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Depreciation in the Electric Vehicle Transition: Sustainability of the Second-Hand Electric Vehicle Market

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Abstract: Electric vehicles (EVs) are revolutionizing road transport. They represented the most reliable and realistic option to decarbonize road transport in the last 10 years and look to be holding a promising future. EVs are in competition with internal combustion engine (ICE) vehicles, but they still have a lower performance, particularly in range, and they remain more expensive. To guarantee the EV development and make it a sustainable substitution to ICE vehicles, the EV industry and technology development had been mostly supported by governments' subsidies. One of the main issues EVs are facing is that they depreciate much faster than ICE vehicles, principally due to rapid technological progress that drives the market on the one hand and, on the other, makes older EV models prematurely obsolete. The other variable that contributes to faster EV depreciation is subsidies. It is expected that the end of subsidies will bring the necessary leverage to slow down EVs fast depreciation due to the wider price gap between new and pre-owned EVs. Batteries, which make EVs a practical reality, play a major role in EV depreciation. Besides the possible degradation of EV batteries, the technology development and price drop give newer models better range at a lower cost. The second-hand EV market is a fair reflection of the fast depreciation of EVs; naturally, the two subjects should be studied correlatively. It may not be obvious to draw an obvious correlation, but it seems clear that the fast depreciation of EVs is one of the major reasons why the second-hand EV market is still minor. Depreciation is a major driver of the second-hand EV market. In this manuscript are presented the main aspects of EV depreciation, particularly those related to fast technological evolution, including batteries and subsidies, as well as the second-hand EV market.

Keywords: electric vehicles; depreciation; second-hand market; subsidies; technology

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Citation: Gautam, P.; Pode, G.; Pode, R.; Ayetor, G.K.; Diouf, B. Depreciation in the Electric Vehicle Transition: Sustainability of the Second-Hand Electric Vehicle Market. *Vehicles* **2024**, *6*, 2044–2074. https://doi.org/10.3390/vehicles6040101

Academic Editor: Mohammed Chadli

Received: 29 October 2024
Revised: 17 November 2024
Accepted: 29 November 2024
Published: 30 November 2024

1. Introduction

Electric vehicles have evolved into a reliable technology to the point where some countries have an objective of 100% EVs for new registrations by 2035 [1,2]. EV technology is matured and competitive. The performance of EVs is comparable to that of ICE vehicles, even if EVs are still lagging in some ways, such as range and faster depreciation, particularly.

Based on literature review, it seems that EV fast depreciation does not have much influence in the vehicle acquisition decision process. Nevertheless, at a second look, buyers indirectly include depreciation of EVs in their main motivations or fear to buy an EV because while deciding, they consider factors such as range, availability of charging network, and obviously acquisition cost before all other variables. The broader EV market is still subject to alternating consumer preferences. These variations induce high-demand periods and other moments when sales are much slower. Despite great brand reputation and leading technology, attraction in EVs can be shifted by external factors like economic conditions, such as energy prices; changes in incentives; frequent issues related to EVs, such as accidental fires; or even new models from competitors. As an illustration, when gas prices spike or environmental restrictions become too strict, there may be an important increase in EV demand; this leads to price increases and consequently slower depreciation. In the opposite case, when incentives are reduced or consumer attention shifts to the latest technology vehicles, potential buyers' interest in EVs may decrease, leading to a fast drop in value.

Another significant factor contributing to the depreciation of EVs is the preoccupation of buyers regarding the after-warranty period. This is mostly because, unlike ICE vehicles, where maintenance and repair costs are more predictable and well understood, EVs are likely to have a high level of uncertainty and cost of repair, particularly related to battery remaining useful life or its possible replacement when necessary. These factors are the main variables affecting EV fast depreciation. This can be understood when considering the influence of fast depreciation of EVs in consumers decision to acquire an EV. Therefore, it is important to look at the reality of the EV and the depreciation of famous models. Manufacturers and governments, through their road transport decarbonization policies, promote EVs for their lower cost of ownership, ignoring the variable depreciation in the process.

Governments subsidized EVs to jump-start their adoption [3–5] and reduce dependence on fossil fuels on the one hand. EVs that are produce zero emissions, are more environmentally friendly than ICE vehicles [6–8], and they also produce zero emissions. On the other hand, subsidies can also be a way to boost the domestic EV manufacturing industry.

Acquisition subsidies have created a market distortion [9–11]. It is expected that the end of subsidies will bring a renewed dynamism to the second-hand EV market due to a wider price gap between used and new EVs. But if subsidies are only concerned with operation and not acquisition, it is likely that the second-hand market will only be marginally affected unless there is an important progress in battery technology making range less sensitive to battery age or density of energy so important that the capacity decrease will be so minor that it will not affect much the expected range.

Presently, it does not look clear what the long-term impact of the subsidy cut will be. But it seems obvious that some EV companies may be strongly affected. With subsidies ending, some of them may find it difficult to compete. Manufacturers with enough leverage may absorb the subsidy loss, while smaller players may face important issues. As a result, only a few large companies may dominate the market in the future. Nevertheless, there are still several factors that could drive the growth of the EV market, including rising fuel prices, governments policies, and technological advancements. If these factors play out favorably, the EV market may continue growing rapidly in the coming years without subsidies.

The post-subsidy EV market may lead to new dynamism in the global used EV market.

The depreciation of EVs has an impact for owners as well as manufacturers. So far, ICE vehicles retain their value better than EVs [12–15], but the market dynamic and the progress in EV technology are likely to lead to comparable depreciation rates in the near future with mature EV markets. This is illustrated with Tesla vehicles that hold their value better, mostly due to the brand's high reputation and proven advanced technology.

It is expected that as technology improves and market demand increases, EVs will retain their value better, leading to slower depreciation rates and a more important second-hand market.

The fast depreciation of EVs is a real problem when considering the average between 4 and 5 years when the first owners put their vehicles on the market. The fast depreciation of EVs may delay the moment when EVs arrive on the second-hand market.

In this manuscript is presented the interplay between depreciation and the second-hand market. Obviously, a fast depreciation is not in the favor of an important second-hand market, particularly at early stages of an innovative industry like the EV. It can be reasonably expected that when the factors driving the fast depreciation of EVs are under control, particularly subsidies and "better" battery technology, price parity achieved between EVs and ICE vehicles will lead to a bigger second-hand EV market.

2. Non-Subsidy EV Market Drivers from Consumers' Perspective

2.1. Depreciation in the Cost of Ownership

The total cost of ownership of a vehicle involves retail price, subsidies, cost of operation as fuel, insurance, maintenance, and depreciation. Nevertheless, depreciation is not generally put forward or not included at all when comparing EVs and ICE vehicles.

Lower cost of ownership of EVs compared with ICE vehicles is commonly cited as a main driver in all countries with a high EV penetration [1]. Lower cost of operation goes along with subsidies and fast technical progress to strengthen the EV transition. These latter two factors respectively contribute to mainstream acceptance of EVs and EVs fast value loss due to rapid obsolescence. Premium EVs, such as Tesla, with a higher technological footprint and integration of artificial intelligence (AI) and range, depreciate at a slower rate corresponding to higher demand on the market compared with lower-end EVs illustrated in this work with the example of the Nissan Leaf. These less sophisticated vehicles undergo a faster depreciation rate. Battery technology is constantly progressing, with increasing energy density that allows longer range at lower cost as battery prices are continuously dropping [16,17]. The increasing technological integration in the automobile industry, particularly EVs, is AI. AI assists in machine learning, safety, efficiency, battery management, vehicle driver interaction, and smart driving [18,19]. AI is becoming an integral part of the vehicle technology; furthermore, its integration in EVs grows very rapidly.

The cost of ownership is a major driver of the EV industry, particularly in countries with the highest rate of EV penetration, as represented in Table 1. Cost of ownership is first of all concerned with the price of electricity compared with gasoline. Countries with the lowest cost of electricity and the highest cost of gasoline will have a tendency to witness the highest EV penetration rate, particularly in urban areas. Table 1 below shows that the typical EV owner is an individual with a high income in a country where electricity is much more affordable than gasoline, lives in a city in a low-density neighborhood, and where EVs already have a certain popularity.

Table 1. Non-subsidy drivers of the EV market in the top 20 markets.

	[20]	[21]	[22]		[23]	Density [24]	[25]
Country	**% of E-cars**	**1l Gasoline (USD)**	**1 kWh (USD)**	**1 l/1 kWh**	**GDP per Capita**	**Pop/km^2**	**%Urban**
Norway	86%	2.091	0.129	16.209	89,154.30	43	84
Iceland	72%	2.242	0.146	15.356	68,727.60	4	94
Sweden	43%	1.853	0.361	5.132	61,028.70	60	88
Denmark	35%	2.066	0.576	3.586	68,007.80	352	88
Finland	31%	2.209	0.454	4.865	53,654.80	43	86
Netherlands	30%	1.945	0.489	3.977	57,767.90	520	93
Germany	26%	1.94	0.554	3.501	51,203.60	605	78
Switzerland	22%	2.014	0.234	8.606	91,991.60	545	74
Portugal	20%	1.778	0.293	6.068	24,567.50	289	67
United Kingdom	19%	1.806	0.412	4.383	46,510.30	715	84
France	19%	1.979	0.217	9.119	43,659.00	303	82

Table 1. *Cont.*

	[20]	[21]	[22]		[23]	Density [24]	[25]
Country	**% of E-cars**	**1l Gasoline (USD)**	**1 kWh (USD)**	**1 l/1 kWh**	**GDP per Capita**	**Pop/km^2**	**%Urban**
Belgium	18%	1.793	0.521	3.441	51,247.00	985	98
China	16%	1.196	0.08	14.95	12,556.30	385	64
Italy	9%	1.959	0.576	3.401	35,657.50	509	72
Spain	8%	1.702	0.369	4.612	30,103.50	243	81
Greece	7%	1.984	0.272	7.294	20,192.60	205	80
Canada	7%	1.3	0.119	10.924	51,987.90	11	82
South Korea	6%	1.233	0.101	12.207	34,997.80	518	81
United States	5%	1.011	0.18	5.616	70,248.60	91	83
New Zealand	4%	1.622	0.193	8.404	48,781.00	49	87

It is then understandable that Norway, Iceland, and Sweden present the highest rate of EV penetration (Table 1).

The EV sales were up to 14% of global sales in 2022 [26], and some studies project EV sales to reach 54% of new cars on the market by 2040 with projections to reach about 70 million EVs to be sold in 2040 [27,28].

Affordability is the first criterion for car buyers to acquire an EV, followed by range and availability of public charging stations [1]. Most of the other criteria from the owners' perspective can be translated in terms of affordability. This can be understood as a potential strong second-hand EV market, provided the vehicles are affordable with a wide price gap with new models and the battery still holds an important proportion of its original capacity to fulfill the range requirements. Subsidies have a major influence on acquisition cost, therefore the gap between new and second-hand EVs.

Among the countries with the highest percentage of EV sales, Norway and Iceland are, respectively, the first and second markets, in percentage, in the list of the top 20 countries with the highest proportion of EVs sold in 2022, ranking, respectively, 2nd and 4th highest GDP per capita in the list presented in Table 1. These countries present as well other remarkable specificities: the highest cost of gasoline and one of the highest ratios of cost of gasoline to electricity. Norway is the country that presents the highest ratio, followed by Iceland. This shows that without subsidies, the operation cost of an EV would be much more beneficial in these countries compared with all the other countries in the list.

The bottom line is that the markets with the highest EV penetration are those where the ownership of ICE vehicles is more expensive and countries where subsidies are higher.

Most of the other variables are directly related to batteries, such as the cost of the vehicle, the performance of EVs, safety, or lifespan. Based on market requirements, more research is still needed even if EV technology has reached a competitive maturity. In the longer run, more research is needed to develop higher-performance batteries to be more competitive in cost, energy density, lifespan, and complexity of materials for easier recycling.

These non-subsidy parameters in Table 1 above obviously concern new EVs as well as pre-owned EVs. The main difference between new EVs and second-hand EV owners is most likely about budget.

The hidden part of the lower cost of ownership of EVs is their faster depreciation rate that is not generally included while comparing EVs and ICE vehicles with potential buyers. When depreciation is included, the cost of ownership of an EV may be much higher than the cost of ownership of an ICE vehicle of the same brand and model.

As an illustration, in 2023 an electric Kia Ray is retailed at USD 21,000 vs. USD 11,000 for a gasoline Kia Ray [29]. Table 2 below compares the real cost of ownership, including depreciation, between an EV Kia Ray and a gasoline Kia Ray after 5 years of operation with the assumption that maintenance is covered by the manufacturer's guarantee.

Table 2. Comparison of cost of ownership between an EV and gasoline Kia Rays.

	EV Kia Ray	**Gasoline Kia Ray**
Cost of acquisition	USD 21,000	USD 11,000
Cost of energy	USD 0.131/kWh	USD 1/l
Average energy consumption	10.5 kWh/100 km	8.5 L/100 km
5 years of accumulated cost of energy	USD 687.75	USD 4250
Total distance covered in 5 years	50,000 km	50,000 km
5-year depreciation rate	50%	35%
5 years of cost of ownership	USD 11,1187.75	USD 8100

Table 2 above presents a comparison between the EV and gasoline Kia Ray, including the vehicles' depreciation. A full consideration of fast depreciation of EVs should lead to a longer period of ownership for EV buyers for the cost of ownership to remain advantageous.

Obviously, the depreciation rate of EVs will depend on countries due to factors that influence it. As an illustration, in countries with lower subsidies, the demand for second-hand EVs will be higher, and the depreciation rate will be slower.

Reaching cost of ownership parity between electric and ICE cars will create an important financial advantage to make the switch to a full EV transition with a more dynamic second-hand EV market.

Subsidies can significantly reduce the number of years required to reach total cost of ownership parity between electric and ICE vehicle equivalents.

2.2. Batteries for a Practical EV Transition

The sustainability of EV transition and its environmental impact will greatly depend on the future of battery technology. Li-ion batteries look to hold a promising future despite the progress in other technology, such as sodium-ion (Na-ion) [30–32].

Between 100% and 80–70% of the state of health (SOH) of batteries remains acceptable [33]. Below 80–70%, some concerns are raised, and the battery needs to be replaced for reliable operation of EVs.

Some technical and economic challenges in EV batteries are in the tradeoff between cost and scarcity of some elements, such as cobalt. Lithium Iron Phosphate (LFP) [1,33–35] technology that is cobalt-free is well used in EVs but with still a lower energy density than Lithium Nickel Manganese Cobalt (LNMC) [1,33].

Currently, standard EV batteries lose 2 to 3% of their capacity per year, corresponding to 7 to 10 years before the capacity drops to 70–80% and the need to replace the battery [36,37]. A 10-year-old EV would not be very attractive to buyers unless the battery is replaced.

In 2015, the battery represented 57% of the EV cost; 33% in 2020, and by 2025 it is expected to be 20% [38]. As well, improved battery life will reduce consumer anxiety over replacement costs and after-post-warranty coverage. Consumers concerns are not only about battery cost but also about faster charging, longer range, and higher energy density for lighter vehicles.

Another role played by the battery price drop is the future price parity between EVs and ICE vehicles. It will be a perfect situation to cut subsidies [38].

The progress in battery technology has been determinant in the adoption of EVs. Important improvements were achieved in safety, performance, and range, with more environmentally friendly materials, longer life, and higher energy density batteries. The plateau in the technical improvement is yet to be reached, as there is still a lot of progress possible in energy density for longer-range and lighter batteries, particularly with the objective of generalized solid-state batteries [39]. Despite all these tremendous achievements that made the EV presently the most credible alternative to decarbonize road transport, the battery seems to be only the main tool that makes EVs a practical reality, along with the distribution of charging stations. In fact, without acceptable ranges and a well-distributed charging network, the EV would not have been a practical means of transportation and adopting it would have been less attractive to drivers. Nevertheless, the main variable that makes the EV a different driving experience compared with ICE vehicles is more than just the powertrain: it is likely to be the technology that brings the biggest novelty with the EV experience, and such a fact is more and more pronounced as time goes on with higher integration of AI, ML (machine learning), and DNN (deep neural network). These algorithms make more and more autonomous driving a standard in EV experience as well as better battery management, more safety, better driver–vehicle experience, and soon more automobile internet, as once upon a time it was for mobile phone technology going from 2G to 3G and 4G to 5G. A transition from a basic phone to a smartphone is more than just about phone calls. The rapid progress in technology looks to be the driving factor of the EV industry but also one of the main reasons for the rapid depreciation of EVs. The role of the battery in EV depreciation looks more to come from their dropping cost, making EVs more affordable, and a trend toward price parity with ICE vehicles. Battery price was divided by about a factor of 10 between 2010, which marks the takeoff of the mainstream EV industry, and 2023. Most manufacturers offer warranties covering 100,000 miles or 70% battery health, whichever comes first, reducing risks considerably for owners.

Subsidies were adopted by governments in different forms to get the industry started for both consumers and manufacturers benefit, as EVs are still more expensive than their ICE vehicle counterparts. More investment will continue to develop batteries to equip EVs of the future with much better range, lighter weight, and more life to outlast the vehicles. Some Tesla models already claim 500,000 miles before the need to replace the battery pack, making obvious the potential of the battery to outlast the vehicle [40]. China is the first country to claim the cut of subsidies as a sign of market maturity; such a decision may not be necessary and will come naturally in all markets as battery prices are continuously dropping and the parity with ICE vehicles will arise naturally.

Furthermore, despite inflation, EV prices did not increase as they could be expected; they even decreased in some cases. For example, in the USA, between 2010 and today, there is an accumulative price increase of 44.03% corresponding to an average yearly dollar inflation rate of 2.64%. USD 1 in 2010 is equivalent in purchasing power to about USD 1.44 today, an increase of USD 0.44 over 14 years [41].

Since 2010, the average cost of Li-ion batteries used in EVs declined by almost 100%, including an adjustment for inflation [42]. As an illustration, Nissan Leaf prices in the US changed from USD 28,120 in 2011 with a battery of 24 kWh to USD 38,839 in 2022 with a battery of 62 kWh, an increase of 258.3% of battery capacity [43].

Most EV manufacturers offer warranties covering batteries between 8 and 10 years or up to 100,000 miles [44]. In the United States of America (USA), federal laws impose on car manufacturers to warranty EV and HEV batteries for a minimum of 8 years or 100,000 miles. The state of California pushes further the protection of customers with a 10-year or 150,000-mile warranty required [45].

However, often EV batteries lifespans can exceed this period and are expected to last up to 20 years. Such a fact should go improving thanks to the evolution of EV battery technology. EV batteries are getting cheaper; the price was divided by a factor of 10 between 2010 and now [46]. As well, the technology is constantly evolving, offering longer lifespans and better performance, particularly the range directly related to the energy density. Nevertheless, replacing an EV battery can be expensive. Some manufacturers offer battery replacement packages including installation. Nissan Leaf, one of the pioneers in the EV industry, offers a battery replacement scheme at a flat rate of £5000 in the UK, and car owners receive an extra £1000 back for their old battery [47]. Yet, the Nissan Leaf is one of the EV models facing one of the fastest depreciation rates. Obviously, the cost of EV battery replacement can be much higher, but it is generally expected to decrease as the battery technology evolves and the demand for affordable battery replacement service increases.

Warranty seems to be a standard in EVs, and it does not contribute much to keeping vehicles value, particularly in the first 3 years when the coverage is full and a long operation time is still left.

Technology drives customers' choice of EVs over ICE vehicles. The continuous battery price drop is likely to bring parity between EVs and ICE vehicles by 2030 [46,48].

There will be two main diverging roads related to EV batteries. If the battery life and performance allow a dynamic second-hand EV market, there will be an important export market, and developing countries may be those where there is a need to invest in the recycling industry, and extracted materials will be sent back to manufacturing countries. Nevertheless, most developing countries have not yet established a real electric mobility policy. On the other hand, if the used EVs are not much exported to developing countries, the recycling industry will increase in most of the countries where EVs have an important penetration rate.

3. The Global Used Cars Market and EVs: The State of Art

The average vehicle age in the United States, as a reference market, has reached a new record lifespan of 12.6 years [49]. The average age of a retail used vehicle can be estimated to be between 4 and 5 years; it corresponds to the age the first owners want to part with their vehicle [50]. Researchers found that the average age of used cars people are seeking is 6.47 years old [51].

The global used car market size was estimated at USD 1.67 trillion in 2023 and is projected to reach around USD 3.05 trillion by 2033 (Figure 1), corresponding to a compound annual growth rate of 6.2% during the forecast period of 2024 to 2033 [52].

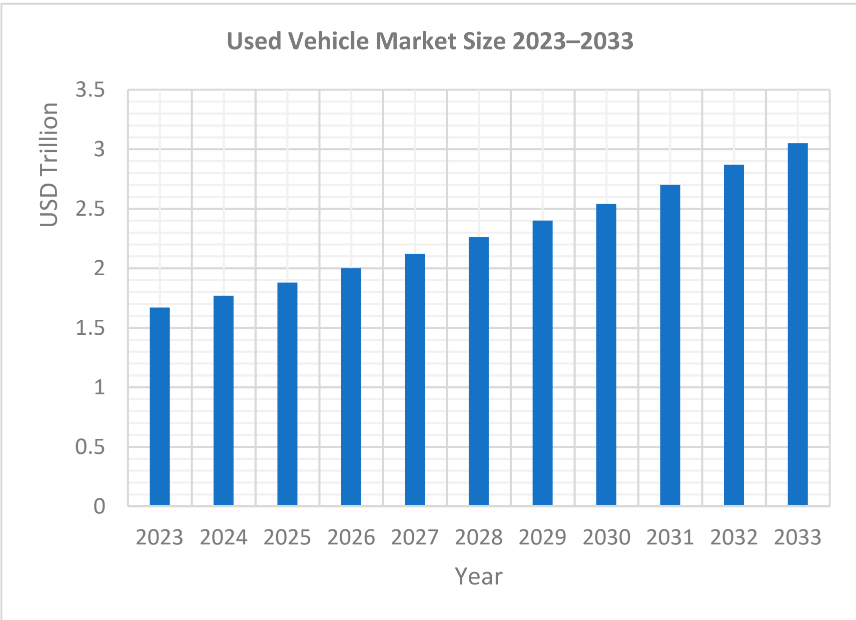

Figure 1. Projection of used car market size between 2023 and 2033 [52].

The most important market for used vehicles is North America, with 30% of the global share, followed by Europe; China, the Middle East, and Africa represent the smallest markets with only 5% of the global sales (Figure 2). Meanwhile, the United States accounted for less than 10% of all new EV registrations worldwide in 2022 [53].

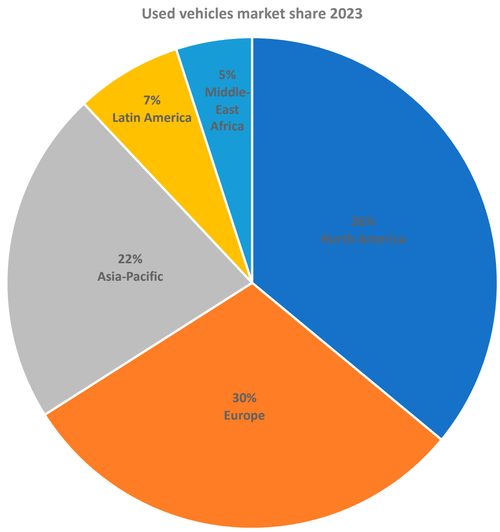

Figure 2. Used car market share by region in 2023 [54].

A new vehicle is generally out of most people's budget. High-income households are more likely to be new car owners than low-income households. In the case of Norway, the country with the highest EV penetration rate, in 2019 a study shows that 31% of new cars were registered by the 10% of highest-income families, while the 10% of households with the lowest incomes are concerned with only a share of 0.6% [55]. Such a disparity is more important when considering the EV market. In the same year, 2019, in Norway, 37% of new EVs were registered by the 10% richest households in 2019 and only 0.7% by the 10% least affluent households [55]. More affordable, second-hand EVs can help to serve the needs of a broader consumer group around the world.

One of the most important features continuously shaping the used vehicle market is the increasing demand for EVs and hybrid vehicles (HEVs) [56]. Figure 3 below shows the spectrum of the used vehicle market, with gasoline and diesel cars largely leading used car sales.

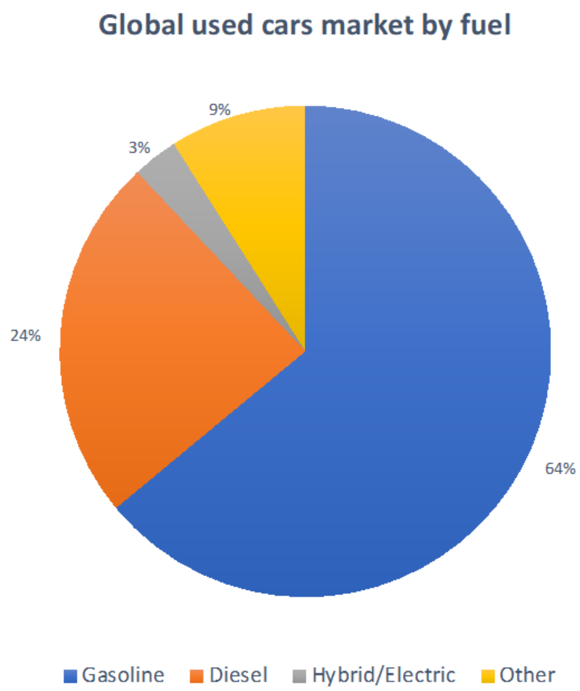

Figure 3. Spectrum of the global used car market by fuel type [57].

As presented in Figure 3 above, even if it is constantly growing, the market of used EVs remains very small compared with traditional ICE vehicles. The increasing viability and affordability of pre-owned EVs can, to some extent, transform the market visibility in the coming years. Furthermore, the popularity of high-end models of HEVs and plug-in hybrid electric vehicles (PHEVs) has added a positive reputation to EV technology. The dynamic of the used EV market may show a clear behavior when the market reaches full maturity.

As for other technologies, the second-hand market for EVs is now growing as earlier adopters switch or upgrade. Second-hand markets are critical to fostering mass-market adoption, especially as new EVs remain expensive and used ones become more available. For ICE vehicles, buying second-hand is often the primary method of acquiring a car in both emerging and advanced economies; it is likely going to be similar with EVs. It is estimated that 80% of the European Union citizens buy their cars second-hand, and this share increases to about 90% among low- and middle-income economies [58]. In the United States, about seven out of ten vehicles sold are pre-owned, and only 17% of lower-income households buy a car new [59].

As major EV markets reach maturity, more and more used EVs arrive on the second-hand market. Nevertheless, the size of the second-hand EV market is still very small compared with new EV registrations. Almost 14 million new EVs were registered globally in 2023, bringing their total number on the roads to 40 million. In 2023, just under 60% of new EV registrations were in China, about 25% in Europe, and 10% in the United States—corresponding to nearly 95% of global EV sales combined. On the other hand, it is estimated that in 2023, the market size for used EVs reached nearly 800,000 in China, 400,000 in the United States, and more than 450,000 when combining France, Germany, Italy, Spain, the Netherlands, and the United Kingdom. In the United States, used EV sales are set to increase by 40% in 2024 relative to 2023. Despite the progress, the second-hand EV market remains insignificant compared with second-hand ICE markets that had decades to mature: 30 million in France, Germany, Italy, Spain, the Netherlands, and the United Kingdom combined; nearly 20 million in China; and 36 million in the United States.

Nevertheless, second-hand EVs are increasingly becoming more affordable so that they can compete with used ICE equivalents in the near future. In the United States, for example, an important proportion of second-hand EVs are already priced below USD 30,000 [60]. Moreover, the average price is expected to quickly fall towards USD 25,000, the price at which used EVs become eligible for the federal used car rebate of USD 4000, making them directly competitive with the best-selling new and used ICE options. The price of a second-hand Tesla in the United States dropped from over USD 50,000 in early 2023 to just above USD 33,000 in early 2024, making it competitive with a second-hand SUV and many new models as well. In Europe, second-hand EVs can be found between EUR 15,000 and EUR 25,000 (USD 16,000 and 27,000), and second-hand plug-in hybrids are around EUR 30,000 (USD 32,000). Some European countries also offer subsidies for second-hand EVs, such as the Netherlands (EUR 2000), where the subsidy for new cars has been steadily declining since 2020, while that for used cars remains constant, and France (EUR 1000). In China, used EVs were priced around CNY 75,000 on average in 2023 (USD 11,000) [60].

While looking at the markets with the highest EV penetration, such as Norway, the same drivers should explain the dynamics in the used EV market. The main difference is direct subsidies that may be decisive in the adoption of a new EV. There should be an important difference between subsidy-driven markets and post-subsidy markets. Subsidies are not the only limiting factor affecting the used EV market; fast progress in technology, the performance and depreciation of EV components, such as batteries, motors, etc., have an impact on the success of the global used EV market [61,62].

The introduction and evolution of EVs in the global EV market and their contribution to road decarbonization is likely to follow an S-curve (Figure 4) [1]. It corresponds to an early stage when the pickup is slow as consumers' do not have enough knowledge and confidence in investing in used EVs. As EVs' popularity grows more and more, thanks to subsidies, consumers will have increasing trust in EV technology and invest in used EVs more as they will know what to expect. This will continue till saturation corresponding to an equilibrium between new and pre-owned EVs on the market every year. The proportion between new and used vehicles on the market depends on countries. In the USA it is about 30% of new vehicles versus approximately 70% for used vehicles in 2022 [62].

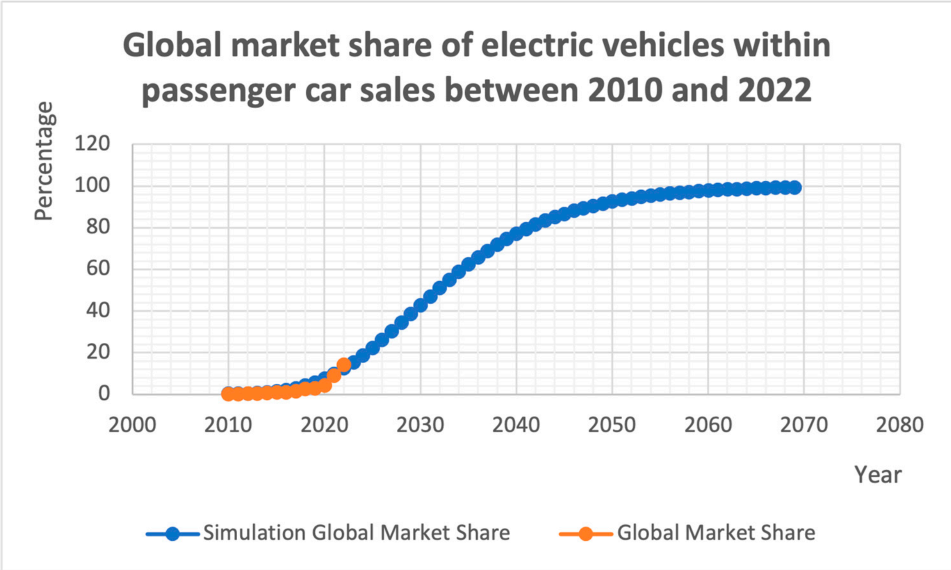

Figure 4. Global EV transition statistics and simulation.

The S-curve above is given by the following expression 1:

$$f(t) = \frac{100}{[1 + \exp(-\alpha t)]^k}, \text{ where } \alpha > 0 \text{ and k} > 0, \tag{1}$$

where $f(t)$ represents the rate of market penetration of used EVs when t increases to infinity $f(t)$ tends to saturation.

In the above curve, $\alpha = 0.25$ and k = 11 as in reference [1], where α and k are obtained from an empirical method [1].

One of the main questions that needs an anticipated response is the dynamic that will take the proportion of used EVs in the electric transport transition, globally and by country.

A main role will be played by EV depreciation rates and technical evolutions. Second-hand EVs are expected to meaningfully enter the market now that it has been more than 10 years after the introduction of EVs in road transport around the world. It is then expected that the ratio between new and used EV registrations will reach an equilibrium of x% for new EVs and y% for pre-owned EVs. Similar equilibrium applies to most of the non-perishable commercial goods: mobile phones, computers, and bicycles. Such an equilibrium between new and changing ownership will depend on markets. Developed countries with generally good access to financial systems will have a higher proportion of new vehicles in total new registrations, while in the least developed countries, almost 100% of new registrations are made up of pre-owned imported vehicles. It is accepted that worldwide, in the first 10 years, almost all EV registrations will be made of new EVs.

In recent years, the resale value of EVs has been increasing. In Europe, the resale value of EVs sold after 12 months has steadily increased over the 2017–2022 period, surpassing that of all other powertrains and standing at more than 70% in mid-2022. The resale value of EVs sold after 36 months stood below 40% in 2017 but has since been closing the gap with other powertrains, reaching around 55% in mid-2022. This is the result of many factors, including higher prices of new EVs, improving technology allowing vehicles and batteries to retain greater value over time, and these factors slow down depreciation and increase demand for second-hand EVs. Similar trends have been observed in China.

The question of the second-hand EVs can be more complex when we consider the possible future coexistence between EVs and ICE vehicles. In fact, as presented, energy transition technologies are often envisaged to follow S-curves: rapidly inflecting, then reaching 100% market adoption. However, it is very likely that EVs will continue to coexist with ICE vehicles; it is therefore important to ask the question of the future balance between the two technologies globally. Some analysts argue that EVs will more likely saturate at 15–30% of sales in 2025–2030 [63]. EV sales, already at 15% of global vehicle sales in 2023, will keep progressing, particularly due to some policies. So, what would the more limited EV upside mean for energy demand and capacity of supply and materials?

Affordability remains one of the major barriers to EV adoption. Hence, without coercive policy, income will be a limit to EV adoption and therefore impose a form of saturation in the EV market. Data related to income distributions will determine the saturation limit to EV adoption. Climate attitudes are another barrier to EV adoption.

Market saturation for EVs would have extreme implications across energy and materials markets due to the important demand. The demand across EVs and ICE vehicles will be concerned with oil demand, the electricity demand of EVs, lithium demand for batteries, and with implications across new energy sources and investment.

4. Depreciation of EVs: Statistics

4.1. Depreciation of Some Famous EV Models

EVs lose their value faster than any other type of vehicle. In 2023, the average EV had lost 49.1% of its value after the first five years of operation [64]. Among the most famous brands that lost an important value after their first five years of operation are Chevrolet Bolt EV, which lost 51.1%, and the Nissan Leaf, 50.8% [65].

Fast technological progress and incentives that effectively made new EVs more affordable are two of the causes of EVs fast depreciation compared with equivalent ICE vehicles (Tables 3 and 4). This scheme may continue until the EV market reaches maturity and no longer requires heavy incentives matching consumers' confidence in their long-term ownership costs. With a mature market and technology, the end of subsidies will create a higher demand for used EVs, consequently increasing their value.

Table 3. EV depreciation from leased vehicles study [65].

Audi A6	55.8%
Ford Fusion Hybrid	54.9%
BMW 3 Series	53.4%
Volvo S60	53.2%
Mercedes-Benz E-Class	52.7%

Table 4. Five EV models with the highest depreciation rates after 3 years [65].

BMW i3	60.4%
Nissan LEAF	60.2%
Kia Soul EV	58.7%
Hyundai Ioniq Electric	47.7%
Chevrolet Bolt	47.5%

A study focused on a better understanding of how EV and ICE vehicle depreciation differs. The study was concerned with off-lease cars that have completed their contract [64].

The study looked for the off-lease car models that lost the highest value at the end of a three-year contract. The study showed that the typical model lost 39.1% of its original price by the time it turned three years old.

Among the off-lease car models covered by the study, the Audi A6 was the biggest loser. The luxury car depreciated by 55.8% of its original selling price [65].

Of those five vehicles, the Ford Fusion Hybrid and the Volvo S60 are EVs.

The second-hand market with high resale values benefits leasing companies. Their advantage is a market with the lowest depreciation so that they can resell their vehicles at the best price after a few years. These companies have a significant impact on second-hand markets due to their large volumes of vehicles for a shorter period. They generally conserve their vehicles under three years, compared with 3 to 5 years for a private household. They can have an important influence as well on the new vehicle market; as an illustration, in 2022, leasing companies accounted for over 20% of new cars sold in Europe.

Here are in Table 4 five EV models with the highest depreciation rates after three years of use:

The depreciation rates of the BMW i3, the Nissan LEAF, and the Kia Soul EV are higher than that of the Audi A6.

It would not be surprising to have these vehicles arriving in the second-hand market with an important delay compared with slower depreciation models.

4.2. EVs vs. ICE Vehicles Depreciation

Figure 5 below shows that between 2020 and 2023, the average depreciation rate of EVs was 51% for EVs vs. 31% for ICE vehicles.

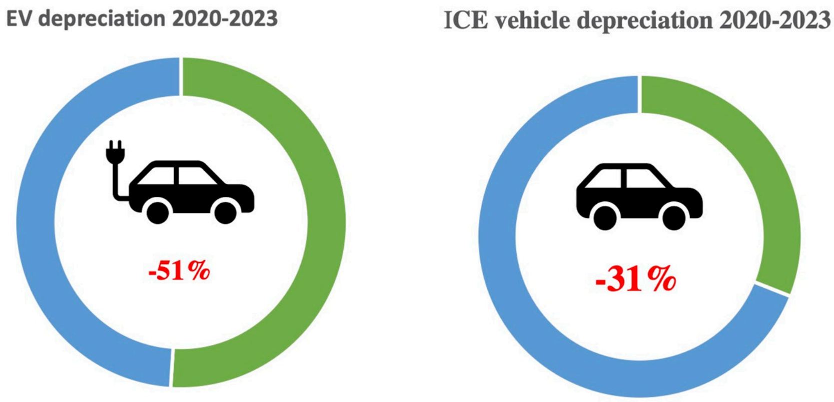

Figure 5. Depreciation rates of EVs vs. ICE vehicles [66–68].

According to a study, most three-year-old EVs generally lose 52% of their price tag as brand-new units, which is higher than the 39.1% of conventional counterparts. Table 5 shows the depreciation of famous EV brands and models in the United Kingdom.

Table 5. Depreciation of famous EV brands and models [69].

Car Make	Initial Range	Price New in 2020 (Pound UK)	Value in 2023 (Pound UK)	Depreciation (Pound UK)	Depreciation
Hyundai ionic	295 km	32,950	15,500	17,450	−53%
VW ID3	405 km	39,425	23,000	17,425	−42%
Nissan Leaf	340 km	26,995	14,000	12,995	−48%
Mini Electric	310 km	27,500	17,500	10,000	−36%
Honda E	335 km	28,000	22,000	6000	−21%
Renault Zoe	315 km	29,000	14,000	15,000	−52%
Kia e-nero	385 km	36,145	24,000	15,145	−34%

Table 5. *Cont.*

Car Make	Initial Range	Price New in 2020 (Pound UK)	Value in 2023 (Pound UK)	Depreciation (Pound UK)	Depreciation
Polestar 2	470 km	49,900	38,000	11,900	−24%
Tesla 3	420 km	40,500	25,000	15,500	−38%
Tesla S	575 km	75,000	50,000	25,000	−33%

4.3. Deprecation of Some Gasoline Vehicles

Table 6 shows the depreciation of famous ICE vehicle brands and models [69] in the United Kingdom.

Table 6. Depreciation of famous ICE vehicle brands and models [69].

Car Make	Price New in 2020 (Pound UK)	Value in 2023 (Pound UK)	Depreciation (Pound UK)	Depreciation
Hyundai i30	22,000	15,000	7000	−32%
VW Golf TSI	26,000	16,500	9500	−37%
Nissan Micra	17,200	11,500	5700	−33%
BMW 3 Series	32,000	23,000	16,670	−28%
Mini Clubman	21,000	16,500	4500	−215
Honda Jazz	20,000	11,000	9000	−45%
Renault Clio	17,595	11,500	6095	−35%
Kia Ceed	25,450	14,500	11,450	−43%
Jaguar F Type	54,000	42,000	12,000	−22%
Mercedes E Class	39,000	32,000	7000	−18%
Range Rover	85,000	65,000	20,000	−24%

Table 6 above shows the depreciation of famous EVs and ICE brands and models.

The current second-hand EV market is affected by two main independent factors: the subsidies that make a new EV affordable and the deterioration of the battery that can substantially decrease the initial range, leading to the depreciation of the EV. Obviously, EVs are still in their infancy compared with ICE vehicles.

The comparison between Tables 5 and 6 shows the important difference between the depreciation of EVs and ICE vehicles.

5. EV Evolution and Depreciation of Entry vs. Premium Models: Nissan Leaf vs. Tesla Model S

Depreciation has the same causes almost in all markets; nevertheless, the importance they may have on depreciation depends on the market. It remains generally accepted, though, that EV depreciation curves are not linear. EVs experience significant initial depreciation within the first few years of ownership. On average, new models can lose between 40% and 50% of their value within the first three years. This initial depreciation is typically steeper for high-end vehicles, where the market is smaller, and buyers are often looking for the latest and greatest features.

On the other hand, what is called long-term depreciation tends to stabilize after the first few years, leading to a quasi-linear section of the curve. A well-maintained EV, still under warranty, that is about 5–7 years old can retain about 40–50% of its original value, depending on the condition, mileage, and any aftermarket upgrades. Some EVs tend to hold their value better in the long term compared with some other models, based on brand recognition and features. Older EV variants may struggle to keep up with the latest technology, leading to further depreciation. Additionally, the out-of-warranty concerns discussed earlier can also play a significant role in the long-term value retention of EVs.

The importance of technology and brand reputation in the depreciation of EVs can certainly be seen while comparing two models of different categories commercialized during the last 10 years: the Nissan Leaf and the Tesla Model S in the USA market. The Nissan Leaf for the lower-end EVs faces a higher depreciation rate, and the Tesla Model S for premium EVs keeps its value better [70].

These two different categories of EVs show the importance of technology integration as well in the depreciation of EVs; this is particularly the case of batteries that have better performance over the years with higher energy density and lower price and AI that is becoming more and more a standard in EVs.

The transformation witnessed today in the automobile sector is comparable to the change that affected the smartphone industry in the early 2000s. An EV is a programmable device that is upgraded consistently and regularly. There are certain improvements happening constantly in parts of the vehicle, such as sensors, the safety system, the battery management system, electric powertrain systems, navigation systems, among others.

One of the main issues that the EV industry is starting to face is obsolescence, particularly for lower-end vehicles. Vehicles are outdated due to fast technological innovation that brings a mismatch between the latest software and older hardware.

a. *Nissan Leaf [70]*

The Nissan Leaf, a pioneer in the EV industry and one of the most affordable EVs currently on the international market, is nearing the end of its lifespan. According to a report in Automotive News, Nissan does not plan on introducing a next-generation version of the Leaf and may even discontinue the nameplate altogether. The Nissan Leaf as an EV is certainly an excellent example due to its longevity on the market; it was first commercialized in 2010 with an announced range of 159 km with a battery of 24 kWh. Nissan's 2017 model had a range of 172 km with a 40 kWh battery; the 2018 model is at 243 km; the 2019 model is 346 km with an upgraded battery of 62 kWh, and the current 2021 model is rumored to be around 362 km. As well, important upgrades are being made in the navigation system, powertrain, and safety systems, making the car efficient and high-tech.

Since its launch in December 2010, the Nissan LEAF has sold more than 650,000 units worldwide. The model, currently sold in approximately 50 markets centering on Japan, the U.S., and Europe, continues to be highly evaluated by customers around the globe and has won numerous prestigious awards in multiple markets [70].

Table 7 below shows the evolution of the battery for the Nissan Leaf between 2011 and 2022. The evaluation is based on the United States Environmental Protection Agency officially rating different figures from Nissan-quoted figures.

Table 7. Battery and range (EPA) evolution Nissan Leaf [70].

Model	Battery (kWh)	Range (EPA) km
2011/2012	24	117
2013	24	121
2014/2015	30	121–135
2016	30	172
2017/2022	40/62	243/341

The second generation, 2017–2022, has a 40 kWh battery pack with an EPA-rated range of 243 km. Propilot Assist, a lane-centering system, is available on the two highest trim levels for an additional cost and has automatic parking in some markets. From 2019, a Leaf e+ (Leaf Plus in North America) variant has been offered. It has a larger 62 kWh battery

(59 kWh usable) providing an EPA range of 364 km and a new 160 kW motor. In June 2022, the Leaf received a facelift for the 2023 model year. In the US, the EPA range was slightly reduced to 240 km for the 40 kWh version and 341 km for the 62 kWh version [71].

Caredge, an experienced and renowned car seller, presented a study on EV depreciation [72] as presented Table 8. The price remains fairly stable over the years, particularly considering inflation, while the range increased, due obviously to the price drop of Li-ion batteries and improved technology.

Table 8. Nissan Leaf price evolution [72].

Years Old	Depreciation (USD)	Residual Value	Resale Value (USD)	Mileage
0	0	100%	38.309	0
1	5187	86.46%	33,122	12,000
2	8930	76.69%	29,379	24,000
3	18,745	51.07%	19,564	36,000
4	19,143	50.03%	19,166	48,000
5	20,855	45.56%	17,454	60,000
6	22,740	40.64%	15,569	72,000
7	25,246	4.10%	13,063	84,000
8	27,207	28.98%	11,102	96,000
9	27,885	27.21%	10,424	108,000
10	29,073	24.11%	9236	120,000

Figure 6 below shows the price depreciation of the Nissan Leaf over 10 years in the USA market based on a study conducted by CarEdge [72]. The curve Figure 6 is nonlinear and fits one of the models of depreciation as presented in this manuscript, Section 6; the first years are steeper than the rest. The behavior shows a linear behavior after 4 years of usage.

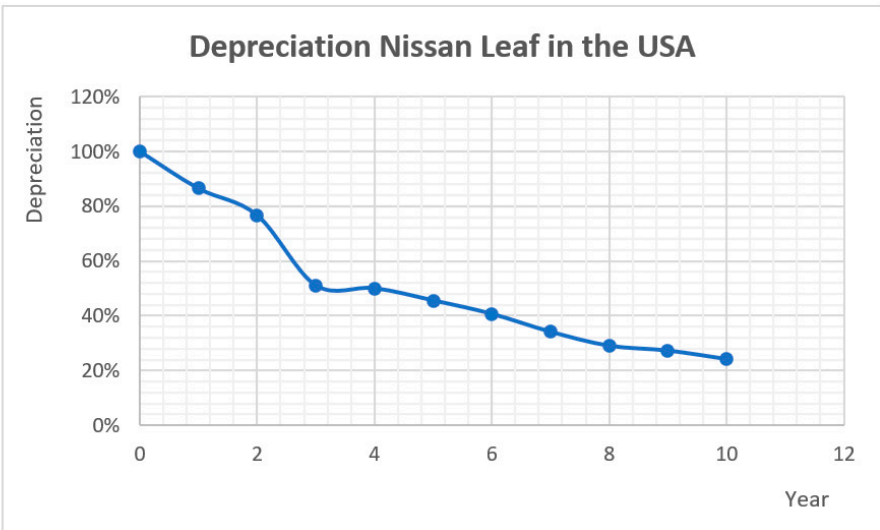

Figure 6. Evolution of the Nissan Leaf value left with time of use.

b. *Tesla Model S [73]*

The Tesla Model S is a full-sized, all-electric luxury sedan. It played a pivotal role in establishing Tesla's reputation as a producer of high-performance and long-range electric vehicles. Since its introduction in 2012, the Model S has garnered significant attention and has been instrumental in pushing the broader auto industry toward electrification. The Tesla Model S was unveiled in 2009 and began deliveries in 2012. It followed the Tesla Roadster, which was the company's first production vehicle. The Model S was a statement that electric cars could provide long range, high performance, and a host of technological features without compromising on luxury. The Model S introduced the large central touchscreen interface, which controls most of the car's functions, setting a trend that many automakers have since adopted. Over-the-air updates allow Tesla to remotely upgrade the software of the vehicle, introducing new features, improvements, and fixes. The Model S has seen multiple updates since its introduction. As of 2023, Tesla has sold a total of about 630,000 Models S/X vehicles in the world.

Based on a study in reference [26], a Tesla Model S will depreciate 35% of its original value after 5 years. This model does remarkably well for an alternative fuel vehicle, as most EVs and plug-in hybrids do not do well when it comes to maintaining their value. Tesla's depreciation curve shows that it loses a lot of value in the first three years but flattens out significantly in later years. This can be a result of purchasers of new Teslas historically getting significant incentives from the government for buying an EV—at times as much as USD 7500 upon purchase. If one buys a used one, however, there is no incentive benefit. All things considered, for a higher-end EV with performance, the Model S is in a class by itself and is tough to beat.

In the technical evolution, Table 9 below shows for the Tesla Model S a range evolution from 426 km in the 2012 model to 603 km in the 2022 model, including an autopilot; meanwhile, the catalog price dropped from USD 115,050 to USD 99,990.

Table 9. Technical evolution of Tesla Model S [73].

Model S	2012 85 RWD	2022 Long Range Dual Motor
Price (Long Range)	USD 115,050	USD 99,990
Price (inflation adj.)	USD 144,069	USD 99,990
Range (miles)	265	375
0–60 MPH	4.3 s	3.1 s
Autopilot/FSD	None—no cameras (Autopilot was introduced in 2014)	Autopilot standard, FSD Upgrade USD 12,000
Charging Rate (kW)	150 (12.55 km/min max)	250 (17.7 km/min max)
Gaming	Chess, Backgammon, some 80s arcade games	Equivalent to modern game consoles. Steam client support planned

The curve Figure 7 shows the depreciation of the Tesla Model S in the USA market over a period of 10 years; it follows a nonlinear depreciation model as well based on a study conducted by CarEdge [74] as presented Table 10. Tesla cars defied the trend in depreciation while most EV models lost a considerable amount of their original value. A study showed a depreciation rate of 36.3% for the Tesla Model S (Figure 4) and 33.9% for the Model X, two of the company's most popular models. Tesla vehicles match their ICE counterparts in terms of value conservation.

Tesla cars are resilient when it comes to preserving their value for different reasons. Tesla vehicles receive remote updates throughout their service life. Such a technical possibility reduces the loss of value caused by obsolescence because any upgrades to new model years will also apply to older vehicles. As well, another factor is the exclusivity that consumers have come to associate with Tesla. The company also operates a supercharger network. Tesla also does not rely as much on buyer incentives as other manufacturers.

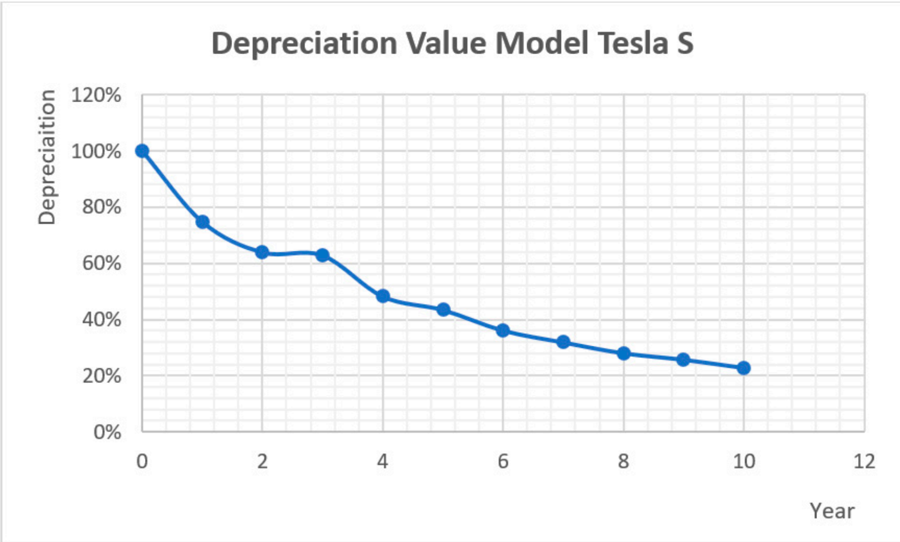

Figure 7. Depreciation of Tesla Model S 2012–2022.

Table 10. Evolution cost of Tesla Model S and depreciation [74].

Years Old	Depreciation (USD)	Residual Value	Resale Value (USD)	Mileage
0	0	100%	83.915	0
1	21,155	74.79%	62,760	12,000
2	30,277	63.92%	53,638	24,000
3	31,166	62.86%	52,749	36,000
4	43,409	48.27%	40,506	48,000
5	47,420	43.49%	36,495	60,000
6	53,555	36.18%	30,360	72,000
7	57,079	31.98%	26,836	84,000
8	60,301	28.14%	23,614	96,000
9	62,231	25.84%	21,684	108,000
10	64,665	22.94%	19,250	120,000

The popularity and reputation of Tesla among EV brands as the most selling brand in new EVs and with the most advanced technology and slowest depreciation stand with the same posture in the second-hand EV market. Pre-owned EVs with the steepest price drops tend to be older models with what many consider to be dated technology, particularly the Nissan Leaf and Chevrolet Bolt EV. Tesla is the best-selling brand in the used EV market in the United States, with the Model 3 that held 34.9% of the share in 2023.

One-to-five-year-old models witness the steepest depreciation. A study from iSeeCars [75] classified the top sellers in the United States as a reference market in 2023, with the market percentage of one-to-five-year-old models.

As shown in Table 11 below, in almost all markets, the most selling used EVs will have in the top list the Tesla Model 3 and Nissan Leaf for vehicles under 5 years old.

Table 11. Market share of EVs in the USA [75].

Brand and Model	Market Share	Observations
Tesla Model 3	34.9%	Technology and brand
Tesla Model Y	11.9%	Technology and brand
Chevrolet Bolt EV	6.9%	Affordability
Nissan Leaf	6.2%	Affordability
Tesla Model S	5.6%	Technology and brand
Tesla Model X	5.5%	Technology and brand
Ford Mustang Mach-E	4.6%	Symbol
Audi e-tron	2.9%	Brand reputation
Porsche Taycan	2.4%	Symbol
Volkswagen ID.4	2.2%	Brand reputation

6. Depreciation Calculation Methods for Electric Vehicles

From an empirical point of view and from professionals, as in references [64–66,68,72–74], as well as analysts, the reality of depreciation is that it follows a nonlinear curve. It is steeper the first years before slowing down with a quasi-linear behavior in the later years.

Several methodologies can be applied to assess the depreciation of EVs. Both Figures 6 and 7 show a nonlinear behavior of the depreciation of the Nissan Leaf and Tesla Model S with a steeper drop the first 3 years and a quasi-linear behavior as the EV is aging. The global depreciation corresponds to the declining balance method, while the depreciation corresponds better to the straight-line approach in the later ages of the EV.

6.1. The Straight-Line Depreciation Method [76]

The straight-line depreciation method is a common approach, as in Figures 6 and 7. This straightforward and widely used method assumes a constant rate of depreciation each year over the vehicle's lifespan. As an illustration, an EV expected to have a lifespan of 10 years and retain 40% of its value would depreciate by 6% of its original value annually.

The calculation is performed by dividing the depreciable balance (purchase price minus salvage value) by the number of years of useful life.

$$\text{Depreciation} = (\text{Purchase Price} - \text{Salvage Value})/\text{Years of Useful Life}$$

The straight-line method assumes equal depreciation each year and implies the asset is held for the entire year.

6.2. Declining Balance Method [77]

The declining balance method is an alternative method. The depreciation is more important in the first years of operation of the vehicle. This can be more reflective of the actual wear and tear on the vehicle, as well as the rapid pace of technological obsolescence in the EV sector. For instance, a new EV model with cutting-edge battery technology may lose value more quickly in the first few years as newer models with even better performance are released.

To calculate depreciation under the declining balance method, it must first be known what the rate at which depreciation was to take place was. Those rates were specified as a maximum allowed for various classes of assets or any rate less than those. The rate chosen at purchase must now stand for the remaining years of useful life for each asset.

In year one, depreciation was calculated as follows:

$$\text{Depreciation} = \text{Rate (Purchase Price)}/\text{Useful Life}$$

At the end of year one, the remaining value was calculated as follows:

$$\text{Remaining Value} = \text{Purchase Price} - \text{Depreciation}.$$

In year two, depreciation was calculated as follows:

$$\text{Depreciation} = \text{Rate (Remaining Value)/Useful Life}.$$

A new remaining value was calculated by subtracting current depreciation from the last remaining value. All succeeding years are calculated in the same manner. Salvage value is not used in the equations anywhere, but the remaining value can never fall below the specified salvage value. Furthermore, the rate chosen and used in the equations will not change throughout the useful life.

The declining balance computation must be adjusted for assets held less than a full year. Like a straight line, the adjustment process is simple and involves only the multiplication of the full-year depreciation amount by a fraction representing the portion of the year the asset was held.

This method could apply to the depreciation of EVs if the study was extended to a longer period.

Other methods to evaluate EV depreciation are the sum-of-years digit method and the residual value models [78]. These models consider the expected value of the vehicle at the end of its lease term or ownership period. Based on factors such as projected mileage, anticipated condition, and future market conditions, the residual value of the vehicle is calculated. As an illustration, an EV with a high expected residual value after three years may be more attractive to lease than one with a lower residual value, influencing the monthly lease payments.

7. Sources of EV Depreciation

EVs are reshaping the automotive landscape, offering an eco-friendly alternative to traditional ICE vehicles. However, like all assets, EVs depreciate over time. The rate and factors of depreciation for electric vehicles can differ significantly from their internal combustion counterparts, affecting both consumer choices and long-term financial planning. Understanding how electric vehicle depreciation works is crucial for buyers, sellers, and industry stakeholders [79]. It not only influences individual purchasing decisions but also impacts broader economic and environmental policies. EVs are relatively new to the market; evaluation of depreciation can be more complicated compared with ICE vehicles. For example, in the USA, electric vehicles depreciate by the amount of the tax credit that is available on that EV. For used vehicles, the problem of depreciation is even more complicated.

Experts present that the reasons for EV depreciation vary from the flood of new models to battery degradation. Facing "EV deprecation over the initial years of ownership is the most expensive part of owning a new vehicle". A possible consequence is that as more EV potential buyers are aware of such a fact, the fewer will be interested in acquiring an EV.

In a three-year cost-of-ownership analysis studying comparable Ford and Hyundai EV/ICE vehicles in the market today, Car and Driver looked at maintenance, refueling, and depreciation costs while driving 24,000 km a year. The study found that the Hyundai Kona and Ford F-150 EVs outperformed their ICE peers in the cost of fuel and maintenance, but that depreciation was the EVs' Achilles heel.

"It's clear that EVs depreciate quicker than their gas counterparts", the study reports that the Kona ICE depreciated by USD 9795 compared with USD 15,305 for the Kona Electric. And the Ford F-150 depreciated by USD 13,981 while the F-150 Lightning EV lost USD 15,738 [80].

Studies show that EVs generally depreciate faster than their ICE vehicle counterparts. It is worth it to point out that the EV market is still relatively new for the comparison to be definitive. The average three-year-old EV loses about 52% of its original value, higher than the 39.1% typically seen in ICE vehicles. Such a difference comes from several factors, such as technology, brand reputation, and government incentives.

Different Factors Affecting EV Depreciation

- Government Incentives

Government subsidies for EVs have been established around the world to support the adoption of EVs and the development of the industry. These incentives in different forms are mainly concerned with acquisition subsidies materialized with purchase rebates, tax exemptions and tax credits, and additional advantages from access to bus lanes to waivers on fees (charging, parking, tolls, etc.). The amount of the financial incentives may depend on vehicle battery size in some countries or all-electric range in others.

Subsidies that are concerned with only new EVs are more likely to negatively affect depreciation rates. In the case of China, for example, where second-hand EVs face faster depreciation than in other regions, subsidies for EVs are based on their mileage, which is largely determined by battery capacity. Consequently, vehicles with longer mileage were eligible for higher subsidies, the amount of which was calculated directly from the size of the battery. That may explain the faster EV depreciation in China.

A prior detailed study conducted by the authors of incentives for EVs is presented in reference [2].

Incentives for EVs come in many forms, including tax credits, rebates, and manufacturer discounts. These incentives reduce the initial purchase price, making EVs more accessible to a broader range of consumers. However, their impact on the secondary market, particularly on resale prices, is a complex and evolving story. Subsidies and tax credits can reduce an EV's purchase price, which may lead to a lower resale value as these incentives are factored into the depreciation calculation.

The rate at which EVs depreciate is a critical factor influenced by incentives. Traditional ICE vehicles have well-known depreciation figures, while EVs are yet to get theirs established. Incentives that make acquisition more affordable lead to faster depreciation, particularly in the first years, but this may level off as the market gets more mature.

These incentives make it easy for new EV owners, but they will certainly affect the second-hand EV market. More affordable new EVs make used ones less appealing as long as the depreciation rates are not adequately adjusted.

Incentives certainly lead to lower resale prices. When new EVs are heavily subsidized, the value of used models drops from the buyers' perspective. Consumers preferences will go to new incentivized EVs rather than pre-owned vehicles. Such consumers' choice is likely to result in an offer of used EVs higher than demand, driving down their prices.

EVs are steadily gaining attention in the automotive market due to incentives promoting their adoption by making them more affordable.

While the immediate impact of incentives might seem negative for resale prices, the long-term effects are less clear. As more drivers adopt EVs, the used EV market becomes larger. This increases over time, the acceptance and adoption of EVs possibly leading to higher demand and better resale values.

Looking ahead, the growing popularity of EVs is likely to boost their residual values over the coming years compared with now. In 2023, EVs saw a resale value retention of just 41%, whereas ICE vehicles held 66% of their value. Such a situation is expected to improve for EVs.

Experts predict that as the market for EVs grows resale values will become more stable and predictable. According to a study, EVs that return to the market after a standard 36-month lease term are expected to retain an average of 53% of their value by 2027. This is a significant improvement from the 41% retention seen in 2023.

Increased incentives for electric vehicles undoubtedly influence their resale prices, creating both challenges and opportunities. While these incentives can initially depress resale values, the growing acceptance and adoption of EVs are likely to stabilize the market over time. For consumers and industry stakeholders, understanding these dynamics is crucial for making informed decisions in the evolving EV landscape [81].

- Technology

Electric vehicles are merging with AI, creating a smarter transportation landscape. AI optimizes charging schedules, personalizes the driving experience, and even assists in battery production. This collaboration improves efficiency, extends driving range, and paves the way for autonomous driving. Ready to explore the future of sustainable transportation? Learn more about AI-powered EVs in this comprehensive article.

The pace of technological advancements is one of the most critical factors influencing EV depreciation. Battery technology's continuous improvement leads to longer ranges and shorter charging times, which can make an important difference between two generations of the same EV model. The integration of artificial intelligence as advanced driver-assistance systems (ADAS) as well as other various technological innovations could also increase the value retention of EVs.

As EV technology rapidly advances, older models can become outdated quickly, leading to faster depreciation. The demand for EVs also plays a crucial role in determining their resale value. Besides batteries, continuous progress in performance (Figure 8) and price drop (Figure 9), the other increasing technological integration in EVs is artificial intelligence (AI).

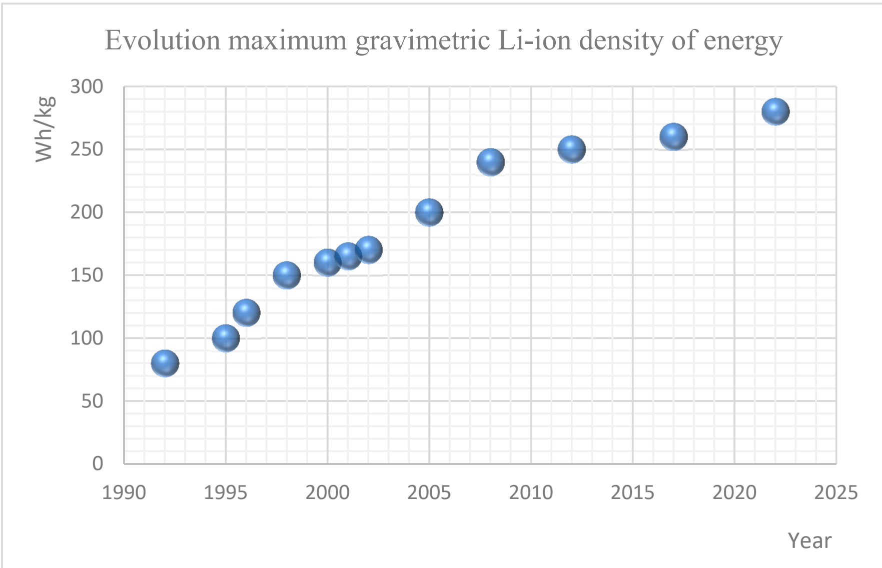

Figure 8. Technology advances: the energy density of Li-ion batteries has increased from 80 Wh/kg to around 300 Wh/kg since the beginning of the 1990s [82].

Figure 8 above shows the continuous progress in energy density in Li-ion batteries, particularly in the density of energy, compared with nickel metal hydride (NiMh) and nickel cadmium (NiCd) batteries that reach saturation in their performance or energy densities.

Figure 9 below shows the Li-ion battery price drop between 2010 and the projection in 2030.

Better battery lifespan and lower cost of replacement or upgrade will add to pre-owned EVs value.

AI assists in machine learning, safety, efficiency, battery management, vehicle driver interaction, and smart driving. AI is becoming an integral part of the vehicle technology; furthermore, its integration in EVs grows very rapidly, as shown in Figure 3.

The rapid evolution of AI, ML (machine learning), and DNN (deep neural network) algorithms in EVs contributes to increasing the depreciation rate of EVs due to the difference between two same models of different years. There is a total increase in the number of algorithms of about 820% between 2010 and 2022 (Figure 10). There is presently no inflection in the evolution of technology in the EV industry. A plateau in the integration of technology in EVs would most likely result in a rebirth of the second-hand EV market.

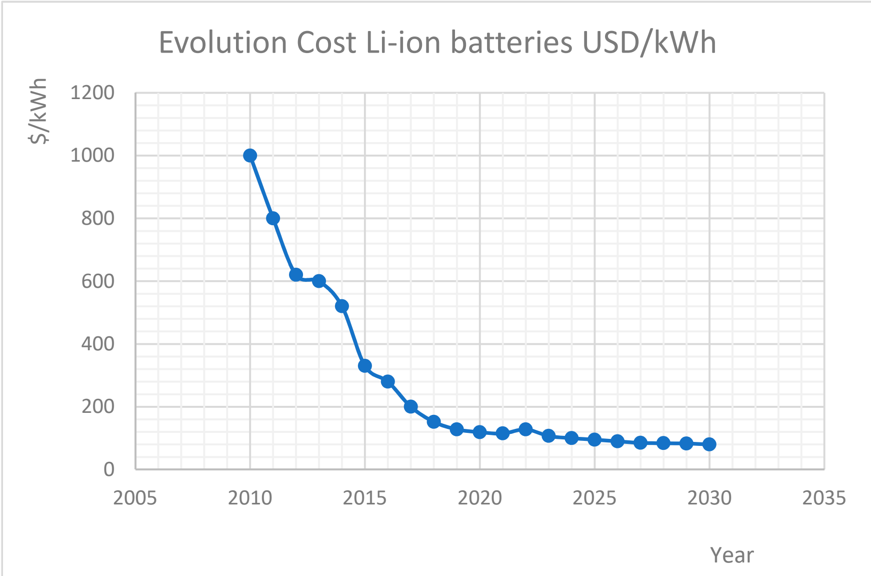

Figure 9. Lithium-ion battery price history and forecast [83].

Figure 10 below shows the trend in algorithm usage for autonomous vehicles.

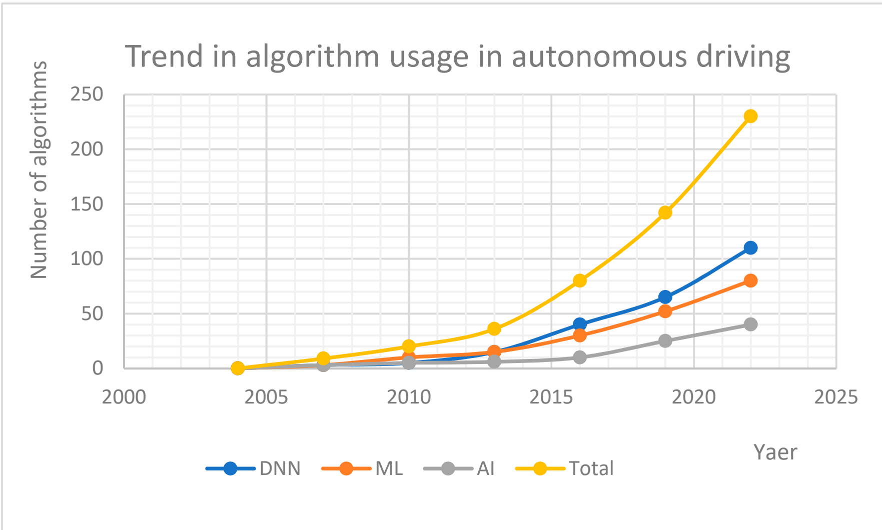

Figure 10. Evolution of technology-related algorithm usage for autonomous vehicles [84].

Prior to 1993, the number of patents increased gradually with a small slope; between 1993 and 1997, there was a huge increase before a slowdown and a peak in 2012 with more than 20,000 patents and then a decrease in the number of intellectual properties filed. The same trend was observed for the number of institutions authorized to EV patents. Furthermore, since 2008, EV patents have been authorized in more than 20 countries every year.

- The Battery

Battery condition significantly impacts EVs value. The older the battery and the higher the mileage, the lower the value of the EV, exactly as it is for ICE vehicles. The more a car is driven, the less it is worth. This holds true for EVs, where higher mileage and older age contribute to faster depreciation.

The residual value of an EV is determined by several factors, among which the battery is certainly one of the most important. Regarding the battery, it is its state of health (SoH) that determines the residual value of the EV. There is still no standard method of calculating EV battery SoH in the battery diagnostic; the range remains the main reference.

Electric cars: battery condition and service life

Lithium-ion batteries are said to have a service life of eight to 15 years or 150,000 to 300,000 km, depending on usage and charging patterns and methods. Various manufacturers issue warranties for their batteries, often with a SoH of at least 70% over eight years or 160,000 km. Such warranties can have a positive impact on the residual value of an electric car since they provide credibility and safety. Furthermore, reputable EVs hold a higher residual value.

The following aspects are important in terms of service life:

Capacity loss: The battery of an EV naturally and progressively degrades over time even if it is not used. The residual capacity of the battery is determined as a percentage of its original value. As a reference, Tesla has published data showing that its batteries still have around 80% of their original capacity after 240,000 km. Similarly, other sources indicate that it is possible to travel several hundreds of thousands of kilometers before the battery power decreases significantly. Obviously, from the manufacturers' perspective, it is important for this figure to remain as high as possible for the longest period of time, ideally throughout the life of the vehicle.

The number of battery cycles: The battery cycle is an important parameter in the knowledge of the battery condition. A battery's lifespan is determined by its potential number of cycles, which is obviously limited. For given conditions of usage, the number of cycles a battery has completed indicates its capacity drop.

Fast charging (DC charging): Cars charged primarily at fast-charging stations may experience quicker battery degradation, affecting resale value. Fast charging may sound attractive, but it remains one of the main variables negatively affecting the life of a battery. It puts a much more important strain on the battery than slow charging. Batteries that frequently undergo quick charging are likely to lose capacity at a faster rate.

For a better knowledge of the value of an EV, batteries need diagnostics and evaluation. On average, owners replace their vehicles every five years or after 90,000 km, before they arrive on the second-hand car market. Presently, there is no standard method accepted to determine the residual value of a used EV [85].

- Brand Reputation and Loyalty

Vehicles from reputable manufacturers tend to retain their value better. For instance, Tesla models have shown slower depreciation rates due to the brand's strong market presence and continuous software updates. Brand loyalty can also impact resale values. As consumers become more familiar with and loyal to specific EV brands, the resale market for those brands may strengthen. This loyalty can mitigate some of the depreciation effects seen with increased incentives.

- Low Gas Prices

The cost of gasoline and diesel can affect the electric vehicle depreciation rate. While fuel prices will never be as low as EV charging prices, they can get low enough to make people stick to ICE vehicles. The resulting loss of interest will reduce the value of EVs, especially the older models.

Of course, the opposite is possible as well. In fact, gas prices are several times higher than their EV charging equivalent halfway through 2022.

- Decreasing Sticker Prices on Brand-New EVs

Every year, car manufacturers introduce new EV models. Most have been designing electric cars for lower budget drivers to expand their market base.

The lower sticker prices on budget-friendly options not only encourage drivers to invest in an EV but also increase the depreciation rate.

- Range Anxiety

Many people are concerned that their EVs cannot match the range of ICE vehicles. Depending on the type of EV, their concerns may be valid.

Hybrid and plug-in hybrid EVs have gas or diesel engines that can power their electric motors when their batteries run out. However, all-electric vehicles (AEVs) rely exclusively on their batteries. There are also fuel cell vehicles that burn hydrogen fuel.

AEVs can only replenish their batteries at a charging station. While there are more than 46,000 charging stations in the US, gas stations still outnumber them throughout the country. As for hydrogen stations, there are less than 60, and most are in California [86].

- Evolution of EV Depreciation

As the EV market matures and grows, several factors are likely to influence their depreciation rate. Here are a few points that may determine the future of EV depreciation:

- Market Share

The demand in the EV market is likely to increase as the number of EV owners increases and these vehicles become more mainstream. This higher demand will have a positive impact on the pace of EV depreciation.

- Availability of Charging Infrastructure

The availability of charging infrastructures will limit issues related to EVs range and consequently improve the image and appreciation of EVs. This is in favor of the used EV market.

- Consumer Appreciation

Increased public awareness, acceptance of EVs, and recognized benefits of EVs will help used EVs retain their value.

- The Used EV Market Effect on Depreciation

As the EV market continues to grow, the share of the second-hand EV market will also be more significant, and these used vehicles will have better depreciation rates.

Here are a few points related to the impact of the second-hand EV market on the depreciation of used EVs.

- Availability of Second-Hand EVs

After more than 10 years of operation, the first wave of EVs will arrive on the second-hand vehicle market. This market will constantly grow. This increasing offer of pre-owned EVs may as well lead to a form of saturation with offers higher than demand, leading to a faster depreciation rate.

- Economic Aspects

The offer of government incentives for new EVs makes them more affordable and makes used EVs financially less attractive to buyers unless their price is significantly lower.

- Consumer Awareness and Confidence in EV Technology

Once EV technology reaches a higher level of maturity, the likelihood for consumers to invest in used EVs will be more of a reality, and their value will be higher [87].

The way forward: solid-state Li-ion in EVs

Solid-state lithium batteries are said to be next-generation batteries with a higher energy density and improved safety. They use solid electrolytes and no separator [88,89].

It is very likely that lithium will continue to play a central role in the EV industry. Car manufacturers have been working on a rapidly emerging new battery technology, such as solid-state batteries. Solid-state lithium batteries use a solid material rather than a potentially combustible gel. These materials are neither volatile nor combustible. The higher energy density would increase the range of EVs by between one-third and 50%. Toyota has a solid-state battery-powered car prototype with production expected in 2024 [90].

Energy storage for electric transport still needs a longer lifespan, a lower rate of degradation, a higher energy density, less sensitivity to high temperatures and temperature variations, and less sensitivity to humidity as well. There is a significant amount of research being conducted to improve battery quality and performance based on experiment, theory, or simulation [91–96]. The main orientations to reach such a goal are design and heat management, material composition, and the structure [91–96].

8. Lessons from China

8.1. End of Subsidies

The EV sector in China, as in all major markets, has benefitted from government support in its early phase as an up-and-coming green industry. In China, the government has been subsidizing EV manufacturers since 2009. Similarly, EV owners have received direct subsidies for several years. Governments subsidized EVs to encourage their adoption and reduce dependence on fossil fuels. Subsidies are also a way to boost the domestic EV manufacturing industry. On consumers, the subsidy cut will make EVs more expensive. Prices surged by 15–18% [97], which will make them less affordable for some people. Manufacturing companies have expressed concerns about their financial stability and may also consider passing on charges to the customers, leading to higher prices.

More than USD 28 billion was spent on EV subsidies and tax breaks in China during the period 2009–2022 [98,99]. As the market has matured, government support and subsidies have declined. Purchase subsidies for EV consumers were phased out at the end of 2022.

Table 12 below shows the breakdown of ending government subsidies in China.

Table 12. Breakdown of ending government subsidies in China [99].

Policy	End Date	Specifics
Exemption from consumption tax and vehicle and vessel tax	Not specified	Car makers exemptions from consumption tax and vehicle and vessel tax for the production, subcontracted processing, and importation of EVs.
Purchase subsidy	End of 2022	Maximum subsidy of 12,600 yuan per vehicle for battery electric vehicle (BEV) passenger cars and 4800 yuan for plug-in hybrid (PHEV) passenger cars, including extended-range PHEVs. Maximum subsidy of 50,400 yuan per vehicle for non-fast-charging BEV buses; 36,400 yuan for fast-charging BEV buses; and 21,300 yuan for PHEV (including extended-range) buses. Maximum subsidy of 28,000 yuan per vehicle for BEV trucks and 17,600 yuan for PHEV (including extended-range) trucks.
Purchase tax exemption	End of 2027	New EVs purchased by 31 December 2025 are exempted from vehicle purchase tax. New EVs bought between 1 January 2026 and 31 December 2027 have their purchase tax reduced by half.
Infrastructure support	Not specified	Provision for discounted electricity tariffs at EV charging and battery-switching facilities. Government-guided pricing of service fees for EV charging and switching. Grid-conversion costs for EV charging and switching facilities are incorporated into generator tariffs for power transmission and distribution.

In 2022, the country sold about 3.5 million EVs, accounting for over half of all sales globally [100]. The sales are supposed to continuously grow in the coming years. This is a sign of the maturity of the Chinese EV market and the minor role of subsidies.

The main question that remains unanswered is if China's EV industry can maintain its pace in the long run as subsidies are no longer offered.

China is one of the most dynamic EV markets for both manufacturers and consumers. It is seen also as the most mature market. The Chinese government decided to end subsidies in 2022, with the claim that the market is not driven by subsidies but technology with continuous innovations. The government also attributed China's EV edge to "well-established supply chain systems and market competition" [101].

Ending subsidies without a major shift in the market dynamic is possible when the law of demand and supply only is not enough to keep the necessary equilibrium as a sign of market maturity.

Figure 11 below shows that sales did not drop despite the end of subsidies in 2022, nor was there a surge in the year prior to the suppression of subsidies despite the awareness of potential buyers. This shows the importance of non-subsidy drivers as technological innovation and cost of ownership compared with ICE vehicles. There is as well progressively a price parity between EVs and their ICE counterparts as already presented.

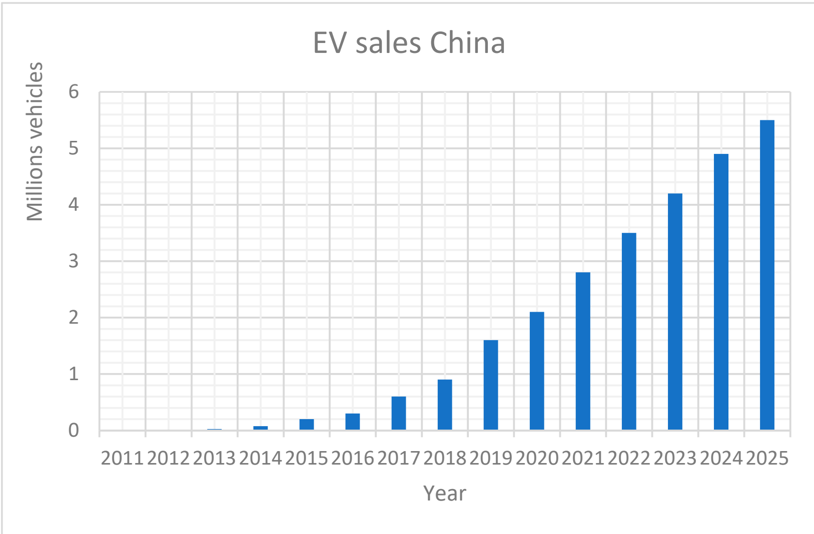

Figure 11. EV sales in China [102].

The end of subsidies will change the dynamics of the second-hand EV market as consumers will pay the real cost of new EVs, and the gap between new and used EVs will be much wider. Second-hand EVs will look relatively much more affordable compared with new EVs, possibly leading to a slower depreciation rate of EVs.

8.2. Second-Hand EV Market

In China, the number of new electric car registrations reached 8.1 million in 2023, increasing by 35% relative to 2022. Comparatively, the used EV market in China is still small, with only 500,000 used passenger electric models sold in 2020 [103] and a progress to almost up to 800,000 in 2023. Most of those vehicles were compact, short-range models that dominated EV sales in China from 2015 to 2019 [103]. Some of these models were also aimed at capturing the maximum subsidy from the government rather than being designed fully around consumer needs. Subsidies in China were based on the range of EVs [1]. While the second-hand EV market is just starting in China, like in many other countries with an important EV penetration, it is an important step for the industry. It is a sign of growing buyers' confidence in their reliability. Due to the lack of transaction volume, it is hard to fully track used EV sales yet. Changes may be expected in the coming years. Many car manufacturers are extending battery warranties and offering valuations and certifications for pre-owned EVs. That should be a great support for the second-hand market [103]. Average EV range could also begin stabilizing in the next few years after a continuous progress. In fact, the average EV range has increased by about 13% each year since 2011 [103], but with average standard ranges now pushing almost 400 km, that may start to plateau in the next few years.

As for now, a study shows that for over 20,000 pre-owned EV sales in China, their value dropped by an average of 45% after the first year, 58% after the second, and 67% after the third year [103,104]. Such a depreciation is much faster than for ICE vehicles as well as in other EV markets. In China, the residual value of EVs drops far more quickly than for ICE vehicles, which can stay at about 60% to 75% even after three years. The typical profit for a dealer is also far lower, or below 3000 yuan (USD 423) [105]. The rapid depreciation of Chinese used EVs is due to the fact that the technology is still progressing very fast among Chinese EV manufacturers, bringing different and rapid improvements and therefore making early models obsolete. An optimistic sign that can be pointed out is that the situation of pre-owned EVs will turn around soon; high-end EV brands like Tesla already have much lower depreciation rates [106–108].

The Chinese used EVs may find a second life out of China. In fact, in the last decades, China rose gradually to a global automobile manufacturing power for both EV and ICE vehicles. With growing exports of new vehicles in the last few years, the country even overtook Japan in 2023. In fact, in the first quarter of 2023, China overtook Japan as the global leader in the export of new cars, with a total of 1.07 million vehicles exported, of which nearly 40% were electric. 2009 was already a breakthrough year as China passed the USA in new car sales [109].

As for now China's exports are expanding to used cars. In fact, until 2019 exporting used vehicles was prohibited for domestic policy reasons. Furthermore, the country reimagined its long-term strategy on used car exports including EVs.

After the final owner of an EV decides to replace his vehicle, it could have different types of second lives as being used locally or sent abroad as long as the vehicle is fit for road use.

If in the future there are equal chances to export EVs as ICE vehicles, analysts project that 40% of Sub-Saharan Africa vehicles will be EVs through imports. Even if these projections may be over evaluated, they show that there is an important potential to export used EVs to developing countries [110].

Developed economies are progressively adopting EVs to decarbonize road transport. Since fleets in developing countries mostly rely on the import of used vehicles, these fleets will have their EVs share through imported pre-owned EVs rather than new vehicles. In fact, as EVs terminate their life cycle in developed countries, it is likely that they will be increasingly exported to developing countries for a second life. The consequence of fast depreciation may be an increasing volume of EV exports to developing countries. That requires that emerging economies have appropriate infrastructure and policy to create the demand for EVs.

To support EV exports to developing countries and therefore strengthen and secure its own industry, China may develop new types of partnerships to assist developing countries in defining and expanding their electric transport policy; it may particularly concern charging stations and battery replacement, as already witnessed with mobile phone batteries. EV manufacturing countries may develop the same strategies to expand their markets.

In fact, used EV exports from major EV markets have been growing in the last few years. In 2022, China exported about 70,000 used vehicles; this is a considerable increase on 2021, when less than 20,000 vehicles were exported. About 70% of these were EVs. In 2023, the Ministry of Commerce released a draft policy on second-hand vehicle export that, once approved, will allow the export of second-hand vehicles from all regions of China. Used car exports from China are expected to increase significantly due to the 2023 draft from the Chinese Ministry of Commerce allowing used vehicle exports from all regions of China against the 27 cities and provinces that were approved in 2019 to export used vehicles of any kind.

9. Conclusions

For the past 10 years, the EV has proven itself to be an important tool in the decarbonization of road transport. EV technology has reached a certain maturity even if it is still progressing, particularly regarding battery technology and the integration of AI. The market was able to pick up thanks to subsidies; it grew and gained popularity thanks to EVs lower cost of operation compared with ICE vehicles but higher cost of ownership when depreciation is considered. The second-hand vehicle market is an important proportion of the global automobile market. Pre-owned EVs similarly will bring an important contribution to road transport decarbonization.

The second-hand EV market is still in its infancy, and consequently it is not yet fully determined. Nevertheless, some variables seem determinant:

- Subsidies on new EVs that contribute to faster depreciation of used EVs, on the one hand, but contribute to making EVs a mainstream means of transportation, so in the long run it will be beneficial to the used EV market as customers would have built more confidence about EVs.
- The integration of technology in EVs, particularly AI, contributes to faster depreciation of older EV models as the technology is still progressing very fast.
- The battery technology increasing performance allows better range for new models while older models suffer shorter range due to battery deterioration with mileage.

Presently, EVs have a shorter range than ICE vehicles; they are more expensive and depreciate faster. High-end EVs will retain their value better, while low-end EVs will depreciate much faster.

The maturity of the EV market will correspond to the end of subsidies, a form of price parity between EVs and their ICE counterparts. EVs and ICE vehicles will depreciate at comparable rates.

Author Contributions: Conceptualization, B.D.; Methodology, B.D.; Validation, G.K.A. and B.D.; Formal analysis, B.D.; Investigation, G.K.A. and B.D.; Resources, P.G. (Patil Gautam), G.P. (Gayatri Pode), R.P., G.K.A. and B.D.; Writing—original draft, B.D.; Supervision, B.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author(s).

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

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