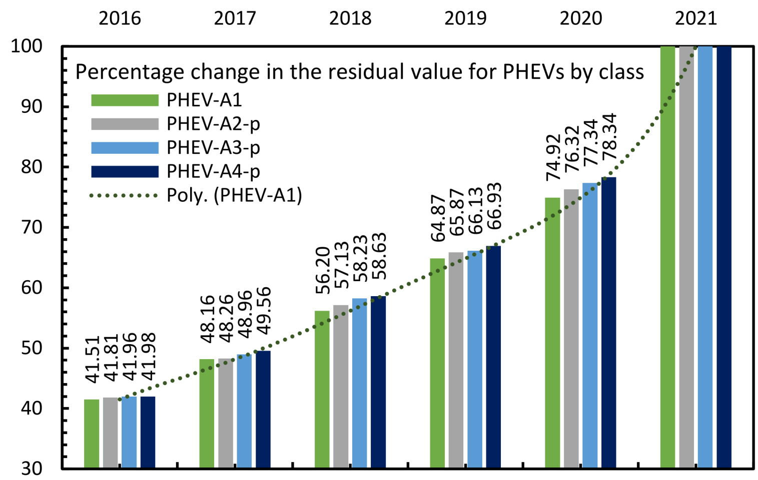

Figure 7. Analysis of the residual values of the PHEV vehicle over a period of 5 years on the example of Toyota Prius 1.8 2021-data values based on a commercial program.

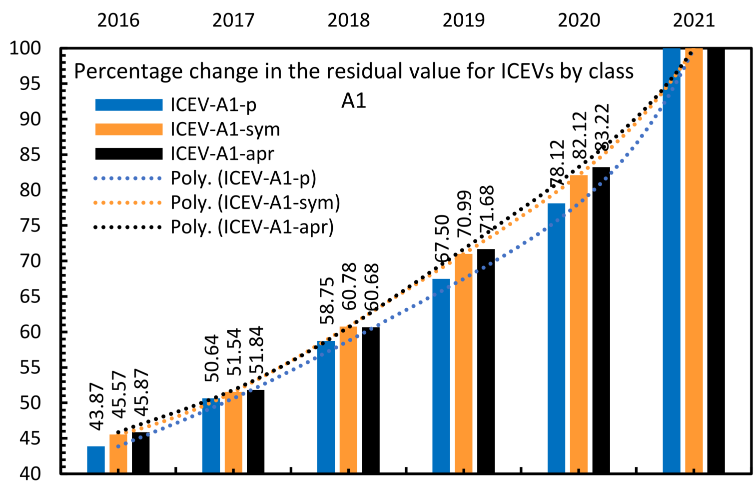

Figure 8. Analysis of the ICEV residual values over a period of 5 years on the example of Toyota Corolla 2021 for class A1.

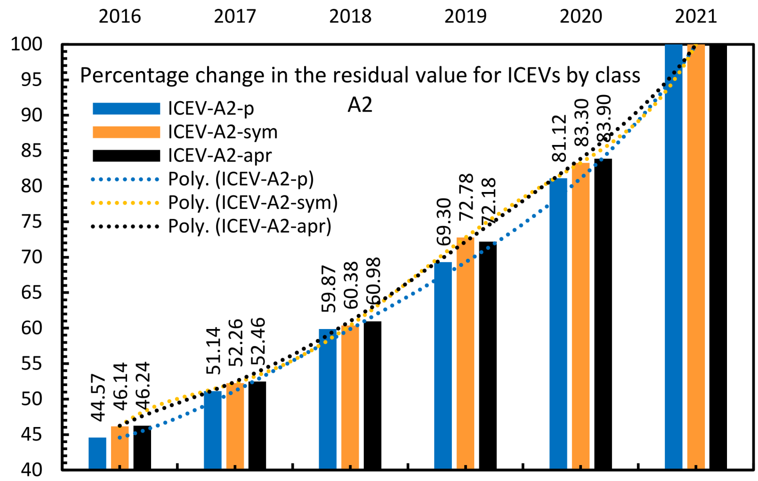

Figure 9. Analysis of the ICEV residual values over a period of 5 years on the example of Toyota Corolla 2021 for class A2.

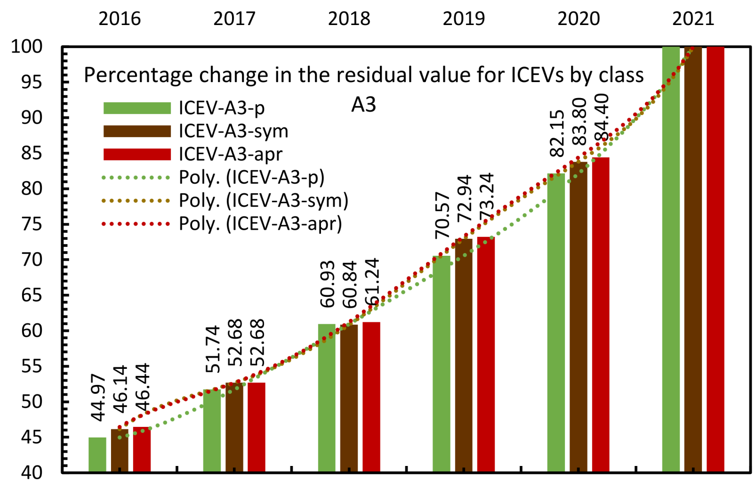

Figure 10. Analysis of the ICEV residual values over a period of 5 years on the example of Toyota Corolla 2021 for the A3 class.

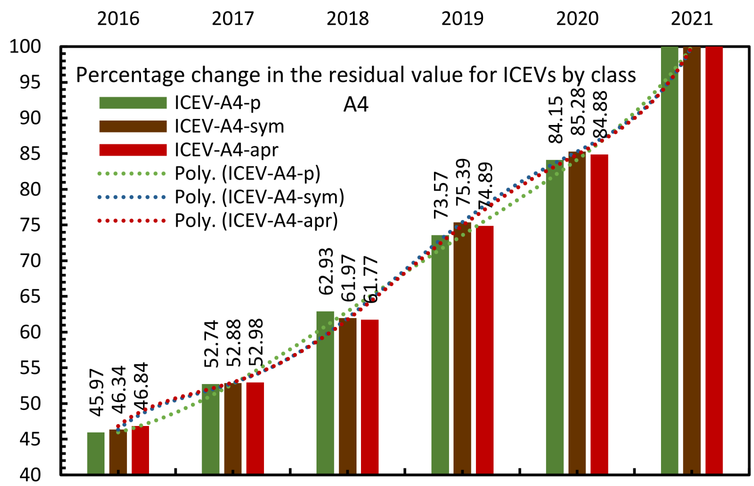

Figure 11. Analysis of the ICEV residual values over a period of 5 years on the example of Toyota Corolla 2021 for the A4 class.

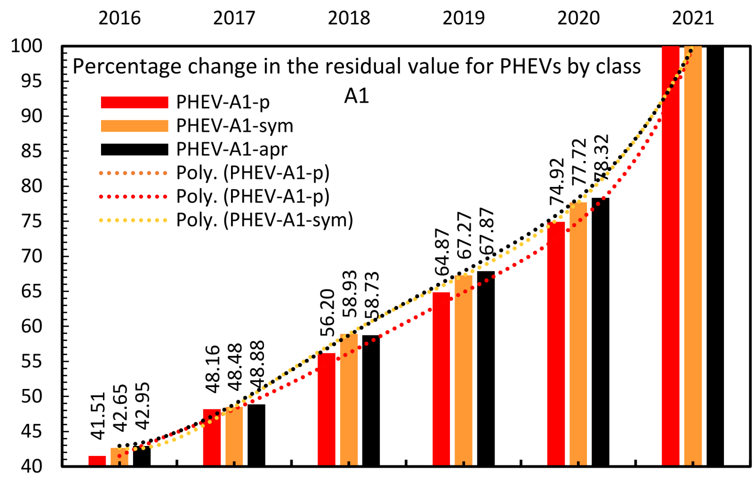

Figure 12. Analysis of the PHEV vehicle residual values over a 5-year period based on the Toyota Prius 2021 for the A1 class.

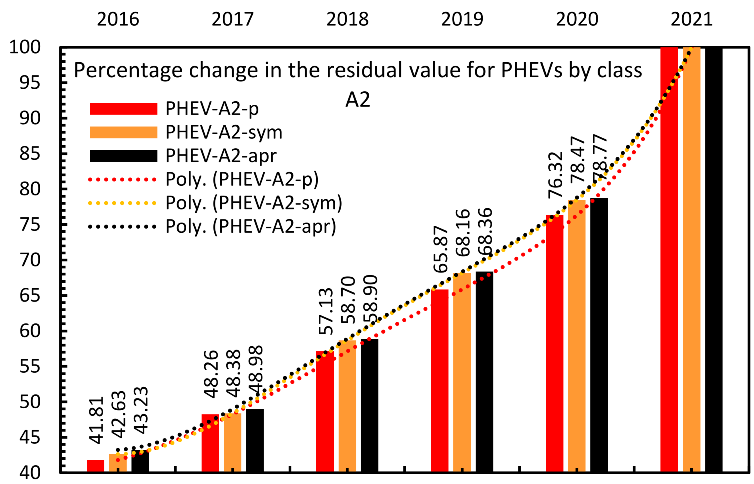

Figure 13. Analysis of the residual values of the PHEV vehicle over the period of 5 years on the example of Toyota Prius 2021 for the A2 class.

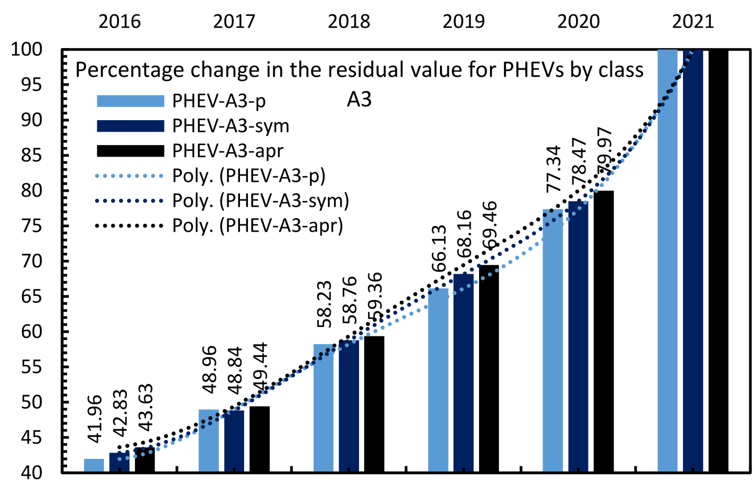

Figure 14. Analysis of the PHEV vehicle residual values over a 5-year period based on the Toyota Prius 2021 for the A3 class.

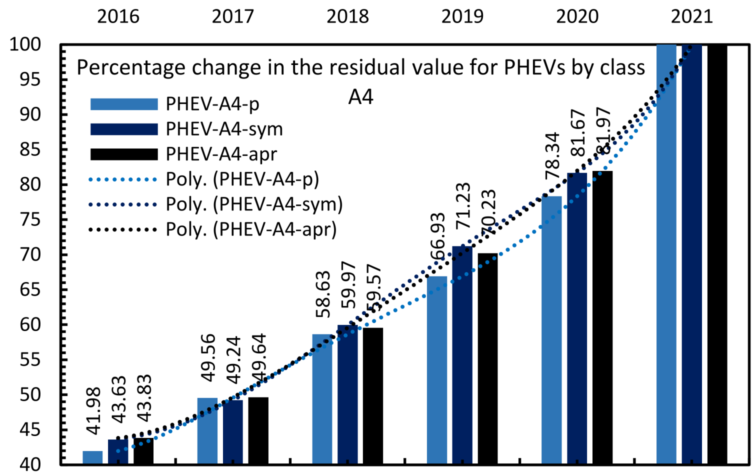

Figure 15. Analysis of the PHEV vehicle residual values over a 5-year period based on the Toyota Prius 2021 for the A4 class.

3.3. Forecast ICEV, PHEV and BEV Residual Values on the Example of Toyota Corolla, Prius, VW E-Golf

A model program was used to forecast the residual value for the next 5 years. Archival data was used and all trend changes in the perception of BEV and PHEV vehicles by users were taken into account. The introduction of these variables in a significant way affects the resale price of the vehicle. This greatly improves the residual value in the initial period of use of BEVs and PHEVs. This is due to the constant expansion of the electric vehicle charging infrastructure, reducing the costs of operating and using electric vehicles. This condition is also influenced by the increasing availability of vehicle users to the service and repair infrastructure in large urban agglomerations. The growing number of short- and long-range electric vehicles also translates into prices and the availability of spare parts. This has a huge impact on the decrease in vehicle prices from the moment of its purchase to 5 years of use. So far, these losses have been very significant, what discouraged customers from purchasing electric vehicles. Changing trends and the policy of car manufacturers will certainly lead to an increase in the popularity of electric vehicles in the automotive market. The presented simulation results for the two equipment classes A1 and A4 can be seen in Figures 16 and 17.

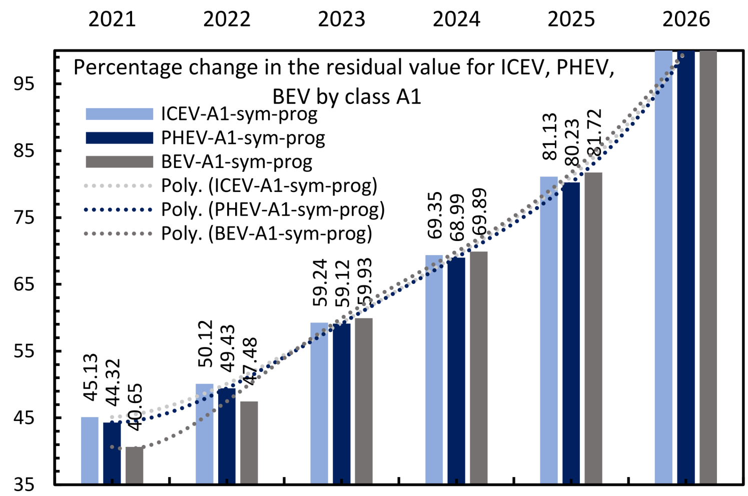

Figure 16. Forecast of residual values of ICEV, PHEV and BEV vehicles on the example of Toyota Corolla, Prius, VW E-Golf-for equipment class A1.

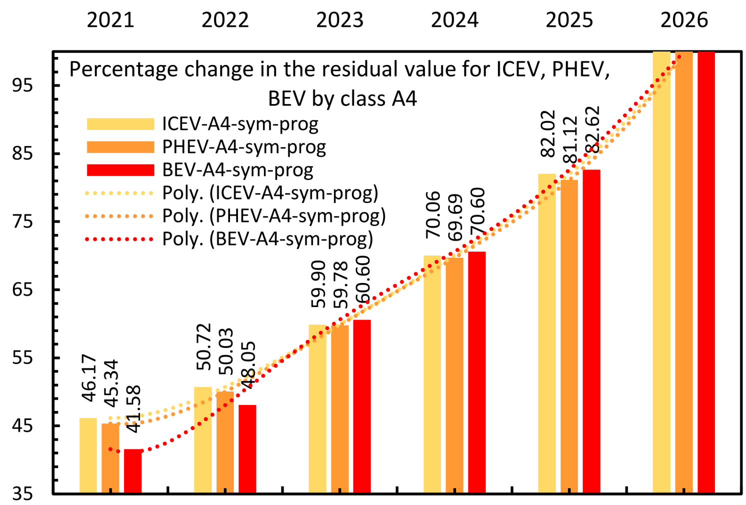

Figure 17. Forecast of residual values of ICEV, PHEV and BEV vehicles on the example of Toyota Corolla, Prius, VW E-Golf-for equipment class A4.

4. Summary

Observations of the automotive market indicate that in the current decade, model changes in individual market segments are more frequent than in the previous decades. Car concerns, wishing to gain a new market segment, introduce design innovations on average, every 2–3 years, supplementing the offer of drive systems and additional equipment. The new PHEV and BEV power units are becoming more and more competitive with the ICEV drive. The profitability of using electric or hybrid vehicles is influenced by many interdependent factors. One of them is the residual value, which constantly changes its trends in line with technological progress. The changed model, in line with the low-emission idea, is an opportunity for producers to attract new customers and increase sales, and thus increase the profitability of production. As a consequence, an increase in the starting price of a low-emission vehicle compared to a conventionally powered model may lead to a faster decline in residual value. On this basis, the authors forecast that this practice will force the introduction of price discounts on low-emission models. However, even such a sales strategy may also result in them losing their price on the secondary market more quickly. As a consequence, a high price margin for the purchase of a given model may, in extreme cases, lead to a significant loss of value of the car in the first year of its use.

Based on the analyzes carried out using a standard program, proprietary numerical model and data approximated from auction portals, the following conclusions can be drawn:

- The most reliable source of the residual value assessment is the modeling of a given vehicle, taking into account the class of its equipment and the type of drive unit, using data approximated from auction portals. It is the users and their prevailing liking trends that determine the percentage of price loss in each year of use of the vehicle.
- The commercial program used by many appraisers gives slight errors in relation to the data approximated from auction websites.
- The created numerical model and the introduction of variables defining the equipment classes, technical condition of the vehicle at the time of resale, the demand trend factor, brand evaluation factor and many others discussed in the paper gives much more accurate results than commercial programs. This is reflected in the very similar results of the residual values in relation to the approximated data.
- The equipment class of the vehicle has a significant influence on the residual value in the initial years of use, after 3 years, the equipment class has a moderate impact on the resale price of the vehicle. The equipment class mainly affects the residual value of ICEVs in the case of PHEV and BEVs this value is only relevant in the initial period of use.

- PHEVs show significantly greater loss in value at resale than ICEVs. This is especially important for the first 3 years of use. The initial price losses for the PHEV vehicles are significant.
- The created tool enables conducting accurate analyzes of forecasting changes in the residual value of vehicles depending on the type of drive system and other factors.
- As part of the forecasts for the next 5 years, it can be expected that the loss in residual value for BEVs will continue to be very large after exceeding the 3rd year of use. In the initial period of use of BEVs, the price loss in the resale of the car is lower than for PHEV vehicles. In the first 2 years of operation, BEVs will have lower residual drops than ICEVs.
- Despite the tendency to expand the charging network infrastructure, new technologies of battery construction and their operation, lower costs of use, repair and maintenance of PHEV and BEV vehicles, ICEV vehicles after more than 5 years of use will still be characterized by the lowest loss of value in the automotive market.

Summarizing the analyzes presented by the authors on the residual values of ICEV, PHEV and BEV passenger cars on the example of selected low-emission vehicles from individual market segments, by exploring these values, they do not fully exhaust the essence of the issue, but are only an attempt to signal the complexity of the issues under study, concerning both the structure of creating numerical models and difficulties in taking into account many variables. These issues will certainly be the subject of further analysis and research in order to create a tool that allows to forecast residual values with very high accuracy in relation to approximate data obtained from auction sites with a highly detailed breakdown into equipment classes and trends in the perception of given vehicle propulsion.

Author Contributions: Conceptualization, methodology, validation, formal analysis, investigation, writing. P.W. and W.L.; original draft preparation, visualization, P.W. and W.L.; writing—review and editing, supervision, P.W. and W.L.; project administration: P.W. and W.L. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

ICEV	Internal Combustion Engine Vehicle
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
HEV	Hybrid Electric Vehicles
FCEV	Fuel Cell Electric Vehicles
SOM	symptom observation matrix
PSPA	Polish Alternative Fuels Association
PZPM	Polish Association of the Automotive Industry
IEA	The International Energy Agency
CEPIK	IT system that includes the central register of drivers (CEK) and the central register of vehicles (CEP)

References

1. Cidell, J. Sustainable transportation: Accessibility, mobility, and derived demand. In *Sustainability: A Comprehensive Foundation, Textbook Initiative*; Theis, T., Tomkin, J., Eds.; Connexions: Kolkata, India, 2012; pp. 566–576.
2. Russo, F.; Comi, A. City Characteristics and Urban Goods Movements: A Way to Environmental Transportation System in a Sustainable City. *Procedia-Soc. Behav. Sci.* **2012**, *39*, 61–73. [CrossRef]
3. Al Maghraoui, O. *Designing for Urban Mobility-Modeling the Traveler Experience Interfaces*; Université Paris Saclay: Paris, France, 2019.
4. Webb, J. The future of transport: Literature review and overview. *Econ. Anal. Policy* **2019**, *61*, 1–6. [CrossRef]
5. Kupczyk, A.; Mączyńska, J.; Redlarski, G.; Tucki, K.; Bączyk, A.; Rutkowski, D. Selected Aspects of Biofuels Market and the Electromobility Development in Poland: Current Trends and Forecasting Changes. *Appl. Sci.* **2019**, *9*, 254. [CrossRef]
6. O'Driscoll, R.; Stettler, M.; Molden, N.; Oxley, T.; ApSimon, H.M. Real world CO2 and NOx emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars. *Sci. Total. Environ.* **2018**, *621*, 282–290. [CrossRef]
7. Kryzia, D.; Kuta, M.; Matuszewska, D.; Olczak, P. Analysis of the Potential for Gas Micro-Cogeneration Development in Poland Using the Monte Carlo Method. *Energies* **2020**, *13*, 3140. [CrossRef]
8. Kok, R. Six years of CO 2-based tax incentives for new passenger cars in The Netherlands: Impacts on purchasing behavior trends and CO 2 effectiveness. *Transp. Res. Part A Policy Pr.* **2015**, *77*, 137–153. [CrossRef]
9. Połom, M. Technology Development and Spatial Diffusion of Auxiliary Power Sources in Trolleybuses in European Countries. *Energies* **2021**, *14*, 3040. [CrossRef]
10. Połom, M.; Wiśniewski, P. Implementing Electromobility in Public Transport in Poland in 1990–2020. A Review of Experiences and Evaluation of the Current Development Directions. *Sustainability* **2021**, *13*, 4009. [CrossRef]
11. Olczak, P.; Kryzia, D.; Matuszewska, D.; Kuta, M. "My Electricity" Program Effectiveness Supporting the Development of PV Installation in Poland. *Energies* **2021**, *14*, 231. [CrossRef]
12. Haasz, T.; Vilchez, J.J.G.; Kunze, R.; Deane, P.; Fraboulet, D.; Fahl, U.; Mulholland, E. Perspectives on decarbonizing the transport sector in the EU-28. *Energy Strat. Rev.* **2018**, *20*, 124–132. [CrossRef]
13. Dróżdż, W.; Szczerba, P.; Kruszyński, D. Issues related to the development of electromobility from the point of view of Polish utilities. *Polityka Energetyczna Energy Policy J.* **2020**, *23*, 49–64. [CrossRef]
14. Borucka, A.; Wiśniowski, P.; Mazurkiewicz, D.; Świderski, A. Laboratory measurements of vehicle exhaust emissions in conditions reproducing real traffic. *Measurement* **2021**, *174*, 108998. [CrossRef]
15. Olczak, P.; Olek, M.; Matuszewska, D.; Dyczko, A.; Mania, T. Monofacial and Bifacial Micro PV Installation as Element of Energy Transition—The Case of Poland. *Energies* **2021**, *14*, 499. [CrossRef]
16. Berylls Strategy Advisor. Battery Production Today And Tomorrow: Too Many Manufacturers, Too Few Customers. 2018. Available online: https://www.berylls.com/wp-content/uploads/2018/03/20180323_Studie_E-Mobilitaet_EN.pdf (accessed on 17 May 2021).
17. MacDonald, J. Electric Vehicles to Be 35% of Global New Car Sales by 2040, Bloomberg New Energy Finance (BNEF). 2016. Available online: https://about.bnef.com/blog/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/ (accessed on 17 May 2021).
18. Sendek-Matysiak, E.; Łosiewicz, Z. Analysis of the development of the electromobility market in Poland in the context of the implemented subsidies. *Energies* **2021**, *14*, 222. [CrossRef]
19. Ministry of Energy. Act of 11 January 2018 on Electromobility and Alternative Fuels. Available online: http://dziennikustaw.gov.pl/du/2018/317/1 (accessed on 8 June 2021).
20. Wróblewski, P.; Kupiec, J.; Drożdż, W.; Lewicki, W.; Jaworski, J. The Economic Aspect of Using Different Plug-In Hybrid Driving Techniques in Urban Conditions. *Energies* **2021**, *14*, 3543. [CrossRef]
21. Wróblewski, P.; Drożdż, W.; Lewicki, W.; Miązek, P. Methodology for Assessing the Impact of Aperiodic Phenomena on the Energy Balance of Propulsion Engines in Vehicle Electromobility Systems for Given Areas. *Energies* **2021**, *14*, 2314. [CrossRef]
22. Ajanovic, A.; Haas, R.; Wirl, F. Reducing CO2 emissions of cars in the EU: Analyzing the underlying mechanisms of standards, registration taxes and fuel taxes. *Energy Effic.* **2015**, *9*, 925–937. [CrossRef]
23. Bradley, T.H.; Frank, A.A. Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. *Renew. Sustain. Energy Rev.* **2009**, *13*, 115–128. [CrossRef]
24. Wörner, R.; Morozova, I.; Schneider, D.; Oncken, M.; Bauer, P.; Blesl, M.; Wiesmeth, M.; Brodecki, L.; Jochem, P.; Märtz, A.; et al. Prediction on future electric vehicle market shares in urban areas and related consequences for energy delivery & grid stability-investigation of Stuttgart. In Proceedings of the 32nd International Electric Vehicle Symposium, Lyon, France, 19–22 May 2019.
25. Wróblewski, P.; Drożdż, W.; Lewicki, W.; Dowejko, J. Total Cost of Ownership and Its Potential Consequences for the Development of the Hydrogen Fuel Cell Powered Vehicle Market in Poland. *Energies* **2021**, *14*, 2131. [CrossRef]
26. Dziubak, T.; Boruta, G. Experimental and Theoretical Research on Pressure Drop Changes in a Two-Stage Air Filter Used in Tracked Vehicle Engine. *Separations* **2021**, *8*, 71. [CrossRef]
27. Wróblewski, P.; Koszalka, G. An Experimental Study on Frictional Losses of Coated Piston Rings with Symmetric and Asymmetric Geometry. *SAE Int. J. Engines* **2021**, *14*, 51. [CrossRef]
28. Dziubak, T. Experimental Studies of Dust Suction Irregularity from Multi-Cyclone Dust Collector of Two-Stage Air Filter. *Energies* **2021**, *14*, 3577. [CrossRef]

29. Dziubak, T.; Bąkała, L. Computational and Experimental Analysis of Axial Flow Cyclone Used for Intake Air Filtration in Internal Combustion Engines. *Energies* **2021**, *14*, 2285. [CrossRef]
30. Dziubak, T. Material Properties Analysis with Addition of Nanofibres for Air Intake Filtration in Internal Combustion Engines. *Int. J. Automot. Mech. Eng.* **2021**, *18*, 8621–8636. [CrossRef]
31. Ahmad, M.; Kamiński, P.; Olczak, P.; Alam, M.; Iqbal, M.; Ahmad, F.; Sasui, S.; Khan, B. Development of Prediction Models for Shear Strength of Rockfill Material Using Machine Learning Techniques. *Appl. Sci.* **2021**, *11*, 6167. [CrossRef]
32. Szelka, M.; Woszczyński, M.; Jagoda, J.; Kamiński, P. Wireless Leak Detection System as a Way to Reduce Electricity Consumption in Ventilation Ducts. *Energies* **2021**, *14*, 3774. [CrossRef]
33. Kamiński, P. Development of New Mean of Individual Transport for Application in Underground Coal Mines. *Energies* **2021**, *14*, 2022. [CrossRef]
34. Kamiński, P.; Dyczko, A.; Prostański, D. Virtual Simulations of a New Construction of the Artificial Shaft Bottom (Shaft Safety Platform) for Use in Mine Shafts. *Energies* **2021**, *14*, 2110. [CrossRef]
35. D'Obyrn, K.; Kamiński, P.; Motyka, J. Influence of Hydrogeological Investigation's Accuracy on Technology of Shaft Sinking and Design of Shaft Lining—Case Study from Southern Poland. *Energies* **2021**, *14*, 2050. [CrossRef]
36. Kennedy, D.; Philbin, S.P. Techno-economic analysis of the adoption of electric vehicles. *Front. Eng. Manag.* **2019**, *6*, 538–550. [CrossRef]
37. Contestabile, M.; Offer, G.J.; Slade, R.; Jaeger, F.; Thoennes, M. Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner? *Energy Environ. Sci.* **2011**, *4*, 3754–3772. [CrossRef]
38. Shankar, R.; Marco, J. Method for estimating the energy consumption of electric vehicles and plug-in hybrid electric vehicles under real-world driving conditions. *IET Intell. Transp. Syst.* **2013**, *7*, 138–150. [CrossRef]
39. Achtnicht, M.; Bühler, G.; Hermeling, C. The impact of fuel availability on demand for alternative-fuel vehicles. *Transp. Res. Part D Transp. Environ.* **2012**, *17*, 262–269. [CrossRef]
40. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **2015**, *137*, 511–536. [CrossRef]
41. Waseem, M.; Sherwani, A.F.; Suhaib, M. Integration of solar energy in electrical, hybrid, autonomous vehicles: A technological review. *SN Appl. Sci.* **2019**, *1*, 1459. [CrossRef]
42. Wróblewski, P. An Innovative Approach to Data Analysis in The Field of Energy Consumption and Energy Conversion Efficiency in Vehicle Drive Systems-The Impact of Operational and Utility Factors. In Proceedings of the 37th International Business Information Management Association (IBIMA), Cordoba, Spain, 1–2 April 2021; ISBN 978-0-9998551-6-4.
43. Wróblewski, P. Effect of asymmetric elliptical shapes of the sealing ring sliding surface on the main parameters of the oil film. *Combust. Engines* **2017**, *168*, 84–93. [CrossRef]
44. Wróblewski, P. The effect of the distribution of variable characteristics determining the asymmetry of the sealing rings sliding surfaces on the values of friction loss coefficients and other selected parameters of oil film. *Combust. Engines* **2017**, *171*, 107–116. [CrossRef]
45. Szabo, J.; Fabok, M. Infrastructures and state-building: Comparing the energy politics of the European Commission with the governments of Hungary and Poland. *Energy Policy* **2020**, *138*, 111253. [CrossRef]
46. Zhang, X.; Liang, Y.; Yu, E.; Rao, R.; Xie, J. Review of electric vehicle policies in China: Content summary and effect analysis. *Renew. Sustain. Energy Rev.* **2017**, *70*, 698–714. [CrossRef]
47. Van Vliet, O.P.; Kruithof, T.; Turkenburg, W.C.; Faaij, A.P. Techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars. *J. Power Sources* **2010**, *195*, 6570–6585. [CrossRef]
48. Larson, P.D.; Viáfara, J.; Parsons, R.V.; Elias, A. Consumer attitudes about electric cars: Pricing analysis and policy implications. *Transp. Res. Part A Policy Pract.* **2014**, *69*, 299–314. [CrossRef]
49. Teixeira, A.C.R.; Sodré, J.R. Impacts of replacement of engine powered vehicles by electric vehicles on energy consumption and CO 2 emissions. *Transp. Res. Part D Transp. Environ.* **2018**, *59*, 375–384. [CrossRef]
50. Tromaras, A.; Aggelakakis, A.; Margaritis, D. Car dealerships and their role in electric vehicles' market penetration-A Greek market case study. *Transp. Res. Procedia* **2017**, *24*, 259–266. [CrossRef]
51. Ouyang, D.; Zhou, S.; Ou, X. The total cost of electric vehicle ownership: A consumer-oriented study of China's post-subsidy era. *Energy Policy* **2021**, *149*, 112023. [CrossRef]
52. Hagman, J.; Ritzén, S.; Stier, J.J.; Susilo, Y. Total cost of ownership and its potential implications for battery electric vehicle diffusion. *Res. Transp. Bus. Manag.* **2016**, *18*, 11–17. [CrossRef]
53. Al-Alawi, B.M.; Bradley, T.H. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. *Appl. Energy* **2013**, *103*, 488–506. [CrossRef]
54. Ellram, L.M. Total cost of ownership-An analysis approach for purchasing. *Int. J. Phys. Distrib. Logist. Manag.* **1995**, *25*, 4–23. [CrossRef]
55. Kumar, P.; Chakrabarty, S. Total Cost of Ownership Analysis of the Impact of Vehicle Usage on the Economic Viability of Electric Vehicles in India. *Transp. Res. Rec.* **2020**, *2674*, 563–572. [CrossRef]
56. Roda, I.; Garetti, M. Application of a Performance-Driven Total Cost of Ownership (TCO) Evaluation Model for Physical Asset Management. In Proceedings of the 9th WCEAM Research Papers, Pretoria, South Africa, 28–31 October 2014; Springer: Cham, Switzerland, 2016; pp. 11–23.

57. Bubeck, S.; Tomaschek, J.; Fahl, U. Perspectives of electric mobility: Total cost of ownership of electric vehicles in Germany. *Transp. Policy* **2016**, *50*, 63–77. [CrossRef]
58. De Jong, G.; Fox, J.; Daly, A.; Pieters, M.; Smit, R. Comparison of car ownership models. *Transp. Rev.* **2004**, *24*, 379–408. [CrossRef]
59. Propfe, B.; Kreyenberg, D.; Wind, J.; Schmid, S. Market penetration analysis of electric vehicles in the German passenger car market towards 2030. *Int. J. Hydrogen Energy* **2013**, *38*, 5201–5208. [CrossRef]
60. Bertram, V.; Moussault, S.; Voort, E.V.; Veder, A.; IJserloo, G.V. Modelling Maintenance – Cost Optimised Maintenance in Shipping. In Proceedings of the HIPER '20: 12th Symposium on High-Performance Marine Vehicles, Cortona, Italy, 12–14 October 2020.
61. Propfe, B.; Redelbach, M.; Santini, D.J.; Friedrich, H. Cost analysis of plug-in hybrid electric vehicles including maintenance and repair costs and resale values. In Proceedings of the EVS26 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Los Angeles, CA, USA, 6–9 May 2012.
62. Puthz, M. Batterie oder Benzin- Womit fahrt man besser. *Autobild* **2011**, *14*, 55–59.
63. Batchelor, J. EVs Lose Two Thirds? CarDealer. 2011. Available online: http://cardealermagazine.co.uk (accessed on 17 May 2021).
64. Woodyard, C. Depreciation Hits Electric Cars Hard. *USA Today*. 2013. Available online: https://www.usatoday.com/story/money/cars/2013/12/26/plug-in-cars-electric-carsdepreciation-resale-residual-value/4194373/ (accessed on 21 September 2018).
65. Tal, G.; Nicholas, M.A.; Turrentine, T.S. First Look at the Plug-in Vehicle Secondary Market.2017, No. UCD-ITS-WP-16-02. Available online: http://websites.umich.edu/~{}umtriswt/PDF/SWT-2018-4.pdf (accessed on 4 April 2021).
66. Schoettle, B.; Sivak, M. Resale Values of Electric and Conventional Vehicles: Recent Trends and Influence on the Decision to Purchase a New Vehicle 2018, No. SWT-2018-4. Available online: http://websites.umich.edu/~{}umtriswt/PDF/SWT-2018-4.pdf (accessed on 4 April 2021).
67. Hidrue, M.K.; Parsons, G.R.; Kempton, W.; Gardner, M.P. Willingness to pay for electric vehicles and their attributes. *Resour. Energy Econ.* **2011**, *33*, 686–705. [CrossRef]
68. Guo, Z.; Zhou, Y. Residual value analysis of plug-in vehicles in the United States. *Energy Policy* **2018**, *125*, 445–455. [CrossRef]
69. WardsAuto. WardsAuto Data Center. 2017. Available online: http://wardsauto.com/data-center (accessed on 28 May 2017).
70. Albrecht, L. You'll Save Money on Gas with the Tesla Model 3, but You May End up Paying More Elsewhere. Available online: https://www.marketwatch.com/story/youll-save-money-on-gas-with-a-tesla-but-also-consider-these-unique-expenses-2017-07-06 (accessed on 5 January 2021).
71. Li, H.; Chen, C. Research on Residual Value Evaluation of Battery Electric Vehicles Based on Replacement Cost Method. *Proceedings of the IOP Conference Series Earth and Environmental Science*. p. 012027. Available online: https://ui.adsabs.harvard.edu/abs/2020E%26ES..461a2027L/abstract (accessed on 8 June 2021).
72. Cao, X.; Yang, W. Establishment of Residual Value Assessment Model for Electric Vehicle Based on AHP. In Proceedings of the IOP Conference Series Materials Science and Engineering, Kazan, Russia, 4–6 December 2019; p. 033001. Available online: https://iopscience.iop.org/article/10.1088/1757-899X/688/3/033001 (accessed on 8 June 2021).
73. Jian, X. *Establishment and Application of Evaluation Model of Residual Value for Electric Vehicle*; Tongji University: Shanghai, China, 2014.
74. Zhou, Y.; Santini, D.; Stephens, T.; Ward, J. Comparison of Value Retention of Plug-in Vehicles and Conventional Vehicles and Potential Contributing Factors. In Proceedings of the 95th Annual Meeting Compendium of Papers, Washington, DC, USA, 10–14 January 2016. Available online: http://docs.trb.org/prp/16-6732.pdf (accessed on 21 March 2016).
75. Leard, B.; Linn, J.; McConnell, V. Fuel prices, new vehicle fuel economy, and implications for attribute-based standards. *J. Assoc. Environ. Resour. Econ.* **2017**, *4*, 659–700. [CrossRef]
76. Regulation (EU) 2019/631 of the European Parlament and of the Councill of 17 April 2019 Setting CO2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0631&from=EN (accessed on 4 April 2021).
77. Puškár, M.; Kopas, M. System based on thermal control of the HCCI technology developed for reduction of the vehicle NOX emissions in order to fulfil the future standard Euro 7. *Sci. Total. Environ.* **2018**, *643*, 674–680. [CrossRef]
78. Tucki, K.; Orynycz, O.; Świć, A.; Mitoraj-Wojtanek, M. The Development of Electromobility in Poland and EU States as a Tool for Management of CO2 Emissions. *Energies* **2019**, *12*, 2942. [CrossRef]
79. Lewicki, W.; Drożdż, W.; Wróblewski, P.; Żarna, K. The Road to Electromobility in Poland: Consumer Attitude Assessment. *Eur. Res. J.* **2021**, *24*, 28–39.
80. Weiss, M.; Patel, M.K.; Junginger, M.; Perujo, A.; Bonnel, P.; van Grootveld, G. On the electrification of road transport-Learning rates and price forecasts for hybrid-electric and battery-electric vehicles. *Energy Policy* **2012**, *48*, 374–393. [CrossRef]
81. Coffman, M.; Bernstein, P.; Wee, S.M. Electric vehicles revisited: A review of factors that affect adoption. *Transp. Rev.* **2017**, *37*, 79–93. [CrossRef]
82. Fridstrøm, L.; Østli, V. Direct and cross price elasticities of demand for gasoline, diesel, hybrid and battery electric cars: The case of Norway. *Eur. Transp. Res. Rev.* **2021**, *13*, 1–24. [CrossRef]
83. Axsen, J.; Langman, B.; Goldberg, S. Confusion of innovations: Mainstream consumer perceptions and misperceptions of electric-drive vehicles and charging programs in Canada. *Energy Res. Soc. Sci.* **2017**, *27*, 163–173. [CrossRef]

84. Long, Z.; Axsen, J.; Kormos, C. Consumers continue to be confused about electric vehicles: Comparing awareness among Canadian new car buyers in 2013 and 2017. *Environ. Res. Lett.* **2019**, *14*, 114036. [CrossRef]
85. Voelcker, J. Why Everyone Leases Electric Cars rather than Buying. Available online: https://wwgreencarreports.com/news/1115008_why-everyone-leases-electric-cars-rather-thanbuyingand-maybe-you-should-too (accessed on 21 September 2018).
86. Palmer, K.; Tate, J.E.; Wadud, Z.; Nellthorp, J. Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. *Appl. Energy* **2018**, *209*, 108–119. [CrossRef]
87. Berckmans, G.; Messagie, M.; Smekens, J.; Omar, N.; Vanhaverbeke, L.; Van Mierlo, J. Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. *Energies* **2017**, *10*, 1314. [CrossRef]
88. Hao, X.; Lin, Z.; Wang, H.; Ou, S.; Ouyang, M. Range cost-effectiveness of plug-in electric vehicle for heterogeneous consumers: An expanded total ownership cost approach. *Appl. Energy* **2020**, *275*, 115394. [CrossRef]
89. van Velzen, A.; Annema, J.A.; van de Kaa, G.; van Wee, B. Proposing a more comprehensive future total cost of ownership estimation framework for electric vehicles. *Energy Policy* **2019**, *129*, 1034–1046. [CrossRef]
90. Wu, G.; Inderbitzin, A.; Bening, C. Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segments. *Energy Policy* **2015**, *80*, 196–214. [CrossRef]
91. Baik, Y.; Hensley, R.; Hertzke, P.; Knupfer, S. Making Electric Vehicles Profitable. McKinsey & Company. Available online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/making-electric-vehicles-profitable (accessed on 20 May 2021).
92. Parker, N.; Breetz, H.L.; Salon, D.; Conway, M.W.; Williams, J.; Patterson, M. Who saves money buying electric vehicles? Heterogeneity in total cost of ownership. *Trans. Res. Part D Trans. Environ.* **2021**, *96*, 102893. [CrossRef]
93. Info Ekspert. 2021. Available online: https://info-ekspert.pl/zrzuty55.php5 (accessed on 20 May 2021).
94. Ma, Y.; Liu, Y.; Appolloni, A.; Liu, J. Does green public procurement encourage firm's environmental certification practice? The mediation role of top management support. *Corp. Soc. Responsib. Environ. Manag.* **2020**, *28*, 1002–1017. [CrossRef]
95. D'Adamo, I.; Gastaldi, M.; Rosa, P. Recycling of end-of-life vehicles: Assessing trends and performances in Europe. *Technol. Forecast. Soc. Chang.* **2019**, *152*, 119887. [CrossRef]
96. Arribas-Ibar, M.; Nylund, P.; Brem, A. The Risk of Dissolution of Sustainable Innovation Ecosystems in Times of Crisis: The Electric Vehicle during the COVID-19 Pandemic. *Sustainability* **2021**, *13*, 1319. [CrossRef]
97. Ghandriz, T.; Jacobson, B.; Islam, M.; Hellgren, J.; Laine, L. Transportation-Mission-Based Optimization of Heterogeneous Heavy-Vehicle Fleet Including Electrified Propulsion. *Energies* **2021**, *14*, 3221. [CrossRef]
98. Martins, L.D.C.; Tordecilla, R.D.; Castaneda, J.; Juan, A.A.; Faulin, J. Electric Vehicle Routing, Arc Routing, and Team Orienteering Problems in Sustainable Transportation. *Energies* **2021**, *14*, 5131. [CrossRef]
99. ACEA. The European Automobile Manufacturers' Association. Available online: https://www.acea.auto/ (accessed on 22 July 2021).
100. PSPA. Polish Alternative Fuels Association. Available online: https://pspa.com.pl/ (accessed on 22 July 2021).
101. PZPM. Polish Association of the Automotive Industry. Available online: https://www.pzpm.org.pl/ (accessed on 22 July 2021).
102. IEA International Energy Agency. Key World Energy Statistics. 2020. Available online: https://www.iea.org/ (accessed on 22 July 2021).
103. CEPIK. IT System that Includes the Central Register of Drivers (CEK) and the Central Register of Vehicles (CEP). Available online: http://www.cepik.gov.pl/ (accessed on 23 July 2021).