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Development Forecasts for the Zero-Emission Bus Fleet in Servicing Public Transport in Chosen EU Member Countries

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Abstract: Nearly two-thirds of the emissions that cause smog come from road transport. In April 2019, the European Parliament adopted new regulations on public procurement to encourage investment in clean buses—electric, hydrogen, or gas. Directive 2009/33/EC is to apply from the second half of 2021. The aim of this article is to make an attempt to simulate the number of zero-emission buses (ZEB) in European Union (EU) member countries in two time horizons: 2025 and 2030, and to forecast the number of clean vehicles in the precise time horizons, including before and after 2050. Research questions are as follows: (1) what will be the number of ZEBs in individual EU countries over the next few years; (2) which of the EU countries will reach by 2030 the level of 95% share of ZEBs in all buses, which are a fleet of public transport buses; and (3) in which year will which EU countries reach the level of 95% share of zero-emission buses. The method used is a Bass model. The conducted analyses demonstrate that, by 2050, only four of the EU members will be able to reach 95% level of share of clean buses in the city bus transport fleets. It is likely that other countries may not achieve this even by 2050.

Keywords: electric buses; zero-emission buses (ZEB); clean buses; EU policy; zero emission policy; green energy; city management; simulation model; strategy; sustainable development

1. Introduction

Owing to the significant importance of greenhouse gas emissions for climate change, in particular carbon dioxide, arising during the combustion of solid fuels in transport and the process of electricity, or, heat production, many countries have taken steps to consciously reduce harmful emissions [1]. The European Union (EU) is a particularly active entity in international relations, taking active measures to combat climate change. It aims to create a low-carbon economy in the long term.

The European Commission wants Europe to become climate neutral by 2050. Therefore, the EU has set itself targets for a gradual reduction of greenhouse gas emissions by 2050. The main climate and energy goals have been set out in two documents: the climate and energy package until 2020 [2,3] and under the 2030 climate and energy policy. The assumptions of the climate and energy package were determined by EU leaders in 2007, and in 2009, regulations were adopted in this respect. At the same time, there are the main goals of the Europe 2020 strategy for smart, sustainable, and inclusive growth. The main goals are as follows: a 20% reduction in greenhouse gas emissions (compared with 1990 levels), a 20% share of energy from renewable sources in total energy consumption in the EU, and a 20% increase in energy efficiency [3]. In October 2014, this policy framework was adopted by the Council.

The renewable energy and energy efficiency targets were increased in 2018 [4]. Currently, under the 2030 climate and energy policy, the EU plans to reduce gas emissions by at least 40%. Greenhouse gas emissions (compared with 1990 levels) should increase to at least 32% of the share of energy from renewable sources in total energy consumption. An increase of at least 32.5% in energy efficiency, together with a clause should enable this target to be achieved by 2023. Thus, the original target of at least 27% was corrected in 2018.

According to the management system, Member States are required to adopt integrated national energy and climate plans for 2021–2030 and to develop long-term national strategies, including ensuring coherence between these strategies and their national energy and climate plans. A common approach for the period up to 2030 helps to guarantee regulatory certainty for investors and coordination of the actions of the EU countries. This framework is conducive to changes towards a low-carbon economy and the creation of an energy system.

The upcoming EU Budget and in particular the EU Regional Development Funds spending plans (Operational Programs) for 2021–2027 (to be prepared by the Member States in 2020) also offer a range of opportunities to increase both the climate ambition and implementation of the measures foreseen in the National Energy and Climate Plans (NECPs). Under EU legislation, the EU's current economy broad 40% emission reduction target consists of sector contributions covered by its Emissions Trading System (ETS), mainly the energy and industry sectors. It also consists of the other remaining sectors, such as agriculture, construction, waste, and transport.

Transport is currently responsible for a significant proportion of CO_2 emissions. Forecasts assume that, by 2050, carbon dioxide emissions from this sector will increase from 6–7 gigatons to 16–18 gigatons. In addition, around 30% of Europeans live in cities where air pollution exceeds EU quality standards. Conventional fuels burned by buses are one of the largest sources of CO_2, nitrogen oxides, and particulate emissions [5].

In this context, the development of a sustainable public transport system is of key importance. The deployment of zero-emission buses to fleets is today a priority for many urban centers around the world. Metropolises see the development of green transport as a basic instrument for combating air pollution. More than 80 cities worldwide have joined the network of C40 Cities Climate Leadership Group. "The cities use to reduce emissions from transportation include switching to effective modes (e.g., public transit or non-motorised transportation) and enhancing the efficiency of fleets via shifting to zero-emission technologies" [6]. According to the Bloomberg New Energy Finance report [7], the total number of buses with electric drive (e-buses) will increase from 386,000 units in 2017 to around 1.2 million in 2025. The share of electrified buses in the global fleet will reach 47% [5]. It is also a solution decided upon by EU member states. The advantages of zero-emission vehicles are being noticed by more and more cities that decide to operate them. Thus, the share of e-buses in urban transport fleets is growing [8,9].

In the short term, the introduction of clean buses can contribute to the implementation of EU 2020 and 2030 targets, as well as national targets and local targets for CO_2, air quality, and noise in several ways. On the basis of the '2030 Climate and Energy Policy Framework' [10], at least 80% of the transport work in public collective transport is to be carried out using means of transport that are not powered by conventional fuels. In addition, by 2030, CO_2 emissions from the transport sector are expected to be reduced by 40% [5]. The introduction of electric buses to public transport fleets will also allow city authorities to reduce the amount of energy consumed.

In reference to the problems raised, in this article, the authors focused on the forecast of the number of zero-emission buses in individual EU countries by 2025 and 2030, respectively. As mentioned previously, the EU strategies assume two time horizons, 2020 and 2030. Owing to the fact that the most current data, which the authors used to create the simulation, refer to the period 2013–2018, from 2019 and later, a forecast is presented. In order to make it credible and focus on two time horizons that best correspond to the developed EU strategies, the years 2025 and 2030 were taken into consideration. Given the scale of energy consumption by cities in a global perspective, one of the fundamental challenges that the city authorities face is the reduction of energy consumption [11]. The topic taken up by the authors is directly related to the energy consumption market.

It should be emphasized that the vehicles powered by alternatives to the conventional fossil-fuelled engines are a fairly diverse group of vehicles subject to different definitions and classifications. The most promising technologies for use in public bus transport are battery-electric and hydrogen fuel-cells powered engines, which are more energy-efficient and far less pollutant than the conventional diesel engines. Additionally, such vehicles have specific advantages over trolley buses and trams, such as the flexibility of use of road infrastructure without the need for powerlines or rails [12]. In this study, the authors will use the term zero-emission buses (ZEBs), which specifies a group of buses using either of these two fuel technologies, as neither type generates any pollutant emission [12–14].

Such technology applied in public transport is an innovation. Bezruchonak [6] conducted an analysis of the geographical distribution of electric buses in European countries and took into account European cities till 2018. According to him, the increase in European stock suggests that the European market is moving beyond the demonstration phase and into commercial development, and by 2030, the share of battery-electric buses will reach 50%. The United Kingdom, the Netherlands, Germany, Spain, Sweden, Poland, and Lithuania are the major European markets that order and operate fleets of electric buses. However, it is difficult to predict how the new technology will be adopted to the market. The process of adopting an innovation by the market is particularly important from the investor's point of view. In this case, it is extremely important to predict the development of this technology owing to the enormous costs associated with constructing the essential infrastructure and the fact that financing of zero-emission, electric technology in public transport is based almost exclusively on public funds. As investigated by Brozynski and Lejbowicz, predicting the adoption of electric technology in transport is of great importance in investment decisions of policy makers. First of all, it is important when investing public funds. As demonstrated in their research, moving the process forward helps to avoid incurring policy costs repeatedly by lingering in stages affected by the policy [15].

Despite the rapid growth of the number of ZEBs, their share in the entire global bus fleet is still marginal [13]. Referring to the problems raised, this article attempts to create a simulation that shows how quickly EU members will be able to replace traditional buses with zero-emission buses and reach 95% of their share in the public transport bus fleet.

There are several models related to forecasting the development of electric transport technologies in the literature that have been extensively described and analyzed. For example, Meade and Islam present a detailed overview of mathematical (deterministic) models describing the accumulation of adoptions [16]. However, the best known and most frequently quoted model is the one proposed by Bass [17]. The Bass model was chosen, based on the existing data and on the fact that it is a deterministic model that provides precise forecasts [11]. This model is often used alongside the so-called logistic and Gompertz projections, while ordinary predictions based on the Bass model are the most pessimistic [18]. This is an additional argument in favor of this model. An additionally significant aspect is the duality of the model with the Rogers model [19]. The Bass model is the most common model in the literature that discusses forecasting the diffusion of innovation in alternative fuel technology, primarily electric propulsion in transport [20]. Most of the research, however, concerns the diffusion of this innovative technology on the individual automotive market [21], especially e-vehicles [22–24], or on the commercial market of logistics services [25]. It is noteworthy that, despite the popularity of the topic of clean buses and extensive discussions on energy reduction in the scientific literature, the simulation of saturation of ZEBs in public transport bus fleets in the EU member countries has not yet been much presented and described.

Considering the above, the purpose of this article is to make an attempt to simulate the number of ZEBs in EU member countries in two time horizons: 2025 and 2030, and to forecast the number of clean vehicles in the precise time horizons, including before and after 2050. On the basis of the simulation, the year in which the selected countries will reach 95% saturation of their public transport fleets with ZEBs will be indicated.

The research questions posed in the article, to which the authors seek to find answers, are as follows:

Q1: What will be the number of zero-emission buses in individual EU countries over the next few years?

Q2: Which of the EU countries will reach by 2030 the level of 95% share of ZEBs in all buses, which are a fleet of public transport buses?

Q3: In which year which will EU countries reach the level of 95% share of ZEBs in all buses, which are a fleet of public transport buses?

2. Materials and Methods

The use of the Bass model to predict the development of new technologies is a common approach. Especially in areas related to new technological solutions in the field of energy. The practical use of diffusion models for prediction has nearly 40 years of history. In 1980, the U.S. Department of Energy used the Bass model to evaluate the adoption of solar batteries and delayed the technology's introduction to the market [26]. In December 2019, this method was also used to evaluate the lighting market (LED and other technology) [27]. The report [28] indicates effective methods of predicting the development of new technologies at various stages of innovation development (introduction, increase acceptance of new technology, mature technology). Diffusion models are the only one effective method at each of these stages. In addition, other diffusion models can be mentioned: the Fourt and Woodlock model, Mansfield model, Blackam Model, Fisher and Pry model, Kalish model, and many others (a list of diffusion models can be found, among others, in [29]; in most cases, these are various extensions of the Bass model).

The model application in practice remains an open issue and different forecasters use different approaches. The Bass model parameters can be obtained on the basis of questionnaire research, historical analogies from similar technologies, and fitting the model to the data. Each of the approaches has its advantages and disadvantages [27]. The article uses the approach of fitting the model to data on the initial development of technology. There are also many approaches for the technical aspects of modeling. For example, the method of estimating parameters based on the data can be performed with one of the following methods: ordinary least squares (OLS), maximum likelihood estimation (MLE), nonlinear least squares estimation (NLS), or algebraic estimation. Mahajan et al. [30] show that the best way to estimate parameters is NLS. However, more recent research shows that the best least squares estimate for the Bass model does not necessarily exist [31]. The main inconvenience with the Bass model, encountered in this article, is a very significant change in the shape of the Bass curve along with the extension of the observations number [32].

In order to better illustrate the proceedings taken by the authors, the sequence of individual stages is presented below (Figure 1).

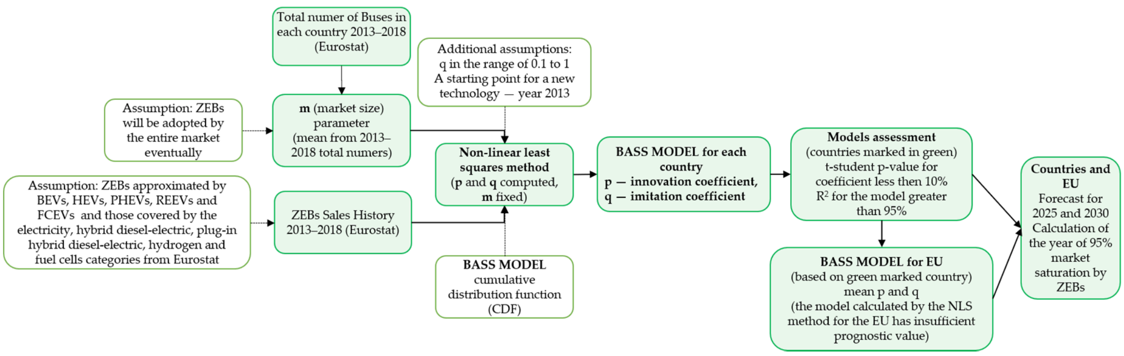

Figure 1. Subsequent stages of the proceedings [own study]. ZEB, zero-emission bus; NLS, nonlinear least square; BEV, battery electric vehicle; HEV, hybrid electric vehicle; PHEV, plug-in HEV; REEV, range-extended EV; FCEV, fuel cell EV.

To analyze the development of ZEBs, data from the Eurostat associated with type of motor energy were used. Among the available groups are the following: Petroleum products, Liquefied petroleum gases (LPG), Diesel, Electricity, Alternative Energy, Diesel (excluding hybrids), Hybrid diesel-electric, Plug-in hybrid diesel-electric, Hydrogen and fuel cells, Compressed natural gas (CNG), Liquefied natural gas (LNG), and Other. The method of data collection was established in 2013. Previous statistics only included Petroleum products and Diesel (until 2013). It should be noted that, currently, there are even more vehicle types available in various reports on Eurostat compared with those listed in the statistics. The "Electric vehicles in Europe" report highlights the following [33]:

- Battery electric vehicles (BEVs)—powered by an electric motor and battery with plug-in charging;
- Hybrid electric vehicles (HEVs)—combine a conventional (petrol/diesel) engine and a small electric motor/battery charged via regenerative braking or the engine;
- Plug-in hybrid electric vehicles (PHEVs)—a conventional (petrol/diesel) engine complemented with an electric motor/battery with plug-in charging;
- Range-extended electric vehicles (REEVs)—powered by an electric motor and plug-in battery, with an auxiliary combustion engine used only to supplement battery charging;
- Fuel cell electric vehicles (FCEVs)—use a fuel cell to create on-board electricity, generally using compressed hydrogen and oxygen from the air.

A combination of vehicles from the electricity, hybrid diesel-electric, plug-in hybrid diesel-electric, hydrogen, and fuel cells categories was selected for analysis, which approximate BEVs, HEVs, PHEVs, REEVs, and FCEVs as best as possible, while the REEVs group is not formally indicated.

Unfortunately, Eurostat guidelines on Passenger Mobility Statistics released in 2018 [34] define groups differing from those shown above:

- Petrol;
- Diesel;
- Petrol-electric, covers both non off-vehicle-chargeable hybrid electric vehicle ("Hybrid electric vehicle") and off-vehicle-chargeable hybrid electric vehicle ("Plug-in hybrid electric vehicle");
- Diesel-electric, covers both non off-vehicle-chargeable hybrid electric vehicle ("Hybrid electric vehicle") and off-vehicle-chargeable hybrid electric vehicle ("Plug-in hybrid electric vehicle");
- Electric vehicle (EV), covers pure electric vehicle ("Battery electric vehicle");
- Other, covers bi-fuel petrol/LPG, bi-fuel petrol/CNG, LPG, CNG, flex-fuel, and other fuels than those previously listed.

The categorization is inconsistent with those in the statistics and is not in line with subsequent studies on electric vehicles (for example, the statistics do not include the petrol electric group). In addition, the scope of the alternative energy group, which appears in the statistics, is unfortunately not explained in the document at all. Furthermore, in 2017, the European commission issued the document "Alternative Fuels (Expert group report)" [35], which defines this type of fuel. According to the document, alternative fuels include the following groups: Methane-based fuels (CNG, LNG, bio-methane, E-gas), LPG (propane- and butane-based fuels, BioLPG), Alcohols, Ethers and esters (ethanol, butanol, methanol, MTBE, ETBE, DME, BioDME, FAE), and Synthetic paraffinic and aromatic fuel (GTL, HVO, BTL, SIP, ATJ, CH, SAK). The aforementioned categorization raises doubts about the LPG, LNG, and CNG gas groups included in the statistics, as well as hydrogen cells, which are also sometimes recognized as alternative energy sources.

As part of the data analysis, a number of tests were performed. In most of the countries represented in Eurostat, the sums for individual groups and the total number of buses were not coherent (even after considering that Diesel is available in different variants). Apparently, the numbers distinguished by Eurostat must be included in several groups at the same time.

For the forecast, it was decided to take the number of buses in a given country, not the number of new registrations. Formally, the Bass model in the basic version does not include the replacement of technology. Regular buses (powered conventionally) have a relatively long life cycle. For example, in Poland, there are about 100,000 diesel buses and about 5000 new diesel vehicle registrations per year, which means about 20 years of their life cycle. However, the data show that the life cycle of electric vehicles is extremely short, as for buses (see Table 1). Estonia in 2013 had 91 electric buses, while that number in 2018 is only 1. Similarly, Bulgaria bought 150 buses in 2014, but only 96 came to market, which means that 54 were withdrawn; then, in 2015, 47 were newly registered and 70 were withdrawn. To maintain the number of buses from 2015, one would have to buy as many as 103 buses. This means that the life cycle of these vehicles varies somewhere between 5 and 0 years, or there are other unknown reasons for their withdrawal. Therefore, the data showing the number of buses in a given country are more suitable for estimating the parameters of the Bass model [11,17].

Table 1. The comparison of data on new registrations and numbers of electric buses on the example of Bulgaria and Estonia [Source: https://www.eea.europa.eu/data-and-maps/indicators/proportion-of-vehicle-fleet-meeting-4/assessment-4].

Bulgaria	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
New registrations	20	150	47	0	:	14
Total number	467	563	540	437	390	376
Estonia	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
New registrations	0	0	0	0	0	0
Total number	91	88	75	63	58	1

Table 2 summarizes the results for ZEBs based on the data available from Eurostat. The order of the countries with the source data from Eurostat has been preserved. Not all of the presented data are suitable for further analysis, therefore, a preliminary evaluation was carried out. The countries that do not have enough data (data not available) in most data fields (NA marked) are excluded; numbers 1,2,3,4 in Table 2 define which data are missing.

In addition, the trend of collected data was also examined. Linear regression was performed for each country. When the slope was negative, it was assumed that the trend is decreasing; the country was marked with the symbol DT and the data were excluded from further analysis. The reason for that is the assumption of growing sales, which is very important in the Bass model, especially at the beginning of innovation development. In the case of a decreasing trend, the Bass curve fit has very poor estimators. In addition, for these countries, more buses are being decommissioned than registered, which does not indicate the development of technology. Countries where data for analysis were missing or where there was a downward trend were marked in gray in Table 2. Data for 2015, 2016 for Poland and 2015 for Macedonia are gross errors (marked in red); they stand out far above the neighboring trend. It looks like the Hybrid diesel-electric fields were mistakenly copied from the Other field (both values were checked to be identical). Additionally, the values in the Other field are consistent with the others. After taking into account the amendments, the corrected data are placed in brackets; Table 2 (Poland in 2015—504 buses and in 2016—526 buses, Macedonia in 2015—1 bus).

The forecasts presented in the article were obtained using the Bass model, usually defined by the following differential equation [17]:

$$f(t) = \frac{dF(t)}{dt} = \left(p + \frac{q}{m}F(t)\right)(m - F(t)), \quad (1)$$

where

$F(t)$—the total number of new technology users by time t (numbers of ZEBs in the market),
$f(t)$—number of users of new technology that adopt at time t,
m—the total number of technology users (total number of buses, see Table 1),
p—the innovation coefficient,
q—the imitation coefficient (for details, see [11]).

Table 2. Motor coaches, buses, and trolley buses, by four types of motor energy (electricity, hybrid diesel-electric, plug-in hybrid diesel-electric, and hydrogen and fuel cells) [Source: own study based on data retrieved from Eurostat].

Country	2013	2014	2015	2016	2017	2018
Belgium	59 [34]	63 [34]	7 [134]	201 [34]	213 [34]	366 [34]
Bulgaria [DT]	467 [234]	563 [234]	540 [234]	437 [234]	390 [234]	376 [234]
Czech Republic [NA]	559 [234]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]
Denmark	0 [2]	0 [2]	5 [2]	7 [2]	6 [2]	8 [2]
Germany	99 [234]	116 [234]	137 [234]	168 [234]	183 [234]	228 [234]
Estonia	91 [34]	88 [34]	99 [34]	87 [34]	102 [34]	45 [34]
Ireland [NA]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]
Greece [NA]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]
Spain	: [1234]	112	152	274	463	701
France	567 [34]	638 [34]	1103 [34]	1682 [34]	1952 [34]	2300 [34]
Croatia	: [1234]	: [1234]	2 [234]	3 [234]	3 [234]	3 [234]
Italy [DT]	495 [34]	488 [34]	494 [34]	463 [34]	: [1234]	488 [34]
Cyprus [NA]	0	0	1	0	0	0
Latvia	0 [1]	257	269	290	255	258
Lithuania [DT]	457 [234]	434 [234]	431 [234]	408 [234]	424 [234]	438 [234]
Luxembourg	4 [234]	2 [234]	48 [34]	59 [34]	7 [234]	33 [234]
Hungary	2	3	6	25	25	24
Malta [DT]	5 [134]	5 [3]	5 [3]	0	5 [3]	: [1234]
Netherlands [NA]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]
Austria	143 [34]	141 [34]	150	154	146	158
Poland	: [1234]	458 [23]	3616 (504) [3]	3636 (526) [3]	581 [23]	803 [3]
Portugal	8 [234]	15	14	17	19	46
Romania	1 [234]	2 [234]	4 [234]	4 [234]	4 [234]	15 [34]
Slovenia	: [1234]	2 [234]	2 [234]	4 [234]	3 [234]	4 [234]
Slovakia [NA]	250 [234]	: [1234]	: [1234]	: [1234]	: [1234]	: [1234]
Finland	2 [13]	7	8	16	24	24
Sweden	50 [34]	56 [34]	73	89	108	151
United Kingdom	: [1234]	: [1234]	194 [4]	261 [4]	305 [234]	511 [23]
Liechtenstein	2	2	2	2	2 [3]	2 [3]
Norway	: [1234]	9 [234]	11 [234]	37	67	167
Switzerland	100	100 [3]	0 [3]	100	100 [3]	200 [3]
Macedonia [6,DT]	3 [234]	2 [234]	2963 (1) [34]	: [1234]	: [1234]	: [1234]
Turkey	0 [234]	1 [234]	12 [234]	24 [234]	57	74
Kosovo [5,NA]	: [1234]	: [1234]	: [1234]	: [1234]	0 [23]	0

Data with gross errors identified; [1] Electricity data not available; [2] Hybrid diesel-electric data not available; [3] Plug-in hybrid diesel-electric data not available; [4] Hydrogen and fuel cells data not available; [5] Kosovo (under United Nations Security Council Resolution 1244/99); [6] North Macedonia; [DT] Decreasing trend; [NA] Insufficient data to build the model.

The analytical solution of the Bass model (1) is as follows:

$$f(t) = m\frac{(p+q)^2}{p}\frac{e^{-(p+q)t}}{\left(1+\frac{q}{p}e^{-(p+q)t}\right)^2}. \tag{2}$$

Usually, (2) corresponds to the probability density function (PDF), which represents how many new technology users have arrived in a given time. Thus, in this study, $f(t)$ would correspond to the changing of the number of buses/the changing number in one year to another (the number of new registrations minus the number of withdrawn buses). Because the data are represented differently, for research purposes, the cumulative number of ZEBs was used. The cumulative distribution function (CDF) for $f(t)$ has the following form:

$$F(t) = m\frac{1-e^{-(p+q)t}}{1+\frac{q}{p}e^{-(p+q)t}}. \tag{3}$$

Nonlinear least square (NLS) method was used to estimate the parameters p and q of the Bass model for individual countries. Parameter m was fixed arbitrarily on the basis of the average total number of buses in 2013–2018. This is justified because this value remains almost at the same level for each country. This also rests on the assumption that, at some point in time, the entire bus market will be taken by ZEBs. In addition, it was specified that the parameter q should be in the range of 0.1 to 1. In the absence of this limitation, the imitation coefficient for some models was very close to zero. In this case, it would mean that there is no natural diffusion of innovation, which is a requirement of market development. On the basis of previous studies [11,26,36–39], the coefficient q for vehicles using clean energy was usually greater than 0.3. Therefore, setting the limit at 0.1 does not constitute a significant interference in the parameterization of the model. The estimation results of the Bass model parameters are summarized in Table 3. Table 3 includes estimates, standard errors, t-test statistics, and p-values for each parameter, as well as the coefficient of determination R^2 for each country model.

Table 3. Estimation of Bass model parameters for EU countries [Source: own study based on data retrieved from Eurostat].

Country	Parameter	Estimate	Standard Error	*T*-Statistic	*p*-Value	R^2
Belgium	p	0.000885394	0.000565631	1.565322522	0.192561721	0948650663
	q	0.410295825	0.172394185	2.379986445	0.075990387	
Denmark	p	0.0000771299	0.000045924	1.679509668	0.168351712	0.926736146
	q	0.100003852	0.212953914	0.469603257	0.663094394	
Germany	p	0.000396186	0.000204596	1.936428221	0.124888934	0.943931675
	q	0.1	0.184882586	0.540883823	0.617301126	
Estonia	p	0.002887886	0.004669849	0.618411127	0.56977991	0.633401476
	q	0.1	0.583379797	0.171414918	0.872219773	
Spain	p	0.000457022	0.0000644608	7.089928856	0.002089651	0.99731596
	q	0.401918954	0.038185946	10.52531079	0.000460806	
France	p	0.003082591	0.000640235	4.814783299	0.008555448	0.990588119
	q	0.1	0.074974179	1.333792525	0.253150892	
Croatia	p	0.0000807419	0.0000502966	1.605314643	0.183695642	0.920360181
	q	0.100009858	0.222797329	0.448882661	0.676761267	
Latvia	p	0.009131224	0.008486617	1.075955683	0.34251624	0.842631191
	q	0.1	0.34176469	0.292598981	0.78437893	
Luxembourg	p	0.002770994	0.004986776	0.555668447	0.608049994	0.582779443
	q	0.100000027	0.649018282	0.154078906	0.885008825	
Hungary	p	0.000181564	0.000113826	1.595099572	0.185919392	0.919813533
	q	0.10466556	0.223167127	0.469000794	0.663489577	
Austria	p	0.002718866	0.002978315	0.91288739	0.412946675	0.790341288
	q	0.1	0.394989813	0.253171086	0.812615238	
Poland	p	0.00091753	0.000469269	1.955231138	0.122221307	0.945055774
	q	0.1	0.183399162	0.545258763	0.614554536	
Portugal	p	0.000171208	0.000111008	1.542300231	0.197864381	0.933889305
	q	0.293996079	0.191424236	1.535835201	0.199380212	
Romania	p	0.00000303032	0.00000320946	0.944183717	0.398537742	0.934794737
	q	0.709422062	0.238694759	2.972088974	0.041059215	
Slovenia	p	0.000206534	0.000116033	1.779960219	0.14969122	0.93427419
	q	0.100016751	0.201013473	0.497562423	0.644902165	
Finland	p	0.00017463	0.000050292	3.47231985	0.02552966	0.982203041
	q	0.118605229	0.100991957	1.174402713	0.305378156	
Sweden	p	0.001315502	0.000452593	2.906593192	0.043827409	0.974409779
	q	0.1	0.123521821	0.809573557	0.463593199	
United Kingdom	p	0.000169943	0.0000722559	2.351959527	0.078347481	0.972186036
	q	0.326811667	0.122009779	2.678569456	0.055310761	
Liechtenstein	p	0.003518262	0.004142058	0.849399656	0.44350691	0.765882685
	q	0.100000655	0.425556385	0.234988027	0.825757503	
Norway	p	0.0000590045	0.0000141281	4.176397302	0.013958849	0.99743895
	q	0.829605613	0.051582606	16.0830496	0.0000874111	
Switzerland	p	0.001742495	0.001962474	0.887907319	0.424757571	0.796458861
	q	0.177589975	0.373654193	0.475278957	0.659377964	
Turkey	p	0.00000330122	0.00000142233	2.320995094	0.081048171	0.979453761
	q	0.480497008	0.109960075	4.36974062	0.011970507	

Countries marked in gray have very bad parameter estimators. It has been assumed that the criterion for such countries would be the coefficient of determination R^2 below 0.9 (determining the quality of model fit). Bad fit of the model to the data can also be recognized. The parameter q set itself at the boundary of the range; that is, it adopted the lowest possible value of 0.1, which is accompanied by a high standard error value for this parameter. The green color indicates countries with a relatively high quality matching of p and q parameters (p-value less than 10%). Spain, the United Kingdom, Norway, and Turkey, are the countries for which forecasts are most likely, and detailed results are presented in the Results chapter.

The forecast for the entire EU was made on the basis of the analysis of the p and q coefficient and its arbitrary selection based on the average. This approach was dictated by the poor fit of the model to the data for the entire EU (see Table 4). Two models were presented where the market size m was calculated automatically. Unfortunately, the values are very low in relation to $m = 1.6 \times 10^6$ for the entire Union. In addition, the best p-value for the imitation coefficient that was obtained is at the level of 63%, which practically cancels any possibility of forecast based on those models.

Table 4. Estimation of Bass model parameters for EU [Source: own study based on data retrieved from Eurostat].

Model Type	Parameter	Estimate	Standard Error	*t*-Statistic	*p*-Value	R^2
EU	m	7508.84	6356.48	1.18129	0.322606	0.980254
	p	0.338689	0.19937	1.69879	0.187921	
	q	0.0001	1.44641	0.000069137	0.999949	
EU fixed m	p	0.000614179	0.000333394	1.8422	0.139242	0.938461
	q	0.1	0.19447	0.514219	0.634204	
EU fixed p	m	611100	260598	2.34499	0.0789462	0.958096
	q	0.0001	0.172262	0.000580512	0.999565	

3. Results

Resulting from the analysis, the following answers to research questions were proposed:

A1 (Q1): According to the methodology, the analysis is feasible in four countries, that is, Spain, the United Kingdom, Norway, and Turkey. In 2025, there will be 10,761 ZEBs in Spain, 5530 in the United Kingdom, 12,658 in Norway, and 2373 in Turkey. However, in 2030, the number of zero-emission buses in the same countries will increase significantly and will amount to 37,854 for Spain, 25,056 for the United Kingdom, 16,267 for Norway, and 25,372 for Turkey.

A2 (Q2): With this predicted number of clean buses, it seems that only Norway will be able to reach 95% level of ZEBs share in all buses possessed by this country.

A3 (Q3): On the basis of analyses conducted, the majority of EU members will have a 95% share of ZEBs in a fleet consisting of all types of buses after 2050. Detailed data are presented in the Table 5 with the forecast of the ZEBs' share in the market in the EU countries in 2025 and 2030. Figure 2 presents the geographical distribution of the results.

Table 5 provides a forecast of the share of ZEBs in the market in 2025 and 2030 for all European countries for which data were available. In addition, it presents in which year the number of buses in this category will constitute 95% of all buses (m). Out of the concern about the quality of the model, the results are marked with different colors. Countries with poor fit parameters are marked in gray, while those in which the quality of the model fits the data very well are shown in green (details described in the Materials and Methods chapter). The presented results are negatively affected by the following factors: short reporting period, data quality, and the issue of technology definitions that are inconsistently interpreted by different countries.

Table 5. Development forecast for the electricity, hybrid diesel-electric, plug-in hybrid diesel-electric, and hydrogen and fuel cells bus market [own study based on data retrieved from Eurostat].

Country	E-Bus Market				Year 95% of *m*	Number of Buses
	2025 Total	2025 %	2030 Total	2030 %		
Belgium	4965	30.99%	12,479	77.90%	2034	16,019
Denmark	27	0.20%	51	0.38%	2113	13,353
Germany	824	1.05%	1548	1.97%	2096	78,591
Estonia	354	7.30%	635	13.10%	2075	4847
Spain	10,761	17.44%	37,854	61.34%	2036	61,712
France	7674	7.77%	13,711	13.89%	2074	98,701
Croatia	11	0.21%	21	0.39%	2112	5365
Latvia	1046	20.75%	1709	33.90%	2061	5041
Luxembourg	132	7.01%	237	12.59%	2075	1883
Hungary	91	0.50%	176	0.96%	2100	18,324
Austria	674	6.89%	1213	12.41%	2076	9776
Poland	2724	2.41%	5062	4.47%	2087	113,175
Portugal	369	2.53%	1506	10.35%	2047	14,557
Romania	1971	4.14%	28,545	60.02%	2033	47,563
Slovenia	14	0.53%	27	1.02%	2103	2658
Finland	92	0.54%	185	1.08%	2091	17,087
Sweden	484	3.43%	892	6.31%	2083	14,126
United Kingdom	5530	3.47%	25,056	15.72%	2044	159,404
Liechtenstein	8	8.00%	15	15.00%	2073	100
Norway	12,658	77.46%	16,267	99.54%	2027	16,342
Switzerland	788	8.28%	1813	19.05%	2054	9516
Turkey	2373	0.35%	25,372	3.77%	2042	672,885

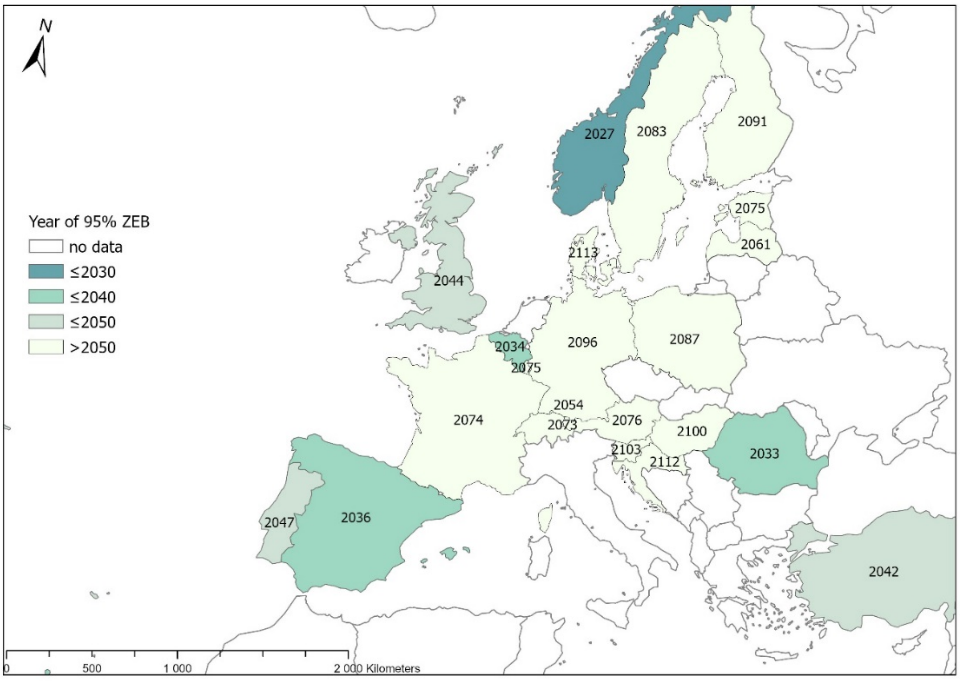

Figure 2. Geographical distribution of the year when countries reach the 95% of ZEBs in their fleets [own study].

The analysis traced the situation of 22 EU countries (Table 5). The detailed analysis of the data showed that only four countries out of all the countries considered show activity related to the replacement of their bus fleet with electric ones. The reasons for this endeavor can be twofold. Either it results from a high level of environmental awareness of the mentioned countries, such as Norway, or it testifies to the countries' high commitment and efficiency in obtaining EU subsidies. The lack of reliable data, including consistent historical sequences for 2013–2018, in the case of the remaining countries may indicate a low level of their activity in this area.

Table 5 contains columns presenting the market share for 2025 and 2030 calculated on the basis of the Bass model. The percentage values are related to the total market share (m). The number of buses in individual countries was estimated based on the average number of all buses in a given country for 2013–2018. Additionally, the year in which market penetration by new bus generations will reach the level of 95% is indicated. The 95% level was chosen arbitrarily and results from the slow growth of the S-shaped Bass curve at the end of a given technology development.

Figure 3 presents a histogram, based on the calculations. It indicates the years when traditional buses should be replaced by buses using electricity, hybrid diesel-electric, plug-in hybrid diesel-electric, and hydrogen or fuel cells.

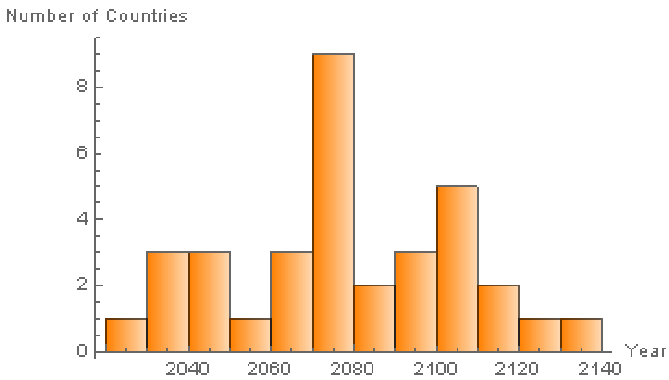

Figure 3. Histogram of years of 95% market adaptation by ZEBs (all EU countries included) [own study].

It should be noted that all European countries were considered in Figure 3 regardless of the quality of the model. The chart shows that the average adaptation to the market should take place around 2077 (average), with a standard deviation of about 28 years. In addition, the above histogram shows compliance with the normal distribution based on the Kolomogorov–Smirnov test, with p-value 2.23745×10^{-7} and statistic 0.473591; however, the Shapiro–Wilk test gives statistic 0.973548 and p-value 0.56575.

In the case of countries for which the coefficient of determination R^2 was higher than 0.9 (see Table 3), the histogram is presented in Figure 4.

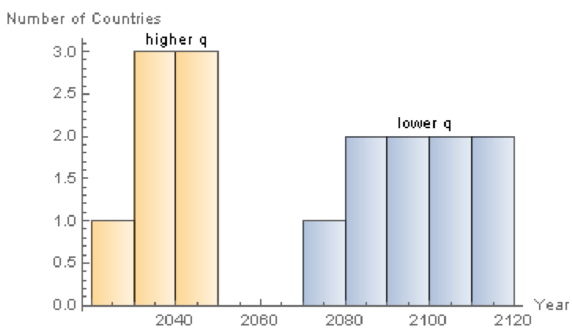

Figure 4. Histogram of years of 95% market adaptation by ZEBs (country with $R^2 > 0.9$ included) [own study].

The countries were divided into two groups with a higher and lower imitation coefficient. A higher imitation factor $q > 0.3$ means that countries are adopting the new technology relatively quickly. Countries classified in this area include Belgium, Spain, Portugal, Romania, the United Kingdom, Norway, and Turkey, with the average of full adaptation in 2038 and a standard deviation of about 7 years. In contrast, the second group with a lower q usually close to 0.1 constitutes the following countries: Denmark, Germany, France, Croatia, Hungary, Poland, Slovenia, Finland, and Sweden, with the average of around 2095 and a 13-year standard deviation. However, statistics for parameters in these countries give a low level of confidence for calculations of the Bass model variables. The forecast was based on available data. The country in which the forecast indicates a very distant time of market acceptance has considerable uncertainty in estimating this year of adjustment. This is partly owing to the fact that countries have not shown significant activities in this area. It should be noted that, if a given country has already begun investment in a given technology and the process of diffusion of innovation, then adjustment could take place quite quickly. With the data we have, there is no basis to assess what will happen in a given country if it changes its policy and makes significant investments in ZEBs (for a more detailed comment, see the Materials and Methods section).

The most reliable results were obtained for countries marked in green (Table 5). They have the best parameter estimators and a very good model fit factor. In Spain, the United Kingdom, Norway, and Turkey, the average saturation of the market with zero-emission buses should occur around 2037. The process of technology adaptation calculated from the Bass model is presented in Figure 5. The vertical axis presents market adoption expressed as a percentage and the horizontal axis represents time in years. The cumulated number of buses for selected countries allows for the assessment of innovation diffusion. For example, on the basis of Figure 4, in 2030 in Norway, the percentage saturation of ZEBs in the total bus transport fleet will reach around 50%.

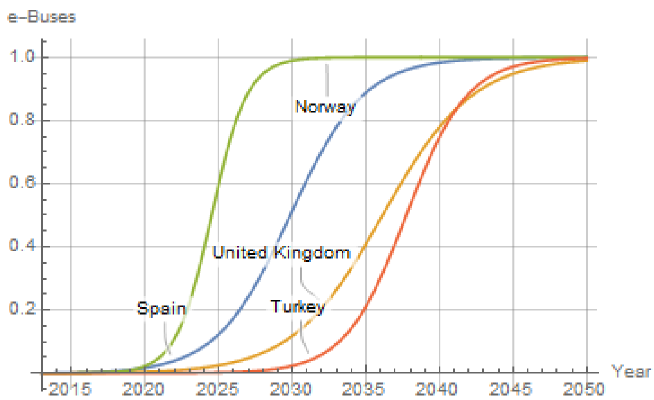

Figure 5. The cumulative Bass curves for Spain, the United Kingdom, Norway, and Turkey [own study].

The development forecast for the entire European Union was made in two versions (Figure 6). The first optimistic variant assumes a high imitation factor. Parameters of the Bass model were calculated on the basis of the average for the best four models, that is, Spain, Norway, the United Kingdom, and Turkey (p = 0.000173, q = 0.5195). The pessimistic variant was created on the basis of average parameter values for all countries from Table 5 (p = 0.001407, q = 0.2178). The above approach results from the fact that an attempt to compile data for all EU countries gave a model with unsatisfactory estimators (please see details in Materials and Methods).

It has to be stated that the predicted number of buses could be estimated only for the chosen EU members. This is owing to the lack of a uniform definition of zero-emission vehicles. An additional factor causing calculation difficulties was errors in Eurostat statistics. In addition, there were gaps in the data collected for individual countries. Thus, the authors could only conduct the correct simulation for four countries: Spain, Great Britain, Norway, and Turkey, as shown in Table 5.

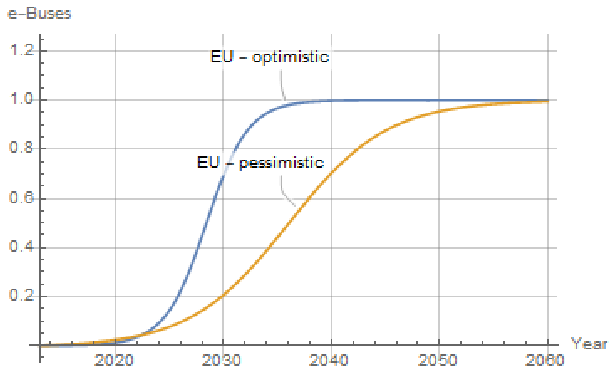

Figure 6. The cumulative Bass curves for Spain, the United Kingdom, Norway, and Turkey [own study].

4. Discussion

A discussion should first refer to the existing research on similar issues, using the same methodology. Although an in-depth review of the literature in the Scopus, Web of Science, and EBSCO databases has not brought the expected results, a number of similar topics were raised within scientific publications. However, it is worth emphasizing that no description of studies alike using the Bass model to describe the diffusion of innovation understood as an increase in the number of ZEBs in the total bus fleet of a given city has been identified. Therefore, the research was conducted in a similar thematic scope, although with the use of different tool or with the same tool, but referring to other issues.

In the study from 2018 conducted by Ma and Zhang [40], the Bass model was used to optimize and predict the number of charging stations for electric vehicles. In order to solve this issue, the researchers used the exhaustion method, regarding minimum cost as the objective function. To finish up their work, they tested the given model using data from a particular Chinese city.

Akbari, Brenna, and Longo [41] adopted similar assumptions when using the Bass model. The authors focused on Milan, Italy. The main purpose of using the model was to calculate how many electric vehicles (EV) will be in 2024, and thus will need charging stations. In further analyses, the aim was to indicate the optimal location of the stations so as to meet the demand generated by customers on the one hand, and on the other hand, to minimize the costs of vehicle charging and management.

What appears to be complementary in the presented approach is the reference of the optimal number of charging stations for electric vehicles to the public transport infrastructure. Thus, the subject of city management in the context of creating optimal urban spaces and the optimal use of ZEBs would find a wider application. A similar objection regarding the narrow approach to the subject of electric vehicles can be formulated against the authors of this article. Taking into account the holistic approach to electric vehicles in cities, it seems to be an interesting research direction.

Rogge, van der Hurk, Larsen, and Sauer [42] also looked at the problem of electric vehicles in an interesting way. Similarly to the authors of this article, they analysed public transport in the context of developing the most optimal saturation of the city transport fleet with electric buses. What was different about their approach was that they did not assume that the fleet should be fully electrified, but rather that the fleet should have different proportions of both electric and conventionally powered vehicles. Undoubtedly, this is a beneficial direction for further research with high potential.

The results of the 2018 research by Mohamed, Ferguson, and Kanaroglou [43] may provide some kind of valuable inspiration for the authors to carry out in-depth EU country-by-country analyses. This study identified factors that hinder the implementation of the electric bus in the public transit context as seen from the perspective of Canadian-based service providers.

With regard to modelling the market share of a specific group of electric vehicles, such as the zero-emission buses described in the article, it should be emphasized that there is a clear inconsistency between the actual market share of ZEBs and the feasibility models. This inconsistency shows a clear gap between the theoretical evidence for the positive environmental impact of ZEBs as well as the benefits from electric buses in the public transport fleet, and its practical application. While some argue that a lack of political support, technological immaturity, and inertia to change are key factors contributing to low participation, others attribute this situation to the sensitivity of technical-economic models related to the operational context. This sensitivity is common ground for all evaluation models of electric buses [44–46]. As a result, this sensitivity increases the uncertainty about the operational benefits of the electric bus in the context of the network, thus limiting market share.

The adoption of the electric bus globally is geographically uneven and limited in scale [47]. Predictions for the development of the ZEB fleet are quite difficult, as replacing the fleet with an electric one faces many obstacles. These obstacles can primarily be divided into two groups dependent on each other. It is a matter of available technologies that affect bus electricity demand and both initial and operational costs that affect the economic efficiency of investment in these solutions. Polish geographers identified the main factors and mechanisms behind the development of low-emission public transport vehicles in Polish cities. They included energy challenges, environmental requirements, governance strategies, and manufacturing capacities [48].

One issue is the high upfront cost of zero-emission buses. The huge costs associated with the investment, both the purchase of a new fleet and the appropriate infrastructure, cause a number of considerations about this technology, as well as its ecological, economic, and organizational effectiveness [49]. A few studies have analyzed the contracting and financing mechanisms that can help accelerate electric bus adoption [47]. The justification for using public funds when purchasing battery electric vehicles is the anticipated reduction of CO_2 emissions [50,51]. Using the Bass model, Brito and others investigated how governmental incentives can influence the diffusion of low emission technology in individual transport decisions. They were able to demonstrate how, for example, tax regulations can affect the increase in the adoption of zero-emission (to be precise, electric) technologies by the individual customer market [21]. There are also several other studies of the impact of the economic and social policy on the development of electric technologies in transport based on technology diffusion models [52].

Therefore, one of the most important discussions in the literature on clean buses is the issue of their real impact on reducing greenhouse gases. The environmental benefits of ZEB in cities should be calculated and assessed from two points of view: emissivity and operational harmfulness as well as emissivity, harmful to the environment at the time of energy production. Ultimately, however, the environmental benefits of ZEB will really depend on what sources electricity is obtained from in the country or city. Some research papers propose the application of a life cycle assessment (LCA) [46,53,54], or through a combination of LCA with an economic analysis [55], or through a cost–benefit analysis [56,57]. The methods adopted to evaluate the transport impact of CO_2 emissions are rather heterogenic, including different phases of the fuel production and the emission phase. Cavallaro et al. [50] propose a well-to-wheel analysis, including the well-to-tank and tank-to-wheel phases, while Topal and Nakir [58] propose a total cost of ownership calculation model. Total cost of ownership from well-to-wheel has been proposed for the three groups of transportation, namely diesel, CNG (compressed natural gas), and electric buses. The analysis showed that the total costs of ownership for electric buses is greater than for those with diesel and hybrid engines. Nonetheless, the authors conclude that high initial costs and amortization points in electric buses can be caught because of low operating costs. Total costs of ownership are directly influenced by the costs of purchasing technology (buses and necessary infrastructure, that is, charging stations) as well as operating costs.

The total operation costs also depend on several factors. The buses' electricity demand depends on the operating time on one battery charge. Electric buses have a limited driving range and need to be charged during the day [13,59–62], which turns them off for some time. That creates the need for more buses to fulfill the transportation demand than the diesel ones. This goes for battery electric buses and, to a lesser extent, for hydrogen fuel cell buses. Regular diesel buses can drive all day without refueling, while battery electric buses need to recharge after about 200–250 km, depending on circumstances such as the climate and road conditions, and hydrogen fuel cell buses need to refuel after about 200–400 km [63]. This also affects the problem of planning courses. The electric bus scheduling problem requires not only satisfying timetable constraints, but also considering battery range limitation and vehicles recharging plans, including available charging infrastructure [64]. Moreover, for example, May [65] proposed planning bus lines served by ZEB based on local environmental impact assessment. The interdisciplinary approach was applied to evaluate the local environmental relief potential of electric buses in comparison with diesel buses. The issue of timetable planning is connected with the problem of charging station location and charging method solutions [62,66–68].

Bus demand for electricity depends on battery type, driving cycle and style, number of stops, traffic level, elevation profile [69,70], and weather conditions including temperature and humidity [8]. In order to improve the driving style, and thus reduce the bus's energy demand, various technological solutions are proposed, for example, the robotized manual gearbox [56,71,72]. Cost effectiveness also varies depending on the energy storage systems in electric buses [71,73] and the choice of charging technology [74]. Operating costs also depend on the price of the battery and the battery life [75]. Ufert and Bäker [9] propose a model for predicting battery life. According to them, the ability to predict battery life can reduce total operation costs by up to 17%.

In turn, Bakker and Konings [13] argue that the technological barriers for replacing the diesel bus fleet with ZEB are not that great compared with institutional barriers in individual countries and cities. Veeneman [76] also draws attention to the tender processes that must take place when purchasing a bus fleet owing to the fact that the funds involved in the purchase are public. What is important here is the low quality of tenders, which are based on the lowest price, which ultimately leads to the purchase of low quality products and services. There are also some studies addressing the public's willingness to pay for environmental-friendly buses [12,77,78].

Knowing the multidimensionality of issues related to the ecological and economic efficiency of electric buses, it is difficult to predict to what extent the forecast presented in this article will be implemented. This will probably depend on both, the direction of technology development, which will allow reduction of electricity demand and greater operational efficiency and on the funds available for cities in the future. The latest reports from the technology market inform about a new type of battery. Catl, a Chinese car battery-maker, says it is ready to manufacture a product capable of powering a vehicle for 1.2 million miles (two million kilometers) across the course of a 16-year lifespan [79]. For now, this technology is to be used in cars, but it is probably only a matter of time before it will also be used in larger vehicles with a higher energy demand.

The current global coronavirus pandemic problem should also be considered. It seems that the impact of Coronavirus disease 2019 (COVID-19) on financing clean buses in the near future cannot be predicted. According to international experts, despite many barriers and the crisis in the automotive industry, electromobility, including the ZEB sector, is developing dynamically and will continue to develop. This is owing to the fact that its expansion is based on very solid foundations, such as EU, national, and regional legal standards or multi-billion investments by automotive concerns [80].

The obligations arising from the Act on electromobility and alternative fuels in the field of zero-emission collective transport remain unchanged, new tenders are announced, subsequent deliveries are carried out, and leading manufacturers such as Solaris record a dynamic increase in orders (506 contracted ZEBs in 2020 compared with 162 in 2019) [80].

However, the survival of many enterprises often operating in key sectors to promote zero-emission transport, which is directly connected with the ZEB sector's development, depends on the government's rapid and decisive action on both local and international levels.

5. Conclusions

It should be stressed that it is likely that most European countries will not be able to replace the traditional fleet of diesel buses with ZEBs by 2050. The analysis shows that most countries will replace the fleet after 2050, around 2077.

As a result of the study based on available European data, the authors isolated two groups of EU countries. The first group consists of four countries for which the fit of the model is appropriate and these countries seem able to achieve the saturation of their fleet by 95% by 2040. For the remaining countries, owing to insufficient data, the model fit is low and these countries do not seem to be able to replace their bus fleet before 2050.

The fact is that, today, the number of ZEBs in EU urban spaces is rising, despite many technological, organizational, and financial barriers. The future of the bus fleet will depend on which way the technology develops and how it can be financed. The economic situation of countries will also be of great importance, especially in the face of COVID-19, to which extent ecological priorities can be further financed in the face of the need to save national economies.

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