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Impact of the Light-Duty Vehicles' Storage and Travel Demand on the Sustainable Exploitation of Available Resources and Air Pollution Abatement

Mihai Machedon-Pisu * and Paul Nicolae Borza

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

Abstract: Light-duty vehicles are the predominant means of road transport. As the world population is expected to increase significantly in the following decades, so too will the car fleet. Due to the rising population, and the implicitly higher travel demand, the energy demand of cars will increase too, and this will put a strain on current resources, with negative effects on the supply chain, possibly leading to more pollution. Many of the current sustainable transport models and frameworks attempt to predict the vehicle market share for different powertrains and the resulting impact based on scenarios that cater to the automotive market and industry demands. At the same time, most neglect aspects regarding resources' depletion and storage demand. In this sense, this study proposes a coherent testing methodology based on the ratio between demand and supply in order to address the limitations of these studies, mainly related to the sustainable exploitation of available resources, which are analyzed herein in correlation with the current predictions. A sensitivity analysis is provided in order to evaluate the uncertainty of utilized predictions. As a result of this analysis, two novel scenarios for assessing the evolution of the vehicle market share are proposed by the authors. When compared to similar scenarios, it was shown that the proposed scenarios lead to noticeable benefits in reducing dependency on the resources associated with a demand of energy and raw materials and in mitigating air pollution, including related costs.

Keywords: light-duty vehicles; sustainable transport; energy; resources depletion; storage demand; supply chain; air pollution

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1. Introduction

Transport activities play an important part in the evolution of our society, assuring the mobility of people and goods [1]. In terms of market, environmental, and human health impacts [2], as well as society's travel needs [1,2], light-duty vehicles (LDV) are the leading road transport means when compared to other transport means (more than 80% of the total fleet), such as buses (that exceed 3.5 tons) and heavy-duty vehicles (HDV), e.g., trucks [3]. The sustainability of transport activities is mainly modulated by two factors: (a) the technological and scientific evolution in the automotive domain [4,5]; (b) the improvement of the legislative frame followed by the implementation of appropriate policies [6]. In the case of LDVs, 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) to battery (all) electric vehicles (BEVs) and to fuel cell vehicles (FCVs) [4,5]. Each type of powertrain requires the improvement of specific components [5]. For example, in the case of electric and hybrid vehicles, energy storage (such as batteries) or generators (such as fuel cells) are essential to achieve high performance [4]. More recently, the development and improvement of autonomous vehicles [7] increased efficiency and safety in operation.

On the one hand, the technological progress is closely related to the evolution of the structure of transport systems and is extensively treated in [4]. On the other, one must take also into account the impact of the LDVs' powertrain evolution on the demand for energy and raw materials in order to address the challenges imposed by the energy transition in [8]. This refers to energy generation including fossil fuels, renewables, and electromechanical sources (in BEVs and FCVs). The on-board energy efficiency, storage capacitance, and type of the LDV's energy converter also play an important role in this sense, as depicted in [9]. Incorporated raw materials can be recovered to a certain degree by recycling and reintroduced in a new industrial cycle, which is a desideratum of circular economy [10]. Starting from the vehicle's production to its end of life cycle, which covers the stages included in a life cycle assessment (LCA)-based analysis, as in [11,12], various studies have assessed the impact of the LDV powertrain related to air pollution [12,13] and the supply chain [14]. As highlighted in [8], the decarbonization of the energy sector can be obtained by opting for renewable energy sources (RESs), as shown in [15].

Many of these considerations are found in the different frameworks and models proposed for sustainable transport in [12,14,16–27]. Dedicated to the decarbonization of the energy sector, the energy–economy simulation models in [16–20] are based on user demand and air pollution abatement, mainly greenhouse gas (GHG) emissions, as detailed in [28,29]. Similar to [16–21], they offer no distinction between the different LDV powertrains when analyzing the various facets of sustainability. However, then, the environmental, economic, and energy impacts of different LDV powertrains are depicted in [12,14,22–27]. Based on various scenarios, the evolution of the vehicle market share for LDV powertrains (ICEVs, HEVs, PHEVs, HEVs, and FCVs) is predicted for all types in [14,23,27] until 2050 and beyond in [24].

Table 1 synthesizes the mentioned sustainable transport studies in terms of data on energy (generation and consumption) including fuels (petroleum, hydrogen), raw materials (supply and demand), storage (battery type and capacity), and on vehicle market share (evolution in time). As seen in Table 1, the main omissions of these studies refer to LDVs' storage characteristics and required raw materials.

Figure 1 offers an image of sustainability which both synthesizes the main characteristics depicted in Table 1 and reflects the methodology to be described in the next chapters.

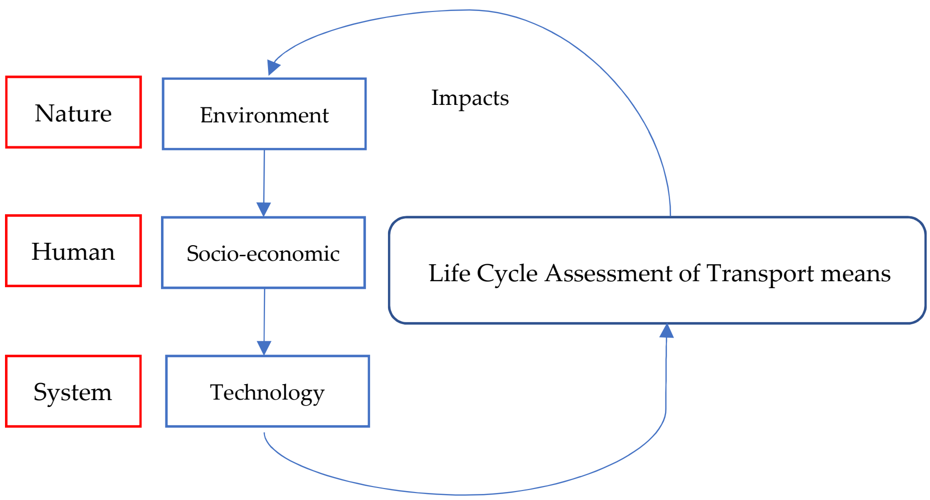


Figure 1. Simplified sustainable transport framework based on the methodology proposed.

Table 1. Comparison between mentioned models and frameworks in terms of data provided based on sustainable transport considerations.

Link	Energy for LDVs		Raw Materials for LDVs		LDV Storage	Vehicle Market Share	
	Gen./Cons.	Fuels/RES	Supply	Demand	Battery Type and Cap.	LDV Powertrain	Period
[12]	Yes/no	Yes/yes	No	No	No	BEV, PHEV [1]	2010–2015
[14]	Yes/yes	Yes/yes	Yes	Yes	Yes	All types	2020–2050
[16]	Yes/yes	Yes/yes	No	No	No	None	-
[17]	Yes/yes	Yes/no	No	No	No	None	-
[18]	No/yes	Yes/no	No	No	No	BEV, PHEV [1]	2017–2030
[19]	Yes/yes	Yes [2]/yes	No	No	No	None	-
[20]	Yes/yes	Yes/no	No	No	No	ICEV, HEV	-
[21]	No/no	Yes/no	No	No	No	All types	-
[22]	No/no	Yes/no	No	No	No	All types	2010–2030
[23]	Yes/yes	Yes/no	No	No	No	All types	2010–2050
[24]	Yes/yes	Yes [2]/yes	No	Yes	No	All types	2020–2100
[25]	No/yes	Yes [2]/no	No	No	No	All except HEV	2015–2050
[26]	Yes/yes	Yes/yes	No	No	No	All except FCV	-
[27]	No/yes	Yes [2]/no	No	No	No	All types	2010–2050

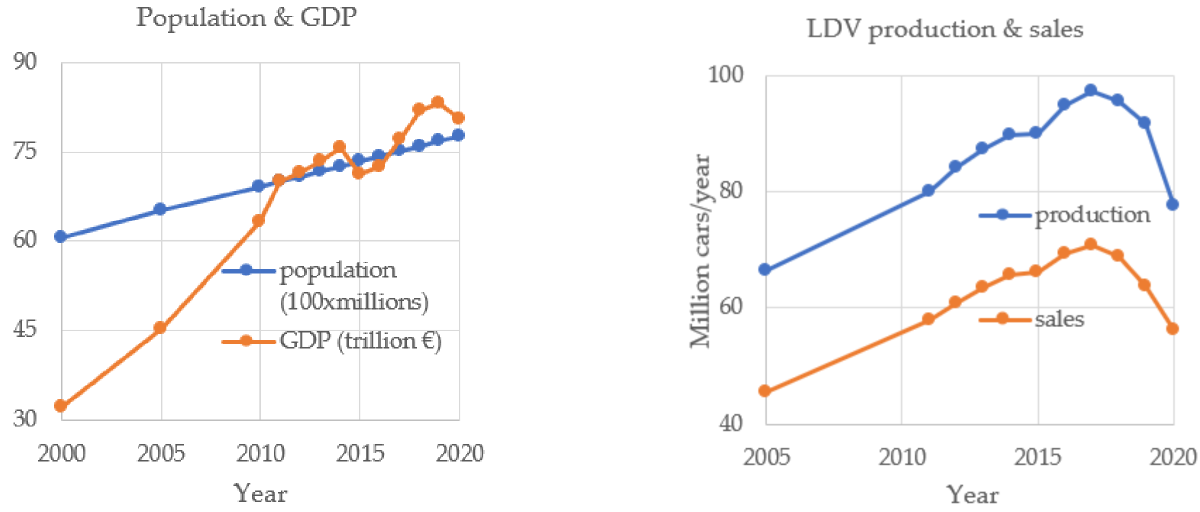
[1] Only regional, [2] Hydrogen included, Gen. = generation, Cons. = consumption.

The paper is structured as follows. The introduction in Section 1 evokes the main LDV powertrain characteristics required in order to analyze the impacts of various sustainable transport models and frameworks mostly related to the exploitation of resources for covering the travel and storage demands and to the decarbonization of the energy sector (GHG emissions).

As a result of this analysis, the paper shortly defines a simplified sustainability framework which represents the basis for the methodology to be presented in the next sections. In Section 2, Materials, an overview of the evolution of LDV sales and production is portraited in correlation with the population and GDP evolutions until 2020, as well as electricity and fuel resources. Future predictions on LDVs' production and travel demand are correlated also with the GDP and population evolution predictions from 2020 to 2050. Based on the LCA analysis, this overview is addressed also in the context of storage demand, which includes both the current battery technologies (mostly based on lithium, nickel, and cobalt) and the new batteries to be implemented (only lithium-based), as well as the decrease in the demand for materials important when recycling, as will be assessed in the next section. Section 3, Methods, includes the proposed methodology used in order to determine the demand over supply ratios (DSRs) for the scenarios proposed in [12,14,16–27], including two novel scenarios proposed herein. The new scenarios proposed in this section are based on a balanced DSR. In Section 4, Results, the most sustainable transport scenarios in terms of DSR that forecast the LDVs' market share evolution are analyzed in terms of the dependency on resources related to energy and raw materials and air pollution abatement. The results are discussed in the final section, Discussion, which highlights the main findings of this study. The uncertainty of the utilized predictions in Sections 2 and 3, which present strong correlations between GDP, population, travel demand, and LDV sales and production evolutions, is also assessed in the final section based on a sensitivity analysis of the projection parameters and their extrapolation.

2. Materials

Based on various reports [30–34], Figure 2 highlights the evolution of population [30], gross domestic product (GDP) [31], and LDV production [32] and sales [33,34] in the last 15–20 years. As seen in Figure 2b, the LDVs' sales and production have a similar slope and show an almost ideal correlation for the study interval. When compared to Figure 2a, correlations can be also found between the evolution in LDVs' production and sales and the evolution of population and GDP.



(**a**) (**b**)

Figure 2. Evolution of: (**a**) population and GDP from 2000 to 2020; (**b**) LDVs' production and sales from 2005 to 2020.

Various predictions for population [35–42] and GDP [36,37,43–49] by 2050 can be compared to the estimated evolution of LDVs' production, depicted in Table 2 and Figure 3, based on three evolution scenarios.

Table 2. Values in million cars/year based on the evolution scenarios for LDVs production.

Year	Linear	LN	EXP
2030	109.1791	109.1025	114.0415
2040	123.6438	123.4236	136.5359
2050	138.1086	137.6747	163.4674

LN = natural logarithm, EXP = exponential interpolations.

Figure 3 displays only the prediction formulas for LN (natural logarithm). In Table 3 only LN and EXP (exponential) evolutions are considered since the Linear one is similar in values to LN. Other types of extrapolations, such as spline, e.g., a third or fourth order polynomial, were also tested; however, they present a poor correlation with the population and GDP predictions [35–49] in most cases. The degree of correlation (%) between the LN and EXP predictions in Table 2 and population and GDP predictions is depicted in Table 3. Various studies that predict the evolution of LDVs' production and sales [14,23–25,27] confirm the feasibility of the adapted predictions shown in Table 2 for the low-demand scenario in [14], for the base and alternative cases in [24], and for the scenarios in [27].

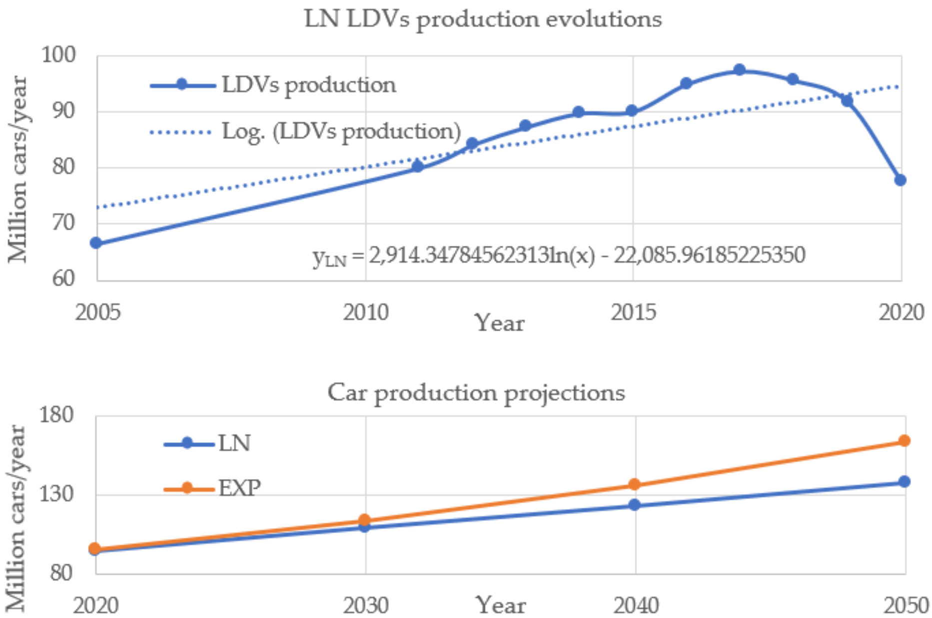


Figure 3. Nonlinear evolution and prediction scenarios (LN and EXP) for LDVs' production including formulas where x = year and y = annual car production.

Table 3. Approximated degree of correlation (%) between Population and GDP predictions and LN and EXP predictions for the LDVs' production from 2020 to 2050 (2020, 2030, 2040, 2050).

Population Predictions Versus LN/EXP LDV Production Predictions										
[35] [1]	[35] [2]	[36]	[35] [3], [37]	[38]	[39]	[40] [1]	[41]	[42] [1]	[42] [1]	[40] [2]
100/100	86/82	−100/−99	100/99	100/100	100/99	100/99	100/99	96/94	99/98	100/99
GDP predictions versus LN/EXP LDV production predictions										
[36]	[43]	[44] [3]	[44] [1]	[37]	[45]	[46]	[47]	[48]	[49]	
−63/−69	100/100	99/100	100/100	99/99	100/100	100/100	99/100	98/99	100/100	

[1] High-, [2] Low-, [3] Medium-valued predictions.

The high demand scenarios in [14] and low stock scenarios in [25] are neglected due to overrated (high) and, respectively, underrated (low) estimated values, which are in contradiction with the population- and GDP-predicted evolutions. The extreme cases that do not match the reasonable assumptions are observed in Table 3 for the low valued predictions in [35] and for [36]. They are also displayed in Figures 4 and 5, which forecast the GDP and population evolutions from 2020 to 2050.

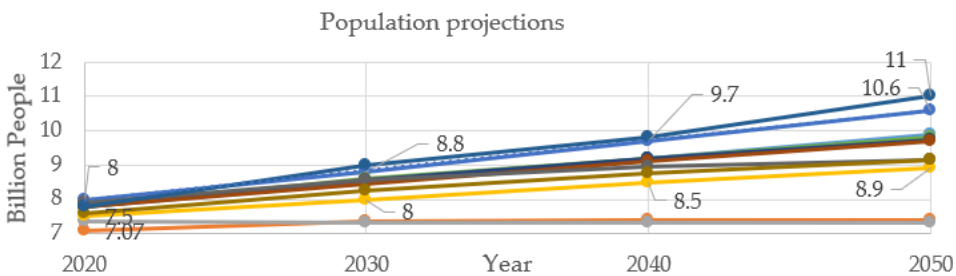


Figure 4. Population predictions from 2020 to 2050 [35–42].

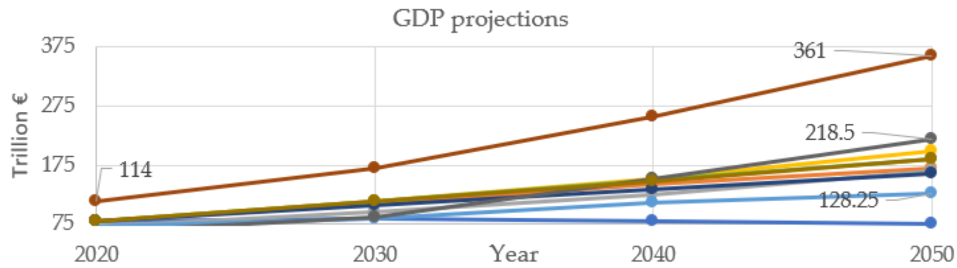
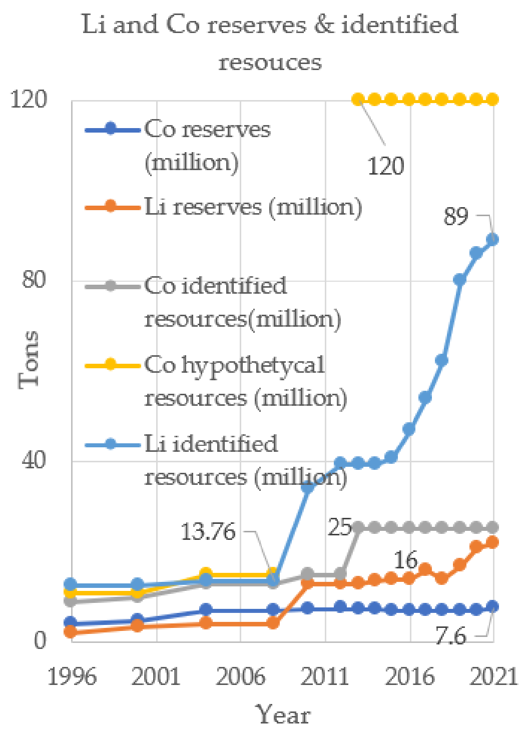
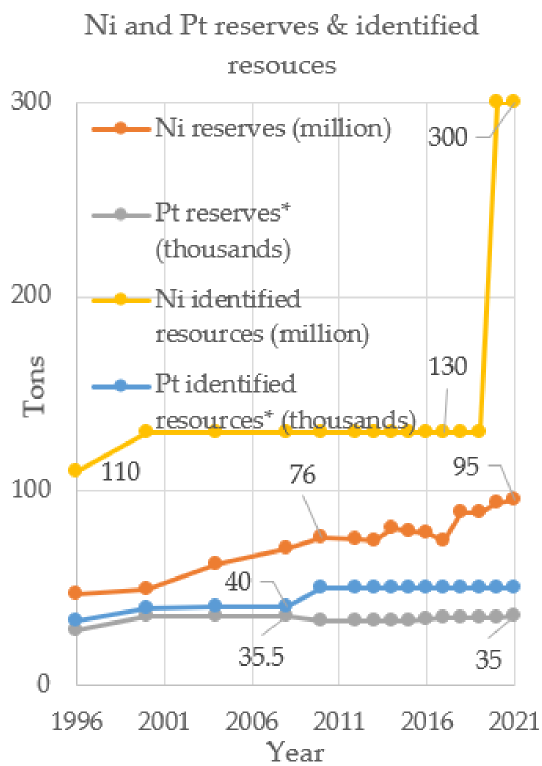


Figure 5. GDP predictions from 2020 to 2050 [36,37,43–49].

Based on the LCA procedure, as shown in [11–13], three main parts (which represent together the whole life cycle) can be identified as Well to Tank (WtT), Tank to Wheel (TtW), and End of Life Cycle (EoL), which include the stages of extraction, manufacturing and assembly (related to WtT or production), and energy generation and distribution (between WtT and TtW), consumption (related to TtW or operation), and recycling (related to EoL). In the production cycle, the main resource indicators are steel, aluminum (Al), lithium (Li), cobalt (Co), nickel (Ni), and platinum (Pt), as presented in [24]. Other materials must be mentioned too, such as iron (Fe), manganese (Mn), copper (Cu), and phosphorous (P) [50]. Due to the high impact on the supply chain, only Li, Co, Ni, and Pt resources will be selected for analysis in the initial cycle, as presented in [14]. Figure 6 is based on the United States Geological Studies (USGS) reports that forecast the identified resources and reserves that are available per year [51].



(**a**)



(**b**)

Figure 6. Evolution of the identified resources and reserves by USGS for: (**a**) lithium and cobalt; (**b**) nickel and platinum from 1996 to 2021. * Pt reserves and resources represent 50% of the total Platinum-group metals (PGM) reserves and resources in [51].

The vehicle's storage demand is crucial in determining how much of the identified resources or reserves to exploit, and this refers to the vehicle's battery type and capacity. Table 4 synthesizes the storage demand per battery type. Since not all resources can be utilized in the production of LDVs, it is also essential to estimate how much of these resources can be allocated. Both aspects were treated in [14], and in the case of allocated resources, the following considerations were made herein: 40% of the total Li resources, 50% of the total Co resources, 10% of the total Ni resources, and 40% of the total Pt resources can be allocated to the production of LDVs.

Table 4. LDV batteries' Li, Co, Ni, and Pt demand per vehicle.

Battery Type	Lithium (kg/kWh)	Cobalt (kg/kWh)	Nickel (kg/kWh)	Platinum (kg)
		For FCV		0.046
		For BEV/PHEV/HEV		
NMC/NCM	0.133	0.32	0.435	-
NCA	0.242	0.142	0.79	-
LFP	0.168	-	0.01	-
Li-S	0.412	-	-	-
Li-Air	0.136	-	-	-

By recycling, more resources will be available for manufacturing LDVs in the future, as will be presented at the end of this section, for the final cycle (EoL).

If, in the production cycle, the storage demand dictates the use of materials for producing the required car components, in the operation cycle, the travel demand must be determined in order to find out how many energy resources are necessary to cover the travel mission. Various predictions for the travel demand have been assessed in [52–60]. Figure 7 displays the estimated evolution of travel demand in Passenger km (Pkm) related to LDVs until 2050.

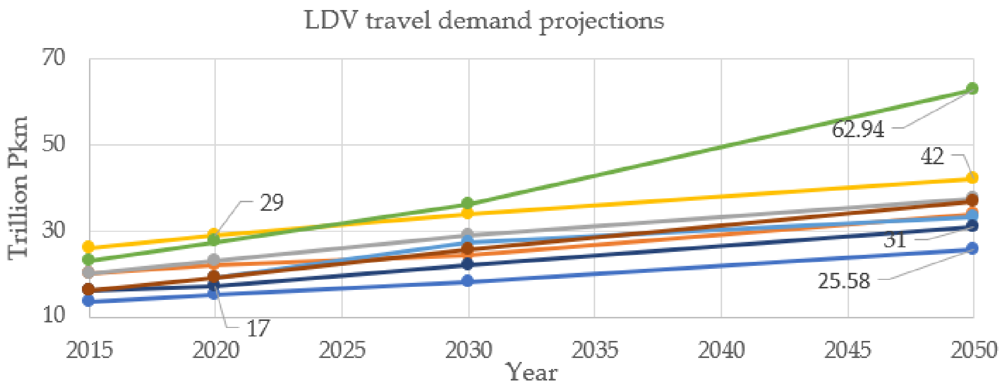


Figure 7. LDVs' travel demand predictions from 2020 to 2050 [52–60].

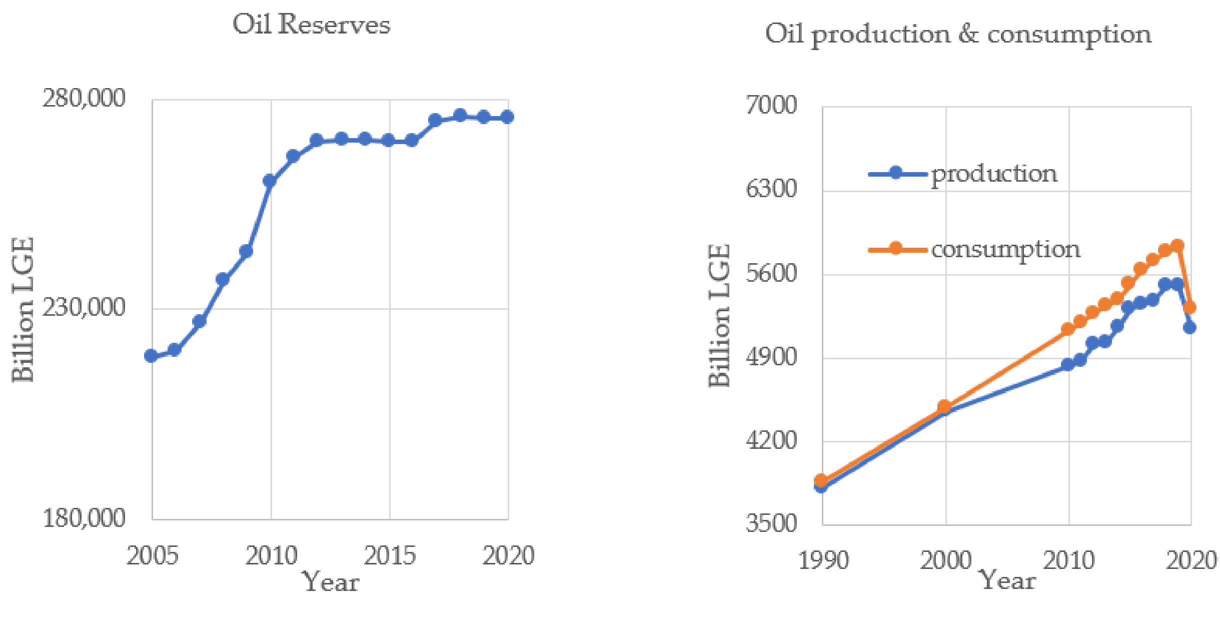
The correlations between these predictions and the population, GDP, car production, and sales predictions are synthesized in Table 5. As seen in Table 5, the predictions in [58,59] offer both reasonable degrees of correlation.

Table 5. Approximated overall degree of correlation (%) between population, GDP, car production and sales predictions, and predictions for the LDVs' travel demand from 2015 to 2050 (2015, 2020, 2030, 2050).

LN/EXP LDV Production and Sales (Including GDP, Population) Predictions Versus LDV Travel Demand Predictions							
[52]	[53]	[54,55]	[56]	[57]	[58]	[59]	[60]
100/100	99/99	100/99	100/99	96/94	99/100	100/100	100/100

To satisfy the travel demand, the main energy resources, which are needed refer to gasoline reserves and their exploitation in order to fuel ICEVs, HEVs, and some PHEVs and the electricity required for charging PHEVs and BEVs, especially by using RESs, which can lead to the decarbonization of the energy sector [8].

Figure 8 presents the evolution of gasoline reserves in liters gasoline equivalent (LGE) [61] and their exploitation in terms of petroleum production and consumption, also in LGE [5,62,63]. Since not all the gasoline can be used for fueling LDVs [64–66], the estimated gasoline use in cars is assumed at 30%, according to the Baseline predictions in [14]. Based on the same predictions, the evolution of oil consumption per car (ICEV/HEV) is expected to drop from an average of 7 LGE/100 km in 2020 to 4 LGE/100 km in 2050, with a decrement of 1 LGE/100 km per decade.



(**a**) (**b**)

Figure 8. Evolution of: (**a**) ail reserves, from 2005 to 2020; (**b**) oil exploitation, from 1990 to 2020.

When charging EVs, renewables (RESs) should come as the first option. The quantity of energy that was available until 2018 is depicted in Figure 9.

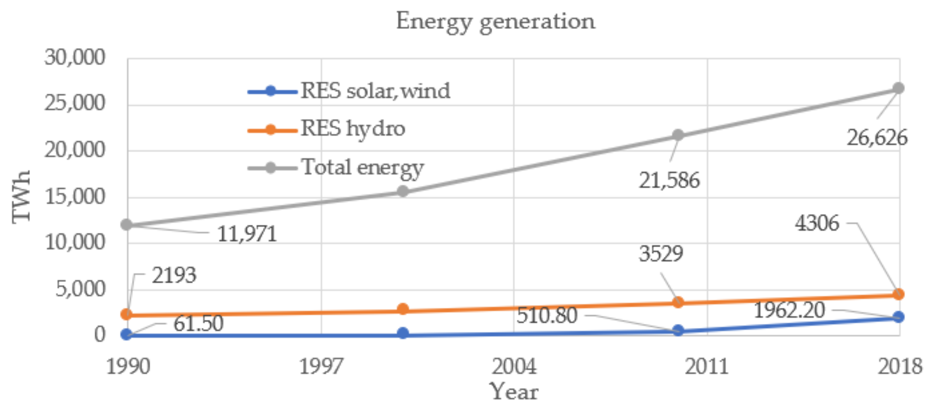


Figure 9. Energy generation from 1990 to 2018.

Based on estimations that reach the year 2050, as presented in the scenarios in [14], solar- and wind-based RESs could increase even by 15–20 times to 40,000 TWh. Table 6 highlights these estimations.

Table 6. Worst-case scenario (WCS) and best-case scenario (BCS) predictions for solar and wind RESs' generation in TWh.

Year	WCS	BCS
2020	2500	3500
2030	8000	16,000
2050	16,500	40,000

The energy demand is directly related to the energy intensity. According to the Baseline scenario in [14], it is estimated at around 20 kWh/100 km in 2020, at 16 kWh/100 km by 2030, at 14 kWh/100 km by 2040, and at 12.5 kWh/100 km by 2050 [67].

The final cycle, which refers to the recycling of car components, can be synthesized in Table 7 when it comes to the raw materials with the most impact on the supply chain, namely, Li, Co, Ni, Pt, as presented in [68].

Table 7. Projected decrease in demand for materials (%) from 2020 to 2050.

Year	Li	Ni	Co	Pt
2020	0.15%	0.13%	0.25%	0.01%
2030	6%	5%	8%	6%
2040	20%	22%	30%	20%
2050	30%	32%	42%	50%

3. Methods

The evolution of the battery capacity for storage-based LDVs: HEV, PHEV, BEV, and FCV is depicted in Figure 10 according to the estimations, predictions, and assumptions in [27,69–81]. Based on the data in Figure 10, the formulas that forecast BEVs' and PHEVs' battery capacity evolutions follow an extrapolation function similar to LN in Figure 3.

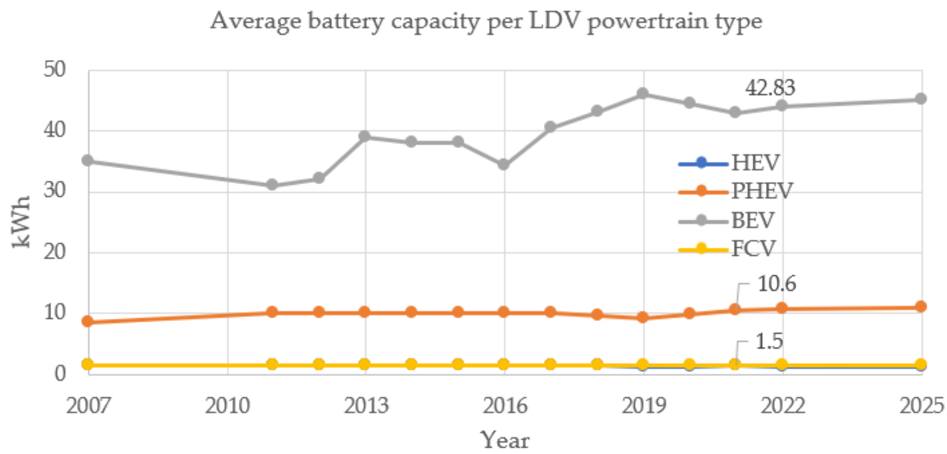


Figure 10. Estimated and predicted evolution of the battery capacity of storage-based LDVs from 2007 to 2025.

Just as important in defining the storage demand as the battery capacity is the adoption rate of the EV's battery chemistry. According to [82], and based on [14] for an optimum ratio between NMC and NCA chemistries, Table 8 highlights the main lithium-based battery technologies that were the most adopted and predicted to be adopted for EVs in the following years.

Table 8. Estimated and projected rate of adoption per battery chemistry in EVs (%), assuming no Li-S or Li-Air market penetration for the 2020–2030 period.

Year	NMC	LFP	NCA
2018 [83]	45%	15%	39%
2019 [83]	53%	3%	43%
2020 [83]	58%	0%	42%
2025 [83]	64%	0%	36%
2030 [14]	72%	0%	28%

Starting from the LDVs' storage and travel demand, plus the decrease in demand of materials, and by taking into account the available resources associated with the production (WtT), operation (TtW), and end of the life cycle of LDVs, it is possible to establish the methodology in Figure 11 which aims to balance the demand over supply ratio (DSR) for various resources available throughout an LDV's whole life cycle.

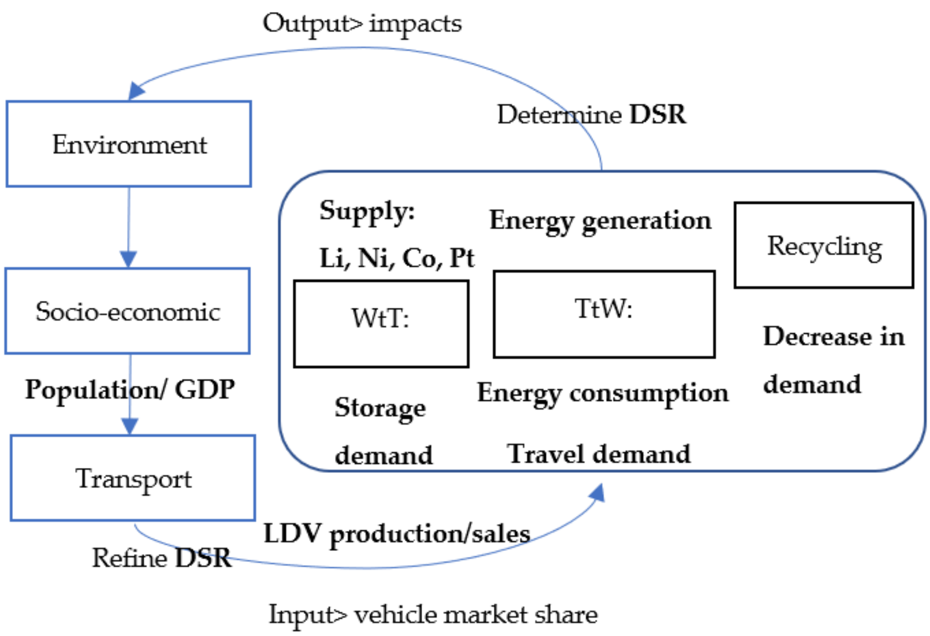


Figure 11. Proposed methodology.

Based on the data in Figure 10, two main scenarios can be formulated for LDV's battery capacity evolution up to 2050 in Table 9: business as usual (BAU), based on tempered storage demand, and natural logarithm-based (LN) predictions.

Table 9. Battery capacity per vehicle (kWh) estimations and predictions for the 2020–2050 period.

Scenario and Year	HEV	PHEV	BEV	FCV
BAU-LN 2020	1.4	10	44.4	1.5
BAU 2030	1.5	11	46	1.5
BAU 2050	1.5	12	50	1.5
LN 2030	1.7	11.2	51	1.7
LN 2050	2	13	67.6	2

The primary inputs for the test methodology addressed in Figure 11, and the vehicle market shares are synthesized in Table 10.

Table 10. Vehicle market share (%) estimations and predictions for the 2020–2050 period.

Scenario and Year	ICEV	HEV	PHEV	BEV	FCV
BAU [23] 2020	91.6	7.2	1.164	0.001	0
BAU [23] 2030	87.6	9.5	2.924	0.001	0
BAU [23] 2050	84	10.8	5.217	0.001	0
S-HEV [23] 2020	80.3	19.2	0.501	0.001	0
S-HEV [23] 2030	53.5	46.1	0.334	0.001	0
S-HEV [23] 2050	0	100	0	0	0
S-PHEV [23] 2020	80.3	4.9	14.786	0	0
S-PHEV [23] 2030	53.5	3.3	43.191	0	0
S-PHEV [23] 2050	0	0	100	0	0
S-EV [23] 2020	80.3	4.9	0.501	14.287	0
S-EV [23] 2030	53.5	3.3	0.334	42.458	0
S-EV [23] 2050	0	0	0	100	0
Base [25] 2020	82.7	12	1.2	4	0.1
Base [25] 2030	33.9	55	3	8	0.1
Base [25] 2050	0.5	10	20	59.5	10
Alt. 1 [25] 2020	82.7	12	1.2	4	0.1
Alt. 1 [25] 2030	17.9	47	15	20	0.1
Alt. 1 [25] 2050	0	0	0	100	0
Alt. 2 [25] 2020	82.7	12	1.2	4	0.1
Alt. 2 [25] 2030	16	47	15	20	2
Alt. 2 [25] 2050	0	0	15	20	65
Scenario [27] 2020	88.5	6.5	3	2	0
Scenario [27] 2030	68	18.5	7.5	5	1
Scenario [27] 2050	45.5	19.5	18	11	6
HER av. NMC [14] 2020	76.613	19.153	0.954	3.18	0.1
HER av. NMC [14] 2030	56	24	1.76	5.865	12.375
HER av. NMC [14] 2050	29.7	29.7	9.362	31.207	0.031
HER av. Li-Air [14] 2020	76.685	19.172	0.933	3.11	0.1
HER av. Li-Air [14] 2030	56	24	1.721	5.735	12.544
HER av. Li-Air [14] 2050	29.7	29.7	9.156	30.519	0.925
LER av. NMC [14] 2020	76.613	19.153	0.954	3.18	0.1
LER av. NMC [14] 2030	49	21	1.496	4.985	23.519
LER av. NMC [14] 2050	15.565	15.565	3.671	12.237	52.962
LER av. Li-Air [14] 2020	76.685	19.172	0.933	3.11	0.1
LER av. Li-Air [14] 2030	49	21	1.463	4.875	23.662
LER av. Li-Air [14] 2050	15.565	15.565	3.81	12.7	52.36

Alt. = alternative case, HER = high exploitation rate, LER = low exploitation rate, av. = average.

Table 11 presents the demand in raw materials sensitive to exploitation (in kg of Ni, Li, and Co and g of Pt per vehicle) for the different LDV powertrains depending on the battery chemistry demand (kg/kWh) data in Table 4 on the scenario type: 72% NMC— 28% NCA, 100% Li-Air, and 100% NMC, based on Table 8, and on capacity evolution scenarios (kWh) BAU and LN in Table 9.

Based on two travel demand scenarios [58] for high demand (WCS) and [59] for low demand (BCS)—, in Figure 7, expressed in Pkm, and by taking into account the estimated consumption in LGE/km, the demand is determined in LGE in Table 12 for the years 2020, 2030, and 2050. Moreover, based on the high and low travel demands, Table 12 includes the available RES solar and wind energy demand in TWh in 2050 if an overall energy intensity of 0.15625 kWh/km is considered, according to the Baseline scenario in [67]. Table 13 synthesizes the available resources for two cases: WCS (low supply) and BCS (high supply) required for battery storage and fueling/charging the vehicle based on low-use scenarios in [14], which considers 0.1 (10%) for Ni, 0.4 (40%) for Li, 0.5 (50%) for Co, and 0.4 (40%) for Pt resources, to which recycling adds more by material recovery, as seen in Table 7.

Table 11. Demand in raw materials (in kg Ni, Li, Co, and g Pt per vehicle) for the BAU and LN battery capacity scenarios based on battery chemistry in 2020, 2030, and 2050.

Scenario and Year	Battery Chemistries	Raw Materials	HEV	PHEV	BEV	FCV
BAU-LN 2020	58% NMC—42% NCA	Ni	0.81774	5.841	25.93404	0.87615
BAU 2030	72% NMC—28% NCA		0.8016	5.8784	24.5824	0.8016
	100% NMC		0.6525	4.785	20.01	0.6525
	100% Li-Air		0	0	0	0
BAU 2050	72% NMC—28% NCA		0.8016	6.4128	26.72	0.8016
	100% NMC		0.6525	5.22	21.75	0.6525
	100% Li-Air		0	0	0	0
LN 2030	72% NMC—28% NCA		0.90848	5.98528	27.2544	0.90848
	100% NMC		0.7395	4.872	22.185	0.7395
	100% Li-Air		0	0	0	0
LN 2050	72% NMC—28% NCA		1.0688	6.9472	36.12544	1.0688
	100% NMC		0.87	5.655	29.406	0.87
	100% Li-Air		0	0	0	0
BAU-LN 2020	58% NMC—42% NCA	Li	0.250292	1.7878	7.937832	0.26817
BAU 2030	72% NMC—28% NCA		0.24528	1.79872	7.52192	0.24528
	100% NMC		0.1995	1.463	6.118	0.1995
	100% Li-Air		0.204	1.496	6.256	0.204
BAU 2050	72% NMC—28% NCA		0.24528	1.96224	8.176	0.24528
	100% NMC		0.1995	1.596	6.65	0.1995
	100% Li-Air		0.204	1.632	6.8	0.204
LN 2030	72% NMC—28% NCA		0.277984	1.831424	8.33952	0.277984
	100% NMC		0.2261	1.4896	6.783	0.2261
	100% Li-Air		0.2312	1.5232	6.936	0.2312
LN 2050	72% NMC—28% NCA		0.32704	2.12576	11.05395	0.32704
	100% NMC		0.266	1.729	8.9908	0.266
	100% Li-Air		0.272	1.768	9.1936	0.272
BAU-LN 2020	58% NMC—42% NCA	Co	0.343336	2.4524	10.88866	0.36786
BAU 2030	72% NMC—28% NCA		0.40524	2.97176	12.42736	0.40524
	100% NMC		0.48	3.52	14.72	0.48
	100% Li-Air		0	0	0	0
BAU 2050	72% NMC—28% NCA		0.40524	3.24192	13.508	0.40524
	100% NMC		0.48	3.84	16	0.48
	100% Li-Air		0	0	0	0
LN 2030	72% NMC—28% NCA		0.459272	3.025792	13.77816	0.459272
	100% NMC		0.544	3.584	16.32	0.544
	100% Li-Air		0	0	0	0
LN 2050	72% NMC—28% NCA		0.54032	3.51208	18.26282	0.54032
	100% NMC		0.64	4.16	21.632	0.64
	100% Li-Air		0	0	0	0
BAU-LN 2020–2050	-	Pt	0	0	0	46

Table 12. Estimated demand in gasoline (billion LGE) in 2020, 2030, and 2050 and in RES energy (TWh) in 2050.

Demand	Year	WCS (High)	BCS (Low)
Gasoline	2020	1923.74	1190
	2030	2168.7	1320
	2050	2517.68	1240
RES energy	2050	9834.688	4843.75

Table 13. Supply (resources) for LDVs' storage and energy (fuel/electricity) available by 2050.

Supply	Unit	Type	WCS (Low)	BCS (High)
Storage for EVs	Million tons	Ni	13.49	42.6
		Li	11.44	46.28
		Co	16.5	79.2
Resources for FCV	Kilotons	Pt	16.5	23.5
Energy for ICEV/HEV	Billion LGE	Gasoline	73,440	
Energy for PHEV/BEV	TWh	RES solar + wind	16,500	40,000

In the case of gasoline and RES resources, the use ratio considered for conventional vehicles (ICEVs/HEVs) is 0.3 (30%) and, respectively, 0.3 (30%) for EVs (PHEVs/BEVs).

Based on the data from Tables 9–13, the following formulas are used in order to determine the demand over supply ratios (DSRs) for LN-WCS (high demand/low supply) and BAU-BCS (low demand/high supply) scenarios, where i = 1:5 in the sum $\sum$ for the 5 LDV powertrains, and the sum $\sum_{year}$ covers the period 2020–2050:

$$\text{DSR\_WCS} = \sum\nolimits_{year} \left(\sum \text{market share}_i \times \text{high demand}_i\right)/\text{Total low supply}, \quad (1)$$

$$\text{DSR\_BCS} = \sum\nolimits_{year} \left(\sum \text{market share}_i \times \text{low demand}_i\right)/\text{Total high supply}, \quad (2)$$

It must be mentioned that, in the case of gasoline resources, in formulas (1) and (2), the Total low supply equals the Total high supply, as seen in Table 13, while, for RES only, the high demand case (WCS) is considered. For simplicity, the sum of ICEVs' and HEVs' market shares is considered altogether in calculations for gasoline resources, and the sum of PHEVs' and BEVs' market shares is the same for RES resources. Based on this, the maximum vehicle market share of EVs (PHEVs and BEVs) that can be charged in WCS (high demand) in 2050 with the available energy (low supply) is around 50.33%.

Table 14 provides the DSR determinations based on the formulas for all scenarios.

As observed in Table 14, most scenarios either exceed the 90–100% range for DSR in WCS or have a very low value of DSR, below 30–40%, in cases mostly related to BCS. While it is unlikely to obtain a one size fits all scenario, which can stay, for example, within the 50–80% range, scenarios with more balanced DSR values can be formulated, such as the two novel scenarios presented in Table 15 together with the calculated DSR values in Table 16.

The two scenarios presented in Table 15 reflect two main battery chemistry evolutions from 2030 to 2050. The first, I Li-Air implies a full transition to Li-Air batteries, which puts the least strain on the supply chain. In the absence of Li-Air battery market penetration, II NMC-NCA proposes an optimum ratio between the two battery chemistries (72% for NMC; 28% for NCA) in terms of least impact on the Ni and Li supply chains. While the first scenario does not consider any restrictions on the Pt dependence of FCVs (46 g Pt per vehicle), the second assumes no Pt is present in FCVs (almost 0 g Pt per vehicle).

Table 14. DSR (%) determinations for the current scenarios for the 2020–2050 period.

Scenario	Nickel WCS/BCS	Lithium WCS/BCS	Cobalt WCS/BCS	Platinum WCS/BCS	Gasoline WCS/BCS	RES Solar Wind WCS
BAU [23]	9.6/2.5	3.5/0.7	4/0.7	0/0	91/52	6.65
S-HEV [23]	19.3/4.3	7/1.2	8/1.2	0/0	94/53.4	0.5
S-PHEV [23]	121/31.8	43.7/9	50/8.6	0/0	38.6/23.6	114
S-EV [23]	601/132	217/37	247/36	0/0	38.6/23.6	113.7
Base [25]	321/67.6	116/19	132/18.3	46.2/27.4	58/35	70
Alt. 1 [25]	529/112	191/31.5	218/30.3	0.64/0.43	43.6/26.7	103
Alt. 2 [25]	200/48	72/13.4	82.2/12.8	306/182	43.6/26.7	54.7
Scenario [27]	95/21.9	34.3/6.2	39/5.9	32.1/19.4	75.5/43.5	33.4
HER NMC [14]	146/31.3	52.7/8.8	86.8/12.1	59.3/39.8	70.9/41	38
HER Li-Air [14]	4.3/1.4	52.7/8.8	1.5/0.3	64.2/42.8	70.9/41	37.1
LER NMC [14]	76.9/17.3	27.7/4.9	45/6.6	354/218	56.7/33.4	18.7
LER Li-Air [14]	4.3/1.4	28.8/5	1.5/0.3	352/217	56.7/33.4	19

Table 15. Vehicle market share (%) for the two novel scenarios for the 2020–2050 period.

Scenario and Year	ICEV	HEV	PHEV	BEV	FCV
I Li-Air 2020	76.6	19.1	1	3.2	0.1
I Li-Air 2030	44.5	20.1	13.5	18.5	3.4
I Li-Air 2050	13.5	20.3	25.4	37	3.8
II NMC-NCA 2020	76.6	19.1	1	3.2	0.1
II NMC-NCA 2030	49	21	9	5	16
II NMC-NCA 2050	15.6	15.6	22	12.2	34.6

Table 16. DSR (%) determinations for the two novel scenarios for the 2020–2050 period.

Scenario	Nickel WCS/BCS	Lithium WCS/BCS	Cobalt WCS/BCS	Platinum WCS/BCS	Gasoline WCS/BCS	RES Solar Wind WCS
I Li-Air	4.43/1.4	80.6/14.2	1.52/0.3	33.7/21.2	55.2/32.4	72.4
II NMC-NCA	111.2/25.7	40.2/7.2	40.1/7	~0/~0 *	56.7/33.4	38

* DSR is almost 0 for no Pt PCVs. If under current conditions (46 g Pt per vehicle), then DSR = 234/145.

4. Results

Figure 12 synthesizes the average DSR values for Li, Ni, Co, and gasoline resources, which represents an average between BCS and WCS values, for the new scenarios: I Li-Air and II NMC-NCA, presented in Table 15, and for S-PHEV [23], Base [25], HER and LER scenarios for NMC and Li-Air in [14], and the Baseline scenario in [27], presented in Table 10. It also includes the DSR values for Pt and RES resources in WCS.

Figure 12 highlights the balanced DSR of the new scenarios, I Li-Air and II No-Pt, except for the case in which Pt will still be used when manufacturing FCVs. It must be mentioned that, in Figure 12f, for the II No-Pt scenario, the value is around 0 if Pt will not be used for FCVs. The value considered is in accordance with the other scenarios which follow the current assumption of a 46 g Pt demand per FCV. Only if the demand in Pt will decrease to 10–20 g per vehicle will the DSR value be acceptable for the II No-Pt scenario. Table 17 assesses the impact on the environment [13,70–72,77,83–90] and, implicitly, on health, including pollution abatement costs [91], and provides the LDV demand profiles of the main operation resources, i.e., gasoline, electricity, and hydrogen [67,70,92].

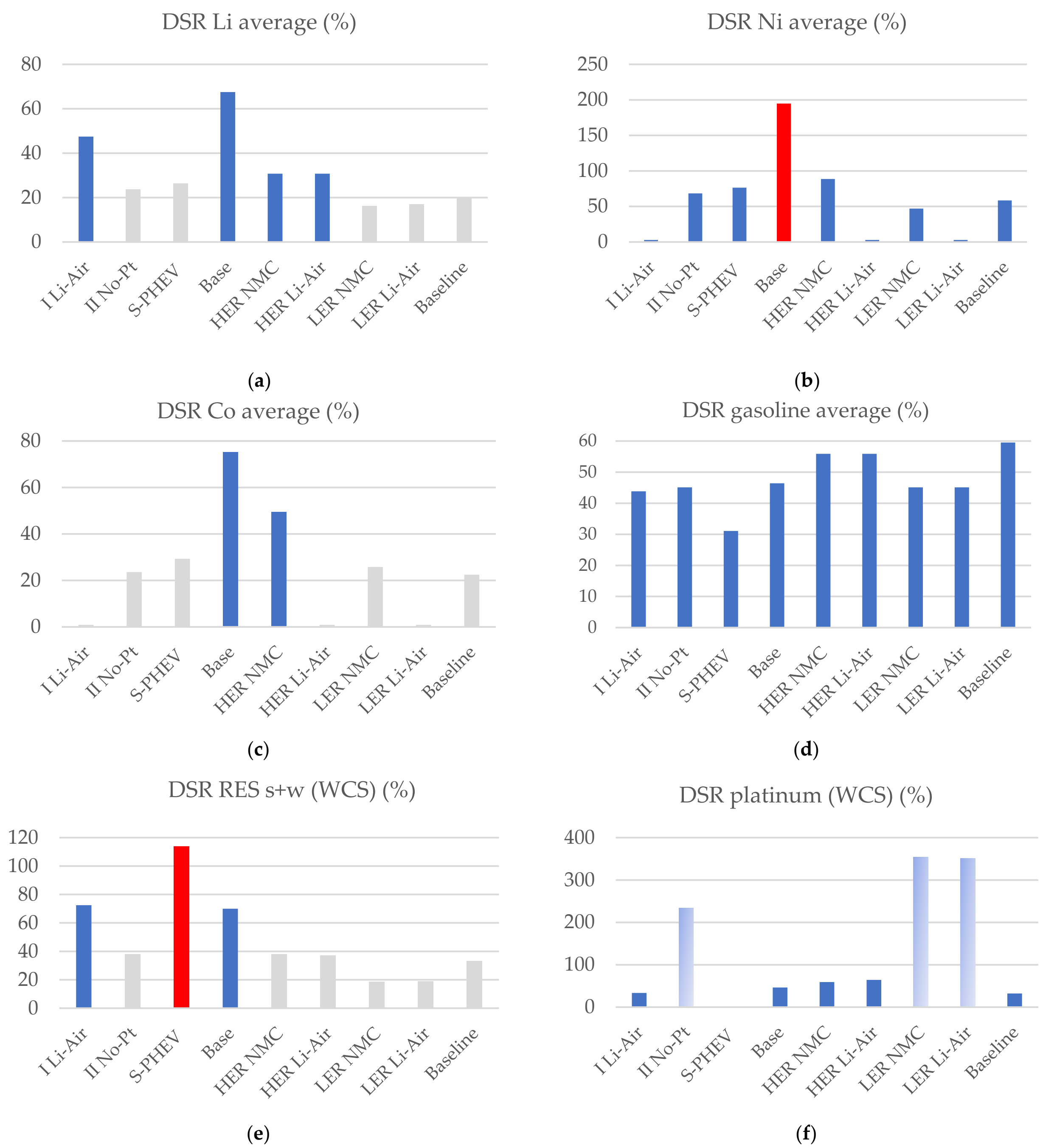


Figure 12. DSR determinations for (**a**) lithium-based storage (average), from 2020 to 2050; (**b**) nickel-based storage (average), from 2005 to 2020; (**c**) cobalt-based storage (average), from 2020 to 2050; (**d**) gasoline resources (average), from 2020 to 2050; (**e**) RES solar and wind resources (WCS), in 2050; (**f**) platinum resources (WCS), from 2005 to 2020, according to nine scenarios.

In order to calculate the total GWP- and PAC-related impacts in Mt CO_2e and Billion EUR- and GEH-related demands in Billion LGE, TWh, and Billion Liters of Hydrogen for the 2020–2050 period (2020, 2030, and 2050); the travel demand in Pkm is added to the formula below, where i = 1:5 in the sum $\sum$ for the five LDV powertrains, and the sum $\sum_{year}$ covers the period 2020–2050:

$$\text{Impact}_{\,GWP/PAC} \text{ or Demand}_{\,GEH} = \sum_{year} \left[\sum \text{market share}_i \times (\text{GWP*}_i/\text{PAC}_i \text{ or GEH}_i)\right] \times \text{travel demand}_{year}, \quad (3)$$

Table 17. Global Warming Potential (GWP) expressed in kgCO_2 e/km, Pollution Abatement Costs (PAC) in EUR/km, and Gasoline, Electricity, and Hydrogen (GEH) consumption in LGE/km, kWh/km, and, respectively, Liter of Hydrogen/km for various LDV powertrains, based on estimations, forecast, and assumptions, for the 2020–2050 period.

Impact and Year	ICEV	HEV	PHEV	BEV	BEV Clean *	FCV
GWP 2020	0.22	0.2	0.18	0.15	0.04	0.15
GWP 2030	0.19	0.18	0.16	0.13	0.03	0.14
GWP 2050	0.145	0.14	0.12	0.1	0.02	0.13
PAC 2020–2050	0.047	0.041	0.042	0.036	-	0.046
GEH 2020 **	6.5	5.5	21	17	-	7
GEH 2030 **	4.23	3.7632	19	16	-	6
GEH 2050 **	3.0576	2.352	16	12.5	-	5

* Based only on solar and wind RES energy, ** LGE/km for ICEV and HEV, kWh/km for PHEV (electric) and BEV, Liter of Hydrogen/km for FCV.

The travel $demand_{year}$ is calculated as an average between the predicted values in [58] and [59], and is 22.241 trillion Pkm (TPkm) in 2020, 29.072 TPkm in 2030, and, respectively, 46.971 TPkm in 2050. Regarding the GWP calculations, the BEV clean* value in Table 17 is not considered in 2020 due to the lack of meaningful global RES penetration; while, in the 2030–2050 period, only BEV clean* values are considered instead of BEV values due to the reduced impact on GWP, associated with clean energy (solar and wind).

Figure 13 presents the total impacts related to GWP and PAC up to 2050 for the nine scenarios according to the predicted vehicle market share.

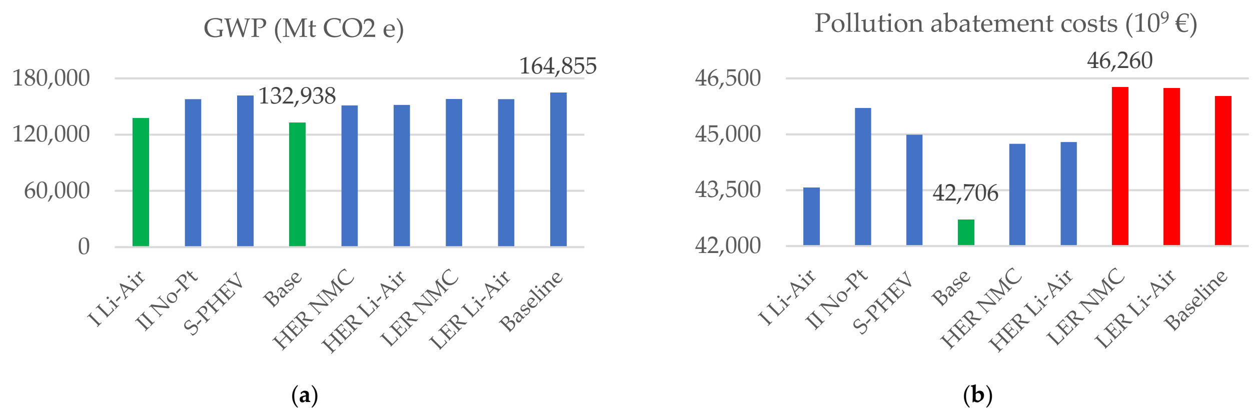


Figure 13. Estimated impacts on: (**a**) GWP; (**b**) PAC, from 2020 to 2050, according to nine scenarios.

Figures 14–16 present the total demand associated with the consumption of gasoline, electricity, and liters of hydrogen required for operating the different LDV powertrains.

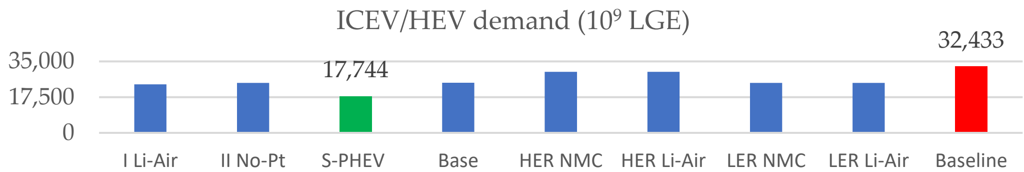


Figure 14. Estimated demand in Billion LGE required for fueling ICEVs and HEVs from 2020 to 2050, according to nine scenarios.

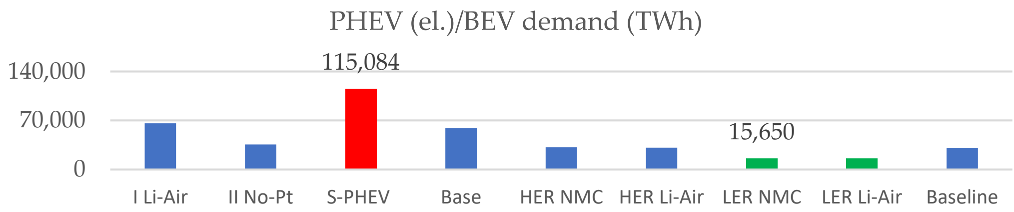


Figure 15. Estimated demand in TWh required for charging PHEVs (electric) and BEVs from 2020 to 2050, according to nine scenarios.

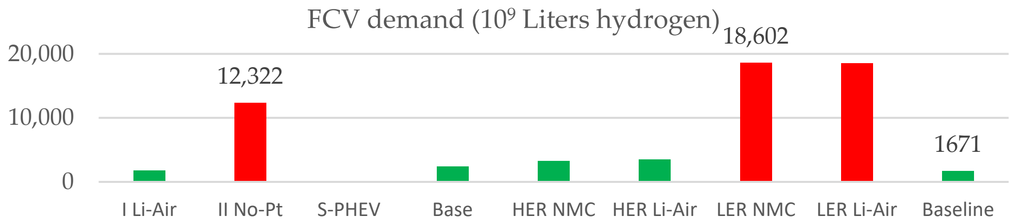


Figure 16. Estimated demand in Billion Liters of Hydrogen required for fueling FEVs from 2020 to 2050, according to nine scenarios.

By analyzing Figures 12–16, it can be concluded that the new scenarios manage not only to balance the DSR in most cases, and thus put less strain on the supply chain, which is related to the available resources' exploitation, but also can prove beneficial in mitigating air pollution, which is mostly related to GHG emissions.

5. Discussion

Due to the uncertain nature of predictions related to the extrapolation functions, which are based on current trends, such as the ones presented in Section 2 and in the beginning of Section 3, it is necessary to provide a sensitivity analysis that can assess the limitations of such projections. Tables 18–22 evoke the projection parameters considered and the type of extrapolations (linear or nonlinear, if known) that modulate the degree of uncertainty, as well as their range when compared to other predictions. The travel demand projections assumed in the methodology depicted in Section 3 are based on a strong correlation with projections that guarantee a 95% confidence interval. Regarding the storage demand projections (modulated by battery's capacity and type), the confidence interval is 80–95% based on the correlations with travel demand and LDV sales. The correlations between GDP, population, and LDVs' travel demand evolutions and LDV sales and production projections are assessed in Tables 3 and 5. The best correlations were those that have shown an almost perfect linear relationship, such as the r coefficient reached values of +0.99 and +1 (+99% to +100% in tables).

In the actual context, of less resources to use for fueling cars, e.g., gasoline, supply chain issues, due to the COVID-19 pandemic, e.g., semiconductor chip shortage and rising prices of gasoline and electricity due to the war in Ukraine, it is more and more important to balance the LDVs' increasing demand of materials and energy with the available resources that must satisfy related travel and storage demands. These can be associated with GDP, population, and emerging technologies' impacts on LDVs' market evolution. The sustainable evolution of the automotive market is reflected also in the air we breathe. Yet, aiming to transition to less polluting cars should be performed without causing disruptions to the supply chain, wherein Li, Ni, Co, Pt, gasoline, hydrogen, and RES resources are at risk of misconduct. One must tackle this issue, as predictions for the vehicle market share are all over the place in terms of market dominance, whether of conventional LDVs (ICE-based) [23,27], of full-electric vehicles (FEVs), mostly BEVs [23,25], or of FCVs [14,25], at the same time almost entirely neglecting the storage demand (battery chemistry and capacity) when predicting the future vehicle market share of various LDV powertrains.

Table 18. Population projections.

Link–Year	Extrapolation *	Parameters	Values	Uncertainty—Confidence Interval
[35]–2004	Nonlinear	Fertility, life expectancy	L to H	Mortality—80–95%
[36]–2015	Almost linear	GDP, growth rate	L	Not assessed
[37]–2006	Unknown	Fertility, growth rate, life expectancy	M	Not assessed
[38]–2020	Unknown	Fertility	M-H	Not assessed
[39]–2017	Nonlinear	Fertility, growth rate, life expectancy	M	Not assessed
[40]–2019	Nonlinear	Fertility-mortality, growth rate-ageing, migration	M to H	Fertility, mortality, migration—95%
[41]–2017	Nonlinear	Fertility, growth rate, life expectancy, education	M	Not assessed
[42]–2021	Nonlinear	Fertility, life expectancy	M	Fertility, ageing, stagnation—0–95%
This study	Nonlinear	Fertility, life expectancy, growth rate, mortality	M to H	Migration, fertility, ageing—90–95%

* Based on current trends, L = low-, M = medium-, H = high-valued predictions.

Table 19. GDP projections.

Link–Year	Extrapolation *	Parameters	Values	Uncertainty—Confidence Interval
[36]–2015	Almost linear	Growth rate, capital, population	L	Population decline—none
[37]–2006	Unknown	Growth rate, production–consumption	L-M	Global public policies—none
[43]–2012	Nonlinear	Growth rate, capital, education, energy–productivity	M	Energy price—none
[44]–2015	Nonlinear	Capital, education, population, energy–productivity	M	Geopolitical context—none
[45]–2018	Unknown	Capital, income, population, and employment data	M	Not assessed
[46]–2022	Unknown	Energy transition	L	Not assessed
[47]–2017	Nonlinear	Investment opportunities	H	Not assessed
[48]–2021	Nonlinear	Growth rate, environment scores	M-H	Not assessed
[49]–2021	Linear	Unknown	M	Unknown
This study	Nonlinear	Capital, population, energy–productivity	L to H	Education, energy price—95%

* Based on current trends, L = low-, M = medium-, H = high-valued predictions by comparison.

Table 20. LDV sales and production projections.

Link–Year	Extrapolation *	Parameters	Values	Uncertainty—Confidence Interval
[14]–2021	Nonlinear	Population, GDP, travel demand	M to H	Vehicle market share—80–95%
[23]–2016	Nonlinear	Population, income, vehicle market share	L-M	Fuel economy, behavior—none
[24]–2019	Nonlinear	Fuel economy **	L to M	Not assessed
[25]–2018	Almost linear	Vehicle market share, purchase probability ***	M	Not assessed
[27]–2012	Nonlinear	Population, GDP	H	Not assessed
This study	Nonlinear	Population, GDP, energy–materials dependency	L to H	Vehicle market share, prices—95%

* Based on current trends, L = low-, M = medium-, H = high-valued predictions when compared to our predictions (this study), ** Based on Chinese and *** U.K. vehicle market reports.

Table 21. LDV travel demand projections.

Link–Year	Extrapolation *	Parameters	Values	Uncertainty—Confidence Interval
[52]–2017	Almost linear	GDP, population, travel preferences	L	Economic growth—none
[53]–2018	Unknown	Unknown	M	Not assessed
[54]–2017	Unknown	GDP, population, travel preferences, technology	M	Not assessed
[55]–2004	Linear	Travel preferences	M	Not assessed
[56]–2012	Nonlinear	Growth rate, travel preferences	M-H	Not assessed
[57]–2015	Nonlinear	Growth rate	M	Fuel prices—none
[58]–2019	Almost linear	GDP, population	H	Not assessed
[59]–2020	Almost linear	Unknown	L-M	Not assessed
[60]–2018	Nonlinear	Population, travel preferences	M	Not assessed
This study	Nonlinear	GDP, population, growth rate, technology	L to H	Economic growth, prices—90–95%

* Based on current trends, L = low, M = medium, H = high-valued predictions by comparison.

Table 22. Battery capacity data estimations and projections.

Link–Year	Study Interval	Vehicle Type (Except ICEV)	Estimation (Studies) or Projection (Uncertainty)
[69]–2021	2012–2019	BEV	Est.: Based on real data/literature (many studies)
[70]–2022	2011–2021	Almost all *	Est.: Based on real data/literature (many studies)
[71]–2020	2019	BEV, PHEV, HEV	Est.: Only one study case
[72]–2021	2021	BEV, HEV	Est.: Only one study case
[73]–2018	2013	BEV, PHEV, HEV	Est.: Only one study case
[74]–2007	2007	BEV, PHEV, HEV	Est.: Based on real data/literature (many studies)
[75]–2011	2007	BEV, PHEV, HEV	Est.: Based on real data/literature (many studies)
[76]–2019	2019	PHEV, BEV	Est.: Based on real data/literature (many studies)
[77]–2022	2013	BEV, PHEV, HEV	Est.: Based on real data/literature (a few studies)
[78]–2018	2017–2025	BEV, PHEV	Pro.: Uncertainty not assessed (based only on 2 years)
[79]-2018	2015–2016	HEV	Est.: Only two study cases
[80]-2019	Unknown	BEV, PHEV, HEV	Est.: Based on real data/literature (many studies)
[81]-2021	2021	BEV, PHEV, HEV	Est.: only one study case
This study	2007–2050	Almost all *	Est.: Based on literature, Pro.: 80–95% confidence

* FCV is neglected for some years, Est. = estimation, Pro. = projection.

In this study, the authors have assessed the impact of the most exploited resources available to LDVs in terms of storage and travel demands. The demand forecast was correlated with the GDP, population, and LDV sales and production for the 2020–2050 period. In order to evaluate the impact on the supply chain, a methodology based on DSR was proposed by the authors for achieving the sustainable exploitation of the resources mentioned above at each stage: WtT (production), TtW (operation), and EoL (recycling), according to an LCA-based analysis. The basis of this methodology is represented by the range defined by the BCS and WCS scenarios that cover the extreme cases of DSR: low demand/high supply (BCS) and high demand/low supply (WCS). Out of the twelve scenarios that forecast the vehicle market share in Table 10, for which the DSR methodology was applied, seven were selected for further analysis, since their DSR values have remained within acceptable bounds. Moreover, based on a balanced DSR, two novel scenarios were proposed herein. These scenarios refer to the future battery chemistry evolutions that can cause less strain on the Ni, Li, Co, and Pt supply chains I Li-Air and II No Pt (72% NMC, 28% NCA), as presented in Figure 12. In terms of air pollution abatement, which aims to decarbonize the energy sector [8], the new scenarios with balanced DSR presented benefits in mitigating GHG emissions (GWP) and reducing related costs (PAC) when compared to the seven selected scenarios, as seen in Figure 13. Moreover, in terms of gasoline, hydrogen, and RES (solar and wind) demand, Figures 14–16 validate that the novel scenarios stay within acceptable limits.

Other aspects that are just as important when making the transition to EVs or FCVs, that were not discussed or detailed in this article, since they are beyond its scope, refer to social and psychological factors, environmental regulations and associated health impact, infrastructure investments and various vehicle costs, and technology transition impacts, to mention a few.

As the system complexity of the future vehicles is expected to increase, wireless sensor networks (WSNs), connected to the cloud, perhaps in a mesh configuration [93–95], will operate beside the Controller Area Network (CAN) bus, and maybe even replace it altogether in the not so far away future, since cables take up a lot of space and require a considerable amount of copper. Moreover, the large deployment of Internet of Things (IoT) and Vehicle to Everything (V2X) permits both the improvement of the extensive traffic management and security and paves the way for autonomous vehicles [96]. Since Industry 4.0 is already here, it is possible that these vehicles will penetrate the automotive market [7]. However, an important aspect that was highlighted in this paper, and that should always work in conjunction with such smart networks based on IoT, is the necessity to charge and store the energy in an effective way. The dependence on energy and raw materials, which was addressed herein, will become more and more demanding in the evolution of LDVs. The energetic challenge also refers to finding new energy management solutions that include the development of communication protocols. The parameters considered are related to the energy and power capabilities of vehicles. Strictly related to the storage of energy, new features such as intelligent power control will facilitate the implementation of heterogeneous solutions such as Hybrid Energy Storage Systems (HESS). Because no single storage device can perfectly fit the applications' requirements, electric hybrid storage solutions were developed in [97,98]. This implies the use of, at minimum, two different storage cells or storage device-like supercapacitors, batteries, and fuel cells [99,100]. Such solutions will increase the overall lifespan of the vehicles' energetic sources, improving not only the energy efficiency, but also allowing a more efficient usage of raw materials for developing the new transport means. Regarding the materials sensitive to exploitation, e.g., Li and Ni, it is possible that new battery chemistries such as NaS and LFP 4680 could reduce this dependence should they become technologically mature. The novel methodology proposed in this study can be adapted accordingly in this sense.

The authors consider that, when addressing the future challenges related to LDV powertrains' adoption, both the demand and supply of energy and raw materials play an important role in defining their market penetration. In this regard, the improvement of on-board electric storage technologies will represent a genuine catalyzer for the new LDVs.

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