sustainability

Article

Is the Transition to Electric Passenger Cars Sustainable? A Life Cycle Perspective

Mihai Machedon-Pisu * and Paul Nicolae Borza

Department of Electronics and Computers, Transilvania University of Brașov, B-dul Eroilor nr. 29, 500036 Brașov, Romania
* Correspondence: mihai_machedon@unitbv.ro

Abstract: Compared to conventional passenger cars, the hybrid and electric alternatives include electric motors and large batteries; the use of clean energy, reduced operation emissions, and decreasing purchase prices can represent solid reasons for their market adoption. The feasibility of the transition to electric cars is analyzed herein in terms of the costs, main pollutants, and energy consumption of compact to large-sized cars. In this regard, the proposed life cycle assessment methodology evaluates the pollution and energetic impacts of the current passenger car models with a weight varying from 1.6 to 1.8 tons, depending on the car type, for a complete life cycle. The life cycle emissions and energy consumption are also determined through simulation in order to validate the estimated values for the considered powertrains. This study has shown that a transition to current full-electric passenger cars, based on a European and United States energy mix, is not currently sustainable in terms of energy consumption. The complete life cycle values are similar for the tested conventional and full-electric passenger cars, ranging from 5 to 5.2 MJ/km. By comparison, the hybrid alternatives and full-electric cars based solely on renewable energy present lower energy consumption, ranging from 3.32 to 4.62 MJ/km. At the same time, the hybrid alternatives and conventional cars provide relevant benefits in life cycle costs: 20–25% lower than full-electric cars. In terms of life cycle emissions, the tested full-electric cars based on renewables show a noticeable reduction in greenhouse gases and in other relevant pollutants: 37% and 62%, respectively, lower than that of conventional cars.

Keywords: energy consumption; life cycle assessment; sustainable transport systems; emissions

check for updates

Citation: Machedon-Pisu, M.; Borza, P.N. Is the Transition to Electric Passenger Cars Sustainable? A Life Cycle Perspective. *Sustainability* **2023**, *15*, 2614. https://doi.org/10.3390/su15032614

Academic Editors: Pietro Evangelista, David Brčić, Mladen Jardas, Predrag Brlek, Zlatko Sovreski and Ljudevit Krpan

Received: 15 December 2022
Revised: 19 January 2023
Accepted: 26 January 2023
Published: 1 February 2023

1. Introduction

Electric cars have gathered a lot of interest from the automotive industry recently, with implications for both the climate and environment, including the need for scarce resources, as discussed in [1]. In the case of passenger cars, the evolution of the powertrain is relevant, starting from internal combustion engine vehicles (ICEVs) to hybrid vehicles, such as hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), and then to battery (full-) electric vehicles (BEVs). Each type of powertrain requires the improvement of specific components. For example, in the case of electric and hybrid vehicles, energy storage (such as batteries or supercapacitors) or generators (such as fuel cells) are essential for achieving high performance [2]. Fuel cell vehicles (FCVs) are also currently available, but the lack of infrastructure and the high vehicle costs represent serious backdrops. More recently, the development and improvement of autonomous vehicles allowed an increase in their efficiency and safety in operation. These are closely related to the evolution of the structure of transport systems and are extensively treated in [3]. Figure 1 provides an overview of the main aspects related to vehicles: their production and operation.

The inferences between resources, the vehicle production market, vehicle manufacturing, the recycling of materials, and reinsertion into a new production cycle represent the typical circular economy cycle [4]. On other hand, an operation cycle based on raw materials and energy should be emphasized, as should the society means that modulate transport systems. In the proposed methodology the authors consider the two cycles: the production and operation of transport means. The inferences between human activities related to transport and well-known concepts such as a circular economy and sustainability are also presented in Figure 1.

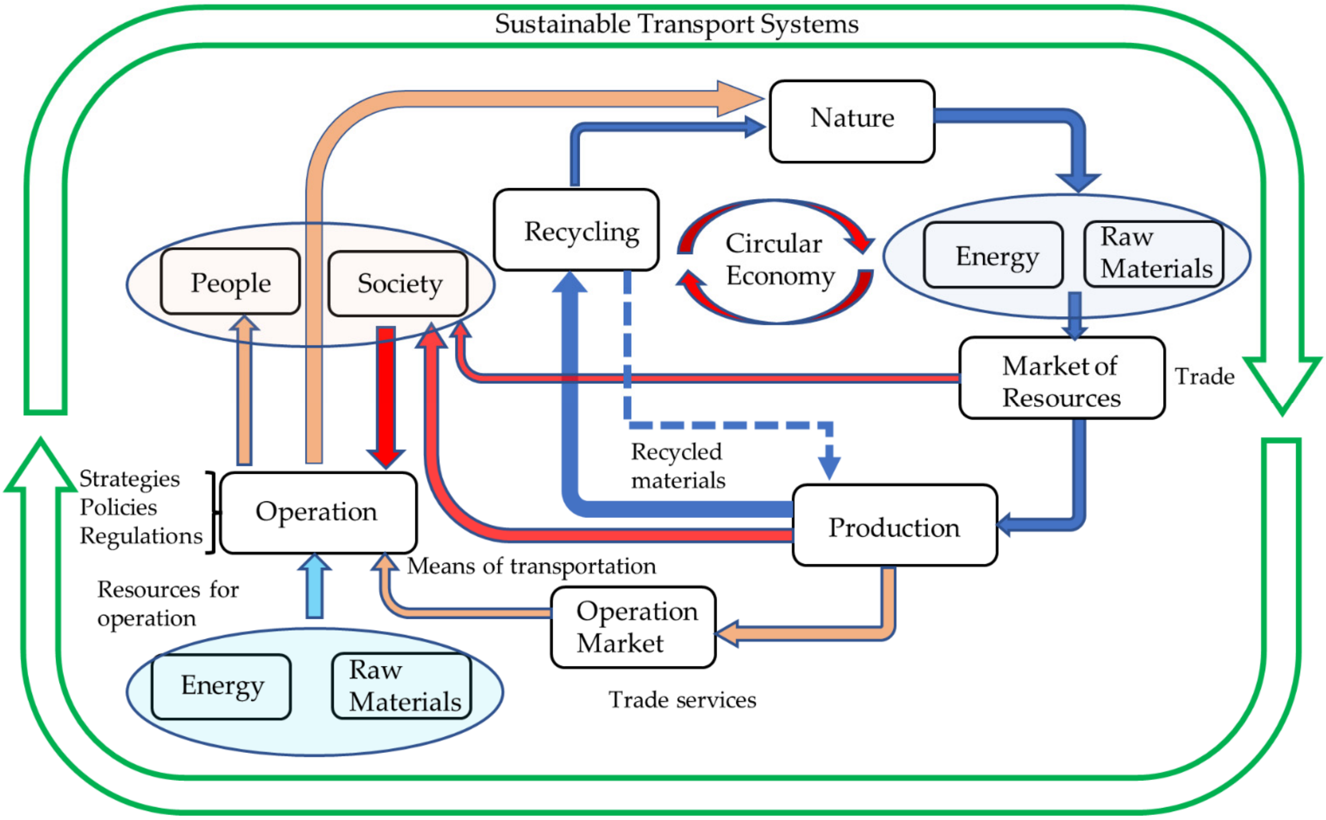

Figure 1. Overview of the main elements that intervene in developing sustainable transport systems.

As two parallel but intercorrelated processes, the transition of transport technologies and the implementation as well as evolution of the clean production of energy must be synchronized in order to maximize energetic efficiency [4]. This should also provide maximum advantages for both nature and our society. Resources, which consist of energy and raw materials, technologies, human resources (economy), society, and the environment, represent the main components of transport activities' sustainability, as highlighted by many frameworks [5–9]. A clear distinction must be made between energy and raw materials as resources. While raw materials are mainly specific to the production of goods and the generation of infrastructure, thus representing limitations in transport, energy has a much greater coverage because its implications must be addressed at every level of a product's life cycle (LC) [10–12]. Yet, both are used for producing elements of infrastructure and vehicles. The life span of these can be between several years and ten (for example, BEVs) or more years (for example, ICEVs and heavy-duty vehicles). This is also the case for the majority of elements of infrastructure [13,14]. The range also differs for various types of vehicles [15].

By means of a life cycle assessment (LCA), it is possible to see to what extent the transition from ICEVs to EVs is sustainable for light-duty vehicles (LDVs), such as passenger cars. As a result of this analysis based on an LCA, which emphasizes not only the environmental (including the use of resources) and energetic impacts but also the socioeconomic impacts of transport means, the sustainability of the transition from conventional to electric passenger cars is under review. The paper is structured as follows: In Section 1, Introduction, the main aspects regarding the development of sustainable terrestrial transport systems, such as passenger cars, in terms of LC are briefly described. In Section 2, a detailed overview of the pollution standards at the levels of the European Union (EU) and United States (US) is portrayed in correlation with the evolution of passenger car emissions in the last 5 to 10 years, as well as the evolution of costs for the main passenger car categories: compact to mid-sized cars (1.3 to 1.5 tons) and large-sized cars (2 to 2.5 tons).

In Section 3, the data for the proposed LCA methodology are analyzed for various powertrains (ICEVs, HEVs, PHEVs, and BEVs based on RES or various energy mixes) and weight categories (compact to mid-sized cars and large-sized cars) in terms of life cycle emissions and energy consumption. These powertrains are simulated in GREET in Section 4 for the predefined models, both for compact cars (with a weight ranging from 1.23 to 1.48 tons) and mid-sized cars (with a weight ranging from 1.41 to 1.68 tons). In this simulation, both the US/EU energy mix and wind RES for BEVs are considered. The same simulation methodology is applied for the test models of current passenger cars, with a weight ranging from 1.6 to 1.8 tons. Section 5, Results and Discussion, offers a comprehensive analysis of the life cycle emissions and energy consumption values obtained by applying the proposed LCA methodology both in concept and in simulation for the powertrains analyzed in the previous sections. In this regard, the separation between vehicle and energy life cycle (LC) is relevant according to the proposed methodology. The results are validated through comparison with relevant studies in terms of LCA methodology and data, emphasizing the main strengths and limitations of the current study. Section 6, Conclusions and Future Work, synthesizes the main findings of the paper and assesses the implications of this analysis.

The paper tries to answer a fundamental question: To what extent is the conversion of transport technologies towards electric vehicles sustainable from the point of view of energy consumption and pollution abatement? These are the main aspects analyzed in the paper. Other aspects, such as the adaptation of infrastructure to the new transport technologies, the necessity to increase electric energy production capacities, and the use of clean production processes, are highlighted but not treated.

2. Overview of Emission Standards in the United States and Europe as Well as Reported Operation Emissions and Costs for the Main Passenger Car Categories

2.1. Motivation

Technologies reflect the ability and knowledge of our society to use resources in an efficient manner. This is closely related to scientific research, production capacities and their degree of development, and also to the "quality", in general, of the exploitation of such transport resources [12,15]. Currently, the Paris Climate Agreement presented a few anti-global warming strategies, among which one of the main refers to a 2 °C stabilization scenario, which should also apply for car emissions. Such a scenario is, however, unlikely to comply with the 2015 levels by 2030, according to [16]. Yet, the net effect of withdrawing from the Agreement can be seen as negative and not justified, as the losses in co-benefits exceed any gain in gross domestic product (GDP). Losses in GDP could refer to carbon pricing systems, especially for key metals. Mining could be made unprofitable for metals such as steel and aluminum, as shown in [17].

Many countries aim to find new strategies with which to cut their dependence on fossil fuels and increase energy efficiency while reducing greenhouse gas (GHG) emissions, associated mainly with CO_2. One such study [18] intends to improve the efficiency of fossil-fueled power plants to 46% alongside the curbing of routine gas flaring by 2030 while cutting GHG emissions by 12% compared to the business-as-usual (BAU) pattern. Such pathways to reduce GHG emissions present a great deal of interest, and their implications for the power sector are of utter importance. Another study [19] shows that, until 2050, the increased penetration of renewables, interconnection capacity, and energy storage, alongside the corresponding power system, are sufficient for staying on the required emissions trajectory imposed by the Paris Agreement. Another solution for a longer term, say 2100, could be based on biomass imports, but at the same time raises questions on energy security. Besides energy security and environmental sustainability, aspects related to socioeconomic equity should also be considered [20]. All in all, energy supply transformation presents a lot of challenges, as the costs for achieving a decarbonized system are far from negligible [16,17].

These pollution aspects are very important since the impact of road transport on human health is relevant especially in terms of particulate matter (PM), ground-level ozone, which refers to nitrogen oxides (NO_x) and volatile organic compounds (VOCs), carbon oxides (CO_x), sulphury oxides (SO_x), and lead (Pb) levels [7]. The effects of these pollutants that result from transport have been thoroughly analyzed in [21–23]. For reducing the impact on health of GHG emissions (mainly associated with CO_2) caused by vehicles, as explained in [24], numerous strategies and policies have been proposed in [25–27].

However, air quality can be improved substantially by using cleaner transport technologies, as long as effective policies are used in conjunction. Such policies must address the economic, social, energy, and resource implications for sustainable transport. For example, simplified in terms of air pollution, GHGs, BEVs, PHEVs, and FCVs are primarily considered in many studies as much cleaner alternatives to ICEVs and HEVs, which are said to pollute more [28]. Such a statement regarding pollution that is only associated with transport activities is inaccurate, since industrial pollution due to battery and electric energy production, use, and disposal is not neglectable. Other issues associated with the range, cost, and resource use of EVs must also be taken into consideration [29].

If, for a long time, society did not take into account the complex effects of the development of transport activities on itself and on the environment in particular, the significant damage and duration of the effects of these activities on the human health have become impossible to neglect, especially due to PM, NO_2, SO_2, and O_3 emissions [30].

2.2. Overview of Emission Standards in the United States and Europe

To limit air pollution, various standards on air quality were proposed by the European Union (EU) and United States (US), examined in [31,32], as well as by the World Health Organization (WHO), examined in [33]. Table 1 compares the limit values between these guidelines. While the EU and US limit values are difficult to compare in terms of health impact, the WHO guidelines are likely to follow, since they are the most restrictive. The pollution caused by human activities is assessed in air quality reports, such as [34].

Table 1. Air quality standards.

Standard For	Averaging Period	Unit	EU [31]	US [31,32]	WHO [33]
$PM_{2.5}$	1 year 24 h	μg/m^3	25 [1] -	12–15 [2,3] 35 [3]	5 [4] 15 [4]
PM_{10}	1 year 24 h	μg/m^3	40 [1] 50 [1]	- 150 [3]	15 [4] 45 [4]
NO_2	1 year 1 h	μg/m^3	40 [1] 200 [1]	103 [3] 195 [3]	10 [4] 25 [4]
CO	1 year 24/8/1 h	mg/m^3	10 [1] -	- 10.65 [3] (8 h) 41.5 [3] (1 h)	10 [4] 4 [4] (24 h)
SO_2	24 h 1 h	μg/m^3	125 [1] 350 [1]	- 203 [3]	40 [4] -
O_3	8 h 1 h	μg/m^3	120 [1] 180 [1]	140 [3] -	100 [4] -

[1] EU standards. [2] Primary and secondary US standards. [3] US standards. [4] WHO standards.

Due to the significant differences between the standard values (see the EU and US vs. WHO in Table 1), the health impact image can be misleading; for example, while only around 6% of EU stations have exceeded the EU standard $PM_{2.5}$ values, more than 77% exceeded the WHO value in 2017. The same can also be said about the premature deaths associated with $PM_{2.5}$. Even if the number has decreased from 456 thousand in 2005 to

337 thousand in EU in 2019 (EU-28), it is unlikely that it will be as low as 205 thousand, which represents the EU target for 2030.

While the contribution to NO_x, PM, VOC, CO, and Pb emissions from the transport sector is appreciable in the EU, as presented in [30,34], the contribution to SO_2 emissions must also be considered, as shown in a US report in [35]. Both the European and US emission standards for vehicles impose limits on PM, NO_x, VOCs, CO, and CO_2 [36]. Table 2 synthesizes these limits for gasoline cars. In EU legislation, passenger cars that do not exceed 2.5 tons represent Category M, while Categories N1 class III and N2 are represented by light commercial vehicles that weigh between 1.76 and 3.5 tons.

Table 2. Emission standards for gasoline cars in the EU and US, in grams per km.

Standard For	EU Category M [36]	EU Categories N1 Class III and N2 [36]	US [36]
PM	0.0045 [1]	0.0045 [1]	0.004827 [1]
NO_x	0.06 [1]	0.082 [1]	0.04 [1]
VOCs	0.068 [1]	0.108 [1]	0.06 [1]
CO	1 [1]	2.27 [1]	2.61 [1]
CO_2	95 [1]	95 [1]	132 [1]

[1] EU and US standards.

As seen in Table 2, the weight of a car can play an important role in imposing limits on air pollution. Additionally, the car type can influence these limits. For example, the EU values for diesel cars are more restrictive for CO (0.5 g/km) and more permissive for NO_x (0.8 g/km for Category M). As highlighted in the full life cycle model known as Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) [35,37], a car's tailpipe emissions refer to the operation phase of the life cycle, known as pump-to-wheels or TTW. These also include methane (CH_4), nitrous oxides (N_2O), and black carbon (BC) alongside CO, CO_2, $PM_{2.5}$, PM_{10}, VOCs, NO_x, and SO_x.

2.3. Overview of Operation Emissions Reported in the Literature

Regarding energy TTW and vehicle operation emissions, the values obtained in the literature [38–56] are compared in Tables 3 and 4 with the automotive emission standards depicted in Table 2.

Table 3. Emission standards for gasoline compact cars in the EU and US versus operation emission values (including TTW) reported in the literature in the 2016–2021 period, in grams per km.

Standard	EU/US	ICEV	HEV	PHEV	BEV—RES	BEV—Energy Mix
	[36]	[38–40,46–50,53,55]				[57]
PM_{10}	0.0045 [1]/0.0048 [2]	0.003–0.052 [3]	0.01–0.02 [3]	0.01–0.024 [3]	0.024 [3]	0.03 [4]
NO_x	0.06 [1]/0.04 [2]	0.05 [3]	0.04 [3]	0.035 [3]	0.03 [3]	0.07–0.1 [5]
VOCs	0.068 [1]/0.06 [2]	0.009–0.21 [3]	0.12 [3]	0.11 [3]	0.012 [3]	0.038–0.075 [6]
CO	1 [1]/2.61 [2]	0.33–1.65 [3]	0.5 [3]	0.2 [3]	0.042 [3]	0.093 [6]
CO_2	95 [1]/132 [2]	139–261 [3]	104–193 [3]	118–174 [3]	90–120 [3]	120 [4]

[1] EU Category M. [2] EU and US standards. [3] According to values reported in literature. [4] Figure of 39 to 68% oil, gas, and coal (OGC) in the energy mix. [5] Figure of 67–91% OGC. [6] Figure of 39–91% OGC.

As can be seen in many cases, the current emission standard values are overall exceeded. The type of energy used for charging EVs is also important, and this depends on both the location and period of charging [57]. For a minimal pollution impact, BEVs should preferably be charged from RES.

Table 4. Emission standards for gasoline large cars in the EU and US versus operation emission values (including TTW) reported in the literature in the 2016–2021 period, in grams per km.

Standard	EU/US	ICEV	HEV	PHEV	BEV—RES	BEV—Energy Mix
	[36]		[38–40,46–50,53,55]			[57]
PM_{10}	0.0045 [1]/0.0048 [2]	0.02–0.26 [3]	0.01–0.045 [3]	0.01–0.033 [3]	0.085 [3]	0.1 [4]
NO_x	0.06 [1]/0.04 [2]	0.205 [3]	0.155 [3]	0.143 [3]	0.088–0.105 [3]	0.243 [5]
VOCs	0.068 [1]/0.06 [2]	0.31–0.45 [3]	0.16 [3]	0.13 [3]	0.07 [3]	0.06–0.2 [6]
CO	1 [1]/2.61 [2]	1.5–2.6 [3]	1.67 [3]	1.12 [3]	0.053 [3]	0.243 [6]
CO_2	95 [1]/132 [2]	175–350 [3]	180–202 [3]	150–174 [3]	100–200 [3]	174 [4]

[1] EU Categories N1 class III and N2. [2] According to EU and US standards. [3] According to values reported in literature. [4] Figure of 39–68% OGC. [5] Figure of 67–91% OGC. [6] Figure of 39–91% OGC.

2.4. Overview of Life Cycle Costs and Benefits Reported in the Literature

Over the last decade, both car weight and purchase price have increased substantially [38,39]. Regarding the 10 best-selling passenger car models, their average curb weight has increased from 1.32 tons in 2011 to 1.62 tons in 2021, while their average manufacturer's suggested retail price (M.S.R.P.) has increased from EUR 17 thousand in 2011 to almost EUR 27 thousand in 2021, as seen in Figure 2. Most of the car models run on gasoline and are endowed with an internal combustion engine (ICE), such as ICEVs and HEVs. Only a few are charged with electricity, such as electric-motor-based EVs (PHEVs, BEVs). The evolutions seen in Figure 3 can be correlated with population and GDP evolutions, which have led to more car sales [40–42].

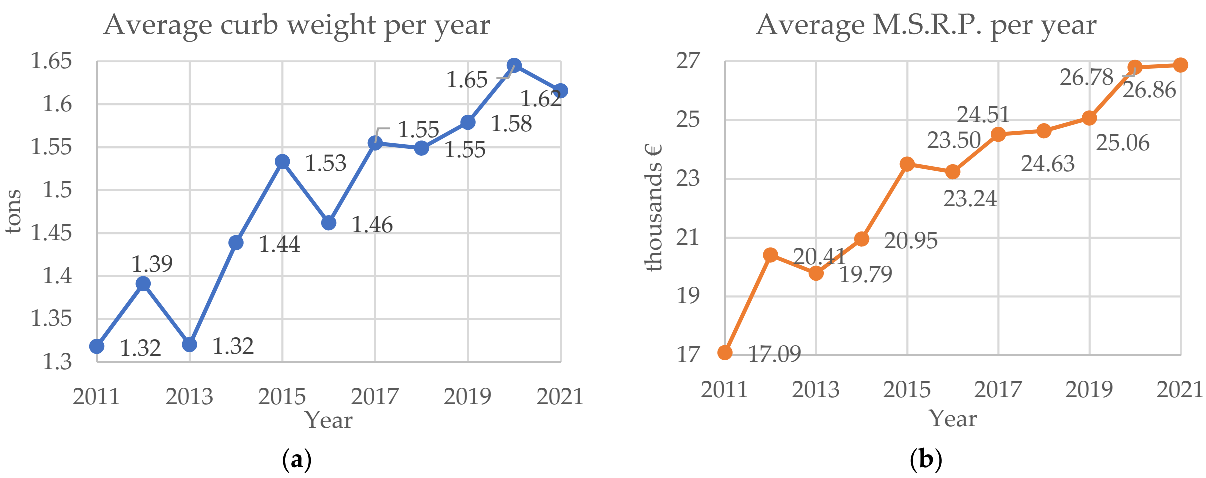

Figure 2. Eleven-year evolution of the 10 best-selling passenger car models in terms of (**a**) average curb weight; (**b**) average M.S.R.P.

This is relevant since, even if the annual production-weighted carbon footprint has decreased from 7.3 metric tons of CO_2 in 1990 to 5.3 in 2020 for cars, and from 9.0 metric tons of CO_2 in 1990 to 6.0 in 2020 for car SUVs (whose curb weight does not exceed 2.3 tons), the world CO_2 emissions have not [35]. It is actually the opposite. In 1990 there were 21 billion metric tons of CO_2 reported, while in 2019 there were more than 35. More specifically, even if EVs present no tailpipe emissions, and thus significantly help decrease the carbon footprint, the upstream emissions must be taken into consideration. For example, vehicle manufacturing cycle GHG emissions are the highest for BEVs: 7 to 10.5 in tons of CO_2 equivalents, depending on mileage (160 to 480 km), and the lowest for gasoline ICEVs: 6.2 [37]. The performance of the various types of vehicles (ICEVs, HEVs, PHEVs, and BEVs) in terms of mileage, energy/fuel/electricity consumption, and battery energy storage is analyzed in [43] from 2011 to 2021. Both fuel/electricity consumption and battery energy storage have grown during this interval. Included in the same study are the total vehicle emissions, such as global warming potential (GWP) in gCO_2/km, photochemical oxidant formation (POF) in gNMVOC/km (non-methane VOCs), terrestrial acidification (TA) in gSO_2/km, human toxicity (HT) in g1,4DCB/km (dichlorobenzene), freshwater eutrophication (FE) in gP/km (potassium), and particulate matter formation (PMF) in $gPM_{2.5}$/km. Greater values were reported for GWP, TA, and FE, while no relevant improvements were detected for PMF and POF in same period.

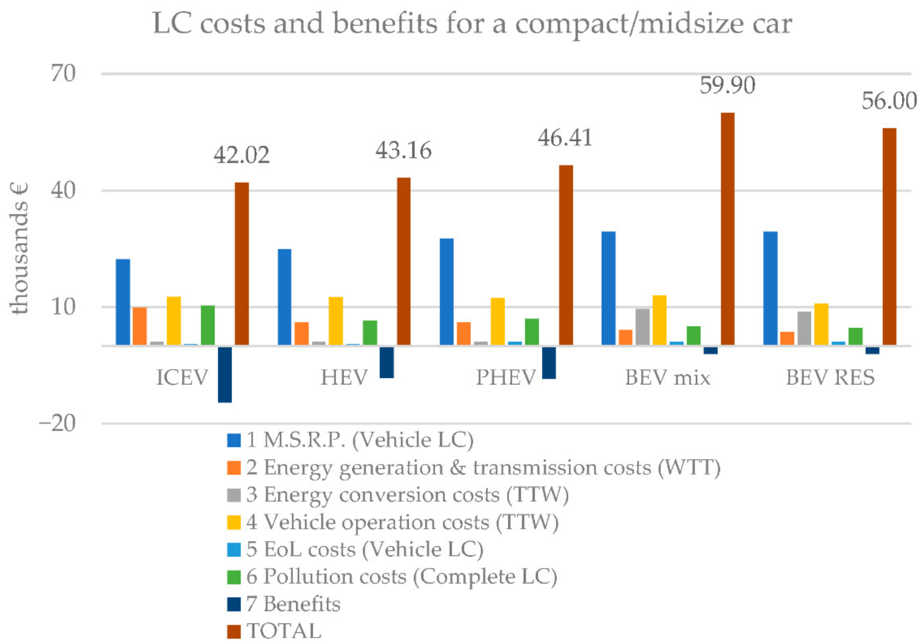

Figure 3. Complete life cycle costs for a compact/mid-sized car (1.3 to 1.5 tons).

Various studies have provided comprehensive analyses in a similar fashion [44–48] but with more emphasis on the stages of the complete life cycle: WTT, TTW, and vehicle LC (including vehicle manufacturing, maintenance, and EoL), as shown in Figure 2.

While BEVs charged with clean energy (RES) are the most promising in terms of reduced TTW and vehicle operation emissions, the purchase price of BEVs can represent a serious impediment, being at least EUR 5000 more expensive than an ICEV with the same weight. Figure 3 presents the life cycle costs of a compact to mid-sized car (1.3 to 1.5 tons) for all five car types, while Figure 4 refers to large-sized cars (2 to 2.5 tons) [38,39,43,50].

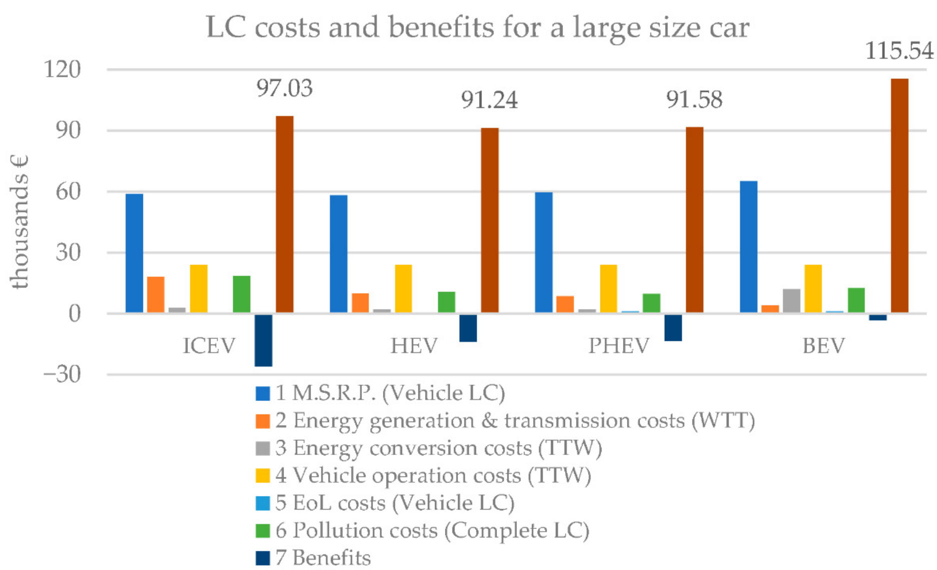

Figure 4. Complete life cycle costs for a large-sized car (2 to 2.5 tons).

The higher values for the various types of EVs reflect the battery weight and capacity evolutions [43–56,58–60]. In the case of BEVs, the compact cars have increased their battery capacity, on average, from 27 kWh in 2005 to more than 40 kWh in 2020, while the large-sized cars have more than 65 kWh capacity in 2020, which is substantial when compared to the figure of 34 kWh in 2014. HEVs show no notable changes in capacity over the last decade, as it is usually around 2 kWh for both compact and large-sized cars. For PHEVs, compact cars' batteries are from 10 to 12 kWh, while for large-sized cars they are approx. 20 kWh. Not only have the mileage (autonomy) and battery costs increased, but so have the cost of materials, as can be seen in Figure 2 for compact cars, such as ICEVs and HEVs from 2005 to 2019, and for large-sized cars, such as HEVs and BEVs from 2014 to 2019. The life cycle costs reflect both the vehicle life cycle (LC) stages (car manufacturing, operation, and end of life (EoL)) and energy LC stages (energy generation and transmission for the WTT (well-to-tank) stage and energy conversion for the TTW (tank-to-wheel) stage). Associated with material extraction and car manufacturing is the manufacturer suggested retail price (M.S.R.P.). The costs for producing the required energy are included in energy generation and transmission costs.

The costs associated with fueling/charging a vehicle, replacing a vehicle's battery, and home charging installation are included in energy conversion costs. The costs that cover vehicle operation include maintenance, repairs, insurance, and fees. The EoL costs refer to shipping and recycling/disposal costs. The pollution costs include the life cycle emissions that consider all of the previous stages (one–five in Figures 3 and 4) in terms of PM_{10}, NO_x, VOCs, CO, SO_x, CO_2, $PM_{2.5}$, CH_4, and N_2O. The benefits help reduce the costs and cover gains in GDP, taxes, compensation, and employment benefits. Table 5 synthesizes the complete life cycle costs.

Table 5. Life cycle costs ($10^3 \times$ EUR), PC = pollution costs, and B = benefits.

Study	Car Manufacturing	Car Operation/Maintenance	Car End of Life	Energy Generation and Transmission	Energy Conversion	Other
Current	22.6–65 [1]	10.75–24 [3]	0.5–1 [6]	3.6–18 [8]	1–9.5 [10]	PC: 4.6–18.6 [13], B: 2–26 [13]
[38]	16.3–36 [2]	18–24 [3]	-	3.2–10 [8]	0–15 [10]	- [14]
[39]	58–65 [1]	24 [4]	-	4–18 [9]	11–13 [11]	B: 3–26 [15]
[43]	-	-	-	-	-	PC: 2.8–4.5 [16]
[50]	18–32 [1]	3–6 [5]	0.5 [7]	-	4–11 [12]	PC: 3–8.5 [17]

[1] M.S.R.P./purchase price. [2] True vehicle cost. [3] Maintenance costs, including repairs, insurance, financing, and fees. [4] Maintenance costs, including insurance and fees. [5] Maintenance costs, including fees. [6] End of life costs, including shipping and disposal. [7] End of life costs, including shipping. [8] WTT costs, including energy/fuel production costs. [9] WTT costs, including fuel costs. [10] TTW costs, including fueling/charging, alternative transportation, battery replacement, and home charging installation costs. [11] TTW costs, including fuel usage. [12] TTW costs, including fueling. [13] Overall pollution costs and benefits for all car types and main car categories. [14] No pollution costs and benefits only for ICEVs and BEVs, for mid-sized and compact cars. [15] Overall benefits for all car types but only large-sized cars, no pollution costs. [16] Some pollution costs for all car types but only mid-sized cars, no benefits. [17] Overall pollution costs for all car types but only mid-sized cars, no benefits.

3. Life Cycle Assessment Data

Based on various studies [38,39,43–56,58–60], the energy generation and transmission (WTT) emissions are depicted in Figure 5 for the main pollutants: PM_{10}, NO_x, VOCs, CO, SO_x, and CO_2. The energy conversion (TTW) and car operation emissions are presented in Figure 6, while in Figure 7 car manufacturing and EoL emissions are presented.

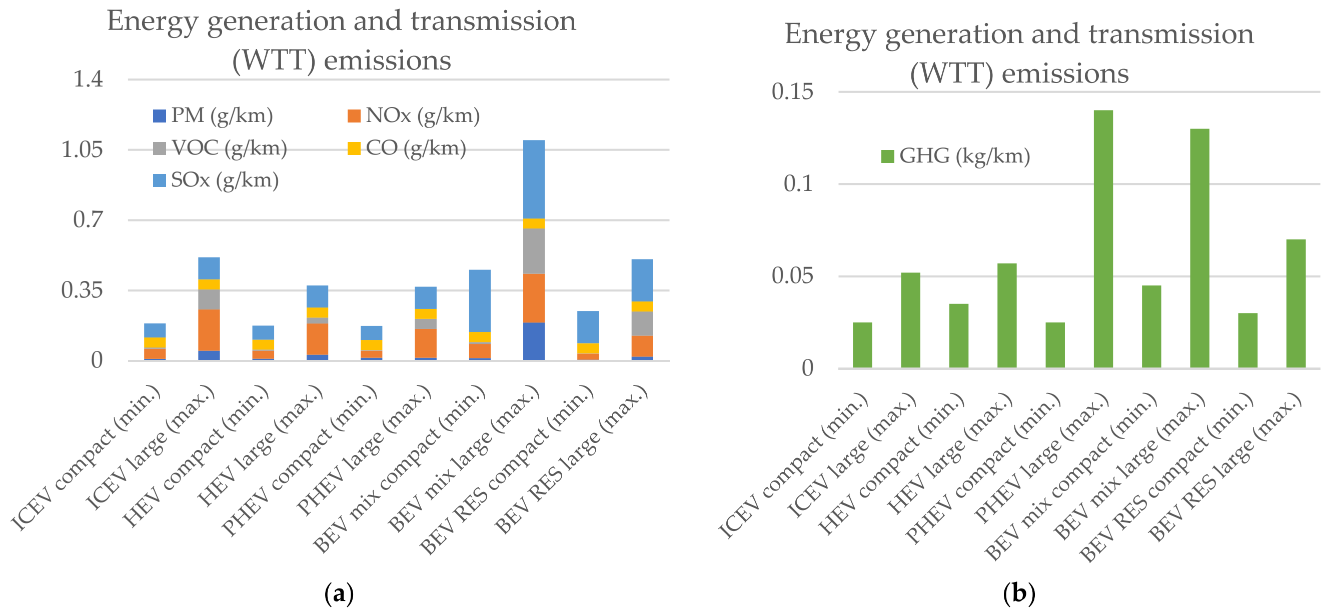

Figure 5. Energy generation and transmission emissions (WTT) in terms of (**a**) PM (only PM_{10}), NO_x, VOCs, CO, and SO_x; (**b**) GHG (only CO_2), during 2016–2021.

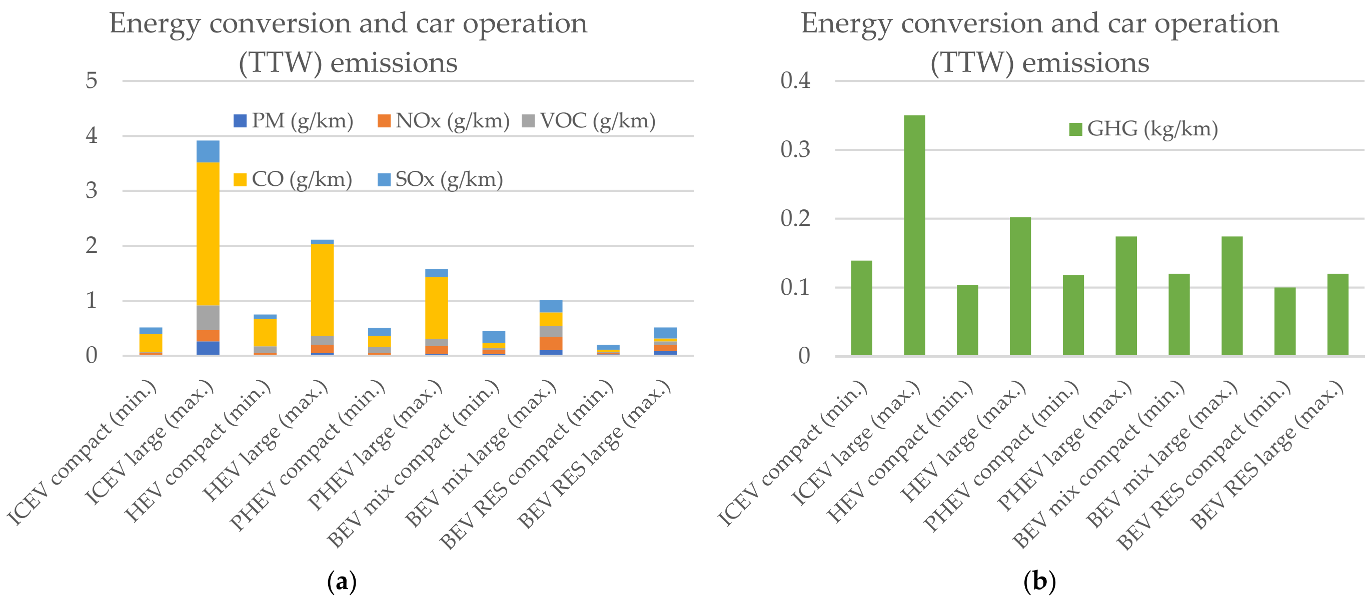

Figure 6. Energy conversion and car operation emissions (TTW) in terms of (**a**) PM (only PM_{10}), NO_x, VOCs, CO, and SO_x; (**b**) GHG (only CO_2), during 2016–2021.

Table 6 synthesizes the main differences between the five types of passenger cars in terms of complete life cycle emissions for compact cars (minimum reported values in th literature) and large cars (maximum values reported in the literature). In Figure 8 other pollutants and depletion potentials are also analyzed in terms of a complete life cycle for the two main car types. The pollutants HTP, FTP, TTP, and MTP refer to human, freshwater, terrestrial, and marine toxicity potentials. FE, HH, and IR refer to freshwater eutrophication, human health, and ionizing radiation. MDP, FFDP, ODP, and RDP are mineral, fossil fuel, ozone, and resource depletion potentials, while WD and LTO represent water depletion as well as land transformation and occupation parameters.

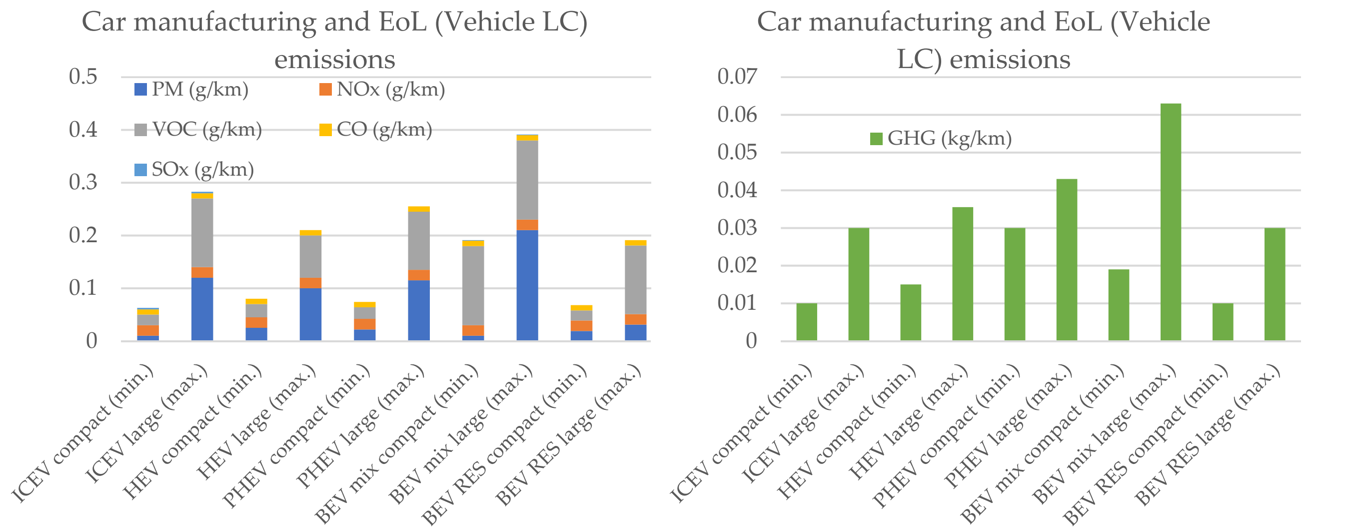

Figure 7. Car manufacturing and EoL emissions in terms of (**a**) PM (only PM_{10}), NO_x, VOCs, CO, and SO_x; (**b**) GHG (only CO_2), during 2016–2021.

Table 6. Complete life cycle emissions reported in the literature in the 2016–2021 period, for compact (min) and large-sized cars (max) in terms of PM_{10}, NO_x, VOCs, CO, SO_x, and CO_2.

Emission	ICEV Min–Max	HEV Min–Max	PHEV Min–Max	BEV Mix Min–Max	BEV RES Min–Max
			[38–40,46–50,53,55,59]		
PM_{10} (g/km)	0.02–0.43 [1]	0.05–0.17 [1]	0.05–0.16 [1]	0.05–0.5 [1]	0.05–0.14 [1]
NO_x (g/km)	0.12–0.43 [1]	0.1–0.33 [1]	0.09–0.3 [1]	0.16–0.51 [1]	0.08–0.23 [1]
VOC (g/km)	0.04–0.68 [1]	0.15–0.27 [1]	0.13–0.29 [1]	0.2–0.57 [1]	0.03–0.32 [1]
CO (g/km)	0.39–2.66 [1]	0.56–1.73 [1]	0.26–1.18 [1]	0.15–0.3 [1]	0.1–0.11 [1]
SO_x (g/km)	0.19–0.51 [1]	0.15–0.19 [1]	0.22–0.26 [1]	0.52–0.62 [1]	0.25–0.41 [1]
Total (g/km)	0.76–4.71 [2]	1.01–2.69 [3]	0.75–2.2 [4]	1.09–2.5 [5]	0.5–1.21 [6]
CO_2 (kg/km)	0.17–0.43 [7]	0.15–0.29 [8]	0.17–0.36 [9]	0.18–0.37 [10]	0.14–0.22 [11]

[1] According to values reported in literature. [2] WTT: 24.4–10.9% (min–max). TTW: 67.3–83.1%. [3] WTT: 17.4–13.9%. TTW: 74.6–78.3%. [4] WTT: 22.9–16.7%, TTW: 67.3–71.7%. [5] WTT: 41.5–43.9%, TTW: 40.9–40.4%. [6] WTT: 48.2–41.8%, TTW: 38.6–42.4%. [7] WTT: 14.4–12%, TTW: 79.9–81%. [8] WTT: 22.7–19.4%, TTW: 67.5–68.6%. [9] WTT: 14.5–39.2%, TTW: 68.2–48.7%. [10] WTT: 24.5–35.4%, TTW: 65.2–47.4%. [11] WTT: 21.4–31.8%, TTW: 71.4–54.6%.

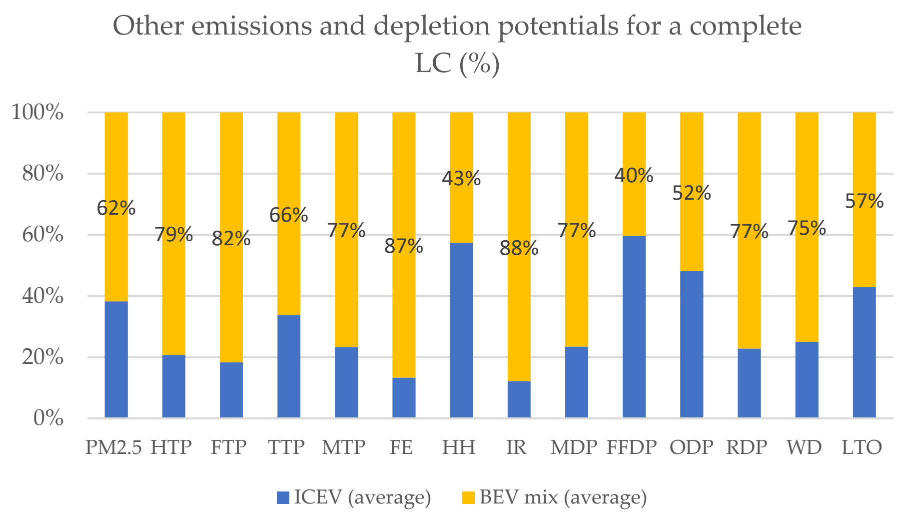

Figure 8. Comparison between ICEV and BEV in terms of fife cycle emissions for other pollutants and depletion potentials, for a medium car (mid-sized to large: 1.5 to 2 tons).

Figure 9 presents the energy consumption of an ICEV and two BEVs, from compact cars (minimum reported values in the literature) to large cars (maximum values reported in the literature). BEV mix (max) refers to an energy mix similar to the China energy mix, which indicates the maximum reported value in the literature, while BEV RES (min) indicates the minimum reported value in the literature.

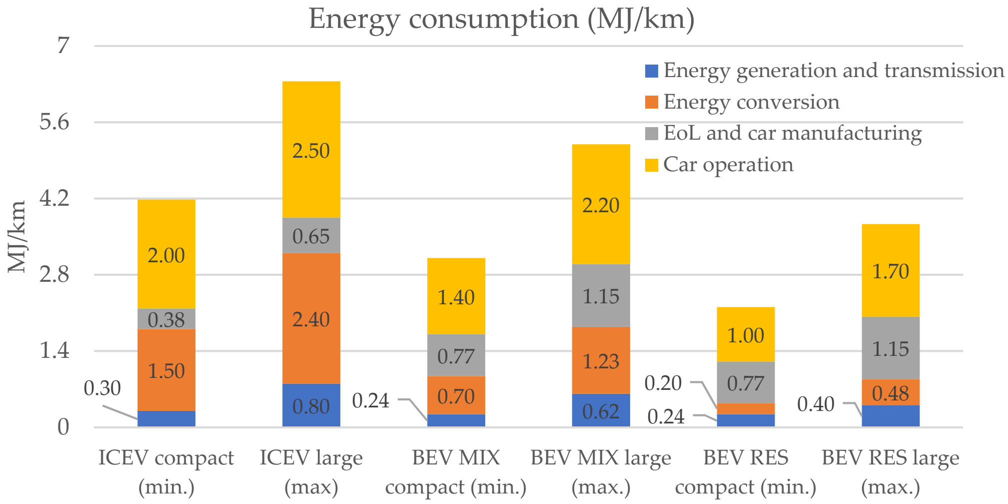

Figure 9. Life cycle energy consumption for ICEVs and BEVs during 2016–2021.

4. Simulation Data

4.1. Predefined Car Models and Simulation Results in Terms of Emissions and Energy Consumption

As seen in Figures 5–7 and 9, weight reduction or light weighting (LW) in cars should prove beneficial in pollution abatement and energy savings. This hypothesis is verified in GREET for the main car types (ICEVs and HEVs on E10, PHEVs on E10 and electricity, and BEVs on electricity as EV300). These consist of two predefined car models: a compact car (1.23 to 1.48 tons, from ICEVs to BEVs for lightweight material) and a mid-sized car (1.41 to 1.68 tons for conventional material). Generated emissions in terms of PM_{10}, NO_x, VOCs, CO, SO_x, and CO_2 are depicted in Figures 10 and 11.

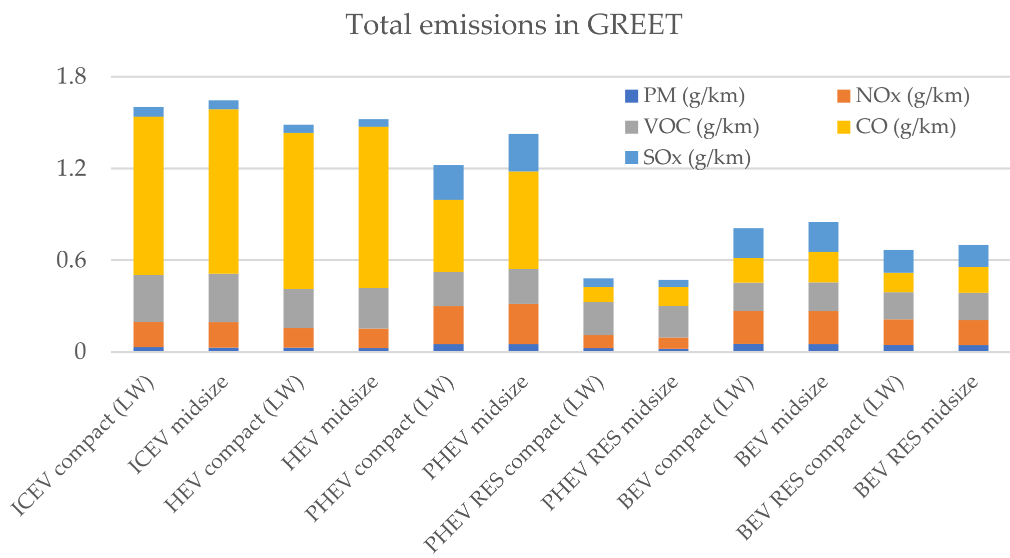

Figure 10. Total emissions in GREET for the predefined models in terms of PM (only PM_{10}), NO_x, VOCs, CO, and SO_x.

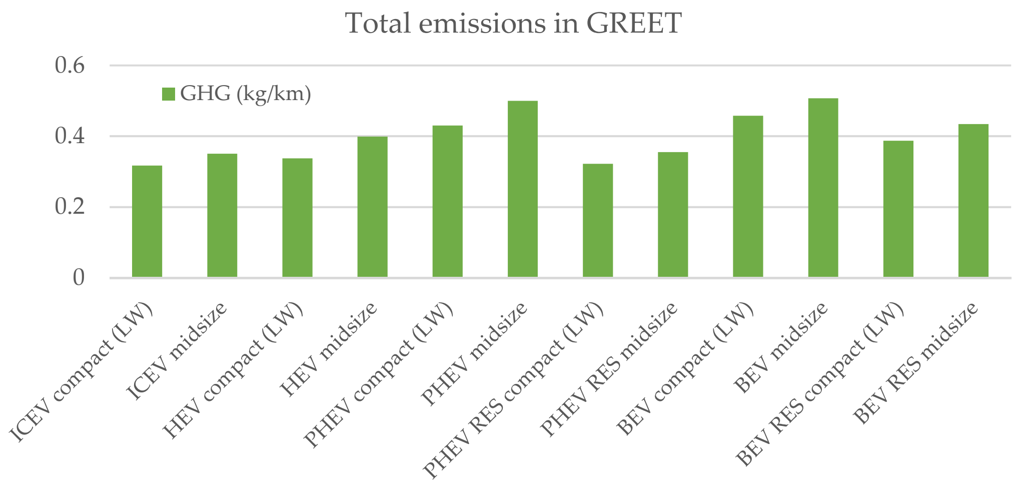

Figure 11. Total emissions in GREET for the predefined models in terms of GHG (only CO_2).

These include the WTT, TTW (energy conversion), and vehicle LC (EoL and car manufacturing) emissions. The following limitations must also be considered when utilizing GREET: car operation emissions are not taken into consideration and no battery replacement is accounted for regarding lithium-ion batteries.

Because the energy generated that covers a car's travel demand depends on both the car type and location, the energy mix used is of utter importance. For an average energy mix, both the EU and US energy mixes are considered. Another reason is the correlation with emission standards. Based on data from 2021 [61–63], the US and EU energy mixes can be analyzed in terms of energy generation share for the main sources: petroleum, natural gas, coal, nuclear energy, and RES. The GREET model [37] provides the energy consumption of these sources for the following main stages: vehicle LC, which includes car manufacturing and EoL, and energy LC, which includes energy generation, transmission, distribution, and conversion. Figure 12 presents the total energy required for each type of car.

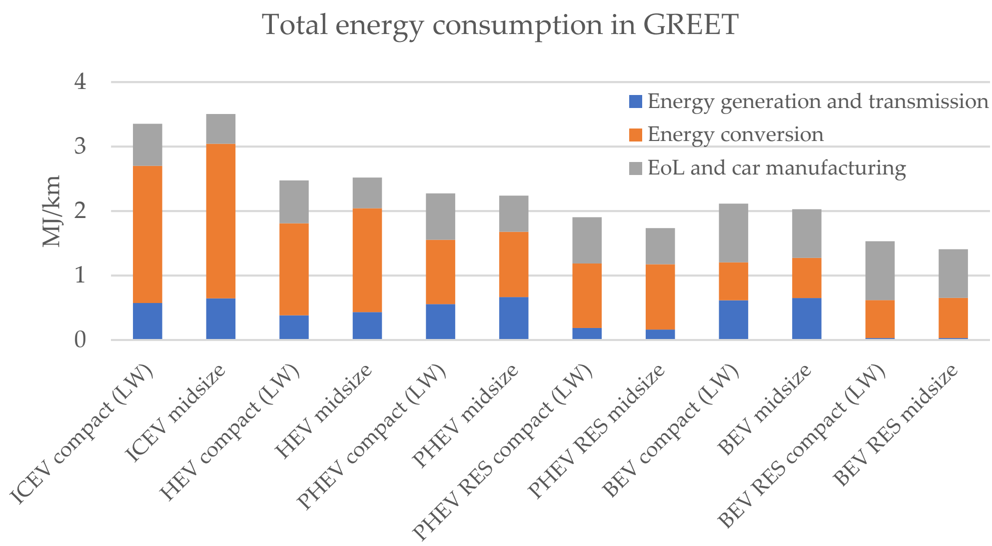

Figure 12. Total energy consumption in GREET for the predefined models.

4.2. Test Models for the Proposed LCA Methodology

The proposed test models (1.6 to 1.8 tons, from ICEVs to BEVs) are depicted in Table 7. The weight distribution of these is based on the predefined models in GREET [37] and data from [47,52,54,58]. The following simulation parameters are considered for the models:

the vehicle lifetime in km of travel is 200.000 km, the payload is 500 kg for five passengers, the electric range is 0 km for ICEVs and HEVs, 52 km for PHEVs—1.38 t, 80 km for PHEVs—1.58 t, and 480 km for BEVs. PHEVs—1.38 t run in charge-depleting (CD) mode 55.95% and in charge-sustaining (CS) mode 44.05%, while PHEVs—1.58 t run in CD mode 69.73% and in CS mode 30.27%. The assembly, disposal, and recycling (ADR) is 907.18 kg for all of the models.

Table 7. Curb weight distribution of the tested models.

Car Type and Weight	Battery	Vehicle Body	Powertrain System	Transmission	Chassis	Motor, Generator, and Controller	Fluids, Tire Replacement
				[37,47,52,54,58]			
ICEV—1.6 t	1% [1]	50.4% [1]	14% [1]	6% [1]	25% [1]	0% [1]	3.6% [1]
HEV—1.67 t	4% [1]	42% [1]	21.3% [1]	4.2% [1]	20% [1]	6% [1]	2.5% [1]
PHEV—1.75 t	8% [1]	41% [1]	21% [1]	4% [1]	18% [1]	7.5% [1]	2.5% [1]
BEV—1.8 t	24% [1]	36% [1]	3% [1]	4% [1]	17% [1]	14% [1]	2% [1]

[1] According to values reported in literature.

5. Results and Discussion

5.1. The Proposed LCA Methodology

The proposed life cycle assessment (LCA) methodology is depicted in Figure 13. In such an analysis, a clear distinction is made between energy LC, which includes the well-to-tank (WTT) and tank-to-wheel (TTW) (energy conversion) stages, and vehicle LC, which includes the production (including vehicle manufacturing), operation (maintenance), and end of life (EoL) stages.

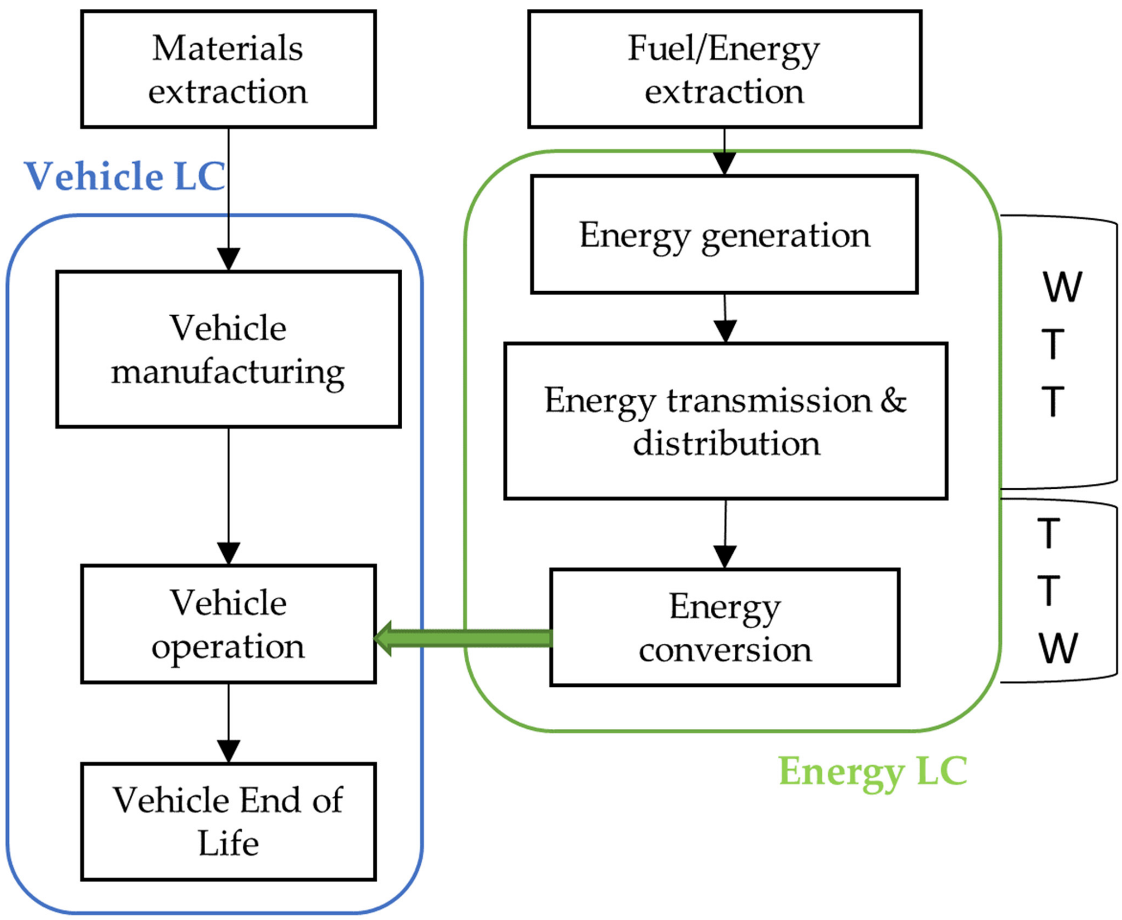

Figure 13. Life cycle assessment of vehicles based on the proposed methodology.

Our evaluation methodology consists of the sum of the two main elements: energy consumed for the production of the transport means (W_p per vehicle) considered as energy/km during vehicle lifetime (EoL), and energy consumed for its operation during its whole life (W_o per vehicle until EoL). The recycling "costs" are also taken into consideration:

$$W_p = W_b + W_r, \tag{1}$$

where W_b represents the energy consumed for manufacturing the vehicle and W_r is the energy necessary for recycling it. In regard to operation, the following formula is representative:

$$W_o = W_{km/o} \times N_{EoL}, \tag{2}$$

where $W_{km/o}$ represents the energy consumed by the vehicle per km during its operation and N_{EoL} represents the total mileage (in km) covered by the vehicle during its life. The following formula depicts the total energy consumed during the vehicle's life cycle:

$$W = W_p + W_o, \tag{3}$$

Additionally, in a similar manner, the authors have considered the whole pollution generated by a vehicle as a vector composed of the pollutants that result from a vehicle's production and operation (P_{EoL}) for the main pollutants: GHGs (CO_2) and other relevant pollutants (PC), which include NO_x, SO_x, PM_{10}, CO, and VOCs. Thus, the comparison between the two transport technologies (conventional, based on ICEVs, and full-electric, based on BEVs) will be illustrated by the following equation:

$$\text{PEoL} = \begin{bmatrix} \text{GHG}_p \\ \text{PC}_p \end{bmatrix} \times \text{NEoL} + \begin{bmatrix} \text{GHG}_o \\ \text{PC}_o \end{bmatrix} \times \text{NEoL}, \tag{4}$$

Thus, the vehicle impact takes into account a certain life span, or mileage. The impacts associated with energy consumption and the resulting emissions are evaluated for the whole vehicle life cycle. With this methodology, the weight factors between vehicle production and its operation are considered equal.

5.2. Evaluation of Vehicle Life Cycle Emissions and Energy Consumption for the Transition to Full-Electric Cars Based on GREET Correlations with the Proposed LCA Methodology

Figures 14–16 depict the data referring to energy consumption and pollutants generated during the vehicle production and operation stages until their end of life (EoL).

As can be seen, the energy consumed in the case of ICEVs is significantly lower in production, mainly as a result of the technologies' maturity in comparison with other types of vehicles, such as BEVs. During operation, BEVs that use clean electric energy, such as RES, present significantly lower emissions. This suggests that the future development of vehicle technologies should evolve in parallel with the greening of electric energy production. Related to emissions, the situation is similar with energy, but it is visible that other pollutants present reduced values just as GHGs, which translate into a lower environmental impact of electric vehicles [64]. Figure 16 illustrates the comparison of the different technologies for the whole vehicle life cycle.

This picture can be affected only by the changes in the energy mix pattern that can differ for each country. The energy mix considered in Figures 14–16 is an average between EU and US mix.

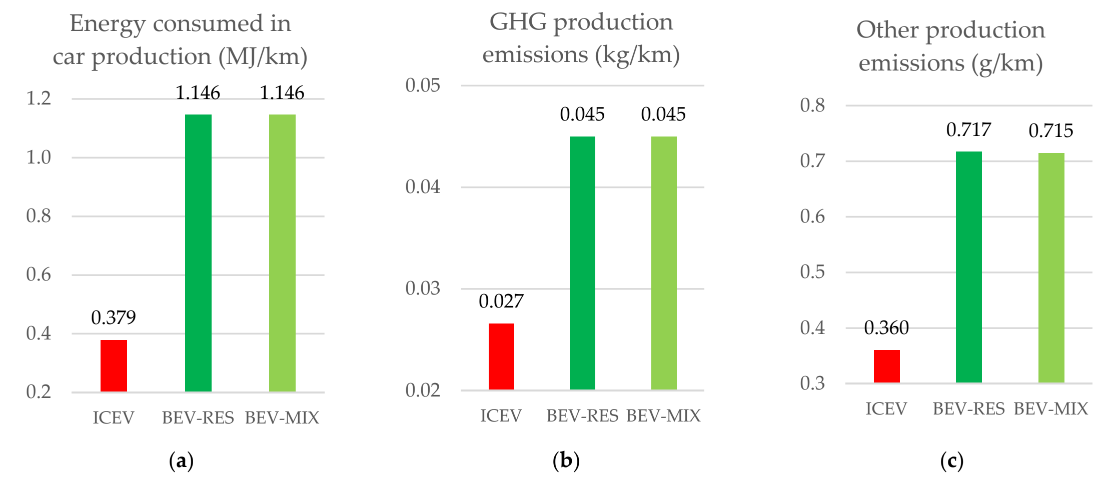

Figure 14. Production stage in terms of (**a**) energy consumption; (**b**) CO_2 emissions; and (**c**) PM_{10}, NO_x, VOC, CO, and SO_x emissions.

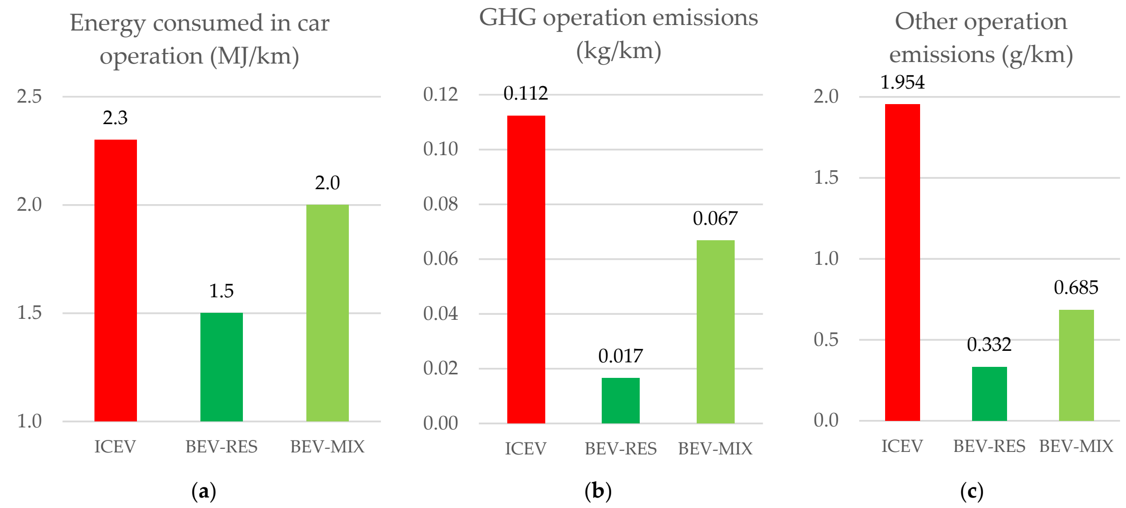

Figure 15. Operation stage in terms of (**a**) energy consumption; (**b**) CO_2 emissions; and (**c**) PM_{10}, NO_x, VOC, CO, and SO_x emissions.

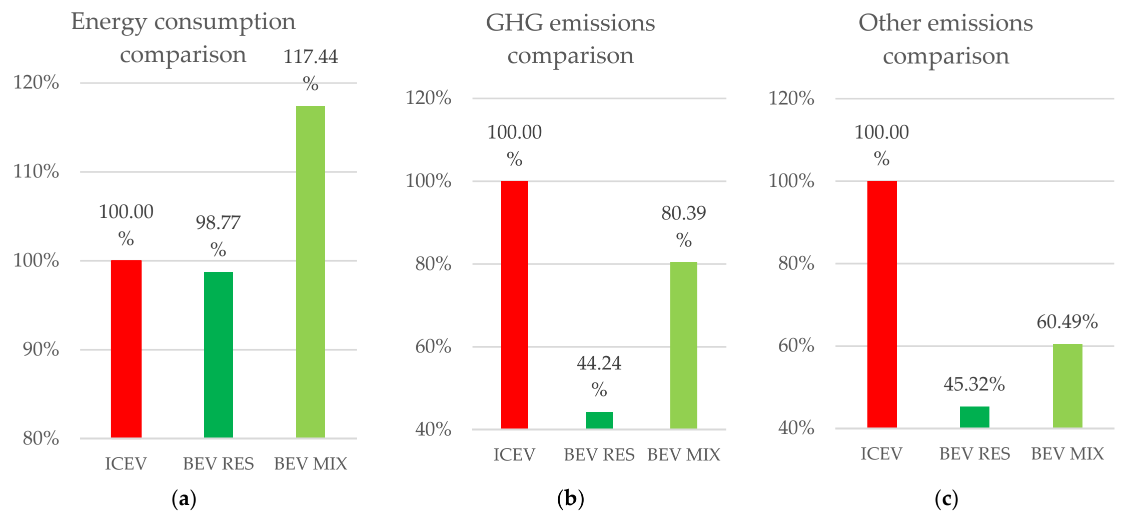

Figure 16. Complete vehicle LC in terms of (**a**) energy consumption comparison; (**b**) CO_2 emissions comparison; and (**c**) PM_{10}, NO_x, VOC, CO, and SO_x emissions comparison.

5.3. Validation of the GREET Correlations with the Proposed LCA Methodology

The results based on the proposed LCA methodology are compared with the GREET simulation results [37] in Tables 8–10. The energy consumption and emissions assumption values show a strong correlation with the simulated values, mostly for HEV and BEV models.

Table 8. Total energy consumption (MJ/km) for the tested models (assumption vs. simulation in GREET)

Car Type and Weight	Vehicle LC (Car Manufacturing and End of Life)	Vehicle LC (Car Operation)	Energy LC (Generation and Transmission)	Energy LC (Conversion)	Total (Without Vehicle LC—Operation)
ICEV—1.6 t [1]	0.38	2.30	0.48	2.01	2.87
HEV—1.67 t [1]	0.48	2.10	0.43	1.61	2.52
PHEV—1.75 t [1]	0.75	1.90	0.67	1.01	2.43
BEV—1.8 t [1]	1.15	1.75	0.47	0.79	2.40
ICEV—1.6 t [2]	0.54	-	0.64	2.40	3.58 (0.71 [3])
HEV—1.67 t [2]	0.52	-	0.43	1.61	2.56 (0.04 [3])
PHEV—1.75 t [2]	0.62	-	0.66	1.01	2.29 (0.14 [3])
BEV—1.8 t [2]	1.17	-	0.64	0.62	2.43 (0.03 [3])

[1] Methodology-based (assumptions of the current study) average between RES and the EU/US mix for BEVs. [2] Simulation (GREET) average between RES and the EU/US mix for BEVs. [3] Difference between assumption (current study) and simulation (GREET).

Table 9. Total GHG emissions (kg CO_2/km) for the tested models in GREET.

Car Type and Weight	Vehicle LC (Car Manufacturing and End of Life)	Vehicle LC (Car Operation)	Energy LC (Generation and Transmission)	Energy LC (Conversion)	Total (Without Vehicle LC—Operation)
ICEV—1.6 t [1]	0.027	0.082	0.036	0.168	0.231
HEV—1.67 t [1]	0.030	0.044	0.040	0.116	0.186
PHEV—1.75 t [1]	0.040	0.040	0.080	0.110	0.230
BEV—1.8 t [1]	0.045	0.028	0.055	0.102	0.202
ICEV—1.6 t [2]	0.030	-	0.080	0.173	0.283 (0.052 [3])
HEV—1.67 t [2]	0.030	-	0.054	0.115	0.199 (0.013 [3])
PHEV—1.75 t [2]	0.036	-	0.221	0.036	0.294 (0.064 [3])
BEV—1.8 t [2]	0.062	-	0.132	0	0.196 (0.006 [3])

[1] Methodology-based (assumptions of the current study) average between RES and the EU/US mix for BEVs. [2] Simulation (GREET) average between RES and the EU/US mix for BEVs. [3] Difference between assumption (current study) and simulation (GREET).

Table 10. Other relevant pollutants' total emissions (g/km) for the tested models in GREET (VOCs, CO, NO_x, PM_{10}, and SO_x).

Car Type and Weigh	Methodology-Based (Without Vehicle LC Car Operation)	Simulation (Without Vehicle LC Car Operation)	Methodology-Based (Vehicle LC, Only Car Operation)	Difference (g/km)
ICEV—1.6 t	1.646 [1]	1.612 [2]	1.954 [1]	0.034 [3]
HEV—1.67 t	1.650 [1]	1.643 [2]	0.700 [1]	0.007 [3]
PHEV—1.75 t	1.150 [1]	0.988 [2]	0.900 [1]	0.162 [3]
BEV—1.8 t [1]	0.910 [1]	0.916 [2]	0.700 [1]	0.006 [3]

[1] Methodology-based (assumptions of the current study) average between RES and the EU/US mix for BEVs. [2] Simulation (GREET) average between RES and the EU/US mix for BEVs. [3] Difference between assumption (current study) and simulation (GREET).

5.4. Discussion of the Results Obtained with the Proposed LCA Methodology

Tables 11 and 12 provide a sensitivity analysis for the current study's limit values on energy consumption and emissions, as well as for other sources, thus highlighting once more the correlations with GREET and other relevant studies in terms of the LCA. Based on the correlations with the GREET simulations and other relevant studies, Figure 17 highlights the complete life cycle emissions in terms of PM_{10}, NO_x, VOCs, CO, SO_x, and CO_2 for the main car types for an average weight (1.5 to 2 tons). Figure 18 synthesizes the complete life cycle energy consumption for the same car types.

Table 11. Life cycle emissions (g/km), GHGs = greenhouse gases, and other = VOCs, CO, NO_x, PM_{10}, and SO_x.

Source	Car Manufacturing and End of Life	Car Operation/Maintenance	Energy Generation and Transmission	Energy Conversion	Total
Current study	GHGs: 27–108, Other: 0.36–0.72	GHGs: 17–112, Other: 0.33–2	GHGs: 30–140, Other: 0.2–1.1	GHGs: 83–238, Other: 0–1.9	GHGs: 143–598, Other: 0.89–5.72 [1]
GREET	GHGs: 26–101, Other: 0.37–0.68	-	GHGs: 35–200, Other: 0.15–0.5	GHGs: 0–172, Other: 0–0.98	GHGs: 59–471, Other: 0.52–2.16 [2]
[50,55]	-	GHGs: 30–150, Other: 0.21–3.63 [3]	-	GHGs: 119–302, Other: 0.13–2.74 [3]	GHGs: 149–452, Other: 0.34–6.37 [4]
[43]	GHGs: 10–52 [3]	GHGs: 25–140 [3]	GHGs: 16–75 [3]	GHGs: 65–182 [3]	GHGs: 116–449 [5]
[59]	GHGs: 10–98 [3]	GHGs: 35–100 [3]	GHGs: 35–70 [3]	GHGs: 65–250 [3]	GHGs: 145–528 [4]

[1] All car types, compact to large-sized cars. [2] All car types, compact to large-sized cars. [3] No clear distinction between vehicle and energy life cycle. [4] All car types, main car categories. [5] All car types, compact to mid-sized cars.

Table 12. Life cycle energy consumption (MJ/km).

Source	Car Manufacturing	Car Operation/Maintenance	Car End of Life	Energy Generation & Transmission	Energy Conversion	Total
Current study	0.18–0.45	1.5–2.3	0.2–0.7	0.32–0.67	0.35–2.01	2.55–6.13 [1]
GREET	0.13–0.36	-	0.07–0.34	0.03–0.63	0.6–2.26	0.83–3.59 [2]
[39]	-	-	-	0.5–2.4	1.4–5.3	1.9–7.7 [3]
[43]	-	1–2.2	-	-	-	1–2.2 [4]
[59]	0.1 [5]	0.1–1.1	0.4 [5]	-	0.1–1 [5]	0.6–2.6 [6]

[1] All car types, mid-sized to large-sized cars. [2] All car types, compact to mid-sized cars. [3] All car types, large-sized cars. [4] All car types, no weight data. [5] No clear distinction between vehicle and energy life cycle. [6] Only ICEVs and BEVs, compact cars.

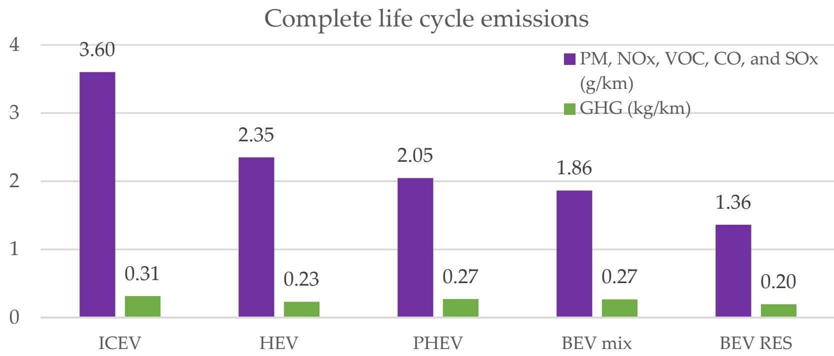

Figure 17. Complete life cycle emissions for a medium car (test model: from 1.6 to 1.8 tons).

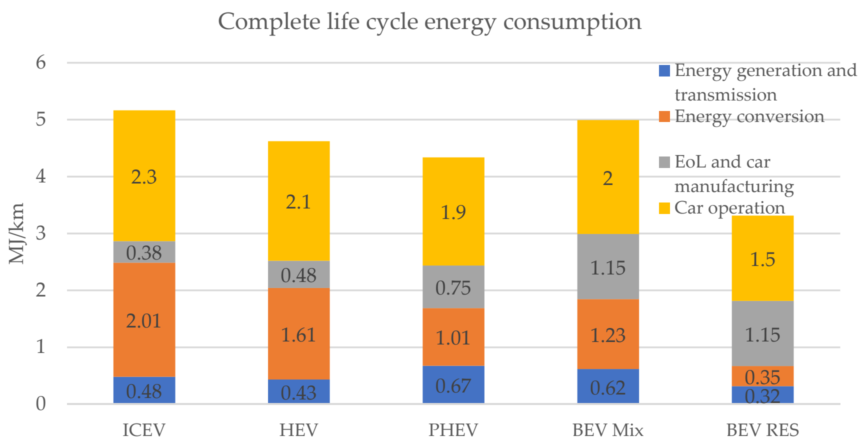

Figure 18. Complete life cycle energy for a medium car (test model: from 1.6 to 1.8 tons).

Figure 18 illustrates that the ICEV model has the maximum complete life cycle energy consumption. At the same time, the BEV mix model also consumes just as much. As expected, BEV RES represents the most energy-efficient type of vehicle. Moreover, it could have even better efficiency if its charging is carried out in an insulated network, such as buildings' microgrids.

Finally, Table 13 underlines the main strengths and limitations of the current study compared to other studies relevant in terms of life cycle assessment methodology.

Table 13. Strengths and limitations of various studies in terms of life cycle (LC).

Source	Costs	Energy Demand	Emissions	Car Type and Weight	Strengths and Limitations
	[38,39,43,50]	[39,43,59]	[38–40,46–50,53,55,59]		[1,2,9,11,12,15,17,19,26,49–52,59,64]
Current study	Complete	Complete	Complete	All types, 1.6–1.8 t	Clear distinction [1]—other aspects [2]
GREET	-	Almost complete [3]	Almost complete [3]	All types, 1.23–1.68 t	Clear distinction [1]—other aspects [2]
Other studies	Mostly incomplete [4]	Mostly incomplete [5]	Mostly incomplete [6]	All	No clear distinction [7]—other aspects [8]

[1] Clear distinction between energy and vehicle life cycle stages, weight and car type categories, and energy mix used (EU/US mix). [2] Energy supply infrastructure, energy efficiency, and driving pattern data not considered. [3] All car types, large-sized cars. [4] Many studies lack data on pollution costs, benefits, and other costs associated with the life cycle stages, except the mentioned references in the table. [5] Many studies lack energy consumption data for all vehicle and energy life cycle stages, except the mentioned references in the table. [6] Many studies lack relevant data on main pollutants for all life cycle stages, except the mentioned references in the table. [7] No clear distinction between vehicle and energy life cycle stages, weight and car type categories, and energy mix used. [8] A few studies contain data on energy supply infrastructure, energy efficiency, the supply and demand of scarce raw materials, and driving pattern.

The limitations of this study refer to the geographical impact of transport services, which was not tackled herein. This implies that the main driving patterns (urban, mixed or interurban, or long distance) were not considered in this analysis. This is important because it is clear that the transition to electric transport technologies will significantly improve the air quality in urban zones, and thus also quality of life and health.

Additionally, the authors did not analyze the considerable effort with regard to electric vehicle technologies in increasing the need for electric power necessary to fulfill the new energy demand levels. Additionally, of course, the changes in the corresponding infrastructure, the development of power transmission and distribution means for the new energy networks, charging stations, and storage technologies are not aspects considered for analysis in this paper. Here, the authors should mention that the time parameter must be considered in order to provide a smoother transition or to significantly improve the management of energy in conjunction with the evolution of electric vehicle technologies.

The transition to electric cars also implies a new type of analysis from an economic point of view. This refers to the use of optimized methodologies as a function of the working regimes of electric vehicle fleets, consisting of traffic control and fleet management, thus leading to intelligent transport systems.

6. Conclusions and Future Work

This paper proposes a methodology that provides an accurate comparison of the main vehicle technologies, having as references the energy consumed and the principal pollutants generated during a vehicle's lifetime. At the same time, the authors have made a correlation with an existing model, GREET, obtaining similar data and conclusions, mainly related to the production of vehicles and consequences. This validates the results obtained within the paper, which can be synthesized as follows.

The complete life cycle values obtained herein are similar for current models of ICEVs and BEVs based on the EU/US energy mix: 5.2 and 5 MJ/km, respectively. By comparison, the current models for HEVs, PHEVs, and BEVs based on RES present lower energy consumption, with life cycle values of 4.62, 4.33, and 3.32 MJ/km, respectively. In terms of complete life cycle costs, current ICEVs, HEVs, and PHEVs provide relevant benefits compared to BEVs: EUR 65–68 thousand versus EUR 86–87 thousand. In terms of life cycle emissions, BEVs based on RES show the greatest reduction in greenhouse gases (37% lower than ICEVs (0.195 versus 0.313 kg pollutant/km)) and in other relevant pollutants (62% lower than ICEVs (1.36 versus 3.6 g pollutant/km)). HEVs, PHEVs, and BEVs based on the EU/US mix present values ranging between the limits imposed by the values for ICEVs and BEVs based on RES.

At the same time, by making herein the clear distinction between the main life cycle stages, the vehicle and energy life cycles, another picture can be depicted. While the vehicle LC emissions reveal serious improvements in both GHG and other relevant pollutants' (PM_{10}, NO_x, VOCs, CO, and SO_x) abatement for BEVs when compared to ICEVs, the energy LC GHG and other relevant pollutants' emissions are similar in values for BEV and and ICEV models, showing almost no improvements. This represents a call for alarm, since the decarbonization of the energy sector is one of the main priorities of our society.

The proposed methodology is obviously not an exhaustive one, but offers a clear image of the evolution of current means of transportation. Moreover, the authors consider that this methodology can be used in the future for the necessary synchronization of the development of electric transport technologies along with new electric facilities for the production and distribution of power networks, as well as charging stations (infrastructure).

The main question that was addressed in the paper can be reformulated as follows: Do new (electric) technologies represent an alternative to established (conventional) passenger cars, ICEVs? The authors argue that, from the energy point of view, electric vehicles based on large batteries require more energy and scarce resources (raw materials) whether the structure of the electric energy produced is more or less clean (RES vs. mix). At the same time, by considering only a vehicle's operation stage, electric transport technologies are more beneficial.

In the end, the authors consider that the proposed methodology, which eventually can be improved, constitutes a useful tool for managing the transition to electric transport. Using it will allow the emphasis of the impact of many influence factors involved in the transition of transport activities in the not-so-far future. It is obvious that local factors, such as geography, climate, and demography, and administrative organization factors will play a significant role in this sense. All of these aspects must be taken into account for implementing a more detailed model.

Author Contributions: Conceptualization, M.M.-P.; methodology, M.M.-P. and P.N.B.; software, M.M.-P. and P.N.B.; validation, M.M.-P. and P.N.B.; formal analysis, M.M.-P. and P.N.B.; investigation, M.M.-P. and P.N.B.; resources, M.M.-P.; data curation, M.M.-P. and P.N.B.; writing—original draft preparation, M.M.-P. and P.N.B.; writing—review and editing, M.M.-P. and P.N.B.; visualization, M.M.-P. and P.N.B.; supervision, M.M.-P. and P.N.B.; project administration, M.M.-P. and P.N.B.; funding acquisition, M.M.-P. and P.N.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ager-Wick Ellingsen, L.; Hung, C.R. Research for TRAN committee—Battery-powered electric vehicles: Market development and lifecycle emissions. In-depth analysis. In *Directorate-General for Internal Policies. Policy Department B: Structural and Cohesion Policies*; European Asylum Support Office: Valletta, Malta, 2018. [CrossRef]
2. Machedon-Pisu, M.; Borza, P.N. Are Personal Electric Vehicles Sustainable? A Hybrid E-Bike Case Study. *Sustainability* **2019**, *12*, 32. [CrossRef]
3. Ehsani, M.; Gao, Y.; Emadi, A. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*; CRC Press: Boca Raton, FL, USA, 2017. [CrossRef]
4. EEA. Electric Vehicles from Life Cycle and Circular Economy Perspectives. In *EEA Report N°13/2018*; European Environment Agency: Copenhagen, Denmark, 2018. Available online: https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle (accessed on 1 January 2022).
5. Keramidas, K.; Kitous, A.; Despres, J.; Schmitz, A. *POLES-JRC Model Documentation*; JRC Technical Reports; JRC: Brussels, Belgium, 2017. [CrossRef]
6. Capros, P.; van Regemorter, D.; Paroussos, L.; Karkatsoulis, P.; Fragkiadakis, C.; Tsani, S. *GEM-E3 Model Documentation*; JRC Technical Reports; JRC: Brussels, Belgium, 2013. [CrossRef]
7. Vilchez, J.J.G.; Julea, A.; Peduzzi, E.; Pisoni, E.; Krause, J.; Siskos, P.; Thiel, C. Modelling the impacts of EU countries' electric car deployment plans on atmospheric emissions and concentrations. *Eur. Transp. Res. Rev.* **2019**, *11*, 40. [CrossRef]
8. EU Commission. The PRIMES Energy Model. 2014. Available online: https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/primes_model_2013-2014_en.pdf (accessed on 1 February 2022).
9. ICCT. European Vehicle Market Statistics Pocketbook 2019/20. International Council of Clean Transportation (ICCT) Report. 2019. Available online: https://theicct.org/publications/european-vehicle-market-statistics-20192020 (accessed on 1 March 2022).
10. Lopez-Arboleda, E.; Sarmiento, A.T.; Cardenas, L.M. Systematic Review of Integrated Sustainable Transportation Models for Electric Passenger Vehicle Diffusion. *Sustainability* **2019**, *11*, 2513. [CrossRef]
11. Hao, H.; Liu, F.; Sun, X.; Liu, Z.; Zhao, F. Quantifying the Energy, Environmental, Economic, Resource Co-Benefits and Risks of GHG Emissions Abatement: The Case of Passenger Vehicles in China. *Sustainability* **2019**, *11*, 1344. [CrossRef]
12. Nordelöf, A.; Messagie, M.; Tillman, A.-M.; Söderman, M.L.; Van Mierlo, J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—What can we learn from life cycle assessment? *Int. J. Life Cycle Assess.* **2014**, *19*, 1866–1890. [CrossRef]
13. Yedla, S. Urban Transportation and the Environment. In *Urban Transportation and the Environment: Issues, Alternatives and Policy Analysis*; Springer: New York, NY, USA, 2015. [CrossRef]
14. European Automobile Manufacturers' Association. Vehicles in Use—Europe 2019. 2019. Available online: https://www.acea.be/publications/article/report-vehicles-in-use-europe-2019 (accessed on 20 January 2021).
15. Machedon-Pisu, M.; Borza, P.N. A methodological approach to assess the impact of energy and raw materials constraints on the sustainable deployment of light-duty vehicles by 2050. *Sustainability* **2021**, *13*, 11826. [CrossRef]
16. Liu, W.; McKibbin, W.J.; Morris, A.C.; Wilcoxen, P.J. Global economic and environmental outcomes of the Paris Agreement. *Energy Econ.* **2020**, *90*, 104838. [CrossRef]
17. Tost, M.; Hitch, M.; Lutter, S.; Feiel, S.; Moser, P. Carbon prices for meeting the Paris agreement and their impact on key metals. *Extr. Ind. Soc.* **2020**, *7*, 593–599. [CrossRef]
18. Ghadaksaz, H.; Saboohi, Y. Energy supply transformation pathways in Iran to reduce GHG emissions in line with the Paris Agreement. *Energy Strat. Rev.* **2020**, *32*, 100541. [CrossRef]
19. Daggash, H.A.; Mac Dowell, N. The implications of delivering the UK's Paris Agreement commitments on the power sector. *Int. J. Greenh. Gas Control.* **2019**, *85*, 174–181. [CrossRef]
20. WEC. World Energy Trilemma 2016 Defining Measures to Accelarate the Energy Transition. In *World Energy Council Report*; WEC: London, UK, 2016.
21. Requia, W.J.; Mohamed, M.; Higgins, C.D.; Arain, A.; Ferguson, M. How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. *Atmos. Environ.* **2018**, *185*, 64–77. [CrossRef]
22. Mac Kinnon, M.; Shaffer, B.; Carreras-Sospedra, M.; Dabdub, D.; Samuelsen, G.; Brouwer, J. Air quality impacts of fuel cell electric hydrogen vehicles with high levels of renewable power generation. *Int. J. Hydrogen Energy* **2016**, *41*, 16592–16603. [CrossRef]
23. Lin, W.-Y.; Hsiao, M.-C.; Wu, P.-C.; Fu, J.S.; Lai, L.-W.; Lai, H.-C. Analysis of air quality and health co-benefits regarding electric vehicle promotion coupled with power plant emissions. *J. Clean. Prod.* **2019**, *247*, 119152. [CrossRef]
24. Vallero, D.A. Air Pollution Monitoring Changes to Accompany the Transition from a Control to a Systems Focus. *Sustainability* **2016**, *8*, 1216. [CrossRef]
25. Liao, Y.-W.; Su, Z.-Y.; Huang, C.-W.; Shadiev, R. The Influence of Environmental, Social, and Personal Factors on the Usage of the App "Environment Info Push". *Sustainability* **2019**, *11*, 6059. [CrossRef]
26. Schmitz, S.; Becker, S.; Weiand, L.; Niehoff, N.; Schwartzbach, F.; von Schneidemesser, E. Determinants of Public Acceptance for Traffic-Reducing Policies to Improve Urban Air Quality. *Sustainability* **2019**, *11*, 3991. [CrossRef]
27. Schmale, J.; Von Schneidemesser, E.; Dörrie, A. An Integrated Assessment Method for Sustainable Transport System Planning in a Middle Sized German City. *Sustainability* **2015**, *7*, 1329–1354. [CrossRef]

28. Li, N.; Chen, J.-P.; Tsai, I.-C.; He, Q.; Chi, S.-Y.; Lin, Y.-C.; Fu, T.-M. Potential impacts of electric vehicles on air quality in Taiwan. *Sci. Total. Environ.* **2016**, *566–567*, 919–928. [CrossRef]
29. Tan, R.; Tang, D.; Lin, B. Policy impact of new energy vehicles promotion on air quality in Chinese cities. *Energy Policy* **2018**, *118*, 33–40. [CrossRef]
30. ECA. *Air Pollution: Our Health Still Insufficiently Protected*; Special Report no. 23; European Court of Auditors: Luxembourg, 2018. [CrossRef]
31. European Comission. Standards—Air Quality—Environment—European Commission: Europa. 2017. Available online: https://ec.europa.eu/environment/air/quality/existing_leg.htm (accessed on 15 December 2020).
32. U.S. EPA. *National Ambient Air Quality Standards (NAAQS) | Air and Radiation*; Environmental Protection Agency, Office of Air Quality Planning and Standards: Washington, DC, USA, 2018.
33. World Health Organization. *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*; World Health Organization: Geneva, Switzerland, 2016.
34. European Environment Agency Air Quality in Europe—2019 Report. 2019. Available online: https://www.eea.europa.eu/publications/air-quality-in-europe-2019 (accessed on 29 August 2020).
35. European Comission. Emissions in the Automotive Sector. 2019. Available online: https://ec.europa.eu/growth/sectors/automotive/environment-protection/emissions_en (accessed on 15 January 2021).
36. European Comission, Directorate General for Internal Policies. *Comparative Study on the Differences between the EU and US Legislation on Emissions in the Automotive Sector*; Institute for European Environmental Policy: Brussels, Belgium, 2016.
37. UChicago Argonne. *GREET-Greenhouse gases, Regulated Emissions, and Energy use in Transportation*; UChicago Argonne: Chicago, IL, USA, 2019.
38. Brennan, J.W.; Barder, T.E. *Battery Electric Vehicles vs. Internal Combustion Engine Vehicles*; Arthur D. Little: Brussels, Belgium, 2015.
39. Onat, N.C.; Aboushaqrah, N.N.; Kucukvar, M.; Tarlochan, F.; Hamouda, A.M. From sustainability assessment to sustainability management for policy development: The case for electric vehicles. *Energy Convers. Manag.* **2020**, *216*, 112937. [CrossRef]
40. UNCTAD. *UNCTAD Handbook of Statistics 2021*; UN: New York, NY, USA, 2021. Available online: https://unctad.org/webflyer/handbook-statistics-2021 (accessed on 10 May 2022).
41. World Bank Group. GDP (Current US$) 1960–2020. 2020. Available online: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD (accessed on 20 May 2022).
42. International Energy Agency. *Passenger Car Sales by Key Region, 2010–2020*; International Energy Agency: Paris, France, 2020.
43. Wang, N.; Tang, G. A Review on Environmental Efficiency Evaluation of New Energy Vehicles Using Life Cycle Analysis. *Sustainability* **2022**, *14*, 3371. [CrossRef]
44. Helmers, E.; Dietz, J.; Weiss, M. Sensitivity Analysis in the Life-Cycle Assessment of Electric vs. Combustion Engine Cars under Approximate Real-World Conditions. *Sustainability* **2020**, *12*, 1241. [CrossRef]
45. Van Mierlo, J.; Messagie, M.; Rangaraju, S. Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment. *Transp. Res. Procedia* **2017**, *25*, 3435–3445. [CrossRef]
46. Puig-Samper Naranjo, G.; Bolonio, D.; Ortega, M.F.; García-Martínez, M.J. Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. *J. Clean. Prod.* **2021**, *291*, 125883. [CrossRef]
47. Hooftman, N.; Messagie, M.; Joint, F.; Segard, J.B.; Coosemans, T. In-life range modularity for electric vehicles: The environmental impact of a range-extender trailer system. *Appl. Sci.* **2018**, *8*, 1016. [CrossRef]
48. de Souza, L.L.P.; Lora, E.E.S.; Palacio, J.C.E.; Rocha, M.H.; Renó, M.L.G.; Venturini, O.J. Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. *J. Clean. Prod.* **2018**, *203*, 444–468. [CrossRef]
49. SShi, S.; Zhang, H.; Yang, W.; Zhang, Q.; Wang, X. A life-cycle assessment of battery electric and internal combustion engine vehicles: A case in Hebei Province, China. *J. Clean. Prod.* **2019**, *228*, 606–618. [CrossRef]
50. Ahmadi, P. Environmental impacts and behavioral drivers of deep decarbonization for transportation through electric vehicles. *J. Clean. Prod.* **2019**, *225*, 1209–1219. [CrossRef]
51. Hayes, J.G.; Goodarzi, G.A. *Electric Powertrain*; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2017. [CrossRef]
52. Hirz, M.; Nguyen, T.T. Life-Cycle CO_2-Equivalent Emissions of Cars Driven by Conventional and Electric Propulsion Systems. *World Electr. Veh. J.* **2022**, *13*, 61. [CrossRef]
53. Wu, Z.; Wang, M.; Zheng, J.; Sun, X.; Zhao, M.; Wang, X. Life cycle greenhouse gas emission reduction potential of battery electric vehicle. *J. Clean. Prod.* **2018**, *190*, 462–470. [CrossRef]
54. Zeng, D.; Dong, Y.; Cao, H.; Li, Y.; Wang, J.; Li, Z.; Hauschild, M.Z. Are the electric vehicles more sustainable than the conventional ones? Influences of the assumptions and modeling approaches in the case of typical cars in China. *Resour. Conserv. Recycl.* **2021**, *167*, 105210. [CrossRef]
55. Nichols, B.G.; Kockelman, K.M.; Reiter, M. Air quality impacts of electric vehicle adoption in Texas. *Transp. Res. Part D Transp. Environ.* **2015**, *34*, 208–218. [CrossRef]
56. Sharma, I.; Chandel, M.K. Will electric vehicles (EVs) be less polluting than conventional automobiles under Indian city conditions? *Case Stud. Transp. Policy* **2020**, *8*, 1489–1503. [CrossRef]
57. The World Bank. *World Bank Electricity Production from Oil, Gas and Coal Sources*; Data Databank; The World Bank: Washington, DC, USA, 2016.

58. Held, M.; Schücking, M. Utilization effects on battery electric vehicle life-cycle assessment: A case-driven analysis of two commercial mobility applications. *Transp. Res. Part D Transp. Environ.* **2019**, *75*, 87–105. [CrossRef]
59. Nimesh, V.; Kumari, R.; Soni, N.; Goswami, A.K.; Reddy, V.M. Implication viability assessment of electric vehicles for different regions: An approach of life cycle assessment considering exergy analysis and battery degradation. *Energy Convers. Manag.* **2021**, *237*, 114104. [CrossRef]
60. Bouter, A.; Hache, E.; Ternel, C.; Beauchet, S. Comparative environmental life cycle assessment of several powertrain types for cars and buses in France for two driving cycles: "Worldwide harmonized light vehicle test procedure" cycle and urban cycle. *Int. J. Life Cycle Assess.* **2020**, *25*, 1545–1565. [CrossRef]
61. US Energy Information Administration. What is U.S. Electricity Generation by Energy Source? 2022. Available online: https://www.eia.gov/tools/faqs/faq.php?id=427&t=3 (accessed on 1 April 2022).
62. Eurostat. Fossil Fuels Led in Electricity Generation in 2021. 2022. Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220630-1 (accessed on 1 June 2022).
63. Centre for Research on Energy and Clean Air. Europe's Zero-Carbon Generation Broke Records in the Third Quarter, Cutting Fuel Bills During the Gas Crisis. 2022. Available online: https://energyandcleanair.org/europe-gas-crisis-vs-clean-energy (accessed on 1 December 2022).
64. Machedon-Pisu, M.; Borza, P.N. Impact of the Light-Duty Vehicles' Storage and Travel Demand on the Sustainable Exploitation of Available Resources and Air Pollution Abatement. *Sustainability* **2022**, *14*, 8571. [CrossRef]